Transportation hazards

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1. Introduction

Transportation systems are designed to move people, goods and services efficiently, economically and safely from one point on the earth's surface to another. Despite this broad goal, there are many environmental hazards that commonly disrupt or damage these systems at a variety of spatial and temporal scales. Whereas road curve geometry and other engineered hazards can be addressed through design (Persaud, et al., 2000), hazards such as extreme weather, landslides and earthquakes are much more difficult to predict, manage and mitigate. These adverse events can dramatically reduce network serviceability, increase costs, and decrease safety. The economic livelihood of many individuals, firms, and nations depends on efficient transportation, and this is embodied in twentieth-century innovations like just-in-time manufacturing and overnight shipping. As the movement of people, goods, and services increases at all scales due to population growth, technological innovation, and globalization (Janelle and Beuthe, 1997), the systematic study of these events becomes increasingly important.

Research in the area of transportation hazards aids governments in allocating scarce resources to the four phases of emergency management: mitigation, preparedness, response and recovery. New fields of study are emerging to address this need, as in the case of *Highway Meteorology*, which focuses on the adverse effects of extreme weather on transportation systems (Perry and Symons, 1991). The growing importance of this particular field in the U.S. can be seen in the recent publication of, "Weather Information for Surface Transportation – National Needs Assessment Report (OFCM, 2002)." Some transportation agencies organize special teams to manage and mitigate the effects of one or more of these hazards. Recurrence intervals for an event span from daily to centuries, while the associated consequences range from inconvenient to catastrophic. In some cases one event may cause another – torrential rain can trigger a landslide that blocks a road. Some occur unexpectedly, while others arrive with significant warning, but all are amenable to some level of prediction and mitigation.

Transportation systems also create hazards. Accelerated movement comes with risks, and the corresponding accidents that occur disrupt lives and transportation systems daily. Vehicles collide, trains derail, boats capsize, and airplanes crash often enough to keep emergency managers and news reporters busy. The transportation of hazardous materials (HazMat) is a controversial example in this regard because it places substantial involuntary risks on proximal people and the environment. From the Lusitania to the World Trade Center, we are occasionally reminded that transportation disasters can be intentional acts. Lesser-known transportation hazards include elevated irrigation canals, gas pipelines, and electrical transmission lines. Intramodal risks are present in many transportation systems, as in wake turbulence behind large aircraft (Gerz, et al., 2002; Harris, et al., 2002), but intermodal risks are also a significant factor –

a train might collide with a truck at an at-grade crossing (Austin and Carson, 2002; Panchaanathan and Faghri, 1995), or a river barge might bump a bridge leading to the derailment of a train.

Transportation systems that are disrupted by a hazardous event also play a critical role in emergency management. Transportation lifelines are generally considered the most important in an emergency because of their vital role in the restoration of all other lifelines. Emergency managers must route personnel to an accident site, restore lifelines, relocate threatened populations, and provide relief, all of which rely on transportation. Research in this area is increasing, and there are many methods and tools to aid in addressing problems in this domain. The 2000 Cerro Grande Fire in Los Alamos, New Mexico is a case where a low-capacity transportation network was partially disabled yet successfully used to manage a large fire and safely relocate more than ten thousand residents.

This chapter reviews recent research and practice in three areas related to transportation and hazards: 1) environmental hazards to transportation systems, 2) transportation risks to proximal people and resources, and 3) the role of transportation in emergency management.

2. Hazard, vulnerability, and risk

The study of adverse transportation events can be broadly divided into transportation *hazard analysis*, *vulnerability analysis*, and *risk analysis*. The focus in hazard analysis is identifying threats to a transportation system, its users, and surrounding people and resources. This is also referred to as *hazard identification*. The term 'hazard' is often used to refer to environmental threats like fog, wind, and floods, but transportation hazards exist at all scales from a sidewalk curb that might trip a pedestrian to the potential for sea-level rise to flood a coastal highway. In the most general sense, a hazard is simply a threat to people and things they value. Vulnerability analysis focuses on variation in the susceptibility to loss from hazardous events. Vulnerability can be viewed as the inverse of resilience, as resiliency implies less susceptibility to shocks. Risk analysis incorporates the likelihood of an event and its consequences, where an event can range from a minor road accident to a dam break that inundates an urban area. For example, identifying the lifelines in a given area that might be compromised by a landslide would be transportation hazard analysis. The loss of a lifeline to a landslide, or a reduction in its service, will have varying consequences depending on the design of the lifeline, its importance in the system, and the spatial economic consequences to the region. Analyzing this variation would constitute vulnerability analysis. In risk analysis, the likelihood of a landslide and its associated consequences would both be incorporated, often with the goal of identifying potential landslides that represent an 'unacceptable' risk. The following sections review these three areas in greater depth.

2.1. Hazard analysis

There are many questions that drive transportation hazard analysis. In the simplest case, we could assemble a list of the potential hazards that might affect transportation systems in a region. This could be accomplished by creating a hazard matrix (hazard against travel mode) that indicates whether a given hazard threatens a mode. The next level would be to identify where and when these events might occur. This is typically approached from two perspectives. In one case, we might map the potential for each hazard in a region and overlay areas of high hazard with road, rail, pipeline, and transmission networks to identify points where the two coincide. In the second case, we could select a link and inventory its potential hazards. The first approach requires a method for hazard mapping. This can be further divided into deductive and inductive modeling approaches to hazards mapping (Wadge, et al, 1993). In a deductive approach, an analyst builds a physical process model using governing equations. For example, if landslides are the hazard in question, one could use slope instability equations to determine landslide hazard along a road. In an inductive approach to landslide hazard mapping, an empirical study is undertaken to map past events to determine the conditions that lead to their occurrence. Areas with similar characteristics are then identified, often with techniques in map overlay, because they may also be hazardous. The line between inductive and deductive approaches should not be drawn too sharply because most hazard analyses rely on both. For example, past events may be studied to help build a deductive process model.

There are a number of important dimensions in transportation hazard analysis, most notably the spatial and temporal scales. The spatial scale includes both the extent of the study and the resolution or detail. The spatial extent might be global, national, regional, local, or an individual link in a network. Detail and spatial extent are correlated, but as computer storage continues to increases, this is weakening, and we may soon see national (or larger) studies with very fine spatial and temporal detail. The temporal extent and resolution are also important. A central question is the time-horizon of the study, which can range from a single time period (cross sectional) to any duration (longitudinal). Time is also important because of the many cycles that affect the potential for hazards. Road icing is most common at night in the winter, thus it varies seasonally and diurnally. Landslides occur more often during the rainy season, avalanches occur in the winter and fires during the dry season. Figure 1 depicts the changing likelihood of hazardous events over time, and this becomes more important in risk analysis.

2.2. Vulnerability analysis

Vulnerability is an increasing focus in researching threats to transportation systems (Berdica, 2002; Lleras-Echeverri and Sanchez-Silva, 2001; Menoni, et al., 2002). There are many definitions for hazard vulnerability in the research literature (Cutter, 1996). As noted, vulnerability in a transportation context recognizes that susceptibility is not uniform across people, vehicles, traffic flow, infrastructure, and the environment. Vulnerability can refer to the physical vulnerability of the users or the potential for an incident to decrease the serviceability of the transportation system. Vulnerability in a transportation context can also be approached from the point of view of network *reliability*, as a reliable network is less vulnerable, and Berdica (2002) links these two concepts. For an example of differing road network vulnerability, a road accident in a two-way tunnel may temporarily cripple a regional transportation system leading to significant delays, but a system with a separate tunnel in each direction would be less vulnerable to an incident halting traffic in both directions. People and environmental resources in proximity to a transportation corridor are also vulnerable to adverse events. For example, in transporting hazardous materials along a populated corridor, vulnerability along the corridor may vary significantly from point to point, and two potential incidents a few miles apart can have very different outcomes. There are also regional economic vulnerabilities because adverse events can disrupt commerce. Individuals can miss meetings, retail outlets can lose customers, commodities can be delayed, and tourism can be adversely impacted, all of which have economic consequences.

2.3. Risk analysis

The most common definition of risk incorporates both the likelihood of an event and its consequences. It is not possible to avoid all risks, only to choose from risk-benefit trade-offs (Starr, 1969). Kaplan and Garrick (1981) define risk as a set of triplets:

$$(s, p, c)$$

where s is a scenario, p its probability and c its consequences. Risk analysis can be viewed as the process of enumerating all triplets of interest within a spatial and temporal envelope. The probability of a scenario varies inversely with its consequences, which is embodied in the concept of a risk curve (figure 2). In Kaplan and Garrick's framework, the definition of a scenario can be arbitrarily precise. For example, one scenario might be an intoxicated driver speeding on a wet road at night, while another might be an earthquake induced landslide above a town. The concept of vulnerability enters the triplet through the consequence term, which varies as a function of the unique vulnerabilities of the scenario elements. In accident analysis, the consequence term can be held constant for comparison purposes, as in a *road casualty*. This effectively removes the *c* term, which allows an analyst to focus on estimating *p* for different scenarios and levels of risk exposure (Thorpe, 1964; Chapman, 1973; Wolfe, 1982). An example would be comparing the probability of a daytime versus nighttime road casualty. It is difficult to estimating *p* for extreme events with little historical data, and Bier, et al. (1999) provide an excellent survey of current methods to address this problem.

A thought experiment might help convey the related concepts of hazard, vulnerability, and risk in a transportation context. Imagine two motorcyclists riding in adjacent lanes with the *hazard* in question being a crash. All characteristics of the drivers, vehicles, and the environment are equal. We would say that the two face the same hazard, vulnerability, and risk because the likelihood and consequences of either motorcyclist crashing are equal. To understand vulnerability, place a helmet on one rider. The likelihood of a crash has not been altered, but both the *vulnerability* and the *risk* of the rider with the helmet have decreased. Now, imagine that both riders are wearing a helmet, but the surface of one lane is wet. The vulnerability of both drivers is equal, but the likelihood of a crash is higher (as is the risk) for the rider in the wet lane. To make it tricky, imagine that the rider in the wet lane is wearing a helmet, but the rider in the dry lane is not. One has a greater likelihood of a crash and the other a greater vulnerability to a crash, but which rider is at greater risk? An empirical approach to this problem would be to compare the casualty rate for motorcyclists wearing a helmet in rainy conditions with the rate for riders without a helmet in dry conditions, attempting to control for all other variables.

Despite the challenges presented by quantitative risk assessment and its many assumptions, risk analysis has many benefits that outweigh the drawbacks. Evans (1997) reviews risk assessment practices by transport organizations for accidents and notes that the benefits of quantitative risk assessment include:

1) it makes possible the prioritization of safety measures when resources are scarce, or where there are different approaches to achieving the same end;
2) it makes possible the design of systems (engineering or management) aimed at achieving specified safety targets or tolerability limits;
3) it facilitates pro-active rather than just reactive safety regulation;
4) it provides a basis for arguing against safety measures whose benefits are small compared with their costs, and for justifying such decisions on a rational basis.

An overarching goal in quantitative risk assessment is to determine if a given transportation risk is 'acceptable'. If it is not, mitigation actions are in order. One approach to this problem is to compare the given risk with commonly accepted risks. So, a rock fall study along a highway might compare the results with other risks like air travel, drowning, lightning, or structural failure to determine if the risk of a rock fall fatality is significantly greater than other risks (Bunce, et al., 1997). Another approach is to compare the risk of two scenarios to compute their 'relative risk' using a risk ratio. For example, if there were 10 road accidents on rainy weekends on average and 5 on dry weekends, then the risk ratio of rainy-day weekend driving to fair-weather weekend driving would be 10 / 5 = 2, or twice as risky, assuming that the amount of driving (aggregate exposure) was roughly the same from weekend to weekend.

3. Hazards to transportation systems

There are many environmental hazards that may damage or disrupt transportation systems, and we only review the more common ones here. For example, figure 3 depicts familiar road hazards grouped by their principal effect along with some of their causal relationships. In general, road hazards can: 1) compromise the quality of the surface, 2) block or damage infrastructure, 3) compromise user visibility, 4) compromise steering, 5) create a temporary obstacle, or 6) some combination of the prior five. From the figure, it is clear that rain, wind, and earthquakes have causal links with many other hazards. Rain and earthquakes can both induce a flood, landslide, rock fall or debris flow. Earthquakes can also start a fire or result in a toxic release. Extreme wind can kick up dust, start a fire, drive smoke from a fire, blow trees and debris into the roadway, or redeposit snow leading to an avalanche. This is only a sample of the many hazards and relationships that might exist. Hazards can also coincide, as in a nighttime earthquake in severe rain. This section reviews recent research in the analysis of many of these hazards, but it should not be considered comprehensive. The review is multi-modal and driven primarily by these questions:

- What is the hazard?
- What has been done to address the hazard in research and practice?
- What travel modes does the hazard affect?
- How well can we predict the hazard in space and time?
- What are the consequences of the hazard and how are they defined and measured?
- What mitigation actions exist and what might be developed?

3.1. Avalanches

An avalanche is a sudden transfer of potential energy inherent in a snow pack into kinetic energy. The principal contributing factors include snow, topographic effects, and wind which can redeposit snow. 'Snow structure' refers to the composition of its vertical profile, which can become instable as new layers are added. An avalanche occurs when the strength of the snowpack no longer exceeds the internal and external stresses. Avalanches are typically divided into 'dry or wet' and 'loose or slab' avalanches. Dry slab avalanches accelerate rapidly and can reach speeds in excess of 120 miles per hour, but wet avalanches move much slower.

The systematic study of avalanches in North America dates back to the 1950's in Alta, Utah. Figure 4 depicts the most active and damaging slide paths in Alta. The most useful, general reference is McClung and Schaerer's (1993) avalanche handbook. Avalanches typically reduce the serviceability of a road, but they can also damage infrastructure and cause injury or death. Other modes affected include rail, pipelines and transmission lines. The science of predicting the timing of avalanches is called *forecasting* (Schweizer, et al., 1998), and it has improved significantly over the last fifty years. Snow pits, weather instrumentation, field observation, and remote sensing are combined to forecast avalanches. The corridors that receive the greatest attention are those with high traffic volume and a documented avalanche history. Avalanche path identification using terrain and vegetation is also a common task in areas where historical records may not be available.

Three challenges that transportation agencies face in avalanche control include: 1) selecting paths where mitigation would be most beneficial, 2) evaluating mitigation measures, and 3) comparing the risks of different roads. The avalanche-hazard index (Schaerer, 1989) combines forecasting with traffic flow volumes to address these needs. The index includes the likelihood of vehicles being impacted by an avalanche along a road as well as the potential consequences. It also incorporates the observation that loss of life can occur when a neighboring avalanche overcomes traffic halted by another slide. The composite avalanche-hazard index for a road is:

$$I = \sum_i \sum_j w_j (P_{mij} + P_{wij})$$

Where P_{mij} is the likelihood with which *moving* traffic might be hit by an avalanche of class j at path i, P_{wij} is the likelihood with which *waiting* traffic might be hit by an avalanche of class j at path i , and w_j is the consequence of an avalanche of class j. The index can also be calculated separately for each avalanche path along a road to determine where mitigation would make the largest contribution to overall hazard reduction.

A number of avalanche risk case studies for transportation corridors have been performed that include Glacier National Park (Schweizer, et al., 1998), the Colorado Front Range (Rayback, 1998), and the Himalaya (De Scally and Gardner, 1994). Avalanche mitigation options, increasing in cost, include explosives, snow sheds, and deflection dams. Rice, et al. (2000) provide an example of system for automatically detecting avalanches on rural roads.

3.2. Earthquakes

The study of earthquakes and seismic risk spans many fields in the sciences and social sciences. They are widely researched by transportation engineers from a variety of perspectives because they can severely damage and disrupt transportation systems. A devastating earthquake epitomizes a low-probability high-consequence event in risk analysis. The recurrence interval for a large earthquake in a region can be centuries, varying inversely with magnitude, yet devastating earthquakes occur almost every year somewhere in the world. For many populated areas without a history of severe earthquake loss, the likelihood of facing an earthquake that damages transportation lifelines is a near certainty because the geologic record reveals past large earthquakes (Clague, 2002). No major transport mode is exempt from the adverse affects of an earthquake. Roadways, railways, pipelines, transmission lines, and air and sea ports can all be damaged with tremendous economic costs (Cho, et al., 2001). Earthquakes can also start fires, trigger landslides (Refice and Capolongo, 2002), release toxic chemicals (Lindell and Perry, 1996), cause dam failures, and create sudden earthen dams via landslides leading to inevitable flooding (Schuster, 1986).

Pre-impact earthquake research in transportation engineering focuses on vulnerable structures like bridges (Malik, 2000), tunnels (Hashash, et al., 2001), and water delivery systems (Chang, et al., 2002). The central problem is estimating the response characteristics of these structures to ground shaking and liquefaction (Price, et al., 2000; Selcuk and Yuceman, 2000; Sevtap and Semih, 2000; Romero, et al., 2000). Werner (1997) notes that earthquake losses to highway systems depend not only on the response characteristics of the highway components, but also on the nature of the overall highway system's configuration, redundancy, capacity and traffic demand (see also Basoz and Kiremidjian, 1996). For example, two bridges may be equally susceptible to ground shaking, but one may be much more important in serving the daily travel demand to an important destination. Retrofitting is typically in high order when a bridge highly susceptible to the effects of an earthquake is also essential in serving a large volume of travel demand.

Post-impact earthquake research focuses on immediate damage assessment (Park, et al., 2001), the performance of the transportation system (Chang, 2000), and the lifeline restoration process (Isumi, et al., 1985; Opricovic and Tzeng, 2002). Chang (2000) examines post-earthquake port performance following the Kobe quake in 1995 and frames the economic loss (and thus vulnerability) in terms of three types of traffic: 1) cargo originating from or destined to the immediate hinterland, 2) cargo from/to the rest of Japan, and 3) foreign transshipment cargo. By examining the pre and post conditions of these cargo types, Chang concludes that (2) and (3) suffered the most resulting in both short-term loss of revenue and long-term loss of competitive position. Economic impacts may last beyond the point where the infrastructure has been repaired. Kobe demonstrates that (3) is especially important, and the central port vulnerability question can be framed as the percent that a port's revenue is tied to transshipment cargo.

3.3. Floods and dam breaks

Floods cause the greatest loss in many countries because they occur frequently and their severity is compounded by dense development along many rivers. The National Weather Service (NWS) in the U.S. estimates that greater than half of all flood-related deaths occur in vehicles at low-water crossings. Flood damage to transportation systems represents one of the largest losses in the public sector. Intense rainfall is the chief cause of floods, but hurricanes also hold the potential to cause a significant amount of storm surge inundation. Dam breaks are included here as a special type of technologically-induced flood. This includes earthen dam breaks caused by earthquake-induced landslides (Schuster, 1986). The modeling of dam breaks has increased in recent years because agencies such as the U.S. Bureau of Reclamation (USBR) are required to submit a report and associated inundation animations of potential dam breaks to local emergency managers downstream from all dams for emergency planning purposes.

Figure 5 depicts an example of modeling flooding across a transportation network. The depth of the flood is shown in meters with the direction and velocity of the flood depicted using a vector field. This example is output from the MIKE 21 flood simulation system for modeling two-dimensional free surface flows. The system can model many conditions that occur in a floodplain including flooding and drainage of floodplains, embankment overtopping, flow through hydraulic structures, tidal forces, and storm surge. MIKE 21 is an excellent example of a deductive process-oriented hazard mapping approach because the system solves non-linear equations of continuity and conservation of momentum for flooding.

Flooding is a serious problem in many areas because of its ability to rapidly degage the serviceability of a transportation network at various points. Ferrante, et. al. (2000) combine a numerical model for flood propagation in urban areas with a network path-finding algorithm to identify “least-flood-risk” paths for rescuing people as well as providing relief. They use Dijkstra’s (1959) shortest path algorithm, but the cost of a link is calculated in a very novel manner using the flood flow depth and velocity across the road. In this way, the “cost” of traversing a link is a function of both the length of the road as well as its flood characteristics:

$$c_{ij} = \frac{L_{ij}}{a_h a_v}$$

where c_{ij} is the cost/risk of traversing the link, L_{ij} is the length of the link, a_h is a parameter (0-1) related to food height and a_v is a parameter related to water velocity (0-1). Each alpha parameter *decreases* as flood height or velocity increases, respectively, until the maximum allowable flood height (e.g. .3 m) or velocity (e.g. 1 m/s) is reached, whereby they become 0. At this point, link cost is infinite, and it is no longer traversable. So, the travel cost of a link without flooding is its length, but as flood height and velocity across the link increase, its cost and risk quickly increase. This example links a hazard process model with a network algorithm, which points to a valuable opportunity for analysts, as many hazards reduce the serviceability of network links. Real-time path finding in a network degraded by a hazard is a very valuable application. The challenge is to develop a means for acquiring accurate, timely information on the hazard as well as to manage and convey the uncertainty in the results.

3.4. Fog, dust, smoke, sunlight and darkness

Fog, dust, smoke, sunlight and darkness are transportation hazards that compromise the visibility of system users. This hazard category does not apply to pipeline networks, transmission lines, and other networks where visibility is not an issue. From a roadway perspective, Perry and Symons (1991) provide an excellent source on these hazards. Musk (1991) thoroughly covers the fog hazard, and Brazel (1991) describes a dust storm case-study for Arizona. Although smoke from wildfires routinely disrupts roadways and inhibits operations at airports each summer, it appears to be an under-researched topic in transportation hazards. Darkness also has an understandably adverse effect on road safety, especially when combined with fog, smoke or dust.

Fog can cause spectacular road accidents involving hundreds of vehicles on a roadway. Musk (1991) describes the Fog Potential Index (FPI) which expresses the susceptibility of a location *p* on a road to thick radiation fog on a scale from 0 to 100. The values of two locations are comparative in that a value of 30 at location A and a value 20 at location B means that location A should experience 50% more hours of thick radiation fog than location B. The index is of the form:

$$I_p = 10d + 10t + 2s + 3e$$

where *d* is the distance of the location *p* from standing surface water, *t* is a function of the local topography at *p* (e.g. hill or valley), *s* is a function of the road site topography (e.g. bridge or embankment), and *e* incorporates other environmental features likely to affect the formation of radiation fog (e.g. proximity to power station cooling). The index coefficients are weights that affect the relative importance of the variables. This index can be applied at any linear resolution, but 1 km is common. The index can then be tested against in situ observations of visibility.

3.5. Rain, snow and ice

Rain, snow and ice are common hazards that compromise visibility and the quality of a road, rail or airport surface (Benedetto, 2002; Andrey, 1990). All road users are familiar with road signs like "slippery when wet" or "bridges may be icy" (Carson and Mannering, 2001). Ice is also a hazard for aircraft because of its effect on lift, as well sea travel because it creates obstacles (Tangborn and Post, 1998). In a road network context, skidding is the most common explanation for accidents that occur in the context of these hazards. The *skidding rate* is the statistic used to quantify this factor, which is the percentage of accidents where one or more vehicles are reported to have skidded (Perry and Symons, 1991). Example skidding rates for cars are given in figure 6 for Great Britain in 1987. This figure shows that rain roughly doubles the percentage of accidents where skidding is a factor over dry conditions, and snow and ice quadruple the rate over dry conditions. The overall skidding rate for cars for all road conditions is about 14%.

The question of how rain, snow, and ice affect the total number of road accidents is not straightforward. Palutikof (1983) found that people drive more carefully in snow or simply postpone or cancel journeys. This leads to reduction in the total number of accidents over that which would be expected. Rain does not seem to have the same effect on travel decision making, and Brodsky and Hakkert (1988) found that the number of accidents increases in wet conditions. Al Hassan and Barker (1999) found a slightly greater drop in traffic activity owed to inclement weather on the weekend (> 4%) than on weekdays (< 3%). In a case study of Chicago, Bertness (1980) found that rain roughly doubled the number of road accidents with the greatest effect in rural areas. It is important to keep in mind that rain, snow, and ice studies tend to underestimate the risk because road accidents are typically underreported.

Hazards that affect the road surface represent the most costly maintenance function for many cities, counties, and state transportation departments. Salt is the most common road de-icer with about 10,000,000 tons applied each year in the U.S. (Perry and Symons, 1991). This is expensive and comes with environmental side effects. Eriksson and Norman (2001) note that road weather information systems have a very high benefit-cost ratio in reducing weather-related risk. The widespread adoption of Doppler radar has greatly improved the reporting of precipitation, and some systems can now report rain-intensity to levels as detailed as an individual street segment. There is much work in developing and installing in situ road sensors to automatically detect poor road conditions. This can greatly improve road maintenance procedures because managers can apply mitigation measures like salt where it is most needed.

3.6. Landslides, rock fall, and debris flow

Many miles of roads, rail, and pipeline travel through areas with rock faces and steep slopes in mountainous terrain. Geomorphic hazards that commonly affect transportation corridors include landslides, rock fall, and debris flow. A debris-flow is essentially a fast-moving landslide. These hazards can damage or reduce the serviceability of infrastructure, crush or bury vehicles, and result in death. In some cases they occur without little or no warning, but they are typically preceded by intense rain (Al Homoud, et al., 1999). They can also be earthquake or volcanically induced (Dalziell and Nicholson, 2001) and create sudden earthen dams that lead to flooding (Schuster, et al., 1998). An excellent, general source on landslides and debris flows is the Transportation Research Board (TRB) report on Landslides edited by Turner and Schuster (1996). In terms of case studies, Marchi et al. (2002) examine ten years of debris flows in the Italian Alps, Evans and Savigny (1994) examine landslides in Canada, He, et al. (2002) looked at debris flows along the China-Nepal Highway, Budetta (2002) conducted a risk assessment for a 1 km stretch of road subject to debris flows in Italy, and Petley (1998) examined geomorphic road hazards along a stretch of road in Taiwan. Fish and Lane (2002) discuss a rock-cut management system, and Franklin and Senior (1997) describe a rock fall hazard rating system.

Bunce, et al. (1996) provide an excellent example method for assessing the risk of loss of life from rock fall along a highway. They used rock fall impact-mark mapping supplemented by documented rock fall records to establish a rock fall frequency for the Argillite Cut on Highway 99 in British Columbia. The method relies on separate calculations for the risk of a rock hitting a stationary vehicle versus a moving vehicle, as well as a moving vehicle hitting a rock on the road. The probability that a one or more vehicles is hit is given as:

$$P(S) = 1 - (1 - P(S \mid H))^N$$

where $P(S \mid H)$ is the probability that a vehicle occupies the portion of the road affected by a rockfall and N is the number of rocks that fall. This equation states that the probability of a vehicle being hit is one minus the probability that a vehicle is not hit. With a series of assumptions, they estimate the risk of death due to rockfall for a one-time road user and daily commuter at .00000006 and .00003 per year, respectively.

3.7. Wind, tornados and hurricanes

Wind is a significant hazard to road, rail, sea, and air transport (Perry and Symons, 1994). Gusts, eddies, lulls, and changes in wind direction are often greatest near the ground in extreme wind episodes. In these episodes, the majority of fatalities are generally transport related. It is difficult to summarize the effects of wind on road and rail transport because little data exists, although it is generally viewed as less of a hazard than ice, snow, and rain. Figure 7 depicts wind that is blowing smoke across an interstate and blocking traffic. Perry and Symons (1994) divide the wind hazard into three categories: direct interference with a vehicle, obstructions, and indirect effects. Direct interference includes its effects on vehicle steering, which may push one vehicle into another or run a vehicle off the road. Extreme winds can overturn high-profile trucks and trains when the wind vector is orthogonal to the direction of travel because the force of the wind is proportional to the vehicle area presented (Baker, 1988). Wind can impede transport by blowing dust or smoke across a road, which can reduce visibility. It can also blow trees and other debris onto a road or railway and create temporary obstacles. Indirect effects include the redeposition of snow leading to an avalanche, as well as its adverse effect on bridges and air and sea-based termini. Overall, wind can impede transport operation or damage vehicles and infrastructure, all of which can result in economic impacts, injuries, and fatalities.

Air transport faces the greatest hazard from wind. A violent downdraft from a thunderstorm (microburst) on takeoff or landing is one example, but any exceptionally large local wind gradient (wind shear) can affect lift adversely at low altitudes (Vorobtsov, 2002; Goh and Wiegmann, 2002). In many air disasters, wind is considered the primary contributing factor. Small aircraft are much more vulnerable to in-flight storms and are often warned to completely avoid storms. Measures to reduce wind hazard include permanent wind breaks, warnings, road closures, and low-level wind shear alert systems. An airport wind-warning system generally consists of a set of anemometers that are analyzed by computer. A warning is issued when levels differ by some threshold. Automated wind-warning systems for individual roads may appear soon because of advances in weather instrumentation. The finest level that wind warnings are commonly issued is at a county scale. Improved weather forecasting is generally viewed as the principal means for reducing the hazard (Perry and Symons, 1994).

Hurricanes and tornados represent special cases of extreme winds. Due to satellite, radar, and other in situ sensor networks, their prediction has greatly increased in recent years. Much of the transportation research in this area focuses on evacuation. Wolshon (2001) reviews the problems and prospects for contraflow freeway operations to reduce the vulnerability of coastal communities by reversing lanes to increase freeway capacities in directions favorable for evacuation. This problem is simple conceptually but represents a significant challenge for both traffic engineers and emergency managers.

3.8. Wildlife

Wildlife is a familiar hazard to most drivers because of the many warning signs along roadways. Wildlife accidents typically result in vehicle damage, but they can also result in injury or death. Two common examples of wildlife hazards include the threat that undulates such as moose (Joyce and Mahoney, 2001) present to vehicles and the threat that birds present to aircraft. The number of these collisions is staggering, and it is estimated that in 1991 greater than half a million deer were killed by vehicles in the United States (Romin and Bissonnette, 1996). Lehnert and Bissonette (1997) review research on deer-vehicle collisions and describe a field experiment on the effectiveness of highway crosswalk-structures as a means of mitigation. The crosswalk system evaluated forces deer to cross at specific areas that are well marked for motorists. Although deer fatalities decreased by 42% following the installation of the crosswalks, they were unable to attribute this reduction to the crosswalks because there was an 11% probability that it may have occurred by chance.

Bird hazards to aircraft are also a significant concern, and Lovell and Dolbeer (1999) provide a recent review with a study to validate the results of the U.S. Air Force (USAF) bird avoidance model (BAM). BAM provides information to pilots regarding elevated bird activity based on refuge surveys, migration dates, and routes. Lovell and Dolbeer note that since 1986, birds have caused 33 fatalities and almost $500 million in damage to USAF aircraft alone. On average, USAF aircraft incur 2,500 bird strikes a year with most occurring in the fall and spring migration. Waterfowl and raptors account for 69% of the damaging strikes to low-level flying military aircraft. Lovell and Dolbeer found that BAM predicted significantly higher hazard for routes where bird strikes have occurred in the past and thus can assist in minimizing strikes.

4. Transportation as hazard

In addition to the many environmental hazards that threaten transportation systems, transportation itself presents hazards to people, property, and the environment. Road traffic accidents are the most common example, and the majority of transportation casualties in most countries can be attributed to road accidents. The contributing factors for road accidents are typically classified into those associated with the driver, vehicle, and the environment. Contributing factors associated with the driver include error, speeding, experience, and blood-alcohol level. Factors associated with the vehicle include its type, condition, and center of gravity. Environmental factors include the quality of the infrastructure, weather, and obstacles. The majority of road accidents are attributed to driver factors (Evans, 1991), and this holds for many other modes such as boats (Bob-Manuel, 2002), bicycles (Cherington, 2000), snow mobiles (Osterom and Eriksson, 2002) and all terrain vehicles (Rogers, 1993). Taken together, this implies that most transportation casualties in the world are road accidents chiefly attributed to the driver. Not surprisingly, research on driver factors represents the largest area of transportation hazards research (see the journal Accident Analysis & Prevention). Transportation accidents have severe effects on those directly involved, as well as side effects to others. Other effects might include severe traffic delays leading to missed meetings, lost sales to businesses, delayed commodity shipments, and increased insurance costs. Research in accident analysis spans all modes and typically focuses on assessing the role of various driver, vehicle, and environmental factors as well as methods for mitigating accidents. (See chapter on incident management).

In addition to common traffic incidents, there are also low-probability high-consequence transportation events that place risks on people and environmental resources in proximity to transportation corridors and ports. Rail, road, pipeline, and marine HazMat transport is the prime example in this area because it places considerable involuntary risks on people (and resources) who do not perceive much benefit to the transport of hazardous materials. HazMat has been studied from a number of perspectives for many materials and modes, so there are numerous frameworks for analysis (Bonvicini, et al., 1998; Cassini, 1998; Erkut and Ingolfsson, 2000; Fabiano, et al., 2002; Helander and Melachrinoudis, 1997; Jacobs and Warmerdam, 1994; Klein, 1991). Aldrich (2002) provides an historic perspective on rail HazMat shipments from 1833 to 1930, and Cutter (1997) reviews recent trends in hazardous material spills. Caputo and Pelagagge (2002) present a system for monitoring pipeline HazMat shipments. Singh, et al. (2002) examine the spontaneous coal combustion in sea transport. Raj and Pritchard (2000) present a risk analysis tool used by the Federal Railway Administration. Hwang, et al. (2001) present a comprehensive risk analysis approach for all modes that includes 90% of the dangerous chemicals. Abkowitz, et al. (1990) describe a method for evaluating the economic consequences of HazMat trucking. Verter and Kara (2001) review HazMat truck routing in Canada. Dobbins and Abkowitz (2002) look at inland marine HazMat shipments. Saccommano and Haastrup (2002) focus on HazMat risks in tunnels. Marianov, et al. (2002) propose that proximal communities receive a tax reduction to offset the risk of proximal HazMat shipments.

Following the events of September 11th 2001, *transportation security* has become a national research priority led by the Transportation Security Administration (TSA) recently reorganized under the Department of Homeland Security. Transportation terrorism has not been a focus of transportation hazards researchers in the past, so there is little to review at this point. However, reports and proposals are beginning to surface that indicate that this will be one of the largest areas of transportation hazards research for many years.

5. Transportation in emergency management

Transportation lifelines are vital during an emergency, and play an important role in all four phases of emergency management: mitigation, preparedness, response, and recovery. The concern in the mitigation phase is reducing the likelihood of an event, its consequences, or both. The focus of the preparedness phase is improving operational capabilities to respond to an emergency such as training emergency personnel, installing notification systems, and redeploying resources to maximize readiness (Sorensen, 2001). The mitigation and preparedness phases both help reduce the impact of hazardous events. The response phase begins immediately following an event, and this is when plans devised in the preparedness phase as well on-the-fly plans are activated. Common concerns include evacuating and sheltering victims, providing medical care, containing the hazard, and protecting property and the environment. The recovery phase addresses longer-term projects like damage assessment and rebuilding, which feeds back into the mitigation phase because this phase presents an opportunity to rethink hazardous areas.

Mitigation strategies for specific hazards and assets were discussed in the prior section on hazards to transportation systems. The overarching challenge in the mitigation phase is identifying and prioritizing mitigation projects in a region and allocating scarce resources to their completion. Benefit-cost analysis is a valuable method in this regard, but it must be preceded by risk assessments for all potential hazards. The effectiveness of the mitigation strategy is also important, and this can be considered part of the benefit.

Research in the preparedness and response phase has been fueled by new technologies. Enhanced 911 (E-911) is a significant relatively recent innovation, and this is covered in the chapter on incident management. Relevant topics that are actively researched in this phase include optimally locating emergency teams (List and Turnquist, 1998), locating and stocking road maintenance stations, optimal fire station location for urban areas and airports (Revelle, 1991; Tzeng and Chen, 1999), and installing hazard-specific warning systems. Evacuation planning in this phase focuses on delimiting emergency planning zones (Sorensen, et al., 1992), designing and simulating evacuations (Sinuany-Stern and Stern, 1993; Southworth, 1991; Cova and Johnson, 2002), developing and testing evacuation routing schemes (Dunn, 1993; Yamada, 1996; Cova and Johnson, 2003), and identifying potential evacuation bottlenecks (Cova and Church, 1997). Reverse 911 systems that allow police to call evacuees are becoming increasingly important in dealing with notification. State-of-the-art systems allow emergency managers to send custom messages with departure timing and routing instructions to zones defined on-the-fly with a mouse. Other research in the preparedness and response phase include methods for keeping roadways open following an earthquake or landslide (Santi, et al, 2002).

One problem that complicates emergency planning by transportation agencies is the increasing amount of development in many hazardous areas. This is nearly universal as populations increase in floodplains, coastal areas subject to hurricanes, fire-prone wildlands, areas near toxic facilities (Johnson and Zeigler, 1986), regions at-risk to seismic activity, and so on. This presents a problem because in many of these areas (and at many scales) the transportation system is not being improved to deal with these increasing populations. This means that evacuating threatened populations is becoming increasingly difficulty at all scales, as new development occurs. In other words, vulnerability to environmental hazards is continually increasing owed both to the fact that populations in hazardous areas are increasing at the same time that the ability of emergency managers to invoke protective actions such as evacuation are decreasing.

Figure 8 show two maps from Cova and Johnson (2002) that show the effect of a new road on household evacuation times for a community at risk to wildfire near Salt Lake City. Before the construction of the new road, homes in the back of the canyon had the greatest evacuation times, as the sole road out of the canyon would get congested. In this scenario, the average vehicle departure-time following notification to evacuate was 10 minutes and the average number of vehicles per household was 2.5, so it can be considered a reasonably urgent evacuation when most residents are home. Note that houses in the back of the canyon stand to gain much more from the construction of the new exit because their evacuation times decrease much more than homes near the original exit from this community. Also, all evacuation times become more consistent because the second exit reduces the delay caused by everyone using one exit. Viewed another way, the new exit reduces the number of households per exiting road from 250/1 = 250 to 250/2 = 125.

6. New technologies

There are many new technologies that hold promise to aid transportation agencies in reducing the effects of transportation hazards. Weather instrumentation is prime example that is improving both in terms of breadth of measurement, as well as the number of installed road weather stations. The suite of geospatial technologies including the global positioning system (GPS), geographic information systems (GIS), and remote sensing also hold much promise to improve the amount of information available to transportation users, planners, and emergency responders. The recent formation of the National Consortia for Remote Sensing in Transportation (NCRST) is dedicated to this task (Gomez, 2002). The consortia are divided into four themes that include hazards, environment, infrastructure, and flow. NCRST Hazards (NCRST-H) is the most relevant in the context of applying geospatial technologies to monitoring and mitigating transportation hazards.

A simple benefit of GPS in accident analysis is that it is an inexpensive means for greatly improving the locational component of crash data (Graettinger, 2001). Remote sensing can be used to detect and monitor fires, volcanoes (Oppenheimer, 1998), landslides, avalanches, and many other hazards. One technology that is having a significant affect on the study of transportation hazards is geographic information systems (GIS). For a comprehensive review of GIS in transportation (GIS-T) see Miller and Shaw (2001). GIS is being used in transportation applications such as mapping collision data (Arthur and Waters, 1997; Austin, et al., 1997), routing HazMat shipments (Brainard, et al., 1996; Lepofsky, et al., 1993), identifying hazardous highway locations (Spring and Hummer, 1995), modeling the vulnerability of populations to toxic spills (Chakraborty and Armstrong, 1996), among many other transportation hazard applications.

7. Conclusion

Transportation and hazards is a growing field in terms of research and practice. New methods for predicting and mitigating hazards are continually being developed, and researchers are linking these methods and models to tasks in transportation planning and mitigation. Globalization is increasing our dependence on transportation systems at all scales. For this reason, disruptions will only become more costly and important to mitigate. New information technologies are converging that promise to drastically change this field in the coming years. These technologies are emerging during a shifting emphasis toward transportation security. This will bring information-based research on reducing the effects of transportation terrorism to the forefront of this research area. Finally, development in hazardous areas is increasingly along with corresponding increases in traffic volumes along many lifelines at-risk to hazards. This will present substantial challenges to transportation researchers and analysts for the foreseeable future.

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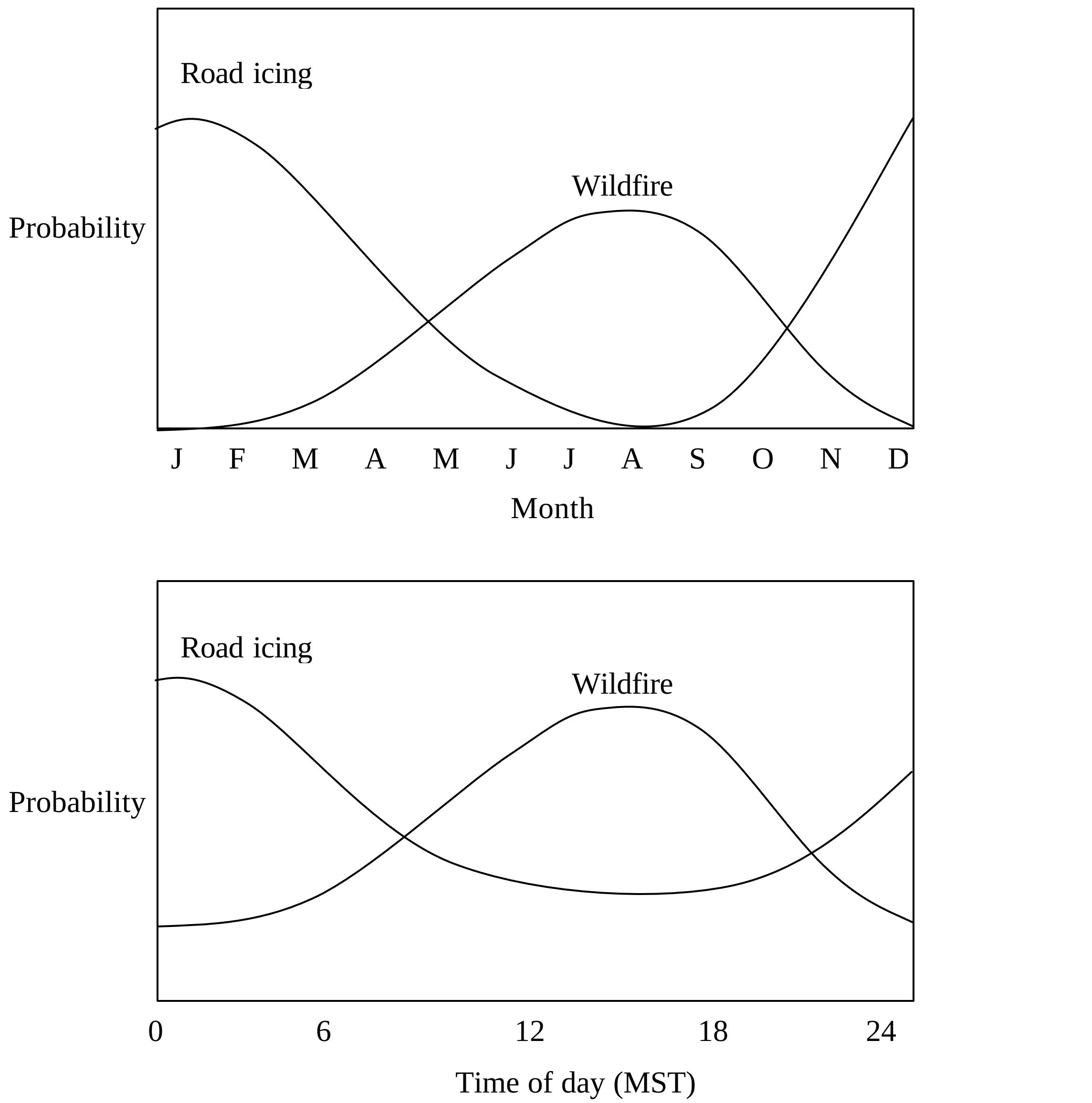

Figure 1. Seasonal and diurnal variation in the probability two North American transportation hazards.

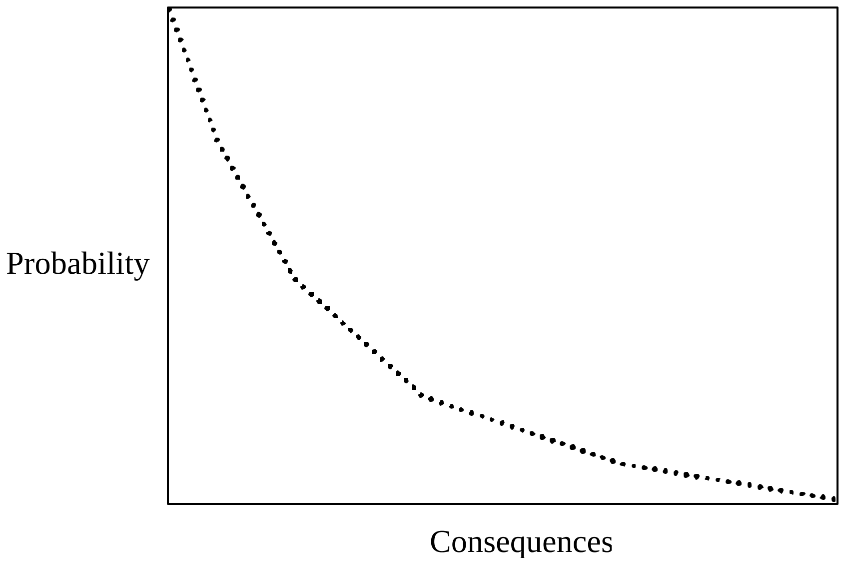

Figure 2. An example risk curve.

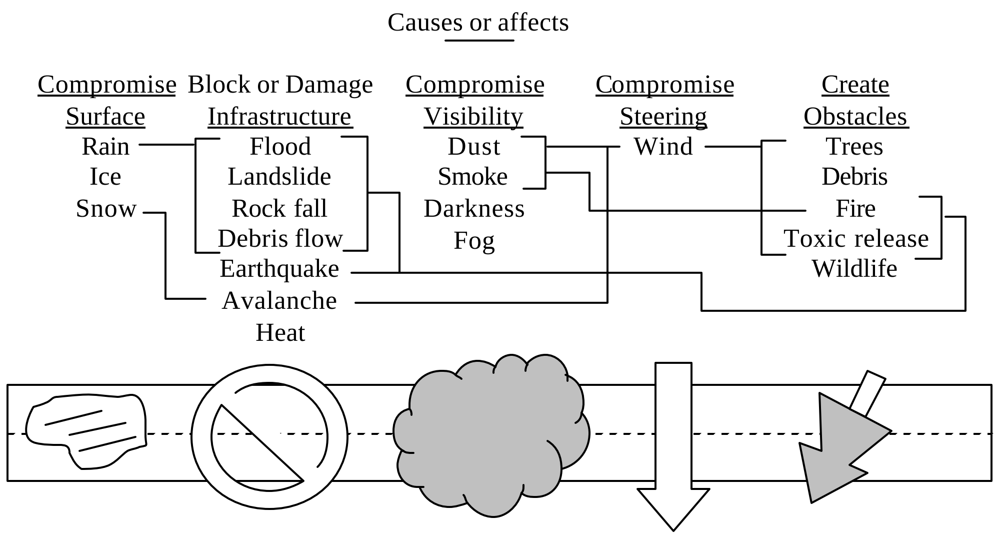

Figure 3. Example road hazards grouped by their principle effect including some of their causal relationships.

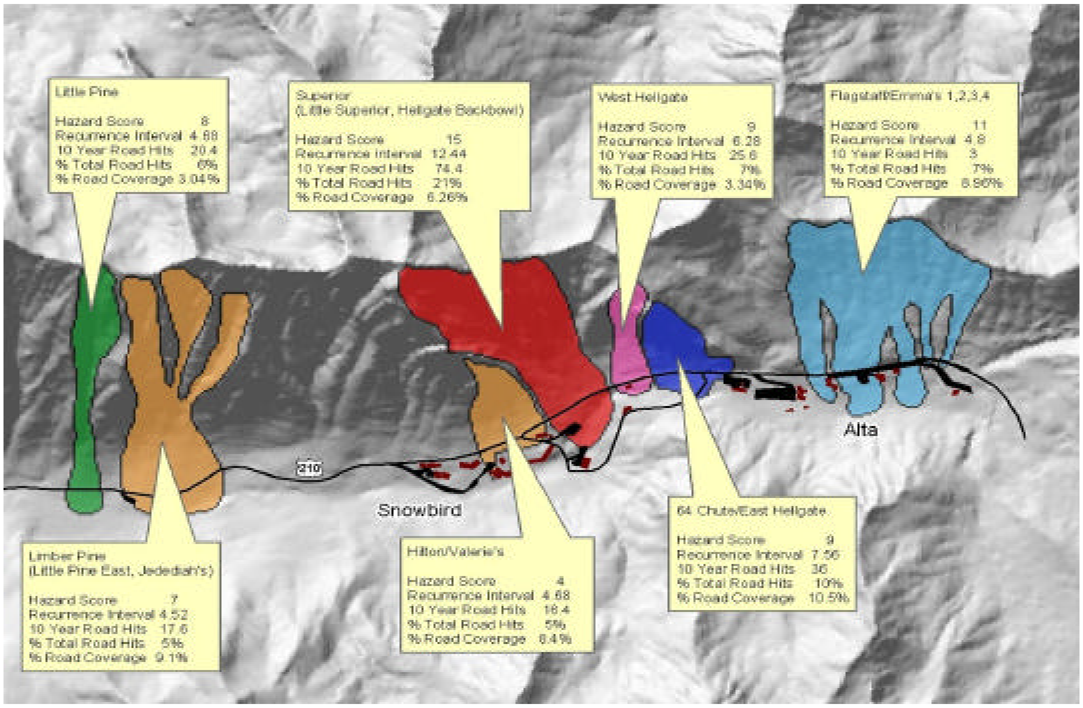

Figure 4. The most active avalanche slide paths in Little Cottonwood Canyon, Utah shown with their mean recurrence interval (years), the number of road hits in the last 10 years, the percentage of times they hit the road, and the percentage of the length of the road they covered (Source: William Naisbitt, Alex Hogle, and Wendy Bates).

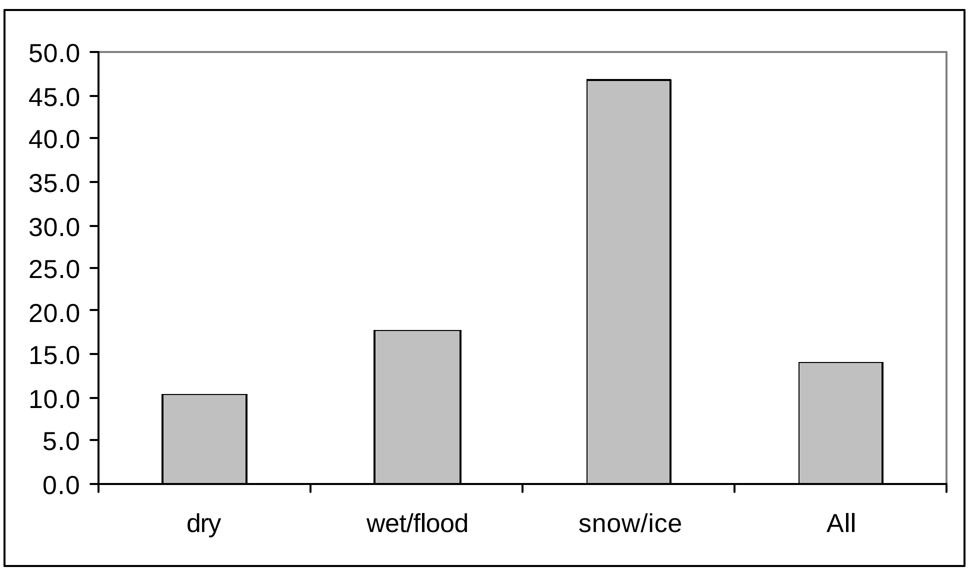

Figure 5. Example skidding rates (the percentage of accidents where skidding is a factor) for Great Britain (adapted from Perry and Symons, 1991).

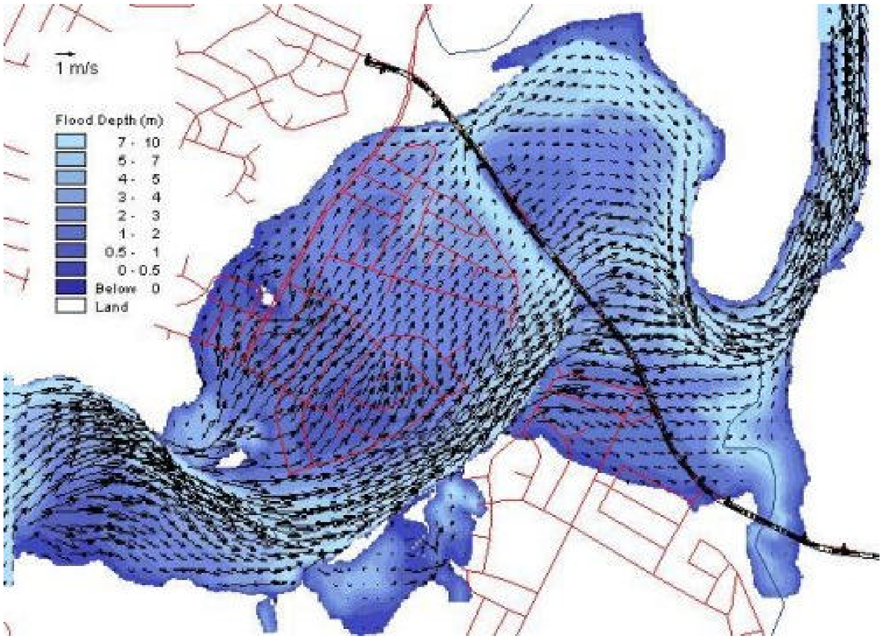

Figure 6. A floodplain inundation map depicting flood depth (m) and velocity (m/s) over a transportation network (Source: http://www.dhiaust.com/general/m21flood.htm).

Figure 7. A wildfire adjacent to an interstate blocking traffic (Source: http://www.commanderchuck.com).

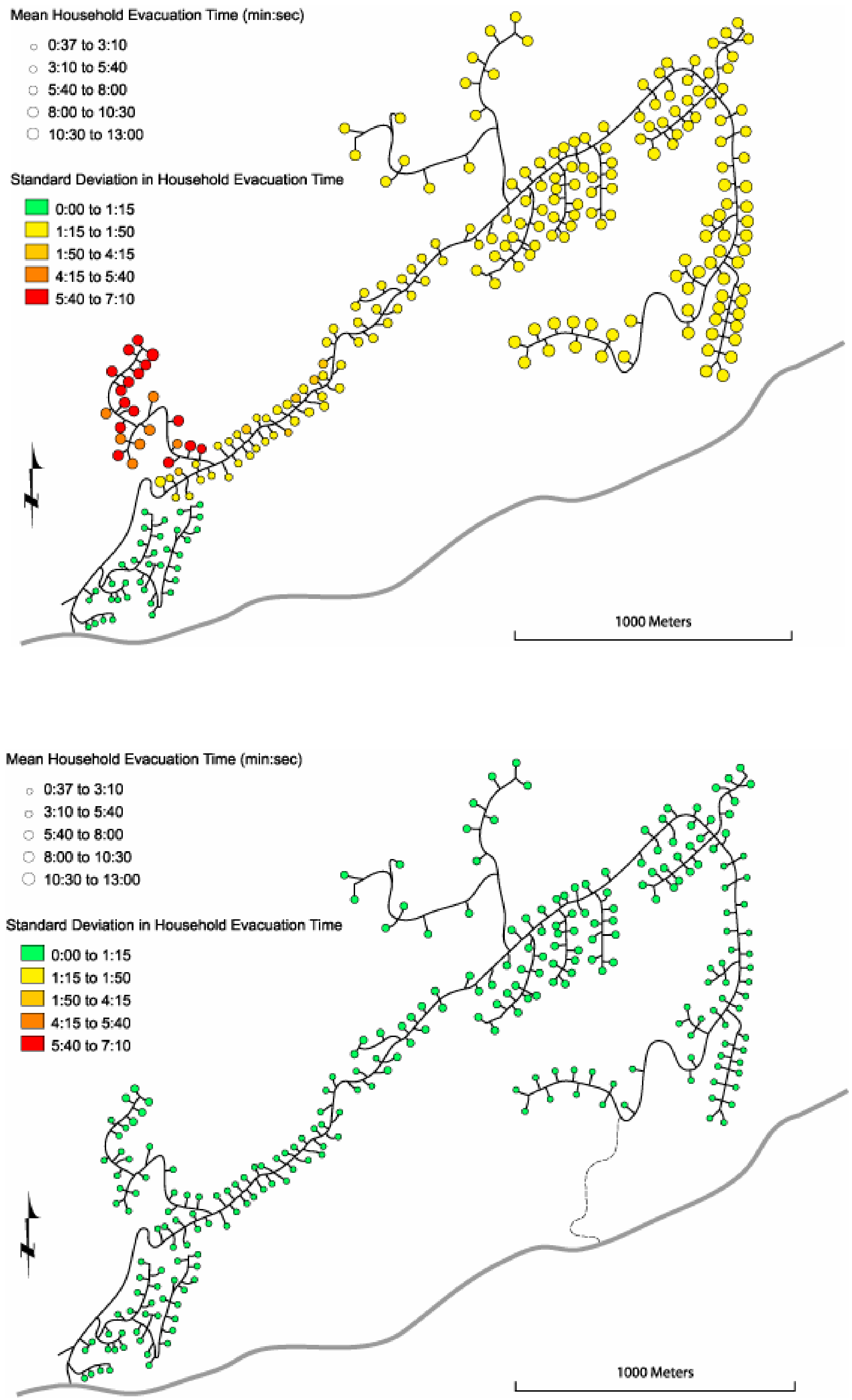

Figure 8. The effect of the construction of a second access road (dashed line) on household evacuation times in a fire-prone canyon east of Salt Lake City, Utah.