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Projected implications of climate change for road safety in Greater Vancouver, Canada

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Abstract The elevated risk of collision while driving during precipitation has been well documented by the road safety community, with heavy rainfall events of particular concern. As the climate warms in the coming century, altered precipitation patterns are likely. The current study builds on the extensive literature on weather-related driving risks and draws on the climate change impact literature in order to explore the implications of climate change for road safety. It presents both an approach for conducting such analyses, as well as empirical estimates of the direction and magnitude of change in road safety for the highly urbanized Greater Vancouver metropolitan region on Canada's west coast. The signal that emerges from the analysis is that projections of greater rainfall frequency are expected to translate into higher collision counts by the mid 2050s. The greatest adverse safety impact is likely to be concentrated on moderate to heavy rainfall days ($\geq$ 10 mm), which are associated with more highly elevated risks today. This suggests that particular attention should be paid to future changes in the frequency and intensity of extreme rainfall events.

1 Introduction

Weather and climate are important considerations for transportation systems worldwide. Increasingly, an important strategic concern of most nations relates to how transportation

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infrastructure and operations may be impacted by climate change, and how to best plan for and adapt to changing environmental conditions.

Over the past two decades, a number of transportation-related climate impact assessments have been conducted, providing insight into the most vulnerable regions and transport activities. For example, there is considerable evidence that sea-level rise is likely to compromise coastal infrastructure of all types (Titus 2002), that warming in some northern regions is already degrading permafrost and reducing the length of the ice-road season (U.S. Arctic Research Commission Permafrost Task Force 2003), and that changes in inland waterways could have serious implications for shipping and barge movements (Millerd 2011). As well, without design changes, increased frequency of excessive summer heat may deform rail lines (Baker et al. 2010) and compromise bridge integrity (TRB 2008), while milder winters may increase freeze-thaw road deterioration in mid-latitude regions (Mills et al. 2009). There are other aspects of transportation systems, however, for which detailed climate-change impact assessments have not been conducted—including road safety. Indeed, Koetse and Rietveld (2009) suggest that the net safety impact of climate change is ambiguous in both direction and magnitude, and thus should be a focus of additional research.

Despite the emergent nature of research on the implications of climate change for road safety, several research threads suggest that the transport community is beginning to take this issue seriously. For example, many of the sensitivities of road safety to climate change have been identified, both in comprehensive ways (Rowland et al. 2007) and as they may affect particular regions/operations (Pisano et al. 2003). Second, localized empirical assessments of climate change impacts on road safety have been carried out for some regions, including the West Midlands, UK (Andersson and Chapman 2011) and for two large Canadian metropolitan areas (Hambly 2011). Third, there is a broad literature on potential adaptations to climate change in the transport sector (Eisenack et al. 2011), some of which is beginning to be integrated into the practitioner environment and has implications for safety (e.g., Macleod 2011; the Transportation Association of Canada's Climate Change Task Force). Finally, there is increased awareness that, even beyond case studies of impacts and adaptations, there is a need for a comprehensive interdisciplinary framework for climate change impact assessment wherein changing socioeconomic conditions and climate dynamics are considered in tandem (Jaroszweski et al. 2010). This is particularly true given that climate change mitigation strategies and policies are likely to effect changes in mobility patterns, which in turn will affect risk exposure and thus safety outcomes (Chapman 2007).

Road collisions are a global problem accounting for more than 1.2 million deaths annually. Worldwide, the economic costs of road collisions have been estimated to be over $US 500 billion per annum (Peden et al. 2004). While numerous risk factors contribute to road collisions and injuries, weather remains one of the most pervasive and difficult-to-mitigate. Indeed, it is widely acknowledged that a significant proportion of collisions occur either during inclement weather or on wet, snowy, or icy roads: in the United States and Canada, approximately one-quarter and one-third, respectively (CCMTA 1994; U.S. DOT 2011). Studies of weather-related (especially rainfall-related) collision risk have been carried out in many countries, including Australia (Keay and Simmonds 2006), Canada (Andrey et al. 2005), India (Mondal et al. 2008), Iran (Nokhandan et al. 2008), Israel (Brodsky and Hakkert 1988), the Netherlands (Brijs et al. 2008), Sweden (Norrman et al. 2000), the United Kingdom (Edwards 1999), and the United States (Eisenberg 2004). Based on these studies, it is clear that inclement weather that reduces tire-surface friction, impairs driver visibility, and/or makes vehicle handling more difficult creates hazardous driving conditions. Indeed, heavy precipitation events can have a crippling effect on mobility (e.g., Mills et al. 2003) and result in large increases in crash frequency. While hazardous conditions are associated with a range of driving adjustments intended to reduce risk and sometimes reduce exposure to risk by deferred or cancelled trips, evidence overwhelmingly suggests that adjustments are typically minor and almost always insufficient to completely offset the hazards presented by inclement weather (Unrau and Andrey 2006; Kilpeläinen and Summala 2007; Billot et al. 2009; Strong et al. 2010; Brooks et al. 2011).

Precipitation is the most pervasive weather hazard for drivers. Many studies have established that collision rates increase during related conditions, typically by 50 to 100 % (Andrey et al. 2003; Qiu and Nixon 2008), with larger increases for winter precipitation versus rainfall (on average, 84 % and 71 %, respectively), higher-intensity precipitation relative to smaller accumulations, and less severe collisions in comparison to those resulting in fatality and serious injury (Eisenberg 2004; Andrey 2010). Other conclusions are more tentative or case-specific, however, including the effect of weather on fatality rates and the long-term trend in weather-related driving risks (Qiu and Nixon 2008; Andrey 2010). Also, the interaction of weather with other risk factors, such as roadway and traffic characteristics has been explored in only piecemeal fashion, and the potential safety benefits of various safety interventions—ranging from advanced driver training to modified speed limits—are largely unknown.

The current study builds on the empirical literature on precipitation-related driving risks and also draws on the climate change impact literature in order to explore the implications of climate change for road safety. The paper presents both an approach for conducting such analyses, as well as empirical estimates of the direction and magnitude of change in road safety for one Canadian metropolitan region: the Greater Vancouver area on Canada's west coast.

2 Study area

Greater Vancouver is Canada's third largest urban area, with 2.1 million residents spread across 2,900 square kilometres in the lower mainland of British Columbia. Vancouver has mild winters, warm summers, and high annual precipitation because of its maritime, temperate climate. A year-round moderating effect is provided by the warm Alaska Current flowing northward in the nearby Pacific Ocean and by warm Pacific air carried onshore by the jet stream (Phillips 1990). Based on meteorological observation data and 1971–2000 climate normals from Vancouver International Airport, the average temperature in January is 3.3 °C (Fig. 1) and in July is 17.5 °C (Environment Canada 2011). Precipitation occurs during 16.7 % of all hours, and on 45.5 % of days on average. There is a strong seasonal pattern to precipitation, with summer being relatively dry and fall-winter being comparatively wet. In November-January, daily accumulations of 10 mm or more typically occur on six days per month (Fig. 2). While there has never been a winter without at least a trace amount of snowfall, most precipitation falls as rain: of the 1,200 mm of annual precipitation recorded at Vancouver Airport, only 50 mm is snow. Indeed, snowfall is observed during less than 1 % of all hours at the airport. However, differences in local climate exist across Greater Vancouver, where the northern and eastern extents of the region typically experience cooler temperatures and greater annual precipitation accumulations than the low-lying airport due to the orographic effects of higher elevation. Nonetheless, the airport represents the most complete source of weather information for the region as a whole.

In terms of road safety, collision data from Transport Canada's National Collision Database for the year 2006 suggest that Vancouver performs better than the national average in terms of per capita casualty collisions (i.e., those involving a fatality or injury) (358 per 100,000 people in Vancouver versus 459 nationally). Moreover, the Greater Vancouver region has a substantially lower rate than the rest of British Columbia (634 per 100,000 people), and also appears to

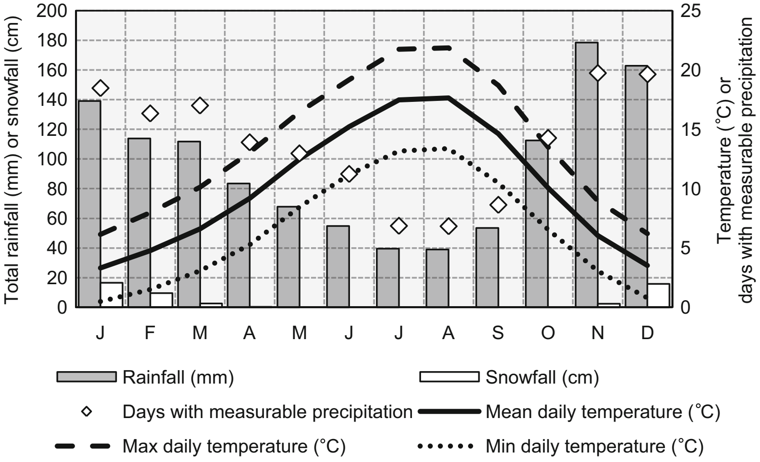

Fig. 1 Monthly climate statistics, Vancouver International Airport, 1971–2000

be safer than the country's largest urban region, the Greater Toronto Area (400 per 100,000 people). Casualty collisions in Vancouver are distributed fairly evenly throughout the year; however, a slight increase is evident throughout the fall and early winter months including November and December, the two wettest months of the year.

3 Data and methods

The analysis was based on two national databases for the years 2003–2007. Collision data from Transport Canada provide particulars on all collisions reported to police services in their respective jurisdictions, including involved persons and vehicles, roadway characteristics, and the date and time of the collision. The dates and times of collisions were used to identify relevant weather data from the nearest principal weather station maintained by Environment Canada. Depending on the variable, weather data are available at hourly, six-hourly, or daily

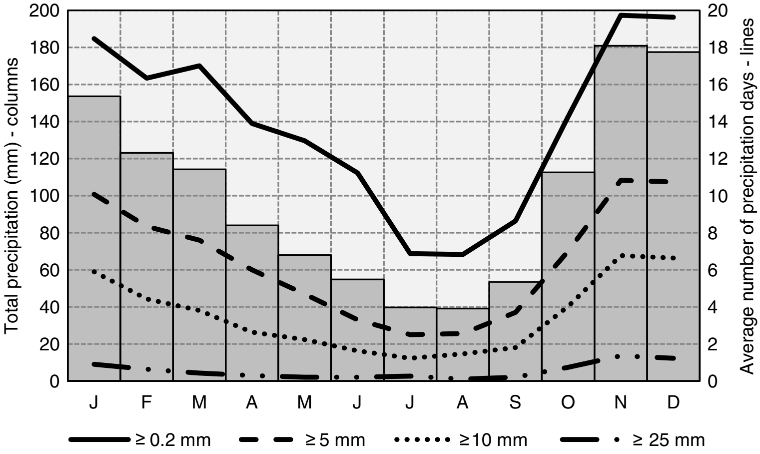

Fig. 2 Monthly precipitation distribution, Vancouver International Airport, 1971–2000

levels, and provide details for precipitation and obstructions to visibility, as well as sufficient information to infer hazardous conditions related to high wind or possible icing.

The overall approach used in the analysis was to first, estimate the extent to which crash rates are elevated during precipitation relative to dry, seasonal conditions; and then to combine these risk estimates with projected changes in the frequency of days with different types and amounts of precipitation.

3.1 Historic precipitation-related crash risk

The focus is on precipitation, although sometimes other associated hazards including wet roads, fog, and high winds accompany precipitation. Table 1 provides a summary of weather and road conditions for the 82,919 reported collisions from 2003–2007 inclusive. As shown here, approximately one-quarter of all reported collisions occur while precipitation is falling; at these times, roads are almost always wet and sometimes they are snowy/slushy/icy, depending on the road and atmospheric temperature.

The first step in the risk analysis was to define climatological days (24-hour periods beginning at 0600 GMT, or 10:00 pm local standard time) with measurable precipitation, and then to divide these into two groups, referred to as 'rain' days and 'winter precipitation' days. Rain days represents the larger of the two groups and includes those days with measurable accumulation (i.e., at least 0.2 mm) and a minimum temperature of 1 °C or higher. This precipitation accumulation represents the minimum amount necessary to wet the road, assuming that the rainfall occurs in a concentrated time period; the temperature threshold ensures that these days are characterized by falling rain and/or wet roads. Of 1,826 total days in the study period, 801 were identified as rain days.

Other days with at least 0.2 mm of precipitation (liquid equivalent) and near- or below-freezing temperatures were dealt with separately as these coincide with conditions where icing and/or snowy conditions were sometimes observed. These 86 days comprised less than one-tenth of all precipitation days, and are referred to as 'winter precipitation' in order to differentiate them from those days with above-freezing temperatures throughout the day. The winter precipitation set includes 42 days with liquid rainfall only, all of which had a maximum temperature of at least 2 °C but a minimum temperature below 1 °C. Some of these days could

Table 1 Weather and road surface condition as identified in collision reports, 2003–2007

	All collisions	Weather condition indicated on collision reporting form					
		Clear or overcast	Rain	Snow	Frozen precipitation[b]	Visibility limitation	Strong wind
Collision count	81,800[a]	61,011	18,436	1,327	78	854	94
% all collisions	100.0	74.6	22.5	1.6	0.1	1.0	0.1
Road surface conditions during specified weather conditions[c]							
% Dry	60.7	80.0	2.2	1.7	35.9	36.1	50.0
% Wet	35.7	17.3	96.9	17.6	46.2	49.6	42.6
% Snow, slush, or ice	3.3	2.3	0.6	80.3	12.8	12.8	7.4

[a] This count does not include 1,119 collisions for which weather condition was unknown or not indicated

[b] In this table, frozen precipitation refers to the presence of freezing rain, sleet, or hail as indicated in police collision reports, rather than the standard meteorological definition that typically also includes snow

[c] Columns do not sum exactly to 100 % because some collisions specify other or unknown road surface conditions

have been included in the larger set of rainfall days, as only 11.1 % of all crashes on these days indicated that they occurred on snowy/icy roads. However, the next phase of the analysis relies on the co-occurrence of measurable precipitation and a specified minimum temperature in order to project the number of winter precipitation days in the future. Therefore, it was decided to consider these days, which had minimum temperatures as low as −3 °C, as potentially being associated with ground frost or icing (Andersson and Chapman 2011). Of the remaining 44 days, 25 had both rainfall and snowfall recorded (with 47.2 % of crashes reporting snowy/icy roads), five had freezing rain or drizzle sometime throughout the day (55.0 % of crashes on snowy/icy roads), and 14 days recorded snowfall as the only form of precipitation (66.0 % of crashes on snowy/ice roads). Only four of the latter 14 days had temperatures below freezing the entire day; the coldest of these had temperatures that ranged from −11.6 to −5.9 °C. Road surface temperature data were not incorporated in the analysis in part because of the challenge of interpolating road surface temperature from a small number of measurement locations, especially in complex terrain as experienced in Greater Vancouver. Road surface temperatures are known to vary over space as a function of altitude, sky view, land use, road characteristics and synoptic conditions, although air temperature remains the most influential parameter controlling road surface temperature (Chapman et al. 2001; Weller and Thornes 2001).

The two sets of days are summarized in Fig. 3, based on their daily minimum and maximum temperatures; in this figure, days with both rainfall and snowfall (25) or freezing rain/drizzle (5) are shown together as 'mixed/frozen' precipitation. Summary data for these days are provided in Table 2. As expected, collision frequency increases as rainfall amount increases. 'Winter precipitation' days have precipitation amounts and collision counts that are similar to days with light/very light rainfall.

In the risk analysis, a matched-pair design was used to estimate differences in collision risk during rainfall relative to dry, seasonal conditions (including 95 % confidence intervals based on Johansson et al. 2009, as elaborated in Mills et al. 2011). In the matching exercise, a rainy Tuesday in July (event), for example, was matched with a Tuesday either 1 or 2 weeks prior or following, where no precipitation or other notable weather occurred (control). In the absence of city-wide travel exposure data, this approach reasonably controls for the influence of time-dependent variables such as traffic volume, driver and vehicle mix, and travel patterns; for this reason, statutory holidays and other 'special-event' days were excluded from both events and controls. This approach does not, however, account for the small reductions in travel that typically occur during inclement weather; and thus relative risk estimates are likely to be on the conservative side. In terms of the spatial unit of analysis, results were based on city-wide daily collision counts.

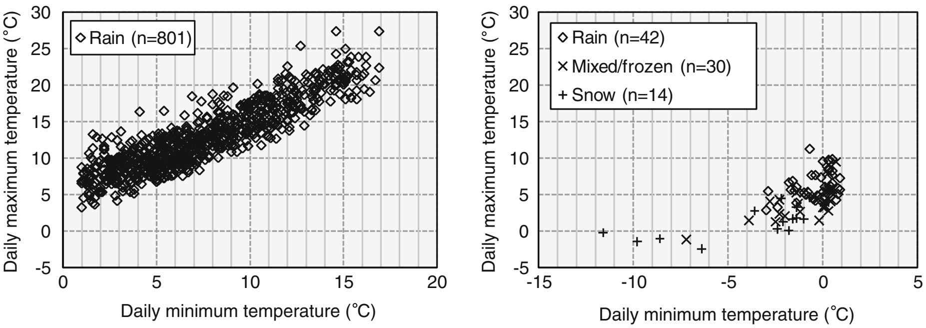

Fig. 3 Minimum versus maximum temperatures on days with measured rainfall (left) and 'winter precipitation' (right), Vancouver International Airport, 2003–2007

Table 2 Comparison of event days

	Count of days	Average daily hours of precipitation	Average daily precipitation amount (mm)	Average daily casualty collision count
Rainfall (≥ 0.2 mm)	801	8.6	7.0	22.9
Very light accumulation (0.2-4.9 mm)	454	5.4	1.8	20.8
Light accumulation (5.0-9.9 mm)	154	10.4	7.0	24.4
Moderate accumulation (10.0-19.9 mm)	135	13.2	13.7	26.1
Heavy accumulation (≥ 20.0 mm)	58	17.9	32.4	28.3
Winter precipitation (≥ 0.2 mm)	86	9.1	5.5	20.9
All days	1,826			21.2
Clear days	939			19.7

3.2 Climate change impact assessment

In the second part of the analysis, the focus is on climate change. In order to estimate the implications of climate change for Vancouver, two pieces of information are required: (i) a climatological baseline for the present-day climate and, (ii) a representation of expected future climate change, which is defined here as the difference between the future climate and the baseline. For the present study, the climatological 'normal' period of 1971–2000 was chosen as the baseline, as this is the period currently employed by Environment Canada for computing climate normals (Environment Canada 2011). This interval also coincides with the period for which output data are available for the present-day climate as simulated by models participating in the North American Regional Climate Change Assessment Program (NARCCAP).[1] The NARCCAP data were chosen to provide the representation of present and future climate change for this study primarily because of the relatively fine spatial resolution of the output data (typically 25–50 km), which makes them more appropriate for assessing climatic changes at specific point locations than using output from global climate models with grid resolutions of 100–200 km. We define the future time interval used to detect rainfall and temperature changes as the period 2041–2070, which coincides with the period of the NARCCAP future simulations. To examine the uncertainty and sensitivity in climate responses associated with using different climate models, output from two NARCCAP model combinations was used in this study: CRCM_cgcm3 and RCM3_cgcm3.[2] Output from an additional model combination, the RCM3_gfdl, was included in the initial stages of this work (Hambly 2011); however, it was removed from the current analysis due to an identified data issue related to temperature specifications, as advised by NARCCAP (2011).

Climate impact assessments that are linked to changes in precipitation are inherently less certain than those dealing with projected changes in temperature. Precipitation varies substantially over time and space. However, along the Pacific coast of North America, including the Greater Vancouver area, "[T]wo factors act to reduce the noisiness … First, convection systems, with their extreme rainfall rates, are infrequent. Second, generally speaking, as the mean annual

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[1] NARCCAP is an international program that provides dynamically downscaled regional climate change projections for use by the impacts and adaptation community, and also as a basis to explore uncertainties in regional projections of future climate based on the SRESA2 emissions scenario (Mearns et al. 2009; Nakićenović et al. 2000). The program attempts to sample many different combinations of global 'forcing' models and regional climate models.

[2] Each model combination is made up of a regional climate model (denoted by the uppercase portion of the model name) that is driven from the boundary by input from a global 'forcing' model (the lowercase portion).

rainfall increases the annual total becomes somewhat less dependent on isolated events" (McGuirk 1982, 43). Still, projections of future precipitation patterns introduce potential biases. Randall et al. (2007) reported that low-resolution global climate models (GCMs) are relatively good at simulating observed mean annual precipitation; however, light precipitation events tend to be overestimated and heavy ones underestimated because observed precipitation is measured at a point, whereas models predict an average amount of precipitation spread evenly across a grid box. Moreover, model simulations of extreme precipitation events typically involve too little precipitation compared to actual observations. However, it is recognized that model ability to simulate observed precipitation patterns improves with greater model resolution (Randall et al. 2007); by using regional climate model (RCM) outputs provided by NARCCAP, it is likely that the GCM bias is reduced somewhat.

There are further reasons why the NARCCAP data may provide a useful first look at the implications of climate change for road safety. First, in the current study, the RCM bias falls in the same direction of the driving GCM. Second, while the two RCMs tend to overestimate observed Vancouver precipitation, this difference is largely explained by the Vancouver area microclimate: the model grids are centred in the north-eastern part of the region, which receives substantially more precipitation than the nearest climate station at Vancouver International Airport (Phillips 1990). Third, the issue of greatest concern in the safety analysis is heavy precipitation events, which tend to be underestimated in models. In the current case, however, these are projected to increase substantially, despite the negative bias typically found in models, suggesting that our estimates of future change are conservative. As well, an effort was made to control for model bias by comparing model-simulated current and future climates to derive an estimate of change, rather than by comparing directly with observed climate normals; this assumes that the same bias is maintained in both current and future climate simulations; this approach is widely accepted as the preferred option (Fronzek and Carter 2007).

As mentioned above, the RCMs suffer from biases in temperature and precipitation, both in the mean and variability. By using a multi-model approach, our expectation is that these biases will largely cancel between the different models, leaving behind a better approximation of the actual forced climate signal (Gillett et al. 2002). This technique assumes that (i) a sufficient number of models are used to achieve adequate sampling and, (ii) the model errors are independent. It is debatable whether two RCM-GCM combinations is sufficient; however, this number was limited by data availability and quality. Of greater concern is the possible correlation of model errors caused by using the same GCM to drive both RCMs. This is because the driving meteorological fields pass any errors present in the GCM to the RCM through the lateral boundaries of the domain (Sushama et al. 2006). However, the influence of the GCM on the RCM simulation decays from 100 % at each lateral boundary to zero at a distance of approximately 300 km from the boundary; this region is known as the 'sponge zone'. Therefore, we do not believe correlated errors pose a significant problem in this study because Vancouver lies sufficiently far outside the sponge zone. At this location the RCM is essentially operating independently of the driving GCM.

4 Results

4.1 Precipitation-related crash risk, 2003–2007

For the five-year study period, the number of days for which there was measureable precipitation was 887. Of these, 801 days recorded a minimum air temperature at or above 1 °C, situations where it is reasonable to assume that precipitation occurs in liquid form. The remaining 86 days with measurable precipitation recorded a minimum temperature below 1 °C, and these were labelled as 'winter precipitation' because of the potential for snowfall, freezing rain, or road icing.

Once holidays were omitted, and the matching exercise was completed, 457 matched event-control pairs were identified. Event-control pairs are distributed fairly evenly throughout the year (Table 3), suggesting that somewhat fewer matches occurred for the rainy fall-winter period than would be expected along with a higher than expected proportion of matches in the dry summer months; this reflects the difficulty in finding suitable control days in a month with more precipitation events. For example, the warm and particularly rainy January of 2006 featured measurable rainfall on 29 of its 31 days; not surprisingly, matched controls were found for just three of the month's precipitation days. This unevenness in the sampling does not appear to have introduced any systematic bias, however, as a simple ratio between the average number of crashes on event and control days, regardless of inclusion in matched pairs, produced a result nearly identical to the weighted risk estimates presented later in Table 6 (i.e., 48.7 / 40.5 = 1.20).

The 457 event-control pairs included slightly more than one-half of all Vancouver collisions over the study period, with approximately 28 and 23 % of crashes captured in events and controls, respectively (Table 4). As expected, overall, collision counts are higher on precipitation days than on their matched controls.

The first part of this section focuses on the results of the risk analysis for the study period, 2003–2007. A relative risk ratio equal to 1.0 would indicate that collision counts are the same on precipitation days as on matched dry days, a ratio that is less than 1.0 would indicate that collision rates are lower during precipitation than during dry conditions, and a ratio that is greater than 1.0 indicates that collision rates are higher during precipitation than in dry conditions. The frequency distribution of relative risk for the 457 matched events and controls is shown in Fig. 4. As illustrated, there is considerable variation in relative risk from one event-control pair to another. In fact, days with similar amounts of rainfall often have very different collision frequencies (as, for example, in Table 5). However, most pairs (70 %) produce relative risks that are greater than 1.0; and 28 (6 %) days are characterized by relative risks greater than 2.0. In the latter case, collision counts are more than twice as high on precipitation days than on the matched dry days.

As Table 6 summarizes, the overall relative risk of collision during rainfall relative to dry, seasonal conditions is well above 1.0. As well, there is a strong progression in risk as rainfall amount/intensity increases. Risk estimates for the 'winter precipitation' events are similar to those for light/very light rainfall. The effect of minimum daily temperature on relative risk was also examined using correlation analysis (Fig. 5); however, there was no apparent relationship between these variables for the Greater Vancouver area. In addition, for all precipitation types and intensities, a greater risk increase is seen for property damage crashes as compared to casualty collisions; this suggests that drivers do reduce their travel speeds during inclement conditions, which reduces crash severity but reductions are not sufficient to avert a highly elevated crash rate.

Table 3 Seasonal distribution of weather events and matched pairs, 2003-2007

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year: 100 % (n=)
% of precipitation days[a]	12.1	7.8	12.0	8.9	7.1	6.9	3.5	3.4	5.4	9.8	11.0	12.2	887
% of matched pairs	8.1	9.2	9.4	9.4	9.6	8.5	5.7	5.9	7.4	9.8	8.3	8.5	457

[a] Includes all annual days, not just those included in event-control pairs

Table 4 Summary of incident counts, 2003–2007, and matched pair inclusiveness

Incident type	Total for all days	Precipitation days		Matched events		Controls		E-C pairs
		Sum	% of total	Sum	% of total	Sum	% of total	% of total
Total collisions	80,908	43,161	53.3	22,574	27.9	18,397	22.7	50.6
Casualty collisions	38,676	20,172	52.2	10,641	27.5	8,923	23.1	50.6
PDO collisions	42,232	22,989	54.4	11,933	28.3	9,474	22.4	50.7
Casualties (all severities)	54,448	28,518	52.4	15,046	27.6	12,388	22.8	50.4

The point estimates given in Table 6 are comparable with previous findings for the City of Vancouver reported by Andrey et al. (2005) .[3]

4.2 Projected climate change impacts, 2050s

Now we present the findings from the climate change assessment. Table 7 and Fig. 6 summarize the model differences in simulating annual precipitation days for the 2041–2070 period relative to present. While the two experiments do not provide identical projections of future precipitation in the Greater Vancouver area, they do agree in their projections of more precipitation days and higher precipitation amounts. The Vancouver area is expected to experience substantially more rainfall days (19 to 25 %) by mid-century. Additional rain days are expected across all rainfall intensity categories, especially moderate to heavy rainfalls (increases of 24 to 48 %). Indeed, an altered distribution is likely wherein moderate and heavy rainfall days are expected to comprise a greater proportion of annual rainfall days (Fig. 7). Not surprising, given the projected temperature trends, days with winter (i.e., near- or below-freezing) precipitation are expected to decrease substantially, although the additional rain days will more than offset this reduction, for a net overall increase in annual precipitation days of 12 to 19 % (Table 8). These changes are consistent with GCM-based projections reported in the IPCC's Fourth Assessment Report (Christensen et al. 2007).

Estimates of future safety were obtained by calculating the anticipated annual change in the number of precipitation days and combining this with the precipitation-related collision risk calculated for the 2003–2007 period. Projected changes in the number of collisions brought about by the increased frequency of precipitation days are summarized in Table 9.

Overall, the annual increase in casualty collisions is expected to be between 1.4 and 2.3 %. However, the annual number of crashes attributable to precipitation is expected to increase by approximately 17 to 28 %. The greatest projected impact in terms of casualty collision counts is associated with the increased frequency of moderate to heavy rainfalls (≥ 10 mm), which are associated with more highly elevated risks. This suggests that particular attention should be paid to future changes in the frequency and intensity of extreme rainfall events, as reflected in recent work by Wang and Zhang (2008) and Mladjic et al. (2011).

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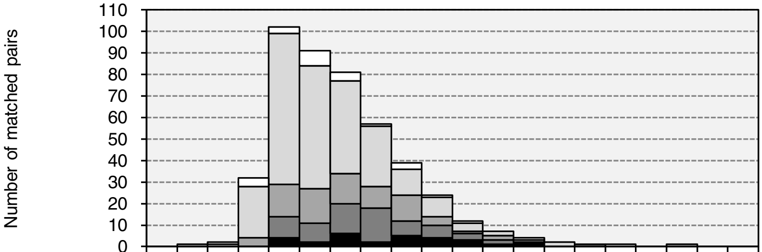
[3] Andrey et al. (2005) identified an overall six-hourly risk estimate of 1.9 for casualties during rainfall in Vancouver; this roughly translates to an expected daily estimate of 1.32, based on rain occurring an average of 8.6 h per rain day, or 35.8 % of daily hours, as it does in the current dataset (i.e., [(1.9 - 1) * 0.358)]+1=1.32). The conservative nature of daily relative risk estimates is reflected here, with the expected estimate slightly higher than the 1.20 reported in Table 6; indeed, as more non-rainfall hours are typically included in a 24-hour event than a 6-hour one, estimates tend to be diluted somewhat—i.e., they are less 'pure'. Moreover, the Andrey et al. study was more restrictive in that events were required to have inclement weather reported in at least 50 % of collisions, and zero percent for controls; such criteria, however, are not feasible in a daily analysis.



	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0
□ Winter	0	0	1	4	3	7	4	1	3	1	1	0	1	0	0	1	0	0	0	0
░ Very light rain	0	1	1	24	70	57	43	28	12	9	4	2	1	2	0	0	0	1	0	0
▒ Light rain	0	0	0	4	15	16	14	10	12	4	1	2	0	0	0	0	0	0	0	0
▓ Moderate rain	0	0	0	0	10	9	14	16	7	6	3	2	0	0	1	0	0	0	0	0
■ Heavy rain	0	0	0	0	4	2	6	2	5	4	3	1	2	0	0	0	0	0	0	0

Top row is x-axis: relative risk estimate (upper bin limits)
Other rows indicate matched pair counts in each bin

Fig. 4 Frequency distribution of relative risk estimates by precipitation category for 457 matched pairs

5 Conclusions and discussion

This study provides a methodology as well as empirical estimates of the implications of climate change for road safety. The approach taken combines risk estimation from safety research with climate change impact assessment using RCM-based scenarios of daily temperature and precipitation to the 2050s. The approach warrants caution in dealing with model biases, but provides a first estimate of potential changes in regional precipitation that are relevant to road safety analysis. The value of this type of detailed micro-level analysis is that it takes into account the ways in which local weather translates into collision risk, given the particular driving circumstances of a locale (e.g., terrain, traffic, roadway mix, driving culture, demographics). Previous studies have clearly established that there are regional differences both in the level of road safety overall and the relative risk of collision during inclement weather (Andrey et al. 2003).

For the urban region of Greater Vancouver, the signal from the analysis is clear: projections of greater rainfall frequency are expected to translate into higher collision counts. Because of the strong progression in risk with greater precipitation intensity, it is important to consider the frequency of days with different precipitation amounts. Indeed, the larger increase in heavier rainfalls in Vancouver accounts, in large part, for the increases in road collisions projected to occur by the middle of the century. This finding has importance beyond the study area, as it would be expected that areas that are projected to experience more frequent and/or heavier rainfalls in the future will observe elevated levels of collision risk during these times, and potentially more rainfall-related crashes overall unless this risk is offset by safety interventions or concurrent changes that ameliorate the risk. Expected changes in temperature are likely to affect

Table 5 Difference in risk for two similar precipitation events

Event date	Day of week	Event type	Hours of precipitation	Total precipitation	Event crashes	Control date	Control crashes	Risk estimate
Jan 17/05	Mon	Heavy rain	23	56.6 mm	36	Jan 10/05	33	1.09
Oct 17/03	Fri	Heavy rain	22	55.8 mm	107	Oct 24/03	53	2.02

Table 6 Comparison of risk estimates, 2003–2007 (95 % confidence intervals)

Daily precipitation type/intensity	Event-control pairs	Collision count	Total collisions	Casualty collisions	Property-damage collisions	Casualties (all severities)
All rainfall (≥ 0.2 mm)	430	38,306	1.22 (1.18–1.25)	1.19 (1.14–1.23)	1.25 (1.21–1.29)	1.20 (1.16–1.25)
Very light (0.2–4.9 mm)	255	21,414	1.13 (1.09–1.17)	1.08 (1.03–1.13)	1.17 (1.12–1.23)	1.08 (1.03–1.14)
Light (5.0–9.9 mm)	78	7,158	1.26 (1.18–1.34)	1.25 (1.15–1.35)	1.27 (1.18–1.36)	1.30 (1.19–1.42)
Moderate (10.0–19.9 mm)	68	6,636	1.40 (1.31–1.48)	1.39 (1.30–1.50)	1.39 (1.27-1.52)	1.44 (1.34–1.56)
Heavy (≥ 20.0 mm)	29	3,098	1.51 (1.36–1.68)	1.47 (1.31–1.64)	1.55 (1.34-1.79)	1.55 (1.36–1.77)
Winter precipitation	27	2,665	1.19 (1.01–1.39)	1.14 (0.95–1.36)	1.23 (1.04-1.46)	1.17 (0.97–1.41)

the frequency with which snowfall and other winter weather occurs—both in Vancouver and elsewhere. The projected safety effect of changes in precipitation type had only a marginal effect on the overall safety record in Vancouver, in large part because of the limited number of snow/ice events at present. We would expect the safety implications of changes in winter precipitation to be more pronounced in many other parts of Canada, northern USA, and northern Europe.

In conclusion, climate change has implications for the frequency with which hazardous driving conditions occur. Changes in temperature will affect the type of precipitation that falls, and also the probability of road icing. Changes in precipitation amount will translate into different collision signatures as a function of the degree to which visibility and/or friction are compromised. While not considered in this research, additional or compound hazards involving fog, blowing snow, and high winds are also important to consider.

The considerable research that has been conducted on weather-related collisions and driver adjustments over the past two decades underscores the extent to which current automobile systems are vulnerable to environmental hazards, notwithstanding the numerous advances in roadway and vehicle engineering and the considerable investments in snow and ice control. The

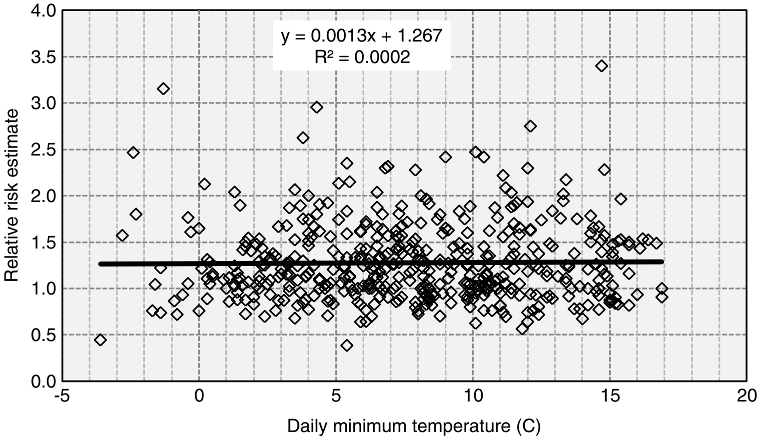


Fig. 5 Differences in relative risk by daily minimum temperature for 457 matched pairs

Table 7 Model differences in simulating annual precipitation days, 2050s

Experiment	General outcome (for both models)	Δ annual mean temperature	Δ annual total precipitation	Δ annual precipitation days
CRCM_cgcm3	Overall increase in total precipitation and days with precipitation	+ 2.4 °C	+ 219.0 mm (+ 8.8 %)	+ 32.2
RCM3_cgcm3	Increase in days with rainfall Decrease in days with winter precipitation Change in rainfall distribution, with more moderate and heavy rain days	+ 2.1 °C	+ 328.5 mm (+ 7.5 %)	+ 20.0

Table values refer to difference between model-simulated 21 C and 20 C, i.e., ΔC

implications of climate change for weather-related collisions will be region-specific, and will depend on local travel and risk patterns, as well as the changing frequency and mix of weather events. Planning for improved road safety, in the context of climate change, therefore requires a comprehensive approach to transportation planning, taking into consideration potential changes in both mobility and environmental conditions. We see the analysis presented here as only the first step in a more comprehensive, forward-looking approach to road safety research. The next steps should incorporate other trends that are likely to influence safety in the coming decades. In the Canadian context, it is clear that the relative risk of collision during rainfall has been declining over the past two decades (Andrey 2010). As well, a wide range of advanced vehicle technologies—many of which are beneficial during inclement weather—are being introduced (Transport Canada 2011). There are also changes in Canadian demographics (aging population), travel choices (intensified automobile dependence), and driving norms (less impaired driving but more in-vehicle distractions)—all of which affect safety, in both good weather and during times of impaired visibility or friction. And there is growing interest in the potential implications of increased fuel prices, transportation demand management programs, and climate change mitigation for travel patterns around the world. Future work should extend the analysis to consider scenarios of both climate change and societal change, leading to a set of plausible road safety outcomes in the coming century.

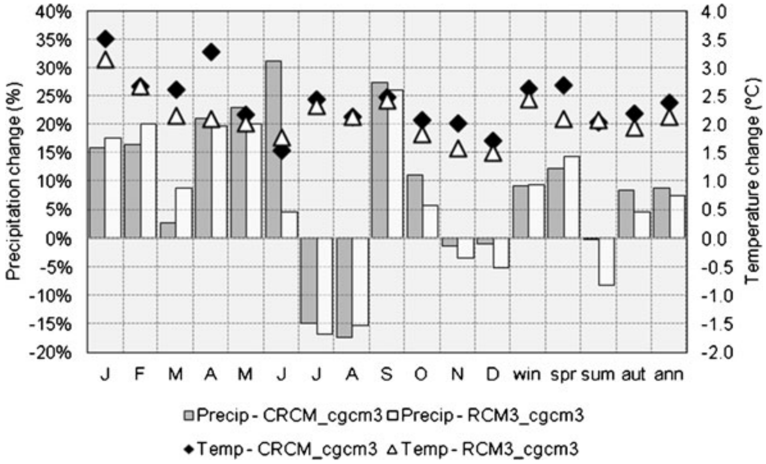


Fig. 6 Model-simulated climate anomalies, Vancouver, present to 2050s

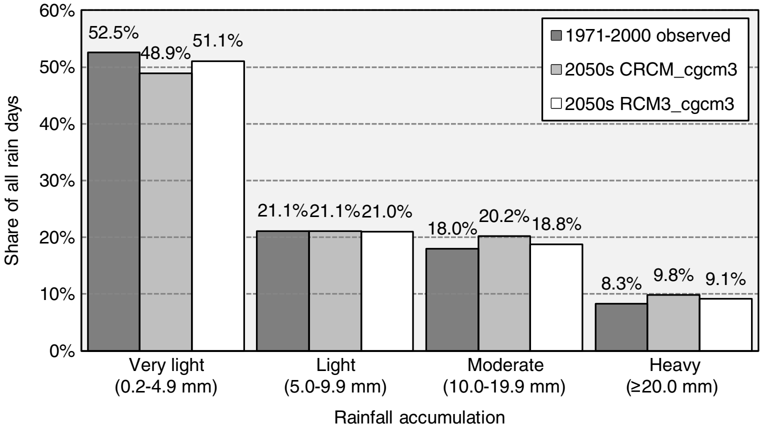


Fig. 7 Frequency distribution of rainfall days, Vancouver, present (1971–2000) versus modelled future (2050s)

Table 8 Average annual change in days with precipitation

	Rainfall (mm)					Winter precipitation	All precipitation
	All (≥ 0.2)	Very light (0.2–4.9)	Light (5.0–9.9)	Moderate (10.0–19.9)	Heavy (≥ 20.0)		
Observed normal (1971–2000)	146.4	76.9	30.9	26.4	12.2	19.4	165.8
% change in days ([21 C – 20 C / 20 C], i.e., ΔC)							
CRCM_cgcm3	+24.7 %	+16.1 %	+24.7 %	+39.5 %	+47.7 %	−20.8 %	+19.4 %
RCM3_cgcm3	+18.7 %	+15.3 %	+18.0 %	+23.7 %	+30.4 %	−37.8 %	+12.1 %
Change in # days relative to observed normal (% change * observed number of days)							
CRCM_cgcm3	+36.2	+12.3	+7.6	+10.4	+5.8	−4.0	+32.2
RCM3_cgcm3	+27.3	+11.8	+5.6	+6.3	+3.7	−7.3	+20.0

Table 9 Average annual change in casualty collisions, 2050s

	Rainfall (mm)					Winter precipitation	All precipitation
	All (≥ 0.2)	Very light (0.2–4.9)	Light (5.0–9.9)	Moderate (10.0–19.9)	Heavy (≥ 20.0)		
CRCM_cgcm3	+185.9	+19.7	+36.8	+76.9	+52.5	−10.1	+175.8
RCM3_cgcm3	+125.2	+18.8	+26.9	+46.2	+33.4	−18.4	+106.8

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References

Andersson AK, Chapman L (2011) The impact of climate change on winter road maintenance and traffic accidents in West Midlands, UK. Accid Anal Prev 43:284–289

Andrey J (2010) Long-term trends in weather-related crash risks. Accid Anal Prev 18:247–258

Andrey J, Mills B, Leahy M, Suggett J (2003) Weather as a chronic hazard for road transportation in Canadian cities. Nat Hazards 28:319–343

Andrey J, Christie M, Michaels S, Unrau D, Mills B (2005) Toward a national assessment of the travel risks associated with inclement weather. ICLR research paper series. Institute for Catastrophic Loss Reduction, London, ON

Baker CJ, Chapman L, Quinn A, Dobney K (2010) Climate change and the railway industry: a review. J Mech Eng Sci 224:519–528

Billot R, El Faouzi N-E, De Vuyst F (2009) Multilevel assessment of the impact of rain on drivers' behavior: standardized methodology and empirical analysis. Transport Res Rec 2107:134–142

Brijs T, Karlis D, Wets G (2008) Studying the effects of weather conditions on daily crash counts using a discrete time-series model. Accid Anal Prev 40:1180–1190

Brodsky H, Hakkert AS (1988) Risk of a road accident in rainy weather. Accid Anal Prev 20:161–176

Brooks JO, Crisler MC, Klein N, Goodenough R, Beeco RW, Cuirl C, Tyler PJ, Hilpert A, Miller Y, Grygier J, Burroughs B, Martin A, Ray R, Palmer C, Beck C (2011) Speed choice and driving performance in simulated foggy conditions. Accid Anal Prev 43:698–705

CCMTA (1994) National Collision Database, updated 2010. NCDB Working Group, Canadian Council of Motor Transport Administrators, obtained October 27, 2010

Chapman L (2007) Transport and climate change: a review. J Transport Geogr 15:354–367

Chapman L, Thornes JE, Bradley AV (2001) Statistical modeling of road surface temperature from a geographical parameter database. Meteorol Appl 8:461–474

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor MMB, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 847–940

Edwards JB (1999) The temporal distribution of road accidents in adverse weather. Meteorol Appl 6:59–68

Eisenack K, Stecker R, Reckien D, Hoffmann E (2011) Adaptation to climate change in the transport sector: a review of actions and actors. Mitig Adapt Strat Glob Chang. doi:10.1007/s11027-011-9336-4

Eisenberg D (2004) The mixed effects of precipitation on traffic crashes. Accid Anal Prev 36:637–647

Environment Canada (2011) Canadian climate normals 1971–2000. National Climate Data and Information Archive. http://climate.weatheroffice.gc.ca/climate_normals/index_e.html

Fronzek S, Carter TR (2007) Assessing uncertainties in climate change impacts on resource potential for Europe based on projections from RCMs and GCMs. Clim Chang 81:357–371

Gillett NP, Zwiers FW, Weaver AJ, Hegerl GC, Allen MR, Stott PA (2002) Detecting anthropogenic influence with a multi-model ensemble. Geophys Res Lett 29(20):1970. doi:10.1029/2002GL015836

Hambly D (2011) Projected implications of climate change for rainfall-related crash risk. MES thesis. Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON

Jaroszweski D, Chapman L, Petts J (2010) Assessing the potential impact of climate change on transportation: the need for an interdisciplinary approach. J Transport Geogr 18:331–335

Johansson O, Wanvik PO, Elvik R (2009) A new method for assessing the risk of accident associated with darkness. Accid Anal Prev 41:809–815

Keay K, Simmonds I (2006) Road accidents and rainfall in a large Australian city. Accid Anal Prev 38:445–454

Kilpeläinen M, Summala H (2007) Effects of weather and weather forecasts on driver behaviour. Transport Res F 10:288–299

Koetse MJ, Rietveld P (2009) The impact of climate change and weather on transport: an overview of empirical findings. Transport Res D 14:205–221

Macleod D (2011) Beyond the storm: Toronto's climate change adaptation program. Toronto Environment Office. http://www.toronto.ca/teo/adaptation/pdf/beyond-the-storm-presentation.pdf

McGuirk JP (1982) A century of precipitation variability along the Pacific coast of North America and its impact. Clim Chang 4:41–56

Mearns LO, Gutowski W, Jones R, Leung R, McGinnis S, Nunes A, Qian Y (2009) A regional climate change assessment program for North America. Eos 90:311–312

Millerd F (2011) The potential impact of climate change on Great Lakes international shipping. Clim Chang 104:629–652

Mills B, Suggett J, Wenger L (2003) You and who's army: A review of the January 1999 Toronto snow emergency. In: Andrey J, Knapper C (eds) Weather and Transportation in Canada. Department of Geography Publication Series, No. 55. University of Waterloo, Waterloo, pp 161–195

Mills B, Tighe SL, Andrey J, Smith JT, Huen K (2009) Climate change implications for flexible pavement design and performance in southern Canada. J Transport Eng 135:773–782

Mills BN, Andrey J, Hambly D (2011) Analysis of precipitation-related motor vehicle collision and injury risk using insurance and police record information for Winnipeg, Canada. J Safety Res 42:383–390

Mladjic B, Sushama L, Khaliq MN, Laprise R, Caya D, Roy R (2011) Canadian RCM projected changes to extreme precipitation characteristics over Canada. J Climate 24:2565–2584

Mondal P, Dalela S, Balasubramanian N, Sharma GK, Singh R (2008) Critical analysis of road crashes and a case study of wet road condition and road crashes in an Indian metropolitan city. SAE International, Technical Paper 2008-28-0079

Nakićenović N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) Emissions scenarios. A special report of working group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

NARCCAP (2011) Rerun of the RegCM3 using GFDL driving data: Improvement in the treatment of the Great Lakes (but sea ice problem remains). North American Regional Climate Change Assessment Program. http://narccap.ucar.edu/about/caveats.html#rcm3-gfdl-rerun

Nokhandan MH, Bazrafshan J, Ghorbani K (2008) A quantitative analysis of risk based on climatic factors on the roads in Iran. Meteorol Appl 15:347–357

Norrman J, Eriksson M, Lindqvist S (2000) Relationships between road slipperiness, traffic accident risk and winter road maintenance activity. Clim Res 15:185–193

Peden M, Scurfield R, Sleet D, Mohan D, Hyder AA, Jarawan E, Mathers C (2004) World report on road traffic injury prevention. World Health Organization, Geneva

Phillips D (1990) The climates of Canada. Environment Canada, Ottawa

Pisano P, Goodwin L, Stern A (2003) Surface Transportation Safety and Operations: the impacts of weather within the context of climate change. Proceedings of The Potential Impacts of Climate Change on Transportation, US Department of Transportation Centre for Climate Change and Environmental Forecasting, US Environmental Protection Agency, US Department of Energy, and US Global Change Research Program, Washington, D.C.

Qiu L, Nixon WA (2008) Effects of adverse weather on traffic crashes: systematic review and meta-analysis. Transport Res Rec 2055:139–146

Randall DA, Wood RA, Bony S, Colman R, Fichefet T, Fyfe J, Kattsov V, Pitman A, Skukla J, Srinivasan J, Stouffer RJ, Sumi A, Taylor KE (2007) Climate models and their evaluation. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor MMB, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 589–662

Rowland BD, Davey JD, Freeman JE, Wishart DE (2007) Road transport sensitivities to weather and climate change in Australia. In: Proceedings of the 30th Australasian Transport Research Forum, Melbourne, Australia

Strong CK, Ye Z, Shi X (2010) Safety effects of winter weather: the state of knowledge and remaining challenges. Transport Rev 30:677–699

Sushama L, Laprise R, Caya D, Frigon A, Slivitzky M (2006) Canadian RCM projected climate-change signal and its sensitivity to model errors. Int J Climatol 26:2141–2159

Titus J (2002) Does sea level rise matter to transportation along the Atlantic Coast? In: U.S. DOT, 2002. The Potential Impacts of Climate Change on Transportation, Summary and Discussion Papers. U.S. Department of Transportation. Federal Research Partnership Workshop, Brookings Institution, Washington, DC, Oct. 1–2, pp 135–150

Transport Canada (2011) Advanced vehicle technologies, road and motor vehicle safety. www.tc.gc.ca/eng/roadsafety/

TRB (2008) Potential impacts of climate change on U.S. transportation. Special report 290. Transportation Research Board, Washington, DC

U.S. Arctic Research Commission Permafrost Task Force (2003) Climate change, permafrost, and impacts on civil infrastructure. Special report 01–03. U.S. Arctic Research Commission, Arlington, VA

U.S. Department of Transportation, Federal Highway Administration (2011) Road weather management program. How do weather events impact roads? http://ops.fhwa.dot.gov/weather/q1_roadimpact.htm

Unrau D, Andrey J (2006) Driver response to rainfall on urban expressways. Transport Res Rec 1980:24–30

Wang J, Zhang X (2008) Downscaling and projection of winter extreme daily precipitation over North America. J Climate 21:923–937

Weller J, Thornes JE (2001) An investigation of winter nocturnal air and road surface temperature variation in the West Midlands, UK under different synoptic conditions. Meteorol Appl 8:421–436