

A coupled wind-vehicle-bridge system and its applications: a review

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Abstract. The performance of bridges under strong wind and traffic is of great importance to set the traveling speed limit or to make operational decisions for severe weather, such as controlling traffic or even closing the bridge. Meanwhile, the vehicle's safety is highly concerned when it is running on bridges or highways under strong wind. During the past two decades, researchers have made significant contributions to the simulation of the wind-vehicle-bridge system and their interactive effects. This paper aims to provide a comprehensive review of the overall performance of the bridge and traffic system under strong wind, including bridge structures and vehicles, and the associated mitigation efforts.

Keywords: vehicle aerodynamics; bridge aerodynamics; strong wind; traffic; bridge

1. Introduction

Strong wind, as one of the most common natural hazards, may threaten the safety of transportation infrastructures and passing vehicles. News about severe storms blowing over semi-trucks on highway and leading to fatalities has appeared on newspapers from time to time (Alleyne 2012, Jacobs 2008). These accidents caused by wind usually result in traffic blockage and driver injury, posing negative effects on transportation safety and human health. Specifically, wind effects on the vehicles traveling on bridges, instead of roadways, in wind-haunted areas need extra attention. For example, as shown in Fig. 1, the severe storm at wind speed over 65 miles per hour blew over a semi-truck on the Mackinac Bridge on July 18, 2013 (Torregrossa 2013). Oregon State Police reported that a semi-trailer was lifted into the air by huge gust of wind while it was traveling through the Waldport Bridge, causing blockage of three out of four lanes, as shown in Fig. 2 (Admin 2011).

Along with the advances in construction materials and technologies, the spans of suspension and cable-stayed bridges have been greatly extended to new limits (Holmes 2001), and a high

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number of those long-span bridges are in wind-prone areas. These critical bridges often cross over straits and canyons and support important regional traffic (Kitada 2006, Zhang *et al.* 2011). The complex interaction between vehicles, bridges, and wind plays a significant role in the safety of traffic on these long-span bridges. Such interaction effects are important to the safety of not only bridge structures themselves, but also the passing vehicles. On one hand, with a large volume of passing traffic, the bridge girders and decks are subjected to cyclic loadings due to the coupled vibration excited by both the turbulent wind and moving vehicles. As a result, the fatigue life of the bridge may be reduced and possible damage could occur on some local members or connections. On the other hand, the dynamic coupling effects also influence the vehicle vibration, the driving controllability, and even accident risks. In addition to the safety concern, the comfort ability for the drivers of vehicles passing on long-span bridges subjected to strong wind is another issue (Xu and Guo 2004).



Fig. 1 A semi-truck blown over on the Mackinac Bridge (Torregrossa 2013)



Fig. 2 Wind-induced accidents on Waldport Bridge (Admin 2011)

Compared to normal windy conditions, hazardous windstorms, such as hurricane and tornado, cause much more property damage and life loss. For example, hurricane Katrina took 1,836 lives and resulted in a total loss about \$108 billion, which makes Katrina the most destructive and costly natural disaster in the history of the United States (Knabb *et al.* 2005). Thus, in hurricane-prone areas, the evacuation during such kinds of wind hazards is very necessary. Since windy conditions typically remain before, during, and after the evacuation process, accidents constantly happening on the highways will greatly delay or even obstruct the important transportation line before or upon the landfall of hurricanes (Chen and Cai 2004a). Therefore, the associated safety assessment of the transportation system during hurricane evacuations becomes critical in terms of minimizing accident risks and possible delay.

Currently, decisions on driving speed limits and closing of the traffic on bridges and highways in windy environments are mostly made based on intuition or subjective experience. While driving speed limits could be too high to be safe or too low to be efficient, closing the traffic will totally obstruct the evacuation through such a transportation line. A rational prediction of the performance of vehicle-bridge systems under strong wind is of utmost importance to maximize the evacuation efficiency and to ensure the safety of the transportation system, including both vehicles and bridges. For these reasons, active research has been carried out in the last decade worldwide regarding the vehicle-bridge-wind coupled analysis. This paper aims to provide a comprehensive review of the state-of-the-art regarding the previous research on the overall performance of the bridge and traffic system under strong wind, including bridge structures and vehicles, and the associated mitigation efforts.

2. Bridge and vehicle aerodynamics

During the last two centuries, major structural failures due to the wind action have occurred, for instance, the collapse of the Tacoma Narrows Bridge in 1940, which have provoked much interest on investigating the wind effect on bridges (Davenport *et al.* 1971, Simiu and Scanlan 1996, Bucher and Lin 1988, 1989, Larose 1999). The wavelike motion of Volgograd Bridge (BBC News 2010) due to the local wind at some particular wind speeds further highlights the importance of wind effects on bridges even without causing bridge failures.

2.1 Bridge aerodynamics

Wind loads on bridges are dynamic in nature, which have to be considered when designing bridges in wind-haunting area, especially for long-span bridges. When the cross wind blows on bridges, the blockage of the decks influences the flow path, yielding an uneven pressure distribution around the bridge deck surface. The combined effects of non-uniform pressure distribution, flow turbulence, and vortex shedding on the bridge produce the wind loads that further cause complicated dynamic vibrations of the bridge. Wind loads acting on a bridge typically consist of the mean wind load component and the fluctuating wind load component (Mohammadi and Mukherjee 2013). Under both mean and turbulent wind loads, a typical long-span bridge may experience considerable dynamic vibrations, which is often predicted by conducting the aerodynamic analysis in the time or frequency domain (Chen and Kareem 2002, 2003). The wind-induced vibrations of long-span bridges and also cable components occur in the vertical, lateral, and torsional directions. Depending on specific wind and bridge properties (e.g.,

cross-sections, spans, and materials), several wind-induced phenomena may occur, such as the torsional divergence (or lateral buckling), vortex-induced oscillation, flutter, galloping, and buffeting in the presence of self-excited forces (Simiu and Scanlan 1996). Usually, the divergence, galloping, and flutter are classified as aerodynamic instability problems, while the vortex shedding and buffeting are classified as wind-induced dynamic vibration problems (Chen *et al.* 2004).

Buffeting is a type of random vibration caused by the wind turbulence in a wide range of wind speeds (Scanlan 1988), which leads to the bridge fatigue accumulation and also possibly discomforting issues for bridge users. When the wind speed is low, each torsional or vertical mode of the bridge mainly vibrates at a frequency around its natural frequency; however, the buffeting vibration is essentially a type of multi-frequency vibration in nature (Chen and Cai 2003). Buffeting is a continuous dynamic phenomenon on a long-span bridge as long as wind exists and it typically becomes stronger as the wind speed increases. When the wind speed keeps increasing and approaches the flutter wind velocity, the buffeting response of the bridge will be significantly amplified and the flutter instability is about to occur. Flutter is a type of diverging vibration of bridge, and is known as the instability phenomenon that would result in fatal damage to structures. Flutter instability is often the outcome of the evolution process during which the multimode buffeting vibration gradually transforms into a single-frequency flutter vibration. While many flutter studies traced the critical flutter velocity (Jeong and Kwon 2003), very few studies were carried out focusing on the time-dependent process of buffeting and flutter occurrence with the increase of wind speeds (Namini 1992, Ge and Tanaka 2000). Chen and Cai (2003) investigated the mechanism of transition from the multi-frequency buffeting to the single-frequency flutter, including the merging process of different frequencies when the wind speed keeps increasing. Coupled multimode analyses of buffeting and flutter are usually adopted to predict the wind-induced vibration of the bridge. A common approach to predict the multimode response is to solve the simultaneous equations with selected modes. A study by Chen *et al.* (2004) introduced a concept of Modal Coupling Factor (MCF), which can provide quantitative assessment of the coupling effects in the process of selecting modes.

The existing studies on bridge aerodynamics can be typically classified into the following three categories: wind tunnel tests, analytical approaches, and Computational Fluid Dynamics (CFD) methods:

Wind tunnel tests play an essential role in revealing the nature of the aerodynamic phenomena of structures under strong wind. Based upon the free vibration method, in the early 1970's, Scanlan and Tomko (1971) presented a method to obtain aerodynamic derivatives in wind tunnels according to the Theodorsen's theory, which leads to the rapid growth of the application of wind tunnel tests in the bridge aerodynamic analysis. The primary purpose of wind tunnel test is to provide researchers the information of the flow field and wind loads around a complex structure (e.g., wind pressure coefficients), which is essential to the rational prediction of the structural response. Wind tunnels used for the civil engineering applications are typically referred to the boundary-layer wind tunnels that can generate the vertical distribution of velocity at the test section similar to the profile of the wind encountered by prototypes. In general, the wind velocity distribution along the height follows the logarithmic or power law, which is yielded in wind tunnel with the use of roughness elements and spires upstream of the structures. On the other hand, the similitude theory requires that the wind tunnel tests must be conducted with models bearing the geometric, kinematic, and dynamic similarities. In other words, in wind tunnel experiments, the shape of the model and topographical features, velocity field, flow pattern, pressure distribution, and forces generated on the structures must be as close to the ones in real structure and its

surroundings as possible (Liu 1991). According to the size of the test section in wind tunnel and the objective of the wind tunnel test, different model tests can be designed. Generally, three types of vibration models are frequently used in wind tunnel tests, namely, the full aeroelastic models, section models, and taut-strip models. The full aeroelastic models require the geometric scaling of all dimensions and the use of appropriate material properties. Preparing the detailed model with all the scaled properties usually takes a long time and a high cost. The section models are the most frequently used model in wind tunnel tests and a representative segment of bridge deck is typically replicated following some scaling rules (Jurado *et al.* 2012, Chen *et al.* 2010b). The taut-strip model is regarded as an in-between model between the full aeroelastic model and the section model (Ma and Chen 2007) and used for studying the buffeting response of structures under natural wind (Davenport *et al.* 1992) or extracting the aerodynamic characteristics of bridge deck (Jiang 2000, Li *et al.* 2003). As a rigid model with springs and damping devices, the manufacture process of taut-strip models is more complicated than that of the section model, but much easier than that of the full aeroelastic model (Ma and Chen 2007).

Analytical approaches are often used to study the bridge aerodynamics through building an analytical model and investigating the concerned parameters and responses of the structure based upon the knowledge of structural dynamics and fluid mechanics (Ge and Tanaka 2000, Scanlan and Jones 1990). It typically involves the development of advanced finite element models of the bridge, characterization of wind fields and loads based on experimental measurements on sectional models, and the development of aerodynamic equations of the bridge-wind system. Such a dynamic system can be solved in either a time or frequency domain. The advantages of the analytical approach include low cost, easy to replicate, and the ability to cover various scenarios. However, due to the existing constraints on understanding the aeroelastic phenomena, some coefficients essential to the analytical studies, such as the static wind forces coefficients and flutter derivatives, are still dependent on experimental studies.

Computational fluid dynamics (CFD) is an efficient tool to investigate the aerodynamic characteristics of structures. With the developments of computer technology, CFD has made a promising progress on the application to the wind engineering (Shirai and Ueda 2003, Keerthana *et al.* 2011). Compared to traditional wind tunnel tests, CFD method requires less time and financial burden, and can visually reproduce the concerned processes (Rocchi and Zasso 2002). During the development of CFD technique, from 1950s to 1990s, the application of CFD method in wind engineering encountered specific difficulties associated with the flow around bluff bodies with sharp edges, such as buildings and bridges (Blocken 2014). The difficulty in conducting accurate simulation of complicated turbulence in high Reynold number flow due to the large dimension of bridges has hindered the CFD applications in bridge wind engineering. There are two approaches frequently used to model the turbulence in CFD techniques: Reynolds-Averaged Navier-Stokes (RANS) models and large eddy simulation (LES).

In a RANS model, the dependent variables of turbulent flow are expressed as time averaged variables to make the equation set numerically solvable. A 'Reynolds stress' is raised as an additional pseudo-stress from the turbulent motion of all scales in the procedure of averaging. How to determine the 'Reynolds stress' yields many types of approximated equations known as turbulence models, such as, k - ϵ model and k - ω model, each of which currently works well for the corresponding type of flow (Gosman 1999). In general, more complex models tend to give a better representation of the unsteady flow, for example, the full Reynolds Stress model can be used in the situation involving turbulent dispersion and buoyancy effects by computing each of the six Reynolds stress directly (Gosman and McGuirk 1993). Although the RANS models are applicable

to most of engineering problems, they only offer limited information for the turbulent characteristics of the unsteady flow, requiring additional efforts to solve the problems. Moreover, RANS can not well capture the behavior near the wall regions in low Reynolds number flow and needs to be facilitated using wall functions (Murakami *et al.* 1996).

LES is well suited to simulate the massively separating flow around bluff bodies and can provide useful information of the flow structure. In LES the scales of the turbulence are divided into large and small groups by a spatial filter. Only the large-scale turbulent motions are solved directly, while the small scales are represented with sub-grid scale (SGS) models. Obviously, direct solving the Navier-Stokes equation demands more time and computer power than solving the RANS models. In addition, the fine mesh requirement of LES will cause the mesh quantity as well as computing time to increase dramatically. However, the advantage of providing more accurate results and detailed information of the instantaneous flow often makes LES more acceptable than RANS despite the higher computational cost (Hemida and Baker 2010). Although CFD technique has gained much attention in wind engineering field during the past few decades, it still faces some major challenges hindering the process towards high-quality simulations. These challenges include the high Reynolds number in turbulent flow due to high wind speeds and large dimensions of structures, the complex flow patterns of separation and vortex shedding, and the accuracy of CFD simulation limited by the boundary condition in numerical simulations (Murakami 1998).

2.2 Vehicle aerodynamics

For vehicles driven on highways, the wind loading on the vehicle, along with the grade and curvature of the road, may cause safety and comforting problems (Baker 1991a, Baker 1991b, Baker 1991c, Baker 1994). To more accurately predict the associated accident risks in strong wind, appropriate data is required to quantify the aerodynamic forces and moment coefficients for different types of vehicles (Baker 1986a). In the automobile industry, the research on vehicle aerodynamic performance is mainly focused on reducing the drag force of the vehicle in order to conserve fuel consumption (Malviya *et al.* 2009, Patten *et al.* 2012), or on understanding the flow field around vehicles moving on the ground (Angelis *et al.* 1996, Guilmineau 2008, Corin *et al.* 2008).

When a vehicle is subjected to cross wind, or overtaking other vehicles, the flow field around the vehicle becomes asymmetric, which is very different from the drag force investigations in the automobile industry. In such a case, the resultant aerodynamic forces have six components that include the side force, yawing moment, and rolling moment in addition to drag force, lift force and pitching moment (Hucho 1993). As the drag force influences the velocity of the vehicle, the side force and yawing moment may cause vehicle instability and handling difficulties. Baker and his co-workers (Coleman and Baker 1990) conducted a series of tests on the vehicle aerodynamic forces and moments under different yaw angles and found that the stream turbulence has significant effect on the lift force, which increases significantly the accident risk. To study the effect of atmospheric turbulence or train and ground relative motion, a catapulted setup experiment was carried out in an atmospheric boundary layer wind tunnel (Baker 1986b), and different types of vehicles (e.g., high side road vehicle, car and small vans), wind speeds and flow fields were studied as the influence factors on the wind load coefficients of vehicles (Baker 1991a, Baker 1991b, Baker 1991c, Humphreys and Baker 1992). The aerodynamic force coefficients of vehicles were found to vary with the vehicle's motion state, the vehicle position relative to others, and the

terrain characteristics (Baker 1986b). To investigate the gust effect on ground vehicles, a special testing track was designed and constructed to measure the transient load on the vehicle passing through the gust wind with various resultant yaw angles (Cairns 1994) and it was found that the effect of turbulence is fairly obvious at high yaw angles (Cheli *et al.* 2011b). A numerical simulation of unsteady cross wind aerodynamics considering the wind-gust boundary layer profiles illustrated that the force coefficients showed highly transient behavior under gusty conditions (Favre 2011).

To investigate the relationship between the wind speed, truck speed and propensity for truck rollover, Bettle *et al.* (2003) adopted the CFD method and obtained the aerodynamic forces acting on a truck travelling through a bridge under cross wind. The results showed that the vehicle with higher speed was suffering a larger aerodynamic moment tending to overturn a vehicle in the windward lane of the bridge. The corresponding moments were considerably less for the vehicle in the leeward lane. However, the traveling situation was simulated with fixed vehicles subjected to a resultant wind velocity of the wind velocity and vehicle speed. To investigate the aerodynamic forces on a moving vehicle, Krajnovic and Davidson (2005a) used the resultant wind velocity method in CFD and assigned the ground a moving velocity relative to the fixed vehicle to simulate the vehicle moving on the ground. Corin *et al.* (2008) simulated the transient aerodynamic forces on overtaking road vehicle models by using two-dimensional (2D) CFD method. In the study, moving mesh was used to produce the relative motion (overtaking) between two road vehicles. Later, more situations were considered, such as the different supporting infrastructure scenarios, the position of vehicles mounted on the bridge, and the vehicle geometry (Cheli *et al.* 2011a). Osth and Krajnovic (2012) investigated the flow field around the vehicle body and demonstrated the influence of leading edge shape and gap width between the cab and trailer on the drag force of a simplified tractor-trailer model through the CFD method. As a cross check with the experimental measurements, Han *et al.* (2013) predicted aerodynamic force coefficients of vehicles on bridges using a commercial CFD solver ANSYS CFX 12 on a three-dimensional computational model of the vehicle on the section of the bridge shown in Fig. 3. The Shear Stress Transport (SST $k-\omega$) turbulence model is applied to represent the turbulence of the flow. The turbulence model is designed to deal with the adverse pressure gradients and separated flows and the results show good performance. A reasonable agreement was observed between the experimental and numerical results. By using the similar method to the moving ground case, Wang *et al.* (2013) studied the aerodynamic coefficients of a moving vehicle-bridge system and evaluated the moving effects on the aerodynamic characteristic of the vehicle and the bridge.

In comparison with the applications of the RAN models as discussed above, Krajnovic and Davidson (2002, 2003, 2005b, 2005c) have conducted a series of investigations of flow around bluff bodies such as trains, buses and ground vehicles by using Large-Eddy Simulation (LES) model to simulate the flow turbulence, in which the LES results showed good agreement with the experimental data. In addition to the vehicles on highways, aerodynamic behavior of trains to cross wind was also investigated by means of CFD methods and wind tunnel tests (Cheli *et al.* 2010). Through using LES, Krajnovic *et al.* (2011, 2012) investigated the flow around a simplified train moving through a cross wind flow. Guilmineau *et al.* (2013) studied the cross wind effects on a simplified car model by a Detached Eddy Simulation (DES) approach. However, in these studies, DES and LES are used in predicting the aerodynamic forces of the vehicle on the ground rather than the vehicle on bridges. Osth and Krajnovic (2014) studied the aerodynamics of a generic container freight wagon using LES.

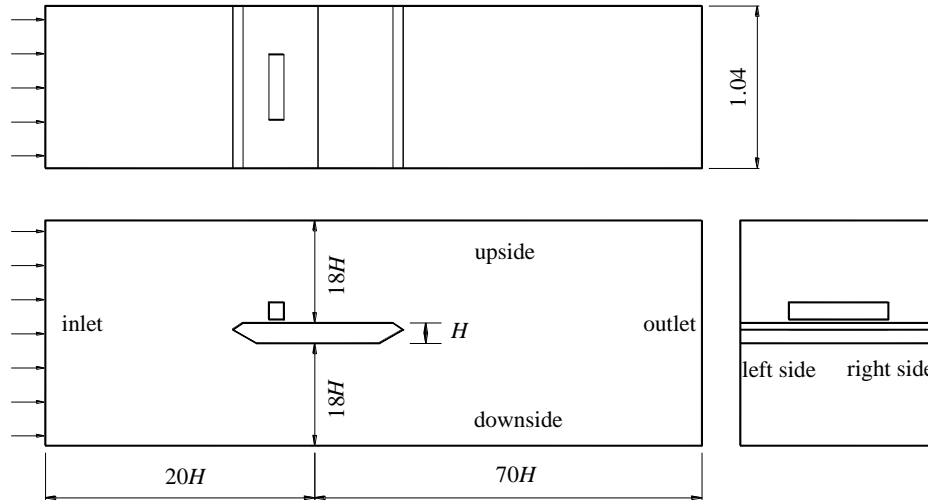


Fig. 3 Computational domain used in the CFD simulations (Han *et al.* 2013)

3. Wind-vehicle-bridge (WVB) coupled system

Typical buffeting analyses of slender long-span bridges in the analytical modeling and wind tunnel investigations usually do not consider the existence of vehicles (Jain *et al.* 1996, Simiu and Scanlan 1996). This was typically believed justifiable based on the assumption that bridges will be closed to traffic at relatively high wind speeds or the excitations from vehicles are negligible. In fact, long-span bridges are rarely closed even when wind speeds exceed the criterion commonly quoted to close a long-span bridge, for example, 55 mph in the AASHTO code (AASHTO 2012). It is known that bridge buffeting studies cover a wide range of wind speeds, and ignoring the combined effect of wind and traffic cannot reflect the fact that the traffic loadings usually do exist on the bridge while wind exists on the bridge simultaneously.

Daily traffic is the main live load with significant impacts on the strength and serviceability of bridges. Bridge and vehicle interactions have been studied since the middle of 20th century (Blejwas *et al.* 1979, Olsson 1985). Initially, the impact of a vehicle on a bridge was modeled as a moving load without considering the inertia effect. Later, a vehicle was simplified as a moving mass considering inertial effects, but not dynamic behavior (Sadiku and Leipholz 1987). In recent years, the analytical model for vehicles is essentially a dynamic system consisting of mass, spring and damping parts, which have significant effects on the dynamic analysis of vehicles and their interactions with bridges. In the dynamic system, dynamic interactions between the bridge and vehicles are modeled as coupling forces between the tires and the road surface. The coupling forces were proven to be significantly affected by the vehicle speed and road roughness conditions of short-span bridges (Shi *et al.* 2008, Deng and Cai 2010, Zhang and Cai 2012). All these studies were primarily focused on short-span bridges with wind effects being ignored. For long-span bridges that are more sensitive to wind actions, pretty strong wind usually exists at the height of the bridge deck, requiring more comprehensive consideration of the combined effects from wind and vehicles.

3.1 Aerodynamic characteristics of vehicle and long-span bridge system

Moving vehicles on the bridge deck more or less change the flow field around the bridge and then influence the dynamic performance of the bridge; on the other hand, the vibrations of bridges due to wind in turn increase the risk of accidents for the passing vehicles. In recent studies, the aerodynamic interference between vehicle and bridge has attracted a lot of attention in studying the response of bridge and vehicle in strong wind. For road vehicles, Bettel *et al.* (2003) investigated the aerodynamic forces of North American transport truck mounted on bridge with different speeds, which is the first step to develop strategies for accident avoidance. Suzuki *et al.* (2003) studied the aerodynamic characteristics of a train under cross wind obtained from a series of wind tunnel experiments and pointed out these aerodynamic forces are dependent on the shape of the train as well as the supporting bridge. Li *et al.* (2004, 2013, 2014) developed an innovative separation device as shown in Fig. 4, called the cross-slot system, to measure the aerodynamic characteristics of the rail vehicle-bridge system, taking the aerodynamic interaction between the rail vehicle and bridge into account. Dorigatti *et al.* (2012) measured the aerodynamic loads for three kinds of road vehicles on a typical bridge deck as well as an idealized bridge deck in wind tunnel tests in order to improve the performance of a long-span bridge in strong wind. Zhu *et al.* (2012) examined the aerodynamic coefficients of road vehicles on a bridge deck. In their experiments, various scenarios were considered, such as different types of road vehicles, wind direction, and vehicle position on bridge deck. Later, numerical simulations were carried out to determine the aerodynamic forces on the vehicle and the bridge in different motion status of the vehicle (Wang *et al.* 2013). Meanwhile, Han *et al.* (2013) developed an experimental setup to measure the aerodynamic characteristics of road vehicles and the bridge for different layout scenarios of vehicles, different wind turbulence intensities and various wind speeds, in a wind tunnel considering the aerodynamic interference. Fig. 5 shows a measured wind pressure distributions across the bridge deck with the existence of vehicles on the bridge deck.

Furthermore, the wind loads on vehicles can change dramatically due to the wind blocking or vortex shedding of bridge towers or other passing vehicles. Charuvisis *et al.* (2004a, b) discussed and clarified transient mechanism of the aerodynamic forces on a vehicle passing through the wake of a bridge tower in cross wind through an analytical study with experimental verifications. Li *et al.* (2013) conducted comprehensive wind tunnel experiments with moving train models to test the effect of bridge towers and passing vehicles on the wind loads on the trains and road vehicles. The results showed that the force coefficients of trains had sudden changes and those on the road vehicles are comparatively more obvious. In the meantime, the impact of vehicles on the aerodynamic derivatives of the bridge was found to be not negligible. Wu *et al.* (2012a) obtained the flutter derivatives from the wind tunnel experiments of various modified bridge cross-section profiles by traffic flow. Han *et al.* (2014b) adopted forced vibration tests of bridge with different traffic conditions in a wind tunnel to investigate the effect of traffic on aerodynamic characteristics of bridges and found that the vehicles can obviously affect the flutter derivatives.

3.2 Vehicle subsystem model

In advanced vehicle dynamic modeling, a road vehicle is modeled as a combination of several rigid bodies connected by several axle mass blocks, springs, and damping devices. In typical numerical models, the suspension system and elasticity of tires of vehicles are simulated by springs; the dissipation capacities of the suspension as well as tires are modeled with viscous

damping devices; the mass of the suspension system and the tires are concentrated on the axle mass blocks, while the mass of springs and damping devices are assumed to be zero. Different types of vehicles can be modeled by defining appropriate parameters, such as the number of mass blocks, springs and damping devices, and associated dynamic parameters. Fig. 6 shows a complicated tractor-trailer model with five axles and ten wheels (Cai and Chen 2004a). In this model, each rigid body is specified with four degrees of freedoms (DOFs): lateral movement, vertical movement, pitching movement, and rolling movement. Each mass block has two DOFs: vertical and lateral directions. In the whole Wind-Vehicle-Bridge (WVB) analytical coupled model, the external excitation on the vehicle subsystem model includes wind and road surface roughness excitation. In most studies of WVB system, the wind loads on the vehicle configuration is considered as quasi-static wind loads (Xu and Guo 2003, Cai and Chen 2004a, Han 2006). In 2005, Li *et al.* (2005) proposed the theoretical formula of wind loads on vehicles that include not only the mean wind velocity but also vertical and along-wind fluctuating velocities.

For the train subsystem model, the mechanism of modeling a train is similar to a road vehicle. Train includes bogies and wheel sets, which are equivalent to the tires of road vehicles. While the rigid body and bogies can have displacements in five directions, each wheel set can only have the lateral displacement and yawing displacement. Fig. 7 shows a typical train vehicle model in the coupled WVB system (Li *et al.* 2005). The consideration of wind load on trains is similar to the one on road vehicles, the steady-state wind loads (Xia 2008).

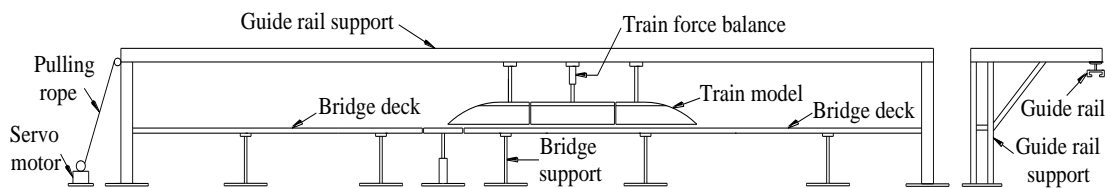


Fig. 4 Schematic diagram of testing system (Li *et al.* 2013)

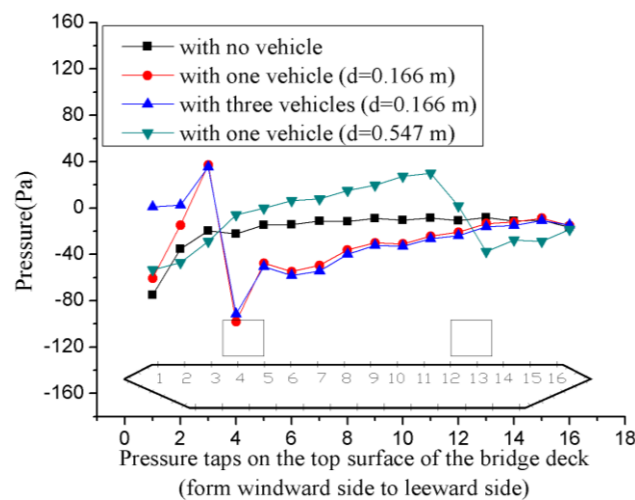


Fig. 5 Measured pressure of top pressure taps of the middle strip (Han *et al.* 2013)

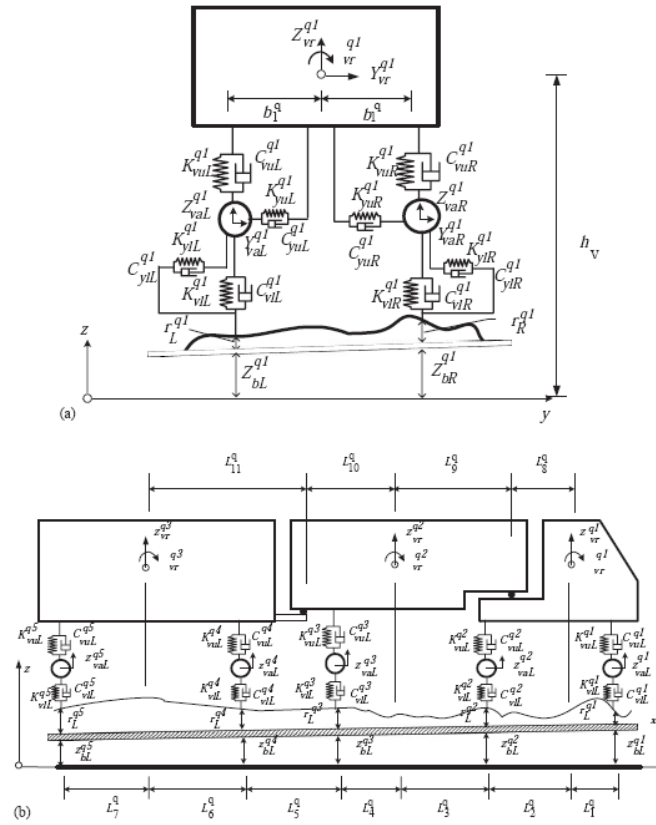


Fig. 6 General dynamic model for various vehicles: (a) cross section view and (b) elevation view (Cai and Chen 2004a)

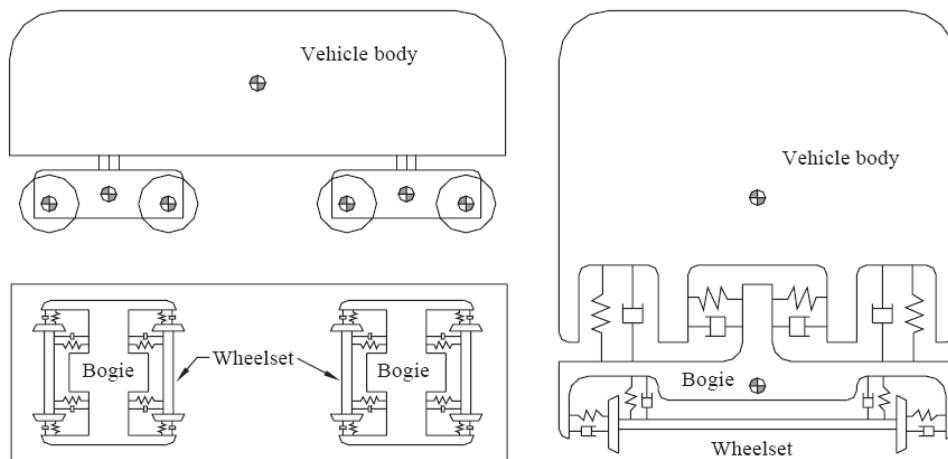


Fig. 7 Mass-spring-damper model of train vehicle (Li *et al.* 2005)

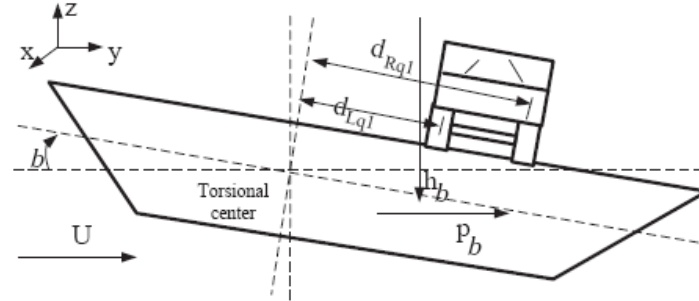


Fig. 8 Coupled model of vehicle on bridge (Cai and Chen 2004a)

3.3 Bridge subsystem and wind effects modeling

The analytical model of a long-span bridge can be established through finite element modeling with various types of elements such as beam elements, truss elements, and shell elements. Based on the modal superposition technique, the response corresponding to any point along the bridge can be evaluated in the time domain (Xu *et al.* 2003, Cai and Chen 2004a). Motions of the bridge include three directions as, lateral, vertical and torsional, as shown in Fig. 8 (Cai and Chen 2004a). The wind forces on the bridge are also separated into three directions accordingly. In each direction, steady state, self-excited, and buffeting forces components are incorporated. In the time domain, the vibration frequency at any given time should be determined to quantify the self-excited force under a certain wind speed due to the difficulty to capture the frequency-dependent variables, namely, the flutter derivatives (Chen and Cai 2003). The flutter derivatives of the bridge can be obtained from wind tunnel tests (Scanlan 1978) or CFD simulations and can be expressed in the time-domain through the rational function approximation approach (Chen *et al.* 2000). The self-excited force can also be calculated in terms of convolution integrals between the bridge deck motion and the wind (Lin and Yang 1983), which includes an impulse function derived based on the flutter derivatives. In order to simulate the buffeting forces on the bridge, appropriate stochastic wind velocity should be produced. The fast spectral representation method (Cao *et al.* 2000) and the simplified spectral representation method (Deodatis 1996) are the popular ways to simulate random wind fields.

3.4 Analytical framework of coupled WVB system

It was not until 2003 that the coupling effects among bridge, wind and vehicle were considered by using the time-history analysis of the coupled finite element model (Xu and Guo 2003, Cai and Chen 2004a, Chen and Cai 2006, Li *et al.* 2013). Both the bridge and vehicle are modeled analytically with dynamic systems composed of mass, spring, and damping matrices. By assuming there is no separation at the contact point between vehicle tires and bridge deck, the vehicle, bridge, and wind form a coupled system that takes the static, aeroelastic, and aerodynamic effects of wind into account. As one of the main excitations of vehicle vibrations, the interaction between vehicle and the road roughness on bridge deck is of importance as well. The road surface roughness is investigated in the highway WVB system and the rail irregularities are considered in the railway

WVB system. Their effects on different types of vehicles or trains are usually described by various power spectral density (PSD) functions (Dodds and Robson 1973, Wang and Huang 1992). The road surface roughness is usually assumed to be a zero-mean stationary Gaussian random process and can be expressed through the inverse Fourier transformation as a power spectral density function (Huang and Wang 1992). Rail irregularities are random and can be approximately regarded as stationary stochastic processes with considerations of the track vertical, alignment, and cross-level irregularities (Li *et al.* 2005). Xu *et al.* (2003) investigated the dynamic response of suspension bridges to strong wind and a running train through an appropriate combination of 3D finite-element bridge model and 27-degrees-of-freedom train model. The dynamic response of a long-span suspension bridge was found to be dominant by high-speed wind loads, while the running train only affected the vertical motion of the bridge. The study also gave out the critical train speed under certain wind velocities.

For roadway vehicles, Xu and Guo (2003) assembled the motion equations of the coupled road vehicle and cable-stayed bridge systems under turbulent wind by a fully computerized approach. A case study of a real long-span cable-stayed bridge indicated that the proposed framework was efficient in predicting the responses of the coupled system under turbulent wind. Cai and Chen (2004a) derived the motion equations of the vehicle-bridge coupled system under strong wind by the virtual work principle and developed a coupled WVB analytical framework. The coupled equations can be expressed as

$$\begin{aligned} & \begin{bmatrix} \mathbf{M}_v & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_b \end{bmatrix} \begin{Bmatrix} \ddot{\gamma}_v \\ \ddot{\gamma}_b \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_v & \mathbf{C}_{vb} \\ \mathbf{C}_{bv} & \mathbf{C}_b^s + \mathbf{C}_b^v \end{bmatrix} \begin{Bmatrix} \dot{\gamma}_v \\ \dot{\gamma}_b \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_v & \mathbf{K}_{vb} \\ \mathbf{K}_{bv} & \mathbf{K}_b^s + \mathbf{K}_b^v \end{bmatrix} \begin{Bmatrix} \gamma_v \\ \gamma_b \end{Bmatrix} \\ & = \begin{Bmatrix} \{\mathbf{F}\}_r^v + \{\mathbf{F}\}_w^v \\ \{\mathbf{F}\}_r^b + \{\mathbf{F}\}_w^b + \{\mathbf{F}\}_G^b \end{Bmatrix}, \end{aligned} \quad (1)$$

where subscripts “b” and “v” stand for bridge and vehicle, respectively; superscripts of “s” and “v” in the stiffness (K) and damping (C) terms refer to the contributions of bridge structure itself and those due to vehicles, respectively; subscripts “bv” and “vb” refer to the vehicles–bridge coupled terms; “r”, “w” and “G” represent for road roughness, wind, and gravity force, respectively; and “cv” and “cb” are the displacement vectors of the vehicles and the bridge, respectively.

Such a framework can be used to predict the dynamic performance of the coupled WVB system and analyze various vehicle cases, such as multiple vehicles and multiple-axle vehicles by simply adjusting the number of mass blocks, springs, and dampers. The assumptions of this model include full point-contact and no lateral relative movement between the vehicle wheel and the bridge deck. Driving speeds were found to have more influence on the vertical response of vehicles than rolling response of the vehicle. When the wind speed is high, the vehicle response is dominated by the contribution of the bridge vibration. When the wind speed is low, the vehicles response is dominated by the excitation from road roughness (Cai and Chen 2004a). Han *et al.* (2014a) studied the effects of aerodynamic parameters on the dynamic responses of the road vehicles and bridge under cross wind. The static forces on the vehicle of the coupled system model were based on the results from wind tunnel tests that focused on the aerodynamic interference between the bridge and vehicles.

For railway transportation, Li *et al.* (2005) built an analytical model for the dynamics of WVB system in the time domain with wind, train, and bridge modeled as a coupled vibration system. Similar to vehicle and bridge model in the road WVB system, the rail vehicle was a combination of mass block, springs and damping devices and bridge was modeled in a FEM form. Xia *et al.*

(2008) made improvement of the train WVB system based on the model proposed by Xu *et al.* (2003). In this model, the vehicle was applied with wind as external forces directly.

4. Applications

4.1 Road vehicle accident and ride comfort analysis

Every year, hazardous weather alone is associated with more than 1.5 million vehicular crashes in the United States, which results in 800,000 injuries and 7,000 fatalities (The National Academies, 2006). Of the various problems caused by wind, though with little statistical information, threats of strong wind on vehicle stability do have caused serious concerns (Xu and Guo 2004). As a result, continuous research efforts were made in determining the critical wind speed and vehicle speed limits to reduce wind-induced accidents. The criteria for detecting an accidental situation are of importance in accident prediction. Baker (1986a) classified the cross wind accidents into three types, rollover accident, rotating accidents, and sideslip accident. Based on field data analysis of wind-induced vehicle accidents, rollover accidents are found to be the most common one, accounting for 47% of the total. Rotating accidents make up 19% of the total (Baker and Reynolds 1992). For the three types of high risk vehicle accidents, rollover accidents happen when the restoring moment provided by the mass of the vehicle acting on its center of gravity is less than the rolling moment that is generated by the combination of wind flows and vehicle speed about the lee side tire contact point (Gawthorpe 1994). In addition, the possibility of road vehicles to rotate under cross wind is largely related to the shape of the vehicle and its weight distribution. In the sideslip accidents, the friction between the tires and bridge deck is smaller than the wind forces on the vehicle in the corresponding direction and the vehicle is blown sideways for a significant distances. Accident criteria shown in Table 1 were proposed by Baker (1986a), in which an accumulated displacement of vehicle entering an edged cross gust within 0.5s was considered. These criteria have been adopted in several accident risk quantification investigations for road vehicles in cross wind (Chen and Cai 2004a, Guo and Xu 2006).

Vehicle accidents due to strong wind sometimes may be avoided by driver's proper handling (Martin 2012), therefore, the effect of driver's behavior on the vehicle accidents was considered in the accidents analysis as well. Baker (1994) introduced two driver dependent parameters, λ_1 and λ_2 , to consider the steering angle handled by the driver. As an experimental method considering the driver behavior in accident assessments of road vehicles, the driving simulator, which was developed by Mitsubishi Precision Co. Ltd, can be used to monitor the drivers' behavior and simulate the response of the vehicle handled by the driver under strong wind. Based on the comparison of the results obtained from the simulator experiments and actual automobile experiments, it was expected that the driving simulator experiments can well produce the equivalent moving conditions in the actual environment (Maruyama and Yamazaki 2006).

Baker (1986a) proposed a model called BLOWOVER to predict wind speeds for different accident types and to provide the vehicle aerodynamic coefficients over a wide range of yaw angles for vehicles on roadways. The BLOWOVER can be used in both scenarios of considering driver reaction or not. In this model, time histories of lateral movement and rotational vibration of vehicles in wind fields can be obtained (Baker 1994).

Table 1 The criteria of three accident types (Baker 1986a)

Accident types	Criteria
Rollover	Contact force reduces to zero
Rotating	The value of yaw angle is over 0.2 rad
Sideslip	Lateral displacement exceeds 0.5m

To study the safety of vehicles on bridges, Chen and Cai (2004a) built a framework of vehicle accident analysis model on long-span bridges in windy environments considering road roughness effect, friction effect, and the excitations from the supporting structure such as bridges. The vehicle accidents model was proposed based upon the WVB coupled system, the accident criteria, and the effect of driving behavior. In general, the vehicle vibration was obtained based on the analysis of the global bridge-vehicle interaction. With the global vibrations as inputs of the accident model, the lateral and yaw response of the vehicle and the reaction forces of each individual wheel were then obtained. The combination of the local accident model and vehicle-bridge-wind system models enables the prediction of the bridge responses in all directions and the vehicle responses of the vertical, rolling, pitching, lateral, and yaw directions. Finally, the stability condition and the accident risk of the vehicle were identified with the given accident criteria, as shown in Fig. 9 where the accident driving speed versus wind speed on both the bridge and road way is compared. Such kind of information will be potentially useful for transportation management agencies to plan traffic in windy environments.

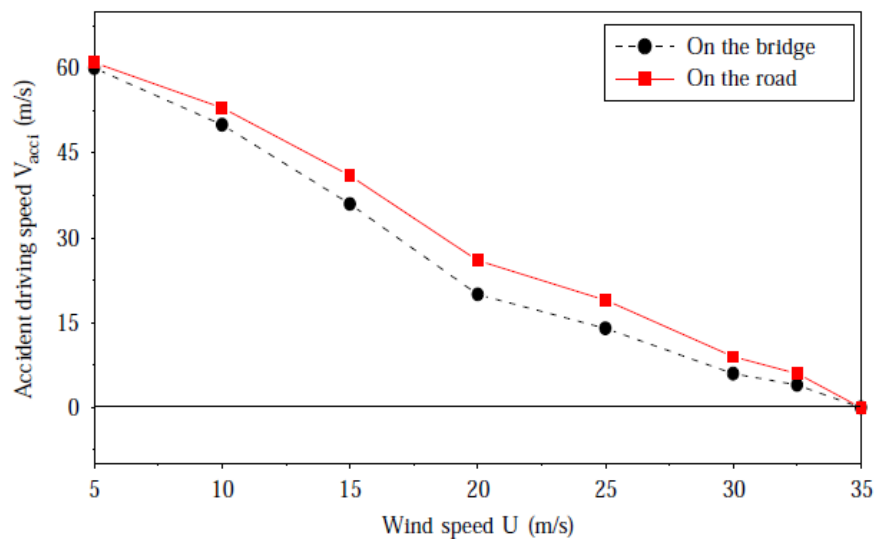


Fig. 9 Accident driving speed versus wind speed (Chen and Cai 2004a)

Meanwhile, Guo and Xu (2006) proposed a vehicle safety assessment model to consider the road vehicle entered a sharp-edged cross wind gust while the bridge was oscillating under fluctuating wind. They built the mathematical model and carried out the dynamic interaction of coupled highway vehicle–bridge systems under cross wind, which include road surface roughness, vehicle suspension, and the sideslip of the vehicle tire relative to the bridge deck in the lateral direction. Moreover, the ride comfort criteria of road vehicles based on the document issued by International Standard Organization (ISO) were used to study the effect of bridge motion and cross wind on the ride comfort of road vehicles. Since then, a series of studies for the safety of moving vehicles have been carried out with many of them being related to the Tsingma bridge (Guo *et al.* 2007, 2010, Xu *et al.* 2004, 2007, Wang *et al.* 2014, Zhang *et al.* 2013) and protection measures have been developed (Xiang *et al.* 2014).

Based on their previous work, Chen and Chen (2010) developed an integrated vehicle safety behavior simulation model, which adopts more realistic dynamic equations and accident criteria to characterize the transient process of accidents. This new model introduced two critical variables, critical sustained time (CST) and critical driving speed (CDS) of accident, to assess the accident risks under more comprehensive characterization of adverse driving conditions. More realistic accident criteria were checked at each time step to identify if the accident criteria were exceeded, specifically the possibility that the wheel would be lifted up or would start to sideslip. Due to the variation of wind profile influenced by specific terrain and surroundings, the actual wind environment varies from one site to another. However, the vehicle-specific cross wind velocity is often required for an accurate safety assessment of high-sided vehicles with unique shapes. Chen *et al.* (2010a) developed a mobile mapping technology aiming at collecting the site-specific as well as vehicle-specific wind velocity data for traffic safety evaluations.

4.2 Vibration mitigations of wind and vehicle induced vibrations

In contrast to buffeting existing in a large range of wind speeds, flutter may occurs at a certain high wind speed. Long-span bridges exhibit complex dynamic behaviors under wind and vehicle excitations, which may lead to dangerous traveling of vehicles and fatigue problems of the bridge. Therefore, it is necessary to suppress the adverse vibration of the bridge subjected to the actions of wind and passing traffic. Some research efforts have been made in mitigating excessive buffeting vibrations and improving flutter stabilities for long-span bridges during construction (Conti *et al.* 1996, Takeda *et al.* 1998, Chen and Wu 2008) and at service (Pourzeynali and Datta 2002, Omenzetter *et al.* 2002, Miyata and Yamada 1998). As a traditional control device, dynamic energy absorbers perform well in suppressing the excessive dynamic buffeting (Gu *et al.* 2001) or enhancing the flutter stability of bridges (Pourzeynali and Datta 2002, Gu *et al.* 1998). Dynamic energy absorbers, such as tuned mass damper (TMD) and tuned liquid damper (TLD), are categorized into three types, namely, passive, active, and hybrid control devices. Chey (2007) investigated hybrid control strategy in order to enhance the cost effectiveness and potential reliability of the active control. In the hybrid control strategy, the dynamic energy absorbers dissipate the external energy through providing supplemental damping to the modes of concern. In a conventional TMD control design, the TMD control strategy is to suppress the resonant vibration. However, with the increase of wind speeds, the modal damping ratio increases, which leads to the decrease of efficiency of TMD that focus on a certain modal frequency. On the other hand, mode-coupling effect cannot be ignored when frequencies of modes become closer, due to the slender nature of long-span bridges in strong wind.

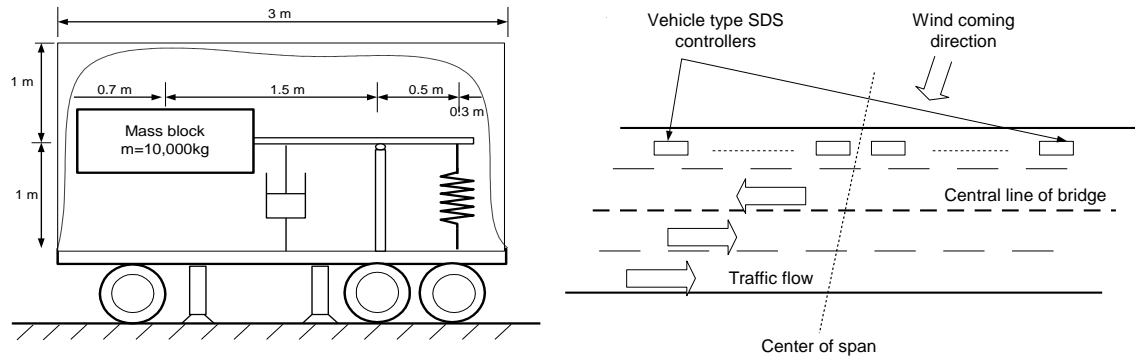


Fig. 10 Concept of moveable tuned mass dampers (TMD) (Cai and Chen 2004b)

Most studies of structural control of long-span bridges usually consider either only the wind loading or moving vehicles, but not both at the same time (Chen and Wu 2008). Wang *et al.* (2003) applied the passive TMD to suppress the train-induced vibration on bridges; however, it did not take wind effects into account. Chen and Cai (2004b) introduced an alternative TMD design approach that was based on suppression of modal coupling effects among modes under strong wind and designed a coupled vibration control with TMD without considering vehicle effects. More and more studies on the interaction between vehicles, the bridge, and wind field have found that the dynamic response of bridges under the combined effects of strong wind and moving vehicles becomes critical daily maintenance of bridges. Cai and Chen (2004b) proposed a movable/temporary passive control approach based on a general formulation of the Spring-Damper-Subsystems (SDS) system as shown in Fig. 10. Application of the movable vehicle-type of control facility on the Humen suspension bridge subjected to strong wind demonstrated its high control efficiency. Compared to TMD with a specific frequency, a new type of mechanical damper is proposed to overcome the multi-frequency vibration of cables, namely, TMD-MR damper system for cable vibration mitigation. Experimental results show that the TMD-MR system has good vibration reduction effects (Cai *et al.* 2007).

Similar to TMDs, tuned liquid damper (TLD) is a low cost but efficient device to mitigate the structure vibrations due to external excitations, such as wind loads. Fujino *et al.* (1992) developed a two-dimensional TLD model and the effectiveness of the system was discussed with both experimental and numerical simulations. Patten *et al.* (1996) designed a semi-active hydraulic bridge vibration absorber that can be applied on existing bridges. Kareem *et al.* (1999) introduced the general mechanism and summarized the applications of TLDs. Comprehensive investigations have been carried out on the TLDs with analytical, numerical, and experimental methods (Ibrahim 2005). Wang *et al.* (2005) carried out the optimal design of viscous dampers for multimode vibration control of bridge cables. Chen *et al.* (2008) applied TLD on vehicles to improve the stability performance of a long-span suspension bridge considering the vehicle-bridge-wind interaction. Wind fences were introduced to prevent the wind-induced rollover of vehicles caused by the interference of bridge towers on the aerodynamic forces acting on a moving vehicle (Rocchi *et al.* 2012).

4.3 Fatigue reliability assessment of bridges under combined actions of wind and vehicles

Fatigue, one of the main forms of structural damages, is a typical failure mode caused by repeated dynamic loads, for instance, wind loads and vehicle loads. With the increase of span lengths, bridges are becoming more flexible and more vulnerable to wind induced vibrations. Virlogeux (1992) and Gu *et al.* (1999), by neglecting the vehicle effects, conducted buffeting-induced fatigue analysis on two cable-stayed bridges and the fatigue life was found to be much longer than the design life of the bridges. Based on the recorded data of the Tsing Ma Bridge, Xu *et al.* (2009) found that when the vehicle effects were not considered the monsoon wind-induced fatigue damage is not significant. In addition, many works have been carried out on the vehicle-bridge dynamic analysis or vehicle-bridge-wind dynamic analysis (Byers *et al.* 1997a, b, Guo and Xu 2001, Cai and Chen 2004a, Xu *et al.* 2009, Chen and Wu 2010, Chen *et al.* 2011a, b). While these dynamic responses can be used to assess the fatigue damage of bridges, fatigue analysis of bridges under the combined actions of both wind and vehicles have been conducted only in a few studies so far. However, given to the simultaneous presence of multiple dynamic loads, possible fatigue damage due to the combined effect of loading from highway vehicles or railway trains and wind loading could accumulate and cause safety concerns. As many structural health monitoring systems (SHMSs) are installed in long-span bridges, it is possible to use the two typical stress data resources for fatigue damage assessment, namely, on-site monitoring data from SHMSs and numerical simulations based on WVB dynamic system. Based on the integrating data from numerical simulation and SHMSs installed on Tsing Ma Bridge, Chen *et al.* (2011, 2012) proposed fatigue reliability analysis approaches to consider multiple dynamic loads from railway, highway, and wind loading. Meanwhile, Wu *et al.* (2012b) proposed a reliability-based fatigue analysis approach, which started with a scenario-based deterministic fatigue analysis model, to consider combined dynamic effects from wind and traffic. Cumulative yearly fatigue damage, therefore, can be predicted by superposition of representative damage scenarios.

Later, Zhang *et al.* (2013) proposed a general framework of fatigue reliability assessment for long-span bridges under combined dynamic loads from wind and vehicles. By solving the equations of motions of the vehicle-bridge-wind dynamic system, the dynamic stress histories for given structural details are obtained for a given vehicle speed, wind velocity and direction, and road roughness condition. Based on a given fatigue damage model, such as linear damage rule (LDR), the progressive fatigue damage accumulation in the bridge's life cycle was calculated and the fatigue life and reliability for the given structure details in a bridge's life cycle was predicted. It was demonstrated that while the traffic or wind loads alone are not able to induce serious fatigue problems, the combined dynamic effects from wind and vehicles might result in serious fatigue problems for long-span bridges. Recently, Zhang *et al.* (2014) also discussed the fatigue life reduction of existing long-span bridges due to the non-stationary hurricane wind loads and environmental corrosion. However, since the structural local failures have been identified as the main reason for the failure or unavailability of structure systems, it is necessary to understand how the coupled vehicle-bridge-wind dynamic system interacts with local damage initiation and propagation with the presence of environmental corrosion. Since there are large scale differences for the local damages and the coupled vehicle-bridge-wind dynamic system, incorporation of damage propagation in the coupled dynamic system is still challenging.

5. Conclusions

Previous research on the wind-vehicle-bridge system has been briefly reviewed by introducing the methodology, the simulation procedure, and the performance assessment of vehicles and bridges in strong wind. The application of the WVB dynamic coupled system is focused on the vehicle accident issues, the mitigation of the bridge vibration, and the fatigue damage predictions. Numerical simulations proved that the WVB dynamic coupled system can be potentially applied to practical engineering. However, due to the simplifications adopted in both the numerical and experimental investigations, the complex of the problem involved, and the uncertainties associated with the system, further research is needed in the following aspects to develop more realistic and practical applications:

- Most of the vehicles used in the previous experimental and numerical simulations were statically placed on the roadway or bridge deck when characterizing the wind loading on the vehicle and bridges. Considering movable vehicles on a bridge deck is necessary to more realistically include the interaction of the vehicle, bridge, and wind, but significant challenge still exists in both CFD simulations and wind tunnel tests.
- For a more reliable vehicle risk assessment, more realistic drivers' behavior model is needed from driving simulations, which is also a challenging task. This is because different people respond differently under windy and/or other weather related hazard conditions.
- More comprehensive and reliable accident criteria are needed to improve the vehicle safety assessment. Current criteria in the literature are either over simplified or not verified in the field.
- Vehicle models and/or vehicle distribution patterns used in predicting the aerodynamic forces of the vehicle need to be more representative and more specific to bridge sites.
- More efforts are still needed to develop more effective and more realistic simulations for the WVB coupled system. Currently, vehicle-bridge wind loading and vehicle-bridge response are treated as two separate subsystems. A unified simulation can be done by adopting more advanced numerical simulations and/or using more realistic wind-tunnel tests to obtain the vehicle and the bridge aerodynamic forces, clearly understand the aerodynamic characteristics of the vehicle, and study the interaction of moving vehicles, wind, and bridge vibrations.
- Nearly all the work in the literature is numerical or laboratory based. There is essentially no references related to field verifications, such as critical driving velocities, loads on bridges and vehicles. Field verifications of the developed procedures are needed.
- There exist significant uncertainties associated with the numerical models, experimental techniques, and wind characteristics, among others, for the WVB system. These uncertainties need to be considered and the detailed mathematical approach need to be consistent with these uncertainties. A reliability based approach for the accident assessment of vehicle safety is needed.
- Most CFD simulations are currently based on 2D models. More realistic 3D simulations are needed and are possible with the advancement of computing capability.

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