



THE ROLE OF INTELLIGENT TRANSPORTATION SYSTEMS IN MITIGATING ADVERSE WEATHER EFFECTS ON TRAFFIC SAFETY AND EFFICIENCY

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Abstract

Climate change, i.e. warmer temperatures, intensifies the frequency and severity of extreme weather events. Adverse weather conditions present significant challenges to the safety and efficiency of transportation systems worldwide. Inclement weather, including rain, snow, fog, and storms, has been identified as a major factor contributing to increased road accidents, traffic congestion, and delays. Intelligent Transportation Systems (ITS) have emerged as a solution to mitigate these adverse effects by optimizing traffic flow and enhancing safety.

This paper explores the various components and functionalities of ITS in addressing adverse weather impacts on traffic safety and efficiency. Based on real-time weather data, ITS provide drivers with accurate information, enables automated traffic management and control strategies, and optimizes traffic flow during adverse weather events. Furthermore, the paper presents different ITS applications in reducing the risks associated with adverse weather. This review highlights the potential of ITS as a crucial tool in weather-responsive transportation systems, emphasizing the need for continued research, technological advancements, and multidisciplinary approach to further enhance the resilience of transportation system. Implementing comprehensive ITS solutions holds the promise of significantly reducing the adverse impacts of weather on traffic safety and efficiency, ultimately contributing to a more sustainable and resilient transportation infrastructure.

Keywords: ITS, adverse weather, traffic management

1 Introduction

Adverse weather conditions have a significant impact on the safety and efficiency of the road transportation system. Precipitation in the form of rain, snow or ice, reduces pavement friction, thus increasing the potential for traffic accidents, especially when vehicles are travelling at inappropriate speed for prevailing conditions. Under these circumstances, the posted speed limit may no longer be safe and appropriate. The speed limit at a given location is usually set taking into account several considerations, including road surface characteristics, free flow speeds (85th percentile) [1], road alignment and other factors [2].

Speeding under adverse weather conditions is perceived as hazardous due to breaking distance, limited visibility and reduced pavement friction [3]. Also, the increased speed variability present in adverse weather conditions results in increased crash potential [4]. While the exact relationship between weather related crashes and pavement friction is difficult to quantify, much empirical research has been done that shows that the number of traffic accidents increases as pavement friction decreases.

Research [5] developed two fuzzy logic models to predict wet-pavement crashes. The pavement friction, posted speed, average daily traffic (ADT), pavement wet time, and driving difficulty were the variables selected as having the greatest effect on the risk of skidding crashes at a site. In research [6] a comprehensive evaluation of friction measurements and crash rates revealed that decreasing pavement friction does increase crash rates significantly, e.g. pavement friction less than 0.15 results in a four times increase in crash rate relative to friction above 0.35. In another study [7] the results also showed that pavements with friction less than 0.35 had the highest accident risk whereas the risk was constant for pavement with a friction greater or equal to 0.45. These findings were consistent with the results obtained by [8] and [9].

Empirical evidence from the abovementioned research studies shows that when pavement friction falls below a site-specific threshold value, the risk of crashes increases significantly. The exact nature of the relationship between pavement friction and crashes is site specific, as it is defined by not only pavement friction but many other factors such as pavement surface characteristics, vehicle operation parameters, tire characteristics and environment [6]. From an operational standpoint, inclement weather could have considerable impacts on road capacity and traffic efficiency. Crash-related closures, reduced speeds and increased headways are all examples of inclement weather operational effects. Heavy rain can reduce road capacity by up to 30%, and poor visibility can shrink capacity by 12% [10]. Research [11] finds that reductions in free-flow speed vary from 4.5% to 11.6%, depending on rain category and traffic lanes, while reductions in capacity range from 2.5% to 13.0%.

This paper focuses on providing insight into current literature and practice in the field of weather-responsive Intelligent Transportation Systems. The paper aims to lay the groundwork for future research on the impact of weather conditions on traffic flow.

2 Components of weather-responsive ITS

Weather-responsive ITS refers to advanced technology implemented within road networks to dynamically adapt and respond to changing weather conditions, enabling them to make decisions and adapt their driving behavior accordingly. Weather-responsive ITS encompass a range of applications and functionalities, that can be generally classified into two types of application:

- Road Weather Information System (RWIS) - ITS applications that inform travellers about weather and road conditions that may cause an increased risk level concerning traffic safety.
- Variable Speed Limits (VSL) - These advanced ITS applications dynamically adjust speed limits in response to weather and road conditions. VSL systems proactively reduce speed limits when conditions deteriorate, mitigating the risk of accidents and enhancing overall safety and efficiency.

Regardless of the specific ITS application, weather-responsive ITS consists of two fundamental components: functional and physical. The functional component is a key for interpreting real-time weather data, analyzing its impact on road networks, and generating appropriate responses or recommendations. Whether it's assessing road conditions, predicting weather patterns, or optimizing traffic flow, the functional component serves as the brain of the weather-responsive ITS, orchestrating intelligent responses to changing environmental conditions [12].

Complementing the functional aspect is the physical infrastructure of the weather-responsive ITS, incorporating sensors, cameras, communication networks, and hardware devices. These physical components are responsible for collecting, transmitting, and disseminating data, from weather stations and road sensors to traffic controllers and variable message signs.

3 Road weather information systems (RWIS)

RWIS is defined as a combination of technologies that uses historical and current climatological data to develop road and weather information to support road traffic related decisions [13]. The implementation of these systems is expected to result in the following effects by providing reliable and accurate information on the weather and road conditions:

- Enable road users to plan their travels avoiding bad weather and road conditions by cancelling or delaying the travel,
- Enable road users to be better prepared for their journey concerning travel time, delays and equipment,
- Enable fleet managers to plan, monitor and control their vehicles during periods with reduced weather and road conditions,
- Enable road operators to monitor the status of the roads and the traffic flows and control the traffic flows,
- Provide ITS application developers with data that could be used for new services.

RWIS practices vary across different countries due to factors such as geographical location, climate, infrastructure, and technological advancements. While the core objectives of RWIS remain consistent the specific implementation and features can differ significantly. For instance, in countries with harsh winter conditions, such as Canada and Nordic countries, RWIS systems often include specialized sensors for monitoring snow accumulation, ice formation, and visibility. In regions prone to heavy rainfall or flooding, like parts of Southeast Asia or certain coastal areas, RWIS may focus on monitoring precipitation levels, water accumulation on roads, and the risk of hydroplaning. Furthermore, some countries may prioritize the use of mobile applications or online platforms to disseminate RWIS data to the public, while others rely on VMS or broadcasted information through radio stations.

4 Variable speed limits (VSL)

VSL use variable speed signs, mandatory or advisory, to assist drivers to travel at an appropriate speed considering the prevailing traffic or weather conditions. This dynamic approach to speed regulation ensures that drivers are aware of and comply with safer speed limits tailored to prevailing environmental factors. The implementation of such system is expected to have the following impacts:

- Speed reduction - as the drivers comply better to the dynamic speed limits than the static speed limits.
- Speed harmonization - smoother driving and less differences in the speed selected by the different types of drivers which again causes less sudden breaking and more environmentally friendly driving.

Most existing weather-responsive VSLs are developed based on sample-level statistical measures (e.g. 85th percentile speed). Some literature [4] argues the credibility of using such sample due to limited sampling conditions prevalent under adverse road weather conditions. The study [14] evaluated drivers' response to a fixed speed limit in different road-weather conditions and proposed a novel approach to set weather-responsive VSL for rural divided highways. The authors proposed a compliance-driven speed limit setting approach based on reliability theory. The weather controlled VSL is based on data received from various sensors like air temperature, air humidity, wind speed, visibility, road surface temperature and precipitation intensity sensors. Based on data collected by weather sensors, road conditions can be classified into different categories according to precipitation or estimated friction level.

It is important that applied speed limits are accepted by a majority (85%) of the drivers avoiding too many speed violators and loss of credibility of traffic signs and control. For this reason, VSL is mostly combined with variable text messages to explain speed reduction to drivers.

4.1 Examples of VSL practice

In the case of weather-responsive VSL, German guidelines MARZ [15] recommend using a five-level scale for precipitation levels to define the appropriate speed limit to a minimum of 60 km/h, with defined threshold values corresponding to both the ON and OFF states.








Precipitation Grade	Precipitation Grade ON	Precipitation Grade OFF	Display
0	0,0 mm/h	-	-
1	≥ 0,3 mm/h	< 0,2 mm/h	
2	≥ 1,2 mm/h	< 1,0 mm/h	 
3	≥ 5,0 mm/h	< 4,0 mm/h	 
4	≥ 12,0 mm/h	< 10,0 mm/h	 

Figure 1 Classification of precipitation intensity levels by MARZ [15]

On the other hand, FGSV [16] defines different weather condition levels and corresponding speed limits based on various combinations of two parameters, precipitation and road surface water film depth.

Table 1 Classification of road-weather conditions according to FGSV [16]

Road-weather condition	Precipitation [mm/h]	Water film depth [mm]	Speed limit [km/h]
WC0:	no	no	-
	no	≥ 0.15	
WC1:	≥ 0.30 mm/h	≥ 0.15	100
	≥ 0.60	no	
WC2:	no	≥ 0.60	80
	≥ 0.30	≥ 0.30	
	≥ 0.60	≥ 0.15	
	≥ 1.20	no	
WC3:	no	≥ 1.20	80
	≥ 0.30	≥ 1.20	
	≥ 0.60	≥ 0.60	
WC4:	≥ 1.20	≥ 0.15	60
	≥ 0.60	≥ 1.20	
	≥ 1.20	≥ 1.20	
	≥ 2.50	≥ 0.15	

In the Finland, road-weather conditions are categorized into four classes, with road surface friction serving as one of several parameters to determine the class of road condition [17]:

- Good condition (A), $\mu \geq 0.4$, (120 km/h or 100 km/h during winter conditions)
- Reduced condition (B), $0.40 < \mu \geq 0.3$
- Poor condition (C), $0.30 < \mu \geq 0.15$
- Dangerous condition (D), $\mu < 0.15$

Figure 2 shows an example of the current parameters for classifying the road conditions as dangerous (D) in Finland. The figure also shows that the speed will automatically be reduced from 120 or 100 km/h to 80 km/h when the road conditions (road surface condition, rain, or visibility) are classified as (D). Additionally, the speed may be manually reduced to 60 km/h.

PARAMETERS	VALUES	VMS-SIGN	INFO SIGN
(D) DANGEROUS ROAD CONDITIONS			
Speed limit by automatic system 80 km/h			
Speed limit 60 km/h manually, if traffic control center officer decides that it is necessary.			
VMS/INFO-signs automatically according to following rules.			
AT LEAST ONE OF FOLLOWIN TERMS (D1...D3) FULL-FILL			
(D1) DANGEROUS CONDITIONS BECAUSE OF ROAD SURFACE CONDITIONS			
Right lane friction	$\mu < 0,15$	Slippery road	"DANGEROUS ROAD SURFACE CONDITIONS"
AND	AND		
Road surface temperature	Road surface $< +2^{\circ}\text{C}$		
(D2) DANGEROUS CONDITIONS BECAUSE OF RAIN			
Form of rain	freezing rain	Slippery road	"FREEZING RAIN"
(D3) DANGEROUS CONDITIONS BECAUSE OF VISIBILITY			
Visibility	$< 100\text{ m}$	Danger	"POOR VISIBILITY"

Figure 2 Example of VSL conditions in Finland [17]

In the USA, the logic used for adjusting speeds was based on four categories, with the system being checked every 5 to 10 minutes. The major weather condition categories will be [18]:

- dry pavement, no precipitation, high grip level,
- moist/wet pavement, light precipitation ($<1.0\text{ mm/h}$), moderate to high grip level,
- wet pavement, moderate to high precipitation ($>1.0\text{ mm/h}$), moderate grip level,
- ice/snow/slush/frost pavement, any precipitation, low grip level.

The Swedish transport administration uses following weather condition categories, based on expected friction level [18]:

- No adverse weather condition: speed limit 120 km/h,
- Friction expected to be 0.4: speed limit 110 km/h,
- Friction expected to be 0.3: speed limit 100 km/h,
- Friction expected to be 0.2: speed limit 80 km/h,
- Friction expected to be 0.1: speed limit 60 km/h.

In a study of real speed and friction levels at 5 locations in Norway [17], it is recommended to use 5 categories for reducing speed limits in increments of 10 km/h based on the friction level:

- $\mu \geq 0.6$: speed limit 110 km/h,
- $0.6 > \mu \geq 0.5$: speed limit 100 km/h,
- $0.5 > \mu \geq 0.3$: speed limit 90 km/h,
- $0.3 > \mu \geq 0.2$: speed limit 80 km/h,
- $\mu < 0.2$: speed limit 70 km/h, in extreme situations.

Research [19] identified appropriate speed limits for given rain intensities and developed an algorithm that employed weather radar data to lower speed limits based on weather conditions in the Netherlands.

Table 2 Speed limits for different rain intensities in Netherlands [19]

Water film depth [mm]	Precipitation [mm/h]	Speed limit [km/h]
0.0	0.0	120
0.2 to 0.6	0.0 to 2.5	120
0.6 to 2.0	2.5 to 6.0	90
0.6 to 2.0	6.0 to 30.0	80

Based on a review of current practices, it is shown that VSL systems employ various parameters as well as different threshold values for parameters and speed limits. Some approaches utilize a single, while others rely on a combination of multiple parameters. Additionally, the parameters can be directly measured or modelled.

5 Conclusion

Water-pavement interaction is one of the most challenging road safety problems. Rainfall is drained from the pavement surface in order to prevent aquaplaning and provide skidding resistance. Revision of current design standards and methods related to road geometry, identification of critical sections, and recommendations for using porous asphalt on critical road sections represent preventive measures to mitigate the impact of weather conditions on traffic flow. Weather-responsive ITS play a crucial role in mitigating the adverse weather effects on traffic safety and efficiency. The literature review examined two different weather-responsive systems, RWIS and VSL.

RWIS represents the basic Traffic and Travel Information Services, which provide general information about weather conditions. Although the implementation of this service has a proactive impact on travel planning, it is difficult to precisely determine its influence on driver behavior. However, its application is cost-effective for implementation at the network level. On the other hand, the VSL system directly impacts driver behavior at a micro-location by harmonizing traffic flow speed, i.e. reducing speed dispersion. However, clear criteria and recommendations for selecting sections where it should be applied are lacking in literature and practice. It can be concluded that due to the absence of a unified approach in the application of this system, the selection of parameters and speed limits must be adapted depending on the location characteristics, infrastructure conditions, and the vehicle fleet characteristics.

Future research should focus on identifying suitable parameters that describe road conditions, defining their threshold values, and determining appropriate credible speed limits, taking into account modern in-vehicle technologies, tyre characteristics, pavement hydraulic properties, etc. Additionally, studies should be conducted under various traffic flows and weather conditions.

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