Vehicle ride comfort analysis with whole-body vibration on long-span bridges 

subjected to crosswind 

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Abstract 

Vehicle ride comfort issues for the drivers are related to not only individual satisfaction of driving experience, but also driving safety and long-term health of the drivers. A new methodology of ride comfort analysis is presented for typical vehicles driven on long-span bridges considering realistic traffic and environmental loads such as wind excitations. Built on the simulation framework developed previously by the writers, complex interactions among the long-span bridge, all the vehicles in the traffic flow and wind excitations are appropriately modeled. Vehicle ride comfort condition is evaluated by extending the advanced procedures as currently recommended in the ISO 2631-1 standard to the scenarios of multiple vehicles in the stochastic traffic flow, including obtaining the whole-body vibration response, frequency weighting the original response and determining the Overall Vibration Total Value (OVTV). The proposed methodology is then applied to a prototype long-span cable-stayed bridge and traffic system to demonstrate the proposed ride comfort evaluation methodology. The study starts with the baseline scenario when the vehicles are driven on the rigid road without considering the interactions with the supporting structure and wind excitations, followed by the scenarios of vehicles driven on the bridge. The influences of dynamic interactions, presence of other vehicles and wind excitations on the ride comfort are also numerically evaluated. 

Keywords: Long-span bridge; vehicle ride comfort; whole-body vibration; traffic flow; dynamic interaction; wind
1 Introduction

Vehicle ride comfort issues for the drivers are not only related to individual satisfaction of driving experience, but more importantly, driving safety and long-term health of the drivers due to the deteriorated driving environments and performance. This is particularly true for those occupational drivers with extended driving time and also higher responsibilities such as those for public transportation and large cargo trucks (USDOT 2005; NIOSH 2007). It is known that ride comfort is directly related to the vibrations of the vehicle body experienced by the drivers or passengers. Exposure to excessive whole-body vibration of the vehicle may cause short-term body discomfort and long-term physical damage, which are often related to back and neck, such as musculoskeletal pain and back pain (Griffin 1990). Automobile and highway transportation industry have devoted significant efforts on studying ride comfort issues during the past decades and the recent studies on ride comfort analysis primarily focused on the so-called whole-body vehicle vibration measurements. The criteria associated with the whole-body vehicle vibration were also recommended in several existing standards to evaluate vibration severity and assessing vibration exposures (ISO 2631-1 1985, 1997; BS 6841 1987).

Although vehicle ride comfort issues are usually evaluated before any new vehicle is approved to be on the roads, these studies are typically conducted considering normal driving conditions, such as on roadways under normal weather. For adverse driving conditions, for example on slender long-span bridges and/or with adverse weather, related studies on ride comfort are still very limited. Long-span bridges regularly support a large amount of vehicles throughout a day, and therefore these critical bridges play an important role in maintaining the safety and efficiency of the entire transportation system. Since long-span bridges are often built in wind-prone regions with bridge decks at heights of over 50 m above the water, wind acting on the bridges and the passing vehicles on the bridges can be pretty significant. These bridges usually exhibit high flexibility and low structural damping due to slender girders and large spans, and therefore are susceptible to considerable wind-induced dynamic vibrations. In addition to wind, other service conditions such as high traffic volume and the presence of multiple heavy vehicles can prevail on long-span bridges. Existing studies show that both the vibration of passing vehicles and the
long-span bridges can be significantly affected by the complex dynamic interaction among the bridge, 
vehicles and wind excitations (Chen and Wu 2010; Zhou and Chen 2014, 2015a, b; Han et al. 2014). 
Consequently, the oscillation on the vehicles may induce ride discomfort and fatigue issues for the drivers, 
which may further pose increased traffic safety concerns related to the degraded driving behavior and 
performance.

Most existing studies on vehicle ride comfort evaluation focused on the vehicles that are driven on 
rigid roads without considering the interaction with supporting structures as well as wind excitations (e.g., 
Navhi et al. 2009). Xu and Guo (2004) evaluated the ride comfort of a group of heavy vehicles on a long-
span cable-stayed bridge under crosswind. Yin et al. (2011) evaluated the ride comfort of a single truck 
when it moves through a multi-span continuous bridge at constant driving speeds. No other related studies 
are found for the vehicle ride comfort analysis in which the coupled effects from the supporting structure 
and crosswind excitations are taken into account. Besides, the traffic considered in the existing ride 
comfort studies was usually very approximate. For example, in the study by Xu and Guo (2004), the 
group of vehicles was assumed to be equally distributed and move along the bridge at a constant speed, 
which are apparently different from the realistic traffic on the roadway or bridges. In the study by Yin et 
el. (2011), only one vehicle is present on the bridge when vehicle comfort analysis is conducted. During 
the past years, stochastic traffic flow simulation has been incorporated into the bridge dynamic analysis 
(Chen and Wu 2011) to offer more realistic replication of real traffic on the bridges by considering the 
change of vehicle speeds and instantaneous positions following some traffic rules. Such technique offers 
promising venue for many studies involving dynamic interactions with stochastic traffic, including the 
study of ride-comfort issues with more realistic traffic flow. In addition to the oversimplified traffic 
simulation, the ride comfort analysis in the study by Xu and Guo (2004) was based on the single-axis 
root-mean-square (RMS) value with respect to one-third octave-band frequency in ISO 2631/1: 1985, 
which has been replaced with a new method in a later version (ISO 2631-1 1997). In the new method 
(ISO 2631-1 1997), the frequency-weighted RMS values are evaluated for ride comfort criterion based on 
multi-axis whole-body vibrations. Yin et al. (2011) evaluated the vehicle ride comfort performance based
on the criteria in the latest version of ISO 2631-1 (1997). However, only the vehicle responses at the translational axes are involved to obtain the final RMS value and the participation of the response at other rotational axes are ignored.

This paper presents a general ride comfort evaluation framework for any vehicle in stochastic traffic flow by considering essential dynamic interactions with supporting structures and environmental loads (e.g., wind). Specifically, such a framework will be applied on long-span bridges by considering the complex dynamic interactions and also possible presence of various crosswind conditions. Built on the analytical framework developed previously by the writers (Zhou and Chen 2015a, b), the fully coupled dynamic analysis is firstly conducted on the bridge-traffic system under crosswind, in which the complex interactions among the bridge, vehicles and wind can be incorporated. The ride comfort is evaluated using the frequency weighting and averaging procedures as currently recommended in Ref (ISO 2631-1 1997).

In order to investigate the significance of the proposed study in terms of incorporating the stochastic traffic flow and wind effects, the study will start with the baseline scenario in which the vehicles move on the rigid road without considering the dynamic interactions with the supporting structure or crosswind. The coupled simulation framework is then applied to evaluate the driving comfort performance of representative vehicles of the simulated stochastic traffic flow on a long-span cable-stayed bridge subjected to crosswind excitations. Finally, the influences of dynamic interactions, presence of other vehicles and wind excitations on the ride comfort are numerically evaluated.

2 Fully coupled bridge-traffic-wind interaction analysis

2.1 Stochastic traffic flow simulation

Stochastic traffic flow is simulated to represent the realistic vehicle motion on the bridge when cable breakage occurs (Chen and Wu 2010, 2011). The instantaneous behavior of vehicles in the traffic flow is simulated by means of the cellular automaton model. It is a computationally efficient microscopic simulation methodology in the sense that time advances in discrete steps and space is discretized into multiple cells, each of which remains empty or occupied with one vehicle. By applying a set of
probabilistic traffic transition rules regulating the accelerating, decelerating, lane changing and braking, the discrete variables in each cell are updated based on the vehicle information in the adjacent cells.

2.2 Structural idealization and finite element modeling of the bridge

The long-span cable-stayed bridge system is established as a three-dimensional finite element model in this study using two types of finite elements. The bridge superstructure and pylons are modeled with nonlinear three-dimensional spatial beam elements. The three-dimensional beam element is modeled based on the Timoshenko beam theory in which the axial, bending, torsional warping and shear deformation effects are considered at the same time. The stay cables are modeled as two-node catenary cable element based on the analytical explicit solution, which is obtained from the differential equations and boundary conditions for a cable with elastic catenary (Irvine 1981). The geometric nonlinearities in the beam elements originate primarily from beam-column effects due to the presence of large axial forces, which are modeled through the motion-dependent geometric stiffness matrix. The geometric nonlinearities in the stay cables are considered using the analytical equilibrium formulation of elastic catenary, through which cable-sag effect, large displacement and tension-stiffening effects are taken into account.

2.3 Modeling of road vehicles

Typical vehicles in the traffic flow are categorized into three types, which are heavy truck, light truck and light car (Chen and Wu 2010, 2011). The representative vehicle of each category is modeled as several rigid bodies and wheel axles connected by series of springs, dampers and pivots. The upper and lower springs are used to model the suspension system of each axle and elastic tires, respectively. Viscous dampers are used to model the energy dissipation system. The mass of the suspension system is assumed to be concentrated on the secondary rigid body at each wheel axle while the springs and dampers are assumed massless. The displacement vector $d_v$ for the heavy truck model with 19 DOFs includes 8 independent vertical, 8 lateral and 3 rotational DOFs. The displacement vector for light truck and light car
includes 5 independent vertical, 5 lateral and 2 torsional DOFs. The response vector of a typical heavy truck is expressed as follows.

\[
d_v = \{Z_1, \theta_1, \beta_1, Z_2, \beta_2, Z_{a1L}, Z_{a1R}, Z_{a2L}, Z_{a2R}, Z_{a3L}, Z_{a3R}, Y_1, Y_2, Y_{a1L}, Y_{a1R}, Y_{a2L}, Y_{a2R}, Y_{a3L}, Y_{a3R}\}
\]

(1a)

in which, each degree of freedom in the vector is independent as shown in Fig. 1a-b.

\[
\theta_{r_2} = (Z_{r_2} - Z_{r_1} - L_s \theta_1) / L_b
\]

(1b)

(a) Elevation view

(b) Side view

Fig. 1 Numerical model of the heavy truck

The displacement vector \(d_v\) for the light truck and light car is expressed in Eq. (2). The elevation view of the light car and light truck is shown in Fig. 2. The side view of the light car and truck is similar to that of the heavy truck and is omitted here.

\[
d_v = \{Z_1, \theta_1, \beta_1, Z_{a1L}, Z_{a1R}, Z_{a2L}, Z_{a2R}, Y_1, Y_2, Y_{a1L}, Y_{a1R}, Y_{a2L}, Y_{a2R}\}
\]

(2)

Fig. 2 Elevation view of light car and light truck

2.4 Modeling of wind forces on the bridge

The wind forces acting on the bridge girder are commonly separated into three components: steady-state forces resulting from average wind speed, self-excited forces resulting from wind-bridge interactions and buffeting forces resulting from turbulent wind velocity component. The wind forces are usually discretized as lift force, drag force and torsional moment for each of the three wind force components. For the bridge pylons and stay cables, only drag force from steady-state wind speed is considered. The lift force on the bridge girder is selected as the demonstration for the self-excited and buffeting forces.
The self-excited lift force on a unit span can be expressed by the convolution integral between the arbitrary bridge deck motion and the associated impulse functions, as shown in Eq. (3).

\[ L_{sl}(t) = L_{slp}(t) + L_{slh}(t) + L_{sl\alpha}(t) = \int_{-\infty}^{\infty} f_{slp}(t-\tau)p(\tau)d\tau + \int_{-\infty}^{\infty} f_{slh}(t-\tau)h(\tau)d\tau + \int_{-\infty}^{\infty} f_{sl\alpha}(t-\tau)\alpha(\tau)d\tau \]  

in which, \( f \) is the response impulse functions; The subscripts “p”, “h” and “\( \alpha \)” indicate responses in lateral, vertical and torsional directions, respectively.

The buffeting lift force can be formulated using similar method as that for self-excited lift force:

\[ L_{b}(t) = L_{bu}(t) + L_{bw}(t) = \int_{-\infty}^{\infty} f_{bu}(t-\tau)u(\tau)d\tau + \int_{-\infty}^{\infty} f_{bw}(t-\tau)w(\tau)d\tau \]  

in which, the subscripts “u” and “w” indicate turbulent wind horizontal and vertical velocities, respectively. Detailed modeling of wind forces on the bridge can be referred to the Ref (Zhou and Chen 2015b). The effective wind attack angle for each bridge girder member is calculated as the summation of the initial wind attack angle and the torsional displacement of the bridge member, which is obtained from the nonlinear static analysis on the bridge under gravity and wind forces. The fluctuation of wind coefficients during nonlinear dynamic analysis is ignored because the calculation of a new wind attack angle and the corresponding wind coefficients in each time step are very complicated and time consuming while they have little influence on the dynamic response.

### 2.5 Modeling of wind forces on road vehicles

The aerodynamic wind forces acting on the vehicles are determined by means of a quasi-static approach proposed by Baker (1986). Assuming that the steady-state wind velocity is perpendicular to the longitudinal direction of the bridge girder, the relative wind velocity \( U_R \) to a vehicle driving on the bridge can be expressed in the following equation.

\[ U_R(t) = \sqrt{(U_v + u(x,t))^2 + U_w^2(t)} \]  

in which, \( u(x,t) \) is the turbulent wind speed; \( U_v(t) \) is the instantaneous driving speed of the vehicle.
The aerodynamic forces and moments on the vehicles have six components, which are drag force, side force, lift force, rolling moment, pitching moment and yawing moment, as expressed in Eqs. (6a-6f), respectively.

\[ F_{v_i} = \frac{1}{2} \rho U_R^2(t) C_D(\Psi) A \quad (6a) \]

\[ F_{v_y} = \frac{1}{2} \rho U_R^2(t) C_L(\Psi) A \quad (6b) \]

\[ F_{v_z} = \frac{1}{2} \rho U_R^2(t) C_M(\Psi) A \quad (6c) \]

\[ M_{v_i} = \frac{1}{2} \rho U_R^2(t) C_D(\Psi) A h_v \quad (6d) \]

\[ M_{v_y} = \frac{1}{2} \rho U_R^2(t) C_M(\Psi) A h_v \quad (6e) \]

\[ M_{v_z} = \frac{1}{2} \rho U_R^2(t) C_L(\Psi) A h_v \quad (6f) \]

in which, \( \Psi \) is the yaw angle, which is the angle between the direction of relative wind speed and the vehicle driving direction in the range from 0 to \( \pi \); \( \psi = \arctan[U_w + u(x,t)/U_w(t)] \); \( h_v \) is the vehicle reference height; \( A \) is the reference area; \( C_D(\Psi), C_L(\Psi), C_M(\Psi) \) and \( C_M(\Psi) \) and \( C_Y(\Psi) \) are the drag force coefficient, side force coefficient, lift force coefficient, rolling moment coefficient, pitching moment coefficient and yawing moment coefficient, respectively.

### 2.6 Equations of motion for the fully-coupled bridge-traffic-wind system

Nonlinear dynamic analysis is conducted on the vibrating bridge-traffic system under cross wind, in which the vehicles move along the bridge following certain traffic rules. The coupled equations of motion of the bridge-traffic system can be built as shown in Eq. (7a).

\[
\begin{bmatrix}
M_{b} & 0 & \cdots & 0 \\
0 & M_{v_1} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & M_{v_n}
\end{bmatrix}
\begin{bmatrix}
\ddot{q}_{b} \\
\ddot{q}_{v_1} \\
\vdots \\
\ddot{q}_{v_n}
\end{bmatrix}
+
\begin{bmatrix}
C_{b} & 0 & \cdots & 0 \\
0 & C_{v_1} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & C_{v_n}
\end{bmatrix}
\begin{bmatrix}
\dot{q}_{b} \\
\dot{q}_{v_1} \\
\vdots \\
\dot{q}_{v_n}
\end{bmatrix}
+
\begin{bmatrix}
K_{b} & 0 & \cdots & 0 \\
0 & K_{v_1} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & K_{v_n}
\end{bmatrix}
\begin{bmatrix}
q_{b} \\
\dot{q}_{v_1} \\
\vdots \\
\dot{q}_{v_n}
\end{bmatrix}
= \sum_{i=1}^{n} F_{v_i}^C + \sum_{i=1}^{n} F_{v_i}^R + \sum_{i=1}^{n} F_{v_i}^C + \sum_{i=1}^{n} F_{v_i}^C + \sum_{i=1}^{n} F_{v_i}^C
\begin{array}{l}
F_{v_i}^R + F_{v_i}^C + F_{v_i}^C \\
F_{v_i}^C + F_{v_i}^C + F_{v_i}^C
\end{array}
\]

\[ F_{v_i}^C = \sum_{i=1}^{n} C_{b,v_i} \dot{q}_{v_i} + \sum_{i=1}^{n} K_{b,v_i} q_{v_i} + \sum_{i=1}^{n} C_{b,v_i} \dot{q}_{v_i} + \sum_{i=1}^{n} K_{b,v_i} q_{v_i} \]

\[ F_{v_i}^C = C_{n,b,v_i} \dot{q}_{v_i} + K_{n,b,v_i} q_{v_i} \]

in which, \( n \) is the total number of vehicles; \( q \) is the displacement vector; \( M, K, C \) and \( F \) are structural mass, stiffness, damping matrices and force vector; subscripts \( b \) and \( v_i \) \((i = 1, 2, \ldots, n)\) indicate that the parameters are for the bridge and the \( i \)th vehicle, respectively; \( K_{bci} \) and \( C_{bci} \) refer to the stiffness and damping contributions to the bridge structure due to the coupling effects between the \( i \)th vehicle in the traffic flow and the bridge system, respectively; \( K_{b,v} (K_{v,b}) \) and \( C_{b,v} (C_{v,b}) \) are the coupled stiffness and
damping matrices contributing to the bridge (vehicle) vibration, respectively; the superscripts $G$, $R$, $C$, $W$, $S_e$ and $B_u$ refer to the external loads caused by gravity, road surface roughness, coupling interaction forces, static wind, self-excited and buffeting forces, respectively.

The coupling matrices between the bridge and vehicles need to be updated at each time step according to the instantaneous contacting location of each vehicle during the movement on the bridge (Cai and Chen 2004). The self-excited forces due to turbulent wind speeds and coupling interaction forces between the bridge and vehicles are dependent on bridge unknown motion, therefore they should be calculated iteratively starting with an initial motion vector at each time step until the prescribed convergence criterion is satisfied. The whole simulation framework is established as an in-house program using MATLAB.

3 Ride comfort analysis on road vehicles

There are several standards that have provided procedures for evaluating human exposure to whole-body vibration and repeated shock. The tolerance of human vibration to vehicle ride vibration is known difficult to be evaluated despite extensive research efforts during the past several decades. There is thus no consensus on a criterion that can be unanimously accepted around the world for ride comfort. The regulations issued by the International Standard Organization (ISO) are one of the most popular criteria in current practice for ride comfort evaluations. The latest version (ISO 2631-1 1997) has been updated from the previous 1985 version (ISO 2631/1 1985) and is the only international standard for evaluating the whole-body vibration, which can be used for health, comfort, perception and motion sickness. Due to its popularity and applicability, the whole-body vibration measures (ISO 2631-1 1997) are adopted in the present study for vehicle ride comfort analysis and a brief summary is provided in the following sections.

3.1 Whole-body vibration measures

The ISO 2631-1 (1997) standard (called “standard” hereafter) is applied to assess the motions transmitted to a human body as a whole through all the supporting surfaces. For example, for a seated person, the three supporting surfaces are the seat, backrest and floor supporting the buttocks, back and
feet of the person; for a standing person, the supporting surface is only the floor supporting the feet of the person; for a recumbent person, the supporting surface only includes the side supporting area of the person. This study takes the seated position to investigate the driver comfort by considering all the three supporting surfaces. Apparently, the other two positions are comparatively less complicated by involving only one supporting surface and thus can also be evaluated using the proposed approach.

The standard measures the body vibration through 12 axes of a seated person, which are the vertical, lateral, fore-and-aft, yawing, pitching and rolling axes for the seat surface and the vertical, lateral and fore-and-aft axes for both the backrest and floor surfaces. The axles and locations where vibrations should be measured for comfort analysis based on a seated person are demonstrated in Fig. 3.

Fig. 3 Axles and locations for vibration measurements for a seated person (ISO 2631-1 1997)

From the coupled analysis of the bridge-traffic system, the acceleration response at the centroids of rigid bodies and mass axles of each vehicle can be obtained. The vehicle acceleration response at the seat, backrest and floor of the vehicles can be further determined through the vehicle response from the coupled analysis. It is known that the fore-and-aft acceleration of a vehicle primarily depends on the traction and braking forces exerted by the driver. Since this study focuses on ride comfort issues on long-span bridges under windy conditions, such acceleration has little impact on dynamic interaction and in turn related ride comfort results. Therefore, the fore-and-aft DOF is not included in the vehicle model and the associated acceleration response is not involved in the ride comfort analysis in the present study. In addition, the yawing effects of the vehicles are usually much less significant than the rolling and pitching effects when the bridge-vehicle interaction and wind excitations are considered. In the present study, the yawing acceleration is also ignored to obtain the total vibration effects of the vehicles.

There will be a total of 8 axes that participate in the ride comfort evaluation, including three vertical and three lateral axes at seat, backrest and floor locations, one pitching and one rolling axis at the seat location. The eight axes are noted as $v_s, v_b, v_f, l_s, l_b, l_f, p_s$ and $r_s$ in the present study, in which the first letter indicates the response direction and the second letter indicates the axis location. The response
direction can be \( v \) (vertical), \( l \) (lateral), \( p \) (pitching) and \( r \) (rolling). The axis location can be \( s \) (seat), \( b \) (backrest) and \( f \) (floor). The acceleration response at each participating axis of the vehicle can be expressed in Eqs. (8a-8d).

\[
a_{rz} = a_{lb} = a_{zf} = \ddot{Z}_{r1} \quad (8a) \quad a_{rl} = a_{lb} = a_{lf} = \ddot{Y}_{r1} \quad (8b)
\]

\[
a_{ps} = \ddot{\theta}_{r1} \cdot d \quad (8c) \quad a_{rs} = \ddot{\beta}_{r1} \cdot y_s + \frac{1}{2} \dot{\beta}_{r1} \cdot h_s \quad (8d)
\]

where \( a \) indicates acceleration at different axis; \( \ddot{Z}_{r1}, \ddot{Y}_{r1}, \ddot{\theta}_{r1} \) and \( \ddot{\beta}_{r1} \) are the accelerations at the first rigid body centroid of the vehicle in the vertical, lateral, pitching and rolling directions, respectively; \( d, y \) and \( h \) are the longitudinal, transverse and vertical distances between the centroid of the first rigid body and the seat, respectively. It is noted that angular acceleration in the pitching and rolling directions are transformed into linear acceleration to be consistent in dimension for calculating the total vibration effects.

3.2 Frequency weighting technique

According to the standard, the acceleration response of the supporting surface at each axle should be frequency-weighted before calculating the total effects from vibration exposure. The purpose of weighting the original acceleration data is to more realistically model the frequency response of the human body. Since no specific frequency weighting methodology is recommended in the standard, Fast Fourier Transform (FFT) convolution is adopted in the present study. For a response signal \( x \) with \( N \) discrete values with respect to time, the Discrete Fourier Transform (DFT) is conducted to obtain the signal value \( X \) with respect to discrete frequency in the frequency domain, as shown in Eq. (9).

\[
X(r) = \sum_{k=0}^{N-1} x(k) e^{j\omega_{N}k} \quad (9)
\]

in which, \( \omega_{N} = e^{-2\pi i / N}, \quad r = 0, 1, ..., N - 1 \).

The weighted signal \( X' \) in the frequency domain can be obtained as the product of the real and imaginary part of \( X \) and the corresponding frequency weighting \( \chi \), as shown in Eq. (10).

\[
X'(r) = X(r) \cdot \chi(r) \quad (10)
\]
The weighted signal $X'$ is then transformed back into the time domain using the inverse DFT to obtain the frequency-weighted signal $x'$ in the time domain.

$$x'(j) = \frac{1}{N} \sum_{r=0}^{N-1} X'(r) e^{-j\omega r}$$

(11)

in which, $j = 0, 1, ..., N-1$.

### 3.3 Weighting factors and multiplying factors

The standard (ISO 2631-1 1997) gives the multiplying factors for each of the axes in order to compensate the varying vibrating effects due to different locations and directions. There are four multiplying factors $M_k, M_d, M_e$ and $M_c$ for the participating axes, which are shown in Table 1 indicating the application in different locations and directions. The multiplying factors with the subscript “$k$” are used for vertical axis on the seat and all translational axes on the floor. The multiplying factors with the subscript “$d$” are used for lateral axes on the seat and floor. Those with the subscript “$e$” are applied for the rotational axes on the seat. The factor with the subscript “$c$” is only used in the vertical axis on the backrest.

<table>
<thead>
<tr>
<th>Multiplying factor</th>
<th>Value</th>
<th>Location</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_k$</td>
<td>1.00</td>
<td>Seat</td>
<td>Vertical</td>
</tr>
<tr>
<td>$M_d$</td>
<td>1.00</td>
<td>Seat</td>
<td>Lateral</td>
</tr>
<tr>
<td>$M_e$</td>
<td>0.40</td>
<td>Seat</td>
<td>Pitching</td>
</tr>
<tr>
<td>$M_c$</td>
<td>0.20</td>
<td>Seat</td>
<td>Rolling</td>
</tr>
<tr>
<td>$M_k$</td>
<td>0.40</td>
<td>Backrest</td>
<td>Vertical</td>
</tr>
<tr>
<td>$M_d$</td>
<td>0.50</td>
<td>Backrest</td>
<td>Lateral</td>
</tr>
<tr>
<td>$M_k$</td>
<td>0.40</td>
<td>Floor</td>
<td>Vertical</td>
</tr>
<tr>
<td>$M_c$</td>
<td>0.25</td>
<td>Floor</td>
<td>Lateral</td>
</tr>
</tbody>
</table>
The frequency weighting factors are named in a similar way to the multiplying factors. The weighting factors $W$ with the subscripts “$k$”, “$d$”, “$e$” and “$c$” are used in the same locations and directions as those of the multiplying factors. The weighting factors are originally quantified in decibel (dB) in the standard and in the present study, the unit of $dB$ is transformed to a dimensionless ratio $\delta$ through the following equation.

$$\delta = 10 \exp\left(\frac{dB}{10}\right)$$

Equation (12)

The weighting factors $W_k$, $W_d$, $W_e$, $W_c$ that are used in the frequency domain are shown in Fig. 4, which act as several filters to the original response. It is seen that the application of frequency weighting factors reduces the effects of the low and high frequency contents of the response signal. Taking $W_k$ for instance, the frequency contents below 0.63 Hz will account for the total vibrating effects with less than 45 percent of the original record. As the frequency goes lower, the weighting factor will become smaller. The frequency contents in the range between 5 Hz and 8 Hz will be weighted by a weighting factor that is slightly larger than 1.0. After 8 Hz, the weighting factor becomes smaller than 1.0 as frequency increases.

![Fig. 4 Weighting curves of ISO 2631-1 standard for different axes](image)

### 3.4 Determining the Overall Vibration Total Value (OVTV)

After applying the frequency weighting factors, the Root-Mean-Square (RMS) values of the weighted response acceleration vector for each axis can be obtained. The weighted RMS values will then be combined for all measurement locations and directions to obtain the overall vibration total value (OVTV). Based on the response at the eight axes involved in the present study, the OVTV can be obtained from the following equation:

$$\text{OVTV} = \sqrt{M_k^2 \text{RMS}_{v}^2 + M_d^2 \text{RMS}_{l}^2 + M_e^2 \text{RMS}_{p}^2 + M_c^2 \text{RMS}_{r}^2 + M_k^2 \text{RMS}_{v}^2 + M_d^2 \text{RMS}_{l}^2 + M_e^2 \text{RMS}_{p}^2 + M_c^2 \text{RMS}_{r}^2}$$

Equation (13)

in which, $\text{RMS}$ is the RMS value of frequency-weighted acceleration for each measurement location; the first subscripts “$v$”, “$l$”, “$p$” and “$r$” indicate the vertical, lateral, pitching and rolling directions,
respectively; the second subscripts \(s\), \(b\) and \(f\) for the acceleration RMS refer to the locations on the seat, backrest and floor, respectively.

### 3.5 Subjective criteria for ride comfort

The criteria of different discomfort levels as suggested by ISO 2631-1 (1997) are shown in Table 2. The subjective criteria for ride comfort have overlapping ranges of the OVTV values. The ride comfort of the vehicles is evaluated based on the criteria in Table 2 in the present study.

<table>
<thead>
<tr>
<th>OVTV value (m/s²)</th>
<th>Subjective indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.315</td>
<td>Not uncomfortable</td>
</tr>
<tr>
<td>0.315-0.63</td>
<td>A little uncomfortable</td>
</tr>
<tr>
<td>0.5-1.0</td>
<td>Fairly uncomfortable</td>
</tr>
<tr>
<td>0.8-1.6</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>1.25-2.5</td>
<td>Very uncomfortable</td>
</tr>
<tr>
<td>&gt;2.0</td>
<td>Extremely uncomfortable</td>
</tr>
</tbody>
</table>

### 4 Numerical demonstration

#### 4.1 The prototype long-span cable-stayed bridge

The prototype long-span cable-stayed bridge in the present study has a main span, two side spans and two approach spans. The main span length and the total bridge length are 372.5 m and 840 m, respectively, as shown in Fig. 5a. The cable-stayed bridge deck has a steel twin-box cross-section with a width of 28 m and a height of 4.57 m, which is shown in Fig. 5b. The two steel pylons have A-shaped cross-sections and are 103.6 m in height. The two cable planes of the bridge are placed in a fan-shaped arrangement with 12 sparsely located cables in each cable plane. The bridge superstructure is partially supported by the reinforced concrete bridge piers with sliding bearing supports at the side spans. The simulation process adopts the Rayleigh damping model, in which the damping coefficients for the mass
and stiffness matrices are obtained by assuming a damping ratio of 0.005 for the first two fundamental modes, respectively. The first two fundamental frequencies are 0.43 Hz and 0.65 Hz corresponding to the dominant vertical and lateral bending modes, respectively. Detailed modal properties for the prototype bridge structure can be found in the Reference (Zhou and Chen 2015a).

(a) Elevation view

(b) Cross section of the bridge deck

Fig. 5 The prototype long-span cable-stayed bridge

4.2 Traffic flow simulation and the prototype vehicles

4.2.1 Simulated traffic flow pattern

The vehicles in the stochastic traffic flow are categorized as three types, which are light car, light truck and heavy truck. The percentages in the simulated traffic flow are 20%, 30% and 50% for light car, light truck and heavy truck, respectively. In the driving direction, the entire travel path for the traffic flow includes three sections, which are the bridge section with the length of 840 m and two road sections with the length of 210 m each at the two ends of the bridge section. In the transverse direction, the entire travel path contains a total of four lanes with two lanes in each of the two driving directions. When the vehicles move on the approaching roadways, the external excitations on the vehicles are only from road surface roughness and wind. Therefore, the vehicle and the bridge are decoupled without incurring bridge-vehicle interaction forces. A stochastic traffic flow pattern with a density of 21 vehicles per kilometer per lane is simulated using double-lane cellular automaton model (Chen and Wu 2011). The number of total vehicles remains the same by using periodic boundary conditions. There are a total of 108 vehicles in the simulated traffic flow, including 54 light cars, 32 light trucks and 22 heavy trucks. The initial locations of the vehicles are randomly distributed on the whole travel path. One representative vehicle for each type of vehicles is selected as the ones with the initial locations at the far end in the road section before entering
the bridge. The driving paths for the representative light car, light truck and heavy truck are shown in Fig. 6. It is seen that the vehicles experience varying driving speeds as reflected by the changing of line slopes of the driving curves. The decreasing and increasing of the line slopes indicate that the vehicle accelerates and decelerates, respectively. The slope of 90° indicates the vehicle takes a complete brake and remains still. Except for at around 20 second when all the three vehicles stop moving by following some realistic traffic rules of congestion, the vehicle speeds generally keep steady in the range between 22.5 m/s and 30 m/s.

Fig. 6 Vehicle longitudinal location of the representative vehicles

4.2.2 Numerical properties of the prototype vehicles

The baseline dynamic parameters for each type of vehicles involved in the present study, including mass, mass moment of inertia, stiffness coefficients and damping coefficients, are listed in Table 3. The baseline dimension parameters for three types of representative vehicles are listed in Table 4. The vehicle dimensions and dynamic properties are quantified from the several references (Cai and Chen 2004; Xu and Guo 2003; Wang and Huang 1992).

Table 3 Dynamic parameters of the vehicles used in the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Heavy truck</th>
<th>Light truck</th>
<th>Sedan car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of rigid body 1</td>
<td>kg</td>
<td>4000</td>
<td>6500</td>
<td>1600</td>
</tr>
<tr>
<td>Pitching moment of inertia of rigid body 1</td>
<td>kg·m²</td>
<td>10500</td>
<td>9550</td>
<td>1850</td>
</tr>
<tr>
<td>Rolling moment of inertia of rigid body 1</td>
<td>kg·m²</td>
<td>3200</td>
<td>3030</td>
<td>506</td>
</tr>
<tr>
<td>Mass of rigid body 2</td>
<td>kg</td>
<td>12500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pitching moment of inertia of rigid body 2</td>
<td>kg·m²</td>
<td>28500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rolling moment of inertia of rigid body 2</td>
<td>kg·m²</td>
<td>10500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mass of axle block 1</td>
<td>kg</td>
<td>370</td>
<td>800</td>
<td>39.5</td>
</tr>
<tr>
<td>Mass of axle block 2</td>
<td>kg</td>
<td>1250</td>
<td>800</td>
<td>39.5</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Heavy truck</td>
<td>Light truck</td>
<td>Sedan car</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Mass of axle block 3</td>
<td>kg</td>
<td>1100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Upper vertical spring stiffness</td>
<td>kN/m</td>
<td>100</td>
<td>250</td>
<td>109</td>
</tr>
<tr>
<td>Upper vertical spring stiffness</td>
<td>kN/m</td>
<td>250</td>
<td>250</td>
<td>109</td>
</tr>
<tr>
<td>Upper vertical spring stiffness</td>
<td>kN/m</td>
<td>400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lower vertical spring stiffness</td>
<td>kN/m</td>
<td>150</td>
<td>175</td>
<td>176</td>
</tr>
<tr>
<td>Lower vertical spring stiffness</td>
<td>kN/m</td>
<td>400</td>
<td>175</td>
<td>176</td>
</tr>
<tr>
<td>Lower vertical spring stiffness</td>
<td>kN/m</td>
<td>500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Upper lateral spring stiffness</td>
<td>kN/m</td>
<td>75</td>
<td>187.5</td>
<td>79.5</td>
</tr>
<tr>
<td>Upper lateral spring stiffness</td>
<td>kN/m</td>
<td>187.5</td>
<td>187.5</td>
<td>79.5</td>
</tr>
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<td>Upper lateral spring stiffness</td>
<td>kN/m</td>
<td>300</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Lower lateral spring stiffness</td>
<td>kN/m</td>
<td>72</td>
<td>100</td>
<td>58.7</td>
</tr>
<tr>
<td>Lower lateral spring stiffness</td>
<td>kN/m</td>
<td>131</td>
<td>100</td>
<td>58.7</td>
</tr>
<tr>
<td>Lower lateral spring stiffness</td>
<td>kN/m</td>
<td>167</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Upper vertical/lateral damping coefficient</td>
<td>kN·s/m</td>
<td>5</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Upper vertical/lateral damping coefficient</td>
<td>kN·s/m</td>
<td>30</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Upper vertical/lateral damping coefficient</td>
<td>kN·s/m</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lower vertical/lateral damping coefficient</td>
<td>kN·s/m</td>
<td>1.2</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Lower vertical/lateral damping coefficient</td>
<td>kN·s/m</td>
<td>4.5</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Lower vertical/lateral damping coefficient</td>
<td>kN·s/m</td>
<td>4.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4 Dimensions of the vehicles used in the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Heavy truck</th>
<th>Light truck</th>
<th>Light car</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_1 ) between axle 1 and rigid body 1</td>
<td>m</td>
<td>1.83</td>
<td>1.8</td>
<td>1.34</td>
</tr>
<tr>
<td>( d_2 ) between axle 2 and rigid body 1</td>
<td>m</td>
<td>1.83</td>
<td>2.0</td>
<td>1.34</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Heavy truck</td>
<td>Light truck</td>
<td>Light car</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>------</td>
<td>-------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>$d_3$ between axle 2 and rigid body 2</td>
<td>m</td>
<td>3.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$d_4$ between axle 3 and rigid body 2</td>
<td>m</td>
<td>2.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$d_5$ between pin and rigid body 1</td>
<td>m</td>
<td>1.83</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$d_6$ between pin and rigid body 2</td>
<td>m</td>
<td>3.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$Y_i$ between axle and rigid body</td>
<td>m</td>
<td>1.10</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Frontal area $A$</td>
<td>$m^2$</td>
<td>10.5</td>
<td>6.5</td>
<td>1.96</td>
</tr>
<tr>
<td>Reference height $h_v$</td>
<td>m</td>
<td>2.0</td>
<td>1.65</td>
<td>1.1</td>
</tr>
<tr>
<td>$d_i$ between centroid and seat location</td>
<td>m</td>
<td>0.6</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$y_i$ between centroid and seat location</td>
<td>m</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>$h_i$ between centroid and seat location</td>
<td>m</td>
<td>0.7</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### 4.3 Baseline scenario for vehicle driving comfort analysis on roadways

In the baseline scenario, all the three sections of the driving path are assumed to be rigid roadways without considering the interactions between the vehicles and supporting structure. No wind speed is applied on the vehicles, which vibrate on their own under only the external excitations from road surface roughness. The road surface roughness is modeled as a stationary Gaussian random process using spectral representation method (Zhou and Chen 2014). The equations of motion are solved by the Newmark's constant average acceleration method with a time step of 0.04 s. It is found from preliminary sensitivity analyses that simulations with time steps of no more than 0.04 s give very similar results for both the bridge and vehicles with a time step of 0.01 s. Therefore, a time step of 0.04 s is selected for integration in the analysis to provide accurate response results with reasonable computational time. The dynamic responses of the representative vehicles for a simulation time period of 50 seconds are investigated for vehicle ride comfort analysis at the driver location.
4.3.1 Whole-body acceleration response

The acceleration responses of the representative light car in the vertical, pitching and rolling directions at the driver seat location are depicted in Fig. 7a, b and c, respectively. When the vehicle is driven on the rigid road, the lateral vibration is minimal since the only external excitation is road surface roughness. The accelerations from vertical, pitching and rolling movements of the light car have nearly zero mean values and similar magnitudes of extreme values.

(a) Vertical acceleration

(b) Pitching acceleration

(c) Rolling acceleration

Fig. 7 Acceleration response at the driver seat location for the representative light car

The RMS values of the vertical, pitching and rolling accelerations at the driver seat for the representative light car, light truck and heavy truck are shown in Fig. 8. The light truck has the largest RMS values in the vertical, pitching and rolling directions at the driver seat location among all the three representative vehicles. For the light truck and light car, the RMS values in the vertical axis are the largest among all the three axes and the RMS values in the pitching and rolling axis are close to each other. Different from the light car and light truck, the heavy truck has similar values in the vertical and pitching directions, which are larger than the value in the pitching direction.

Fig. 8 RMS values of the vertical, pitching and rolling acceleration for the representative vehicles

4.3.2 Frequency weighting of the acceleration response

After the original acceleration response of each axis is obtained, the response signal should be frequency-weighted to obtain the OVTV. Taking the vertical acceleration at the seat location of the light
car for instance, the acceleration spectrum for the original response is shown in Fig. 9a. By applying the frequency-weighting curve $W_k$ to the original spectrum, the frequency-weighted spectrum of the response can be obtained, which is shown in Fig. 9b. Through the comparison between Figs. 9a and 9b, it is found that after the acceleration response is frequency-weighted, the acceleration magnitude at the frequency range below 2 Hz is significantly reduced.

(a) Spectrum of the original response

(b) Spectrum of the frequency-weighted response

![Fig. 9 Single-Sided Amplitude Spectrum of the vertical acceleration response of the light car](image)

Through the inverse Fast Fourier Transform, the frequency-weighted acceleration response time history is obtained, which is shown in Fig. 10 in comparison with the original acceleration response. The frequency-weighted response has smaller extreme response than the original response because the response magnitudes at certain frequency ranges are significantly reduced. The RMS values of the vertical, pitching and rolling acceleration at the seat location of the light car are demonstrated in Fig. 11. It is seen that the RMS of the weighted vertical and pitching accelerations only account for 49 % and 39 % of the total RMS of the original response, respectively. Compared to the vertical and pitching accelerations, the frequency-weighting filter has relative smaller influence on the rolling acceleration response. Considering the pitching and rolling accelerations use same frequency-weighting filter $W_e$, the difference is mainly due to the fact that the frequency components of the rolling acceleration in the lower (< 0.8 Hz) and higher frequency (> 90 Hz) range account for less proportion of the total response than pitching accelerations. Since the frequency-weighted response may differ largely from the original vehicle response, the process of frequency weighting is apparently important in obtaining proper OVTV for the following ride comfort evaluation.
Fig. 10 Comparison of the original and frequency-weighted vertical acceleration response at seat location for the representative light car

Fig. 11 RMS values of the original and frequency-weighted response of the light car at the driver seat

4.3.3 Generation of OVTV

After the RMS values of the frequency-weighted acceleration response for each axis are obtained, the multiplying factors are applied to obtain the OVTV of the vehicle in order to evaluate the ride comfort level. The OVTV value for each representative vehicle is listed in Table 5. It is shown that when the vehicles move normally on a rigid roadway in moderate traffic flow, the ride comfort of the vehicles satisfies the criteria as specified in ISO 2631-1.

<table>
<thead>
<tr>
<th></th>
<th>Light car</th>
<th>Light truck</th>
<th>Heavy truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVTV (m/s²)</td>
<td>0.1161</td>
<td>0.1337</td>
<td>0.0985</td>
</tr>
</tbody>
</table>

The contributing percentages in OVTV from the acceleration response at each of the eight participating axis are computed for each of the three representative vehicles. The contributing proportion is obtained using the following equation.

\[
X_{ij} = M_{ind} \cdot \frac{a_{ij}^2}{OVTV^2}
\]  

(14)

in which, the subscript \(i\) and \(j\) indicate the response direction and location, respectively; the subscript \(i\) can be \(v, l, p\) and \(s\), representing vertical, lateral, pitching and rolling direction, respectively; the subscript \(j\) can be \(s, b\) and \(f\), indicating seat, backrest and floor location, respectively; the subscript \(ij\) is the axis index that participates in calculating the OVTV and the subscript \(ind\) refers to the different multiplying factors that are applied to different axis, which can be referred to Table 1; \(a_{ij}\) is the RMS value of the frequency weighted acceleration response at the designated axis \(ij\).
It is shown in Fig. 12 that the vertical acceleration at the seat location takes up the largest portion in the OVTV for the light car and heavy truck. While for the light truck, the proportion of the pitching acceleration at the seat location is the largest. When the vehicle moves normally on the rigid road, the lateral accelerations are minimal and barely contribute to the OVTV. The responses at the axes in the seat location contribute much more in the OVTV than those in the backrest and floor locations. The proportions of the response in the seat locations for the light car, light truck and heavy truck are 0.817, 0.853 and 0.838, respectively. The largest proportion of OVTV contributed by the response at one single axis for the light car, light truck and heavy truck is 0.537, 0.408 and 0.606, respectively. It is indicated that the whole body vibration response including those in different participating axes is essential for evaluating ride comfort based on the criteria by ISO. To consider only the vibration in one axis like many earlier studies may underestimate the total vibration response and in turn ride comfort evaluation results.

4.4 Effects of interactions between the vehicles and the supporting bridge structure

The effects of the interaction between the vehicles and the supporting bridge are investigated in this section. The coupled bridge-traffic interaction analysis is conducted to obtain the dynamic response of the bridge and each participating vehicle. The study firstly conducts the coupled analysis with only one single vehicle on the bridge. The effects of the bridge-vehicle interaction due to the presence of multiple vehicles are further investigated by conducting the coupled analysis of the bridge and the entire traffic flow. No wind excitations are considered in this section and only the effects due to bridge-vehicle interactions are considered.

4.4.1 Single vehicle vibration analysis

In the present case, only one single representative vehicle is involved in the bridge-vehicle interaction analysis and all other vehicles in the traffic flow are excluded. Each of the representative vehicles is driven through the road-bridge-road path separately. For each simulation, the driving path for each representative vehicle exactly follows the curve in Fig. 6 in order to make sure the vehicle moves
following the same pattern as in the baseline scenario. The difference as compared to the baseline scenario is that the dynamic interactions between the bridge and vehicle are considered in the present case. By comparing the acceleration response at each axis of the vehicles, it is found that the vehicle responses are not affected significantly by the interactions between the bridge and a single vehicle. The RMS values of the response at each participating axis are listed in Table 6 for the three representative vehicles. It can be seen that the RMS value in the case considering the bridge-single-vehicle interaction is very close to the corresponding value in the baseline case with a difference less than 1 percent.

Table 6 RMS values for the case with single vehicle on the bridge and baseline case

<table>
<thead>
<tr>
<th></th>
<th>Light car</th>
<th>Light truck</th>
<th>Heavy truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>At axis vs (on bridge)</td>
<td>0.1734</td>
<td>0.1317</td>
<td>0.1630</td>
</tr>
<tr>
<td>At axis vs (on road)</td>
<td>0.1744</td>
<td>0.1342</td>
<td>0.1623</td>
</tr>
<tr>
<td>At axis ls (on bridge)</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0001</td>
</tr>
<tr>
<td>At axis ls (on road)</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>At axis ps (on bridge)</td>
<td>0.1647</td>
<td>0.2965</td>
<td>0.0851</td>
</tr>
<tr>
<td>At axis ps (on road)</td>
<td>0.1649</td>
<td>0.2976</td>
<td>0.0849</td>
</tr>
<tr>
<td>At axis rs (on bridge)</td>
<td>0.2687</td>
<td>0.3436</td>
<td>0.3044</td>
</tr>
<tr>
<td>At axis rs (on road)</td>
<td>0.2687</td>
<td>0.3437</td>
<td>0.3044</td>
</tr>
</tbody>
</table>

After the acceleration response at each axis of the vehicles is frequency-weighted, the OVTV of each vehicle driven on the bridge can be obtained and the results are listed in Table 7. For comparison purposes, the OVTVs of the vehicles on rigid road from the baseline scenario are also listed. Very similar results suggest that the influence on the vehicle ride comfort from the interaction between the bridge and a single vehicle is negligible.

Table 7 The OVTV of the representative vehicles in the case of a single vehicle on the bridge and on the road
4.4.2 Effects of the presence of multiple vehicles

In this scenario, the coupled bridge-vehicle interaction analysis is conducted on the bridge and all the vehicles in the traffic flow. The acceleration responses of the three representative vehicles are compared with the corresponding results of the single representative vehicle case on the bridge in the previous section. Figs. 13a-13c give the vertical, lateral and pitching acceleration results of the light truck for the traffic flow case, respectively, with the results of the single-vehicle case being also plotted for a comparison. No discernible difference of the rolling acceleration of the comparative cases can be observed and the results are therefore not listed for the sake of brevity.

(a) Vertical acceleration

(b) Lateral acceleration

(c) Pitching acceleration

Fig. 13 Comparison of the acceleration response of the representative light truck in the traffic flow and single vehicle case

As shown in Figs. 13a-13b, the vertical and lateral accelerations of the light truck with the presence of multiple vehicles are much larger than those with only a single vehicle after the vehicle enters the bridge. The pitching acceleration of the vehicle is notably influenced due to the presence of other vehicles. However, the extreme values of the traffic flow case and single vehicle case don’t exhibit as large difference as compared with those from vertical and lateral directions (Fig. 13c), e.g., the maximum

<table>
<thead>
<tr>
<th>OVTV (m/s²)</th>
<th>Light car</th>
<th>Light truck</th>
<th>Heavy truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle on bridge</td>
<td>0.1158</td>
<td>0.1337</td>
<td>0.0987</td>
</tr>
<tr>
<td>Vehicle on road</td>
<td>0.1161</td>
<td>0.1337</td>
<td>0.0985</td>
</tr>
</tbody>
</table>
positive extreme pitching accelerations with the traffic flow and with only the single vehicle are 0.990 and 0.794 m/s², respectively. The RMS values of the vertical, lateral, pitching and rolling accelerations at the seat location are obtained for each representative vehicle in the traffic flow case and single vehicle case, which are shown in Fig. 14. It is found that the RMS value of the acceleration in the lateral direction is minimal when compared to those in other directions. The RMS values of rolling acceleration in the comparative cases are very close for all the three types of representative vehicles, indicating that the presence of multiple other vehicles has little effect on the rolling acceleration of the vehicle. In contrast, the presence of multiple vehicles may significantly affect the vertical acceleration of the representative vehicle, as evidenced by the much larger RMS value in the traffic flow case than in the single vehicle case. The ratios of the RMS values of the vertical acceleration in traffic flow case over those in the single vehicle case are 2.67, 3.72 and 1.65 for the light car, light truck and heavy truck, respectively. The vertical acceleration at the seat location of the light truck and heavy truck are the most and least vulnerable to be affected by the presence of multiple vehicles in the traffic flow, respectively. Such an observation also holds true for the pitching acceleration at the seat location, as it is found that the RMS ratios in the traffic flow case over the single vehicle case in the pitching direction are 1.07, 1.12 and 1.06 for the light car, light truck and heavy truck, respectively. However, it should be noted that the influence of the multiple vehicles on the pitching acceleration is comparatively much smaller than that on the vertical accelerations of the representative vehicles.

Fig. 14 RMS values of the acceleration response at the seat location for the representative vehicles

The original acceleration response at each axis is frequency weighted and the RMS value of the filtered/weighted acceleration is obtained. The OVTVs in the traffic flow case for each representative vehicle are obtained and listed in Table 8. The OVTVs of each single representative vehicle on the bridge are also listed for comparison. It is shown that the OVTV for ride comfort evaluation is much larger when the vehicle travels on the bridge with the simultaneous presence of multiple other vehicles than that in a single vehicle scenario. The ratios of OVTV in the traffic flow over that with the single vehicle are 2.11,
2.55 and 1.46 for the light car, light truck and heavy truck, respectively. The OVTV of the light truck and heavy truck are the most and least likely to be affected by the presence of other vehicles, respectively. From the OVTV results in Table 8, it is found that the drivers of the light car and heavy truck may experience acceptable comfortable levels on the bridge while the driver of the light truck may experience some discomfort on the bridge according to the ride comfort criteria set by ISO 2631-1. Considering that the presence of multiple vehicles is the most common scenario on the bridge, it can be concluded that the interactions between the bridge and the moving traffic may significantly influence the ride comfort level of a typical vehicle. Therefore realistic simulations of stochastic traffic flow and dynamic interaction should be appropriately made to accommodate the impacts from other vehicles on the ride comfort evaluations on long-span bridges.

Table 8 OVTV of the vehicles in the traffic flow and single vehicle case

<table>
<thead>
<tr>
<th></th>
<th>Light car</th>
<th>Light truck</th>
<th>Heavy truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the traffic flow</td>
<td>0.2457</td>
<td>0.3415</td>
<td>0.1437</td>
</tr>
<tr>
<td>Single vehicle</td>
<td>0.1158</td>
<td>0.1337</td>
<td>0.0987</td>
</tr>
</tbody>
</table>

Similar to Fig. 12, the proportion of the acceleration response in the OVTV when the traffic is on the bridge is also evaluated and shown in Fig. 15 for the representative vehicles. Compared to those in the baseline scenario in Fig. 12, the results for different types of representative vehicles on the bridge are actually close considering interactions due to multiple other vehicles. When the representative vehicles are driven on the bridge as part of the traffic flow, the vertical acceleration at the seat location becomes the dominant contributor to the OVTV for each type of representative vehicles. This is consistent with the previous observation about stronger dynamic interactions in the vertical direction for the bridge/traffic system than other directions (Fig. 13). In the mean time, the pitching and rolling accelerations account for much less proportions in the OVTV than those in the baseline scenrio, especially for the light car and light truck. It is indicated that the motions of the supporting bridge structure as well as dynamic
interactions with multiple vehicles may practically “even” the difference of the contributing proportions by different axes to the OVTV among different types of representative vehicles.

Fig. 15 Proportions of the response in each participating axis in OVTV for the representative vehicles

4.5 Effects of wind excitations

The effects of wind excitations on the ride comfort of the vehicles are investigated when these vehicles move through the bridge. It is assumed that wind excitations at a steady state wind speed of 20 m/s are applied on the bridge and all the vehicles in the traffic flow. Coupled bridge-traffic-wind interaction analysis is conducted to obtain the acceleration response of the vehicles in the traffic flow under wind excitations of 20 m/s. The vehicle acceleration response histories of the vehicles are compared with those without wind excitations. In both of the comparative cases, the interactions between the bridge and multiple vehicles in the traffic flow are considered. Figs. 16a, b and c demonstrate the vertical, lateral, pitching and rolling accelerations of the light car for instance, respectively.

(a) Vertical acceleration

(b) Lateral acceleration

(c) Pitching acceleration

(d) Rolling acceleration

Fig. 16 Comparison of the acceleration response of the representative light car under different wind speeds

It is found in Fig. 16 that the acceleration responses of the vehicle experience an abrupt increase at the start time when wind excitations are applied suddenly. This is especially notable for the acceleration
response in the lateral and rolling directions. It is observed that the lateral and rolling accelerations of the vehicle are more likely to be influenced in the wind environment than the vertical and pitching accelerations. The RMS of the accelerations in the vertical, lateral, pitching and rolling directions at the seat locations for the cases with wind excitations are given in Figs. 17a, b and c in comparison with the cases without wind excitations for the representative light car, light truck and heavy truck, respectively.

(a) Light car

(b) Light truck

(c) Heavy truck

Fig. 17 RMS values of the acceleration response of the representative vehicles for the cases with or without wind excitations

It is seen from Fig. 17 that the RMS values of the pitching acceleration are hardly affected by the wind excitations for the vehicles. The accelerations in the other three directions are affected by the wind excitations to various extents, among which the influence of wind speeds on rolling accelerations is most remarkable. Unlike the response results without wind excitations, the RMS values of rolling and pitching accelerations become the largest and smallest ones among the four axes for each type of the vehicles, respectively.

The RMS values of the frequency-weighted acceleration responses in all different axes are then obtained in the case with wind speed of 20 m/s in order to obtain the OVTV for the vehicles. The proportions of the weighted acceleration response at each participating axis in OVTV are obtained for the three representative vehicles (Fig. 18). It is noted that for vertical acceleration at the seat location, applying the frequency-weighting filter \( W_k \) causes a significant decrease of the RMS value of the acceleration response, as demonstrated in Fig. 11 in the previous sections. However, for lateral acceleration at the seat location, the frequency weighting filter \( W_d \) doesn’t pose significant influence on
the response and the filtered acceleration history in the lateral direction is very close to the original acceleration history. Therefore, although it is shown in Figs. 17a-c that RMS values in the vertical direction are notably larger than those in the lateral direction for the vehicles, the proportions of the weighted response in OVTV in the vertical axis are not always larger than those in the lateral axis. By comparing Fig. 18 with Fig. 15 in which no wind excitation was considered, it is obvious that the proportion of the lateral acceleration at the seat location increases significantly when wind excitations are considered. For the light truck and heavy truck, the lateral acceleration at the seat location account for the largest portion in the respective OVTV, which are much larger than the corresponding values of the vertical acceleration. For the light car, the proportion of the vertical acceleration is slightly larger than that of the lateral acceleration. As the high-sided vehicles, the light truck and heavy truck are more prone to the lateral excitations from cross wind than the low-sided light car.

Fig. 18 Proportion of acceleration response at each participating axis in OVTV for the representative vehicles

In addition to the wind excitations at the speed of 20 m/s, the coupled bridge-traffic-wind interactions are also conducted when the wind speeds are 10 m/s and 30 m/s. Although it is assumed in AASHTO specifications (AASHTO 2010) that bridges may be closed when the steady-state wind speed reaches 25 m/s, realistically, long-span bridges are often not closed even such wind conditions are met (Chen and Wu 2010). Therefore, wind excitations at the speed of 30 m/s are also considered in the present study considering that there might be strong wind gusts lasting for a relatively short time period not allowing the drivers or emergency managers to respond in time. The OVTVs are obtained for the representative vehicles as wind speed increases, as shown in Fig. 19.

Fig. 19 The OVTVs for the representative vehicles at different wind speeds

The OVTVs for the driver of the vehicles increase as wind speed increases for all three types of representative vehicles. When the wind speed is not higher than 20 m/s, the increase of the OVTV keeps
steady with the increase of wind speeds. When the speed is over 20 m/s, the OVTVs increase more significantly as the wind speed goes higher. Among the three representative vehicles, the largest and smallest OVTVs under the same wind speed occur on the light truck and the heavy truck, respectively. This also holds true in the cases without considering wind excitations as shown earlier. When the wind speed reaches 20 m/s and higher, the OVTV of the light truck increases at a larger rate than that of the light car and heavy truck. By interpolating the curves at the OVTV value of 0.315 m/s$^2$ as recommended by ISO in Fig. 19, it can be found that the driver will not feel uncomfortable if the wind speed is lower than 8.6 m/s and 23.8 m/s for the light car and heavy truck, respectively (on the bridge with moderate traffic flow). For the light truck, the driver may feel a little uncomfortable even if when the wind speed is zero. As long as the wind speed is not higher than 20.5 m/s, the driver will only feel a little uncomfortable when driving on the bridge in a moderate traffic flow based on the ISO ride comfort criteria. It is however pointed out that when the wind speeds increases beyond 20 m/s, the vehicle safety issue may replace the vehicle ride comfort issue to become dominant, which is usually assessed separately (Zhou and Chen 2015b).

5 Conclusions

This paper presents a new methodology of ride comfort analysis for typical vehicles driven on long-span bridges in the windy environment by considering the complex dynamic interactions and adopting advanced techniques for ride comfort evaluation. With the dynamic analytical framework proposed by the writer in previous studies, the long-span bridge, wind and all the vehicles in the traffic flow are directly coupled and more accurate vehicle responses can be obtained. The guidelines recommended in ISO 2631-1 (1997) for vehicle ride comfort evaluation are interpreted specifically in the context of stochastic traffic flow involving multiple vehicles. The essential processes in the vehicle comfort analysis are described in details, which include obtaining the whole-body vibration response, frequency weighting the original response and determining the OVTV (overall vibration total value). Taking a prototype long-span bridge and typical traffic flow as an example, this study further evaluated the ride comfort level of three types of
representative vehicles numerically. Firstly, the numerical study started with the baseline scenario when the vehicles move on the rigid roadway as a moderate traffic flow. Secondly, the effects of incorporating dynamic interactions between the bridge and the vehicles on the ride comfort of the vehicles were then assessed. Finally, the effects of wind excitations on the ride comfort of the vehicles were evaluated. The main findings of the numerical studies can be summarized in the following aspects:

- The frequency weighting is essential for obtaining proper OVTV for ride comfort evaluation. The ISO standard provides four frequency-weighting filters for different axes and at different locations. The filtering effects from different frequency weighting filters vary notably. It is found that the RMS value of vertical and pitching acceleration at the seat location is significantly reduced through the frequency-weighting filter $W_k$. However, the frequency-weighting filter $W_d$ has little effect on the lateral acceleration response at the seat location.

- When a single vehicle is driven through the long-span bridge, the interaction between the bridge and the designated vehicle is minimal and barely affects the vibration of the vehicle as well as the associated ride comfort condition. When the interactions between the bridge and all the vehicles in the moderate traffic flow are considered, the vehicle acceleration response can be significantly affected. It was found that the dynamic interactions with the supporting bridge structure considerably affect the ride comfort level of the vehicles.

- The lateral and rolling accelerations of the vehicle are more likely to be influenced in the wind environment than the vertical and pitching accelerations. The acceleration response of the vehicle is significantly influenced by the wind excitations.

- The response at the axes of the seat location account for the majority part of the OVTV for the vehicles. Unless wind excitations are applied, the accelerations in the vertical direction usually remain the larger portion in OVTV than those in other directions. The lateral acceleration only becomes notable in OVTV when wind excitations are applied. Under strong wind excitations, the acceleration in the lateral direction at the seat location may become dominant among all the participating axes.
When the vehicles move normally on the rigid road in a moderate traffic flow, the ride comfort of the vehicles satisfies the criteria specified in ISO 2631-1. When the vehicles move through the long-span bridge as a part of the traffic flow, the OVTV for the light car and heavy truck are below 0.315 m/s\(^2\), which is the threshold of ride discomfort as defined in the ISO standard. The OVTV of the light truck is slightly over the discomfort threshold value.

The light truck is more prone to the ride discomfort issue compared with the other two types of vehicles. This becomes more remarkable when the vehicle travels through the oscillating bridge under wind excitations. Although the ride comfort issues on this particular prototype bridge is not critical, other long-span bridges may exhibit more severe ride comfort issues. With the proposed framework, extensive studies on various long-span bridges from different regions need to be carried out in order to comprehensively investigate the ride comfort issues on long-span bridges.

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Figure 3

Diagram showing the various axes of human motion and orientation:
- **Vertical axis**
- **Yawing**
- **Backrest**
- **Seat**
- **Floor**
- **Lateral axis**
- **Pitching**
- **Fore-and-aft axis**
- **Rolling**
Figure 4

The graph shows the frequency response with different weighting factors: $W_k$, $W_d$, $W_e$, and $W_c$. The vertical axis represents the weighting factors, and the horizontal axis represents frequency in Hz. The graph indicates that each weighting factor has a peak at different frequency ranges, with $W_k$ having the highest peak at a lower frequency, followed by $W_d$, $W_e$, and $W_c$.
Figure 5a
Figure 5b
Figure 6
Figure 7a
Figure 7c
Figure 8

The graph shows the root mean square (RMS) values for different types of vehicles: Light car, Light truck, and Heavy truck. The x-axis represents the axis index, and the y-axis represents RMS in meters per second squared (m/s²). The graph indicates a decrease in RMS values as the axis index increases from vs to rs.
Figure 9b

Frequency-weighted spectrum

Acceleration amplitude (m/s^2)

Frequency (Hz)
Figure 11

- **Original response**
- **Frequency-weighted response**

**Axes:**
- **Y-axis:** Acceleration RMS (m/s²)
- **X-axis:** Axle index

Data points for:
- vs
- ps
- rs
Figure 13c

The figure shows a graph of pitching acceleration (m/s²) over time (s). The graph compares the acceleration in traffic flow (blue line) with that of a single vehicle (dotted green line). The experiment appears to be conducted on a road (On road), a bridge (On bridge), and back on the road again (On road).
Figure 14

A graph showing the acceleration RMS (m/s²) as a function of the axis index. The graph compares different types of vehicles:
- Light car (traffic flow)
- Light truck (traffic flow)
- Heavy truck (traffic flow)
- Light car (single)
- Light truck (single)
- Heavy truck (single)

The x-axis represents the axis index, while the y-axis represents the acceleration RMS.
Figure 16c
Figure 16d

- Wind speed of 20 m/s
- No wind speed

Rolling acceleration (m/s²)

Time (s)
Figure 17a

- Blue line: Light car (wind speed of 20 m/s)
- Green line: Light car (no wind speed)

Graph showing acceleration RMS (m/s²) vs. axis index.
Figure 17b

- Blue line: Light truck (wind speed of 20 m/s)
- Green line: Light truck (no wind speed)

Axes:
- Y-axis: Acceleration RMS (m/s²)
- X-axis: Axis index

Legend:
- Square: Light truck (wind speed of 20 m/s)
- Triangle: Light truck (no wind speed)
Figure 17c

- Heavy truck (wind speed of 20 m/s)
- Heavy truck (no wind speed)