Potential Impacts of Climate Change on Railroads

By **Michael A. Rossetti**

The purpose of this paper is to identify and evaluate the effects associated with the potential impacts of climate change on railroad operators. It describes weather and climate factors affecting railroads along different time scales. It recommends the development of partnerships among governmental, industry, academia, and the research community in the study of the potential impacts of climate variability and change on transportation systems.

Railroads and their Physical Operating Environments

Throughout their existence, railroad operators have faced difficult environmental conditions that expose tracks, facilities, trains, and crews to an array of severe weather situations. Operating in sometimes remote and wilderness locations, railroad companies must deal with thunderstorms, tornadoes, flash floods and river floods, rock and mud slides, avalanches, desert heat, extreme cold, high crosswinds, snow and ice storms, limited visibility, lightning, and tropical cyclones (see Box 1).

The certainty and severity of some of these events often requires specific actions such as train rerouting or halts with little advance warning. Still other events are amenable to planning and strategies with longer lead times, but sometimes with more uncertainty. Terrorist threats have now placed urgent emphasis on the security of hazardous materials shipped by rail, with the intentional release and dispersion of such materials then potentially affected by existing meteorological conditions, and perhaps even climate anomalies.

Implications of Climate Change

Climate models suggest a future warming of 0.2 - 0.3°C per decade.[1] Sea levels are expected to rise at a rate of 4 to 10 cm per decade. Ancillary effects include changes in regional distributions of rainfall and soil moisture, and possibly more frequent and more intense storm systems. In recent years, the complexities of climate change and predictions of climate model outputs have introduced an additional measure of uncertainty for railroad operators. Weather events, climate oscillations, and climate trends hence affect railroad safety, including fatalities, injuries, and property damage. Through their interactions with maintenance, planning, operating efficiency, scheduling, and demand for freight and passenger services, weather and climate may also affect a firm's balance sheet, and cash flow, capital investment decisions, and even competitive stance within the industry.

Box 1. *How weather affects railroad operations.*

Weather is a major influence on many aspects of the transportation system: particularly safety, mobility, accessibility, economic efficiency, and infrastructure. While the nature and extent of this influence may vary between modes, all modes are affected. Railroads are no exception, and in fact suffer from a variety of atmospheric and environmental factors, many of which are unique to this particular mode and deserving of special focus by the transportation and meteorological communities.

Weather adversely affects railroad safety, efficiency, and property in many ways. Intermodal crossing points, such as grade crossings and waterway/railroad trestle intersections are vulnerable, as are remote stretches far removed from observational networks. Railroads may also be subject to sudden weather-induced mode shifts, such as occurred during the East Coast blizzard of January 1996.

Precipitation and fog lead to decreased visibility of signals to locomotive engineers. Flash floods can lead to washout of tracks and consequent derailment. Seasonal floods from rivers may make some track segments impassable. Warping of tracks due to uneven thermal expansion in the summer, or buildup of snow and ice on the tracks in the winter, can lead to decreased speeds and derailment. Extreme cold causes brittle track and track separation. Since railroad locomotives and cars are high-profile vehicles, high-speed crosswinds can influence their stability.

Weather can lead to serious delays on the railroads and resulting loss of economic efficiency, as had happened during the Midwestern floods of 1993. Damage to tracks due to weather, besides being a safety hazard as mentioned earlier, also has serious economic consequences. Additionally, weather induced delays contribute to inefficient fuel use and reduced air quality.

These impacts represent the potential benefits in saved lives and saved resources from enhanced weather information to support railroad decision-making. Two reasons why we have unique opportunities to apply better weather information are 1) major gains on the weather side. Advances in meteorological science and technology have led to the development of advanced weather sensing capabilities (such as NEXRAD and weather satellites). They have also led to improved forecasting capabilities through major advances in our understanding of atmospheric behavior (for example, of the physics of storms), and in computational power. Forecasting technology today has the capability to provide fine-grid weather information, near or at the required spatial (~1km) and temporal (~30 minutes) resolution for railroad decision making. 2) Gains on the transportation side that facilitate the use of enhanced weather information. One example is Positive Train Control (PTC) technology, which some analysts suggest is part of the intelligent transportation system (ITS). Established in 1991, the ITS embodies a unified set of electronics, communications, hardware, and software. It also includes "intelligent vehicles" driver assistance and control systems and represents a collection of mostly existing technologies arrayed to produce benefits to surface modes.

Railroads can be both a consumer and producer of atmospheric and environmental data. Onboard sensors may one day prove useful as a data source for meteorological models and forecast decisions. Similarly, stationary sensors mounted in wayside bungalows and along track right-of-ways may provide meteorologists and railroad traffic managers with valuable, multipurpose observations from remote locations.

Railroad operations and infrastructure adapt or respond to short term weather conditions as well as longer-term climate conditions. Longer-term effects include cyclical or transient climate changes within a normally expected climatology. Longer-term effects also include secular changes that require a more permanent response. Figure 1 depicts some of these comparative interactions and how the railroad industry and emergency response industry may respond. The planning and decision making functions in railroads have time horizons that vary according to the hypothetical forecast accuracy and lead time required for a given weather event. Compared to emergency managers, railroad personnel have generally less need for real-time information, but greater requirements for long-range guidance.

Cyclical and Secular Changes in Climate

Fluctuations in local, regional, and national climate regimes occur at intervals ranging from periodic to irregular. Some of these processes, such as volcanic activity and the El Niño southern oscillation (ENSO), are better understood than are others, but most have some direct or indirect implications for transportation and railroads (see Table 1). Some are naturally occurring conditions, while others are forcing mechanisms, such as a change in solar radiation or the atmospheric accumulation of greenhouse gases (GHG).

Climate models offer predictions about the future chemistry of the atmosphere, about the response of the oceans, and potential effects on broadly defined land areas. They also predict potential large-scale atmospheric and hydrologic regimes within which day-to-day weather events occur. There are two general types of climate prediction work: seasonal to interannual (e.g. El Niño and other types of oscillations), and decadal to century (global warming studies/secular trends).

Because short-term weather events are affected by the same processes that climate changes may alter, it may be possible to use seasonal or interannual oscillations, or long-term secular trends, to adjust forecasts for weather events. Intrinsic skill levels for weather forecasts have generally improved over the past two decades, thus input from climate knowledge may help local forecasters at the margin, particularly in situations where short-term models disagree on things such as storm tracks and intensity, or the likelihood of severe convection. Given that, climate models provide some lead information about tendencies toward:

- Changes in sea surface temperatures and major currents (polar ice cap melt)
- Changes in ocean salinity levels (from above)
- Changes in regional rainfall patterns that result in regional droughts or excessive precipitation.
- Warmer winters
- Increased cloudiness
- Decreased snowfall
- Increased storminess (overall higher amounts of heat energy can be converted into storminess, or transferred to the oceans)
- Rising sea levels (when combined with more intense storms, this will allow battering waves to produce coastal erosion and destruction of infrastructure)

Evidence of a Climate Change

Although the reliability of regional scale climate and weather predictions is still low, and the degree to which climate variability may increase remains uncertain, potentially serious changes have been identified. These changes include increases in some regions in the frequency and intensity of extreme weather events such as high temperature waves, droughts, floods, and storm tides. Climate change and its associated effects (e.g., temperature, sea level, precipitation, and water levels) could jeopardize portions of the railroad system.

The vulnerability of the railroad system to climate change arises mainly from the susceptibility to sudden unforeseen changes in weather or climate patterns and from potential increases in the intensity and frequency of extreme weather events. Analysis of the potential effects of climate change and variability on railroad systems must also distinguish between their potential effects on railroad infrastructure and on railroad system operations. Railroad infrastructure includes all physical capital infrastructure elements for both freight and passengers. Railroad operations include all recurring activities related to the movements of goods and people.

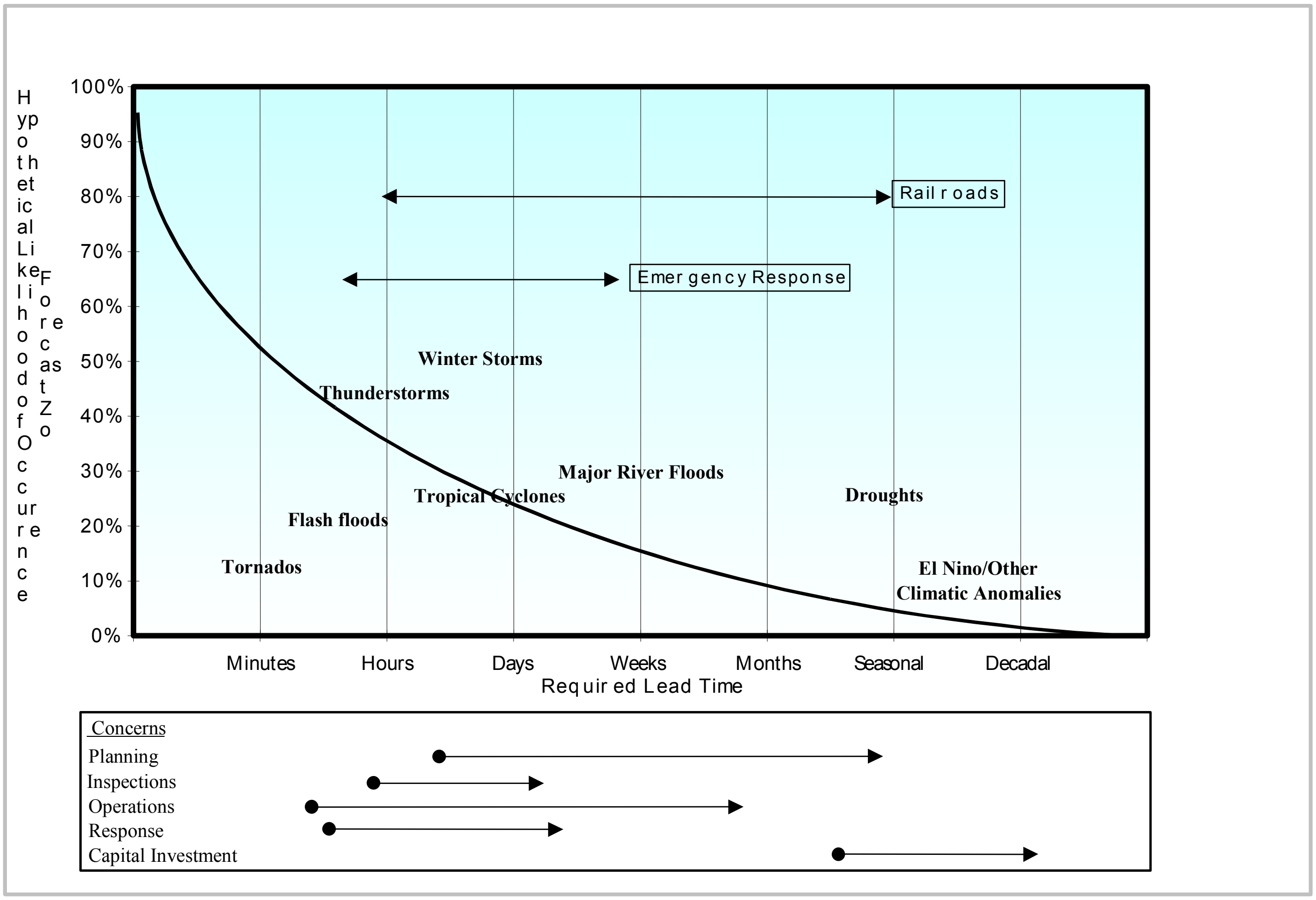

Figure 1. *Weather and climate events, hypothetical forecast likelihood and lead times required by railroads and emergency response.*

Railroad Systems and Climate and Weather

In order to begin to investigate relationships between weather and climatic data and railroad operations, the FRA Accident/Incident database[2] was consulted, and data were downloaded for analysis. It is important to begin to identify, collect, and analyze data of potential use in establishing interrelationships between climate and weather events and railroad operations. In addition to FRA and industry information sources, such data could potentially include local, regional, and national climate and weather averages and events, as well as short term and localized weather information (see Box 2 for a

Table 1. *Climate indices and transportation impacts.*

Climate Influence	Description	Periodicity	Sample Effect on Climate	Sample Impacts on Transportation
El Niño Southern Oscillation (ENSO)	Long term changes in sea surface temperatures in the Pacific Ocean. Dominant southern jet stream results in warmer conditions, and heavy precipitation in the western U.S.	1-3 years	Warm phase: flooding, storm tracks, violent weather, fewer Atlantic hurricanes Cold phase: regional droughts, more Atlantic hurricanes	Pacific coastal infrastructure exposed to stronger storms, heavy precipitation, high winds and waves. Heavy snows in Sierras and Rockies.
North Atlantic Oscillation (NAO)	Long-term pressure changes over the Atlantic	Broad band spectrum with no significant dominant periodicity	Positive phase: milder, wetter, east coast winters Negative phase: colder, snowier winters in eastern states	More frequent episodes of difficult travel conditions. Colder temperatures may result in price increases for fuels.
Pacific Decadal Oscillation (PDO)	A cycle of long term variability of sea surface temperatures in the North Pacific	23-30 years	Warm phase: warmer, drier winters in northern states- wetter and cooler in the south Cold phase: colder, snowier condition in the eastern U.S., warmer in the west and Alaska	Cold phase makes transportation more difficult in northern areas.
Arctic Oscillation (AO)	Changes in pressure patterns of polar vortex	Broad band spectrum with no significant dominant periodicity	Positive phase: milder U.S. winters Negative phase: Colder winters	More frequent winter travel conditions
Pacific-North American Teleconnect-ion (PNA)	A strong trough and ridge pattern over the North Pacific and North America	4 years	Warmer conditions in western U.S, more polar outbreaks and storms in east	Similar to negative AO
Madden Julio Oscillation (MJO)	Iintra-annual fluctuation that explains weather variations in the tropics.	30-60 days	Low-frequency variations in the tropics produce weak eastward/poleward moving waves	Large-scale changes in tropical convection from MJO affect jet streams over North Pacific and South Pacific – modulations in jet can cause blocking patterns in North America
Global warming from greenhouse gases: carbon dioxide, black carbon, and methane	Combustion of fossil fuels results in higher levels of carbon dioxide, methane, black carbon, and particulates	Secular trend	Rising sea levels, warmer and wetter conditions, more frequent and intense storms	Coastal infrastructure at risk (ports, airports, roads, rail)
Volcanic activity	Large ejection of particles into upper atmosphere	n/a	Reduced sunlight causes cooling	Air traffic affected by volcanic ash, more winter-like conditions

preliminary agenda for research and data analysis).

Methodology

By examination of a ten-year period of FRA safety data (1993-2002 partial), approximately 5,700 records were available. Through the application of screening criteria, the fields listed below were considered to be a reasonable portrayal of weather related data. It should be noted that weather data are not as comprehensive as would be desirable, and there is reason to believe those weather-related accidents and incidents are probably under-represented in the records. For example, frozen air lines are a chronic problem in cold weather operations, but there is no code available to approximate this activity. The same problem exists for brittle or broken tracks caused by extreme cold.

Train Accident Cause Codes Possibly Weather Related

T001	Roadbed settled or soft
T002	Washout/rain/slide/flood/snow/ice damage to track
T109	Track alignment irregular (buckled/sun kink)
M101	Snow, ice, mud, gravel, coal, etc. on track
M102	Extreme environmental condition - TORNADO
M103	Extreme environmental condition - FLOOD
M104	Extreme environmental condition - DENSE FOG
M105	Extreme environmental condition - EXTREME WIND VELOCITY
M199	Other extreme environmental conditions (provide detailed description in narrative)
M305	Highway user unawareness due to environmental factors (angle of sun, etc.)
M306	Highway user inability to stop due to extreme weather conditions (dense fog, ice or snow packed road etc.)

In addition to the causal data fields above, all accident records were downloaded that were reported as having snow, sleet, rain or dense fog present at the time of the event. This yielded a total of 795 usable records out of the original 5,700. Code T001, while not directly weather-related, was included to capture all possible soft roadbed activity arising from excess soil moisture or heavy rains. Code T002 directly captures this activity, but only if there is an observed consequence, i.e., a washout, mudslide, etc. Code T109 directly captures sun kinks, a perennial problem for trains operated in hot, sunny regions of the country. Table 2 shows some preliminary tallies of the T-type codes:

Considering the problems posed by flash floods and slides, it is surprising to see how few accidents are associated with T002, as well as the lack of any seasonality from years with known flood events. Only 18 such incidents were reported in the 10-year period. Sun kinks (T109) present slightly better, with an average of about 7 incidents per year, and with some weak seasonality apparent in 1994 and 1999.

Table 3 shows a similar tally for accidents where environmental conditions were listed as the primary cause. Extreme winds were most frequently reported as an environmental cause, although the total of 26 incidents over ten years again seems on the low side. Track obstructions – snow, ice, mud, rock – appeared 22 times as the primary cause. Only four tornadoes and four floods were reported during the period.

Table 4 looks at the specific weather factors reported present at the time of the accident, though not reported as a cause of the accident. There is probably some classification error present when accident forms are filled out, and perhaps there is a bias against citing weather as a primary cause. The presence of these weather conditions – snow, sleet, rain, and dense fog – may act to increase overall risk in a given situation regardless of causality. Considering the usual confusion involved in identifying sleet, it could probably be eliminated as a data field. Freezing rain may prove a more useful attribute. Fog seems underreported, especially in view of

Table 2. *Reported cause of accident/incident was track, roadbed, or structures.*

Year	T001 Roadbed settled or soft	T002 Washout/rain/slide/flood/ snow/ice damage to track	T099 Other roadbed defects (Provide detailed description in narrative)	T109 Track alignment irregular (buckled/ sunkink)
1993	6	3	0	8
1994	8	4	0	10
1995	4	0	0	9
1996	3	0	0	6
1997	3	2	0	2
1998	4	3	0	6
1999	5	2	0	13
2000	6	2	0	7
2001	4	1	1	6
2002	3	1	0	0
Totals	46	18	1	67

Box 2. *An agenda for further research and analysis to investigate climate and railroads.*

Climate variability and change assessments and scenarios

1) *Analysis of the climatic record*. Develop an understanding of the influence of natural processes and human activities – including railroads – on climate variability and change. Establish basis to understand the relationship between railroad activities and the climate system. Define hypothesis under which DOT and FRA operate in the climate change arena.

2) *Analysis of climate change assessments and forecast scenarios*. Develop an understanding of the projected changes in climate and weather patterns at the local, regional, and national levels, and study the relationship between – and effects of – climate change on weather. This includes review of models and reports from the USGCRP and others.

Impacts of climate change on the railroad system

1) *Identification of critical climate and weather parameters*. Identify and analyze climate and weather parameters that affect railroad operations and infrastructure (e.g., visibility, precipitation).

2) *Scaling of data on the interaction between railroad and weather*. Scale weather data to the temporal and spatial resolutions required to develop relationships at the level of climate change data.

3) *Analysis of climate change effects on railroad operations*. Identify relationship between climate and weather parameters and railroad operations. Analyze safety, mobility, accessibility – and the resulting economic – implications of climate change under forecasted scenarios.

4) *Analysis of climate change effects on railroad infrastructure*. Identify vulnerable railroad infrastructure elements (e.g., coastal and low-lying areas), survivability (e.g., life-cycle degradation due to corrosion and water flow effects) of infrastructure elements, and construction implications (e.g., evacuation infrastructure and infrastructure replacement) of climate variability and change.

Table 3. *Reported cause of accident/incident was an environmental condition.*

Year	M101 Snow, ice, mud, gravel, coal, etc. on track	M102 Tornado	M103 Flood	M104 Dense fog	M105 Extreme winds	M199 Other extreme environmental condition	M305 Highway user unawareness due to environmental factors (angle of sun, etc.)	M306 Highway user inability to stop due to extreme weather conditions (dense fog, ice or snow packed road etc.)
1993	2	1	1	0	1	0	0	0
1994	1	0	1	0	1	2	0	0
1995	2	2	0	0	2	1	0	0
1996	2	0	1	0	4	1	0	0
1997	2	0	1	0	2	1	0	0
1998	1	0	0	0	4	2	0	1
1999	3	0	0	0	3	1	0	0
2000	3	0	0	0	4	0	0	0
2001	5	1	0	0	2	0	0	1
2002	1	0	0	0	3	0	0	0
Totals	22	4	4	0	26	8	0	2

Table 4. *Weather conditions reported at time of accident/incident.*

Year	6 Snow	5 Sleet	4 Fog	3 Rain
1993	16	1	11	38
1994	14	3	10	41
1995	12	2	8	54
1996	13	2	4	41
1997	12	0	5	38
1998	5	1	8	43
1999	12	1	9	33
2000	26	3	11	63
2001	16	0	14	51
2002	5	3	1	9
Totals	131	16	81	411

the many remote locations through which railroads operate.

Figure 2 looks at the data according to month. As might be expected, weather-related accidents reach their peak in the December to January time frame, with a secondary peak in April, likely coinciding with the problems of spring floods, soft roadbeds and the like.

The final graph (Figure 3) shows weather related accidents distributed by state. Generally, the number of accidents conforms to state distributions of track mileage or similar indicators of volume. Out of the top 5 states, however, Arkansas and Washington are slight exceptions to this rule. The rough terrain crossing Washington State probably accounts for some of this activity, as there are frequent days of heavy snow, rain, and fog, all requiring navigation through steep grades.

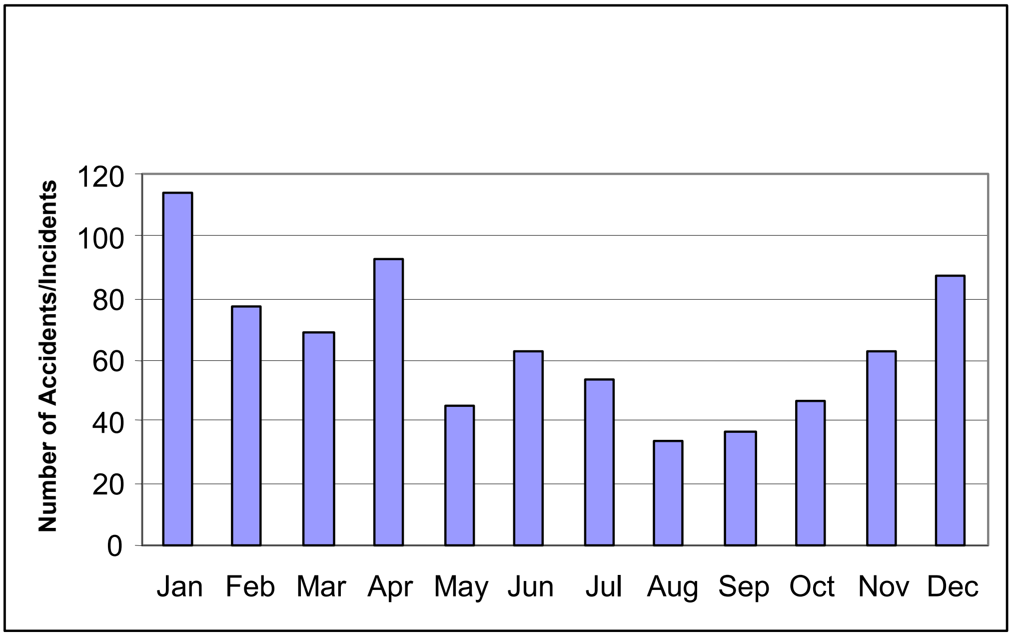

Figure 2. *Weather-related railroad accidents/incidents, by month of occurrence, 1993-2002.*

Weather Hazards that Could Be Affected by Fluctuations or Changes in Climate

Floods and Flash Floods

The nature of the problem is both meteorological (understanding the location, duration, and quantity of rainfall in the atmosphere) and hydrological (understanding soil absorption, runoff, how the water will behave after it hits the ground). Despite technology modernization, advances in modeling, and increases in computer power, quantitative precipitation forecast (QPF) skill levels remain low. Adding a climate dimension to model output may impart a more valuable forecast for the public, government, emergency management field, and businesses with exposures to such events. Problems posed by high waters from flash floods, river floods, persistent heavy rains, and hurricanes have historically been one of the most prominent weather-related concerns facing the railroad industry, as well as the nation as a whole. Some climate models predict increased precipitation in specific regions. This, along with faster melting of mountain snow and seasonally high spring water levels, may significantly impact railroad operations in the next century.

Among weather events, floods annually produce some of the largest amounts of economic damage and fatalities. The Midwestern river floods of 1993 devastated railways, with over 4,000 miles of track either flooded or idled and over $200 million in estimated losses. A flash flood that weakened an existing wooden trestle led to the 1997 Kingman, Arizona derailment of an Amtrak passenger train that injured 183 and produced damages of $7.2 million. The Kingman incident generated a special FRA safety advisory, concerning the use by railroads of official weather watches and warnings.

Rockslide and Avalanche Hazards

Aside from possible increases in the number of floods, hurricanes, tornadoes, and other violent storms, climatic fluctuations that produce increased precipitation and greater temperature swings are likely to trigger more earth, rock, and snow slides in mountain areas. Because of the mitigation efforts that the railroad industry has

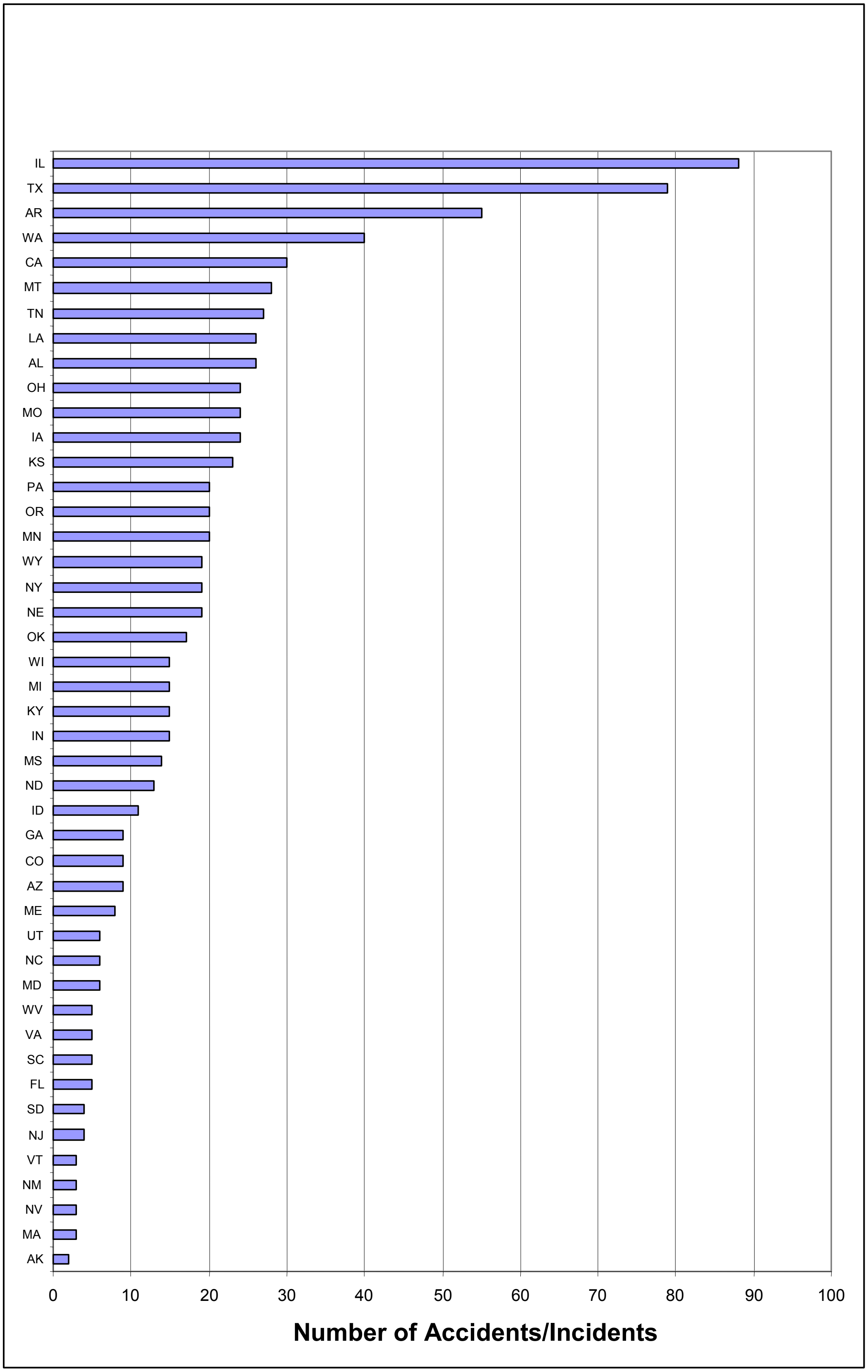

Figure 3. *Weather-related railroad accidents/incidents by state, 1993-2002.*

taken, serious accidents, injuries, and fatalities due to these natural hazards are relatively few, but they still result in a considerable number of disruptions and delays. As with any surface transportation, slides can threaten the safety of railroad operations, but slide mitigation planning and implementation for railroads must consider the following characteristics of railroad operations and of the U. S. railroad network. First, warnings must allow for trains to safely stop in advance of a hazard. For heavy freight trains or faster passenger trains on descending grades, stopping distances are often between one and two miles. Second, trains cannot steer around even the smallest slides or obstructions. And third, especially in the western U. S., there are relatively few alternative railroad routes, and the detour distances for accessing these may be hundreds of miles long.

Avalanches pose a seasonal threat to railroad operations in the western U.S. Avalanche zones occur in four areas: the intermountain zone of the northern Rockies, the coastal zone of the Sierra Nevada and Cascades, the continental zone of Utah, Colorado, Wyoming and New Mexico (Mock and Birkeland 2000)[3]. The authors found relationships between two types of climate processes and subsequent avalanche activity – the Pacific-North American (PNA) teleconnection pattern, and the Pacific decadal oscillation (PDO). These findings emphasize the connections between application of long-term climate records and current forecasts.

Temperature Extremes

When exposed to the summer sun, railroad tracks occasionally develop heat kinks that may in turn create a hazardous condition for oncoming traffic. Track misalignments caused by sun kinks have often been identified as a cause of train derailments with the potential for injuries, fatalities, property damage, and toxic release of hazardous materials. In addition to the direct effect of solar radiation, railroad tracks may also be exposed to uneven thermal expansion when shade covers nearby sections, thereby posing the risk of warp and misalignment to freight traffic. A similar condition may occur in winter, when extreme cold results in brittle track, thus increasing the risk of breakage. Cold temperatures are also the cause of frozen air lines, when moisture present in the distal part of the line cannot be dislodged by heat from the locomotive.

Thunderstorms and Tornadoes

Exposed to weather in nearly all directions in parts of the Midwest and western U.S., train operators are often direct, in-line targets of large-scale convection and supercells that generate tornadoes. The FRA database reports four tornadoes causing accidents during the 1993-2002 period, but the actual effects are likely much higher when slow orders or halts are dispatched to train conductors, thus impeding efficiency and cost-effectiveness. Similarly, thunderstorm activity may harm rail operations through various means, including lightning strikes to switching equipment, flash floods of poor drainage areas, and high winds associated with microbursts and squall lines. Although a separate meteorological phenomenon, intense crosswinds that often set-up in the front range of the Rocky Mountains may disrupt, halt, or even force the rerouting of downwind rail traffic.

Tropical Cyclones

Landfalling hurricanes along the Gulf and Atlantic seaboards adversely affect transportation interests and sometimes inflict heavy damage to the infrastructure and assets of the system. Railroads often sustain damage from flooding, washouts, storm surges, and debris flows associated with the passage of these storms. Many notable examples appear in historical records.

The effects of Hurricane Floyd on inland North Carolina showed the importance of pre-existing soil moisture as a critical indicator of flood potential in areas previously saturated by heavy rains. Unable to absorb typical 10+ inch rainfalls produced by landfalling storms, such areas are especially vulnerable to rapid rises in local streams and rivers. Flood amplification is a real concern. Rain runoffs quickly undermine structures such as dams, railroad beds, bridges, and buildings. Outputs of land-surface models help by providing risk estimates of land surface temperatures, soil moisture, and surface wetness, where wetness depends on precipitation and soil texture. Land surface temperatures fall during the passage of a hurricane. This decrease in temperature also then decreases evaporation levels.

Winter Storms

Across the eastern seaboard, the intermountain states and northern tier of the U.S., severe winter storms sometimes disrupt the entire transportation system. Railroad operations degrade in such conditions, due to lowered visibility, icing, snowdrifts, and cold temperatures. Railroad segments dependent on overhead electrical cattenaries may fare especially poorly since their exposure tends to allow ice build-up. Winter storms also adversely affect rail in an indirect way – by preventing producers of goods from shipping to intermodal terminals or delivering goods to rail sidings, freight traffic becomes backlogged and trains may not run at full economic efficiency.

Rising Sea Levels

Although slight rises in ocean levels have now been observed, the increase is likely not yet high enough to force changes in coastal rail infrastructure or capital planning decisions. The future effects of storm tides and wave battering from large storms may amplify the risks posed by changes in sea levels.

It is probably still not too early for railroads to begin thinking about vulnerabilities in the location of rail infrastructure. Consideration should be given to limiting construction in highly vulnerable areas (e.g., floodplains, coastal areas). The industry may also want to begin thinking about infrastructure design, framing specifications determined by a new set of (uncertain) environmental constraints (e.g., number of 100-year storms the element is expected to face and survive). Another related concern is the adequacy of existing insurance policies against natural disasters and extreme weather events, and the likelihood that premiums – for bridges, tunnels, vehicles, and other structures – will begin rising in line with the higher risks posed by global warming and rising sea levels.

Conclusions and Recommendations

This report has reviewed the possible linkages between railroad operations, weather, and climate change. Where pertinent, the predictions of climate change models were connected with specific weather events encountered by railroad operators, with the objective of speculating on how these might increase or decrease in frequency or intensity under a long period of climate change. The report considered the effects of climate change on all aspects of railroad operations, from traffic management, to safety, to capital investment in new infrastructure. It also offered speculation on the effects of climate fluctuations (interseasonal and interannual) on railroads, as distinct from the secular changes anticipated by global warming.

As a preliminary approach to looking at these possible relationships, an analysis was performed on 10 years of FRA railroad accident data, specifically examining any data items that might shed light on these emerging issues. In setting up this approach, a proposed agenda for future research and analysis was set forth, outlining areas where efforts may be most fruitful. To re-emphasize some of those points and to investigate others, the following recommendations are made:

- Advance the understanding of the interrelationship between railroad systems and climate and weather, by developing baseline data and a framework on how climate and weather conditions currently affect railroad operations, infrastructure, and planning.

- Synthesize the findings of climate change assessments and future scenarios of climate and weather changes at both the national and regional level. Emphasize the understanding of those projected changes that are expected to most affect railroads (based on the previous analysis of baseline sensitivity).

- Develop probabilistic analyses of the occurrence of forecasted events and changes.

- Analyze the potential impacts of climate change on the railroad system. Spatial and temporal coupling of baseline and climate change assessments and future scenarios data would be used to establish relationships between climate change and railroad systems.

- Identify the safety, economic, mobility, and accessibility implications of climate change.

- Identify the railroad infrastructure elements and railroad operations most at risk under scenarios of widespread or large scale climate change.

- Develop strategies to address the potential implications of climate change impacts on the railroad sector, including mitigation efforts, adaptation of railroad system operations and infrastructure, and railroad planning under uncertainty to minimize the effects of future climate change.

- Assess the effectiveness of strategies to address climate change impacts on the railroad sector.

Institutional Strategy

- *The Department of Transportation (DOT) and Federal Railroad Administration (FRA) should develop a public-private partnership program for the design and conduct of research on the potential impacts of climate change on transportation systems*.

This research can be most effectively undertaken through a collaborative effort that builds on the expertise, resources, and common interests of DOT and other agencies. Collaborative technical work by the DOT, the railroad industry, and other research organizations could build on both existing departmental expertise in relevant areas (e.g., radar meteorology, climate analysis) and also take advantage of departmental participation in related activities. These elements should be pursued through an overall private-public partnership on the potential impacts of climate change on railroads.

[1] "Climate Change Projections from the Hadley Centre." http://www.met-office.gov.uk/research/hadleycentre/models/modeldata.html.

[2] Federal Railroad Administration, Office of Safety Analysis. http://safetydata.fra.dot.gov/officeofsafety/.

[3] Mock, Cary J. and Karl W. Birkeland. 2000. Snow avalanche climatology of the western United States Mountain Ranges. Bulletin of the American Meteorological Society. 81, 2367-2392.

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