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Design criteria of wind barriers for traffic. Part 2: decision making process

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Abstract. This study presents a decision making process for installation of wind barrier which is used to reduce the wind speed applied to running vehicles on expressway. To determine whether it is needed to install wind barrier or not, cost and benefit from wind barrier are calculated during lifetime. In obtaining car accidental risk, probabilistic distribution of wind speed, daily traffic volume, mixture ratio in the volume, and duration time for wind speed range are considered. It is recommended to install wind barrier if benefit from the barrier installation exceed construction cost. In the numerical examples, case studies were shown for risk and benefit calculation and main risky regions on Korean highway were all evaluated to identify the number of installation sites.

Keywords: wind barrier; driving stability; side wind; car accident risk.

1. Introduction

When a running vehicle is exposed to high side wind on expressway, sliding between tires and road surface may occur and it can lead to traffic accident. Although this kind of instability of driving vehicle has been reported, literatures related to criteria or action plan have not been much found yet.

Wyatt (1992), Smith and Barker (1998) have introduced wind barriers as well as action plan used in British bridges. Dellwik *et al*. (2005) have calculated a total percentage of time for bridge restriction for the Fehmarn Belt bridge, Oresund bridge and Great Belt bridge in Denmark. Kwon and Jeong (2004) proposed a criterion on which driving vehicle is assessed whether it is under risky state or not. Wang *et al*. (2005) presented wind speed criteria for the Sutong bridge in China. However, the safety criteria and the decision making process are mostly based on intuition or subjective experience (Chen and Cai 2004).

Wind barrier is surely a good measure to reduce wind speed on expressway. Therefore, there are

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frequent demand from drivers that wind barrier should be installed to certain risky region where they have once experienced an instant loss of steering control due to strong side wind. However, if a wind barrier installed on the road where there is no significant risk by wind, benefit such as accident reduction can not be expected. In that case, it can be said that the wind barrier is redundant and may be an excessive measure. Therefore, a reasonable and systematic decision making process for wind barrier installation is needed.

To this end, benefits which can be obtained from wind barrier and costs are calculated in this study. Then, it is proposed that wind barrier should be installed only if the benefit due to barrier is bigger than cost. Benefits include the reduction of both accident risk and driving time due to wind barrier and cost are calculated during lifetime. Car accident risk was calculated based on wind tunnel test and probabilistic distribution of wind speed. In the numerical example, 75 regions at which drivers once asked to install wind barrier were considered. Then, optimal installation points based on the proposed criterion were identified.

2. Decision making process

2.1 Accident risk

Fig. 1 shows a plan view of two running vehicles on expressway. In the circumstance, accident takes place when one crosses the center line due to side wind attack and simultaneously vertical distance between them is short enough to collide with the other. By using the condition, limit state functions for vehicle collision can be expressed as

$$Z_1 = X_1 - X_2 - B \tag{1}$$

$$Z_2 = |Y_2 - Y_1| - L \tag{2}$$

Two vehicles running side by side collide with each other when the limit state functions above become negative. The accident probability of the two vehicles can be expressed as

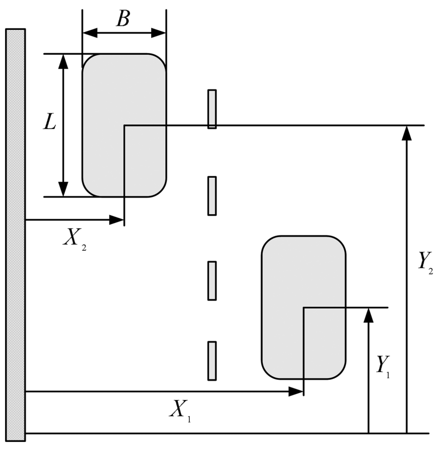

Fig. 1 Plan view of vehicles on highway

$$P_f = \int_{Z_1 < 0,\, Z_2 < 0} f_{X_1X_2Y_1Y_2}(x_1, x_2, y_1, y_2)dx_1dx_2dy_1dy_2 \tag{3}$$

where X_1,X_2,Y_1,Y_2 are random variables and $f_{X_1X_2Y_1Y_2}(x_1, x_2, y_1, y_2)$ is the joint probability density function. Random variables X_1,X_2,Y_1,Y_2 are affected by driver's habit, sexuality of a driver, traffic volume, time in a day, weather, etc. Since those factors cannot be easily formulated in a closed form, it is quite difficult to obtain the accident probability directly. Therefore, an indirect approach should be sought to estimate it.

Accident probability of two cars can be divided into two parts as

$$P_f = (1 - P_{V_S})P_{A|V_S^-} + P_{V_S}P_{A|V_S^+} \tag{4}$$

where P_{V_S} denotes the probability that a vehicle crosses neighboring lane due to cross wind. It equals the exceeding probability of critical wind speed. $P_{A|V_S^+}$ and $P_{A|V_S^-}$ denote the accident probability with and without violation of traffic lane, respectively. The first term in the right side of Eq. (4) represents the accident probability of two vehicles when wind blows under critical wind speed. The second term means one with critical wind speed being exceeded. When dealing with wind induced vehicle accident, the first term is negligible since most of the accidents occur during severe wind condition. Therefore, accident probability can be approximated as

$$P_f \cong P_{V_S}P_{A|V_S^+} \tag{5}$$

The exceeding probability of critical wind speed, P_{V_S}, and the conditional probability, $P_{A|V_S^+}$, are enough to calculate accident probability by high side wind.

2.2 Cost and benefit

There may be diverse benefits when wind barrier is installed to protect running vehicles. However, two main benefits are considered in this study. The first one is drawn from the reduction of car accident by decreased wind speed. If wind barrier is installed on a gusty expressway, wind speed can be reduced (Kwon and Jeong 2004). This reduction of wind speed can decrease accident probability. The other benefit is the reduction of running time on expressway. When there is no barrier and wind speed is high, vehicle speed limit is downed or even vehicle running is not allowed until wind speed goes below certain limit. In this case, wind barrier which reduces wind speed can guarantee vehicle running to normal vehicle speed. The difference in running time between the two can be expressed as economic value.

If a probability of vehicle accident by daily maximum wind is defined by P_{fi}, upper limit of yearly accident probability can be expressed as

$$P_{fi}^y = 1 - (1 - P_{fi})^{365} \quad (i = s,b,t) \tag{6}$$

where i denotes the vehicle type such as passenger car(s), bus(b) and truck(t). The annual expected days having car accidents can be calculated as

$$D_{ai} = 365P_{fi}^y \tag{7}$$

The number of accidents for i type vehicle in a year can be found as

$$N_{ai} = Q_d R_i D_{ai} \quad (i = s,b,t) \tag{8}$$

where Q_d denotes daily mean of traffic volume, R_i the vehicle type mixture ratio. If the number of wounded persons is denoted by N_{wi}, total cost per a accident by C_{i0}, inflation rate by j, discount rate by r, lifetime of barrier by T_b, then current value of total cost by vehicle accidents during lifetime can be found as

$$C_a = \sum_{i = s, b, t}\left[N_{ai}N_{wi}\sum_{T=1}^{T_b} C_{i0}\left(\frac{1+j}{1+r}\right)^T\right] \tag{9}$$

Cost difference between with and without barrier can be considered as benefit as

$$B_a = C_a^n - C_a^f \tag{10}$$

where superscript n and f denote without and with wind barrier.

The second benefit from wind barrier is based on driving time reduction. For example, let's assume severe wind blows on expressway whose normal speed limit for vehicle is 110 km/h. If the vehicle speed limit is reduced to 80 km/h due to the wind, passing time for the windy interval increases. In this case, wind barrier can save driving time by reducing wind speed and thus by keeping normal speed limit for vehicle.

If wind speed occurrence probability for the k-th wind speed interval is expressed by I_k, and wind duration time by τ_k, and time value for a vehicle by b_i, total time cost during lifetime can be calculated as

$$C_t = \sum_{i = s, b, t}\left[\sum_{T=1}^{T_b}\left\{b_i\left(\frac{1+j}{1+r}\right)^T Q_d R_i \sum_{k=1}^{I_V} I_k \Delta_k\left(\frac{\tau_{nk}}{24}\right)\right\}\right] \tag{11}$$

where T_b denotes the lifetime in year, I_V the number of wind speed intervals used. And delay time can be calculated by using vehicle speed limit, V_{car}, and the considered length of expressway, L, as

$$\Delta_k = \frac{L}{V_{car}} \tag{12}$$

If wind speed is so high that vehicles cannot run on the road, delay time is increased by the duration time of the wind. So it can be written as

$$\Delta_k = \tau_k + \frac{L}{V_{car}} \tag{13}$$

Thus, benefit from wind barrier in terms of time can be summarized as

$$B_t = C_t^n - C_t^f \tag{14}$$

Finally, benefit to cost ratio due to wind barrier installation is

$$R_{B/C} = \frac{B_a + B_t}{C_I} \tag{15}$$

where C_I denotes wind barrier installation cost. Using the ratio, decision making is possible. If the ratio is larger than 1.0, it is recommended to install wind barrier on the expressway. But if it is below 1.0, it is not recommended since cost cannot be compensated by benefit.

3. Numerical examples

3.1 Wind characteristics

Daily maximum wind data were collected from the wind measurement stations near expressways. Then the wind speed at the elevation of bridges to be evaluated were found by using the power law and the measured wind speed at the reference elevation in each station(Simiu and Scanlan 1996). Four types of distribution functions as in Table 1 were used to identify probabilistic characteristics of wind speed on the road. By using moment method, cumulative distribution functions were estimated from measured wind data at 10 different stations. Fig. 2 shows estimation errors for each

Table 1 Distribution functions considered

Function type	Closed form
Type I	$F_V(x) = \exp[-\exp\{-a(x-b)\}]$
Type II	$F_V(x) = \exp\left[-\left(\frac{v}{x}\right)^k\right]$
Type III	$F_V(x) = 1 - \exp\left[-\left(\frac{v}{x}\right)^k\right]$
Generalized Extreme Value(GEV)	$F_V(x) = \exp\left[-\left\{1 + k\left(\frac{x-\mu}{\sigma}\right)\right\}^{-1/k}\right]$

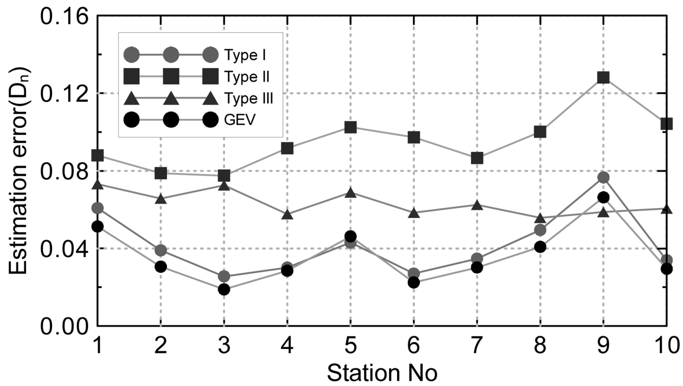

Fig. 2 Estimation error in distribution functions

distribution function and each station. It seems that GEV (generalized Extreme Distribution) function (Gatey and Miller 2007) can best fit the wind data. Therefore, GEV function was used in the following analysis.

3.2 Conditional accident probability

Finding analytic solution for $P_{A|V_S^+}$ is almost impossible since it includes lots of variables that cannot be easily formulated. Only a practical and possible way to estimate it is to use statistical data for car accidents caused by wind. The number of accident averaged over the main Korea expressways can be found according to accident statistic. But it is also the function of conditional probability, $P_{A|V_S^+}$, theoretically as in Eqs. (5)~(8). Therefore, the mean accident can be drawn as a function of empirical conditional probability as in Fig. 3. The number of mean accidents increases linearly as $P_{A|V_S^+}$ increases. If a mean accident is determined from statistics, an empirical $P_{A|V_S^+}$ can be estimated by Fig. 3.

Accident statistics for last five years are shown in Table 2 (KEC 2008). In fact, the number of accidents by wind is not clearly classified in the table because it is quite rare compared with other causes. Wind induced accidents belongs to the others case hatched in the table. Upper limit to the number of wind induced accident is the values shown in the last line of the table. Mean accident averaged over five years and 75 highway points thus can be estimated as

$$E(N_{ai}) = \frac{129}{5} \times \frac{1}{75} = 0.344 \tag{16}$$

Finally, the conditional accident probability can be estimated as 2.165×10^{-8} from Fig. 3.

3.3 Decision making

It was found that wind speed can be decreased by 50% in almost 90% of the behind a barrier (Kwon *et al*. 2011). So, wind speed behind a barrier can be assumed to be incident wind speed multiplied by 0.6 with some safety margin. It was assumed that vehicle speed limits are controlled by 10 minutes averaged wind speed. Then, vehicle speed limit according to maximum wind speed

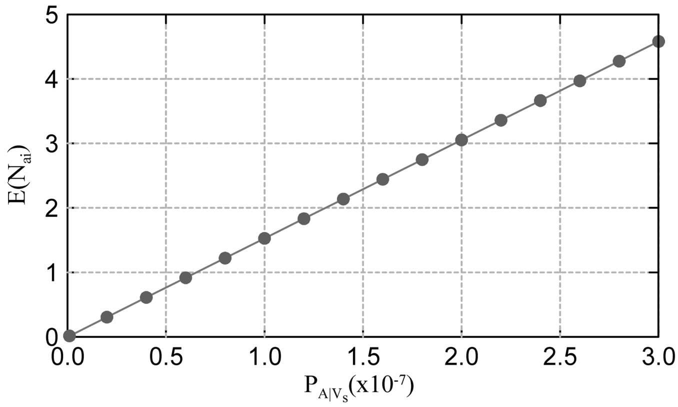

Fig. 3 Conditional accident probability vs. mean accident

Table 2 Accident statistics on highway

Main class	Minor class	2003	2004	2005	2006	2007
Driver	Falling asleep	765	768	668	630	585
	Attention	583	459	375	325	327
	Short interval	168	145	90	80	61
	Overspeed	841	661	623	518	572
	Bad steering	456	439	474	434	416
	Etc	201	235	201	210	198
Vehicle	Tire damage	291	268	251	197	166
	Break fault	69	57	55	37	46
	Etc	79	75	58	70	58
The others	Pedestrian crossing	13	24	9	12	23
	Obstacles on road	50	46	23	25	28
	Overload	47	34	27	26	35
	Road condition	3	0	0	1	0
	Etc	19	31	26	18	35

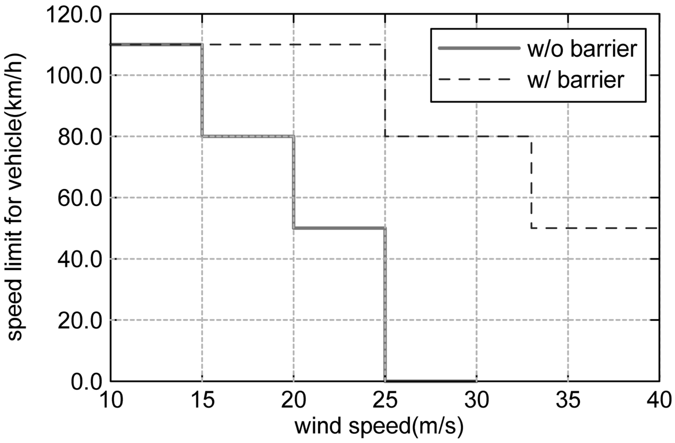

Fig. 4. Vehicle speed limit vs. maximum wind speed (10 min)

(10 minutes averaged) can be plotted as Fig. 4.

Maximum wind speed intervals to control vehicle speed are under 15 m/s, 15~20 m/s, 20~25 m/s and over 25 m/s without wind barrier. But they are shifted to under 25 m/s, 25~33 m/s, 33~41 m/s and over 41 m/s with barrier. This shift of vehicle speed limit brings us economic value by shortening driving time on expressway.

Cost and benefits were calculated on two expressway points. The first example is Baekwoon bridge whose length is 180 m and elevation is 30.4 m. The second example is Rhodong bridge which is 90 m long and 37.1 m high. Mean daily traffic volume for the bridge is 15,090 and vehicle types mixture ratios are 0.67 (car), 0.03 (bus) and (truck). Wind duration time of Korea proposed by Hwang *et al*. (1995) was used as Table 3. The number of mean wounded persons for each type of

Table 3 Wind duration time

	Without barrier			With barrier		
Interval(m/s)	15~20	20~25	25~41	15~25	25~33	33~41
Duration time(hr)	1.73	1.23	0.63	1.45	0.83	0.50

Table 4 Mean wounded persons by accident

	car	bus	truck
number	0.425	1.660	0.627

vehicle is used as Table 4 (KEC 2008).

Mean cost due to an accident is assumed to be KRW31,750,000 and time values for car, bus and truck are assumed to be KRW11,000, KRW44,000 and KRW12,000 (MOCT 2007). Barrier installation costs KRW810,000 per meter. Inflation rate and discount rate averaged from 1999 to 2007 are 2.72% and 6.96%, respectively (Cho *et al*. 2008). Cost and benefit for Baekwoon bridge and Rhodong bridge are summarized in Tables 5 and 6. In the first example, the estimated benefit is 1.429 times the installation cost. Therefore, it is recommended to install wind barrier. In the second example, however, the estimated cost is bigger than the benefit. So, it is better not to install wind barrier on Rhodong bridge.

Table 5 Cost and benefit at Baekwoon bridge

		Without barrier	With barrier
GEV parameters		μ = 12.899, σ = 4.187, k = –0.0433	
Exceeding probability(P_{V_s})	car, truck	2.317×10^{-2}	7.062×10^{-5}
	bus	6.634×10^{-2}	6.660×10^{-4}
Cost by accident(C_a)		KRW264,716,000	KRW1,236,000
Cost by running time(C_t)		KRW283,280,000	KRW130,193,000
Total benefit($B_a + B_t$)		KRW416,567,000	
Installation cost(C_I)		KRW291,600,000	
$R_{B/C}$		1.429	

Table 6 Cost and benefit at Rhodong bridge

		Without barrier	With barrier
GEV parameters		μ = 7.687, σ = 3.098, k = 0.0513	
Exceeding probability(P_{V_s})	car, truck	5.391×10^{-3}	1.093×10^{-4}
	bus	1.385×10^{-2}	4.032×10^{-4}
Cost by accident(C_a)		KRW53,876,000	KRW 1,194,000
Cost by running time(C_t)		KRW 58,748,000	KRW 24,473,000
Total benefit($B_a + B_t$)		KRW 86,957,000	
Installation cost(C_I)		KRW 145,800,000	
$R_{B/C}$		0.596	

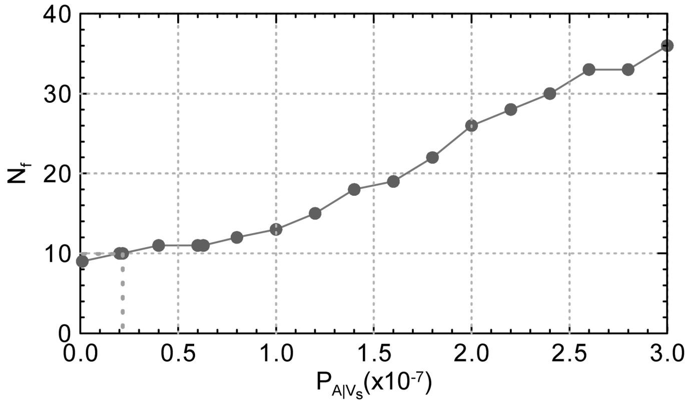

Fig. 5 Number of points for barrier installation

3.4 Sensitivity

The conditional accident probability is one of the most influential variables in making a decision. If one uses a different value of the probability, considerably different result can be obtained. Therefore, it is very important to identify the effect of conditional accident probability. To this end, the number of recommended installation points was estimated by above decision making technique for different conditional accident probability. Among all 75 points, the recommended points increase smoothly as Fig. 5. If $P_{A|V_S^+}$ is increased to 3.0×10^{-7} ($\beta = 4.991$), 36 points of all candidates (48%) are recommended to install barrier. Therefore, it can be said that one should estimate the probability in exact and reasonable way to obtain high quality of decision making on whether to install a wind barrier or not.

4. Conclusions

Cost and benefit based decision making procedure for wind barrier installation was proposed. Critical wind speed for different vehicles were numerically analyzed and exceeding probability for the wind speed was estimated by using wind data from weather measurement station. Accident probability when a vehicle crosses neighboring traffic lane was indirectly estimated from accident statistics. A procedure to calculate benefits that can be drawn from wind barrier and cost for installation was derived. A wind barrier is recommended to install when benefit is bigger than cost. In numerical example, benefits and costs were calculated and compared. Finally, it was shown that the accident probability is very influential in calculating benefit and cost. Therefore, one should be careful in estimating the probability and more accident statistics with high quality is necessary to have more reasonable decision making process.

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