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# Safety analysis of a road vehicle passing by a bridge tower under crosswinds

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ABSTRACT

As a road vehicle passes by a bridge tower under crosswinds, the vehicle will be briefly shielded from the crosswinds by the tower within a very short period of time, but when it gets out of the tower it enters a sharp-edged crosswind gust with the obvious danger of overturning or course deviation. The accident vehicle/wind speed associated with such an event is currently estimated by applying a 0.5 s sudden step crosswind gust to the vehicle to see if overturning, sideslip or rotation accident will occur. In reality, a much more complicated wind condition than a sudden crosswind gust is confronted by the vehicle when it passes by a bridge tower. This study aims at a more accurate safety analysis of a road vehicle passing by a bridge tower under crosswinds. Varying wind loads experienced by a road vehicle passing by a bridge tower are first formulized in terms of time-varying aerodynamic coefficients obtained from computational fluids dynamics. Varying wind loads are then enforced on the vehicle together with a coupled road vehicle-bridge-wind (RVBW) system. Safety analysis is finally performed to examine the behavior and safety of the vehicle. The results show that the rolling and lateral motions of the vehicle are influenced significantly by the tower and that the driver needs to take quick action with a high steer angle to keep the right course. The influence of the bridge dynamic response on the safety of a single vehicle passing by the tower under crosswinds is insignificant.



## 1. Introduction

Road vehicle accidents caused by crosswinds happen throughout the world and many research works have been carried out for the safety of road vehicles moving on the ground under crosswinds. Baker (1986) presented an analytical method for assessing the safety of road vehicles under crosswinds in the time domain, which was then supplemented by taking into account the driver behavior (Baker, 1988). Macadam (1992) conducted the dynamic response analysis of large vehicles exposed to sudden crosswind gusts. Sigbjörnsson and Snæbjörnsson (1998) presented a probabilistic analytical model, while Xu and Guo (2003) investigated the safety of vehicles under crosswinds in considering the effects of road surface roughness and vehicle suspension. Cheli et al. (2006, 2011) obtained the aerodynamic admittance function and aerodynamic forces of a road vehicle moving on flat terrain, viaduct and embankment. The turbulent wind condition was then enforced on the vehicle model based on the quasi-steady theory. Chen and Chen (2010) developed a single-vehicle accident assessment model considering the coupling effects between vehicles and hazardous driving conditions.

As a road vehicle passes by a bridge tower under crosswinds, the vehicle will be briefly shielded from the crosswind by the tower within a very short period of time, but when it gets out of the tower it enters a sharp-edged crosswind gust with the obvious danger of overturning or course deviation (Pritchard, 1985). On 11 August 2004, seven high-sided road vehicles were overturned by crosswind gust when they run on the Humen suspension bridge in China just before a strong typhoon. Vehicle accidents caused injury of life, transportation interruptions and economic loss.

Baker (1986) conducted a systematic study on the safety of high-sided road vehicles running on the ground and quantified the accident wind speeds of road vehicles as overturning, sideslip and rotation accidents. The accident vehicle/wind speed was estimated by applying a 0.5 s sudden step crosswind gust to the vehicle. An accident was said to occur if one of the vehicle wheel reactions falls to zero, the lateral deviation exceeds 0.5 m, or the rotational deviation exceeds 0.2 rads.

While the above accident criteria are widely used in the accident assessment of road vehicles on the ground, they were also used by Chen and Cai (2004) and Guo and Xu (2006) for the accident assessment of road vehicles running on a long span

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bridge under crosswinds. The effects of bridge motion on vehicle motion were taken into account in their studies, but the interference effects on the aerodynamic forces (coefficients) of the vehicle and the bridge deck were not considered. The aerodynamic forces on the vehicle moving on the bridge deck were approximated with those on the stationary vehicle on the ground, and the aerodynamic forces on the bridge deck were also approximated without considering the influences of the vehicles moving on it (Xu and Guo, 2003b; Xu and Guo, 2004; Cai and Chen, 2004; Cheung and Chan, 2010). In fact, the aerodynamic forces on the vehicle are influenced considerably by the local environment, such as the geometric shape of the bridge deck and tower in front of the vehicles. In return, the motion of the vehicle alters the aerodynamic forces acting on the deck naturally. Therefore, the interference effects between the vehicle and the bridge on their aerodynamic forces shall be considered. Furthermore, when a vehicle is passing by a bridge tower, a much more complicated wind condition than a sudden crosswind gust of 0.5 s duration is confronted by the vehicle. The vehicle is first shielded from the crosswinds by the tower within a very short time, and it then enters into a crosswind gust of varying speed within another very short period (Charuvisit et al. 2004; Argentini et al. 2011; Wang et al. 2014). The crosswind gust of varying speed and the corresponding duration depend on many factors, such as vehicle speed, the size and shape of tower cross section and driver behavior, which cannot be modeled by a sudden crosswind gust of 0.5 s duration as currently used. Therefore, the actual wind loads acting on the vehicle passing by the bridge tower should replace the sudden crosswind gust of 0.5 s duration to have a more realistic assessment of vehicle safety.

Rocci et al. (2012) and Sabbioni et al. (2012) measured the aerodynamic forces on a stationary vehicle model behind a bridge tower in wind tunnel in order to assess the safety of the vehicle passing by the tower. However, the aerodynamic forces on a stationary vehicle are different from those on a moving vehicle. Furthermore, Maruyama and Yamazaki (2006) included a driver model, which was established based on the experiment results, in the safety analysis of road vehicles but the sudden crosswind gusts were used other than the actual wind loads acting on the vehicle passing by the bridge tower. The effects of the bridge motion at the location of the bridge tower on the vehicle safety were also neglected (Maruyama and Yamazake, 2006; Rocci et al., 2012; Sabbioni et al., 2012).

This study aims at a more accurate safety analysis of a road vehicle passing by a bridge tower under crosswinds. An advanced and coupled road vehicle-bridge-wind (RVBW) system is employed, which includes a vehicle model, a bridge deck model, a bridge tower model, road roughness in plane, driver reaction and aerodynamic interference between the moving vehicle and bridge. Varying wind loads experienced by a road vehicle passing by a bridge tower are first formulized in terms of time-varying aerodynamic coefficients obtained from computational fluids dynamics. Varying wind loads are then enforced on the vehicle together with the coupled RVBW system. Safety analysis is finally performed to examine the behavior and safety of the vehicle, in which the currently-used definition of overturning accident is revised. The effects of varying aerodynamic coefficients of the moving vehicle passing by a bridge tower and the vibration of the bridge on the vehicle safety are discussed in detail.

## 2. Description of problem

Fig. 1 illustrates a road vehicle passing by a bridge tower under crosswinds. During the passage, four main positions of the vehicle in the lateral direction of the bridge (see S1, S2, S3 and S4 in Fig. 1) shall be noted. In the position S1, the vehicle is far from the bridge tower. The aerodynamic forces on the vehicle are influenced by the bridge

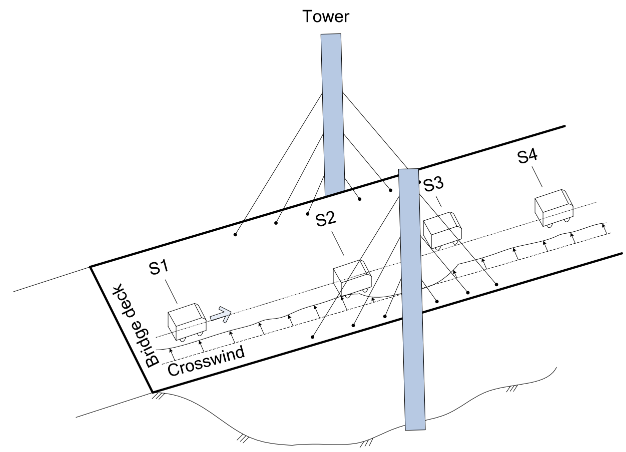


**Fig. 1.** Schematic diagram of a vehicle passing by a bridge tower under crosswinds.

deck only, compared with those on the vehicle moving on the ground, and the aerodynamic forces on the deck vary with the location of the vehicle. It shall be pointed out that the interference between the deck and the moving vehicle described above and considered in this study is in a simple manner and that the effects of both vehicle vibrations and turbulent winds on the aerodynamic coefficients are not considered in the computational simulation. Since the vehicle is subjected to lateral wind forces due to crosswinds, it tends to move downwind and the driver will thus steer the wheels to get the vehicle back to the original lane. As the vehicle approaches the tower and then moves behind the tower, the crosswinds on the vehicle will be shielded by the bridge tower. This position of the vehicle is denoted as the position S2. At this position, the aerodynamic forces on the vehicle reduce as the vehicle moves behind the tower. As a result, the vehicle departs from the moving lane in the counter-direction of the crosswinds due to the reduced aerodynamic forces. Accordingly, if there is enough time, the driver will steer so that the vehicle can be controlled back to the moving lane. As the vehicle gets out of the tower, the crosswinds restore to the normal ones within a very short time. This position is characterized as the position S3. In this position, the wind loads on the vehicle increase and lead to the lateral motion of the vehicle downwind. The lateral motion of the vehicle may not be balanced by the steer angle due to the time delay of the driver system. Consequently, the vehicle departs from the original moving lane again, but in the opposite direction to the case of S2. The vehicle will go back to the original lane eventually under the action of the driver, which is designated as the position S4.

During the entire passage of the vehicle passing by the bridge tower as described above, the responses of the vehicle are induced by the wind loads with the interference of both the deck and the tower, the dynamic response of the bridge, and the action of driver. To analyze the behavior and safety of the road vehicle passing by the bridge deck in a natural way, two aspects shall be taken into account. One is that the RVBW system used in the analysis shall consider the interference between the deck and the vehicle on their respective aerodynamic forces and shall include the lateral motion of the vehicle for possible sideslip. The other is that the varying aerodynamic coefficients of the vehicle passing by a bridge tower shall be available for the entire passage of the vehicle. More specifically, under the normal positions of the vehicle without influence from the tower (before S1 and after S4), the responses of the vehicle can be simulated directly using the RVBW system. While the vehicle moves into the shielding positions of the tower (S2), the varying aerodynamic coefficients of the vehicle passing by the bridge tower should be used together with the RVBW system until the vehicle reaches the position S4.