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Safety Assessment of Road Vehicles and Realization of On-board Wind Pre-warning System

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Abstract

Safety assessment of road vehicles suffering from crosswinds is conducted considering multiple road vehicles in the traffic. The vehicles are divided into five vehicle types and simulated by five vehicle models. For each vehicle model, representative parameters are assigned, during which the side force coefficient and the vehicle weight are generated randomly obeying properly defined probability distributions. Then, traffic volume of 10000 vehicles, with the observed vehicle proportions of different vehicle types, is applied to calculate the overturning probability of the traffic. With this method, the effects of the vehicle proportion and vehicle speed on overturning probability of the traffic are investigated. In addition, the overturning probability of current highway traffic regulation rule in Japan is also studied. On the other hand, on-board wind pre-warning system is realized with a combination of the Characteristic Wind Curves, short-term wind velocity and direction prediction, and risk analysis. It provides the permitted vehicle speed V_p to the driver before the vehicle traversing the strong wind section, which can ensure the vehicle running safety under crosswinds.

Introduction

Traffic regulation is a common measure to avoid wind-induced vehicle accidents, by either stopping the traffic or slowing down the vehicle speed during period of strong wind at exposed windy sites, such as bridges and embankments. However, for current highway traffic regulation in Japan, the restriction is conducted based on the 10-minute mean wind velocity, as mentioned in [2], without considering the wind fluctuation component. This may lead to the underestimation of the risk, since the instantaneous wind velocity may reach the critical velocity of overturning while the corresponding mean wind velocity remains a relative smaller value. In addition, the vehicle proportion of different vehicle types in the traffic is not incorporated in the traffic regulation rule, which may affect the risk of wind-induced accident significantly.

In this study, a safety assessment method is proposed to consider the traffic, in other words, to consider the multiple road vehicles with a certain vehicle proportion. It provides a base for determination of highway traffic regulation rule. The conditional overturning probability of current highway regulation rule is investigated by this method with the instantaneous wind velocity being considered. On the other hand, an on-board wind pre-warning system is built. It is considered to be capable of overcoming the risk induced by the time delay in conduction of traffic regulation.

Safety Assessment Considering the Traffic

The idea is described as follows. Vehicles in the traffic are firstly divided into five vehicle types and simulated by five different models separately. They are light motor vehicle, regular vehicle, medium-sized vehicle, large-sized vehicle, and extra large-sized vehicle. For each model, representative values or distributions are defined for its parameters (dimensional size, aerodynamic coefficients and weight). Then each single vehicle is simulated by the model corresponding to its vehicle type. In a certain traffic section, if the traffic volume is assumed, and given the vehicle proportions of different vehicle types, the overturning probability can be obtained for various wind condition.

In this study, dimensional sizes of Wagon, Sedan type passenger car, Medium truck, the truck overturned on Ohmishima Bridge, and Tour bus are adopted as the representative ones of each vehicle model mentioned, as listed in table 1. B, H, W, and D denote vehicle length, vehicle height, vehicle width and distance from ground to vehicle subsurface, respectively. The side force coefficient is determined by the product of the representative value and the scale factor S, which obeys reasonably defined uniform probability distribution $S\sim U(a,b)$ and is randomly generated from the corresponding distribution. The side force coefficient of a truck obtained by CFD simulation in [3] is taken as the representative one for all the models, while the probability distribution of S is defined separately as shown in table 2. The vehicle weight is defined by the representative log-normal distribution $G\sim\ln N(\mu,\sigma^2)$ as shown in table 3, based on [1]. It is generated randomly in a similar way in the calculation.

	Light motor	Regular	Medium -sized	Large-sized	Ex. large-sized
B	3.395	4.58	8.485	11.76	11.99
H	1.64	1.475	2.55	3.77	3.75
W	1.475	1.74	2.47	2.49	2.49
D	0.15	0.13	0.40	0.40	0.53

Table 1. Dimensional sizes of each type of vehicle (unit: m).

	Light motor	Regular	Medium -sized	Large-sized	Ex. large-sized
a	0.5	0.4	0.85	0.9	0.9
b	0.8	0.8	1.05	1.1	1.2

Table 2. Distributions of scale factor $S\sim U(a,b)$ for each vehicle type.

	Light motor	Regular	Medium -sized	Large-sized	Ex. large-sized
μ	0.88	2.24	5.37	13.2	19.6
σ	0.095	0.51	0.82	2.8	4.9

Table 3. Distributions of vehicle weight $G\sim\ln N(\mu,\sigma^2)$ (unit: ton).

Applied vehicle proportions in the calculation are the ones observed in the traffic of Tarumi-Awaji section in Kobe-Awaji-Naruto Expressway, as shown in figure 1.

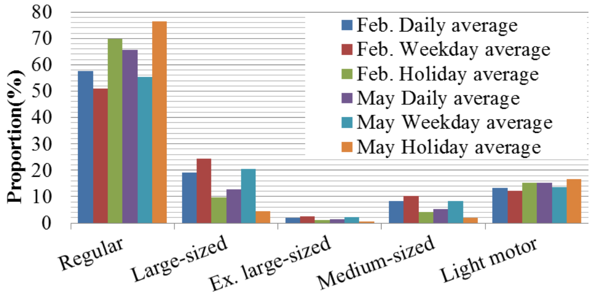


Figure 1. Vehicle proportions in the traffic during Feb. and May 2014.

The total amount of vehicles is assumed N=10000. The ranges of wind velocity and wind direction considered are [10 40] m/s and [10 150] degree with the intervals of 1 m/s and 1 degree, respectively. For i-th time of calculation, the total traffic is input and the overturned vehicle amount n_i is obtained for each wind condition. The calculation is repeated 100 times to gain the average overturning probability P_{OT}:

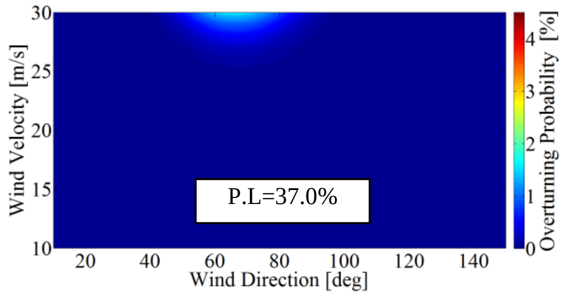
$$P_{OT} = \frac{\sum_{i=1}^{100} n_i \Big/ 100}{N} \tag{1}$$

For each single vehicle, determination of overturning is based on the static equilibrium equation of the vehicle defined as follows:

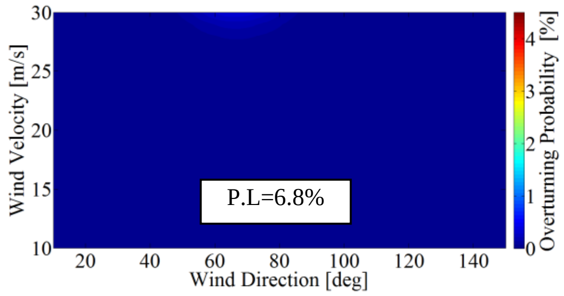
$$M_{ov} > M_{re} \tag{2}$$

where M_{ov} and M_{re} are the overturning moment induced by crosswind, and the resistance moment of the vehicle, respectively.

Given a certain vehicle proportion, the summed proportion of relative large-sized vehicle, including medium-sized vehicle, large-sized vehicle and extra large-sized vehicle, is calculated and denoted as P.L.. The effect of P.L. on the overturning probability is investigated and the result is shown in figure 2.



(a)



(b)

Figure 2. Overturning probability (V=80km/h) when P.L.=37.0% and P.L.=6.8%, shown in figure (a) and figure(b), respectively.

In the figure, the overturning probability is displayed by the colour, as shown by the colorbar on the right side of the figure. By comparing figure 2(a) and figure 2(b), it is found that the larger P.L., the higher overturning probability of vehicles in the traffic. It is considered to be caused by the higher side force action centre of relative large sized-vehicles, say, truck and bus, than that of the regular vehicle, which leads to the relative large-sized vehicle being more vulnerable to overturning. Therefore, for the traffic with high P.L., it is more important to make suitable countermeasure to crosswinds.

The effect of vehicle speed V on the overturning probability can be confirmed by comparing figure 3 with figure 2(a), both of which are with the same P.L. but different V. Figure 3 shows the result with vehicle speed V=100 km/h, while figure 2(a) is the result with vehicle speed V=80 km/h. From the comparison, it is found that the overturning risk increases with vehicle speed.

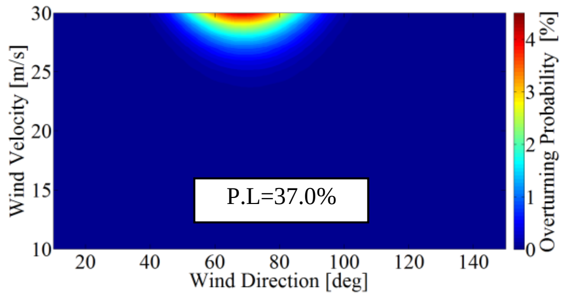


Figure 3. Overturning probability (V=100km/h) when P.L.=37.03%.

For current regulation rule widely applied in Japan as introduced in [2], the most dangerous conditions are those when the vehicle moves with normal speed under the crosswind of 15m/s, and when the vehicle moves with half of the normal speed under the crosswind of 25m/s. Hence, the corresponding overturning probabilities are investigated and denoted as upper limits of overturning probability. The 10-minute average wind velocity is transformed to the 3-second maximum instantaneous wind velocity by

$$U_{\max} = U + g_d \sigma \tag{3}$$

where $U_{\max}$ is maximum instantaneous wind velocity, U is 10-minute mean wind velocity, g_d is the peak factor (g_d=3), σ is the standard deviation of 3-second instantaneous wind velocity observed on Ohmishima Bridge. The normal vehicle speed is assumed to be V=100 km/h. Then, the most dangerous conditions considering the instantaneous wind speed can be gained, as listed in table 4. The upper limits of overturning probability for two different P.L.s are obtained and also shown in the table.

P.L. (%)	Most dangerous conditions	
	U_{max}=20m/s, V=100km/h	U_{max}=30m/s, V=50km/h
37.0	0.0021%	0.1813%
6.8	0.0003%	0.0311%

Table 4. Upper limits of overturning probability corresponding to current highway traffic regulation rule in Japan.

By comparing the results of two different P.L.s, it is found that overturning risk increases significantly with P.L.. It indicates that even if the same regulation rule is applied in the period of strong wind, the wind-induced risk can vary significantly for the traffic with different P.L. Besides, for a certain vehicle proportion (say, P.L.=37.03%), the two upper limits of overturning probability differ from each other obviously. In general, it is more rational that they are close to each other. Therefore, it provides an alternative method to determine the wind speed thresholds of the regulation rule, say, the thresholds can be decided as the ones making two upper limits equal.

On-board Wind Pre-warning System

The pre-warning system is installed on the road vehicle and provides the permitted vehicle speed V_p to the driver in advance. Hence the safety of traversing the strong wind area can be assured if the vehicle moves with a speed $V \leq V_p$.

The assumptions for realization of the system are listed:

1) The instantaneous wind velocity U_{in} can be expressed as the sum of the mean wind component U and fluctuation wind component u;

2) Prediction residuals obey a Gaussian distribution, hence the mean wind velocity in the near future satisfies $U \sim N(U_P, \sigma_{Ue}^2)$, where U_P is the predicted mean wind velocity and σ_{Ue} is the standard deviation of the corresponding prediction residuals;

3) The fluctuation wind component satisfies $u \sim N(0, \sigma_u^2)$, from which, $U_{in} \sim N(U_P, \sigma_{Ue}^2+\sigma_u^2)$ can be deduced, where σ_u is the standard deviation of u; Similar assumptions are applied to the wind direction Φ_{in} and $\Phi_{in} \sim N(\Phi_P, \sigma_{\Phi e}^2+\sigma_\varphi^2)$, where Φ_{in}, Φ_P, $\sigma_{\Phi e}$, and σ_φ are instantaneous wind direction, predicted mean wind direction, standard deviation of wind direction prediction residuals, and standard deviation of fluctuation component of wind direction, respectively;

4) If the independence between U_{in} and Φ_{in} is further assumed, the joint probability distribution can be calculated by the expression of $p(U_{in}, \Phi_{in})=p(U_{in})p(\Phi_{in})$.

An example for realization of the on-board pre-warning system is given here. Firstly, the Characteristic Wind Curves (CWCs) are obtained, which represent the critical wind velocity of overturning for various vehicle speeds. The CWCs can be gained based on the static equilibrium equations of the vehicle. The actions exerted on the vehicle are shown in figure 4. In the figure, f_{y1}, f_{y2}, f_{z1}, f_{z2} are the friction forces and reactions on the tires, F_s and F_l are the wind-induced side force and lift, respectively, mg is the weight of the vehicle, h_{ac} is the height of equivalent action centre of side force, W is the vehicle width.

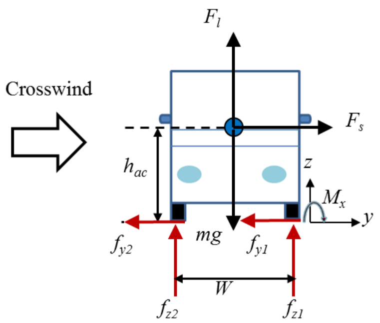


Figure 4. Actions on the vehicle (front view).

The static equilibrium equation along M_x direction, which corresponds to overturning direction, is expressed as

$$F_s h_{ac} + \frac{1}{2} F_l W - \frac{1}{2} mgW + \frac{1}{2} f_{z2} W = 0 \tag{4}$$

where

$$F_s = \frac{1}{2} \rho U^2 BHC_s \tag{5}$$

$$F_l = \frac{1}{2} \rho U^2 BWC_l \tag{6}$$

If the condition for the overturning accident is defined as

$$f_{z2} = 0 \tag{7}$$

then the corresponding critical relative wind velocity can be deduced as

$$U_{rOverturn} = \sqrt{\frac{mgW}{\rho B\left(Hh_{ac}C_s + \frac{1}{2}W^2 C_l\right)}} \tag{8}$$

Based on the law of cosines, the CWCs can be further gained numerically for various vehicle speeds. The CWCs are then approximated by polynomial curves, and the explicit expressions can be gained and stored. The expression of the polynomial curves is of the form

$$f(x) = p_1 x^6 + p_2 x^5 + p_3 x^4 + p_4 x^3 + p_5 x^2 + p_6 x + p_7 \tag{9}$$

In calculation of CWCs, the large-sized vehicle is considered and the dimensional sizes are listed in table 1. The weight is defined as 6.74 ton, corresponding to the weight of the unloaded vehicle. The side force coefficient and lift coefficient of vehicle are the results of wind tunnel experiment from the study [3], which are further fitted by polynomial curves, as shown in figure 5.

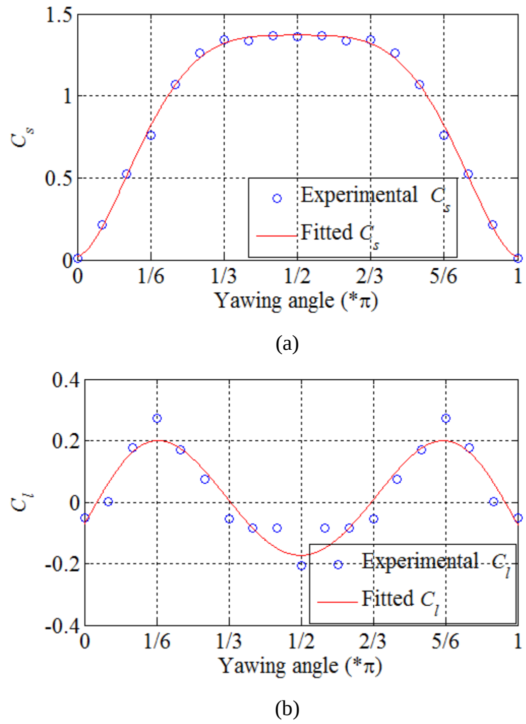


Figure 5. Aerodynamic coefficients applied for calculation of CWCs: side force coefficient (a) and lift coefficient (b)

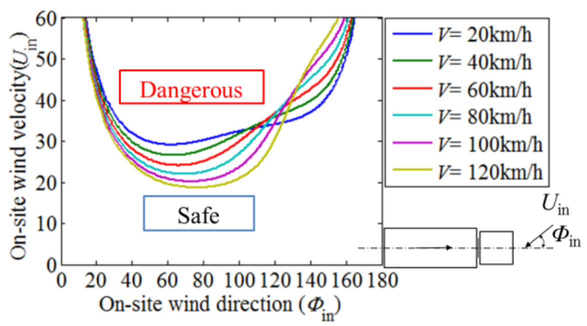


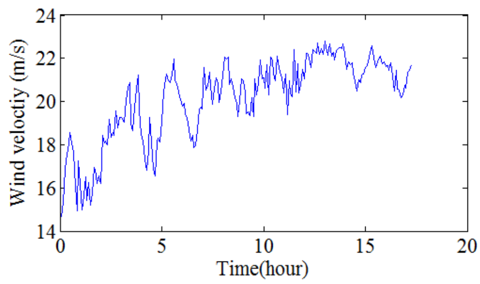
Figure 6. CWCs of overturning of the unloaded large-sized vehicle.

With all the parameters being defined, the CWCs corresponding to various vehicle speeds, from 5km/h to 200km/h at an interval of 5km/h, are obtained, with some of them being shown in figure 6. If the on-site wind condition falls into the area above the curve corresponding to the vehicle speed V, then the overturning accident of the vehicle happens. Some of the coefficients of the curves fitted to the CWCs are listed in table 5.

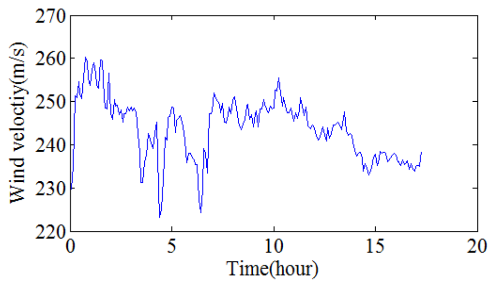
V \ p	5 km/h	10 km/h	15 km/h	...	200 km/h
p_1	1.46E-10	1.64E-10	1.56E-10	...	1.27E-09
p_2	-7.80E-08	-8.78E-08	-8.31E-08	...	-5.88E-07
p_3	1.74E-05	1.94E-05	1.83E-05	...	1.07E-04
p_4	-2.07E-03	-2.28E-03	-2.15E-03	...	-9.81E-03
p_5	1.39E-01	1.51E-01	1.44E-01	...	4.73E-01
p_6	-5.04E+00	-5.39E+00	-5.21E+00	...	-1.18E+01
p_7	1.08E+02	1.11E+02	1.09E+02	...	1.47E+02

Table 5. Coefficients of the fitted CWCs of overturning.

Secondly, given the real-time observations, the probability distributions of U and Φ in the near future are gained by the prediction model. In this study, Autoregressive Integrated Moving Average (ARIMA) model is applied for prediction, because of its good prediction performance as investigated in the study [4]. For the purpose of simulation of high wind velocity, in condition of which the warning message can be provided by the pre-warning system, an artificial time series of mean wind velocity is used. It is generated by simply increase 10m/s for each observation of on-site wind speed on Ohmishima Bridge. Time series of mean wind direction as well as fluctuation components of both velocity and direction keep the same with the observations. Here 5-minute mean wind speed and direction are adopted, as shown in figure 6. These time series are assumed to be received by the pre-warning system installed in the vehicle, which is going to move into the exposed windy section. The corresponding one-step predictions can be completed within 1.3 second and 1.1 second, respectively. The predictions obtained are U_P=21.7 and Φ_P=69.8, with σ_{Ue}=0.70 and $\sigma_{\Phi e}$=1.38, respectively. Therefore, the distributions of mean wind speed and direction during the next 5 minutes are $U \sim N(21.7, 0.70^2)$ and $\Phi \sim N(69.8, 1.38^2)$.



(a)



(b)

Figure 7. Mean wind velocity (a) and mean wind direction (b) received.

Thirdly, the joint probability distribution of U_{in} and Φ_{in} can be obtained by $p(U_{in}, \Phi_{in})=p(U_{in})p(\Phi_{in})$ from the distributions: $U_{in} \sim N(21.7, 0.70^2+1.07^2)$ and $\Phi_{in} \sim N(69.8, 1.38^2+6.59^2)$, where 307.1 denotes the moving direction of the vehicle, σ_u=1.07 and σ_φ=6.59 are obtained from the observations of fluctuation components of wind velocity and direction, separately.

Finally, the permitted vehicle speed V_p can be identified given an allowed overturning probability P_0. The overturning probability $P_c(V)$ corresponding to each possible vehicle speed V can be calculated by

$$P_c(V)=\int_0^{180}\int_{U_V(\Phi_{in})}^{U_0} p(U_{in},\Phi_{in})dU_{in}d\Phi_{in} \quad (10)$$

where $U_V(\Phi_{in})$ is the CWC corresponding to vehicle speed V, U_0 is the possible strongest instantaneous wind velocity observed. The permitted vehicle speed V_p satisfies conditions as follows:

$$\begin{cases} P_c(V_P) \le P_0 \\ P_c(V_P+\Delta V) > P_0 \end{cases} \quad (11)$$

where ΔV=5km/h and P_0=0.0005 is assumed. V_p is then identified by Binary Searching Algorithm. The identification course is listed in table 6. It is identified that V_p=45km/h.

Searching time	V (km/h)	P_c
1	105	0.87154
2	55	0.00460
3	30	0.00000
4	45	0.00015
5	50	0.00096

Table 6. Identification course for V_p.

Conclusions

In the first part, safety assessment considering the traffic is conducted. The dependence of overturning probability on P.L. (vehicle proportion of relative large-sized vehicle type) and vehicle speed is confirmed. For the traffic with relative higher P.L., it is more important to make suitable countermeasure to crosswinds. Besides, the overturning risk increases with the vehicle speed. The two upper limits of overturning probability corresponding to current highway traffic regulation rule in Japan are also obtained. They increase significantly with P.L.. Therefore, it is more rational that the traffic regulation rule takes the traffic into consideration. In addition, the wind speed thresholds of the regulation rule can be determined by an alternative method, say, the thresholds can be decided as the ones making the two upper limits equal.

In the second part, a method to realize the on-board wind pre-warning system is proposed and the mechanism is introduced in detail. However, some issues remain for its application, e.g., development of more proper prediction model for wind direction, investigation of the dependence between the wind speed and the wind direction, determination of proper accident probability, etc.

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