
Flash Back: A Review of Lightning-related Damage and Disruption in Canada

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**DRAFT TECHNICAL REPORT Do not cite or quote
September 2007**

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ACKNOWLEDGEMENTS

The authors wish to thank the following people for contributing data or reviewing elements of this report: (to be completed)

This research was supported by Environment Canada. Any errors, omissions, or misinterpretations of data are the sole responsibility of the authors.

EXECUTIVE SUMMARY

Cloud-to-ground (CG) lightning is a common natural atmospheric hazard in Canada. Its significance to health and property is recognized in weather watches and warnings for severe thunderstorms that are issued by Environment Canada and in general public safety and emergency preparedness information provided by government agencies and non-government organizations. The importance of lightning is also reflected in support for the development of the Canadian Lightning Detection Network (CLDN), which was launched in 1998 and forms part of the larger North American and global detection systems. Despite this recognition, no contemporary studies have been conducted to assess the extent of property damage and disruption caused by lightning in Canada—the baseline against which the benefits of lightning detection, monitoring, forecasting, and other sector-specific actions and investments can be measured.

In an effort to address this need, Environment Canada initiated a review of available literature concerning the damage, disruption and costs associated with lightning and an initial multi-sector assessment of impacts and costs for Canada. The study was a logical follow-up to an analysis of lightning-related injuries and fatalities completed in 2006. Lacking resources to produce original data explicitly for the project, the authors relied upon secondary data and impact relationships drawn from studies completed in the United States. The specific sources of information, references, and steps used to develop the estimates for each sector are defined such that others can repeat and improve upon the initial results that are summarized below:

- Lightning routinely damages property and disrupts economic and social activities in Canada. Affected sectors include health; property and casualty insurance; forestry; electricity generation, transmission, and distribution; agriculture; telecommunications; transportation; and tourism and recreation—the first four sectors are the most important in terms of contributing to overall impacts and costs.
- Secondary data and extrapolations from U.S. studies were used to develop cost estimates for the health, property, forestry, and electricity sectors. When aggregated, annual lightning-related damage and disruption costs in Canada range from \$600 million to \$1 billion. This estimate is conservative.
- Annual lightning-related injuries (9-10) and fatalities (92-164) are estimated to cost between \$3.6 million and \$79.2 million.
- Municipal fire agencies respond to over 800 fires ignited by lightning each year. These fires cause an average of \$16.4 million in property damage.
- Between 3,900 and 5,300 insurance claims are estimated to be filed for lightning-related property damage (excluding fires) each year. Annual insured losses, coupled with deductible payments, amount to between \$7.9 million and \$23.5 million.
- Lightning-ignited wildfire is estimated to cost fire fighting agencies between \$307 million and \$438 million in pre-suppression and fire suppression expenditures each year.
- Sustained and momentary power outages are estimated to cost Canadian customers between \$267 million and \$445 million each year. At about \$16,000, estimated utility revenue losses are small by comparison.

The following recommendations are suggested based on the results of this initial investigation:

- Results from this study should replace current estimates of lightning-related damage that are used by Environment Canada and other federal departmental in various communications with the public and stakeholders.
- Damage estimates should be shared and discussed with representatives of the electricity, forestry, and insurance sectors.
- In terms of continued research, additional or more refined studies using Canadian empirical data are warranted for the insurance and electricity sectors. Detailed insurance claim or outage data would permit analysis at the storm level and potentially discern finer-scaled risk patterns. Further effort is also required to evaluate risk or damage prevention measures, particularly those that relate to expanded or enriched use of the CLDN data by both public and private sector clients. Both the degree of adoption and efficacy or cost-effectiveness should be investigated.

1.0 INTRODUCTION

Approximately 14,000 warnings of severe weather are issued each year by Environment Canada (MSC, 2003). During the spring, summer and early autumn seasons, the bulk of these warnings are issued to alert the public of the development and imminent arrival of severe thunderstorms and the potential for damaging winds, heavy rainfall, large hail, and intense cloud-to-ground (CG) lightning. Surprisingly, very little information exists that documents the number of casualties and amount of damage attributable to lightning in Canada—seemingly important statistics that could be used to help evaluate the effectiveness of monitoring and warning information and associated short- and longer-term responses (i.e., immediate emergency response through to education programs).

In response to this need, Environment Canada and university partners have undertaken an assessment of the impacts of lightning in Canada. The first phase of activity established an updated estimate and profile of lightning-related casualties (Mills *et al.*, 2006) while the current report summarizes progress made towards understanding the impact of lightning in terms of property damage, service interruptions and associated economic implications. In doing so, the extent to which our systems and activities are currently adapted to lightning-related risks will also become apparent, the basis for identifying and assessing future improvements/solutions.

The report first provides a review of Canadian and international studies that have examined the impact of lightning in a variety of sectors. The review sets the context and methodological stage for analyzing direct and indirect impacts across several sensitive economic sectors in the case study. A combination of media, expert opinion, and industry data sources are described and used to develop empirical estimates for Canada. The report concludes with a general discussion and summary of results and recommendations for future applications and research.

2.0 LITERATURE REVIEW

A broad characterization of the lightning hazard and implications for injuries was completed in the first phase of the project (Mills *et al.*, 2006). The current literature review was conducted to identify Canadian and international studies that had analyzed lightning-related damage and disruptions. Emphasis was placed on North American research obtained through traditional library journal search engines (e.g., *Web of Science*, *Scholar's Portal*) and general internet searches focused on combinations of the term lightning with damage, impact, cost, prevention, and a range of sensitive economic sectors (e.g., electricity generation, transmission, and distribution). The review was intended to provide a list of sectors and activities that regularly experience impacts; general understanding of damage mechanisms; quantified estimates of economic and social costs, or other measures of physical impact; and an evaluation of data sources and analysis methods.

2.1 Human Casualties (health sector)

Human casualties were discussed extensively in Mills *et al.* (2006) who estimated that 9-10 deaths and 92-164 injuries are attributable to lightning each year in Canada. The literature review from that publication also provides an inventory and interpretation of estimates for other countries (Mills *et al.*, 2006:8). No references were found that examined the costs of lightning-related mortality and morbidity, somewhat surprising given the inclusion of this direct cost element in other hazard studies (e.g., air quality; DSS Management Consultants Inc., 2000). Studies assessing the value of a statistical life based on human capital, contingent valuation (willingness-to-pay or –accept), and revealed preference approaches (e.g., Albernini, 2005; Health Canada, 2002; Hirth *et al.*, 2000; Viscusi, 2004), along with evaluations of injury costs (e.g., Health Canada, 2002; Harlan *et al.*, 1990) are considered in section 3.2 of the empirical analysis.

2.2. General Property Damage: Insured and Uninsured Losses

Property damage is a frequently examined aspect of lightning impact. It has also been an important concern of the insurance industry for over a century—an observation supported by the titles of early insurance companies which contained explicit references to lightning (e.g., *Virginia Assessment and Cooperative Fire, Lightning and Storms Insurance companies*; Valgren, 1925). Lightning strikes to power facilities, vehicles, livestock, forests, dwellings, and other public or private buildings and structures may cause immediate damage to assets. Physical damage to concrete structures and masonry has been documented, but is relatively uncommon (Blumenstein, 2006; Erlin, 2007). More often property damage results from either lightning-ignited fires or lightning-caused power surges through electrical, communication or other utility lines that affect equipment and the electronic contents of homes and businesses.

Several researchers, mostly within the natural hazards and applied climatology fields, have sought to understand the impact of a large spectrum of weather and climate-related events that cause insured and uninsured property damage (e.g., Changnon *et al.* 2001; Changnon, 2003; Kunkel *et al.*, 1999; Dore, 2003; Cutter and Emrich, 2005; Mileti, 1999). Lightning is occasionally treated as a distinct hazard in such assessments but more commonly is included in a broader category like thunderstorms (e.g., Changnon, 2001). Much of this research is based on national or international disaster or catastrophe event databases where entries must exceed a relatively high (often greater than \$5 million) damage, insured loss, or casualty count for inclusion (e.g., EM-DAT¹, Canadian Disaster Database², SHELDUS³). Lightning strike events rarely achieve these thresholds and thus are often poorly represented in the aggregate damage estimates (Mills, 2005).

Table 1 identifies general lightning-related property damage analyses and references that were uncovered through the literature review. The list is composed of estimates derived from analyses or interpretations of actual damage data from multiple sectors as opposed to more theoretical or conceptual risk models (e.g., Mazzetti and Flisowski, 2000). Although there is some degree of overlap, research focused on individual sectors (e.g., damage to power generation facilities) is reported in subsequent sections. References were excluded if supporting documentation for statements was not provided or could not be verified (e.g., Briët, 2004). The bulk of the work included in Table 1 was conducted in the United States, most often relying on the U.S. National Oceanic and Atmospheric Administration (NOAA) *Storm Data* database which uses a combination of media references and reports from law enforcement agencies, local government officials and others in documenting weather-related fatalities, injuries and property damage (NOAA, 2007). Household and commercial property and casualty insurance claim data were also used in a few studies, either alone or in combination with NOAA Storm Data. Proprietary constraints often restrict the use of insurance data such that only samples or partial coverage (i.e., records from one company) are usually available.

Kithil (n.d., 1997) provides the most comprehensive collection of damage estimates and his annual average U.S. loss figure of up to \$5 billion appears to be referenced most frequently in broader hazard assessments. However, for the purposes of the current investigation and the empirical analysis, the most rigorous studies have been completed by Holle *et al.* (1996), Curran *et al.* (1997, 2000) and Stallins (2002). The following general points have emerged from their work and are consistent with the results of other studies referenced in Table 1:

- Lightning is one of the most common sources of weather-related property damage, whether measured in absolute terms or normalized for population or cloud-to-ground (CG) lightning flash density.
- NOAA Storm Data consistently and significantly underreport the number of damaging events and the value of damage when compared with insurance claim data. Presumably this underestimation applies to all media report-based damage data sets.

¹ EM-DAT <http://www.em-dat.net/>

² Canadian Disaster Database <http://www.ps-sp.gc.ca/res/em/cdd/index-en.asp>

³ Spatial Hazards Events and Losses Database <http://www.cas.sc.edu/geog/hrl/SHELDUS.html>

Table 1. Summary of published estimates of lightning-related insured and uninsured property damage

Author	Timeframe	Location	Scope	Estimated Lightning Impact ¹	Data Sources
Aguado <i>et al.</i> (2000)	1950-1999	Navarra, Spain	Property damage (all sectors)	<ul style="list-style-type: none"> Estimated costs of 270M pesetas (>US\$1.5M) over study period 	Media reports and stakeholder survey
Curran <i>et al.</i> (1997, 2000)	1959-1994	United States (state-level)	Property damage (all sectors)	<ul style="list-style-type: none"> 19,814 damage reports over period Over 50% costing between \$5,000-\$50,000 Average annual damage of \$32M (1992-1994) 	US NOAA Storm Data
Ferrett and Ojala (1992)	1959-1987	Michigan	Property damage (all sectors)*	<ul style="list-style-type: none"> 645 lightning strike events caused property damage over the 29-year study period with 173 of these events producing \$50,000 or more in damage 	US NOAA Storm Data
Holle <i>et al.</i> (1996)	1987-1993	Colorado, Utah, Wyoming	Property damage (insured personal and commercial)	<ul style="list-style-type: none"> One claim per 52-57 CG flashes 4.7, 1.4, and 3.9 claims per 10,000 population for Colorado, Utah and Wyoming, respectively \$7M average annual 3-state loss (including \$150/claim deductible) Average annual U.S. loss of \$332M 	Colorado Chapter of Chartered Property and Casualty Underwriters and a large member insurer
Holle <i>et al.</i> (2005)	1890-94, 1990-94	United States	Property damage (all sectors)	<ul style="list-style-type: none"> Tremendous shift in types of damages from 1890s to 1990s, with much reduced farm and animal impacts (from ~52% to ~9% of reports) and much higher impacts to dwellings and utilities (from ~20% to ~49% of reports) 	US NOAA Storm Data Kretzer, H.F. 1895. <i>Lightning Record: A Book of Reference and Information</i> . Vol I, 106 pp.
Hornstein (1961,1962)	1939-1958	Canada	Property fire loss Forestry (fire loss)	<ul style="list-style-type: none"> CA\$1.5M average annual property fire loss (1,771 fires) CA\$3.5M average annual cost related to forest loss and fire suppression 	Dominion Fire Commissioner Provincial Forest Fire statistics
Insurance Information Institute (2007)	2004-2006	United States	Property damage (homeowner insured losses)	<ul style="list-style-type: none"> 266,500 average annual claims \$812.4M average annual losses \$3,048 average loss per claim 	Participating insurers
Kithil (n.d., 1997) with figures also cited by Best's Review (1998), McGraw (2003), Kunkel <i>et al.</i> (1999)	1980s-2006	United States	Property damage and disruption (all sectors)	\$2-5B in annual losses (interpretation of sector statistics from 1980s to 2006: fire-related, insurance, storage/processing, aviation, electrical infrastructure, electrical components)	References to published estimates Personal and/or written communications with industry representatives
Lopez <i>et al.</i> (1995)	1950-1991	Colorado	Property damage (all sectors)	<ul style="list-style-type: none"> 331 damage reports over period Average of 7.9 damage reports per year 	US NOAA Storm Data
Mileti (1999)	1975-1994	United States	Property damage (all sectors)	<ul style="list-style-type: none"> Average annual loss between \$20-200M 	US NOAA Storm Data
Stallins (2002)	1996-2000	Georgia	Property damage (insured)	<ul style="list-style-type: none"> 19,582 claims and \$22.9M insured losses over 5-year period for one Georgia insurer (\$1,100 per claim) \$91.6M insured losses if results extrapolated statewide using relative market share 	Large Georgian insurer claims database US NOAA Storm Data

¹ costs reported in \$US unless noted otherwise

- While the frequency of damage appears to follow the same diurnal and seasonal pattern apparent for casualties, additional research is necessary to characterize and explain the relative roles of population density, household consumer trends (e.g., prevalence of consumer electronics), and CG flash density in influencing the observed geographic and longer-term temporal variation in property damage.

2.3 Forestry (Forest Fire Management)

Forest fire, also commonly known as wildfire, is a natural and important part of the ecology of a forest (Podur *et al.*, 2003). Nevertheless, forest fires may impact hydrology, water quality, air quality, and forest ecosystems. Where fires interface with people and settlements, they may cause injuries, damage property, force evacuations, close roads and railway lines, interrupt power and energy supplies, and necessitate substantial investments in fire suppression activities (Hardy, 2005). Lightning is a well-established and recognized ignition source for forest fires (e.g., Gisborne, 1926) and long, continuous current and positive polarity CG strikes are generally thought to account for most lightning-caused fires (Wotton and Martell, 2005; Latham and Williams, 2001). Studies have examined the relative significance of lightning as compared to anthropogenic ignition sources on the frequency and spatial extent of forest fires. Canadian figures for the 1959-1997 period indicate that more than 70 percent of large (>200ha) fires and 85 percent of the average annual 1.8 million ha burned are attributable to lightning (Stocks *et al.*, 2002). Lightning accounts for a smaller proportion of fires less than 200 ha in size, however these only make up a few percent of the total area burned each year (Weber and Stocks, 1998). Variations in the potency of lightning have recently been observed in Ontario (Podur *et al.*, 2003) and Western Canada (Wierzchowski *et al.*, 2002). In a study of the Central Cordilleran area, Wierzchowski *et al.* (2002) determined that one fire occurred for every 50 and 1400 lightning discharges in British Columbia and Alberta sections, respectively. Differences are attributable in part to elevation, vegetation, fuel and lightning characteristics (Podur *et al.*, 2003; Wierzchowski *et al.*, 2002; Wotton and Martell, 2005).

The general costs and economics of forest fires and fire prevention have also received treatment in the literature. While no studies were found that explicitly evaluated the aggregate costs of lightning-ignited fires, research has been undertaken on individual fires or exceptional fire seasons (e.g., Kelowna, B.C., Filmon, 2004; Chisholm, AB, CFRC, 2001), summary statistics of provincial/state and national suppression costs (e.g., NRCan, 2004; Johnston, 2006), and specific forest use impacts (e.g., parks, Starbuck *et al.* 2006). Fire management costs in Canada typically range from \$400-800 million each year (NRCan, 2004). The value of timber lost to fire is substantial and in extreme fire years can equal or exceed the value that is harvested commercially (NRCan, 2004). Where fires occur at the wildland-urban interface, significant costs can result from forced evacuations and property damage to homes, other buildings, and transportation or energy infrastructure. Other non-timber impacts, including ecological effects, are more difficult to analyze but are no less important than other types of impact. Some quantified impact work has been completed for tourism and recreation and health sectors. If parks and other

recreation areas are shut down over large areas because of fire, economic impacts associated with reduced visitation can cost tens of millions of dollars (Starbuck *et al.*, 2006). Rittmaster *et al.* (2006) estimated one-day health impacts of \$9-12 million for the 2001 Chisholm forest fire whose smoke plume affected the large urban area of Edmonton, Alberta. These costs were comparable to those incurred for fire suppression (\$10 million) and about half of the value of lost timber (\$20 million) as determined by CFRC (2001). Regardless of cost type, it is apparent from studies that provide very detailed accounts of losses and expenditures for specific fires that the form and magnitude of impact are strongly influenced by the individual circumstances of each event (i.e., nature of the fire, forest qualities, and socio-economic considerations) (Lynch, 2004).

2.4 Power Generation, Transmission and Distribution

Power utilities, in particular transmission and distribution facilities, bear a significant portion of the overall lightning-related damage burden. Although generation is largely unaffected by the outdoor environment (Billinton and Acharya, 2005), studies have noted the impacts of lightning to the safety-related instrumentation and control systems of nuclear power plants (e.g., Trehan, 2001; Bernstein *et al.*, 1996) and have provided detailed accounts of lightning damage to wind turbines (Cotton *et al.*, 2000; McNiff, 2002; Glushakow, 2007).

Most of the literature regarding the power sector, however, relates to the effect of lightning on the transmission and distribution infrastructure of electric utilities. Lightning was a major contributing cause of very significant blackouts, including the July 1977 blackout in New York City that affected 9 million people for up to 26 hours, and a June 1998 blackout that shut down electricity systems in the U.S. Upper Midwest, Ontario, Manitoba and Saskatchewan for upwards of 19 hours (U.S.-Canada Power System Outage Task Force, 2004). More commonly though lightning is a frequent local hazard that regularly trips small sections of transmission and distribution networks. Two general forms of impact are widely cited:

- physical damage to lines, towers, poles, transformers, insulators, fuses, and surge arrestors which generate repair and replacement costs, and
- outages and power quality events that result in lost revenue to utilities and various costs to electricity consumers.

Whether or not a particular segment of a transmission or distribution system is affected depends on many factors. For instance, the location and properties of the lightning strike (i.e., direct overvoltage or adjacent strike causing induced overvoltage, current strength); voltage rating and length of power line; construction design and maintenance of towers, poles, transformers and lines (e.g., height, insulation rating, material deterioration); ground resistance (i.e., flashover potential greater if resistance is high); and extent of investment in lightning protection (e.g., surge arresters, overhead shield wires) have all been identified as being important in determining the vulnerability of a network (Carpenter and Auer, 1995; Drabkin and Carpenter, 2004; Parrish, 1991; Rakov, 2003;

Shen *et al.*, 1999; Koval and Chowdhury, 2005; Allan and Billinton, 1993; Chisholm *et al.*, 2001; Nakada *et al.*, 1998; Short, 1992; Porrino *et al.*, 1997). In general, higher voltage components of the system (i.e., transmission element, substations) are constructed to higher standards and with greater levels of lightning protection than the lower voltage (i.e., distribution) portion.

Reliability statistics are used by electric utilities to track, explain and manage impacts, most often outages, on a particular system. General measures include the annualized number of outages per standard line-length, total customer hour interruptions, percentage or count of total unplanned outages, total duration of outages, total customers affected. Standard industry indices include the System Average Interruption Frequency Index (SAIFI) (average number of interruptions per customer per year) and Customer Average Interruption Frequency Index (CAIFI) (average number of interruptions per customer affected per year) (Allan and Billinton, 1993; Keener, 1997; McCracken and Rylska, 2005; McDaniel *et al.*, 2003; Mitsche, 1989; Tarchini and Giminez, 2003; Viscaro *et al.*, 2005). In general, adverse weather accounts for most of the unplanned sustained and transient line-related outages that are experienced in Canada (Koval, 1994). Table 2 summarizes a selection of studies that have identified lightning-specific influences on outages. As with the property damage studies referenced in Table 1, estimates in Table 2 were extracted from research that analyzed observed outage data as opposed to modeled or simulated values (e.g., Anderson and Short, 1993; Savic, 2004; Pyrgioti *et al.*, 2000; Torres, 1999; Teixeira and Pinto, 2004). Lightning consistently appears as a major cause of service interruptions.

Despite the documented significance of lightning, few articles were found that assessed or referenced estimates of the direct or indirect costs of lightning-related outages and utility equipment damage. Diels *et al.* (1997) note that lightning accounts for about half of all power failures experienced in regions of the U.S. that are subject to thunderstorms and costs the electric utility industry up to \$1 billion annually in damaged equipment and lost revenue. Considering annual estimates of \$50 million (Mitsche, 1989) and \$100 million (Keener, 1997) for repairing lightning-caused damage and service restoration from the Electric Power Research Institute (ERPI), it appears that much of the impact may reside in lost income (i.e., electricity sales) rather than property damage.

An even greater cost may be that borne by electricity consumers and society-at-large. While not lightning-specific, several researchers have recently examined the economic value of electricity reliability and the costs of power disturbances to consumers in a number of countries including Brazil (Massaud *et al.*, 1994), Canada (Allan and Billinton, 1993; Billinton and Wangdee, 2003, 2005), Denmark (Baarsma *et al.*, 2005), South Africa (Mushwana, 2005), United Kingdom (Allan and Karuiki, 1999), and the United States (Balducci *et al.*, 2002; Caves *et al.*, 1992; CEIDS, 2001; Chowdhury *et al.*, 2004; Eto *et al.*, 2001; LaCommare and Eto, 2004; Lawton *et al.*, 2003). Disturbances include momentary, temporary and sustained power outages (0-10 percent of voltage for fractions of a second to many hours) and power quality phenomenon (all other deviations from perfect power including voltage sags, surges, transients, and harmonics) (CEIDS, 2001; LaCommare and Eto, 2004). Such events affect residential, industrial, commercial,

and institutional consumers through lost production, labour, lost or damaged electronic data, materials loss or spoilage, equipment damage, backup generation, overhead, and restart costs which are offset to some extent by unused materials and fuel, scrap value of damaged materials, lower energy bills, and unpaid labour (Eto *et al.*, 2001; CEIDS, 2001; Balducci *et al.*, 2002). Broader or secondary social costs (e.g., looting and other crime, injuries/deaths related to alternative fuel use and CO poisoning) have also been acknowledged but never included in costing studies (Eto *et al.*, 2001; Balducci *et al.*, 2002).

Several methods have been used to determine costs, including market-based approaches that rely upon observed consumer behaviour (e.g., choice of interruptible and curtailable electricity rates, investment in back-up generation, insurance for utility service interruptions) and survey approaches (e.g., direct costing, contingent valuation) (Koomey *et al.*, 2002). The latter seem to dominate the literature and have produced a wide variety of estimates (or damage/cost functions) for residential, commercial, industrial, and institutional user classes. A sample set of results produced through a meta-analysis of published U.S. studies (Lawton *et al.*, 2003) is presented in Table 3.

Results are generally broken down by use sector and expressed as a cost per event per customer of a particular duration (i.e., second, minute, hour, 8-hour) and are often normalized by annual average, annual peak, or unserved electricity demand. Lawton *et al.* (2003), CEIDS (2001), and other researchers have evaluated the influence of several variables on power outage costs including:

- sector type (i.e., orders of magnitude greater costs for industry relative to residential; most costs borne by commercial and industrial sectors);
- sub-sector type and customer size (due to particular equipment and process requirements);
- outage duration (costs generally increase through 8 hours); and
- timing of outage (i.e., seasonal, day-of-week, diurnal, and hourly influences; for instance winter heating generates greater impacts in north; weekday costs higher than weekends for commercial and industrial sector but reverse for residential sector).

While few studies have explicitly assessed the costs of power quality impacts on consumers, CEIDS (2001) estimates that power quality events may cost the U.S. economy between \$15-24 billion each year. When combined with aggregate outage impacts across all business sectors, it is estimated that power disturbances cost the U.S. economy between \$119 billion and \$188 billion annually (CEIDS, 2001). LaCommare and Eto (2004) provide a smaller base estimate of US\$79 billion for outage costs but suggest that two-thirds of the impact are the result of momentary interruptions (less than 5 minutes duration)—important for the current investigation in that many of these short-term events are caused by lightning strikes. Assuming that the Canadian economy is similarly sensitive to that of the U.S., if even a small fraction of such large costs are associated with lightning, then the potential lightning-related impacts could be significant.

Table 2. Selection of published estimates of lightning-related damage (electricity generation, transmission and distribution sector)

Author	Timeframe	Location	Sector(s)	Estimated Lightning Impact	Data Sources
Adler <i>et al.</i> (1994)	1965-1985	Canada and United States	Electricity transmission	<ul style="list-style-type: none"> 0.596 line-related forced outages per mile-year (583,712 mile-years of circuit exposure) 	1985 Utility survey by IEEE
Chisholm (2001)	1989-1992	Southwestern Ontario	Electricity distribution	<ul style="list-style-type: none"> Average system experienced 15 sustained outages per 100km-year (FAIRS data) Average lightning-related line disturbances per 100km-year for Drayton DS (55) and Cedar Mills (29) based on ELDS 	Hydro-One (FAIRS) data ELDS Station Event Recorder data (2 stations in SW Ontario)
Gelineau (2000)	2000	Canada	Electricity transmission and distribution	<ul style="list-style-type: none"> 5.9% of customer interruptions were due to lightning 	Canadian Electricity Association
Hidayat <i>et al.</i> (2002)	1996-2000	Jakarta, Indonesia	Electricity distribution	<ul style="list-style-type: none"> 36.2 line outages per 100 km-year (1,779 km medium-voltage lines) 	Regional utilities
Karlsson and Norberg (2001)	Not stated	Sweden	Electricity transmission	<ul style="list-style-type: none"> 1.8 outages per 100 km-year (130kv line) 	Vattenfall AB (utility)
McCracken and Rylska (2005)	1999-2003	Canada	Electricity transmission and distribution	<ul style="list-style-type: none"> 3.1M average annual customer hour interruptions (5-year average) 5.2% of total average annual customer hour interruptions 	Canadian Electricity Association (based on 31 major utilities)
McDaniel <i>et al.</i> (2003)	1997-1999	United States	Electricity transmission and distribution	<ul style="list-style-type: none"> Lightning-related outages/flash density (flashes/km²) statistics: Detroit Edison (9,583/2.1) (13kv system over 20,000 km²) Carolina Power & Light (30,831/3.9) (23kv system over 35,000 km²) Florida Power (37,683/9.3) (12kv system over 10,155km²) Average annual lightning-caused transformer failure rate of 0.25% and transformer fuse operating rate of 0.43% based on 2,448 transformers at 1,789 locations and 154.4km of exposed circuit 	Reliability data from Detroit Edison, Carolina Power and Light, and Florida Power
Parrish (1991)	1986-1988	Florida	Electricity distribution	<ul style="list-style-type: none"> Lightning was the primary cause of 10, 5 and 23% of 72kV, 144kV, and 244 kV line-related sustained forced outages, respectively. Mean/median durations for 72kV, 144kV and 240kV line outages caused by lightning were 7.12/1.83, 104.21/1.26, 1.45/0.39 hours, respectively. 	Florida Power Corporation
Shen <i>et al.</i> (1999) and Koval and Chowdhury (2005)	1977-1996	Alberta	Electricity transmission	<ul style="list-style-type: none"> 15 line outages per 100 km-year (132kv line) 	Alberta Power Limited
Tarchini and Gimenez (2003)	1997-2001	Argentina	Electricity transmission	<ul style="list-style-type: none"> 57 of 135 recorded outages (42%) over the period and approximately 20-mile network were attributed to lightning 	Empresa Distrihuidora de Electricidad de Mendom
Tolbert <i>et al.</i> (1997)	1960-1992	Tennessee	Electricity distribution	<ul style="list-style-type: none"> 65% of 1009 reported transmission line outages in 1987 were lightning-related 	Oak Ridge National Laboratory
Whitehead and Driggans (1990)	1987	Southeast United States	Electricity transmission and distribution	<ul style="list-style-type: none"> Number of lightning-related outages explained by simple linear model $N=58.94(\text{flash density}/\text{mile}^2)-27.975$ (r-squared, 0.919) 	Tennessee Valley Authority
Zhu <i>et al.</i> (2006)	1995-2004	United States Unspecified**	Electricity distribution	<ul style="list-style-type: none"> 88-168 direct and indirect flashovers per 100km-year (4-20kv lines, 260 km of total circuit) 	Unspecified utility's power outage data
Zoro and Mefiardhi (2005)	2002-2004	West Java, Indonesia	Electricity distribution		Regional utilities

Table 3. Average per customer per event results from a U.S. outage cost meta-analysis (Lawton *et al.*, 2003)

<u>OUTAGE SCENARIO</u>		<u>SECTOR OUTAGE COST ESTIMATE (2000 \$US)</u>		
Timing	Duration	Residential	Small Commercial and Industrial	Large Commercial and Industrial
Summer afternoon	1 hour	\$2.90	\$1,200.00	\$8,200.00
	8 hour	\$7.20	\$4,400.00	\$41,000.00
Winter afternoon	1 hour	\$3.30	\$1,800.00	\$20,000.00
	8 hour	\$8.32	\$6,300.00	\$105,000.00

Source: Lawton *et al.*, 2003:46

An alternative and complementary approach to gauging the impact of lightning-related interruptions to customers is to assess the level of investment in preventive measures and realization of benefits. In the general power disturbance literature, this technique has been used to determine the impact of power quality on consumers. Clemmensen *et al.* (1993), as cited in LaCommare and Eto (2004) and Koomey *et al.* (2002), estimated that 1.5-3 cents per manufacturing sales dollar was spent to prevent or correct power quality problems, a figure that when multiplied by 1987 sales totals yielded a national U.S. estimate of \$25.6 billion per year. No studies were found that examined specific retail figures for lightning prevention equipment, technologies and consulting or investments in certain forms of business interruption insurance. This is likely because such information tends to be proprietary and difficult to obtain at a national level with sufficient levels of disaggregation. While several studies have evaluated the technical efficacy or small-scale feasibility of lightning arresters, alternative pole designs and other protection technologies across a transmission or distribution network (e.g., Karlsson and Norberg, 201; Carpenter and Auer, 1995; Tarchini and Gimenez, 2003), minimal research was found on the aggregate economic costs and benefits of adoption. Bernstein *et al.* (1996) provide a series of U.S. utility-specific accounts of savings attributable to data produced through the U.S. National Lightning Detection Network though. While not comparable to a fully quantified valuation and cost-benefit analysis, reported cost savings for 8 utilities amounted to several hundred thousand dollars per year (Bernstein *et al.*, 1996). General areas of cost reduction or benefit interpreted from the paper include:

- reduced labour-intensive monitoring effort;
- more accurate and cost-effective pre-positioning of resources (e.g., repair crews) in response to lightning threat compared to deployment based on general forecasts or waiting for customers to identify problems;
- reduced system down-time;
- validation of insurance claims for lightning-caused interruptions;
- reduced time and labour explaining cause of outages to customers; and
- justification for allocation of additional lightning protection equipment in infrastructure designs (i.e., to higher-prone parts of system)

2.5 Agriculture

Many of the studies referenced in section 2.2 that relied on *Storm data* included lightning-related agricultural losses, such as damage to homes, barns, sheds and other buildings, in their analyses. Livestock mortality has also historically been important to insurers (Kopf, 1928) with weather in general causing about 7 percent of the 3.9 million cattle and calves lost in the U.S. in 2005 (USDA, 2007). Linn (1993) observed that lightning accounts for more than 80 percent of accidental livestock losses, presumably in the U.S., and Williams (2000) describes lightning mortality in horses. However, aside from these references, a few isolated anecdotal accounts from insurers, and papers describing farm-specific lightning protection measures (e.g., Chamberlain and Hallman, n.d.), no contemporary documentation was found in the literature that could be used to define the extent and magnitude of lightning-related impacts to agriculture. Intuitively, and through experiences with other natural hazard events (e.g., Ice Storm 1998; Kerry *et al.*, 1999), power supply interruptions as discussed in the previous section are important and costly to certain operations (e.g., dairy) and often necessitate the purchase of standby generators.

2.6 Transportation and Pipelines

In comparison to the electricity sector, little research has been conducted on the impacts of lightning on transportation. Much of what exists has been completed in the U.S. and provides evidence of general impact mechanisms but little indication of the frequency, severity or magnitude of impacts let alone costs. Most of the detailed and quantitative research has been completed for the aviation mode with less activity concerned with surface transportation, which for this analysis includes energy supply pipelines.

Concerns about the impact of lightning on aviation, in particular the safety and protection of aircraft and space vehicles, have been expressed in the literature for several decades (e.g., Cobb and Holitza, 1968; Plumer *et al.*, 1985). Weather is a contributing factor in about 23 percent of U.S. accidents involving aircraft (Kulsea, 2003) and several studies have isolated the impact of lightning. Cherington and Mathys (1995) identified 40 lightning-related aviation entries in the US National Transportation Safety Board accident data over the 1963-1989 period. Ten commercial and 30 private aircraft incidents resulted in 290 fatalities and 74 serious injuries (Cherington and Mathys, 1995). Uman and Rakov (2003) reviewed past studies to determine the nature of lightning-aircraft interactions, documenting both direct effects (e.g., holes in metal skin, puncturing or splintering of non-metallic structures, welding or roughening of moveable hinges and bearings, exterior antenna and light damage, fuel ignition) and induced voltage impacts that affect many aircraft electronic systems (e.g., VHF communication set, compass, instrument landing system). Based on a meta-analysis of commercial aircraft strike data (1950-1974) they estimated an exposure of 1 strike for every 3000 hours or about once per year for each commercial aircraft though impacts of strikes are often minimal and are only very rarely catastrophic (Uman and Rakov, 2003). This observation is also supported by Weber *et al.* (1998) who noted that only 11 percent of lightning strikes to aircraft in the United States require repair or replacement of equipment. Damage incidence is much lower for newer aircraft with avionics or full High-Intensity

Radiated Fields (HIRF) protection (O’Loughlin and Skinner, 2004) thus one would expect impacts to diminish over time as fleet stocks are replaced.

Only one report of damage to an airport was found in the literature review. Gopalan (2005) provides an extensive account of lightning damage to runways and an access road over 3 separate lightning strike incidents at an international airport in Kerala, India. Although such events are likely more frequent than one paper would suggest, such damage would be caught at modern airports through routine runway inspections and quickly repaired at minimal cost.

The greater significance of lightning for aviation is the impact on flight delays, diversions, or cancellations as well as on ground operations. Weather-related accident damage and injuries, delays, and unexpected operating costs amount to \$3 billion annually in the U.S. (Kulsea, 2003). In assessing the utility of a new lightning mapping sensor, Weber *et al.* (1998) suggest that \$2 billion per year in operating costs and passenger delays are associated with thunderstorms. This figure, based on U.S. Federal Aviation Administration information, has also been attributed, perhaps incorrectly, to lightning alone (NOAA, 2006). Research by Evans *et al.* (2004) suggest that it is very difficult to determine and allocate delay costs related to convective weather, let alone an aspect of it such as lightning:

...the bulk of the convective delays result from the very complicated dynamic behavior of a highly nonlinear NAS [National Aviation System] network in which both terminal and en route capacity losses due to convective weather lead to delay (Evans *et al.*, 2004:30).

Other researchers such as Post *et al.* (2002) have utilized lightning data to develop an enroute weather severity index that can be applied to determine travel delays associated with convective weather—and ultimately costs (Kettunen *et al.*, 2005). In addition to providing information on the impacts of convective weather, such studies, along with those of Evans *et al.* (2004), are important for assessing the potential benefits and costs of various planned improvements to aviation systems.

Surface transportation, including road, rail, and marine modes, along with pipelines, that account for most of the economic value of the transport sector, is also affected by lightning. Although no research has been conducted to determine the overall economic significance of lightning, a recent survey of U.S. surface transportation representatives to assess their weather information needs (OFCM, 2002) identified the following lightning-related impacts:

- potential for injuries to maintenance and operations personnel (small boat marine, aviation ground operations, rural/urban light rail transit);
- potential equipment damage (pipelines);
- occasional damage to towers and antennae disrupting communications (State police);
- restrictions on certain hazardous operations such as refueling or maintenance;
- signal and track sensor malfunctions/outages from lightning strikes to switches or electrical boxes causing delays, stops, or traffic congestion (long-haul rail, rural/urban light rail transit); and
- sensor damage and disruption of monitoring data flow and communications from sensors and control facilities (pipelines).

Several studies have examined the general impacts noted above and the efficacy of lightning protection for rail or light rail systems in greater detail (Morris and Dinallo, 1996; Lucca and Buffarini, 2000; Helig *et al.*, 2002; Pham *et al.*, 2003; Theethayi *et al.*, 2007). For the road

sector, measures to mitigate lightning-caused damage to traffic sensor and data communication surge protection infrastructure in Florida were assessed by Harvey and Mussa (2003). Some simulation research has also been completed to examine impacts on and preventive measures for pipelines (e.g., Metwally and Heidler, 2005). Overall though, research on the impacts of lightning on surface transportation interests seems lacking which likely suggests that existing lightning protection technology and operating rules and standards are effective at mitigating impacts at acceptable cost levels for most users.

2.7 Telecommunications

The telecommunications sector has expanded rapidly over the past two decades. In Canada, approximately 64 fixed telephone lines, 53 mobile cell subscribers, 87 computers, 68 Internet users and 24 broadband Internet subscribers existed in 2005 for every 100 inhabitants (ITU, 2007). Expansion in telecommunications, as measured by these and other indicators, is positively correlated with economic growth (Correa, 2006). Despite the increasing importance of telecommunications, no published information was found that described the aggregate impact of lightning on telecommunications infrastructure, operations, and services. However, several studies generally note and discuss various means to reduce the vulnerability of systems and infrastructure to direct strikes or, more commonly, induced voltages and associated electromagnetic damage or interference (Barreto, 2002; Kijima, 1999; Baker and Ahmad, 1999; ITU 1997; Janklovics, 1997; Shintaku *et al.*, 1998; Woodward, 1991). For instance, Kijima (1999) described 3 cases of lightning damage to telecommunications installations (private branch exchange, digital switch, and transmission equipment elements) and simulated countermeasures for each event. Baker and Ahmad (1999), Janklovics (1997) and Shintaku *et al.* (1998) also used models to simulate potential damage or the efficacy of protective measures such as lightning rods, grounding systems, surge by-pass with arresters, and insulation.

2.8 Tourism and Recreation

Tourism and recreation activities that take place outdoors are exposed to lightning. Although businesses and facilities may be subject to direct damage from lightning strikes or affected by lightning-related power or telecommunication outages, the published literature pertains almost exclusively to the protection of people (active participants, spectators). Several studies have shown that a large and growing proportion of lightning-related casualties involve those engaged in recreation activities such as hiking, camping, boating or golfing (e.g., Holle *et al.*, 2005; Makdissi and Brunner, 2002; Mills *et al.*, 2006). These risks are acknowledged in various guidelines that have been developed to alert the public of the lightning hazard, threats to safety, and precautions necessary to minimize exposure in a wide range of settings (Zimmerman *et al.*, 2002). Most of the literature obtained for the review dealt with either stadiums (or other events with concentrated gatherings) or golfing⁴. General threats to stadiums and other large event venues from severe storms have been studied by Edwards and

⁴ Lightning-ignited forest fires are also a threat to parks (e.g., Heathcott, 1999), but this was generally treated in section 2.3

Lemon (2002) with more detailed, lightning-specific risks and safety recommendations provided by Walsh *et al.* (1997, 2000, 2003), Gratz *et al.* (2004), Gratz and Noble (2006). Lightning safety policies have also been developed for participants in sports and athletics activities (e.g., Makdissi and Brukner, 2002; Bennett, 1997) which often take place in large event venues during the peak lightning season and time-of-day (Walsh *et al.*, 1997).

The prime golfing season also overlaps peak lightning months which in part explains why a significant number of lightning casualties occur on golf courses (Kithil, 2007; Flynn, 1995; Waddell, 2006). High profile events, such as the 1991 tragedy at Hazeltine National Golf Club during the U.S. Open golf tournament, which killed one man and injured 5 others (Kindred, 2002), have encouraged a number of golf facility operators to invest in some level of lightning protection (e.g., mobile or permanent shelters) or detection/alert technology whereby golfers are ordered off a course (e.g., Waddell, 2006; Bonner, 2005; Mooney, 2003). No figures were found that quantified the market penetration of such systems, but cost estimates for individual courses were between US\$3,000 (Flynn, 1995) and CDN\$30,000 (Crawford, 2001). Such costs may explain why many courses lack such policies or interventions and simply rely on golfers to use common sense in lightning situations (Crawford, 2001). As adoption of policies and new technologies increase, liability may become an issue if a failure to provide lightning-proof weather shelters or protection can be proven an act of negligence though, according to research by Flynn (1995), this has not yet occurred in U.S. courts.

In addition to the direct and indirect social costs of injuries and deaths, lightning may affect the tourism and recreation sector through lost revenue due to cancelled events or reduced participation rates (because of safety concerns) and property damage. As noted previously, there is little evidence documenting the extent or magnitude of either type of cost to the industry. Flynn (1995) anecdotally noted that significant lightning activity can close a golf course thus reducing the number of rounds played and associated revenue (Flynn, 1995). Other researchers have examined the impact of weather elements, including precipitation, on participation levels in golfing and other recreation activities (e.g., Scott and Jones, 2007) but no quantified estimates of the impact of lightning were found.

In terms of property damage, descriptions of particular events are evident (e.g., golf course green, Krider, 1977) and U.S. National Golf Foundation figures estimate that lightning damage to trees, irrigation systems or buildings occurs on average 2 times per golf course each year (Crist, 1995). Cheng (2002) notes a potential grounding (and therefore damage) issue for the moving components of retractable stadium roofs. Overall, the lack of literature suggests that for most forms of recreation, property damage is not a large concern. Recreational boating may be an exception though. In his review of the U.S. code for lightning protection of boats, Thomson (1991) surveyed 71 owners of small recreational sailboats in southwest Florida that were damaged by lightning. By combining the survey information with general repair records, Thomson (1991) estimated that about 3 percent of all moored sailboats in the region experience lightning-induced damage each year. In general, sailboats in freshwater experienced the most severe and frequent electronics and hull damage; lightning protection equipment seemed to afford only modest reductions in damage (Thomson, 1991).

2.9 Other Impacts

A couple of studies were also discovered that dealt with hazardous material accidents. Rasmussen (1995) extracted and analyzed data from the MHIDAS (SRD)⁵ and Facts (TNO)⁶ data bases of (global) accident case histories for the period 1941-1991. Lighting accounted for 61 percent of 232 hazardous material accidents where natural events were the cause or a major contributing factor (Rasmussen, 1995). At a smaller geographic scale, Ruckart *et al.* (2004) determined that lightning was a causal factor in over 19 percent of the 110 weather-related acute releases of hazardous substances that were reported to the HSEES system in Texas during 2000-01.

Finally, Keskar (1996) cites and explains lightning-related damages to water and wastewater treatment plants in Florida and Arkansas, respectively, arising in part from improper surge protection equipment installation. Despite the limited amounts of literature, lighting impacts to water utilities may be relatively common. A survey of community water system managers conducted in South Carolina and the Susquehanna River Basin in 2000 revealed that over 50 percent had experienced lighting events over the past 5 years (Dow *et al.*, 2007). Over 40 percent of system managers in South Carolina and over 20 percent of those in the Susquehanna River Basin expected to be impacted with considerable or catastrophic problems related to lightning during the next 10 years (Dow *et al.*, 2007).

Summary

In summary, three general types of impact were revealed through the literature review: human casualties, property damage, and losses associated with the interruption of electricity and other critical services. Affected sectors include health; property and casualty insurance; forestry; electricity generation, transmission, and distribution; agriculture; telecommunications; transportation; and tourism and recreation—the first four sectors are the most important in terms of contributing to overall impacts and costs. Impacts were usually reported in terms of physical indicators (i.e., number of people injured, damage report counts, electricity outage frequency and duration, number of insurance claims, etc.) with a smaller set of studies also estimating economic costs. Based on the available though often limited descriptions of analyses, virtually all of the research that was examined reported direct lightning-related damage costs or cost savings associated with preventive measures. No formal economic analyses of indirect costs or non-market costs attributable to lightning damage were uncovered. Much of the work that has been completed is focused on the U.S., with only a few Canadian studies. The case study described in the following section attempts to address the apparent need for additional Canadian research by developing an aggregate picture of lightning impacts and costs across multiple sectors.

⁵ Major Hazard Incident Data Service developed by AEA Technology plc on behalf of the Major Hazards Assessment Unit of the United Kingdom Health and Safety Executive (HSE).

⁶ Facts (TNO)

<http://www.factsonline.nl/tabid/178/Default.aspx>

3.0 A CANADIAN CASE STUDY

The Canadian case study involved two major components that drew upon very different sources of impact data: 1) analysis of Canadian media reports of lightning-related damage and disruption, and 2) development of specific impact and cost estimates for the most-affected sectors as identified through the literature review and media report analysis. For both components, damage or disruption costs were the primary metric sought and used to evaluate the extent of lightning-related impact.

3.1 Analysis of Canadian Media Reports

Media reports were a primary source of data used in the lightning-related injury study conducted by the authors (Mills *et al.*, 2006). Since many instances of property damage were uncovered in the search for injury events, it was decided to utilize media accounts in the current study. Such data also forms the basis of several national hazard impact data bases, including *Storm Data* published in the United States by NOAA and used in several analyses of lightning damage noted in the literature review (see Table 1). A more detailed rationale for their use is available in Mills *et al.* (2006).

Data and methods

An online media search was performed using both individual newspaper search engines as well as media conglomerate and global search engines (Factiva and LexusNexus). The search covered major daily Canadian newspapers (e.g., Globe and Mail, Toronto Star, Winnipeg Free Press, Calgary Herald) as well as numerous community newspapers (Toronto Star Group, Canada's Community Newspaper Association, Ontario Community Newspaper Association, and Quebec Community Newspaper Association). In total, 460 searchable archives were accessed with a majority based in Ontario (207), followed by Quebec (67) and Alberta (50). Many of the archives in Quebec had a maximum searchable time span of 7 days, whereas the others ranged from 1-21 years. Thus fewer media reports were obtained for Quebec than for other regions.

Keyword searches were performed on all available newspaper databases in order to target stories dealing with lightning related topics. For English newspapers, only the word *lightning* was used; both *éclair* and *foudre* were used for French-language papers. In total, 406 unique stories were found from 1986-2006. The annual number of reports is charted in Figure 1. Given the dearth of stories prior to 1994, coincident with general availability of internet services, and to keep the period consistent with that used in the injury analysis (Mills *et al.*, 2006), it was decided to limit the media report study from 1994-2006. The subsequent analysis is therefore based on 371 reports of damage over 13 years.

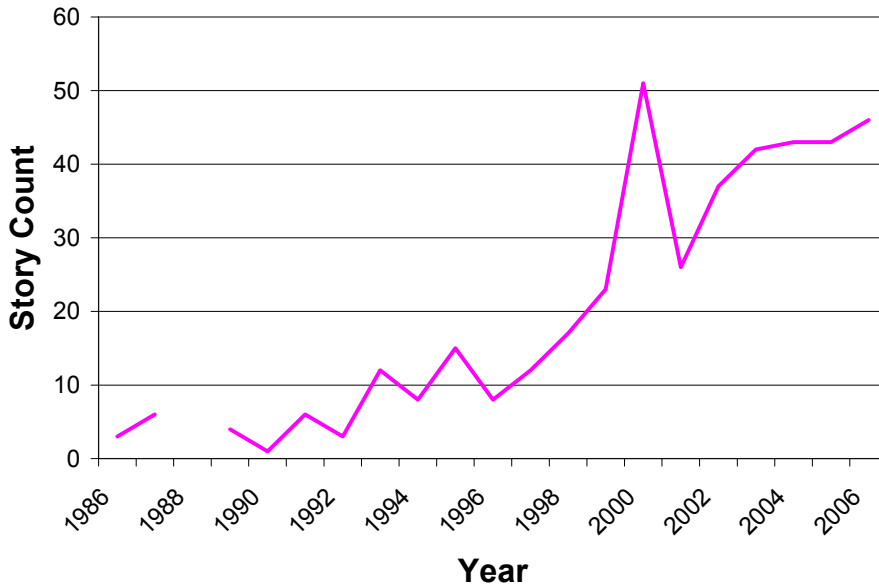


Figure 1. Annual count of unique media reports of lightning damage or disruption, 1986-2006

Data extracted from the archived media reports varied in detail, accuracy, and extent, however, each story and applicable derived information were added to a lightning incident database. When discernible, entries included information on the location (city and province) of the incident, damage or disruption mechanism (e.g., house or forest fire, power interruption), types of property damaged or disruption (e.g., building/home, evacuation), various indicators of impact magnitude (e.g., number of homes damaged, number of people/households evacuated) and estimated losses or costs. Where possible, the source of information contained in the article (i.e., witness/victim account, police/fire/emergency official, etc.) was also recorded.

Results

The survey of media reports revealed examples that define a broad range of damage and disruption types, however, it was less helpful in characterizing the extent or magnitude of impacts and costs. Three categories of impact were evident from the reports:

- 1) Physical damage from direct or indirect strikes and fires to homes and sheds, churches, schools, hospitals/extended care facilities, commercial buildings, recreational buildings, sailboats, lighthouses, water treatment plants, agricultural buildings and contents, livestock, hay/straw bales, forests, pastures, oil and natural gas pipelines, oil storage facilities/tanks, traffic signals, vehicles, communication towers and systems, electrical transformers/stations, and hydroelectric plants;
- 2) Electricity and to a lesser extent communication service interruptions affecting a variety of customers and forcing, among other things, a nuclear power plant shutdown, traffic signal failures, and alarm system failures; and
- 3) Evacuations or evacuation alerts related to forest fires.

Table 4 summarizes data obtained or inferred from the media reports for several indicators of impact that could be quantified. Over the 1994-2006 period cumulative costs exceeded \$17.5 million; about 900 buildings and 700 power transformers were damaged or destroyed by lightning; and in excess of 3.3 million people are estimated to have been affected by power outages.

The results are strongly influenced by a few extreme values and incomplete reporting. For instance, 700 buildings were reported damaged or destroyed in only two events. Removing these extremes reduces the annual average from 69 to 15. Similarly, over half of the total cost is attributable to a single report of \$10 million in forest fire suppression costs. In terms of reporting, information concerning damage costs and the number of people affected by power outages was discernible for only about 10 and 50 percent of reports, respectively. As well, the total number of damage or disruption reports (371) was only 2.5 times greater than those for human casualties (148) as analyzed in Mills *et al.* (2006). These observations support findings from U.S. studies that damage incidents are severely underreported by media (Holle *et al.*, 1996; Curran *et al.*, 1997, 2000). At best, media reports obtained in the current study provide a qualitative and complementary source of information to the sector-specific empirical estimates developed in subsequent sections of the paper.

Table 4. Summary of media-based damage reports, 1994-2006

Impact	Total number or cost (1994-2006)¹	Annual average¹
<i>Physical Damage</i>		
Buildings	899	69
Transformers	672	52
Livestock mortality	105	8
<i>Interruptions</i>		
People affected by electricity outages ²	3,358,214	258,324
Reports of communication failures	11	1
People evacuated or on alert due to forest fires	67,156	5,166
<i>Costs</i>		
Electricity-related	\$2,995,000	\$230,385
Buildings	\$4,633,000	\$356,385
Fire suppression	\$10,000,000	\$769,231
Other	\$70,000	\$5,385
Sum of reported costs	\$17,698,000	\$1,361,385

¹ all figures rounded to whole numbers

² figures estimated where not explicitly defined by using Statistics Canada (2007a,b) population data for affected communities/regions or by applying population factor (2.6) where only the affected number of households was identified

3.2 Compilation of Sector-specific Impact Estimates

While limited or incomplete in terms of quantifying costs and impacts, the media reports did verify the general importance of lightning to particular sectors as revealed through the literature review. These sectors and major impact areas include: health (injury burden), insured and uninsured personal and commercial property damage and disruption, forestry (wildfire management), and electricity transmission and distribution. A variety of empirical data and methods were used to derive impact and ultimately cost estimates for each sector. These are explained in detail in subsequent sections. While not fully comprehensive, the authors believe that the final summary estimate accounts for a majority of the costs incurred as a result of lightning strikes in Canada.

Health (injury burden)

Mills *et al.* (2006) estimated that, on average, 9-10 deaths and 92-164 injuries are attributable to lightning each year in Canada. Based on Ontario data, it is estimated that 19-33 of the injuries required hospitalization while the remainder (73-131) were treated in an emergency room and later released without being admitted to hospital (Mills *et al.*, 2006). While casualty statistics stand on their own in terms of motivating policy or action to reduce impacts, the economic burden associated with casualties is often significant and should not be overlooked when aggregating or comparing costs across sectors.

A sample of literature concerning the value of a statistical life (VSL)⁷ and the costs of injuries was consulted in order to develop a rough estimate of the social costs of lightning casualties. Studies have assessed VSL and injury costs based on contingent valuation (willingness-to-pay or –accept), human capital, and revealed preference approaches (e.g., Alberini, 2005; Health Canada, 2002; Hirth *et al.*, 2000; Viscusi, 2004; Viscusi and Aldy, 2003). The lowest values generally come from studies that have adopted human capital methods where only discounted future earnings losses of those killed or injured are considered. Estimates from contingent valuation (e.g., based on an individual’s willingness to pay to reduce or accept compensation for the risk of being killed or injured) and revealed preference (e.g., observed wage-risk relationships) tend to produce much larger figures and are more representative of the broad costs to society. In addition to the costs of the human consequences, there are also time and material costs associated with emergency response (i.e., ambulance, fire) and healthcare (Vodden *et al.*, 1994).

Specific VSL and illness burden estimates range widely, in part because of methodological and contextual differences among studies (i.e., the nature of risk being measured, the degree of change in risk and the characteristics of the population measured) (DSS Management Consultants Inc., 2000). For instance, Hirth *et al.* (2000) reviewed 41 VSL studies with estimates ranging from \$192,056-\$25,926,349 (1997 USD) and a median meta-analysis value of \$ 4,101,153. VSL figures used by various government agencies in cost-benefit analyses that support policy decisions generally fit within this range though estimates may vary among

⁷ VSL s should not be confused with the value of a specific individual person (i.e., priceless)

agencies within the same government (e.g., \$1 million, U.S. Federal Aviation Administration; \$6.3 million, US Environmental Protection Agency) (Viscusi and Aldy, 2003).

For the current project, lightning-related casualty cost estimates were derived from two Canadian studies that dealt with both injuries and fatalities but using different methodologies (Angus *et al.*, 1998; Vodden *et al.*, 1994). Angus *et al.* (1998) evaluated the economic impact of unintentional injury in Canada using a cost-of-illness approach that valued both direct (i.e., treatment-related) and indirect (i.e., lost productivity) costs. In principle, indirect costs include those related to impaired quality of life, pain, suffering, etc., however, for the purposes of their study, only lost productivity estimates developed using a human capital approach were incorporated (Angus *et al.*, 1998).

Direct and indirect costs derived from Angus *et al.* (1998) are presented in Table 5. Costs are expressed per casualty in 1995 dollars for several classes of injury. The variability in part reflects the effect of injury severity on the degree of disability, required treatments, lengths of hospitalization, and demographics. Lightning-related injuries typically would fall in either the *fire* or *other* classes presented in Table 5. Lacking specific data for lightning injuries, the authors chose to apply figures from both of these classes as well as a total case estimate to determine lightning-related costs. Results are detailed in Table 6 with total costs inflated to 2007 dollars using the all-item Consumer Price Index (CPI). Low and high estimates were generated using the low and high average annual injury counts (and hospitalization/ER breakdown) provided by Mills *et al.* (2006). Total annual average costs range from \$3.6 million to \$5.9 million.

Table 5. Direct and indirect costs (\$1995) per case by injury type (derived from Angus *et al.*, 1998)

Average Costs per Case	Motor Vehicle Collisions	Falls	Drowning and Suffocation	Poisoning	Fires	Other	All cases combined
Direct							
Hospitalized	\$6,719	\$8,975	\$4,211	\$2,702	\$5,198	\$5,096	\$7,463
Non-hospitalized	\$1,485	\$2,083	\$4,420	\$1,745	\$1,204	\$1,197	\$1,603
Indirect							
Morbidity	\$1,548	\$1,267	\$6,271	\$1,281	\$1,695	\$1,192	\$1,268
Mortality	\$328,004	\$27,292	\$332,178	\$304,348	\$348,408	\$287,586	\$229,465
TOTAL	\$3,871	\$1,997	\$31,406	\$3,133	\$6,434	\$1,412	\$2,010

Source: Angus *et al.*, 1998, Tables III-1,8,15-17,21

Table 6. Lightning-related costs based on injury estimates derived from Angus *et al.* (1998)

Costs	<u>Based on Fires Injury Class Estimate</u>		<u>Based on Other Injury Class Estimate</u>		<u>Based on Total (all cases) Estimate</u>	
	Low	High	Low	High	Low	High
Direct						
Hospitalized	\$478,170	\$852,391	\$468,805	\$835,697	\$686,616	\$1,223,969
Non-hospitalized	n/a	n/a	n/a	n/a	n/a	n/a
Indirect						
Morbidity	\$155,918	\$277,940	\$109,660	\$195,481	\$116,677	\$207,989
Mortality	\$3,135,669	\$3,484,076	\$2,588,270	\$2,875,855	\$2,065,186	\$2,294,651
Total (1995\$)	\$3,769,757	\$4,614,408	\$3,166,735	\$3,907,032	\$2,868,479	\$3,726,609
INFLATED TOTAL (2007\$)	\$4,795,246	\$5,869,668	\$4,028,184	\$4,969,805	\$3,648,793	\$4,740,360

Source: Angus *et al.*, 1998, Tables III-1,8,15-17,21

Vodden *et al.* (1994) assessed the social costs of motor vehicle collisions in Ontario. Costs associated with human consequences were determined using a willingness-to-pay approach that measures the value an individual places on reducing the risk of being killed or injured. Time and material costs attributable to emergency response and healthcare were added to determine the total social cost of collisions (Vodden *et al.*, 1994). Human consequences and healthcare time and material costs that were abstracted from Vodden *et al.* (1994) are summarized in Table 7. Costs are expressed per injury in 1990 dollars for 4 classes of severity. Other time and material costs considered by Vodden *et al.* (1994) such as emergency response, towing and administration of insurance claims, were not applied in the current study as they pertain to motor vehicle crashes as opposed to lightning incidents and casualties. Total costs per injury and severity were then multiplied by corresponding lightning-related injury counts developed by Mills *et al.* (2006). As with the application based on Angus *et al.* (1998), this application produced low and high estimates. Results are provided in Table 8 with total costs inflated to 2007 dollars using the all-item Consumer Price Index (CPI). Total annual average costs, ranging from \$70.3 million to \$79.3 million, are more than an order of magnitude greater than those determined through the previous application and reflect the large WTP-based social values adopted by Vodden *et al.* (1994).

Table 7. Social costs per injury by level of severity (Vodden *et al.*, 1994)

Injury Severity	<u>Cost per injury (\$1990)</u>		
	Human Consequences	Healthcare	TOTAL
Fatality	\$5,327,511	\$2,620	\$5,330,331
Major injury (requiring admission to hospital)	\$52,825	\$6,566	\$59,391
Minor injury (emergency room treatment/not admitted)	\$8,866	\$802	\$9,668
Minimal (injured but did not go to ER)	\$1,761	\$609	\$2,370

Source: Vodden *et al.*, 1994:33,46

Table 8. Lightning-related costs based on social cost estimates derived from Vodden *et al.* (1994)

Injury Severity	Low Estimate	High Estimate
Fatality	\$47,971,176	\$53,301,310
Major injury (requiring admission to hospital)	\$1,108,635	\$1,976,263
Minor injury (emergency room treatment/not admitted)	\$173,793	\$309,805
Minimal (injured but did not go to ER)	n/a	n/a
Total (1990\$)	\$49,253,607	\$55,587,378
INFLATED TOTAL (2007\$)	\$70,256,488	\$79,291,126

Source: Vodden *et al.*, 1994:33

Property damage

Commercial, industrial and residential fire costs

Information from annual reports of provincial fire authorities and the Council of Canadian Fire Marshals and Fire Commissioners (CCFMFC) were obtained to estimate the extent of lightning-related fire damage to commercial, industrial, institutional and residential property. The data pertain to all incidents responded to by local government fire departments and include variables for injuries and fatalities in addition to property damage, all stratified by the source of ignition (igniting object). Within this category, lightning is classified as the only example of “no igniting object”. Losses are estimated by the reporting fire agency and encompass only physical damage to structures and contents therein (i.e., not loss of business). Standardized reporting protocols and coding for all variables are documented in CCFMFC (2002).

National level fire loss data and summary statistics obtained or derived from CCFMFC (2006) are listed in Table 9 for the 1990-2002 period. Over this timeframe, CCFMFC member fire

agencies responded to an average of 818 lightning-ignited fires each year causing \$16.4 million in annual losses when inflated to current dollars. If only the most recent 1998-2002 period is considered, then about 390 fires produce \$14.9 million of losses each year. Lightning generally accounts for around 1 percent of all fires and slightly less than 1 percent of all fire losses, though these figures vary by year and, as indicated in Table 10, by province. When inflated, the average reported loss for a lightning-ignited fire was about \$20,114.

Table 9. Annual Canadian losses associated with fires ignited by lightning, 1990-2002 (CCFMFC, 2006)

Year	Fires		Fire Losses (\$ property damage) ¹		
	Lightning-ignited	Proportion of all fires	Lightning-ignited	Proportion of all losses	Inflated Lightning-ignited*
1990	1125	1.67	\$18,894,729	1.54	\$26,951,880
1991	1194	1.75	\$14,830,270	1.20	\$19,913,649
1992	816	1.25	\$11,384,947	0.93	\$15,119,210
1993	574	0.87	\$7,073,621	0.60	\$9,245,835
1994	956	1.43	\$19,806,732	1.72	\$25,889,114
1995	2428	3.78	\$15,807,309	1.42	\$20,107,382
1996	408	0.68	\$5,639,211	0.48	\$7,071,645
1997	1157	2.06	\$11,999,666	0.93	\$14,796,246
1998	412	0.72	\$11,480,924	0.98	\$14,013,481
1999	362	0.66	\$16,424,922	1.33	\$19,739,635
2000	361	0.67	\$9,605,218	0.81	\$11,218,759
2001	387	0.70	\$12,640,892	0.89	\$14,286,898
2002	429	0.80	\$13,471,670	0.90	\$15,033,931
Average	816	1.00	\$13,004,624	0.84	\$16,414,436

¹inflated using all-item mid-year CPI (Statistics Canada, 2007c)
Source: CCFMFC (2006)

Table 10. Select average annual provincial losses associated with fires ignited by lightning, 2000-2005

Province/period	Fires		Fire Losses (\$ property damage)		
	Lightning-ignited	Proportion of all fires	Lightning-ignited	Proportion of all losses	Inflated Lightning-ignited*
British Columbia (2000-2005)	52	0.81	\$1,440,262	0.55	\$1,587,391
Alberta (2002-2004)	22	0.41	\$2,155,388	0.65	\$2,374,890
Saskatchewan (1999-2004)	32	0.78	\$956,540	1.99	\$1,099,184
Manitoba (2000-2004)	20	0.38	\$445,951	0.54	\$495,008
Ontario (1995-2004)	108	0.71	\$4,703,050	1.46	\$5,518,790
New Brunswick (2002-2004)	21	0.87	\$4,172	0.05	\$4,567
Nova Scotia (2000-2005)	6	0.71	\$126,752	0.80	\$140,467

Sources: Government of Alberta (2007), Government of British Columbia (2007), Government of Manitoba (2006), Government of New Brunswick (2007), Government of Nova Scotia (2007), Government of Ontario (2006), Government of Saskatchewan (2007)

Insurance claims

As noted in the literature review, insurance claim data is likely one of the best sources of information for evaluating the impacts of lightning. While claim information is much more comprehensive than media sources and offers the benefit of consistent reporting, it can also be very difficult to obtain, especially for large regions, provinces or entire countries given the multitude of insurance agencies. Insurance data were not available within the timeframe of the current study, however, attempts were made to extrapolate a Canadian estimate from 3 U.S. studies (Holle *et al.*, 1996; Stallins, 2002; Insurance Information Institute, 2007).

Prior to developing a cost estimate, it was necessary to establish baseline lightning-related insurance claim rates for Canada. Tables 11 and 12 identify the baseline results of each study that was used to develop Canadian insurance claim rates as a function of population (per capita rate) or CG flash occurrence (CG flashes per claim). It was assumed from the original literature that these claims did not cover fire losses and thus could be added to other sector estimates in the final aggregation. As noted in Tables 11-12, some adjustments were made based on the original data contained in each study. In recognition of the uncertainty associated with transferring results from one region to another, the extreme low and high estimates from Table 11 (4.5-23.9 claims/10,000 population) and Table 12 (47-102 CG flashes/claim) were extracted for further analysis as they represent the full range of values.

Table 11. Lighting-related insurance claim studies used to derive per capita Canadian estimates

Study	Location	Claims/year	Population ⁴	Claims/10,000 people
Holle et al. (1996)¹	Colorado	5,188	3,294,394	15.7
	Utah	774	1,722,850	4.5
	Wyoming	793	453,588	17.5
	3-State Average	6,755	5,470,832	12.3
Stallins (2002)²	Georgia (low)	15,666	8,186,453	19.1
	Georgia (high)	19,582	8,186,453	23.9
Insurance Information Institute (2007)³	United States	266,567	292,173,345	9.1

¹ based on commercial and homeowner claims; claims were reported in paper as 4.7, 1.4, and 3.9 per 10,000; 1990 population data

² based on commercial, homeowner, and farmowner claims; low scenario based on results in paper, high scenario derived by removing one year from claim data (1998) in which virtually no claims reported; 2000 population data

³ based on homeowners insurance data; 2004-2006 average population data

⁴ all population data obtained/derived from U.S. Census Bureau figures (USCB, 2007)

Table 12. Lighting-related insurance claim studies used to derive Canadian estimates based on CG flash counts

Study	Location	Claims/year	CG Flashes/year	CG flashes/claim
Holle et al. (1996)¹	Denver, CO	2,401	123,663	52
	United States	307,000	17,600,000	57
Stallins (2002)²	Georgia (low)	15,666	911,104	58
	Georgia (high)	19,582	911,104	47
Insurance Information Institute (2007)³	United States	266,567	27,255,605	102

¹ based on commercial and homeowner claims; Denver area CG flash data for 1983; U.S. CG flash value from average 1989-93 NLDN data

² based on commercial, homeowner, and farmowner claims; low claim scenario based on results in paper, high scenario derived by removing one year from claim data (1998) in which virtually no claims reported; CG flash value determined for current study based on 2000-2004 flash density (Vaisala, 2006)

³ based on homeowners insurance data; CG flash value determined for current study based on 2000-2004 flash density (Vaisala, 2006)

An initial set of Canadian estimates were obtained by applying these unadjusted claim rates to provincial-level population⁸ and lightning flash data⁹. Although further geographic resolution may yield more precise results (e.g., county level, Holle *et al.*, 1996) provincial figures were

⁸ Statistics Canada, 2007

⁹ CG average annual flash counts derived from 2000-2004 flash density (Vaisala, 2006)

readily available from Mills *et al.* (2006) and they generally matched the scale of the baseline U.S. state- or national-level figures identified in Tables 11-12. Baseline claim results are presented in Figure 2. Between 14,760-78,580 lightning-related claims are estimated for Canada when provincial population data are applied to the U.S. per capita claim rates. This range narrows to 19,820-43,550 when results are extrapolated using CG flash data. As expected by virtue of the method employed, respective estimates vary by province as a function of population and CG lightning frequency. Regardless, they appear exceedingly high. It is unreasonable to expect per capita results from Utah (low claims per capita estimate) and Georgia (high claims per capita estimate) to be transferred to Canadian provinces without correcting for CG lightning flash density. Similarly, the potency of CG lightning expressed as flashes per claim across the United States (low CG flashes per claim estimate) or Georgia (high CG flashes per claim estimate) should be corrected for population density. Accordingly, low and high per capita rates were adjusted by the relative 2000-2004 average annual CG flash density (derived from Vaisala, 2006) between the source study region (Utah or Georgia) and each province. Relative population densities between the source study region (U.S. or Georgia) and each province were used to adjust the rates of CG flashes per insurance claim.

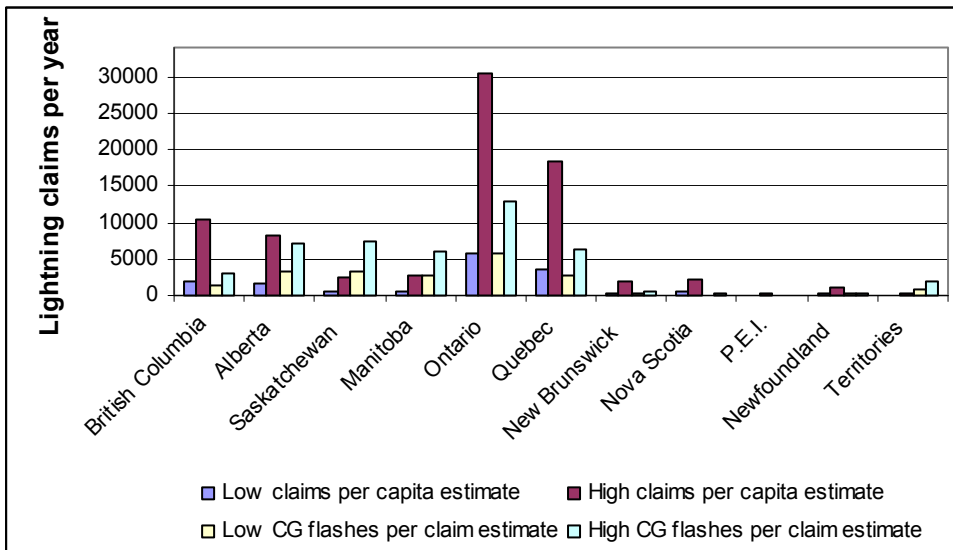


Figure 2. Unadjusted annual lightning-related insurance claim estimates by province

The provincial results of this adjustment are summarized in Figure 3. When summed, Canada-wide estimates are much smaller than the unadjusted values with a range of 3,900-5,250 lightning-related claims per year. These figures include those derived from both the adjusted per capita and adjusted CG flash rates and are surprisingly consistent. The general pattern at the provincial level reflects the combined influence of lightning frequency and population, with Ontario accounting for over 50 percent of estimated claims. Although beyond the scope of the current study, it would be interesting to analyze results at a finer scale given the expanse of many provinces and the concentration of population across “U.S. state-size” southern regions (e.g., Ontario, Quebec) or within a few large cities (e.g., B.C., Alberta, Saskatchewan, Manitoba).

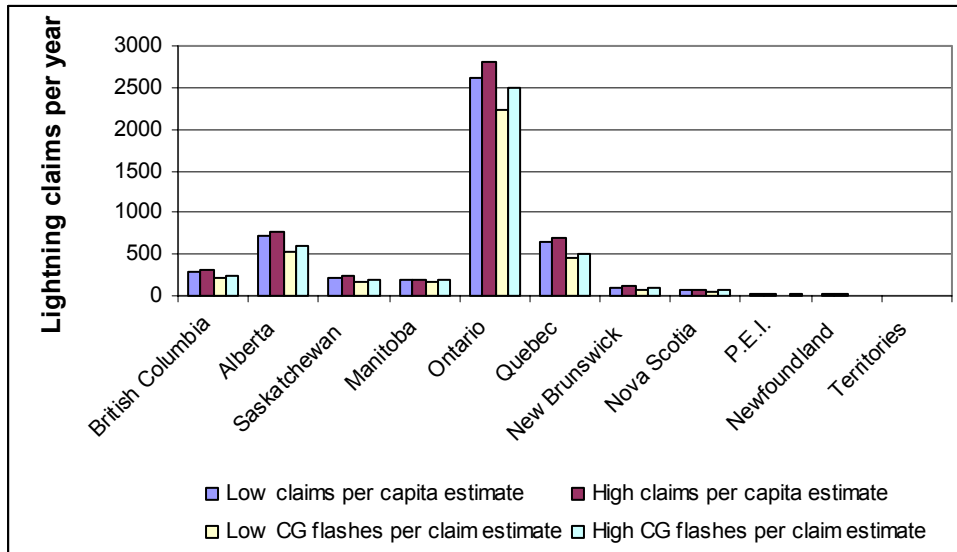


Figure 3. Adjusted annual lighting-related insurance claim estimates by province

In order to assess the losses associated with lightning claims, cost estimates were developed based on values reported in the studies referenced in Table 1 (Holle *et al.*, 1996; Stallins, 2002; Insurance Information Institute, 2007). Baseline costs per claim, corrected for currency and inflation, were applied to the adjusted Canadian claim estimates that were presented in Figure 3. Estimated annual lighting-related insurance claim losses are summarized in Table 13 and amount to \$6-21 million dollars. Application of an average home insurance deductible of \$500 would add from \$1.95 million to \$2.63 million to the low and high scenarios, respectively. The figures that are based on the Insurance Information Institute (2007) study, which was completed using the most current data (2003-2006), are likely more reflective of actual losses. They account for considerable recent growth in losses per claim that is attributable to increased household investment in a greater number of higher-valued consumer electronics.

Table 13. Lighting-related insurance claim loss estimates for Canada

Source study ¹	Cost/claim (US\$)	Inflated cost/claim (CA\$) ²	Estimated annual Canadian losses (CA\$)	
			Low (3,905 claims)	High (5,255 claims)
Holle <i>et al.</i> (1996)	\$916	\$1,525	\$5,954,107	\$8,012,695
Stallins (2002)	\$1,100	\$1,908	\$7,450,041	\$10,025,837
Insurance Information Institute (2007)	\$3,446	\$3,980	\$15,539,990	\$20,912,826

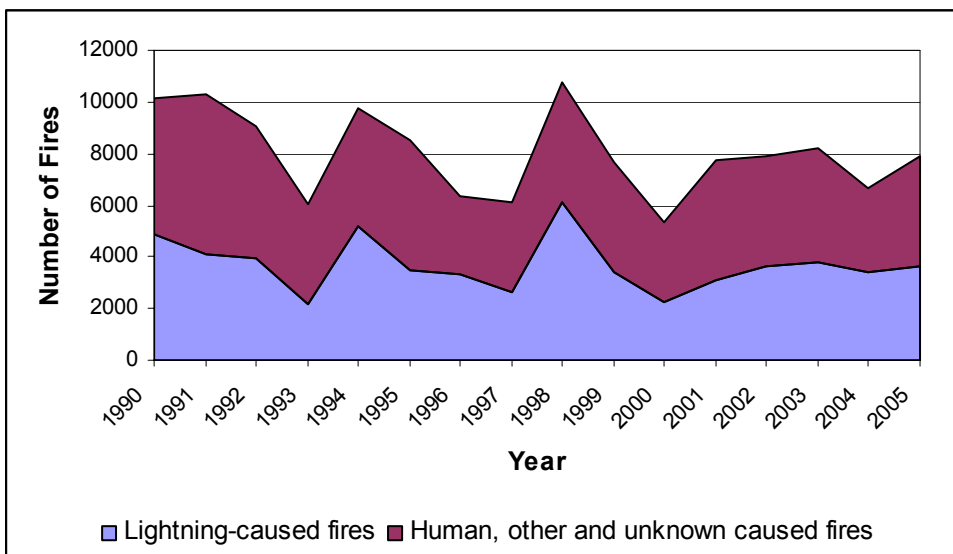
¹ see Table 1 for additional information on each study

² FXhistory-historical currency exchange rates <http://www.oanda.com/convert/fxhistory> and all-item CPI used to adjust/inflate costs; baseline years were 1990 (Holle *et al.*), 2000 (Stallins), and 2006 (Insurance Information Institute)

Forest fires

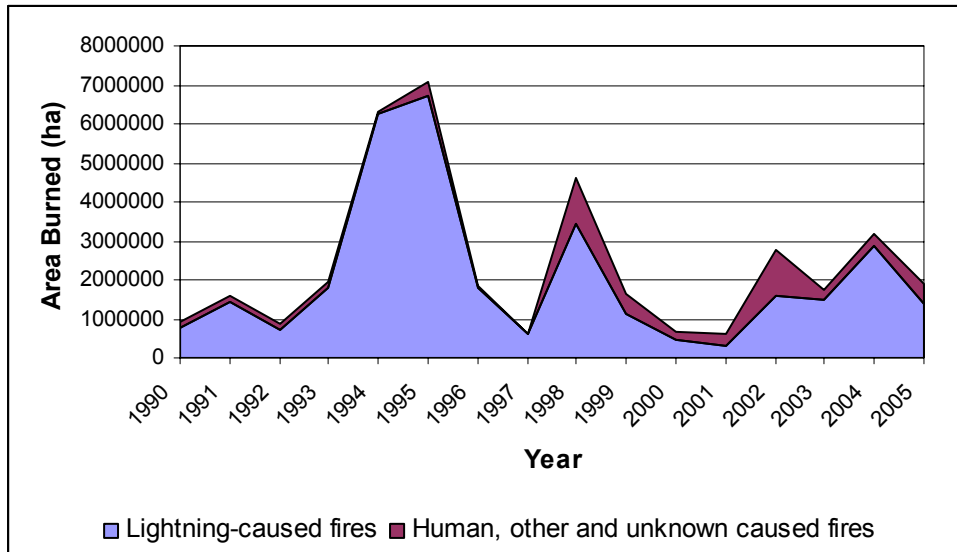
As noted in the literature review, the social costs of forest fires include those related to protection and suppression, property damage to buildings and other infrastructure, lost productive timber, amenity and recreation, and existence values of forests. Only the first two in this list are treated in the empirical analysis.

Two primary sources of data were consulted for the study: the Canadian Interagency Forest Fire Centre (CIFFC, 2007) and the National Forestry Database Program (NFD, 2007a). The NFD provided annual provincial and national summary statistics on fire frequency, cause, hectares burned, response category, and property losses for both the intensive and limited protection zones. These data were used to establish the number of fires and area burned that could be attributed to lightning and formed the basis of apportioning costs. Figures 4-5 plot the annual number of fires and area burned in Canada over the period 1990-2005. During this timeframe lightning accounted for about 46 percent of forest fires and 85 percent of the total area burned. The discrepancy between fire frequency and area burned is explained by the disproportionate number of large fires (i.e., greater than 200 ha) that are caused by lightning. Such fires account for 98 percent of the total area burned (CFS, 2007; Weber and Stocks, 1998).



Source: NFD, 2007a

Figure 4. Annual number of forest fires in Canada by cause, 1990-2005

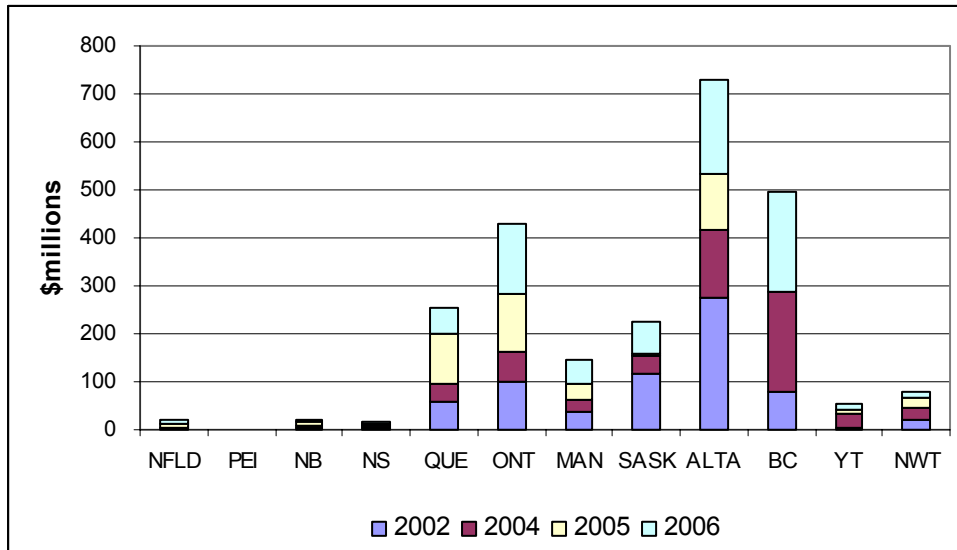


Source: NFD, 2007a

Figure 5. Annual area burned in Canada by cause, 1990-2005

Additional cost data, including property (interface) damage and pre-suppression and suppression expenditures were obtained from CIFFC annual national and agency reports (CIFFC, 2007). Other losses, including forest resource and improvement values, were inconsistently reported and thus were not applied in the current study. Pre-suppression costs are those incurred through fire management activities prior to the occurrence of a fire. The activities include *the organization, training, and management of a fire fighting force and procurement, maintenance and inspection of improvements, equipment, and supplies to ensure effective fire suppression* (CIFFC, 2002:36). Suppression costs result from all activities related to controlling and extinguishing a fire once it has been detected (CIFFC, 2002:19). Relatively complete provincial level data were available for the years 2002 and 2004-2006 while data for National Parks were available for 2002, 2003, and 2005.

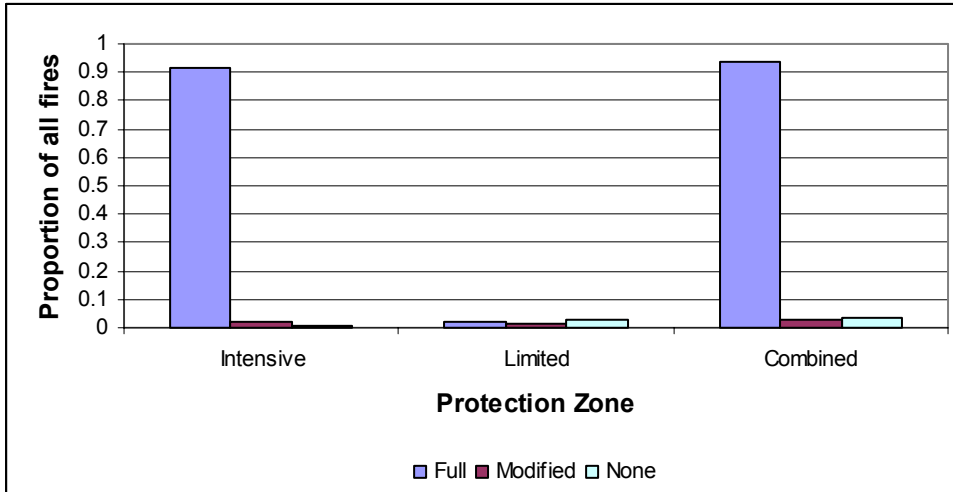
Annual provincial expenditures on pre-suppression and suppression activities for the years 2002, 2004-2006 are presented in Figure 6. Data concerning the relative contribution of lightning-ignited fires to the total number of forest fires that were actioned and area burned were used to allocate a portion of these costs to lightning-related incidents. Figures 7 and 8 provide information on the level of action applied to fires occurring within intensive and modified protection zone areas over the period 2002-2005. The intensive protection zone includes *forested lands of high value and areas where a risk to human life exists* while limited protection zone includes *remote forested lands or other areas of low value where intensive forest protection cannot be justified economically* (NFD, 2007b). A full response fire involves a *full, dedicated attempt to control the fire as soon as possible, consistent with resource availability and values at risk*, while a modified response fire is controlled in a *limited way such that only isolated values threatened by a fire are protected, or attempt to monitor a fire only until it goes out naturally* (NFD, 2007b). Slight variations to these definitions are noted in CIFFC (2002).



Source: CIFFC, 2007

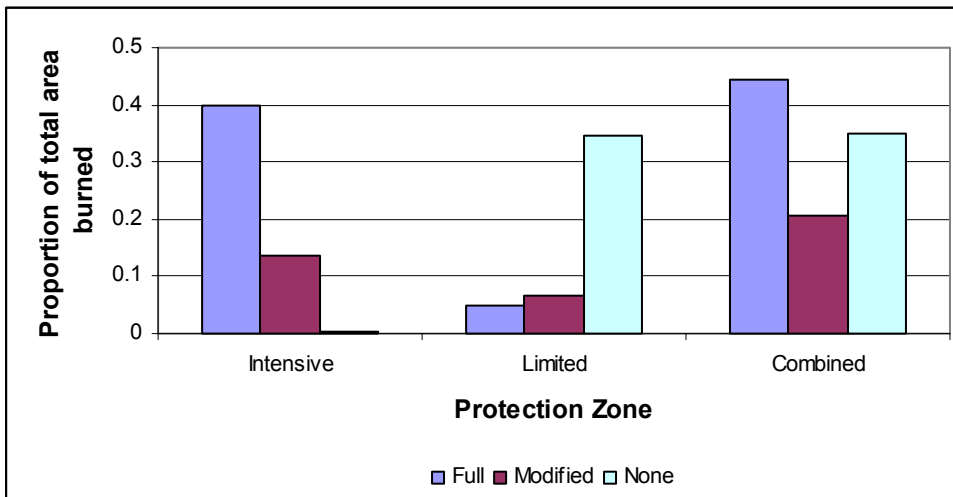
Figure 6. Annual pre-suppression and suppression costs by province, 2002-2005

As shown in Figure 7, most fires reported in the NFDP over the 2002-2005 year period occurred in the intensive protection zone and were fully actioned. A comparable chart for the area burned is presented in Figure 8. Clearly a small number of very large fires, or a large portion of the area burned by very large fires, received little or no response. Lighting accounted for 47 percent of all actioned fires in Canada over the 2002-2005 period and the same portion (47 percent) of actioned fires within the important intensive protection zone. In terms of the area burned, 65 percent of the area that received full or modified response was related to lightning-ignited fires. About 67 percent of the intensive protection area burned that received action was associated with lightning. Given that the level of preparedness and effort expended to fight fires is likely a function of both fire frequency and fire size (i.e., area burned), the minimum and maximum proportions (i.e., factors of 0.47 and 0.67) were used to assign national costs to lightning incidents. Property damage was apportioned in an identical way for the same years. Results are summarized in Table 14. The inflated total Canadian average annual expenditure of about \$620 million fits squarely within the estimated range of \$400-800 million cited in the literature review (NRCan, 2004) with lightning estimated to account for between \$290-415 million of the total.



Source: NFDP, 2007a

Figure 7. Proportion of all fires, by protection zone and response, 2002-2005



Source: NFDP, 2007a

Figure 8. Proportion of area burned, by protection zone and response, 2002-2005

Table 14. Lightning-related forest fire expenditures and property damage (2002, 2004-2006) derived from CIFFC (2007) and NFDPA (2007a)

Costs Category	Total Canadian Expenditure	Lightning-related Expenditure	
		Low Estimate (0.47)	High Estimate (0.67)
Pre-suppression	\$276,097,758	\$129,765,946	\$184,985,498
Suppression	\$339,553,723	\$159,590,250	\$227,500,994
Property damage	\$2,691,683	\$1,265,091	\$1,803,428
TOTAL	\$618,343,164	\$290,621,287	\$414,289,920
INFLATED TOTAL¹	\$656,051,246	\$308,344,086	\$439,554,335

¹inflated using all-item Consumer Price Index
 Source: derived from CIFFC (2007) and NFDPA (2007a)

Electricity transmission and distribution

The literature review revealed that lightning is an important variable in the management and operation of electricity infrastructure, in particular the transmission and distribution systems that provide power to residential, commercial, institutional and industrial customers. Forced outages and impacts to power quality affect these customers as well as the income of electric utilities. In order to derive an estimate of the costs of lightning-related outages and quality events in Canada, information concerning the duration of outages in Canada was combined with cost data originally developed for the U.S. Given the limited scope of this study and availability of data, it was not possible to develop a similarly robust power quality estimate.

Much of the outage cost analysis was based on work by Lawton *et al.* (2003) as interpreted and applied in an analysis of the cost of power interruptions to U.S. electricity consumers by LaCommare and Eto (2004). Customer damage functions were developed by Lawton *et al.* (2003) based on data from 24 studies and over 60,000 customer survey responses covering residential, commercial and industrial sectors in the U.S. Direct costing survey methods, whereby respondents are asked to identify net costs across multiple outage scenarios, were adopted in the commercial and industrial studies. Willingness-to-pay or willingness-to-accept approaches, in which customers are asked how much they are prepared to pay to avoid an outage scenario (or receive a credit remuneration for the costs/inconvenience), were used in the residential studies. The damage function models, developed using Tobit regression procedures for each customer class, estimate the average customer loss per event based on several predictors that account for the influence of outage duration, time-of-day, day-of-week, season, region, household income, and number of employees (size factor). The general form of the models, as defined in LaCommare and Eto (2004), is specified as follows:

$$Y = \text{Exp}[\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \varepsilon] + e$$

Where,

Y is the outage cost for a particular customer class (residential, commercial, industrial);

β_0 is the y-axis intercept;

X_n is the independent variable;
 β_n is the regression coefficient for each parameter; and
 ε and e are model error terms.

The specific regression coefficients for each parameter are defined in Table 15.

Table 15. Summary of select Tobit regression parameters used to predict electricity outage costs (LaCommare and Eto, 2004:23)

Predictor	Customer Sector Regression Coefficients		
	Residential	Commercial	Industrial
Intercept	0.2503	6.48005	7.7954
Duration (hours)	0.2211	0.38489	0.5753
Duration (hours) squared	-0.0098	-0.02248	-0.0338
Number of Employees	--	0.001882	0.0007
Annual electricity consumption (kWh for C&I, MWh for Res.)	0.0065	1.7E-06	2.52E-08
Interaction term (duration*kWh)	--	9.46E-08	-1.8E-09
Morning (1,0)	-0.0928	-0.6032	-0.5624
Night (1,0)	-0.1943	-0.91339	-1.3857
Weekend (1,0)	-0.0134	-0.52041	-0.7149
Winter (1,0)	0.1275	0.37674	0.8992
Household income (log \$)	0.0681	--	--
Southeast region (1,0)	0.2015	--	--
West (1,0)	-0.1150	--	--
Southwest (1,0)	0.5256	--	--

-- denotes not applicable

Source: LaCommare and Eto, 2004:23

Data were then obtained to develop inputs for each of the model parameters, including average annual electricity consumption for each customer type, number of electricity customers broken down by sector, household income, average number of employees for commercial and industrial sectors, and average lightning-related outage duration. A summary of the inputs is provided in Table 16.

Average consumption data for Ontario were obtained from McCracken and Rylska (2005) whose study on the societal costs of excavation-related underground electrical distribution network failures also adapted costing information from Lawton *et al.* (2003). Ontario annual consumption per customer values for residential (11,283 kWh), small-medium commercial and industrial (24,395 kWh), and large commercial and industrial (250,000 kWh) customers were assumed to be representative across Canada. For the purposes of the analysis, the latter two figures were also assumed to represent commercial and industrial values, respectively.

The breakdown of customers by use-sector was developed in two steps. First, the estimated total 2005 electricity demand for the Canadian residential sector (153 TWh) (NRCan, 2006) was divided by average residential customer use (11,283 kWh) to produce an estimate of 13.6 million customers. This figure closely matches the total number of dwellings in Canada in 2006 (also 13.6 million) (Statistics Canada, 2007d) which lends confidence to the residential consumption figure. The second step involved estimating the number of commercial and industrial customers as a proportion of residential customers using the relative distributions found in the U.S. in 2001 (LaCommare and Eto, 2004; Energy Information Administration, 2007). The number of commercial and industrial customers in the U.S. represents about 13 percent and 1 percent of the residential total, respectively. By applying these factors to the Canadian residential estimate, the authors produce an estimate of 1.78 million commercial and 0.18 million industrial customers in Canada.

Household (family) income and employment data were obtained from Statistics Canada (2007e,f). Average income for all families for 2005 was converted to U.S. currency before being entered into the model. Average employee estimates were determined using 2006 “employment by enterprise size interval” information for sectors representing the commercial (retail trade) and industrial (manufacturing) customer categories. The resulting commercial and industrial figures were 18 and 37 employees, respectively.

The duration parameter is the most influential variable of the models. LaCommare and Eto (2004) used System Average Interruption Duration Index (SAIDI) values from over 180 U.S. utilities to establish an average duration of sustained outages (outliers were trimmed) from which total costs were modeled. The SAIDI statistic is calculated by dividing the sum of sustained outage durations for all customers by the total number of customers served. Canadian Electricity Association data summarized by McCracken and Rylska (2005) reveal that lightning was the cause of over 3.1 million customer-hour interruptions each year in Canada over the 1993-2003 period¹⁰. About 59.1 million customer-hour interruptions per year resulted from all causes (McCracken and Rylska, 2005). For the current application, the average annual sum of lightning-related interruptions was divided by the sum of all residential, commercial, and industrial customers (estimated previously) to develop a lightning-related SAIDI score of about 0.2 hours (12 minutes). In addition to sustained outage costs, LaCommare and Eto (2004) also evaluated momentary outages (i.e., duration of zero in model) and incorporated related costs into their national assessment. Their analysis used Momentary Average Interruption Frequency Index (MAIFI) data from U.S. utilities which is calculated by dividing the total number of customer momentary (< 5 minutes) interruptions by the total number of customers served. Lacking equivalent data throughout Canada¹¹, the authors simply scaled a MAIFI estimate from the lightning-related SAIDI using the proportion of U.S. SAIDI to MAIFI values adopted in LaCommare and Eto (2004)¹². This choice is likely somewhat conservative. An average lightning MAIFI value of 0.22 (2000-

¹⁰ Based on data for 31 Canadian CEA-member utilities (i.e., figure is likely greater)

¹¹ Some aggregate data are available from the Canadian Electricity Association but costs were deemed too high for this study

¹² The authors note that LaCommare and Eto (2004) did not find a significant relationship between SAIDI and MAIFI from their data

2005) determined using data for one large Canadian utility, Toronto Hydro, was about 20 percent greater than the chosen factor.

Table 16. Canadian parameter inputs to cost model application

Predictor	Customer Sector Inputs		
	Residential	Commercial	Industrial
Duration (hours)	0.2016	0.2016	0.2016
Average number of employees	--	18	37
Average annual electricity consumption	11.28 MWh	24,395 kWh	250,000 kWh
Household income	US\$54,850	--	--

-- denotes not applicable

The various inputs were entered into the model to produce estimates of the average costs per customer per power outage/interruption for residential, commercial and industrial categories. A combined estimate for each use category was developed by applying the model for six potential time periods in which lightning outages may be expected to occur (i.e., summer x weekday/weekend x morning/afternoon/night). Results were weighted by the relative number of hours in each respective period as in LaCommare and Eto (2004). All of the regional parameters were set to zero which by default represents the northern U.S. region (assumed to be more similar to Canada).

Tables 17-19 present the final set of results for the Canadian electricity sector application. Lightning-caused sustained outages are estimated to cost Canadian customers about \$83 million each year while momentary outages cost an additional \$273 million. The commercial sector accounts for about 73 percent of total costs with the industrial and residential sectors contributing 24 percent and 3 percent, respectively. These proportions are very similar (within 1-2 percent) of baseline costs assessed for the United States (LaCommare and Eto, 2004) and reflect the combined influence of average costs per outage per customer and the total number of customers in each class.

Table 17. Estimated annual lightning-caused sustained outage costs in Canada

Customer Type	Average cost per sustained outage per customer ¹	Total estimated customers	Customers affected by sustained outages (5% total) ²	Total Costs ¹
Residential	\$3.12	13,560,223	678,011	\$2,112,599
Commercial	\$684.70	1,772,152	88,608	\$60,669,254
Industrial	\$2,147.21	187,723	9,386	\$20,153,999
TOTAL		15,520,098	776,005	\$82,935,852

¹ FXhistory-historical currency exchange rates <http://www.oanda.com/convert/fxhistory> and all-item CPI used to adjust/inflate costs from 2002 US\$ baseline to 2007 \$CDN

² conservative estimate based on reported 5.9% lightning proportion of total customer interruptions in 2000 (Gelineau, 2002) (essentially assumes an overall SAIFI of 1.0 and lightning-SAIFI of 0.05)

Table 18. Estimated annual lightning-caused momentary outage costs per customer in Canada

Customer Type	Average cost per momentary outage ¹	Total estimated momentary customer outages ²	Total Costs ¹
Residential	\$2.98	2,429,540	\$7,242,897
Commercial	\$634.14	317,510	\$201,345,671
Industrial	\$1,914.62	33,634	\$64,395,829
TOTAL		2,780,684	\$272,984,397

¹ FXhistory-historical currency exchange rates <http://www.oanda.com/convert/fxhistory> and all-item CPI used to adjust/inflate costs from 2002 US\$ baseline to 2007 \$CDN

² based on ratio of U.S. MAIFI:SAIFI values used by LaCommare and Eto (2004) and applied to Canadian lightning-related SAIFI

The previous analysis permitted examination of another type of cost noted in the literature review. Utilities lose revenue from customers when lighting outages occur. Using the average outage duration applied in the customer cost analysis (0.2 hours), average demand data (McCracken and Rylska, 2005), and electricity pricing information (NRCAN, 2006), revenue losses are estimated to total about \$16,000. Even if the figures presented in Table 19 are in error by a few orders of magnitude, they are dwarfed by the customer losses associated with sustained and momentary outages.

Table 19. Estimated annual lightning-related utility revenue losses in Canada

Customer Type	kWh lost to lightning-caused sustained outages ¹	Electricity rate (¢) per kWh ²	Revenue loss
Residential	177,917	6.54	\$11,644
Commercial	50,053	4.75	\$2,378
Industrial	54,412	3.98	\$2,166
TOTAL	282,382		\$16,187

¹ product of average outage duration (0.2 hours), hourly consumption, and customers affected (table 17)

² Canada-wide estimate based on NRCAN (2006)

An Initial Aggregate Estimate

By combining the range of low and high estimates from each of the four sector analyses, one produces an overall annual lightning-related damage and disruption figure between \$600 million and \$1 billion. While this figure is incomplete, based on the literature review the authors believe that it includes the major contributions to lightning-related costs.

Table 20. Combined annual estimates of lightning-related damage and disruption costs for Canada

Sector	Key impact/cost	<u>Estimated Annual Costs/Losses¹</u>	
		Low	High
Health	Lightning-related injuries and fatalities	\$3,648,793	\$79,291,126
Property	Lightning-ignited municipal fires	\$14,858,541	\$16,414,436
	Insured losses and deductibles	\$7,906,521	\$23,540,272
Forestry	Forest fire suppression and pre-suppression	\$306,981,081	\$437,611,328
Electricity	Sustained and momentary outage costs to customers	\$266,940,187	\$444,900,311
	Lost revenue	\$16,187	\$16,187
TOTAL		\$600,351,310	\$1,001,773,660

¹ low and high estimates taken from report tables; electricity low and high values determined by subtracting and adding 25% to estimates (tables 17-18)

4.0 DISCUSSION

This study provided a review of available literature concerning the damage, disruption and costs associated with lightning and an initial assessment of impacts and costs for Canada totaling between \$0.6-1 billion each year (Table 20). Care must always be taken when interpreting these estimates, not the least of which because of uncertainties that arise from the degree of incompleteness, potential double-counting, transferability of U.S.-based relationships, variable treatments of costs (direct, indirect, social costs, etc.), assumption concerning the Canada-wide applicability of results, and the general use of multiple data sources over variable timeframes. Lacking resources to produce original data explicitly for the particular objectives of this project, the authors relied upon readily available data and impact relationships drawn from studies completed in the U.S. The specific sources of information, references, and steps used to develop the estimates for each sector are defined such that others can repeat and improve upon these initial results.

Overall, the authors believe that the estimates are conservative. In part this is because impacts and costs for several sectors are not included in the analysis. The authors considered deriving lightning-related impact and cost estimates for other Canadian sectors, including transportation (aviation) and tourism and recreation (golfing). In the case of aviation, where convective disturbances are estimated to cost the U.S. industry up to \$2 billion annually (Weber *et al.*, 1998), cause-of-delay and frequency of ground operation interruptions information for Canada were not readily available. Extrapolating from the U.S. estimate would prove difficult given radically different networks and issue with respect to discerning the proportion of U.S. delays and thus costs that are due to lightning as opposed to other aspects of convective weather. Similarly for golfing, where lightning may reduce the potential revenue of a course/operation, it proved very difficult with available sample data to distinguish between the effects of lightning and rainfall on the number of daily rounds played. By not including these and other sectors where even less information was found (e.g., telecommunications), or other impacts to those sectors that were included (e.g., power quality events on electricity customers, utility transformer or surge protection and repair/replacement expenditure, costs of lost timber value due to fires), the study errors on the conservative side.

Despite the caveats noted above, the estimated impact of lightning in terms of damage and disruption to Canadians is very large and certainly much greater than that attributed to other forms of hazardous weather (i.e., tornadoes, hail, hurricanes). With this very basic impact information in hand it is possible to begin evaluating where the introduction of new preventive measures and technologies may yield potential cost savings. This includes further development of the Canadian Lightning Detection Network and related information products, services, and forecasts. While evidence of substantial innovation and investment in lightning protection and detection was apparent for the electricity sector and wildfire management agencies, this study suggests that, at the macro scale, residual costs or impacts may still warrant further investment. Potential benefits may also be realized by the property and casualty insurance sector. Finally, it goes without saying that society will be better off if the number of lightning-related injuries and fatalities can be reduced. The authors hope that this research, together with the previous study (Mills *et al.*, 2006), will help raise awareness of the

importance of lightning in Canada and lead to measurable improvements in safety and reductions in costs.

5.0 SUMMARY AND RECOMMENDATIONS

In summary, the following key observations result from the literature review and analysis:

- Lightning is a frequently occurring meteorological hazard in Canada that routinely damages property and disrupts economic and social activities. Affected sectors include health; property and casualty insurance; forestry; electricity generation, transmission, and distribution; agriculture; telecommunications; transportation; and tourism and recreation—the first four sectors are the most important in terms of contributing to overall impacts and costs.
- Analysis of Canadian media reports of lightning-related damage and disruption confirmed the presence of severe underreporting. Media reports have limited utility in quantifying the magnitude of lightning-related impacts and losses.
- Secondary data and extrapolations from U.S. studies were used to develop cost estimates for the health, property, forestry, and electricity sectors. When aggregated, annual lightning-related damage and disruption costs in Canada range from \$600 million to \$1 billion. Given incomplete coverage, this estimate is conservative.
- Annual lightning-related injuries (9-10) and fatalities (92-164) are estimated to cost between \$3.6 million and \$79.2 million. The wide range reflects different approaches to assessing costs with the high estimate more representative of social costs.
- Municipal fire agencies respond to over 800 fires ignited by lightning each year. These fires cause an average of \$16.4 million in property damage.
- Between 3,900 and 5,300 insurance claims are estimated to be filed for lightning-related property damage (excluding fires) each year. Annual insured losses, coupled with deductible payments, amount to between \$7.9 million and \$23.5 million.
- Lightning-ignited wildfire is estimated to cost fire fighting agencies between \$307 million and \$437.6 million in pre-suppression and fire suppression expenditures. A further \$1.3 million to \$1.8 million of property damage.
- Sustained and momentary power outages are estimated to cost Canadian customers between \$267 million and \$445 million each year. At about \$16,000, utility revenue losses are small by comparison.

The following recommendations are suggested based on the results of this initial investigation:

- Results from this study should replace current estimates of lightning-related damage that are used by Environment Canada and other federal departmental in various communications with the public and stakeholders.
- Damage estimates should be shared and discussed with representatives of the electricity, forestry, and insurance sectors.
- In terms of continued research, additional or more refined studies using Canadian empirical data are warranted for the insurance and electricity sectors. Detailed insurance claim or outage data would permit analysis at the storm level and potentially discern finer-scaled risk patterns. Further effort is also required to evaluate risk or damage prevention measures, particularly those that relate to expanded or enriched use of the CLDN data by both public and private sector clients. Both the degree of adoption and efficacy or cost-effectiveness should be investigated.

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