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Development of a variable speed limit strategy to reduce secondary collision risks during inclement weathers

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ABSTRACT

Inclement weather reduces traveler's sight distance and increases vehicle's stopping distance. Once a collision occurred during inclement weather and resulted in a slow traffic, approaching vehicles may not have adequate time to make emergency responses to the hazardous traffic, resulting in increased potentials of secondary collisions. The primary objective of this study is to develop a control strategy of variable speed limits (VSL) to reduce the risks of secondary collisions during inclement weathers. By analyzing the occurrence condition of secondary collision, the VSL strategy is proposed to dynamically adjust the speed limits according to the current traffic and weather conditions. A car-following model is modified to simulate the vehicle maneuvers with the VSL control. Two surrogate safety measures, based on the time-to-collision notion, are used to evaluate the control effects of VSL. Five weather scenarios are evaluated in simulation. The results show that the VSL strategy effectively reduces the risks of secondary collisions in various weather types. The time exposed time-to-collision (TET) is reduced by 41.45%–50.74%, and the time integrated time-to-collision (TIT) is reduced by 38.19%–41.19%. The safety effects are compared to those with a previous VSL strategy. The results show that in most cases our strategy outperforms the previous one. We also evaluate how driver's compliance to speed limit affects the effectiveness of VSL control.

1. Introduction

Variable speed limit (VSL) is a mainline traffic control technique that has been increasingly used for improving traffic safety on roadways (Robinson, 2000; Lee et al., 2006; Abdel-Aty et al., 2006; Allaby et al., 2007; Hellinga and Mandelzys, 2011; Islam et al., 2013; Lee et al., 2013; Hadiuzzaman and Qiu, 2013; Li et al., 2014; Al-Kaisy et al., 2012; Ali, 2008; Bertini et al., 2006; Buddemeyer et al., 2010; Han et al., 2009; Jonkers et al., 2008; Rama and Schirokoff, 2004; Hassan et al., 2011; FHWA, 2012). The central idea of VSL is to make an intervention proactively by adjusting speed limits on roadside variable speed limit signs. The use of VSL during inclement weather can improve safety by decreasing the risks associated with traveling at speeds that are higher than appropriate for the conditions.

When traveling on roadways drivers need to see roadways head to make emergency responses to dangerous traffic situations. During severe weathers, the poor visibility and road surface condition generally result in a shorter sight distance and a longer stopping distance. After a traffic collision occurs, approaching vehicles from upstream sections may not observe the slow traffic induced by the collision in a timely manner. As a result, a secondary collision is highly likely to occur after the occurrence of the initial collision. Even though some drivers tend to drive slowly and keep a longer car following distance, a secondary collision could still occur in some extreme situations.

Previously, various VSL control strategies have been used in practice to improve traffic safety during inclement weathers (see a summary in Table 1). The common control logic in those strategies is to use a pre-set speed reduction if the current condition is less than ideal. However, only some fixed values of speed limits are recommended for several levels of weather conditions. And the speed limits are usually determined according to practical experiences.

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Table 1
Weather-related VSL control strategies.

State/country	Weather parameter	VSL control strategy
Alabama, US	Fog	Change speed limit in increments of 10 mph within range 35–65 mph in five visibility distance levels
Delaware, US	Precipitation, wind, reduced visibility	Reduce speed limit by 5–20 mph in inclement weathers
South Carolina, US	Precipitation	Reduce speed limit to 45 mph
Washington, US	Rain, snow, fog	Speed limit varies between 35 and 65 mph in 10 mph increments in four types of weather conditions.
Wyoming, US	Visibility, surface condition, snow, wind	Speed limit varies between 35 and 75 mph due to visibility and surface conditions
Arizona, US	Road surface, visibility, wind	Incorporate fuzzy logic to identify appropriate speed limits for different environmental conditions
Tennessee, US	Fog	Speed limit varies between 35 and 65 mph due to visibility conditions
Utah, US	Fog	Speed limit varies between 25 and 65 mph due to visibility conditions
Australia	Inclement weather	The speed limits were set to 60, 80 or 100 km/h based on observations made via CCTV imagery
Finland	Wind, rain, road surface condition	Set 120 km/h for good conditions; 100 km/h for moderate conditions; 80 km/h for poor conditions
Netherlands	Rain	Reduce speed limit to 50 mph according to water on road surface and rain intensity
Netherlands	Visibility, incident	Reduce speed limit to 80 and 60 km/h according to visibility distance; reduce speed limit to 50 km/h if incident was detected
Saudi Arabia	Fog	Reduce speed limit to 40 km/h during foggy conditions
Swedish	Precipitation, road surface condition	Reduce speed limit to 110 km/h if the friction is 0.4; reduce speed limit to 100 km/h if the friction is 0.3; reduce speed limit to 80 km/h if the friction is 0.2; reduce speed limit to 60 km/h if the friction is 0.1

In a recent study by FHWA (2012), a dynamic algorithm was proposed to calculate the real-time maximum safe speed limit during inclement weathers at locations where the operating speed exceeds the design speed and the stopping distance exceeds the available sight distance. The speed limit is calculated by:

$$V_{SL} = \frac{-3.67 + \sqrt{13.47 + (0.12/(\mu \pm G_r))S}}{0.06/(\mu \pm G_r)} \tag{1}$$

where V_{SL} is the speed limit that will be posted, μ is the coefficient of road adhesion, G_r is the roadway grade, and S is the sight distance.

The logic in the above algorithm is that a driver should finish the deceleration from the current speed to the full stop within the sight distance. However, the algorithm only considers the weather-related factors such as the road adhesion and sight distance. The traffic flow variables are not considered. As a result, the algorithm determines constant speed limits for all roadway segments without distinguishing the traffic conditions in different areas. Besides, the algorithm works only in low traffic flow situations when the gap distance between vehicles is larger than the sight distance. Assuming a vehicle platoon is approaching a downstream congestion in a good visibility but slushy road surface condition, Eq. (1) will remarkably underestimate the safe speed limit which may not prevent the occurrence of secondary collision.

The primary objective of this study is to propose a control strategy of VSL for reducing the risks of secondary collisions near tail of queues during various inclement weathers. To achieve the research objective, the occurrence condition of secondary collision was first analyzed. The VSL control strategy was proposed by taking into consideration both the weather and traffic flow situations. A car-following model was modified to simulate the vehicle maneuvers in various weathers. Surrogate safety measures were considered to evaluate the reductions in the collision risks with the VSL control. The safety effects of the proposed strategy were evaluated in simulation for several weather types. For comparison purpose, the effects of the VSL algorithm in Eq. (1) were also evaluated. The study can provide useful information for transportation professionals who are actually designing weather related VSL systems for their jurisdictions.

2. Occurrence condition of secondary collision

2.1. Occurrence condition based on individual trajectory

Suppose that a congestion forms in a roadway section after a traffic collision occurs during inclement weather. Fig. 1(a) shows the trajectories of two consecutive vehicles near the tail of congestion. The following vehicle $n+1$ (see the gray box in Fig. 1(a)) traveling at a high speed v_2 observes the low speed v_1 of the leading vehicle n (see the black box in Fig. 1(b)) at time t. After a perception-reaction time t_a, the following vehicle starts to decelerate (see Fig. 1(b)). The following vehicle reduces its speed from v_2 to v_1 within t_{de} (see Fig. 1(c)).

The variables shown in Fig. 1(a)–(c) are used to depict the condition for the occurrence of secondary collision. A rear-end collision occurs if:

$$d_a(n) + d_{de}(n) + d < d_a(n+1) + d_{de}(n+1) \tag{2}$$

where $d_a(n)$ = traveling distance of leading vehicle n in time t_a, $d_a(n+1)$ = traveling distance of following vehicle $n+1$ in time t_a, $d_{de}(n)$ = traveling distance of leading vehicle n in time t_{de}, $d_{de}(n+1)$ = deceleration distance of following vehicle $n+1$ in time t_{de}, d = distance between two vehicles when the following vehicle observed the low speed of the leading vehicle, measured between the rear of one vehicle and the front of the next, $d_a(n) + d_{De}(n) + d$ = location of leading vehicle rear at time $t + t_a + t_{de}$ with respect to location x, $d_a(n+1) + d_{De}(n+1)$ = location of following vehicle front at time $t + t_a + t_{de}$ with respect to location x.

Using the variables shown in Fig. 1(a)–(c), Eq. (2) can be written as:

$$v_1 t_a + v_1\left(\frac{v_2 - v_1}{a}\right) + d < v_2 t_a + \frac{(v_2)^2 - (v_1)^2}{2a} \tag{3}$$

$$\Rightarrow \quad v_1 t_a + v_1\left(\frac{v_2 - v_1}{a}\right) + d - v_2 t_a - \frac{(v_2 + v_1)(v_2 - v_1)}{2a} < 0 \tag{4}$$

$$\Rightarrow \quad -(v_2 - v_1)t_a + (v_2 - v_1)\left(\frac{v_1}{a}\right) - (v_2 - v_1)\left(\frac{v_2 + v_1}{2a}\right) + d < 0 \tag{5}$$

$$\Rightarrow \quad (v_2 - v_1)\left(-t_a + \frac{v_1}{a} - \frac{v_2 + v_1}{2a}\right) + d < 0 \tag{6}$$

$$\Rightarrow \quad (v_2 - v_1)\left(-t_a - \frac{v_2 - v_1}{2a}\right) + d < 0 \tag{7}$$

$$\Rightarrow \quad -(v_2 - v_1)^2 - 2at_a(v_2 - v_1) + 2ad < 0 \tag{8}$$

where a = maximum deceleration rate of vehicle $n+1$ in current road surface condition.