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Freeway speed limits under inclement weather conditions

Velocidad límite en autopistas con condiciones ambientales adversas

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Abstract

Over the past decade, over speeding has been identified to be the most dominant factor contributing to the occurrence of severe crashes and injuries on freeways, and thus speed limit performs the most popular countermeasure. However, few studies have focused on the problem of freeway speed limits in bad weather due to reduction of visibility and pavement friction. Therefore, the primary purpose of this research is to develop a prototype of speed limits recommendations for basic freeway segments under the inclement weather conditions. If the leading vehicle makes a sudden stop, the travelling distance of the following vehicle is divided into four phases. Assuming the visibility is no less than the safe following distance between consecutive vehicles, consequently, a parabolic equation is constructed to describe the relation between the vehicle's maximum safe speed, pavement conditions, segment slope and visibility, and then maximum safe speed is rounded down to the nearest multiple of 5 as the proposed speed limit under the fogy, rainy or snowy conditions.

----------*Keywords*: Speed limit, inclement weather, visibility, pavement friction, following distance

Resumen

Durante las últimas décadas, el exceso de velocidad ha sido identificado como el factor más dominante que contribuye a la ocurrencia de accidentes graves y lesiones en las vías, de ahí que la medida de fijar la velocidad límite sea lo más común. Sin embargo, algunos estudios han concentrado sus esfuerzos en el

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problema de la velocidad límite en ambientes adversos, debido a la reducción en visibilidad y fricción en el pavimento. El propósito principal de esta investigación es desarrollar un prototipo de recomendaciones de velocidad límite para segmentos básicos de autopistas con condiciones ambientales difíciles. Si el vehículo delantero realiza una parada súbita, la distancia de separación del vehículo trasero es dividida en cuatro fases. Suponiendo que la visibilidad sea menor que la distancia segura entre dos vehículos consecutivos, una ecuación parabólica puede ser construida para describir la relación entre la máxima velocidad segura del vehículo, condiciones del pavimento, pendiente del segmento y visibilidad, y de ahí la máxima velocidad segura es redondeada hacia abajo, el múltiplo de 5 más cercano, y es propuesta como la velocidad límite bajo condiciones nubladas, de lluvia y nieve.

----------*Palabras clave*: Velocidad limite, ambiente hostil, visibilidad, fricción del pavimento, distancia de separación

Introduction

Speed is the quintessential traffic safety issue over the past ten years. There is overwhelming evidence that traffic crash has a close and potential relation with travelling speed [1]. From 2005 to 2008, law enforcement crashes had drawn wide attention in Florida, and about 23% of such crashes occurred due to pursuit and emergencies in higher travelling speed [2]. While analyzing the accident characteristics of a 243km section of Yaounde-Douala freeway in Cameroon using 4-year (2004–2007) crash data, it was found that excessive speed was the third most frequent risk factor that accounted for approximately 20% of fatal crashes [1]. Furthermore, an examination of 1185 fatal vehicle crashes in UK that occurred from 1994 to 2005 also showed that over 65% of the crashes occurred during driving at excessive speed [3]. In our previous study of crashes and geometric factors involving 5426 crashes (fatal, serious or slight) on the Chengyu Freeway (K0~K338), Jingzhu Freeway (K0~K109+175) and Shenda Freeway (K191~K241) over a 4-year period [4], speed was also identified as a contributory factor in 28 percent of the fatal observations and 13 percent of all records.

The greater a vehicle's velocity is, undoubtfully, the less time is available for the operator to make a safe reaction to a potential danger in conflict (i.e., motorists, sharp curve or other hazardous geometric or environmental conditions [5]. Moreover, a high enough velocity increases the crash energy by the square of the speed and would be likely to cause severe crashes [6]. Accordingly, a research or engineering approach to speed management that ignores the injury consequences of vehicle speed could lead to unintended results.

During the past decades, speed involving accidents have drawn the exceptionally heated attention from researchers and engineers, and numerous of effective measures have been proposed (e.g., speed limits, speed enforcement, speed camera, etc.) to regulate the vehicle's speed, so as to decrease the occurrence of crashes and injury severities [7]. Extensively, speeds between 120-140 km/h are recognized as the safe and acceptable limit standard around the entire world [8]. At present, maximum speed limits varies significantly across across regions and countries. For example, Polish has the world's highest posted 140 km/h for speed limit on motorways / freeways, and France, Austria and Switzerland recommend 130 km/h; Serbia, Portugal, Finland, Belgium, Bulgaria and Luxembourg, etc., approve 120km/h; Russia, Great Britain, Sweden, Poland, Czech Republic, Slovakia reduce to 110km/h; and Japan, Hungary, Greece, Denmark, Netherlands and Morocco adopt 100km/h. Specially, Romania, Turkey and Norway even approved a lower speed limit of

90km/h (source: http://wiki.openstreetmap.org/wiki/OSM_tags_for_routing/Maxspeed). In the recent released of "Road Traffic Safety Law of the People's Republic of China", the maximum speed on freeways is limited to 120km/h for cars and light commercial vehicles, and in some cases, 110km/h or lower is also permitted, due to the limitation of topography and highway geometrics. Unfortunately, this is often unrealistically underestimated.

Setting the appropriate speed limits is difficult and the 85th percentile speed is the appropriate speed limit on specific segments of different types of road cases [9-11]. However, it was also reported that the speed limit should be posted below the 85th percentile value by 8-12 mph within specific speed zones [12]. On the horizontal and straight sections of freeways, the maximum speed is generally determined according to the minimum generalized running cost involving time and fuel consumption [13], and should be temporarily reduced when weather conditions such as fog, rain, or snow cause visibility to deteriorate [14].

This study models the internal relation between speed limit and environment constraints, and answers several questions related to setting speed limit quantitatively on freeway. The findings of this study will help to develop more targeted measures to improve the safety in reduced visibility conditions, and more cost-effective awareness in safety driving education, training and management.

Methodology

Weather has a significant impact on the driving safety. In rainy days, the roadway pavement is too wet to provide sufficient friction, and thus the travelling vehicle needs a longer braking distance to stop quickly under emergency [15]. Similarly, the visibility ahead will sharply decrease in a heavy fog, which may pose a higher risk of being involved in a rear end collision, and thus it is more dangerous to drive at the posted speed limit. Since low visibility conditions cause an increase in the crash risk that must be taken seriously, the most common measure of safety is to set and enforce the speed limit [16].

In Washington, the maximum road speed is dynamically recommended according to visibility conditions. When visibility is less than 800m under light or moderate rain conditions, it is limited to be 104.5km/h, but reduced to 88.4km/h when visibility is less than 320m during periods of fog or heavy rain, and 76.3km/h and 72.4km/h in areas subject to light/moderate and heavy snow, respectively (source: Best Practices for Road Weather Management, FHWA-HOP-12-046, 2012). Two important parameters, tire-pavement friction and segment slope, however, are not taken into account. Based on this review, it is urgently required to give a precise result.

Figure 1 illustrates the vehicle's brake procedure while keeping a safe following distance. Let's consider two consecutive vehicles I and II on a segment with downgrade slope i that move at the same speed v and keep the safe following distance L_{sf} between under the visibility L_v. Obviously, it should maintain $L_{sf} \leq L_v$ for safety consideration.

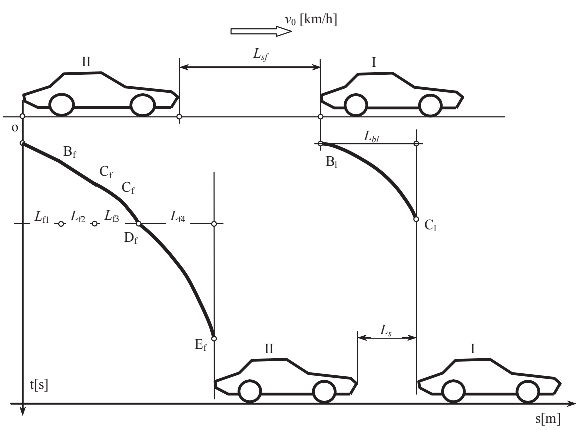

Figure 1 Illustration of vehicle's braking procedure

At a certain moment, the leading vehicle I suddenly finds an incident ahead and makes an emergency brake from point B_1 with deceleration J_1, which travels the distance $L_{bl} = \frac{v_0^2}{25.92(J_1 - i)}$ until it stops at C_l. Meanwhile, the driver of the following vehicle II catches the brake signal in front and also tries to make a brake. According to our previous findings [5], this process consists in four phases: reaction lag, deceleration by the vehicle engine, deceleration by the brake system, and full deceleration.

In phase 1, the following vehicle keeps on moving at v_0 until reaching point B_f, taking t_1 = 0.68~0.93s for normal, caution and experienced drivers, and even as long as 2.0s for unresponsive drivers [5]. Therefore, it considers 1.7s at the 85% confidence level in determining the speed limit. Thus, vehicle II travels $L_{f1} = v_0t_1/3.6 = 0.472v_0$ in this phase.

During phase 2, the driver realizes its necessaries of brake and begins to operate the engine to retard the vehicle by gear within time interval t_2=0.56s [5], moving from B_f to C_f that satisfies $L_{f2} = \frac{v_0t_2}{3.6} - \frac{1}{2}(J_2 - i)t_2^2 = \frac{v_0t_2}{3.6} - 0.157(J_2 - i) \approx \frac{v_0t_2}{3.6} = 0.156v_0$. Here J_2 is the average braking deceleration in gear and it varies from 0.3589 to 0.4379 with respective to 80~120km/h speed. Similarly, the change of speed J_2t_2 is also significantly smaller that can be neglected, and thus the vehicle keeps speed v_0 at point C_f.

Phase 3 witnesses the braking deceleration to increase from zero to a maximum $J_{max}=-g\varphi$ with a general time period of t_3=0.2s [17]. Consequently, the traveling distance between C_f and D_f can be approximated by $L_{f3} = \frac{1}{2}\left[\frac{v_0}{3.6} + \frac{v_0}{3.6} - 0.5(J_{max} - i)t_3\right]t_3 = \frac{v_0t_3}{3.6} - 0.01(J_{max} - i) \approx \frac{v_0t_3}{3.6} = 0.056v_0$, and the speed at point D_f remains the same as $v' = v_0/3.6 - 0.5J_{max}t_3 = v_0/3.6 - 0.1J_{max} \approx v_0/3.6$.

For phase 4, the vehicles exerts its effect with the maximum deceleration $J_{max}=-g\varphi$and finally reaches a complete stop at point E_f; then, we obtain the total distance $L_{f4} = \frac{\left(\frac{v_0}{3.6}\right)^2}{2(g\varphi - i)} = \frac{v_0^2}{25.92(9.8\varphi - i)}$.

From figure 1, the safe following distance between results a seq. (1):

$$L_{f1} + L_{f2} + L_{f3} + L_{f4} + L_s \le L_{sf} + L_{bl} \quad (1)$$

Since $L_{sf} \le L_v$, hence equation (1) can be transferred into eq. (2):

$$L_{f1} + L_{f2} + L_{f3} + L_{f4} + L_s \le L_v + L_{bl} \quad (2)$$

Generally, a speed limit is determined by the vehicle size plus worst-case stopping. Thus we have L_s=0 and L_{bl}=0 and then equation (2) can be simplified into eq. (3):

$$L_{f1} + L_{f2} + L_{f3} + L_{f4} \le L_v \quad (3)$$

and using the notations of $L_{fj}(j = 1\sim4)$, it finally becomes eq. (4):

$$\frac{1}{25.92(9.8\varphi - i)}v_0^2 + 0.684v_0 - L_v \le 0 \quad (4)$$

which is a parabolic function describing the relation between the vehicle's maximum safe speed, pavement conditions, segment slope and visibility associated with the minimal following distance between consecutive vehicles. Its solution yields eq. (5):

$$v_0 \le 12.96(9.8\varphi - i)\left[\sqrt{0.4679 + \frac{L_v}{6.48(9.8\varphi - i)}} - 0.684\right] \quad (5)$$

and thus the maximum safe speed can be given by $V_{max} = \text{Max}(v_0)$.

Subsequently, V_{max} obtains the value of certain combination of L_v, φ and i, and then rounds down to the nearest integer as the speed limit V_{lim}.

Determination of speed limit

During inclement weather, the roadway pavement generally becomes more slippery and causes the surface friction levels to drop sharply. For example, fog and mist conditions cause the coefficient of adhesion φ to decrease to 0.4~0.5, and heavy rain even reduces it to 0.3~0.4. In addition, soft, compressed or freezing snow has different anti-slippery performance, where the coefficient of adhesion φ ranges over 0.1~0.2 [5].

In this study, we choose φ= 0.4 to determine the maximum safe speed by equation (5) with respect to roadway slope, in which the visibility decreases from 200m to 25m. Table 1 presents the calculated results. Obviously, the maximum speed varies inversely with the change of roadway slope at a certain visibility, which means that an increase in slope by a certain percentage cannot be reversed by the same percentage decrease of speed to be limited. For example, let's suppose visibility L_n = 150m, and it obtains only 0.44km/h or approximate 0.47% drop in safe speed, when the slope varies gradually from 1% to 6%.

Table 1 Maximum safe speed V_{max} for freeways in foggy condition

L_v /m	φ	i /%						L_v /m	φ	i /%					
		1	2	3	4	5	6			1	2	3	4	5	6
250	0.4	128.2	128.1	128.0	127.9	127.7	127.6	100	0.4	71.8	71.8	71.7	71.6	71.6	71.5
200	0.4	111.9	111.8	111.7	111.5	111.4	111.3	50	0.4	44.5	44.5	44.5	44.4	44.4	44.4
150	0.4	93.4	93.3	93.2	93.2	93.1	93.0	25	0.4	26.5	26.4	26.4	26.4	26.4	26.4

Following the same process, the coefficient of adhesion φ equals to 0.3, and then the maximum safe speed under rainy conditions is derived from equation (5), as listed in table 2, from which the similar findings can be easily concluded.

Table 2 Maximum safe speed V_{max} for freeways in rainy conditions

L_v /m	φ	i /%						L_v /m	φ	i /%					
		1	2	3	4	5	6			1	2	3	4	5	6
250	0.3	114.2	114.1	113.9	113.8	113.6	113.5	100	0.3	65.0	64.9	64.8	64.7	64.6	64.6
200	0.3	100.0	99.8	99.7	99.6	99.4	99.3	50	0.3	40.9	40.9	40.8	40.8	40.7	40.7
150	0.3	83.9	83.8	83.7	83.6	83.4	83.3	25	0.3	24.8	24.7	24.7	24.7	24.7	24.7

Snow events can cause wet, snow-covered, or icy pavement. While driving across a segment covered by soft snow, especially when freshly fallen, the tires can not exert fully due to low values of the coefficients of friction in the range 0.2 to 0.3; however, the icy or compressed snow pavement may lower the coefficient of friction to 0.1~0.15. Therefore, three conditions are considered: soft snow, compressed snow, and ice, accounting for φ = 0.2, 0.15 and 0.1, respectively, and then the maximum safe speeds on snow paved segments are derived from equation (5) taking the slopes and visibility into account, as presented in table 3.

Table 3 Maximum safe speed V_{max} for freeways in snowy conditions

L_v /m	φ	i /%						L_v /m	φ	i /%					
		1	2	3	4	5	6			1	2	3	4	5	6
600	0.20	157.7	157.4	157.0	156.6	156.3	155.9	250	0.20	96.5	96.2	96.0	95.8	95.6	95.4
	0.15	138.3	137.9	137.4	137.0	136.6	136.1		0.15	85.2	84.9	84.7	84.4	84.2	83.9
	0.10	114.5	114.0	113.4	112.9	112.3	111.7		0.10	71.2	70.8	70.5	70.2	69.8	69.5

L_v /m	φ	i /% 1	2	3	4	5	6	L_v /m	φ	i /% 1	2	3	4	5	6
500	0.20	142.6	142.3	142.0	141.6	141.3	141.0	200	0.20	84.7	84.6	84.4	84.2	84.0	83.8
	0.15	125.2	124.8	124.4	124.0	123.7	123.3		0.15	75.0	74.8	74.6	74.3	74.1	73.9
	0.10	103.9	103.4	102.9	102.4	101.9	101.3		0.10	62.8	62.6	62.3	62.0	61.7	61.4
450	0.20	134.5	134.2	133.9	133.6	133.3	133.0	150	0.20	71.5	71.3	71.2	71.0	70.9	70.7
	0.15	117.2	117.8	117.5	117.1	116.7	116.4		0.15	63.5	63.3	63.1	63.0	62.8	62.6
	0.10	98.1	97.6	97.2	96.7	96.2	95.8		0.10	53.4	53.2	52.9	52.7	52.5	52.2
400	0.20	126.0	125.7	125.4	125.1	124.8	124.5	100	0.20	55.9	55.8	55.7	55.6	55.4	55.3
	0.15	110.8	110.4	110.1	109.7	109.4	109.1		0.15	49.9	49.8	49.7	49.5	49.4	49.2
	0.10	92.1	91.6	91.2	90.7	90.3	89.9		0.10	42.3	42.1	41.9	41.7	41.5	41.4
350	0.20	116.8	116.6	116.3	116.1	115.8	115.5	50	0.20	35.9	35.8	35.8	35.7	35.6	35.6
	0.15	102.9	102.6	102.2	101.9	101.6	101.3		0.15	32.4	32.4	32.3	32.2	32.1	32.0
	0.10	85.6	85.2	84.8	84.4	84.0	83.6		0.10	27.9	27.8	27.7	27.6	27.4	27.3
300	0.20	107.1	106.8	106.6	106.4	106.1	105.9	25	0.20	22.2	22.2	22.2	22.1	22.1	22.1
	0.15	94.4	94.1	93.8	93.5	93.2	93.0		0.15	20.4	20.4	20.3	20.3	20.3	20.2
	0.10	78.7	78.3	77.9	77.6	77.2	76.8		0.10	17.9	17.8	17.8	17.7	17.7	17.6

Subsequently, the determined maximum safe speed is rounded down to the closest multiple of 5 to obtain the speed limit corresponding to certain visibility, roadway slope and pavement condition reflected by coefficient of friction. If the safe speed is 99.98km/h when i =1% and L_n = 200m in rainy days, the value of the speed limit can be rounded down to 95km/h. In addition, it is supposed that the vehicles can drive freely when the safe speed is greater than 110km/h, and the freeway should be closed if the safe speed is less than 20km/h. Table 4 suggests the speed limit for straight freeway segments under fog, rain and snow conditions.

Table 4 Speed limit for freeways in inclement weather

Visibility/m	***Fog***	***Rain***	***Soft snow***	***Compacted snow***	***Freezing***	***Visibility/m***	***Fog***	***Rain***	***Soft snow***	***Compacted snow***	***Freezing***
$L_n>600$	√	√	√	√	√	$200\le L_n<250$	√	95	80	75	60
$500\le L_n<600$	√	√	√	√	100	$150\le L_n<200$	90	80	70	60	50
$400\le L_n<500$	√	√	√	110/105[a]	100/95[b]	$100\le L_n<150$	65	60	55	45	40
$350\le L_n<400$	√	√	√	100	85/80[c]	$50\le L_n<100$	40	40	35	30	25
$300\le L_n<350$	√	√	105	90	75	$25\le L_n<50$	25	20	20	20	×
$250\le L_n<300$	√	√	95	85/80[d]	70/65[e]	$L_n<25$	×	×	×	×	×

Note: √– no speed limit and vehicles can travel freely
×– freeway closed;
a –speed limit 110km/h if slope $i\le3$ and 105km/h if slope $i>3$
b –speed limit 100km/h if slope $i\le5$ and 95km/h if slope $i>5$
c –speed limit 85km/h if slope $i\le2$ and 80km/h if slope $i>2$
d –speed limit 85km/h if slope $i\le1$ and 80km/h if slope $i>1$
e–speed limit 70km/h if slope $i\le4$ and 65km/h if slope $i>4$

Obviously, snow events have the most significant influence on the freeway's safety performance, especially icy conditions, compared with the fog and snow conditions. When visibility L_n> 200m in fog days, the vehicles can drive safely within the posted speed limit of 110km/h, and the visibility L_n increases to more than 250m for vehicle's safe traveling under the rainy conditions. However, the snow paved or icy conditions make the driving an extremely hazardous operation due to the loss of pavement friction. For safety considerations, the vehicles can travel carefully on the snow covered or icy pavement during which visibility is restricted to less than 600m. Moreover, the freeway should be closed when visibility < 25m due to fog, falling rain, or fresh snow, and the managers are also encouraged to close the icy covered freeway if visibility is less than 50m.

Conclusions

As the number of crashes and injuries during the inclement weather days on freeways is still alarming high, it is speculated that the inclement weather speed limit should be addressed to enhance the overall safety performance of freeway operations. In this study, a quantitative analysis is applied to determine the optimal freeway speed limit under bad weather conditions, such as fog, rain and snow, in which the visibility is assumed to be less than the safe following distance between any two consecutive vehicles, and finally, the speed limit values are recommended accounting for a certain combination of visibility, roadway slope and coefficient of friction.

However, this proposed speed limit model is based on some ideal basis, for it assumes that both two consecutive vehicles are initially traveling at the same speed and behaving the same braking performance during an emergency stop. Moreover, it is only approximate for passenger cars traveling on the straight segment of roadway and potential conflicts between different types and lanes of vehicles are not taken into account. Thus, the final speed limit suggestions are not very accurate. Of course, the speed limit is a complex task that can't be understood and expressed by such a simplified approach. But, these efforts can represent a good starting point for tacking this problem from a much more rational perspective.

Moreover, the braking system of trucks is significantly different from that of passenger cars and thus it is urgently required to set the strict speed limit for trucks, due to the increasing commercial truck involved volumes and accidents [17, 18]. The topographical factors merit deep and accurate considerations in setting the speed limit [19], including the curve sections, entrance and exit of tunnel, etc. The average 85th percentile operating speed (V_{85}) is strongly recommended to be surveyed to observe the difference ΔV_{85} between two consecutive sections. These two sections can post the same speed limit, if $\Delta V_{85} \leq 10$; the speed limit can keep unchangeable, if $10 \leq \Delta V_{85} \leq 20$, but the warning signs must be provided. Otherwise, the segments of roadway have to assign different speed limits. Since the variable message signs are effective for exhibiting the real time values of speed limit under changing conditions, thus reducing accidents, it would be better to associate this approach model with the study of variable speed limit signs [20]. Additionally, speed enforcement and management techniques should be emphasized to further improve the level of freeway safety performance.

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