Road transport sensitivities to weather and climate change in Australia

Bevan. Rowland[1], Jeremy. Davey[1], James. Freeman[1], Darren. Wishart[1]
[1] Centre for Accident Research and Road Safety – Queensland, Queensland University of Technology, Brisbane, Qld, Australia

Whether the weather be fine
Or whether the weather be not,
Whether the weather be cold
Or whether the weather be hot,
We'll weather the weather
Whatever the weather,
Whether we like it or not.
(English Nursery Rhyme)

1 Introduction

This paper is not a vehicle to discuss the validity, magnitude nor duration of projected climate change. Rather, the purpose of this paper is to identify several potential interactions between anthropogenic climate change, related weather events and transportation, based on published literature. It should be noted that this review focuses primarily on road transport only and where the word 'vehicle' is used it encompasses all road vehicular types, for example, cars, trucks, motor cycles, busses, etc.

Weather and climate, as represented by several indicators (e.g. rain, storms, winds, etc), contribute to several hazards or sensitivities within the transportation sector (e.g. landslides, reduced visibility, road traction, etc). The statistics of these variables may be affected by anthropogenic climate change. Weather and climate factors directly affect the planning, design, construction and maintenance of transportation infrastructure in several ways – they also indirectly affect the demand for transportation services (Mills & Andrey, 2002). Costs and benefits, measured in terms of safety, mobility, economic efficiency, and externalities, accrue as the operation of transportation facilities and services meets these demands and adjusts to weather and climate hazards.

For thousands of years, people have associated weather and human behaviours. For example, in Shakespeare's *King Lear,* the title character's madness is accompanied by violent storms. Current understanding of driver behaviour and climate change is limited, due primarily to the difficulty of obtaining relevant and valid data. Much of what is known about driver behaviour or adjustment to weather is inferred from either crash analysis or psychological theory, with only a handful of empirical studies that model changes in driver behaviour.

1.1 The need to address climate change and weather-related risks

Compared to the many political, economic and technological factors affecting the evolution of transportation systems and road safety, the role of climate change may be relatively minor.

Nevertheless its implications are still likely to be significant, given the anticipated changes in thermal and moisture regimes (Andrey et al., 2001).

Over the 20th century, average air temperatures at the earth's surface increased by approximately 0.6°C (IPCC, 2001). The 1990's were the warmest decade since the beginning of instrumental records, and various studies have indicated that temperatures in the northern hemisphere at the end of the 20th century were warmer than any point in the past 1-2 thousand years (Mann & Jones, 2003). These temperature increases have also influenced the global hydrological cycle. Precipitation in the northern hemisphere increased 5-10% over the 20th century, with most of this increase manifesting as extreme rainfall events (IPCC, 2001). These global changes have been mirrored in Australia, where average temperatures have increased by about 0.7°C since 1910 (Pittock, 2003). Precipitation in Western Australia and along Australia's east coast has declined steadily since the mid-20th century, while precipitation has increased in the northwest (Pittock, 2003). Australia has also experienced an increase in extreme rainfall events, particularly during winter. Over most of Australia, annual average temperatures are projected to increase by 0.4-2.0°C from 1990 levels by the year 2030 and by 1-6°C by 2070 (Pittock, 2003).

Weather is one environmental risk factor that is known to affect road crash rates in Australia and elsewhere. Weather that reduces road friction, impairs visibility and/or makes vehicle handling more difficult creates a serious road safety threat (Andrey et al., 2001). However, literature regarding the influence of adverse weather on the driving task is scarce. Adverse or extreme weather includes storms, high winds, heat waves and cyclonic conditions, etc. In addition, scant research currently exists in relation to drivers' attitudes regarding the link between weather conditions and crash risk, or their willingness to change their driving behaviour in such conditions.

Rain/wet roads are a significant contributor to road fatalities and crashes in Australia (as a percentage of the road toll). For example, in New South Wales, fatalities due to the contributing factor of rain/wet roads were 15% in 2004 and 20% in 2005 (RTA, 2004,2005); in Queensland fatalities included 4% in 2001 and 6% in 2003 (Queensland Transport, 2002,2005); and Victorian fatalities from 2001 – 2005 recorded 16% of fatalities were contributed to rain/wet roads (VicRoads, 2006). Statistics above should be viewed as potential contributing factors only and not causes. This is primarily due to the process by which crash data is recorded, where wet weather may be one of a number of contributing factors recorded for the same incident. Therefore, with increases in severe weather including storm intensity and occurrence due to aspects of climate change will this increase weather-related crash risk in Australia?

Globally, the World Meteorological Organisation has claimed that extreme events are on the rise as a result of anthropogenic perturbation of the climate system (World Meteorological Organisation, 2003), and climate models indicate the potential for increases in extreme storms, etc (IPCC, 2001). The incidence of extreme weather (storm intensities) in Australia is expected to increase with global warming (Pittock et al., 1999). Changes in hail and lightning frequencies are uncertain, although there are some arguments for expected increases (Price & Rind, 1994; McMaster, 1999; Pittock et al., 1999). Global climate change is expected to result in greater weather variability overall (IPCC, 1996). Relatively minor changes in the average global climate could produce large changes in the frequency of extreme weather events, such as hurricanes (cyclones and typhoons), violent thunderstorms, windstorms and increases in average temperature. Evidently, these disasters have already had a substantial impact on human society.

Previous research has suggested that adverse or extreme weather conditions, including predicted severe storms and heavy precipitation does increase crash risk by 50 to 100 percent (Andrey, 2003). Therefore, increases in weather intensity and occurrence may pose an additional dilemma for drivers in Australia.

As a result, the present research aimed to review literature to investigate the relationship between weather events, climate change and road safety. More specifically, the study aimed to:

a) identify weather-related characteristics that may impact on road safety and driver behaviour;
b) discuss how climate change may impact weather systems, road safety and driver behaviour; and
c) identify areas for further research in relation to the impact of climate change on road safety and driver behaviour.

2 Method

The review is based primarily on peer-reviewed literature in the fields of transportation, engineering and planning; risk assessment and crash analysis; and applied climatology and hazards. Other related literature including government documents, industry/consultant reports, theses, conference proceedings and web pages are used to fill in gaps, where appropriate. The review focused on published research between 1940's to the present, which revealed a scarcity of Australian published research in regards to climate change/weather and transportation. Only research literature which specifically addressed the objectives of this paper was included. In addition, the majority of international research concentrated on the impacts of snow/ice on transportation. When the review of literature was completed, literature that had relevance to the Australian context was analysed and included within this paper. It is acknowledged that there is a considerable body of general literature which makes post hoc references to the impact of weather conditions. However, for reasons of parsimony, the review focuses on published research specifically devoted to weather issues.

Information for this review was undertaken through searching electronic databases and websites, bibliographies, reference lists and university libraries for archives of published and unpublished documents in any language. Information was sort by combining groups of search terms representing climate change, weather, wet weather, adverse/inclement weather, road safety, transportation, driver behaviour, etc.

3 Road safety implications due to weather conditions

This section provides a brief outline of the implications or effects of weather-related events/characteristics on road safety, road user behaviour and the road infrastructure network. Particular attention is devoted to events that may have an impact on Australian roads and drivers. In addition, Table 1 summarises the potential impacts as they relate to roads, traffic flow and driver/vehicle safety.

Previous research has established that adverse weather (see Table 1), such as, precipitation/rainfall (Andrey et al., 2003; Ivey et al., 1975; Pisano, et al., 2002), fog (Edwards, 1999a; Pisano et al., 2002), storms (Andrey et al, 2001; Pisano, et al., 2002, Pittock, 2003), cyclones/hurricanes (Edwards, 1999; Pisano et al., 2002), wind (Edwards, 1999; Pisano et al,. 2002), snow/ice (Andrey et al., 2003; Pisano et al., 2002) and temperature (Houghton et al., 2001; Mills & Andrey, 2002) affects road infrastructure and increases crash risk. The increase in crash risk suggests that drivers' adjustments to weather are insufficient to completely offset the adverse weather hazards associated with reduced road-tire friction, loss of vehicle control and poor visibility (Edwards, 1999a; Unrau & Andrey, 2006). Previous research found that drivers adjust their speed very little in rain (Hawkett, 1978) and are more involved in crashes (Codling, 1974; Satterthwaite, 1976). In addition, several studies suggested that crashes increase during rainfall by 100% or more (Brodsky & Hakkert, 1988; Bertness, 1980; NTSB, 1980; Sherretz & Farhar, 1978), while other studies have found more moderate results (but still statistically significant) increases (Andreescu & Frost, 1998; Fridstrom et al., 1995; Andrey & Yagar, 1993; Andrey & Olley, 1990). However, weather-related increases in risk are not consistent for all collision severities; rather the increase is higher for property damage crashes than for more serious crashes, suggesting that driver compensation does occur (Andrey et al., 2001, 2003; Eisenberg, 2004).

Table 1: Weather Impacts on Roads, Traffic and the Driver/Vehicle

Weather Variables	**Road Impacts**	**Traffic Flow Impacts**	**Driver/Vehicle Impacts**
Precipitation/Rain	• Visibility distance • Road friction • Road obstruction	• Road capacity • Traffic speed • Speed variance • Time delay • Crash risk	• Vehicle performance (e.g. traction) • Driver capabilities • Driver behaviour
Thunderstorms/ Lightning	• Visibility distance • Road friction • Road obstruction • Infrastructure damage • Loss of power, e.g. traffic signals	• Road capacity • Traffic speed • Time delay • Crash risk	• Vehicle performance (e.g. traction) • Driver capabilities • Driver behaviour
Cyclonic Conditions/Floods	• Visibility distance • Road friction • Road obstruction • Infrastructure damage • Lane/road submersion • Road buckling	• Road closures • Travel delays • Crash Risk	• Vehicle performance (e.g. traction) • Driver capabilities • Driver behaviour
Wind Speed	• Visibility distance (due to blowing dust & debris) • Lane obstruction	• Traffic speed • Time delay • Crash risk	• Vehicle performance (e.g. movement) • Driver capabilities • Driver behaviour
Snow/Ice	• Visibility distance • Road friction • Road obstruction	• Traffic speed • Time delay • Crash risk	• Vehicle performance (e.g. traction) • Driver capabilities • Driver behaviour
Fog	• Visibility distance	• Traffic speed • Speed variance • Crash risk	• Driver behaviour
Temperature/ Humidity	• Road surface softening & rutting • Road surface buckling	• Traffic speed • Speed variance • Time delay • Crash Risk	• Vehicle performance (e.g. traction) • Vehicle damage

	• Bleeding of asphalt		• Driver capabilities • Driver behaviour

Although included within Table 1 as a previous reference to crash risk, it is noted that with climate change "snow and ice" will probably decrease in Australia due to an increase in temperature. Also, the frequency of rainfall is expected to decrease in most areas of Australia and the duration of drought is expected to increase with climate change (Keay & Simmonds, 2006).

3.1 Impact of rain after dry spells

Due increasingly to extended periods of no rainfall and drought (especially in Australia), the phenomenon of dry spells (or spell effect) has created considerable interest in regards to weather-related crash risk. An enhancement of the crash count immediately after a dry spell could be due to physical or psychological factors, e.g. the build-up of oil and grime on the road surface or the slow readjustment to wet conditions (Keay & Simmonds, 2006). However, it is possible that drivers have 'forgotten' how to drive appropriately in wet and slippery conditions.

Keay and Simmonds (2006) found that generally there is an increase in the impact of a dry spell when it first rains as the spell duration and rainfall amount increase. In describing the effect of dry spells in their Australian study, Keay and Simmonds (2006) divided their sampling by rain class. The rain classes were 0-5, 5-10 and >10 millimetres (mm). They found that for the 1-5 mm class and spells of 1-5 days there was a 5% increase in crash risk over that for wet days not in spells. For the >10 mm class and spells of >5 days there is a 30% increase compared with wet days not in spells.

Likewise, a study by Brodsky and Hakkert (1988) found that rain presented a greater risk when it follows a dry spell. In Israel the risk of a crash in wet weather appeared to be much higher during the occasional rains of the transitional months of March and November. Using a difference-in-means method and weekday injury crashes for 1979-1981 they found that the daylight risk ratio was 11.2 for the transitional months compared with 2.2 for the winter months, which had more persistent rain. During winter 55% of wet day crashes were attributed to rain, rising to 91% for March and November. The increased risk was attributed to the increased slipperiness of wet roads due to the accumulation of road grime during dry periods.

In addition, Eisenberg (2004) observed a spell effect in an analysis of US daily crash counts. He also cited the build up of oil on roads during a dry spell as a mechanism for causing increased slipperiness when the first rain breaks the spell. He found that after a spell of one day there was a 9.7% increase in the non-fatal injury crash rate on the next wet day for 17 states over 1990-1999. This rate rose to 17.9% after 6 dry days and 23.1% after >21 days.

Research has identified that crash risk in wet weather increases as the duration since the last rainfall increases (e.g. dry spell effect). The dry spell effect is especially relevant in Australia due to significantly extended time durations between rainfall events across most of the country. Further research is required to ascertain how much of this effect is due to driver behaviour (i.e. have drivers "forgotten' how to drive in wet weather) or is it primarily due to the increased oil/grime on the road surface.

4.0 Road safety implications due to potential climate change

Evidence suggests that climate models indicate the potential for increases in future extreme weather, etc (IPCC, 2001). The incidence of extreme weather in Australia is expected to increase with global warming (Pittock et al., 1999) and global climate change is expected to result in greater weather variability overall (IPCC, 1996). Relatively minor changes in the average global climate could produce large changes in the frequency of extreme weather events, such as hurricanes (cyclones and typhoons), violent thunderstorms, windstorms and increases in average temperature.

4.1 Extreme weather implications

Although average rainfall has and is expected to further decrease across most parts of Australia, previous research has estimated that extreme weather frequency and severity is expected to increase with climate change in Australia (Pittock, 2003; Pittock et al., 1999). However, current research relating to the effect of climate change on road transport in Australia is scarce. In addition, no research could be found relating to potential impacts to driver behaviour in relation to climate change. Most of what we do know about the effects of extreme weather and climate change on road safety is from overseas research and in particular the northern hemisphere. Due to differences in weather patterns between the northern and southern hemispheres determination of potential climate change impacts becomes problematic. However, we can derive from the research potential effects on road safety from various weather events and relate these characteristics to the Australian context (e.g. extreme storm frequency and severity, increase in temperature, etc). The paragraphs below identify weather events that are anticipated to increase in severity and frequency in Australia due to climate change.

Vehicles entering areas of heavy rain, which can occur from localised storms to major cyclones, can hydroplane or encounter slow or stopped traffic, thereby increasing crash risk (Pisano et al., 2002). Prolonged heavy rain can produce flooding in underpasses and inundate entire road sections. Heavy rain in mountainous terrain may cause a sudden rise in water in small streams and creeks (known as flash flooding) that can overflow onto roads (Andrey et al., 2001). The possibility of landslides, which can obstruct roadways, also increases during these torrents. Hail and accompanying high winds can blow trees and powerlines down which can also render road unpassable. Lightning may cause disruptions to power, communications and traffic control systems (e.g. traffic signals/lights, etc).

It has been suggested that tropical cyclones and hurricanes might become more frequent or intense in a warmer climate (White & Etkin, 1997). Emmanuel (1987) looked at this issue by modelling the tropical cyclone as a “Carnot” heat engine, and concluded, using thermodynamic arguments that empathise sea surface temperatures (SST), that warmer SST in a doubled CO_2 world would increase the maximum sustainable pressure drop in the storm, potentially increasing storm intensity by 40 -50%. He also suggested the possibility of ultra-powerful hurricanes if the SST rose by 6 ^{o}C or more. In addition, research conducted by Haarsma et al. (1993) estimated a 50% increase in the frequency of cyclones, with relatively more intense ones. However, there is conflicting evidence for the increase in frequency and severity of tropical cyclones due to climate change (Held, 1993; Idso et al., 1990; Lighthill et al., 1994). Therefore, due to conflicting evidence further research is required. What we do know regarding tropical cyclones and other natural disasters is that they provide an additional problem to road safety. As well as the impacts of heavy rain and high winds on the driving task, damage to the road network and infrastructure can be extensive. In the aftermath of cyclones, flooding and debris may submerge roads, render them unpassable and hinder repair/maintenance operations (Edwards, 1999; Pisano et al., 2002). Subsequent damage to roads, bridges and related infrastructure may prolong the operation of re-opening roads to traffic, thereby contributing to traffic volume problems on other roadways and anxiety of drivers.

Strong winds can play a major role in vehicle operation (Edwards, 1999; Pisano et al,. 2002). The buffeting of vehicles may decrease their stability and control, particularly in high-profile vehicles and vehicles towing caravans, etc. In addition, high winds blowing across exposed roadways, elevated expressways or bridges may prevent these vehicles from crossing (Pisano et al., 2002). Strong winds can blow dust (rural areas, etc) reducing visibility, and reduce fuel economy if blowing opposite the direction of travel. Finally, motorists have to avoid lane obstructions due to wind-blown debris (Pisano et al., 2002).

4.1.1 Driver behaviour in extreme weather conditions

The literature review did not find any research relating to driver behaviour and extreme weather conditions. However, limited research was found regarding driver behaviour and adverse weather conditions (e.g. wet weather driving).

Most empirical studies into the relationship between weather and road safety do not deal directly with driver behaviour. Rather, the focus is on risk levels, as indicated by crash rates. The main human errors leading to increased risk are drivers' poor ability to recognise slipperiness and to adapt their behaviour to adverse weather conditions (Heinijoki 1994). In terms of speed, average speeds on a slippery road surface are roughly 4 km/h lower than in good conditions (Saastamoinen 1993, Estlander 1995). The reduction is not sufficient to compensate for the effect of inclement weather (Edwards 1999), nor for the reduced friction (Roine 1993, Saastamoinen 1993, Várhelyi 1996, Malmivuo & Peltola 1997).

Insufficient adaptation of driver behaviour can be expected for a number of reasons. Safe driving behaviour is said to result from a successful interaction of three components: the driver, the vehicle and the road environment (e.g. Häkkinen 1978). Inclement weather alters the road environment, for which the other two components should compensate. However, driving is more demanding than in good road conditions and the driver is responsible for reacting adequately. This, however, is difficult for many reasons: First, drivers are not only safety oriented; they have several parallel goals while driving which may compete with, or even contradict (e.g. time pressure - getting somewhere on time), hence the safety goal may be secondary (Häkkinen 1978). It could be argued that safety is a secondary consideration for every driver at least once in a while. Second, information indicating slipperiness is seldom sufficient (e.g., visual cues indicating hazards). Third, inappropriate behaviour usually does not give immediate or sufficient feedback on the threat of low friction (e.g. speeding, distracted, etc), which the driver detects too late. Finally, there is probably substantial variation in drivers' abilities. It is the development of their cognitive models (Mikkonen and Keskinen 1980) which enables anticipation or proper reactions in risky situations.

Even for a safety-motivated and skilful driver, it may be a demanding task to adjust their behaviour to prevent an increase in accident risk when the road becomes slippery. The decision-making task to adjust to prevailing road conditions is complex and passes through several phases. Applying the general description of the human information processor by Wickens (1992) to driver tasks under poor road conditions, the first step is to create an opinion or hypothesis concerning the friction, based on the drivers' information acquisition and perception of the situation. This is followed by assessment of the impacts of the lowered friction level on the driver's ability to control the movements of the vehicle, then a decision on necessary actions such as decreasing speed or increasing headway. To perceive slipperiness is difficult as such, as there may be minimal visual cues indicating the hazard. Furthermore, it has been shown (Edwards et al., 1965; Edwards 1968) that a human operator when revising a hypothesis (or adjusting odds) is generally conservative, not extracting as much information as necessary from each diagnostic observation of data. The concept of anchoring (Einhorn & Hogart,1982) refers to difficulty by human operators in changing an initial hypothesis in line with subsequent sources of evidence; rather the opinion (cognitive anchor) shifts only slightly. These phenomena and known characteristics of human behaviour make it understandable why behavioural adaptation to slippery conditions is difficult for drivers. It is especially difficult when friction decreases unexpectedly during the trip, which can happen because of changes in temperature or sudden encounters with water pooling on roads or patches of accumulated oil/dirt.

In the event of extreme weather conditions it has been reported that drivers are more likely to postpone or cancel road trips until the extreme conditions have passed. Several overseas studies found that traffic volumes decline during winter storms (Hanbali, 1994; Knapp, 2000; McBride et al., 1977; Nixon, 1998). Likewise, Keay and Simmonds (2005) studied the impacts of rain on traffic volume in Melbourne, Australia, and found statistically significant reductions of traffic in rainy days compared to clear days, and traffic volumes declined with increasing rainfall amounts. Reduced traffic volumes during inclement weather may be due to a number of reasons, including drivers diverting trips to other modes or other paths, drivers cancelling trips, and drivers taking trips at other times, before or after storms, etc (Maze et al., 2006).

Trip adjustments might be taken as a means to reduce risk during inclement weather. The potential response to cancel or defer a trip, which reduces exposure to risk and affects traffic density, both of which have implications for safety outcomes (Golob & Recker, 2003; Unrau & Andrey, 2006). In studies using aggregate data, vehicle counts recorded in fixed periods (from 20-second to one-day intervals) have been used to monitor changes over time (Hanbali & Kuemmel, 1993; Hassan & Barker, 1999; Ibrahim & Hall, 1994; Knapp, 2001). Results indicate that travel levels are typically reduced during inclement weather conditions, with only minor changes during light rain but with reductions of 20 percent or more during heavy precipitation. However, it is reasonable to infer that much of the observed change in volume is due to lower travel speeds rather than to trip rescheduling (Udrau & Andrey, 2006); indeed driver surveys confirm that trip cancellation is rare except in extreme weather, such as freezing rain (Andrey & Knapper, 2003).

In the event of more extreme weather conditions more drivers may decide to defer or cancel road trips, thereby, reducing related risks. Therefore, the event of extreme weather events may not have a substantial impact on road safety statistics. However, the authors suggest that risks may arise in the event of travel immediately before and after the extreme weather events. For example, drivers may tend to outrun a storm and hail, etc to protect their vehicle from damage. This infers speeding, aggressive and other aberrant driver behaviour. Also, road travel after extreme events brings into play road friction, road obstructions due to fallen trees and branches, etc and the dry spell effect (discussed previously).

4.2 High temperature effects

Evidence suggests that climate change in the form of temperature increases in the northern hemisphere may increase the frequency and severity of hot days while the number of extremely cold days will be reduced (Barrow & Hulme, 1992; Houghton et al., 2001; Katz & Brown, 1992). This is expected to be mirrored within Australia with increases in temperatures and prolonged hot seasonal variations are expected. For example, Hennessy and Pittock (1995) using a global warming scenario of 0.5 ºC found 25% more days over 35 ºC in summer and spring within Victoria, and 50-100% more in a 1.5 ºC warming scenario. Furthermore, there is concern that if precipitation becomes more convective with an increase in more extreme weather events and reduction in average rainfall, then the number of dry days will increase and drought will become more severe (IPCC, 1996). This could be exacerbated by increases in potential evaporation due to higher temperatures.

Road surface impacts may become more common as extreme heat conditions and droughts become more severe and frequent:

- road surface softening and traffic-related rutting;
- buckling of road surface (especially older, jointed concrete); and
- flushing or bleeding of asphalt from older or poorly constructed road surfaces (Mills & Andrey, 2002).

The above will generally lead to increased maintenance costs (Mills & Andrey, 2002) and where the road surface is affected may potentially contribute to road safety by negatively affecting the driver's ability to maintain control of the vehicle.

4.2.1 Driver behaviour and high temperature effects

High temperatures were found to be linked to irritability (e.g. driver aggression) (Anderson, 1989; Boyanowski et al., 1981) and to an increase in fatigue (Zohar, 1980). In addition, previous research stated that in hot conditions psychomotor and mental performance decreases (Viteles & Smith, 1946) and reaction time increases (Weiner & Hutchinson, 1945). In addition, loss of concentration (or alertness) caused by heat is most likely to increase the probability of crashes as it reduces reaction time (Stern & Zehavi, 1990). However, evidence linking high temperatures to road crashes is sparse. One Australian study found that crash rates increased on days with dry-bulb temperatures above 26 ºC (Welch et al., (1970). Cantilli (1974) showed that a temperature of only 25 ºC can cause fatigue among bus drivers, while McDonald (1984) found similar results when studying the effects of fatigue on truck drivers. Furthermore, an increase in temperature and/or humidity have been associated with indicators of fatigue, for example, increased sleepiness/tiredness and reduced alertness (Commission of Occupational Health & Safety, 2004). Due to the likely climate change effect on Australian average temperatures further research in relation to high temperatures and driver behaviour is required.

5 Conclusions

This paper has provided a sample of possible interactions or impacts between aspects of climate change including specific weather characteristics and road safety. The published research provides a general account of several significant vulnerabilities within the road safety sector to the effects of extreme weather – all are based on the assumption that contemporary sensitivities can be extrapolated in a linear fashion into the future.

Research has established that adverse weather increases crash risk, suggesting that drivers' adjustments to weather are insufficient to completely offset the hazards associated with reduced road friction and poor visibility. Research is scarce in relation to weather and driving behaviour, especially in relation to climate change effects. However, this paper identified that there is insufficient adaptation of driver behaviour, particularly during wet weather conditions. Also, the phenomenon of dry spells (or spell effect) is of considerable interest, especially in Australia (due to extended periods without rain as a result of climate change), as research indicates a significant increase in crash risk as the duration of time between rainfall events increase.

In a changing climate and differing weather events it would be 'negligent' for us to do nothing. Future weather-related events may increase and/or change compared to those we observe today – changes have already been noticed. Therefore, changes in road safety policy, road infrastructure and driving behaviours may be required to adapt to the impact of weather-related climate change.

5.1 Future research

There are many gaps that exist in our understanding of climate change impacts and related weather events, available adaptation strategies, various costs, and relevant behaviour of drivers. This is especially relevant for the Australian context where weather related research is scarce. A number of areas for further research in Australia were identified through the development of this paper in regards to driving and climate change impacts, etc. These are included as follows (it should be noted that the list above is by no means exhaustive):

- Actual crash rates directly related to extreme weather events in Australia;
- Costs due to weather events in Australia, including damage, injury, business, societal, infrastructure, etc;
- Potential variations of risk due to the impacts (or characteristics) of climate change, for example, extreme weather events and high temperatures;
- Driver behaviour and attitude in relation to the impact of various extreme weather events and high temperatures. In addition, whether drivers' are willing to acknowledge and be prepared for the likely change in driving conditions due to an increase in climate change events;
- Costs and adaptation of road infrastructure development and maintenance to alleviate potential future climate change impacts; and
- Impact of dry spell effects (especially relevant during Australian droughts, etc) on road safety, especially driver behaviour.

References

Anderson, C. (1989) Temperature and Aggression: Ubiquitous effects of heat on occurrence of human violence. *Psychological Bulletin.* 106 pp. 74-96.

Andreescu, M and Frost, D B (1998) Weather and traffic accidents in Montreal, Canada. *Climate Res.* 9 pp 225-230.

Andrey, J (2003) *Weather and Transportation in Canada.* Andrey, J. & Knapper, C. (Eds). Department of Geography Publication Series No. 55. University of Waterloo, Canada.

Andrey, J and Knapper, C K (2003) Motorists' Perceptions of and Responses to Weather Hazards. In *Weather and Transportation in Canada*, Department of Geography. Publication Series No. 55, University of Waterloo.
http://www.fes.uwaterloo.ca/Research/GeogPubs/pdf/transportation_andrey01.pdf/
Accessed July 30, 2005.

Andrey, J, Mills, B, Leahy, M and Suggett, J (2003) Weather as a Chronic Hazard for Road Transportation in Canadian Cities. *Natural Hazards*, 28 pp 319-343.

Andrey, J, Mills, B and Vandermolen, J (2001) *Weather Information and Road Safety.* Paper Series No. 15. Institute for Catastropic Loss Reduction, August 2001.

Andrey, J and Olley, R (1990) Relationships between weather and road safety, past and future directions. *Climatology Bulletin.* 24 (3) pp 123-137.

Andrey, J and Yagar, S (1993) A temporal analysis of rain-related crash risk. *Accident Analysis and Prevention.* 25 (40) pp 465-472.

Barrow, E and Hulme, M (1996) Changing probabilities of daily temperature extremes in the UK related to future global warming and changes in climate variability. *Climate.* 6 pp. 21-31.

Bertness, J (1980) Rain-related impact on selected transportation activities and utility services in the Chicago area. *Journal of Applied Meteorology.* 19 pp 545-556.

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

Brodsky, H and Hakkert, A S (1988) Risk of a road accident in rainy weather. *Accident Analysis and Prevention*. 20 (2) pp 161-176.

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

Codling, P J (1974) *Weather and road accidents*. In: J. Taylor (ed.). Climatic Resources and Economic Activity. Newton Abbot.

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

Edwards, J B (1999) Speed Adjustment of Motorway Commuter Traffic to Inclement Weather. *Transportation Research Part F*, 2 pp 1-14.

Edwards, J B (1999a) The temporal distribution of road accidents in adverse weather. *Journal of Applied Meteorology.* 6 pp 59-68.
Edwards, W (1968) Conservatism in human information processing. In: B. Kleinmuntz (ed.). Formal representation of human judgment. New York: Wiley. pp. 17-52.

Edwards, W, Lindman, H and Philips, L D (1965) Emerging technologies for making decisions. In: T.M. Newcomb (ed.). New directions of psychology II. New York: Holt, Rinehart & Winston.

Einhorn, H J and Hogart, R M (1982) Theory of diagnostic interference I: Imagination and the psychophysics of evidence. Chicago: University of Chicago, School of Business. (Technical Report No. 2).

Eisenberg, D (2004) The Mixed Effects of Precipitation on Traffic Crashes. *Accident Analysis and Prevention*, 36 pp 637-647.

Emmanuel, K A (1987) The dependence of hurricane intensity on climate. *Nature.* 326 pp. 483-484.

Estlander, K (1995) Sään ja kelin vaikutukset eri ajoneuvoryhmien nopeuksiin (Effects of weather on driving speeds). Helsinki: Tielaitos. (Tielaitoksen selvityksiä 23/1995).

Fridstrom, L, Liver, J, Ingebrigtsen, S, Kulmala, R and Thomsen, L (1995) Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts. *Accident Analysis and Prevention.* 27 (1) pp 1-20.

Golob, T F and Recker, W W (2003) Relationships Among Urban Freeway Accidents, Traffic Flow, Weather, and Lighting Conditions. *Journal of Transportation Engineering*, July/August, pp. 342-353.

Haarsma, R, Mitchell, J and Senior C (1993) Tropical disturbances in a GCM. *Climate Dynamics.* 8 pp. 247-257.

Häkkinen, S (1978) Tapaturmateoriat ja niiden kehittäminen (Accident theories and their development). Espoo: Helsinki University of Technology, Laboratories of Industrial Economics and Industrial Psychology. (Report 36/1978).

Hawkett, D C L (1978) Speeds and headways of vehicles on rural roads. *Traffic Engineering and Control.* 19 p. 71.

Hanbali, R M (1994) Economic Impact of Winter Road Maintenance on Road Users. In *Transportation Research Record 1442,* Transportation Research Board, Washington D.C., pp.151-161.

Hanbali, R M and Kuemmel, D A (1993) Traffic Volume Reductions Due to Winter Storm Conditions. *Transportation Research Record: Journal of the Transportation Research Board, No. 1387* TRB, National Research Council, Washington, D.C., TRB, National Research Council, Washington, D.C. pp. 159-164.

Hassan, Y A and Barker, D J (1999) The Impact of Unseasonable or Extreme Weather on Traffic Activity within Lothian Region, Scotland. *Journal of Transport Geography*, 7 pp. 209-213.

Heinijoki, H (1994) Kelin kokemisen, rengaskunnon ja rengastyypin vaikutus nopeusk äyttäytymiseen (Influence of the type and conditions of tyres and drivers perceptions of road conditions on driving speed). Helsinki: Tielaitos. (Tielaitoksen selvityksiä 19/1994).

Held, I M (1993) Large-scale dynamics and global warming. *BAMS.* 74(2) PP. 228-241.

Hennessy, K and Pittock, A (1995) Greenhouse warming and threshold temperature events in Victoria, Australia. *International Journal Climatology.* 15 pp. 591-612.

Houghton, J T, Ding, Y, Griggs, D J, Noguer, M, van der Linden, P J, Da, X, Maskell, K and Johnson, C A (eds.) (2001) *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. [electronic version]. Retrieved 27 January 2007 from http://www.grida.no/climate/ ipcc_tar/wg1/index.htm.

Ibrahim, A T and Hall, F L (1994) Effect of Adverse Weather Conditions on Speed-Flow-Occupancy Relationhips. *Transportation Research Record: Journal of the Transportation Research Board, No. 1457* TRB, National Research Council, Washington, D.C., TRB, National Research Council, Washington, D.C., pp. 184-191.

Idso, S, Balling, R and Cerveny, R (1990) Carbon dioxide and hurricanes: Implications of northern hemisphere warming for Atlantic/Caribbean storms. *Climatology.* 42 pp. 259-263.

IPCC (1996) *Climate Change 1995: The Science of Climate Change.* Houghton, J, Meira Filho, L, Callander, B, Harris, N, Kattenberg, A and Maskell, K (eds). Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC (2001) *Climate Change 2001: Impacts, Adaptation and Vulnerability.* McCarthy, J, Canziani, O, Leary, N, Dokken, D and White, K (Eds). Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Ivey, D L, Lehtipuu, E K and Button, J (1975) Rainfall and visibility; the view from behind the wheel. *Journal of Safety Research.* 7 pp. 156-169.

Katz, R and Brown, B (1992) Extreme events in a changing climate: Variability is more important than averages. *Climatic Change.* 21 pp. 289-302.

Keay, K and Simmonds, I (2005) The Association of Rainfall and Other Weather Variables with Road Traffic Volume in Melbourne, Australia, *Accident Analysis and Prevention,* 37 pp. 109-124.

Keay, K and Simmonds, I (2006) Road accidents and rainfall in a large Australian city, *Accident Analysis and Prevention,* 38 pp. 445-454.

Knapp, K K (2001) Investigation of Volume, Safety, and Vehicle Speeds During Winter Storm Events. In *Proceedings of the Ninth Maintenance Management Conference*, TRB, National Research Council, Washington, D.C., pp. 57-64.

Lighthill, J, Holland, G, Gray, W, Landsea, C, Craig, G, Evans, J, Kurihara, Y and Guard, C (1994) Global climate change and tropical cyclones. *BAMS.* 75(11) pp. 2147-2157.

Malmivuo, M and Peltola, H (1997) Talviajan liikenneturvallisuus . tilastollinen tarkastelu (Traffic safety at wintertime . a statistical investigation). Helsinki: Tielaitos. (Tielaitoksen selvityksiä 6/1997).

Mann, M E and Jones, P D (2003) Global surface temperatures over the past two millennia, *Geophysical Research Letters*, *30* (15) p. 1820, doi:10.1029/2003GL017814.
Maze, T H, Agarwal, M and Burchett, G (2006) Whether Weather Matters to Traffic Demand, Traffic Safety, and Traffic Operations and Flow. CD-ROM. Proceeding of the TRB 2006 Annual Meeting, U.S.

Mc Bride, J C, Benlangie, M C, Kennedy, W J, McCornkie, F R, Steward, R M, Sy, C C and Thuet, J H (1977) *Economic Impacts of Highway Snow and Ice Control.* National Pool Fund Study Report FHWA-RD-77-95, Federal Highway Administration, U.S. Department of Transportation.

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

McMaster, H J (1999) The potential impact of global warming on hail losses to winter cereal crops in New South Wales. *Climatic Change,* 43 pp. 455-476.

Mikkonen, V and Keskinen, E (1980) Sisäisten mallien teoria liikennekäyttäytymisestä (A theory of mental models concerning driver behaviour). Helsinki: University of Helsinki, Department of General Psychology (Report No. B 1).

Mills, B and Andrey, J (2002) Climate Change and Transportation: Potential Interactions and Impacts. Proceedings from The Potential Impacts of Climate Change on Transportation Workshop, U.S. Department of Transportation: Centre for Climate Change and Environmental Forecasting. [electronic version]. Retrieved 27 January 2007 from http://climate.volpe.dot.gov/workshop1002/index.html

National Traffic Safety Board (NTSB) (1980) Fatal Highway Accidents on Wet Pavement – The Magnitude Location and Characteristics, HTSB-HSS-80-1. NTIS, Springfield, VA.

Nixon, W (1998) The Potential of Friction as a Tool for Winter Maintenance. Iowa Institute of Hydraulic Research Report No. 392, College of Engineering, The University of Iowa, Iowa City, Iowa, February, 1998.

Pisano, P, Goodwin, L, and Stern, A (2002) Surface Transportation Safety and Operations: The Impacts of Weather within the Context or Climate Change. Proceedings from The Potential Impacts of Climate Change on Transportation Workshop, U.S. Department of Transportation: Centre for Climate Change and Environmental Forecasting. [electronic version]. Retrieved 27 January 2007 from http://climate.volpe.dot.gov/workshop1002/ index.html

Pittock, A B, Allan, R J, Hennessy, K L, McInnes, K L, Suppiah, R, Walsh, K J and Whetton, P H (1999). Climate change, climatic hazards and policy responses in Australia. In Downing, T E, Oltshoom, A A and Tols, R S (Eds). *Climate, Change and Risk*. Routledge, London, United Kingdom.

Pittock, B, (ed.) (2003) *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australia Greenhouse Office, Commonwealth of Australia.

Price, C and Rind, D (1994). The impact of $2xCO_2$ climate on lightning-caused fires. *Journal of Climate,* 7, pp 1484-1494.

Queensland Transport (2002) *2001 Road traffic crashes in Queensland: A report on the road toll.* [electronic version]. Retrieved 27 January 2007 from http://www.roadsafety.qld. gov.au/qt/LTASinfo.nsf/ReferenceLookup/RTC_2001_new.pdf/$file/RTC_2001_new.pdf

Queensland Transport (2005) *2003 Road traffic crashes in Queensland: A report on the road toll.* [electronic version]. Retrieved 27 January 2007 from http://www.roadsafety.qld. gov.au/qt/LTASinfo.nsf/ReferenceLookup/RTC_2003_new.pdf/$file/RTC_2003_new.pdf

Roine, M (1993) Kuljettajakäyttäytyminen kaarre- ja jonoajossa (Driver behaviour in sharp curves and queues on main roads). Helsinki: Tielaitos. (Tielaitoksen selvityksiä 87/1993).

RTA (2004) *Road traffic crashes in New South Wales Statistical Statement: Year ended 31 December 2004.* [electronic version]. Retrieved 7 February 2007 from http://www.rta.nsw .gov.au/roadsafety/downloads/accidentStats2004.pdf

RTA (2005) *Road traffic crashes in New South Wales Statistical Statement: Year ended 31 December 2005.* [electronic version]. Retrieved 7 February 2007 from http://www.rta.nsw. gov.au/roadsafety/downloads/accidentStats2004.pdf

Saastamoinen, K (1993) Kelin vaikutus ajokäyttäytymiseen ja liikennevirran ominaisuuksiin. (Effect of road conditions on driving behaviour and properties of the traffic flow). Helsinki: Tielaitos. (Tielaitoksen selvityksiä 80/1993).

Satterthwaite, S P (1976) An assessment of seasonal and weather effects on the frequency of road accidents in California. *Accident Analysis and Prevention.* 8 pp. 87-96.

Sherretz, L A and Farhar, B C (1978) An analysis of the relationship between rainfall and the occurrence of traffic accidents. *Journal of Applied Meteorology.* 17 pp. 711-715.

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

Unrau, D and Andrey, J (2006) Driver Response to Rainfall on an Urban Expressway. CD-ROM. Proceeding of the TRB 2006 Annual Meeting, U.S.

Várhelyi, A (1996) Dynamic speed adaptation based on information technology: a theoretical background. Lund: Lund Institute of Technology, Department of Technology and Society, Traffic Engineering. (Bulletin 142).

VicRoads (2006) *Public CrashStats database.* Victorian Government. [electronic version]. Retrieved 28 December 2006 from http://www.vicroads.vic. gov.au/Home/ RoadSafety/ StatisticsAndResearch/CrashStats.htm

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 pp. 162-170.

Weiner, J and Hutchinson, J (1945) Hot humid environment, its effect on the performance of a motor coordination test. *British Journal of Industrial Medicine.* 2 pp. 154-160.

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

White, R and Etkin, D (1997) Climate change, extreme events and the Canadian Insurance Industry. *Natural Hazards.* 16 pp. 135-163.

Wickens, C D (1992) Engineering psychology and human performance (second edition). New York: HarperCollins Publishers.

World Meteorological Organisation (2003) Press release, Geneva, Switzerland, 2 July.

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