VEHICLE-WIND-LONG SPAN BRIDGE INTERACTION AND ITS EFFECT ON SPEED LIMIT AND VEHICLE STABILITY

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Abstract

Currently, the speed limit imposed on bridges under strong wind conditions is mostly determined based on subjective experience. If the speed limit is set too low, the transportation system will be far from efficient. On the other hand, the safety of drivers cannot be guaranteed if the speed limit is set too high. The objective of this study is to simulate the performance of vehicles travelling on long-span bridges under severe wind events, with different speeds and different road conditions, and hence establish a realistic speed limit.

A specially designed analytical model is proposed to study vehicle performance when travelling on long span bridges under strong wind loads. The physical components of the analytical model involve a 7-degrees-of-freedom vehicle; a bridge with 3D finite elements and stochastic and the correlated road roughness profiles. The winds loads acting on the physical components are simulated as stochastic wind velocity fields generated by using the spectral representation method. To more accurately predict the performance of the moving vehicle, the static and buffeting forces acting on the vehicle are also considered. The solution to the analytical model can be found using the vehicle-bridge interaction element concept. By introducing the vehicle and the road-weather characteristics, such as drag coefficient and frictional coefficient, a set of simplified vehicle stability equations are derived. The stability requirements are implemented into the analytical model to study the reliability of vehicles on long span bridges under strong wind loads. A real bridge example is used to study the effects of road roughness, vehicle speed, vehicle type and vehicle mass on the vehicle performance. Based on the above information, the speed limit for such a realistic long span bridge can be established.

It is demonstrated that road roughness and the stiffness of the vehicle's suspension system are the key parameters that significantly influence the performance of the vehicle. The proposed model demonstrates that it can be used effectively to predict the speed limit on a bridge for a particular type of vehicle.

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INTRODUCTION

The allowable speed for vehicles travelling on long span bridges depends on the type of vehicle, including the vehicle shape, type of suspension system and tire condition; the type and geometric properties of the bridge; the wind profile and the road surface conditions. These factors, however, are fully coupled and should not be considered separately. The term "dynamic interaction between bridge and vehicle" has been vigorously developed in the past, a number of researchers started looking at the dynamic effect on bridges subjected to moving vehicle loads in 1929, in which vehicles were modelled as a moving load, without considering the inertia of the vehicle. It is not until 1989 that the moving-mass model was produced. With advancements in the use of the Finite Element Method, more general approaches have been developed to solve the characteristic equations of the bridge and the vehicle together in a Lagrangian formulation. Yang (1995) developed a Vehicle-Bridge Interaction element for dynamic analysis using the above approach, and more recently researchers such as Cai and Xu started to consider the wind induced effect on vehicle-bridge interaction, and set up the general framework for vehicle-bridge-wind dynamic analysis. Nevertheless, these models are usually designed for the analysis of the bridge response instead of the vehicle response.

On the contrary, very little information is available regarding the vehicle stability and wind intensity on long span bridges. Baker (1986, 1991) defined various types of wind-induced road vehicle accident mechanisms for high-sided vehicles on road without considering the dynamic coupling effect.

In this connection, a modified vehicle-wind-long span bridge interaction model was developed as a foundation tool for studying the vehicle performance when travelling along a long span bridge. The physical components of the model involve a 7-degrees-of-freedom vehicle; a bridge sectioned with 3D finite elements and stochastic and correlated road roughness profiles. The winds loads acting on the physical components are simulated as stochastic wind velocity fields generated by using the spectral representation method. With the help of the analytical model, the vehicle response can be studied and by introducing the vehicle instability requirements into the model, the vehicle stability performance is found accordingly.

VEHICLE-WIND-LONG SPAN BRIDGE INTERACTION MODEL

2.1 7-degree-of-freedoms vehicle model

The engine and power output properties of the vehicle are not significant in this study and therefore the vehicle model is simplified as a combination of several rigid bodies(masses) connected by a series of springs, damping devices and pivots. Many different simplified vehicle models exist developed by different researchers. Based on the pros and cons of different models, a 7-degree-of-freedom vehicle model firstly developed by Xu as shown in fig. 1, is adopted.

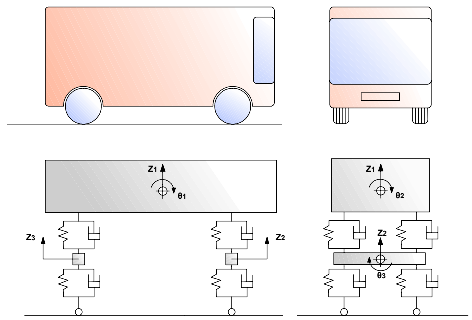


Figure 1 – Vehicle model

By considering the location of the mass centre and resolving the axial stiffness into the rotational stiffness, the stiffness matrix, damping matrix and the mass matrix can be developed.

2.2 Finite Element Bridge Model

A 3-D FEM model is constructed in ANSYS, and the Mass and Stiffness matrices ([M] & [K]) are extracted. For the damping matrix, the classical Rayleigh damping is adopted, whereby damping matrix of the bridge is a function of the stiffness matrix and mass matrix of the bridge:-

$$[C_b] = \alpha_b [M_b] + \beta_b [K_b]$$

Where α_b *and* β_b are the Rayleigh damping factors which can be evaluated if the two structural damping ratios associated with the two specific frequencies are given.

2.3 Correlated Road Roughness Profile

Road roughness usually refers to an uneven, impaired or bumpy pavement on a bridge. The American Society of Testing and Materials (ASTM) defines road roughness as "the deviations of a pavement surface from a true planar surface with characteristic dimensions greater than 15.24mm". In this research, the road roughness profiles are generated using the power spectral density (PSD). The roughness/randomness of the road surface can be simulated /modelled as a periodic modulated random process.

According to ISO-8680 specification and assuming a constant vehicle velocity PSD, the road surface roughness in the time domain can be simulated as:-

$$r(x) = \sum_{i=1}^{N} \sqrt{4S(f_i)\Delta f}\ \cos(2\pi f_i x + \theta_i)$$

Where N is a sufficiently large number, f_i is the frequency, $S(f_i)$ is the cross-spectrum density component at frequency f_i, x is the distance from the initial point and θ_i is random phase angle.

When the road roughness is implemented into the 3D computer model, two or more correlated road roughness profiles ought to be developed, instead of a single line profile. In this case, it was assumed that the road surface material is isotopic and the correlated random process $r(x_2)$ corresponding to the independent random process r(x) may be generated as follows:-

$$r(x_2) = \sum_{i=1}^{N} \gamma_{xy}(f_i)\sqrt{4S(f_i)\Delta f}\cos(2\pi f_i x + \theta_i) + \sum_{i=1}^{N} \sqrt{1-\gamma_{xy}^2(f_i)}\sqrt{4S(f_i)\Delta f}\cos(2\pi f_i x + \phi_i)$$

Where $\gamma_{xy}(f_i)$ is the coherence function, which can be calculated using the procedure presented by Liu(1996). Figure 2 demonstrates a typical correlated road roughness profile.

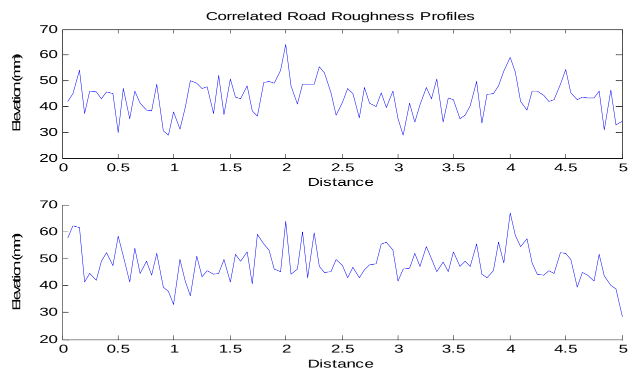


Figure 2 – Typical Road Roughness Profile

2.4 Simulation of Stochastic Wind Velocity Field on Long-Span Bridges

A complete wind velocity field should be regarded as a multidimensional, multivariate, homogeneous Gaussian stochastic process. However, it has been proven that the coherence between different dimensions is usually small and can be ignored without causing significant errors. When the above simplification is adopted, the wind velocity field can be reduced to some one-dimensional, multivariate stochastic process. A number of methods exist for simulating a stochastic process; Shinozuka (1972) established the classical spectral representation method and he further developed the said method and used it to simulate an ergodic stochastic wind velocity field in 1996. For a given one-dimensional, multivariate stochastic process { F(t) } with zero mean components $F_1(t)$, $F_2(t)$, $F_2(t)$, … , $F_n(t)$, One can define the cross-spectral density matrix and $F_j(t)$ can be simulated by the sequence:-

$$f_j(t) = \sqrt{2(\Delta\omega)}\sum_{m=1}^{j}\sum_{l=1}^{N}\left|H_{jm}(\omega_{ml})\right|\cos(\omega_{ml}t - \theta_{jm}(\omega_{ml}) + \phi_{ml}), \qquad j = 1, 2, \ldots, n$$

This equation is similar to the equation for road roughness with ω representing the frequency, φ is the random phase angle, $\theta_{jm}(\omega_{ml})$ is the complex angle and H(ω) us defined by the Cholesky's decomposition of S(ω).

The cross-spectral density matrix is usually a complex matrix and the calculation of its Cholesky's decomposition is tedious and often recursion formulas are used. When the horizontal and vertical wind velocity fields acting on long span bridge are considered, Cao (2001) proved that one can approximately take the spectra of horizontal wind velocity as not varying along the length of the bridge. Thus:-

$$S_{11}(\omega) = S_{22}(\omega) = \cdots = S_{nn}(\omega) = S(\omega)$$

And H(ω) can be expressed in an explicit form:-

$$H(\omega) = \sqrt{S(\omega)}G(\omega)$$

Where

$$G(\omega) = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ C & \sqrt{1-C^2} & 0 & \cdots & 0 \\ C^2 & C\sqrt{1-C^2} & \sqrt{1-C^2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C^{n-1} & C^{n-2}\sqrt{1-C^2} & C^{n-3}\sqrt{1-C^2} & \cdots & \sqrt{1-C^2} \end{bmatrix}$$

With

$$C = \exp\left(-\frac{\lambda\omega\Delta}{2\pi U(z)}\right)$$

Where λ can be taken as 7 to 10, Δ is the distance between successive points and U(z) is the average wind velocity. By rewriting the above formulas,

$$f_j(t) = \sqrt{2(\Delta\omega)}\sum_{m=1}^{j}\sum_{l=1}^{N}\sqrt{S(\omega)}G_{jm}(\omega_{ml})\cos(\omega_{ml}t + \phi_{ml})$$

2.5 Vehicle-Wind-Long Span Bridge Interaction

In the dynamic impact analysis, 2 fully coupled systems, the vehicle system and the bridge system are considered together. In the vehicle system, a simplified mass-and-spring system at each contact point with a generalized form:-

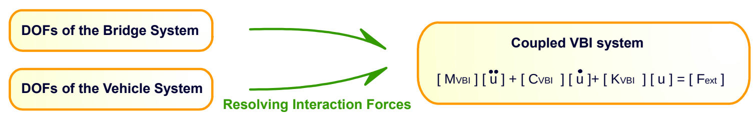
$$\begin{bmatrix} 0 & 0 \\ 0 & m_v \end{bmatrix}\begin{Bmatrix} \ddot{v}_{v1} \\ \ddot{v}_{v2} \end{Bmatrix} + \begin{bmatrix} c_v & -c_v \\ -c_v & c_v \end{bmatrix}\begin{Bmatrix} \dot{v}_{v1} \\ \dot{v}_{v2} \end{Bmatrix} + \begin{bmatrix} k_v & -k_v \\ -k_v & k_v \end{bmatrix}\begin{Bmatrix} v_{v1} \\ v_{v2} \end{Bmatrix} = \begin{Bmatrix} f_i \\ m_v g \end{Bmatrix}$$

Where m_v is the mass of the vehicle above the pivot and f_i is the bridge-vehicle interaction force; v_{v1} and v_{v2} are the DOF's for the wheels and the vehicle body respectively, kv and cv are the stiffness and the damping of the wheel being considered. For the bridge system, the classical characteristic equation can be written as:-

$$[M_b]\{\ddot{v}_b\} + [C_b]\{\dot{v}_b\} + [K_b]\{v_b\} = \{N(x)\cdot f_i\}$$

$\{\ddot{v}_b\}$, $\{\dot{v}_b\}$ *and* $\{v_b\}$ are the nodal displacement, velocity and acceleration vectors of the bridge while the interaction force will act on different elements on the bridge deck, when the vehicle moves across the bridge.

By combining the two systems using the dynamic condensation technique proposed by Yang (1995), a new coupled system with all the DOF's from the bridge and the vehicle can be obtained.



This system can be considered as an initial value problem for ordinary differential equations with 2 arguments (time, displacement). However, it is noted that the mass matrix, damping matrix (if any), stiffness matrix and the force vector are all time and position dependent (as the shape factor N(x) changes with time), and in every time step, the time and position information should be used to evaluate the value of the matrix before proceeding to the next. The external load is contributed by the wind velocity field acting on the corresponding nodes on the bridge and the vehicle.

Vehicle Safety Measurement

Baker (1986) defined various types of wind-induced road vehicle accidents. An overturning accident is a situation when the tire reaction force of any tire falls to zero; a side slipping accident is defined in a situation when the lateral response of the vehicle exceeds 0.5m; a rotation accident is a situation when the yawing displacement exceeds 0.2 radians. In the analysis of vehicle stability on long span bridges, it is suggested that a rotation accident can rarely happen as vehicles will not be subjected to sudden acceleration or deceleration on bridges. Besides, in the vehicle bridge interaction model, the bridge deck and the vehicle should always be in contact and there should not be any lateral response at the contact points. In view of the above, the author modified the accident models and defined the situation "Potential Vehicle Instability" when the following mechanisms occur at a particular instant during the drive:-

- Overturning Instability - when the tire reaction force of any tire fall to zero.
- Sliding Instability – when the sum of lateral frictional forces available on all tires is smaller than the lateral loading acting on the vehicle.

The overturning moment is resisted by the couple of the self-weight and the normal reaction forces on the wheels, while the frictional force available depends on the frictional coefficient and the normal reaction forces on the wheels. The normal reaction forces on the tires can be evaluated by solving the fully coupled system discussed above. The frictional coefficient, however, varies considerably depending on tire type and other vehicle specification. According to information from the Niigata Experimental Laboratory, Public

Works Research Institute, the frictional coefficient should be 0.8-0.9 for dry conditions; 0.7 for wet conditions and 0.4-0.5 for conditions with a thick water film on the road.

The overall simulation procedure:-
With the vehicle-wind-long span bridge interaction model and the vehicle instability criteria, the stability of vehicles travelling on long span bridges under different wind conditions can be simulated. The vehicle safety simulation procedure is summarised in figure 3, and the beauty of the computer simulation is that one can repeatedly simulate the same situation to obtain some statically meaningful results when field measurements are not possible. Due to the limitation of the coupled model, the vehicle should always be in contact with the bridge deck, as once potential vehicle instability occurs, the model can no longer simulate the performance of the vehicle and the simulation shall stop.

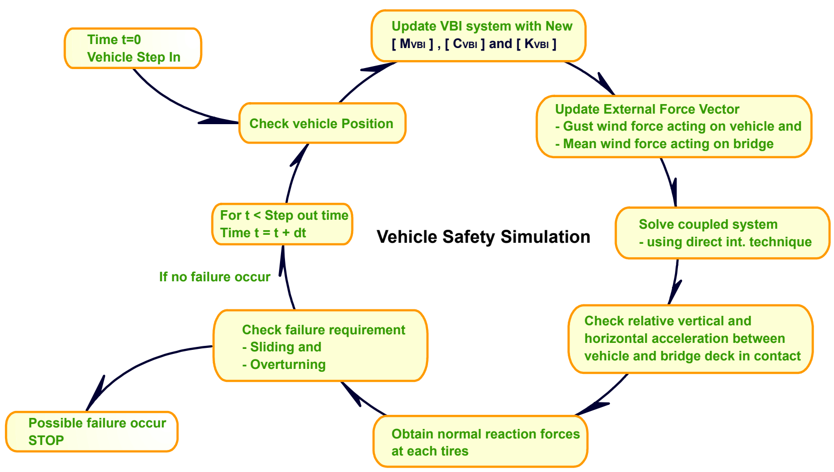


Figure 3 – simulation procedure

Numerical Example
The Confederation Bridge has been the main link in the transportation system between the two Canadian provinces of New Brunswick and Prince Edward Island since 1997. A box girder section of the Confederation Bridge, with 440m span rest on 2 piers 250m apart, is modelled in ANSYS. The natural frequencies and the mode shapes of the first few modes were extracted and these data show good agreement with the theoretical values found by Cheung (2004). The stiffness and the mass matrix were then extracted and used as the input of the Matlab program. The vehicle adopted in this example is a typical bus, with both the fully loaded and the empty cases were studied, and the result indicated that the empty case usually controls the instability mode and therefore, only the empty case is presented.

The vertical and horizontal wind velocity field on the bridge deck acts at 50 different points uniformly distributed along the bridge deck. The horizontal wind velocity profile acts on the vehicle. A Kaimal's wind spectrum is adopted here, with a upper cut off frequency equal to 4π rad/s, the average horizontal wind velocity is 30 m/s. Figure 5 illustrates the typical fluctuating vertical wind velocity profile for point 1, point 2 and point 50 along the bridge deck respectively.

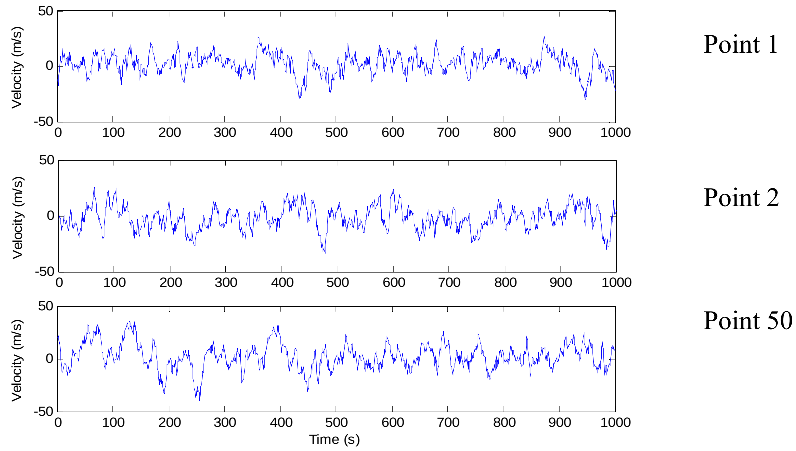


Figure 5 – Vertical wind velocity profile for point 1, 2 and 50 along the bridge deck.

The simulation result for a single trial when the vehicle speeds equal 50km/h and 120km/h is shown in figure 6 and figure 7 respectively.

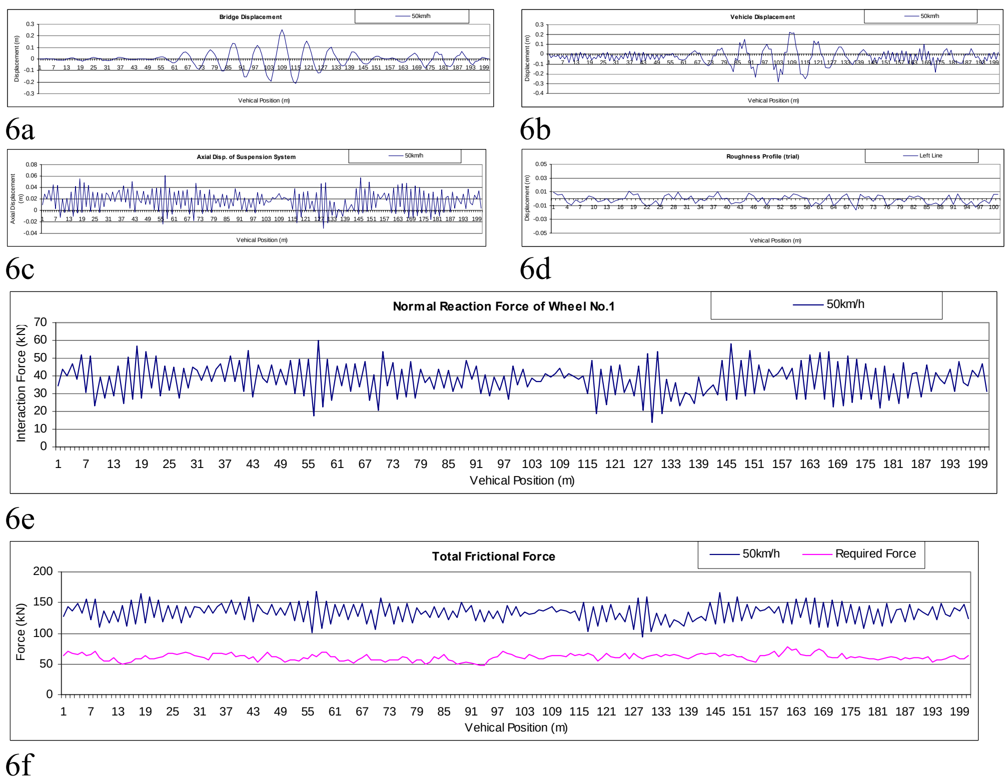
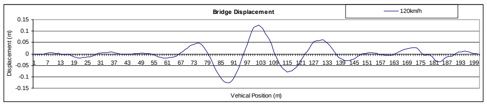


Figure 6 – Vehicle velocity equals 50km/h, mean wind speed equals 30m/s



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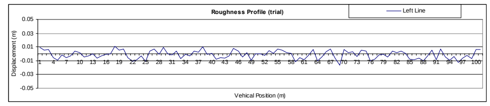

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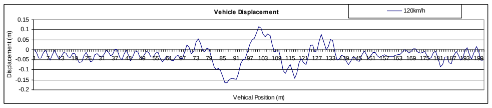

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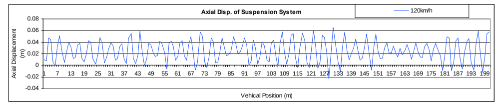

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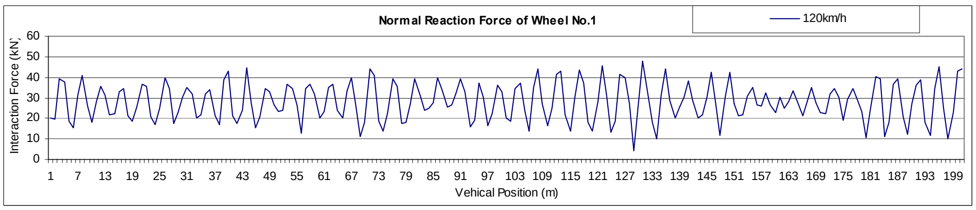

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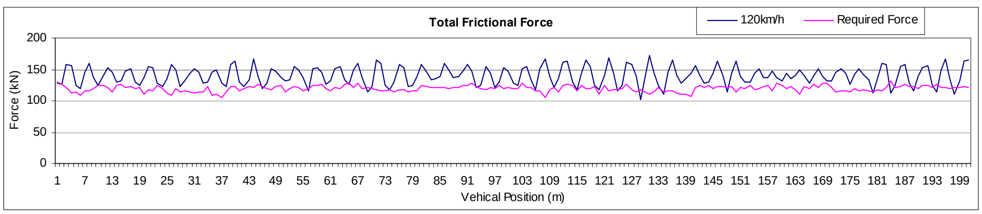

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Figure 7 – Vehicle velocity equals 120km/h, mean wind speed equals 30m/s

The vehicle displacement (6b & 7b), velocity and acceleration can directly extracted from the program while the bridge displacement at the position of vehicle (6a & 7a) is found by locating the element on the bridge deck with the vehicle, and adjusting the bridge displacement with the shape function. By expressing the displacement of the suspension system at each contact point in terms of the above information and the road roughness profile (6d & 7d), the normal reaction forces (6e & 7e) at each wheel and the total horizontal frictional force available (6f & 7f) can be evaluated. The time history of the total equivalent horizontal wind forces acting on the vehicle can be measured by locating the strength of wind profile at the position of vehicle, this information is shown on figure 6f and 7f to indicate the possibility of sliding instability. From the results of different trial runs, it is discovered that the minimum normal reaction force is usually found in the windward front tire and therefore only the normal reaction force at that contact point is presented here. It is suggested that the vehicle in the example is not subjected to any instability condition when travelling at 50km/h as the normal reaction forces always greater than zero and the available horizontal frictional forces are always greater than the horizontal wind forces acting on the vehicle. However, the same vehicle is likely to have sliding instability when the vehicle speed is increased to 120km/h. Besides, it is observed that the minimum normal reaction acting on the windward front tire does not change significantly with the vehicle speed, and indicated that the vehicle velocity has little effect in causing overturning instability.

Moreover, from the risk analysis result, the allowable vehicle velocity falls to zero quickly when the wind speed exceed 35m/s, in which the instability mechanism shift form sliding instability to overturning instability. From these results, it is proposed that a 2 criterion allowable speed should be imposed on a bridge. When the wind speed is not too high, the allowable speed limit, inversely proportional to the wind speed, should be imposed to prevent sliding instability, while no traffic should be allowed if the wind speed reached a certain limit that may cause overturning instability.

Concluding Remarks

Time domain approach to simulate the vehicle response travelling along a long-span bridge with wind loading is presented and the stability requirements are studied, modified and implemented into the simulation package. This simulation package is used to study the possibility of potential vehicle instability when travelling across the bridge with strong winds. Simulation result suggested that under moderate wind speed, overturning instability can rarely occur and sliding instability dominate the instability mechanism when the vehicle speed is high. On the other hand, overturning instability can occur regardless the vehicle speed when the wind speed is extremely high. This indicated that imposing a speed limit on vehicle running along the bridge can be effective only when the wind speed is not too high, when the wind speed is very high (exceed 35m/s in the above example), no traffic should be allowed as overturning instability can occur at all speed.

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