The impact of the weather

SWOV fact sheet, July 2023

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Summary

In general, crash risk is higher in bad weather than in good weather. Adverse weather conditions are mainly rain, snow/hail, fog, strong winds, slipperiness, low sun and high temperatures. Among other things, bad weather conditions can lead to longer braking distances (slipperiness due to rain, snow or hail) and cause the vehicle to be less stable (wind). Visibility can also be reduced, not only by fog, but also by splashing water, fogged-up windows or glare from low sun. Road users generally adapt their behaviour to adverse weather conditions, for example by reducing their driving speed or adapting their headway distance. However, the fact that risk often increases in bad weather conditions indicates that behavioural adjustments are not adequate. The weather also influences the amount and type of mobility: for example, more cyclists and pedestrians will be out and about in good weather than in bad weather.

Measures that may reduce the negative effects of the weather on road safety are very diverse. For example, there are infrastructural measures (good drainage, no rutting, de-icing), conventional vehicle-related measures (windscreen wipers, fog lights, air conditioning, and so on) and more advanced ones (real-time information in the vehicle), regulations (lower speed limits in bad weather) and education (weather alerts, general behavioural advice). Quantitative information on the safety effects of such measures is generally not available. During driver training, generally not much experience is gained in driving in bad weather. Additional training, such as skid courses, are often counterproductive.

1 How does the weather affect road safety?

In general, crash risk is higher in bad weather conditions than in good weather conditions. Bad weather conditions are mainly rain, snow/hail, fog, strong winds, slipperiness, low sun and high temperatures.

Bad weather conditions can lead to longer braking distances (slippery conditions due to rain, snow or hail) and cause the vehicle to be less stable (wind). Visibility can also be reduced, not only by fog, but also by splashing water, fogged-up windows or glare from low sun. Heat/high temperatures can cause people to think and act less effectively. However, people do appear to compensate for poor weather conditions, for example by driving more slowly or adapting their headway distance. This partly reduces the increased crash risk.

The weather also affects mobility, such as choosing whether or not to go out, the length of a trip, the choice of transport mode, the time of departure, and the route [1]. For example, when the weather is fine, people are more likely to walk, cycle or ride motorbikes instead of driving cars or using public transport (mode choice). Fine weather also leads to more recreational trips (additional mobility) by pedestrians, cyclists and motorcyclists, for example. This leads to more casualties among these groups, simply because of the greater exposure to road hazards. Conversely, bad weather will result in fewer casualties among these groups.

Weather versus climate

Due to climate change, extreme weather conditions such as heavy precipitation, severe storms and more extreme drought and heat are expected to become more frequent. This means that weather effects should increasingly be taken into account when studying road safety developments. On its website, CROW offers practical information for road authorities and others on how to deal with the consequences of climate change, or 'climate adaptation' [2]. The online CROW knowledge base also provides information on climate adaptation, for example by means of a series of fact sheets [3].

2 Does the weather effect change over time?

Nowadays, the road safety effect of the weather is different from 10, 20 years ago. This is mainly due to technological developments. New technologies not only increase the opportunities to avoid exposure to bad weather conditions (possible effect on *mobility*), but also to better cope with bad weather conditions (possible effect on *risk*). This means that the results of older research on the effect of adverse weather conditions are not straightforwardly applicable to the current situation. It is therefore important to use recent literature whenever possible and to keep these developments in mind when interpreting research results.

Potential effect on mobility

Innovations based on information technology have taken off in recent years. Think of innovations in vehicle technology, and within the weather context especially the local short-term weather forecast on phones. Whereas precipitation ('bad weather') used to be something that just happened to road users, it is now much more predictable by weather apps on smartphones. This may affect exposure to bad weather: 'We had better go in 15 minutes, a shower is coming... .' The effect of these apps on road safety is unlikely to be the same for all road users. For cyclists and pedestrians, the threat of a shower is probably more reason to stay at home or leave later, than for drivers. Less travelling in bad weather will reduce the effect of bad weather on the number of casualties.

Possible effect on risk

Technological developments are also expected to have an effect on the risk of adverse weather conditions, that is, on how much more dangerous traffic participation is in bad weather than in good weather. For motor vehicles in particular, major advances in technological support for drivers have been made in recent decades. These include Cooperative Adaptive Cruise Control (C-

ACC), Lane Departure Warning (LDW) and Autonomous Emergency Brake (AEB) systems (see SWOV fact sheet *Intelligent transport and advanced driver assistance systems (ITS and ADAS)*). They prevent crashes, including crashes in bad weather. This kind of development implies that more recent research should show a lower crash rate in bad weather than older research.

3 What is the effect of rain?

Most weather research has been done on the effect of rain and specifically on the safety of motor vehicle occupants. An analysis of studies from several European countries over 1991-2016 [4] shows that all studies report a higher crash rate for driving/riding in the rain, than for driving/riding in similar situations without rain. This is in terms of the number of crashes per vehicle or per kilometre travelled. A more recent Finnish study [5] confirms an increased risk for driving in the rain, but the increase is relatively small (see the question *Which weather conditions are most common when crashes occur and how dangerous are they?*). There are far fewer studies that have looked at other road users such as pedestrians and cyclists, and the results do not allow an unequivocal conclusion on the effect of rain on their safety [4].

Reasons why rain increases risk for motor vehicles include longer braking distances, reduced tyre grip (aquaplaning) and reduced visibility due to rain and splashing water on the windscreen. This applies to a lesser extent to roads with very porous asphalt (see the question *What measures can reduce negative weather effects on road safety?*). Moreover, a first light rain shower after a longer dry period often causes slipperiness as road debris such as oil, rubber or dust mixes with the water drops.

On rural roads and motorways, there are more crashes and casualties during rain than when it is dry [4]. Thus, any mobility effects (see the question *How does the weather affect road safety?*) or behavioural adjustments (see the question *Do road users adapt their driving behaviour to weather conditions?*), at least on these roads, do not sufficiently compensate for the increased risk. Studies that have looked at all road types collectively or only at urban roads show a more mixed picture [4]. This may be because rain reduces the mobility of vulnerable road users, who are mostly out and about in urban areas.

4 What is the effect of snow and hail?

During showers, snow and hail lead to many of the same problems as rain, namely longer braking distances, reduced visibility due to the precipitation itself and from splashing water. (Wet) snow and hail showers more often than rain result in a slippery road surface with associated negative consequences for braking distance and road grip. When snow settles, the road surface will remain slippery, with consequences for road safety (see the question *How many crashes occur due to slippery roads?* and *How many crashes occur on or due to slippery bicycle tracks?*).

Much less research has been done on the effect of (wet) snow and hail than on the effect of rain. The research that has been done on snow generally does not distinguish between the effects of the precipitation itself and the effects of the resulting slipperiness. Moreover, the effect of snow on mobility is not considered, or only to a limited extent. Analysis of seven studies from Belgium, the Netherlands and Scandinavian countries on the effect of different characteristics of snow (e.g., snowfall, depth of snow, presence of snow, number of snowy days [4]) does not allow for an unambiguous conclusion. Positive effects (fewer crashes) were slightly more often reported than negative effects (more crashes). Especially the first snow after a period without snow appears to result in a higher crash risk. Adapting behaviour to snowy conditions will help reduce or eliminate a(n) (negative) effect on the number of crashes. What is also important is that snow reduces mobility, including that of more vulnerable road users such as pedestrians, cyclists, motorised two-wheelers and older people [1]. A Finnish study [5] concludes that in Finland crash *risk* in snow, i.e., corrected for mobility, is more than twice the average crash risk (see the question *Which weather conditions are most common in crashes and how dangerous are they?*). In Finland apparently, behavioural adjustments are insufficient to compensate for the more dangerous driving conditions.

5 What is the effect of fog?

Fog impedes visibility and therefore the ability to react to changing conditions in time. This increases crash risk. Lower speeds in fog can only partially reduce the negative effects. The extent to which visibility is impeded is, of course, an important factor. In this regard, the Dutch national weather service KNMI states the following: "At a visibility of less than 400 metres, traffic may be affected. Dense fog with a visibility of less than 200 metres is dangerous. Very dense fog with a visibility of less than 50 metres forces people to drive at walking pace" [6].

Research on the road safety effects of fog is generally somewhat older and, to our knowledge, a recent review article is lacking. A US study on the effect of fog on highway crashes in Florida [7] shows that the effect of fog (visibility less than 1 mile/1.6 km) on crash risk is greatest near entry and exit ramps and in the leftmost lane. The study also showed that, compared to clear visibility, fog results in lower speeds and higher vehicle density (5-minute averages). However, a simulator study [8] showed that the speed reduction is often insufficient to react timely and appropriately to changes in the road environment, speed reduction of a vehicle in front or a suddenly crossing pedestrian. The study also showed that professional drivers maintained a lower speed in fog conditions than non-professional drivers. Another simulator study [9] compared experienced and inexperienced drivers and found that both groups drove equally fast in fog. However, in conditions of clear visibility, experienced drivers drove faster, meaning that experienced drivers showed greater speed reduction in fog than inexperienced drivers. Fog also adversely affects staying on course, a Naturalistic Driving study [10] found.

6 What is the effect of strong wind?

Traffic participation in strong winds can be very dangerous. This is especially true for crosswinds and sudden gusts of wind, and particularly for (unladen) trucks, passenger cars with trailers or caravans and two-wheelers. Strong winds make it harder to control vehicles, and trucks and trailers may tip over. Strong winds may also lead to broken branches and other loose objects and even fallen trees on the road. A timely response is often impossible.

Recent general quantitative information on the road safety effect of strong winds is not available. A somewhat older literature review [11] shows that the road safety effect of wind was only sparingly studied in the past and what research was done, did not lead to consistent conclusions either.

7 How many crashes occur due to slippery roads?

In BRON, the database of crashes recorded by the police in the Netherlands, just under 1% of crashes in recent years appear to have taken place in slippery conditions due to snow, sleet, hail or frost (see Table 1). The extent to which this slipperiness was (partly) the cause of the crash is not known. This 1% is the average over all 12 months. In the winter months, of course, the share of crashes involving slipperiness is higher. In January, this share amounts to more than 4% of crashes and in February to more than 3%. For fatal crashes, the share involving slipperiness is slightly higher than for crashes in which the outcome is less serious. Slipperiness mostly occurred over a number of consecutive days, such as from 7 to 15 February 2021. During that period, about 30% of all registered crashes had involved slipperiness.

Table 1. Share of crashes (irrespective of severity), and share of fatal crashes, injury crashes, and property-damage-only crashes (PDO) in slippery conditions due to snow, sleet, hail and frost over 2012-2021 by month. Source: BRON, edited by SWOV.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	avg.
All	4.3%	3.4%	0.5%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	2.0%	0.9%
Fatal	5.9%	4.9%	1.0%	0.5%	-	-	-	-	-	-	0.2%	3.2%	1.1%
Injury	5.7%	4.6%	0.6%	0.4%	0.0%	-	-	-	0.0%	0.0%	0.4%	2.8%	1.0%
PDO	4.1%	3.2%	0.5%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	1.9%	0.9%

Slipperiness is not only related to cold weather conditions. Slipperiness can also be caused by mud, wet leaves or other forms of soiled road surface. According to the BRON database, an annual average of 0.1% of registered crashes involved this kind of slippery road surface. In fatal crashes, it was noted slightly more often (0.3%) than in crashes with less serious outcomes. Again, it is not known whether this slipperiness was a (co-)cause of the crash, or just a road condition. (Heavy) rain and wet road surfaces also lead to slipperiness. This is addressed in the question *What is the effect of rain?*.

The abovementioned shares of crashes due to slippery roads are most likely considerable underestimates. It is known, for example, that crashes involving cyclists, and certainly cyclist crashes without motor vehicle involvement, hardly show up in police registrations (see, for example, SWOV fact sheet *Cyclists*). Yet, cyclists will be especially sensitive to slipperiness. See the question *How many crashes occur on or due to slippery bicycle tracks?*.

8 How many crashes occur on or due to slippery bicycle tracks?

How many crashes occur on or due to slippery bicycle tracks is not known. There is some information on the role of slipperiness in bicycle crashes in general. For instance, Krul and colleagues [12] report that for 5% of the cyclists who ended up in a Dutch Accident & Emergency department (A&E) after a crash, the crash was (partly) caused by a slippery road surface due to, for example, leaves, and likewise for 5% due to slipperiness caused by snow and sleet. For single-bicycle crashes, these shares are slightly higher, at 6 and 7% respectively.

Schepers and Klein Wolt [13] specifically looked at single-bicycle crashes in which the cyclist had been treated in a Dutch A&E. In these crashes, 18% of the 350 crashes analysed were found to have happened as a result of skidding on a slippery road surface. In a third of these cases, the slipperiness was caused by dirt on the road such as sand, gravel, mud or wet leaves; about a fifth involved slipperiness due to ice and snow.

9 What is the effect of low sun?

Low morning and evening sun may dazzle road users, making it harder for them to see the traffic situation in front of them, which implies they will react less quickly to, for example, brake lights or traffic lights. Among other things, this leads to greater speed differences between vehicles [14]. The angle of the sun to the driver's line of sight is essential here: the inconvenience is greatest when the angle is less than 20°, which roughly corresponds to one hour after sunrise and one hour before sunset [15]. The effects of low sun are greatest in autumn, winter and spring [16].

In 2015 [17], the Dutch Association of Insurers reported that low sun during the morning rush hour leads to 20% more crashes, especially between cars. Low sun during the evening rush hour will mainly lead to an increase in crashes on provincial and municipal roads, as well as more crashes involving pedestrians and cyclists (17%) and animals (7%). For Edmonton, Canada, Sun et al [15] report an increase in crashes of 30%.

When the sun is low, crashes in urban areas mainly occur at intersections and are related to running a red light and failing to give right of way to cyclists and pedestrians [15]. For Tucson, Arizona, Mitra [16] reports more rear-end collisions and more side-impact collisions at intersections when the sun is low. She found no effect on crash severity.

10 What is the effect of high temperatures?

High temperatures increase crash risk [7] [18] [19].

In China [19], high temperatures were found to increase the risk of an injury crash by 20% compared to normal temperatures (relative risk 1.20, 95% confidence interval 1.01 - 1.4). In Italy [18], high temperatures were found to increase the risk of a fatal crash or injury crash by 12% compared to normal temperatures (relative risk 1.12, 95% confidence interval 1.09-1.16). In the United States [7], the relationship between heat waves and the number of fatal crashes was examined: on days during a heat wave, an increase in fatal crashes of 3.4% (95% confidence interval 0.9 - 5.9%) was found.

A major reason why high temperatures lead to a higher crash rate is that heat affects road user behaviour, for instance through poorer sleep, decreased reaction time and concentration, and getting annoyed faster (see, for example, [20]). In addition, heat increases the risk of a blowout, especially if tyres are too soft.

11 Which weather conditions are most common in crashes and how dangerous are they?

US data [21] show that about one in five crashes occurs in bad weather or on slippery road surfaces: 21% of all crashes, 19% of injury crashes and 16% of fatal crashes. Relatively most of these crashes involve a wet road surface (about 75%) and rain (about 50%). Snow/ice (about 15%), melting snow (about 10%) and fog (about 5%) are less common. The percentages mentioned are based on absolute numbers of crashes, they say nothing about risk: certain weather conditions occur less frequently than others and/or result in less mobility, and this partly determines the share of crashes in that type of weather.

A Finnish study [5] did look at crash risk during bad weather, in particular crash risk during different types of precipitation and at different precipitation intensities. As Table 2 shows, crash risk during snow is more than twice as high and during sleet almost one and a half times as high as average (= a relative risk of 1). In rain, crash risk hardly increases and with no precipitation crash risk is slightly lower than average. Looking at precipitation intensity, regardless of precipitation type, crash risk was found to be more than twice as high for heavy precipitation, one and three-quarters times as high for showery precipitation and almost one and a half times as high as average for slight precipitation. Furthermore, crash risk in bad weather conditions was found to be relatively higher on motorways than on non-motorways, while in good weather conditions crash risk was lower on motorways. Also, crash risk in bad weather was higher for single-vehicle crashes than for multiple-vehicle crashes.

Table 2. Relative risk at different types and intensities of precipitation in Finland (based on over 10,000 crashes on 43 major roads in Finland in 2014-2016). Source: [5].

Type and intensity of precipitation		Frequency (Palm probability)	Relative risk	Number of crashes
Type	No precipitation	0.845	0.90	7992
	Rain	0.088	1.06	978
	Sleet	0.005	1.46	77
	Snow	0.062	2.18	1417
Intensity	No precipitation	0.845	0.90	7992
	Slight precipitation	0.140	1.49	2185
	Showers	0.013	1.76	231
	Precipitation	0.002	2.08	51

12 What is the effect of summer/winter time?

The transition from summer time to winter time appears to be associated with a higher crash risk. This is not related to fatigue due to one hour less sleep, but rather to the sudden transition from an evening rush hour in the light to an evening rush hour in the dark, crash risk being higher in the dark [22]. This increased risk remains apparent for several months after winter time has started. Again, this suggests that the higher risk is not so much related to the transition to winter time, but rather to an evening rush hour in the dark. See also SWOV fact sheet *Fatigue*.

13 What is the effect of winter tyres?

There is no clear evidence for the road safety effect of winter tyres. It is claimed that winter tyres are safer than summer tyres at temperatures below 7 degrees Celsius: winter tyres would provide better grip and shorter braking distances. However, there are hardly any crash studies to support this supposed effect. Moreover, the crash studies that do exist were carried out in countries with very different winter conditions than the Netherlands, such as Sweden [23] [24].

More information about winter tyres and their possible road safety effect can be found in SWOV fact sheet *Safe passenger cars*.

14 Do road users adjust their driving behaviour to weather conditions?

Road users generally adjust their behaviour when out and about in adverse weather conditions, such as by choosing a lower driving speed or adapting their headway distance. However, the fact that in many adverse weather conditions crash risk is higher indicates that behavioural adjustments are not adequate.

There seem to be few recent studies on the effects of weather on driving behaviour. A review of studies from particularly the 1990s and early this century [25] indeed shows that drivers adjust their behaviour in rain, snow and fog. This mainly involves lower **driving speeds**. This is confirmed in a study on the speed effects of fog in the US [7] and of rain and snow in Sweden [26]. The latter study additionally found that the speed reduction during rain and snow was greater on roads with a higher limit: about 2.5% on roads with an 80 km/h limit to about 5% on roads with a 110 km/h limit. In all cases, speed reduction was greater in snow than in rain. Furthermore, speed reduction was often found to be greater in the dark, especially on roads without lighting.

In Korea, Woo and colleagues [14] report not so much lower speeds, but in particular greater **speed differences** when road users are blinded by the sun.

The research on **headway distances** in fog, as cited by Hamdar and colleagues [25], shows conflicting results, possibly related to two different driving styles: some studies report a greater distance in fog, others a smaller one, presumably because some drivers want to keep some kind of beacon or reference point in front of them.

Another way to adjust behaviour to bad weather conditions is to choose a **different route** [1]. When the weather is bad, road users may choose a route where the effect of bad weather is expected to be lower, for example by choosing the motorway instead of an unlit shortcut when it is dark and rainy, or by avoiding a road along a canal or waterway when it is slippery. We do not know to what extent this form of behavioural compensation occurs.

At a more strategic level, before they actually hit the road, many road users adjust their travel behaviour: by postponing a trip, choosing a different transport mode or destination, or cancelling the trip altogether [1].

15 What measures can reduce adverse weather effects on road safety?

The measures that can reduce adverse effects of weather on road safety are very diverse. We successively discuss infrastructural measures, vehicle-related measures, regulations, and education/training. Quantitative information on the effects of these types of measures is generally not available.

Infrastructure

For driving in rain, good drainage is very important. Very porous asphalt provides this good drainage. In the Netherlands, it is mainly used on motorways and sometimes on 80 km/h roads. Very porous asphalt is less suited for frost because it becomes slippery sooner than other types of asphalt. This is because the open structure allows the cold to penetrate the asphalt more quickly and ground-source heat has less effect, causing the road surface to freeze faster. The open structure also causes road salt to dilute faster and wash away sooner.

For driving in rain, it is also important that there are **no ruts** where rainwater remains. The combination of ruts and very heavy rain can easily result in aquaplaning. This involves a layer of water between the road surface and the tyres, causing the vehicle to lose grip on the road surface.

Timely and adequate **de-icing** helps prevent crashes due to slipperiness. This certainly applies to bicycle tracks and roads that are frequently used by cyclists. In addition to slipperiness due to snow, sleet and frost, it can also be due to, for example, mud or wet leaves on the road. Keeping roads and in particular bicycle tracks clean will therefore also help to prevent those kinds of slipperiness-related crashes.

Finally, local warning signs and other informational signs may help alert road users to specific local risks, such as skidding hazards, slippery snow and sleet, risk of crosswinds, rutting or mud on the road. Sometimes, there is also a lower local speed limit with a plate below the speed limit sign indicating that it only applies in rain or wet road conditions.

Vehicle (technology)

Motor vehicles have several tools to reduce the most immediate effects of adverse weather conditions. These include maintaining adequate visibility (windshield wipers, air conditioning), being sufficiently visible to others (general lighting, fog lights), maintaining grip on the road (tyres with sufficiently deep tread) and avoiding extreme temperatures inside the vehicle (heating, air conditioning). Spray-suppression is mandatory for trucks (of 7.5 tons and above) and for trailers (of 3.5 tons and above). This limits water spray from the tyres. The safety effect of winter tyres is unclear (see the question *What is the effect of winter tyres?*).

Many cars have a system that visually or audibly indicates that the outside temperature is heading toward or below zero. With the increasing ability to provide vehicles with real-time information (communication between vehicles (V2V) and between vehicles and infrastructure (V2I and I2V)), the ability to warn individual drivers of current or imminent bad weather conditions is also increasing. Several simulator studies have found positive effects of this communication on, for example, speed choice (e.g., [27] [28]), but increasing task load (additional information that must be responded to) is a concern [29].

Regulations

In some countries, the general speed limit changes with current or expected bad weather conditions. A few examples: in France, for example, the general limit on motorways drops from 130 to 110 km/h in case of rain and snow, and from 80 to 70 km/h on rural roads. On wet motorways in Germany, there is a (lower) limit at some locations. The Netherlands also has similar local speed limits for wet roads. Finland uses lower limits in winter than in summer: 100

instead of 120 km/h on motorways and 80 instead of 100 km/h on main roads in rural areas. Estonia, Latvia and Lithuania also have lower limits in winter.

More and more countries, including the Netherlands, use matrix displays to introduce temporarily lower speed limits in case of (current) bad weather conditions such as slipperiness, fog or strong winds. Speed limits on matrix displays have an important signal function and lead to more homogeneous speeds, a decrease in the number of crashes and near crashes and to less intensive braking manoeuvres (see SWOV fact sheet *Speed and speed management*).

Public communication & training

In the Netherlands, the Dutch national weather service KNMI warns of expected bad weather conditions for traffic, among other things, using the codes yellow, orange and red. Warnings are regional, usually by province. Code yellow (be alert) may be issued 48 hours before the weather phenomenon occurs with a certainty of at least 60%. Code orange (be prepared) may be issued 24 hours in advance, likewise at a certainty of at least 60%. Code red (take action) is not issued sooner than 24 hours before the weather phenomenon occurs, even if there is a low probability but high safety risk. For details on the type of weather conditions for which a warning is issued, see the KNMI website [30]. The effect of the code warnings on mobility and/or behavioural choices in traffic is not known.

In addition to these specific warnings, there is also more general advice (in case of slipperiness: keep your distance, look far ahead, accelerate slowly, and apply maximum, non-pumping braking) and slogans ("in case of fog: double your distance, halve your speed"). To what extent people are aware of this type of advice, and are able and willing to take heed, is not known.

In general, road users receive little or no training in dealing with bad weather. There is very little opportunity of practising in bad weather during driver training. Various skid courses are offered for cars and also for motorcycles, one of the aims of which is to teach drivers to cope with bad weather conditions. However, skid courses have often proved counterproductive: they are too short to automate the complex, sometimes counter-intuitive, actions required to control a car when skidding, while after the course people do trust their ability to do so and therefore take more risks in slippery or heavy rain (see SWOV fact sheet *Driver training and driving tests*).

Publications and sources

Below you will find the list of references that are used in this fact sheet; all sources can be consulted or retrieved. Via Publications you can find more literature on the subject of road safety.

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