Original Road Safety Research

Towards linking climate and weather phenomena to road safety outcomes Part 1 of 3: The collective involvement of weather manifestations

John Gaffney[1] and Elizabeth Hovenden[1]

[1] *Department of Transport, State Government of Victoria, Australia*

Corresponding Author: John Gaffney, 60 Denmark Street, Kew Vic 3101, John.Gaffney@roads.vic.gov.au,
Ph: (+61) 400955582

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Key Findings

- Meteorology has been overlooked or had a narrow focus in road safety crash analysis.
- Combinations of meteorological metrics and/or with other conditions impact crash risk.
- The full breadth of weather events is underestimated in its effect on crashes.
- Compound metrics (wind speed, precipitation) are required to understand crash risk.

Abstract

Climate and its many weather manifestations can help explain annual variations in fatalities and casualty crashes. Part 1 of a 3-part series identifies the breadth of weather factors which collectively contribute to crash risk reviewing and consolidating relevant research. The series identifies the need for interventions in advance of and during certain weather events, providing pathways for further research. The key climate drivers for Victoria produce complex interactions forming short-term (hours, days, weeks) and long-term (months, years, decades) weather patterns that influence crash occurrence and their spatial and temporal distribution across the state. Although analysis of Victorian crash records found weather was involved in at least 10% of fatal and casualty crashes, this is considered under-estimated as many weather-related events are not recorded nor considered in crash analysis. Spatial distributions of annual and daily crashes show alignment with movement of weather patterns across Victoria observed in Bureau of Meteorology synoptic charts, particularly in relation to low pressure systems and troughs, duration of damp pavement conditions, suddenly changing/unseasonal events, and periods of extreme heat and cold. Understanding how climate influences variations in crash occurrence can be used to develop appropriate strategies to improve road safety and help reach the target of zero deaths.

Keywords

climate, weather, crash risk, spatial, temporal, multi-variate metrics

Glossary

See Appendix A for a glossary of climate and weather terms used in this paper.

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Introduction

Weather is different every minute, every day, and everywhere in Victoria. No two years are the same, although some parts of the year may appear common with other years. Climate and weather do not precisely follow artificial constructs of years, seasons or months but rather operate on a continuum with considerable variability.

Every time we drive on our roads, many conditions we encounter are not constant. This includes the mix of vehicles and their drivers (and their emotions) we interact with as well as the traffic conditions and the weather condition we pass through. To the lay person these conditions may seem routine, unrelated, and less important, however, closer examination of these factors is critical to understanding road crashes within their context to reduce road deaths.

A literature review has been assembled to highlight the breadth of meteorological factors collectively contributing to crash risk. Though not exhaustive, this review provides a new lens revealing that collective effects of a wide spectrum of weather manifestations, metrics and indexes likely have substantial involvement in crash occurrence. It endeavours to ground segmented, disparate, or relatively complex research into a single narrative by highlighting impacts on the road environment, driver behaviours, and vehicles. The review identified many compound metrics (precipitation and grade of road (slope); wind speed and visibility; ground temperature/moisture, and pavement friction in combination with brake and tyre temperatures) are needed to understand and assign crash risk holistically.

The nature of climate and weather interactions is such that there is a wide range of manifestations covering the long term, annual, seasonal, monthly, weekly, daily, hourly and minute by minute, collectively resulting in large variations in annual road death and casualty crash numbers both at state-level and nationally. Further, increased exposure to higher density traffic (short headways and spacing and certain dangerous “traffic states”; Hovenden, Zurlinden, & Gaffney, 2020) over recent decades, primarily due to road demand outstripping road supply (ratio 4:1), reduces available space for the road system to absorb error. Combined with certain extremes of weather, this can accelerate road user fatigue increasing reaction times, and increase cognitive load on drivers and other road users, making them more susceptible to what is commonly described as “error”.

The dynamism of certain traffic and environmental conditions complicate road safety research. The cause of the crash might not be related to the physical crash location, but rather the collective build-up of conditions which the road user encountered, either whilst on the road network or in their daily (non-driving) activities, in the lead up to the crash. For example, as will be seen in Part 3, many consecutive days of extreme heat waves or high humidity cause increased collective society fatigue and increased crashes. Fatigue can be caused by driving on damp or wet and slippery roads for long periods of time, or in hot and humid weather, and its effect exacerbated when encountering high or varying levels of driving complexity and traffic conditions, including congestion. The presence of many weather events can be a subtle overlay not perceived by motorists as being particularly important to safety nor a cue to slow down, increase alertness, or take driving breaks.

The objective of this three-part series is to identify any linkages between fatal and casualty crashes and the collective impact of key meteorological climate drivers (long-term events, including cyclical patterns) and their many weather manifestations (short-duration events). Part 2 covers longer term climate drivers and their cycles, which impact weather patterns and weather manifestations over many years. Part 3 examines the many weather manifestations which contribute to high and low crash days and sequences of weather affecting longer periods. It is hoped that the broad discussion in the series herein will open up many new lines of enquiry for further research into relationships between many of the meteorological metrics and their compound effects to enable a holistic assessment of crash risk.

Background

According to the Australian Government Bureau of Meteorology (BOM, n.d.) there are six climate drivers that affect Victoria’s weather:

1. East Coast Low (ECL);
2. EL Nino Southern Oscillation Index (SOI, commonly known as ENSO);
3. Indian Ocean Dipole (IOD);

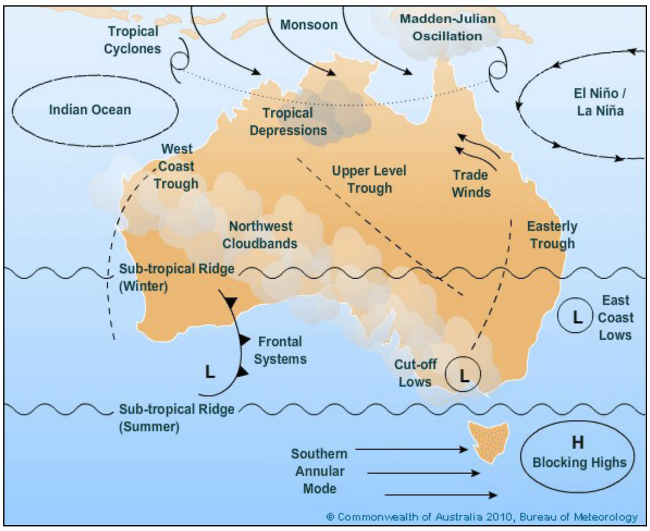

Figure 1. Australia’s key climate influences (source: BOM, n.d.)

Table 1. The manifestations of climate and weather, their effects on environment, vehicles and road users including human factors that are influenced by weather

Manifestations of Climate and Weather			
Hot temperatures	Heat waves	Thunderstorms	Lightning
Cold temperatures	Rain	Floods	Drizzle
Snow	Hail	Sleet	Blizzards
Ice	Frost	Dry	Damp
Dew	Mist	Haze	Cloud
Fog	Smog	Wind gusts	Wind (strength, direction)
Dust storms	Humidity	Day/night length	Troughs and cold fronts
Effects Modifying the Road Environment			
Daylight/darkness	Sun glare	Glare	Smoke from bushfires
Visual distortion	Reflections and shadows	Light intensity	External visibility (e.g., in the environment)
Mirror surface (when wet)	Contrast	Mirages	Internal visibility (e.g., through windscreen)
Reduced pavement friction	Backscatter headlight	Spray/splash	Exposure to animals (e.g., night length & droughts)
Effects Modifying Vehicle Performance and Behaviour			
Cold tyres (increased braking distance)	Cold brakes (increased braking distance)	Fogged up windscreen internal (reduced vision)	Obscured windscreen in heavy rain (reduced vision)
Hot tyres (increased tyre pressures and blowouts)	Hot/soft melting pavements (increased braking distance)	Cold steering wheel and cabin (distraction and slower reaction)	Hot steering wheel, cabin, seat, and seatbelt (distraction, slower reaction)
Effects Modifying Human Capabilities and Perceptions			
Depth/distance perception	Impaired vision	Blindness (dazzle)	Visual discomfort (flickering, strobing)
Reduced tactile feedback	Impaired hearing	Heat stress	Dehydration
Fatigue (body and eyes)	Wind chill	Reduced reaction time	Reduced perception of speed (e.g., fog)

4. Sub-Tropical Ridge (STR);
5. Southern Annular Mode (SAM);
6. Madden Julien Oscillation (MJO).

Three main climate drivers affecting climate and weather in Victoria, discussed in this paper, are SOI, IOD and SAM. Some climate drivers have more effect on weather in other parts of Australia (e.g., MJO) but occasionally influence weather in Victoria (see Figure 1).

Victorian weather can change day to day due to the oscillatory nature of SAM which has a cycle of about two weeks and is manifested as cold fronts arrive and move across the state. SAM contributes to the large variations in weather conditions regularly seen in Victoria, even within one day depending on whether SAM's influence stays well south of Victoria or not. The general trend of climate is driven by longer-term climate effects such as SOI and IOD, and these have a potential relationship with the amount of human activity (agriculture, building, tourism) and thus road use (demand) and potentially crashes. Longer-term cycles can be around 5 to 30 years in length and do not align well with annual assessment of road crashes in Australia and can partially explain annual variations seen in road deaths year to year (more apparent at state-level). In Part 2 and 3 climate drivers will be shown to have an influence on crash causation, with SAM's 14-day cycle likely having the greatest influence. Other shorter-term meteorological metrics and indexes essential for understanding a very wide range of weather-related crashes, identified in Part 3, include:

- Solar radiation (influencing temperature and visibility);
- Water vapour pressure (moisture held in the air influencing extent of cloud cover, or its absence, and/or creating an "apparent humidity" effect);
- Rainfall;
- Relative humidity;
- Dewpoint;

- Frost, fog, and mist;
- Peak wind gusts and dust;
- Warm and cold fronts (high and low pressure systems) and troughs.

In summary, various climate and weather manifestations modify the environment and human activity leading to individual and/or combinations of effects on the environment, vehicles, and human behaviours (see Table 1 and discussion in the literature review). They can affect the human condition physically, mentally, and/or visually, including the ability to see, perceive and assess risk(s), and the ability to react appropriately.

These manifestations can result in increased reaction times (due to reduced visibility and fatigue), and lower pavement friction (due to the presence of moisture including dampness and dew). The combinations of cold pavements, cold tyres and cold brakes, or hot melting (soft) road surface due to extreme heat, where the braking forces can instantly melt the bitumen binder on braking (bitu-planing; Bullas & Hounsell, 2007) can each increase stopping-distances by up to 25%.

Considerable research about weather and crashes has been undertaken in recent decades. Some of which are broad in scope with extensive coverage of weather-related metrics. Others typically have a narrower focus or have been limited to just a few metrics without necessarily considering the compound effects of multiple metrics simultaneously acting on the road environment, human behaviours and vehicle capability.

Single meteorological metrics such as precipitation (rainfall) have been widely studied or discussed, particularly in Australia in relation to road crashes. However, precipitation is just one of many meteorological markers of road crashes as seen in the broader literature review. Moisture, whether held in, on, or near the ground (as dampness, dew, frost, ice or snow), falling through the air (as rain, snow or sleet), held in the air near the land's surface (as mist and fog) or held in the lower, middle and upper atmosphere (as clouds) may collectively influence pavement friction levels, visibility and human comfort levels, fatigue and reaction times and thus affect road users' judgement of road surface conditions. Sometimes these environmental effects (after a long period of heavy rain or flood) may linger for many months after the events occurred (increased ground moisture affecting pavement friction and cloud cover reducing visibility).

Literature Review

There have been many studies on the associations of climate and weather with crashes. Below is a non-exhaustive summary of research studies that have linked crashes to actual meteorological events. Many of the findings involve compound associations combining at least two meteorological metrics or at least one metric combined with another condition (road type, grade, elevation, human capability, time of day, duration, season, peak traffic condition, skid resistance). Examples of compound metrics are highlighted in **bold** in the following paragraphs.

Thordarson & Olafsson (2008) found winds greater than 10m/s (36km/h) were involved in 42% of heavy goods vehicle crashes, 33% of bus crashes, 64 % of towing vehicle crashes and 28% of passenger vehicle crashes. Of the road deaths related to weather, there were twice as many wind-related events compared to other weather-related events (Bhattachan, Okin, Zhang, Vimal, & Lettenmaier, 2019). The study found that **wind speeds** greater than 6 m/s emit **dust** from the surface into the air, affecting **visibility**.

According to Perrels, Votsis, Nurmi, & Pilli-Sihvola (2015), bad weather can raise the number of crashes significantly (20% or more over the base rate). They found that in precipitation events, casualty crash numbers were somewhat attenuated by driver speed reductions, but possibly not true in all-weather situations. They also found that the combination of **wind speed** and **precipitation** was important.

Weather-related crashes have a temporal and spatial component. Call, Medina, & Black's (2019) research found that most crashes associated with adverse weather occurred during **evening rush hours**. However, once crashes were normalised for traffic volume, adverse weather had the biggest effect on crashes during **early morning hours (5-7am)**, followed by **night-time hours**.

Elevation and **slope** play a role in crash frequency. Crashes associated with adverse weather become more common with increases in elevation, although crashes at high elevation only comprise a small percentage of crashes. Any amount of slope, regardless of elevation, greatly increases crash risk. Call et al., (2019) found that with a slope of one degree or less, adverse weather was associated with about 11% of crashes, but with every additional degree of slope, an additional 1% of crashes is associated with adverse weather, with more than 31% of all crashes on steep roadways (greater than 20 degrees) being associated with adverse weather. They also found **weather-related crashes** were more associated with **valley fringes**.

A study by Hermans & Brijs (2007) investigated relationships between hourly number of crashes and corresponding hourly weather variables. Testing for 17 climatic factors, they found crash numbers generally increased with increases in maximum wind gust, global radiation, sunshine duration, precipitation (presence, amount and duration) and cloudiness. Presence of precipitation had the most significant impact, and **duration of precipitation** had more of an impact than amount of precipitation (crash numbers increased by 6.5% on average with 10 extra minutes of precipitation). One possible explanation is when raining, drivers initially react by slowing down and increasing headway and then get comfortable with driving in rain and revert to normal driving. Their preliminary analysis found **weather** effects were different between **coastal areas** and the **centre of the country**.

Hamdar, Qin & Talebpour (2016) confirmed real-world observations that **roadway** (lane width, shoulder width, median existence, median type, horizontal and vertical curves) and **weather-**associated factors (foggy weather, icy and wet road surface conditions) influenced Time-to-Collision (TTC). Their study found **low visibility** caused drivers to increase their gap to the vehicle in front, while in higher visibility drivers followed closer. No **driver behaviour** modification (defensive or aggressive driving) was observed when driving in mountainous areas and rolling terrains. Further research by Hammit, James, Ahmed, & Young (2019) revealed that in all **rain conditions** drivers exhibited **greater oscillatory acceleration behaviour** than in clear conditions and most **aggressive behaviours** occurred in **fog conditions**, potentially because it is harder to judge speed in the absence of visual feedback of objects passing by.

Stevens, Schreck, Saha, Bell, & Kunkel (2019) linked fatalities to high-resolution radar data to understand relationships between precipitation and fatal motor vehicle crashes. They found risk of fatal crashes lowest at light precipitation rates (relative risk 1.29), although still greater than unity. However, with **heavier rates of precipitation**, the relative risk of fatal crashes increased to 2.46 due to **degraded visibility and road conditions**. Importantly, since light precipitation was the most frequent case (approximately 8-10 times more likely), the absolute number of fatalities was highest in those conditions. Stevens et al. (2019) stated ‘precipitation, particularly light precipitation, may be another of these underappreciated risks, with most drivers confident that their risk is not substantially increased during a light rain event’.

Interaction of the vehicle and road pavement is critical in understanding crash causation. Flintsch, McGhee, de Leon Izeppi, & Najafi (2012) found pavement friction varied a great deal depending on actual thickness of the water film. Tyre tread condition was also found to make a big difference. It does not take much moisture to reduce friction and under heavy dew conditions, pavements are often very wet and remain wet for many hours after a rain event. Pavements have the highest measured friction in winter (in cold weather, when pavements are dry). However, friction reduces on wet pavements, damp pavements and in very hot weather when pavement becomes hot and soft.

Flintsch et al. (2012) mention that although most skid resistance analysis is focused on wet roads, work undertaken by Roger Hosking from TRL in the 1980’s showed “apparent” dry road friction can also contribute to crashes. Hosking posited there was misreporting of roads in crash data as ‘dry’ when roads were in fact ‘damp’ as an explanation to the correlation between changes in dry-road skidding rates and wet-road skid resistance. Further to this, simplistic damp or wet pavement crash analysis may assume vehicles did not brake before impact (Rivers, 2010; Levy, 1977) suggesting about 33% of wet skidding is missed in the crash record due to absence of reported skid marks as skid marks require temperatures generated to be such that rubber will melt.

Bullas & Hounsell (2007) described the pavement phenomenon “bitu-planing” where, with dry negative textured road surfaces such as open graded asphalt, a thin layer of bitumen near the surface instantaneously melts (liquifies) the pavement because of friction generated (heat generation) between the tyre and pavement under braking conditions. Physical properties inducive to road crashes occur primarily when roads are damp (dew, not necessarily rain events) and at both **hot and cold extremes** where hot and **melting pavements** (Bullas & Hounsell, 2007) and cold (often damp) pavements **increase braking distance** markedly (up 20 to 25%; Anupam, Srirangam, Scarpas, & Kasbergan, 2013). Sherif & Hassan (2008) examined effects of pavement surface temperature and moisture conditions on vehicle collision risk during wintertime and concluded that **moisture on a pavement surface** increased risk of collision **at temperatures between -8°C and +8°C**, with the risk reaching its maximum at - 1°C.

Wu, Zaitchik, & Gohlke (2018) found “heat waves” affected fatal crash numbers, with a 3.4% increase in fatal crashes on heat wave days compared to non-heat wave days. The odds of a fatal crash during **heat waves** compared to non-heat wave days were even higher for drivers **aged 56 to 65 years (8.2%)** and for driving on rural roadways (6.1%). Wu et al. (2018) found the odds for fatal crashes were higher on **heat wave days with no precipitation** (10.9%) but lower on heat wave days with precipitation (-4.4%). They also found the odds for fatal crashes were higher on **heat wave days with medium or high solar radiation** (24.6% and 19.9% respectively) but lower on heat wave days with low solar radiation (-8.4%).

Research by Stern & Zehavi (1990) from Israel, a country like Australia with very hot summertime temperatures, showed an association between crashes in hot weather and heat stress, defining medium heat stress as **temperatures** between 24.1°C and 28°C and high heat stress as temperatures greater than 28°C. Whilst these levels are not considered extreme in Australia, these temperatures are shown to **reduce alertness, slow down driver’s coordination and increase reaction times**. Under these conditions the longer boring trips on straight roads can cause motorists to progressively become drowsy and fall asleep.

Stern & Zehavi (1990) found most **crashes occurred in the hottest part of the day**, in the early to mid-afternoon 12:00 noon to 4:00pm. They mentioned more crashes occurred during **medium and high heat stress periods**, with crash risk increasing as severity of weather increased. They found most hot weather crashes were "**one-person judgement**" type of crashes, the majority being run-off-road crashes. A possible explanation for increased risk of "one-person judgement" crashes is that passengers provide several positive feedback mechanisms to keep drivers alert and safe, such as additional sets of eyes watching the road, communication keeping the mind active and alert, and added incentives to take regular breaks. Notably, the report identified crash risk changed according to **average daily traffic volume** rather than localised (spatial) variations in traffic volumes. This supports the experience that there is accelerated fatigue when driving longer distances within higher or heavy traffic volume streams. Higher concentration levels must be maintained for considerably long periods of time without being able to relax the eyes, the hands on the wheel, nor the foot on the accelerator.

Rowland, Davey, Freeman, & Wishart, (2007) summarised research into effects of weather and climate on road safety. As cited by Rowland et al. (2007), **high temperatures** were linked to the following driver behaviours:

- **Irritability** (e.g., driver aggression) (Anderson, 1989; Boyanowski, Calvert, Young, & Brideau, 1981);
- **Increased fatigue** (Zohar, 1980);
- **Decreased psychomotor and mental performance** (Viteles & Smith, 1946);
- **Increased reaction time** (Weiner & Hutchinson, 1945);
- **Loss of concentration** (alertness), which can increase probability of crashes as reaction time is affected (Stern & Zehavi, 1990).

Rowland et al., (2007) cited the following research findings linking high temperatures to road crashes:

- Crash rates increased on days where dry-bulb temperatures were above 26ºC (Welch, Vaughan, Andreassend & Folovary, 1970);
- **Fatigue** among bus drivers can be caused by **temperatures** of only 25ºC (Cantilli, 1974) and similarly for truck drivers (McDonald,1984);
- Indicators of **fatigue** (sleepiness, tiredness, and reduced alertness) were associated with **temperature and/ or humidity** (Commission of Occupational Health & Safety, 2004).

A study by Basagana, et al. (2015) showed decrease in **driving performance** (distractions, driver error, fatigue or sleepiness) at **high temperatures**. The study linked daily counts of motor vehicle crashes and daily temperature or occurrence of heat waves. Heat waves were defined as two or more "consecutive days with temperature exceeding the weather station-specific historic 95th percentile of maximum temperature". The study found estimated crash risk increased by 2.9% during heat wave days, but the increase was even higher (7.7%) when considering crashes with driver performance associated factors. The researchers found for each 1°C increase in maximum temperature, estimated risk of crashes with driver performance factors increased by 1.1%. Therefore, there was more driver error the hotter it got.

Lobo, Ferreira, Iglesias & Couto, (2019) found higher crash frequencies were associated with temperatures below 10°C but the correlation with crash frequencies for temperatures above 20°C was negative (but only statistically significant for multi-vehicle and property-damage-only crashes). They found crashes were more prone to occur on rainy days, and that crash risk was higher when rainfall first started due to build-up of oil and grime on the road surface in combination with initial driver behaviour (drivers not immediately readjusting to hazardous weather conditions). However, if there was past precipitation, crash risk started to fall as pavements became cleaner and drivers adapted their behaviour.

In their literature review, Lobo et al., (2019) cited the following:

- Higher crash frequencies occurred when **daily temperatures exhibited extreme deviations** from **seasonal standards** (Brijs, Karlis, & Wets, 2008; Malyshkina, Mannering & Tarko, 2008);
- There may be increased crash risk due to sun glare in winter (Brijs et al., 2008);
- The impact of **wind speed** on crash risk was only significant for **heavy storms** and/or **heavy vehicles** (Brijs et al., 2008).

A study by Malin, Norris & Innamaa, (2019) found that in poor road weather conditions relative crash risks increased and were highest in slippery to very slippery road conditions or where icy rain was present. This study looked at **road surface temperature** rather than the more commonly used ambient temperature and at various combinations of weather (cloudy, half cloudy, broken and overcast) with different intensity and types of precipitation (snow, sleet, light rain, and heavy rain) to determine five different conditions: slippery road, very slippery road, poor visibility, icy rain, and slush. The relative crash risk increased dramatically when road surface temperature fell to **freezing point and below**. The relative crash risk in **poor weather** and road conditions was higher on **motorways** than on other road types despite the former having an overall lower risk. The relative crash risks were also higher for single-vehicle crashes than for multi-vehicle crashes.

The Australian Government Bureau of Meteorology (2017) states "**frost** can also pose a safety risk on the road, particularly **at night and in dips or low-lying areas**, where ice may form". **Frost** occurs in areas where roads move amongst valleys and hills, where roads generally have **grades** (Call et al., 2019).

Mitra (2014) found **sun glare** posed serious driving hazards and could be detrimental to both traffic safety and traffic movement. The research found the odds of a crash occurring due to glare were higher in **eastbound and westbound** directions than in northbound and southbound directions, and the effects were greater in **early spring**, **autumn and winter** than in summer. The research also found that sun glare affected rear-end and angle crashes at signalised intersections. Similar work by Choi & Singh (2005), focusing on safety performance in sun glare, found **older drivers** were more prone to crashes when glare (from headlamps and sunlight) obstructed their vision. Chalkias, Faka, & Kalogeropoulos (2013) found the combination of **complex terrain**, **vehicle motion**, and **position of the sun** could cause a **loss of vision** in some sections of road.

Providing weather information to road users was estimated to reduce occurrence of weather-related crashes by 14% in terms of avoided crashes (Perrels et al., 2015). The Finnish Meteorological Institute (FMI) developed a model-based system, employing numerical weather forecasts, to report road surface temperature, road surface condition classification, road friction and a traffic index for the road network. The numerical weather forecasts include observations from synoptic charts or road weather stations and from their radar precipitation measurement network.

The crash problem and risk can be seen through a new lens by looking at different forms of exposure known as "events of exposure", a concept coined, developed and promoted by Rune Elvik (Elvik, 2014). Certain "events of exposure" often happen within fractions of seconds and precede many crashes. Elvik (2014) states these events are measurable providing researchers with a proper definition of the relationships between exposure and risk and thus "re-establishing the connection between the basic concepts of accident research and probability theory". Weather events can now be measured and quantified, and the road network can be assessed in terms of crash risk based on terrain, geography, and geometry.

Discussion and Conclusions

Preliminary analysis of Victorian crash records found weather was involved in at least 10% of fatalities and 9% of casualty crashes (based on Department of Transport analysis using automated string extraction techniques from multiple fields in police-reported crash data). This is considered by the authors an underestimate as many factors (see literature review) influencing weather and temporal conditions are not systematically captured in crash records (see Table 1).

As detailed earlier, there are many manifestations of climate and weather which can contribute to crash risk. Many weather events are temporal (short lived) and subtle (dew, wind, fog, cloud cover), and can often be overlooked in subsequent police crash reports, nor seen as being of significance by road users, so their influence on crash risk is often ignored. Climate and weather variability may well explain variations in annual road deaths commonly seen at state-level.

Climate and weather can affect human and economic activity and thus road usage (agricultural activity and production, building activity, leisure, travel modes) in any one year, which could be directly linked to exposure and potentially crash numbers. It also impacts a range of factors that are more subtle, varied, and harder to quantify such as: human factors (heat, stress, perception, reaction times, vision, fatigue and comfort levels); environment (visibility, perception of distance and pavement friction); and vehicle braking and handling performance (cold tyres and brakes, and wind gusts on rollovers and run-off road crashes). Collectively these manifestations contribute to a large number of crashes, however crash records do not capture most of them adequately. To achieve road safety goals, a holistic understanding of all these contributors to crash risk are needed. Many climate and weather metrics discussed in the three papers are readily available from the BOM. However, they are generally not included or linked to crash databases, nor considered important in subsequent analyses of crashes. This is despite weather being an everyday event reported in news bulletins and closely followed by the public. Often conclusions are made about crashes without a full understanding of the critical factors involved.

Historically in Australia weather-related crash analysis has primarily focused on a limited number of meteorological metrics. The work shown in this three-part series, found many of the meteorological metrics require other factors to be present (compound meteorological metrics, geometric or road surface condition) to elevate crash risk. This review of broader international research on climate and weather identified a wide range of impacts of weather manifestations on crash causation. However, this collective research has rarely been brought together into a single narrative to enable all elements of weather and climate to be included in a unified crash risk assessment framework. Compound metrics are needed to understand road crash risks, including:

- Visibility and windspeed;
- Precipitation and grade (slope) of road;
- Peak wind gusts and vehicle size and speed;
- Windspeed and precipitation;
- Air temperature and/or ground temperature as it relates to hot pavement friction levels;
- Air temperature and/or ground temperature, tyre temperature and brake temperature (particularly below 10ºC as it relates to tyre/pavement friction levels and braking efficiency).

These plus many more are identified and discussed in Part 3.

Research findings suggest drivers generally do not sufficiently modify their speed and driving behaviour when faced with adverse weather conditions. The authors believe this needs to be part of education programs for new drivers and continually reinforced through campaigns to road users about reducing speed and increasing headways when certain conditions are present. Many road conditions discussed in this 3-part series do not provide most road users with the necessary cues to be conscious of increased fatigue or the need to slow down. Examples include damp pavements, lower daytime light levels, low visibility, fog, cold weather, wind, extreme heat waves and intense sun-glare. Conversely, those drivers who do slow-down in inclement conditions feel pressure (obliged) to drive faster to keep up with those who have not modified their speed or behaviour. Research indicates both younger <=25 years old and older drivers (>=55 years old) are affected more by extremes of weather.

Education needs to target specific groups to increase their awareness and modify behaviours, especially by reducing their exposure in certain extreme conditions such as heat waves, strong winds and precipitation, and to modify driving behaviour in other more subtle conditions. For example, slowing down when dew, fog, mist, cold weather, wind, and rain are present, taking more driving breaks, and drinking more fluids in hot weather. Giving motorists tangible reasons to slow down is an effective form of education.

Importantly as found by Stern & Zehavi (1990) most heat stress related crashes involved a single vehicle, generally with a single occupant/run-off-road crash. Medium and high heat stress levels occur at temperature ranges as low as 24°C which are not considered extreme in Australia but should not be ignored. Heatwave days and sequences will be discussed further in Part 3 of this series. Higher temperatures are shown to reduce alertness, slow down driver's coordination and increase driver's reaction time. The study identified that "one-person judgement" in vehicle crashes is a high risk**.** The presence of passengers can influence driving decisions, behaviours and judgements, help keep a driver's mind active, and prompt more driving breaks.

Part 1 has identified the breadth of weather factors influencing crash risk. Parts 2 and 3 will progressively develop a broader range of relevant climate and weather metrics relating to crash risk showing association with longer term cycles of climate and weather.

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Conflicts of interest

The authors declare that there is no conflict of interest.

References

Anderson, C. A. (1989). Temperature and Aggression: Ubiquitous effects of heat on occurrence of human violence. *Psychological Bulletin*, *106(1)*, 74-96. https://doi.org/10.1037/0033-2909.106.1.74

Anupam, K., Srirangam, S.K., Scarpas, A., & Kasbergan, C. (2013). Influence of Temperature on Tire-Pavement Friction Analyses. *Transportation Research Record: Journal of the Transportation Research Board, 2369(1)*. 114-124. https://doi.org/10.3141/2369-13

Australian Government Bureau of Meteorology [BOM]. (2017). *What is Frost*. Retrieved from http://media.bom.gov.au/social/blog/1510/explainer-what-is-frost/

Australian Government Bureau of Meteorology [BOM]. (n.d.). *Australian Climate Influences*. Retrieved from http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml

Basagana, X., Escalera-Antezana, J. P., Dadvand, P., Llatje, O., Barrera-Gomez, J., Cunillera, J., Medina-Ramon, M., & Perez, K. (2015). High ambient temperatures and risk of motor vehicle crashes in Catalonia, Spain (2000–2011): a time-series analysis. *Environmental Health Perspectives*, *123(12)*, 1309–1316. https://doi.org/10.1289/ehp.1409223

Bhattachan, A., Okin, G. S., Zhang, J., Vimal, S., & Lettenmaier, D. P. (2019). Characterizing the Role of Wind and Dust in Traffic Accidents in California. *GeoHealth, 3(10)*, 328–336. https://doi.org/10.1029/2019GH000212

Boyanowski, E, Calvert, J, Young, J and Brideau, L (1981) Toward a thermoregulatory model of violence. *Journal of Environmental Systems*, *1*, 81-87.

Brijs, T.; Karlis, D.; & Wets, G. Studying the effect of weather conditions on daily crash counts using a discrete time-series model. *Accident Analysis and Prevention*, *40(3)*, 1180–1190. https://doi.org/10.1016/j.aap.2008.01.001

Bullas, J.C. (2007). *Bituplaning: A Low Dry Friction Phenomenon of New Bituminous Road Surfaces* (Doctoral thesis, University of Southampton, UK). Retrieved from https://www.researchgate.net/publication/263852154_Bituplaning_A_Low_Dry_Friction_Phenomenon_of_New_Bituminous_Road_Surfaces

Call, D. A., Medina, R. M., & Black, A. W. (2019). Causes of Weather-Related Crashes in Salt Lake County, Utah. *The Professional Geographer*, *71:2*, 253-264. https://doi.org/10.1080/00330124.2018.1501713

Cantilli, J. E. (1974). *Programming environment improvements in public transportation*. Lexington Books, Toronto.

Chalkias, C., Faka, A., & Kalogeropoulos, K. (2013). Assessment of the Direct Sun-Light on Rural Road Network through Solar Radiation Analysis Using GIS. *Open Journal of Applied Sciences*, *3*, 224-231. https://doi.org/10.4236/ojapps.2013.32030

Choi, E. H., & Singh, S. (2005). *Statistical Assessment of the Glare Issue-Human and Natural Elements*. Retrieved from https://nces.ed.gov/FCSM/pdf/2005FCSM_Choi_Singh_IVA.pdf

Commission for Occupational Health & Safety. (2004). *Code of Practice: Fatigue Management for Commercial Vehicle Drivers*. Western Australian Government.

Elvik, R. (2014). *Towards a general theory of the relationship between exposure and risk*. Institute of Transport Economics, Oslo, Norway. Retrieved from https://www.toi.no/getfile.php?mmfileid=36724

Flintsch, G. W., McGhee, K. K., de Leon Izeppi, E., & Najafi, S. (2012). *The Little Book of Tire Pavement Friction*. Version 1, Pavement Surfaces Properties Consortium. Retrieved from https://www.apps.vtti.vt.edu/1-pagers/CSTI_Flintsch/The%20Little%20Book%20of%20Tire%20Pavement%20Friction.pdf

Hamdar, S., Qin, L., & Talebpour, A. (2016). Weather and Road Geometry Impact on Longitudinal Driving Behavior: Exploratory Analysis Using an Empirically Supported Acceleration Modeling Framework. *Journal of Transportation Research, Part C: Emerging Technologies*, *67*, 193-213. https://doi.org/10.1016/j.trc.2016.01.017

Hammit, B. E., James, R., Ahmed, M., & Young, R. (2019). Toward the Development of Weather-Dependent Microsimulation Models. *Transportation Research Record*, *2673(7)*, 143–156. https://doi.org/10.1177/0361198119844743

Hermans, E., & Brijs, T. (2007). *The Impact of Weather Conditions on Road Safety Investigation on an Hourly Basis*. Hasselt University. Retrieved from https://www.researchgate.net/publication/228554904_The_Impact_of_Weather_Conditions_on_Road_Safety_Investigated_on_an_Hourly_Basis

Hovenden, E., Zurlinden, H. & Gaffney, J. (2020). Safety on Heavily Trafficked Urban Motorways in Relation to Traffic State. *Journal of Road Safety*, *31(1)*, 51-65. https://doi.org/10.33492/JRS-D-19-00247

Levy, J. L. (1977). *The Effect of Pavement Skid Resistance on Wet Pavement Accidents in Indiana*. Publication FHWA/IN/JHRP-77/01. Joint Highway Research Project, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. https://doi.org/10.5703/1288284313942

Lobo, A., Ferreira, S., Iglesias, I., & Couto, A. (2019). Urban Road Crashes and Weather Conditions: Untangling the Effects. *Sustainability*, *11(11)*, 3176. https://doi.org/10.3390/su11113176

Malin, F., Norros, I., & Innamaa, S. (2019). Accident risk of road and weather conditions on different road types. *Accident Analysis and Prevention*, *122*, 181-188. https://doi.org/10.1016/j.aap.2018.10.014

Malyshkina, N. V., Mannering, F. L., & Tarko, A. P. (2008). Markov switching negative binomial models: An application to vehicle accident frequencies. *Accident Analysis and Prevention*, *41(2)*, 217–226. https://doi.org/10.1016/j.aap.2008.11.001

McDonald, N. (1984). *Fatigue, safety and the truck driver*. Taylor and Francis Ltd, London.

Mitra, S. (2014). Sun glare and road safety: An empirical investigation of intersection crashes. *Safety Science*, *70*, 246-254. https://doi.org/10.1016/j.ssci.2014.06.005

Perrels, A., Votsis, A., Nurmi, V., & Pilli-Sihvola, K. (2015). *Weather Conditions, Weather Information and Car Crashes*. ISPRS International Journal of Geo-Information, 4, 2681-2703. https://doi.org/10.3390/ijgi4042681

Rivers, R. W. (2010). *Technical Traffic Crash Investigators Handbook (Level 3) – A Technical Reference, Training, Investigation and Reconstruction Manual* (3rd ed.). Springfield, Illinois: Charles C. Thomas Publisher Ltd.

Rowland, B. D., Davey, J. D., Freeman, J. E., & Wishart, D. E. (2007). Road transport sensitivities to weather and climate change in Australia. *Proceedings of the 30th Australasian Transport Research Forum, Melbourne, Australia*. Retrieved from https://eprints.qut.edu.au/9945/1/9945.pdf

Sherif, A., & Hassan, Y. (2008). Impacts of pavement surface temperature and condition on road safety. *Proceedings of the Canadian Society for Civil Engineering Annual Conference*. Retrieved from https://www.researchgate.net/profile/Yasser-Hassan-6/publication/288804123_Impacts_of_pavement_surface_temperature_and_condition_on_road_safety/links/5c0f11144585157ac1b9140f/Impacts-of-pavement-surface-temperature-and-condition-on-road-safety.pdf

Stern, E., & Zehavi, Y. (1990) Road safety and hot weather: A study in applied transport geography. *Transactions of the Institute of British Geographers*, *15*, 102-111. https://doi.org/10.2307/623096

Stevens, S., Schreck, C., Saha, S., Bell, J., & Kunkel, K. (2019). Precipitation and fatal motor vehicle crashes: continental analysis with high-resolution radar data. *Bulletin of the American Meteorological Society*, *100(8)*, 1453-1461. https://doi.org/10.1175/BAMS-D-18-0001.1

Thordarson, S., & Olafsson, B. (2008). *Weather induced road accidents, road accidents, winter maintenance and user information*. Transport Research Arena Europe 2008, Ljubljana. Retrieved from https://www.researchgate.net/publication/229009186_Weather_induced_road_accidents_winter_maintenance_and_user_information

Victoria State Government Department of Transport. (2020). *Victorian Road Safety Strategy 2021–2030*. Retrieved from https://www.tac.vic.gov.au/__data/assets/pdf_file/0020/502166/RoadSafetyStrategy_DEC2020.pdf

Viteles, M., & and Smith, R. (1946). An experimental investigation of the effect of change in atmospheric conditions and noise upon performance. *American Society of Heat and Ventilation Engineers*, *52*, 162-170.

Weiner, J. S., & Hutchinson, J. (1945). Hot humid environment, its effect on the performance of a motor coordination test. *British Journal of Industrial Medicine*, *2(3)*, 154-160. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1035686/pdf/brjindmed00267-0030.pdf

Welch, J., Vaughan, R., Andreassend, D., & Folovary, L. (1970). Weather conditions and road accidents. *Proceedings of the Australian Road Research Board Conference*, *5(3)*, 190-208.

Wu, C. Y. H., Zaitchik, B. F., & Gohlke J. M. (2018). Heat waves and fatal traffic crashes in the continental United States. *Accident Analysis and Prevention*, *119*, 195-201. https://doi.org/10.1016/j.aap.2018.07.025

Zohar, E. (1980). *Man and Climate*. Keter Publishing House, Jerusalem

Appendix A – Full Glossary

Anomaly / Anomalies. "Anomalies denote the departure of an element from its long-period average value for the location concerned" (Australian Government Bureau of Meteorology, 2021b).

Atmospheric Pressure / Barometric Pressure. The pressure within the atmosphere of the Earth. The standard atmosphere pressure (at sea-level) is 1013.25 hPa (Atmospheric Pressure, n.d.).

Climate. "Climate represents the atmospheric conditions for a long period of time, and generally refers to the normal or mean course of the weather" (Australian Government Bureau of Meteorology, 2021a). It is a description, in terms of the mean and variability, of relevant atmospheric variables such as temperature, precipitation and wind.

Deciles. Deciles gives an element a ranking, compared with the average for the area. Deciles range from one (the bottom 10%) to 10 (the top 10%), having increments of one for each 10% (Australian Government Bureau of Meteorology, 2021b).

Dew-point Temperature. "This is a measure of the moisture content of the air and is the temperature to which air must be cooled in order for dew to form." A dew-point temperature that is the same as the dry-bulb temperature means that the air is saturated, and that relative humidity is 100%. (Australian Government Bureau of Meteorology, 2021b).

Indian Ocean Dipole (IOD). IOD refers to "sustained changes in the difference between sea surface temperatures of the tropical western and eastern Indian Ocean." It is "one of the key drivers of Australia's climate", particularly influencing south-eastern Australia's climate (Australian Government Bureau of Meteorology, 2021c).

Relative Humidity. Relative Humidity "is a traditional indicator of the air's moisture content" (Australian Government Bureau of Meteorology, 2021b).

Southern Annular Mode (SAM). "SAM is a climate driver that can influence rainfall and temperature in Australia", particularly south-eastern and eastern Australia. "SAM refers to the (non-seasonal) north-south movement of the strong westerly winds that blow almost continuously in the mid-to-high-latitudes of the southern hemisphere." These winds are "associated with storms and cold fronts that move from west to east, bringing rainfall to southern Australia" (Australian Government Bureau of Meteorology, 2021d).

Southern Oscillation Index (SOI). "SOI is a measure of the difference in surface air pressure between Tahiti and Darwin. Sustained negative values of the SOI often indicate El Nino episodes" whereas positive values of SOI are known as La Nina episodes (Australian Government Bureau of Meteorology, 2021b).

Solar Radiation / Global Solar Exposure. This is "the total amount of solar energy falling on a horizontal surface. The daily global solar exposure is the total solar energy for a day" (Australian Government Bureau of Meteorology, 2021e).

Trough. It is "an elongated area where atmospheric pressure is low relative to its immediate surroundings. The trough line often extends outward from a low-pressure centre, or an enclosed area of relatively low pressure" (Australian Government Bureau of Meteorology, 2021b). "Near-surface troughs sometimes mark a weather front associated with clouds, showers, and a wind direction shift" (Trough Meteorology, n.d.).

Water Vapour Pressure. "This is the atmospheric pressure which is exerted by water vapour (water in its gaseous state). It is one way of measuring the humidity of the air. At a given temperature, an increase of water vapour in the air corresponds to an increase in the humidity of the air. Water vapour absorbs the sun's radiation. As a result, the sunlight received at the earth's surface will be more intense in a drier atmosphere" (Australian Government Bureau of Meteorology, 2021a).

Weather. "The weather of any place refers to the atmospheric variables for a brief period of time" (Australian Government Bureau of Meteorology, 2021a). It is described in terms of variable conditions such as temperature, humidity, wind velocity, precipitation, and barometric pressure.

Glossary References

Atmospheric Pressure. (n.d.), *Wikipedia*. Retrieved from https://en.wikipedia.org/wiki/Atmospheric_pressure

Australian Government Bureau of Meteorology. (2021a). *Climate Glossary*. Retrieved from http://www.bom.gov.au/climate/glossary/

Australian Government Bureau of Meteorology. (2021b). *Glossary*. Retrieved from http://www.bom.gov.au/lam/glossary/apagegl.shtml

Australian Government Bureau of Meteorology. (2021c). *Indian Ocean influences on Australian climate*. Retrieved from http://www.bom.gov.au/climate/iod/

Australian Government Bureau of Meteorology. (2021d). *Southern Annular Mode and the Australian climate*. Retrieved from http://www.bom.gov.au/climate/sam/

Australian Government Bureau of Meteorology. (2021e). *Solar Radiation Definitions*. Retrieved from http://www.bom.gov.au/climate/austmaps/solar-radiation-glossary.shtml

Trough Meteorology. (n.d.). *Wikipedia*. Retrieved from https://en.wikipedia.org/wiki/Trough_(meteorology)