# Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities Under Climate Change

## Case Study in Portland, Oregon

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**Transportation departments are beginning to recognize that adaptation for climate change must become an integral part of their planning efforts. However, staff members frequently lack the adequate local data, training, and guidance needed to begin adaptation planning assessments. As a result, planning for adapting to climate change has remained generally abstract and lacks the specificity needed to identify potential system vulnerabilities, assess risk, and prioritize responses. This report outlines a geographic information system–based method with which transportation departments can assess vulnerabilities to climate change in their multimodal surface transportation systems. The city of Portland, Oregon, is used as an illustrative case study. The proposed method allows for preliminary vulnerability identification, prioritization, and impact assessment and can also be used as a basis for more advanced analysis and scenario testing. This research also identifies and describes data gaps and other barriers to climate change adaptation planning for surface transportation.**

The changing climate and response to its impacts will affect public life across a variety of sectors. Examples include agricultural changes in where and when crops can be grown, an extended range for mosquito-borne diseases affecting public health, and shifting wildlife habitat patterns that will affect wildlife management practices. The transportation sector is no exception to changes brought on by a shifting climate. Although organizations that own and operate transportation facilities have traditionally focused on efforts to mitigate climate change through reductions in greenhouse gas emissions, many organizations, both public and private, are beginning to recognize that adaptation responses to climate change must also become integral parts of their transportation planning efforts. Increasingly, these organizations are working to develop their understanding of what potential impacts climate change will have on local transportation infrastructure and operations and are preparing plans to adapt to changing conditions so that system disruptions and damage are minimized.

Climate change research in coastal communities has focused on the anticipated transportation impacts of a rise in sea level and on the prospect for more frequent and intense hurricanes; however, a significant threat of climate change in the Pacific Northwest region of the United States is the effect that changes in seasonal precipitation may have on surface transportation. Scientists forecast that average annual regional temperatures in the Pacific Northwest will increase approximately 2°C to 3°C over the course of the next century as a result of climate change (*1*). In addition, average annual precipitation is expected to increase up to 10%, and seasonal variations in rainfall are also expected to change; most notably, summer precipitation is expected to decrease and fall and winter precipitation to increase (*2*). Furthermore, much of the precipitation is anticipated to fall as rain rather than snow, reducing the overall amount of winter snowpack stored in the mountain ranges (*3*). What snowpack remains can be swiftly melted by warmer rains, raising river flows throughout regional waterways and increasing flood risk during the winter and spring months, leaving little snow to replenish these same waterways during dry summer months. Extreme precipitation events, some previously anticipated to occur only once every 100 years, are projected to occur with greater frequency. Winter and spring seasonal flooding and inundation, along with increased erosion and risk of landslides, are likely to damage transportation infrastructure and will undoubtedly impose delay on goods movement and the traveling public.

Operating and maintaining transportation systems under these increasingly unpredictable conditions presents new challenges to transportation organizations as additional impacts associated with climate change continue to be revealed. For example, although increased precipitation and resulting higher river flows have long been anticipated, few in the city of Portland, Oregon, expected that this might affect bridge clearance for traffic navigating the Willamette River through downtown Portland. In fall 2009, a Willamette River cruise boat operator raised concerns about the proposed height of a new bridge currently under design to cross the river. Already prevented from passing under an existing nearby bridge during high winter river flows, he insisted that potentially higher river levels resulting from climate change would only exacerbate these limitations (*4*). He requested that the new bridge be designed with increased clearance to ensure that the legal obligation to preserve a navigable waterway was met. To address concerns regarding vertical bridge clearance, bridge clearances were modeled under a variety of river

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elevations and the project consultant team incorporated current climate change research in its evaluations (*5*).

Although general interest in and awareness of climate change and adaptation responses is increasing among transportation organizations, there remain significant barriers to the development of actionable adaptation plans. Perhaps most significantly, staff members frequently lack adequate data and guidance required to develop adaptation plans that go beyond broad generalizations of climate change impacts to transportation infrastructure and operations. To make real progress in this area, they must answer questions such as these: Where are impacts most likely to occur? How can the levels of risk associated with the impacts be estimated? A lack of answers to these fundamental questions limits transportation professionals' understanding of climate change impacts at the local level and stymies real progress toward identifying vulnerabilities in the transportation system, assessing impacts, and taking action.

This report outlines a transferable method for transportation departments to use in beginning to assess climate change vulnerability in their multimodal surface transportation systems using a geographic information system (GIS). The city of Portland is used as an illustrative case. The resulting framework allows for preliminary identification of vulnerabilities, impact assessment, and prioritization and can be used as a basis for more advanced analysis. This research also identifies data gaps and other barriers to adaptation planning for surface transportation.

## USING TRANSPORTATION ASSET MANAGEMENT TO PLAN FOR ADAPTATION TO CLIMATE CHANGE

In the 2010 paper *Transportation Asset Management Systems and Climate Change: An Adaptive Systems Management Approach,* Meyer et al. outline how transportation asset management (TAM) systems can be used to incorporate adaptation to climate change into transportation planning (*6*). FHWA defines TAM systems as "a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. . . . Thus, asset management provides a framework for handling both short- and long-range planning" (*7*).

A TAM system generally includes goals and policies for system performance, an inventory of all assets, condition assessment and performance monitoring for these assets, system improvement and optimization alternatives, short- and long-range plans, and implementation and monitoring. Meyer et al.'s approach incorporates climate change considerations into each element of the TAM system (*6*). For example, they note that identification of system vulnerabilities to climatic events may be included in asset inventory, risk to assets associated with climatic events may be included in the condition assessment and performance modeling, and so on.

Meyer et al. propose that by, "incorporating the consideration of anticipated effects of climate change into an agency's infrastructure preservation and asset management process . . . transportation officials could end up with the most cost effective approach toward system adaptation to changing environmental conditions" (*6,* p. 12). This approach is advocated as a good use of resources, because most transportation agencies already have some type of asset management system in place upon which to build. The City of Portland, for example, employs a TAM system in the form of a computerized pavement management system to monitor current pavement conditions; project future conditions; evaluate alternatives for improvement, including reconstruction, rehabilitation, and maintenance; and to prioritize repairs on the city's 1,700 mi of roadway based on cost-effectiveness (*8*). Although this tool is primarily used to manage pavement quality, such a system could potentially be modified to assist in planning decisions regarding climate change adaptation. Given that much planning for climate change adaptation takes place at the local level, where staff and funding resources are constrained, the effective reuse of existing tools is particularly appealing (*9*). This study followed the process outlined by Meyer et al., using several data resources commonly available to local transportation organizations, to identify opportunities or constraints presented by this approach. The study focused on asset inventory.

In addition to a lack of local data on climate change, uncertainty regarding the location and magnitude of the potential impacts of climate change is a major barrier to agency action with respect to climate change adaptation (*10*). The primary objective of this study is to develop a method for identifying potential vulnerabilities of a local surface transportation system to anticipated impacts of climate change. Locations with potential vulnerability to flooding and landslides are identified for the surface transportation system in the city of Portland using a GIS. Also explored are recommendations for other TAM elements such as impact analysis (which may be used in risk management) and prioritization after potential vulnerabilities have been identified.

## RISK MANAGEMENT UNDER CLIMATE CHANGE

Risk management is a decision-making process that has traditionally been associated with insurance and financial institutions, but its use has extended beyond these fields. According to Noble et al., "the risk management process offers a framework for identifying, assessing and prioritizing climate related risks, and developing appropriate adaptation responses" (*11,* p. 2). It is particularly appropriate in the context of climate change, because it allows for decisions under uncertainty.

Risk management approaches generally include the following elements, which are described in the context of climate adaptation:

- Preliminary evaluation. Define the scope of the analysis, including the hazards that will be examined and the study limits. Both the geographic field of study and the transportation modes should be defined.
- Risk identification. Identify potential risks, based on a record of historical vulnerabilities as well as projected future scenarios.
- Risk estimation. Determine the costs associated with a particular risk should it occur (magnitude) and assess the likelihood of the event occurring over a specified time span (probability).
- Risk control. Develop strategies for addressing identified risk(s)—protection, accommodation, or retreat—within the context of other competing risks in the system and set priorities.
- Action and monitoring. Develop an implementation plan and evaluate effectiveness.

In the city of Portland, researchers at Portland State University have analyzed the potential impacts of climate change on transportation in terms of travel delay associated with flooding in the Fanno and Johnson Creek watersheds and the resulting closure of two major roads (*12*). This study employed a variety of climate change scenarios, hydrologic modeling, roadway and stream channel surveys, and travel forecast models to estimate potential impacts in locations known to be susceptible to periodic flooding. Although

**TABLE 1 Approaches for Identifying Transportation Vulnerabilities and Assessing Risk**

| Organization | Approach |
|---|---|
| Puget Sound Regional Council (PSRC)—Transportation 2040 (*13*) | The impacts of sea level rise to transportation and other infrastructure are of great concern to PSRC. One of their efforts toward adaptation planning has involved mapping existing and projected sea level in the region using GIS and consulting with local agency and academic experts for reasonableness and consistency. Projections for future sea level incorporated data from both global climate models as well as locally observed vertical land movement (subsiding and rising) and local atmospheric circulation. Light detection and ranging (LIDAR) elevation data were used to map existing sea level, and there is some concern regarding the accuracy and consistency of these data. As a result, only medium- and high-level sea rise scenarios were mapped. A GIS was then used to identify land below a defined threshold and connected by waterways to Puget Sound in order to indicate general locations within the region likely to be inundated. The resulting maps are not intended to identify specific sites vulnerable to climate change, but rather to identify general areas and infrastructure that may be affected and considered in future long-term planning efforts. |
| New York City—New York City Panel on Climate Change (NPCC) (*14*) | As part of the city's long-range sustainability plan, PLANYC, Mayor Bloomberg convened NPCC to advise on issues related to climate change, in terms of both mitigation and adaptation. The panel's climate change adaptation planning efforts employ a combination of local climate scenarios, generally following the process used by the Intergovernmental Panel on Climate Change. Scenarios and their projected impacts to critical infrastructure were then evaluated using a risk-based approach. More than 40 diverse stakeholders were involved in the process, including the insurance industry. The study looks both at historically observed events and potential future impacts and assesses the likelihood of their occurrence. It also recommends an iterative or "Flexible Adaptation Pathways" approach that allows for monitoring and mid-course corrections to projected impacts and associated adaptation responses as needed. NPCC has also developed a Climate Change Adaptation Guidebook to inventory at-risk infrastructure and develop adaptation responses. This guidebook includes risk assessment questionnaires, a risk matrix, and a prioritization framework. |
| Transit New Zealand (*15*) | Transit New Zealand uses a two-stage process to evaluate the potential impacts of climate change to their facilities on state highways and to determine responses. The first stage assesses the necessity of acting immediately to adapt the facility based on the certainty the impact will occur along with the projected magnitude of the impact, the design life of the infrastructure in question, and the ability of the agency to manage the anticipated climate impact with existing procedures. The second phase employs an economic analysis to assess the feasibility of immediate action based on three adaptation approaches: no action, retrofitting potentially affected existing infrastructure against climate impacts, and designing future improvements to accommodate future climate changes. The results of Transit New Zealand's study suggest that for facilities with a design life less than 25 years, the impacts of climate change can be managed with the agency's current asset management system without major changes to standard agency procedures. For longer-term facilities, such as major new bridges, the potential for climate change impacts, such as larger flood flows, should be considered in the design. However the analysis stated that it would not be economical to incorporate these potential impacts in the design, based on the "uncertainty surrounding the if, where, and by how much flooding will increase, the risk of infrastructure obsolescence and the current discount rate" used in the analysis. The approach used in the Transit New Zealand study does not consider the potential social or economic costs of travel delay associated with climate change impacts. |
| Business Sector—Entergy (*16*) | Private-sector organizations recognize climate change as a threat to business operations. In *Adapting to Climate Change: A Business Approach,* Sussman and Freed note how the energy company Entergy is using a three-stage process to insulate its business from climate impacts following Hurricane Katrina. First, likely climatic changes and physical impacts were identified and, on the basis of historic trends, scenarios for different climate impacts were mapped using GIS. In the second phase, climate risks were considered in relation to potentially affected assets and operations. In the third phase (currently underway), alternative adaptation responses are being developed. |

vehicle miles traveled were not significantly affected in this particular model, vehicle delay was affected. This conclusion suggests the need for detour and congestion response plans in areas at risk for disruption from climate change in the short term, as well as for long-term physical improvements, such as locating signal control electronics above flood level. Although a study as detailed as this is not feasible throughout the entire city, such an approach can be used to estimate impacts and weigh response in other vulnerable areas as they are identified, particularly in locations where impacts and the associated adaptation improvements are likely to be costly.

Other organizations have also begun to identify potential locations of transportation system vulnerabilities and to assess risk using a variety of approaches. Examples are provided in Table 1.

## PORTLAND ILLUSTRATIVE CASE

The next three sections describe the application of a GIS-based transferable method with which transportation departments can assess climate change vulnerabilities in their multimodal surface transportation systems. The city of Portland was selected as an illustrative case for this study for several reasons, including the following (*17*):

- Access to GIS data,
- Access to city staff,
- Familiarity with the transportation system, and
- The small size of the study area (134 $mi^2$).

Portland's transportation network is truly multimodal, offering driving, bicycling, walking, bus, light rail and streetcar options for passenger trips, as well as truck, rail, and maritime options for freight trips. With approximately 7% of residents using a bicycle as their primary means of traveling to and from work, Portland has a relatively high rate of cycling compared with other U.S. cities (the average bicycle mode split nationwide is less than 0.7%) (*18*), and an established goal to increase bicycle use to a 25% mode share by 2030 (*19*). Transit use is also relatively high, with 10% using bus, streetcar, or light rail as the primary means of transportation to and from work, compared with 5% nationwide. Seventy-five percent of residents report driving alone or with others as their primary mode of commute transportation, compared with 86% nationwide (*20*). Considering these statistics, it was important not to limit transportation vulnerability analysis to personal automobile routes. Thus, the transportation facilities used in the model include major arterials, rail lines (passenger and freight), bicycle facilities (bicycle routes and multiple-use paths), bus routes, and streetcar and light rail (including planned improvements).

In an online survey conducted in late fall 2009 and winter 2010, transportation planners in the Pacific Northwest were asked about their climate change planning activities, focusing particularly on activities related to climate change adaptation for their transportation systems. Both in the online survey as well as in follow-up interviews, respondents (including staff in the City of Portland Transportation Bureau) indicated that of the potential impacts of climate change likely to occur in the Pacific Northwest, flooding and inundation were considered the biggest threats to the city's transportation infrastructure and operations, because of the tremendous damage standing water does to roadway structures. This response is consistent with a 2007 report of the Intergovernmental Panel on Climate Change, which named urban flooding as the most costly impact of climate change on transportation (*1*). Erosion and landslides associated with heavy precipitation were also of concern because of the city's topography—chiefly the steep, slide-prone hills directly west and southwest of the city center. Respondents expressed particular concern regarding how road closures or delays could not only affect travel delay but also potentially impede emergency response.

Located at the confluence of the Columbia and Willamette Rivers, Portland is no stranger to flooding. In the winter of 1964, flooding on the Willamette River damaged waterfront property, swept away homes and roadways, and ultimately left 12 people dead (*21*). Other major, albeit less devastating, floods have occurred more recently, including the winter flood of 1996. During this event, the Willamette River reached a height of 31.8 ft and lapped at the edges of the city's downtown seawall (flood stage for the Willamette is 21.2 ft and the seawall is at 32.5 ft) (*22*). Significant damage downtown was narrowly avoided thanks to rapid coordination between dam operators upriver to delay the release of additional river water and efforts of city employees and more than 1,500 resident volunteers to build a 4-ft tall, mile-long temporary seawall along the river. However, other parts of the city and the surrounding region experienced substantial flooding that resulted in road closures along local roads and Interstates 5 and 84 (*21*).

City staff also reported significant landslide activity throughout the metropolitan area as a result of storms and flooding during the 1996 event. Approximately 750 individual landslides occurred throughout the Portland region, predominately in the West Hills area of Portland. The amount and extent of landslide activity during this time was so great that, in the report *Landslides in the Portland, Oregon Metropolitan Area Resulting from the Storm of February 1996: Inventory Map, Database and Evaluation*, researchers suggested this was a 100-year event for landslide recurrence (*23*). This report also states that the geological susceptibility to landslide and the steep slopes of many sites in Portland naturally contributed to the extreme landslide activity observed in 1996. Landslide vulnerability increases when the geologic and slope characteristics of these sites are combined with abundant, mismanaged storm water that saturates soils. According to Burns et al., in 76% of the landslides studied after the 1996 landslide events, human activity such as the formation of cut slopes and fill failures contributed to the increased landslide risks (*23*). Furthermore, an estimated 9% of the landslides could have been reduced had there been better storm water control measures (for example, conveying standing water off the property to avoid saturation of soils or better siting of homes on properties).

Both the 1964 and 1996 flood events were attributed to heavy snow precipitation in upper elevations followed by intense, warmer-temperature rain that quickly melted the snowpack and saturated soils. These climatic events are often referred to as "rain on snow" (*23*). Research by Mote and Salathé suggests that while projected increases in annual precipitation in the Pacific Northwest are relatively small, changes in seasonal variations of precipitation are likely, with wetter autumns and winters and drier summers (*2*). With more precipitation projected to fall as rain rather than snow during winter, the potential exists for reduced long-term water storage in the form of winter snowpack, earlier snowmelt and saturated soils, and higher stream flows in waterways. These conditions may not be dissimilar to those observed in previous flood events.

Although they cannot definitively be attributed to climate change, several recent storms have also brought unusual weather patterns to the Portland region for which local transportation agencies were largely unprepared, leading to transportation emergencies. Examples include snowstorms during the winters of 2008 and 2009. Except in higher elevations such as the West Hills area of the city, heavy snow is relatively uncommon in Portland. However, in the winter of 2008, 18.9 in. of snow fell on the city in a short time (*24*). Because the city had little to no equipment with which to handle such a large quantity of snow, several roads were closed, buses were brought to a crawl, flights were canceled, and the city generally closed for business. As events like these suggest, agencies cannot rely on historic events alone when planning for climate change adaptation; they must also develop localized climate change scenarios that include potential extremes.

## STUDY DESCRIPTION

As discussed earlier, one of the earliest steps in TAM and in risk management is the identification of potential system vulnerabilities. In this study, GIS was used to model two anticipated climate change impacts—flooding and landslide hazard locations—that could leave the city of Portland's surface transportation networks vulnerable to the effects of climate change. Risk assessment and development of adaptation responses were not carried out for this case study; however, recommendations for how the results could be used for these purposes are provided.

GIS has been used in a similar function in several studies, including the *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* (*25*). GIS offers several advantages for modeling hazards, including the ability to model multiple data sets simultaneously, the relative ease of adapting new or revised data sets to the model, the range of analysis options from simple to highly advanced, the ability to export data for analysis in other programs (such as traffic-modeling programs), and the ability to visually present spatial data to stakeholders and other interested parties.

Much of the GIS data used in the study was obtained through the Regional Land Information System (RLIS), a clearinghouse for spatial data managed by Metro, the regional government for the Portland metropolitan region (see Table 2). Many jurisdictions lack the resources to collect and maintain a spatial data resource as comprehensive as RLIS. However, a significant amount of spatial data, including transportation networks, waterways, and the Federal Emergency Management Agency (FEMA) 100-year flood map can be

**TABLE 2 Spatial Data Used in the Portland, Oregon, Model**

| Shapefile Data[a] | Source | Purpose |
|---|---|---|
| Surface transportation network—major arterials, bus routes, light rail system, planned transit rail improvements (streetcar and light rail), bike routes, passenger and freight rail lines. | RLIS | Model vulnerabilities |
| Major waterways | RLIS | Reference |
| Flood—Federal Emergency Management Agency 100-year flood, 1996 flood. | RLIS | Model vulnerabilities |
| Landslide hazard areas | City of Portland | Model vulnerabilities |
| City boundary | RLIS | Reference |
| Land use | RLIS | Model vulnerabilities |

[a]The GIS data used in the model are shapefile, a spatial data format that contains both geometric and attribute data and can be displayed as points, lines, or areas.

readily obtained online at no cost through several reputable data clearinghouses such as Geodata.gov, the U.S. Geological Survey, and the Economic and Social Research Institute, to name a few. More specialized spatial data used in this study, including landslide hazards and planned transit improvements, were obtained through city and transit agency staff.

## GIS Processing

Most shapefiles used in the model include data for the entire Metro region and were first clipped to the Portland city boundary. This clipping action limited analysis solely to those areas within the Portland city limits and was done primarily to reduce processing time and keep the analysis at a manageable scale. Shapefiles of both the FEMA 100-year flood maps (last updated in 2004) and a shapefile delineating areas inundated during the 1996 flood were projected. Although the shapefiles are largely identical, some flooding in the 1996 flood occurred outside the 100-year flood boundary. To capture all areas of potential and recent flooding, these two shapefiles were combined using the "union" analysis tool to form a single flood polygon.

Next, a shapefile for a specific transportation network, for example, major arterials, was projected. The "select by location" analysis tool was used to select segments of the major arterials that intersected the flood polygon. The selected segments were then exported and reprojected as a flood-vulnerable shapefile representing the segments of major arterials that may be vulnerable to flooding. Figure 1 provides an example of this type of analysis with major arterials within the city of Portland that are potentially vulnerable to flooding highlighted in red. These red segments are portions of the roadway that intersect with areas historically known to flood and that are likely vulnerable to more frequent or intense flooding as a result of climate change. The map inset provides a larger view of Southeast Foster Avenue, one of the highlighted roadway segments identified using this process. Southeast Foster Avenue is a route that carries approximately 9,100 vehicles daily (*26*). An identical process was carried out for each of the transportation system network shapefiles. After potential flood vulnerabilities were identified, an identical

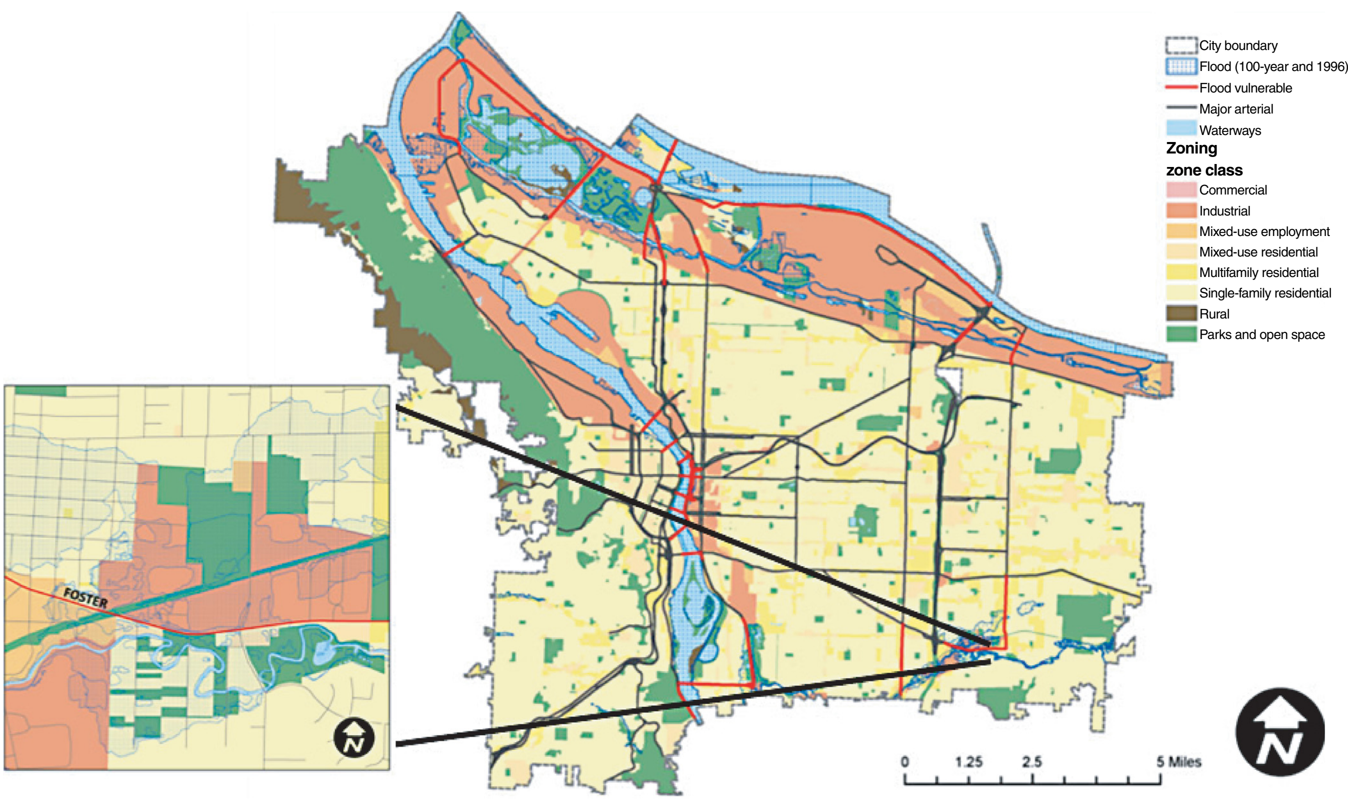


**FIGURE 1 Segments of major arterials potentially vulnerable to flooding.**

analysis was performed using a landslide hazard polygon. These hazard shapefiles where then layered over base shapefiles of the transportation network, along with land use zoning and major waterways for reference.

Each of the transportation shapefiles comprises multiple segments of varying length. When features that intersect the flood or landslide hazard areas are selected, portions of a segment that lie outside of the hazard area may be selected as well. This action provides generalized locations of potential hazards. However, for greater accuracy, a listing of vulnerable segments was compiled by mode based on a description of the segment including the intersections nearest to the hazard area (e.g., "Lombard Street between Ramsey Street and Burgard Street"). A complete listing of segments potentially vulnerable to flooding or landslide by facility type can be found at the web page for this project on the Portland State University Intelligent Transportation Systems Lab website: http://www.its.pdx.edu/project.php?id=2010-02.

### Results

While all segments of the transportation system network that intersect the flood and landslide polygons were identified as potentially vulnerable to flooding or landslide, they will not all be flooded during an extreme event. Although elevation data can be added to the model with more advanced GIS data analysis, this model did not incorporate elevation data; thus, further analysis is required to determine whether intersecting transportation routes are at an elevation susceptible to flooding. For example, several bridges were selected as vulnerable to flooding, although it is known that the height of these bridges makes flooding unlikely. As this model is intended as a preliminary assessment, the focus is on areas that may be subject to flooding rather than specific segments. In this case, although the bridge itself is unlikely to flood, the model highlights potential issues for travelers accessing the bridge (as lower-elevation approaches may be susceptible to flooding), bridge clearance limitations for river traffic, and potential scour to bridge abutments as a result of higher water flow.

In addition to identifying the locations of transportation segments vulnerable to flooding and landslide, for some modes the GIS shapefile also provides length data, allowing for a tally of affected transportation segments within the Portland city limits:

- Major roadways. The model identified 40 mi of major arterials (approximately 7% of major roadways) potentially affected by flooding, primarily located adjacent to major waterways. Roughly 70 mi of major roadways (approximately 13% of major roadways) were identified as vulnerable to landslide, primarily in the West Hills area. This mileage could increase substantially if local roads are included in the analysis.
- Railways. Roughly 70 mi (or approximately 18%) of railways (comprising both passenger and freight lines) within the city limits were identified as vulnerable to flooding, primarily near rail yard facilities adjacent to the Willamette River in northeast Portland. The model identifies roughly 50 mi (approximately 13%) of railways as vulnerable to landslide.

The mileage of transit routes vulnerable to flooding and landslide was not calculated for transit modes (bus, streetcar, and light rail) because of a large portion of identified segments that extended outside of the hazard areas and a lack of data regarding the length of affected route segments. Bus routes were primarily affected by flooding in areas outside of the downtown core, particularly in northern parts of the city. Fortunately, bus routes can be easily detoured (or truncated). According to a TriMet representative (TriMet is the regional transit agency), light rail may also be truncated using crossovers, which allow trains to turn around, and pocket tracks, which allow trains to pass one another, located approximately every 7.5 min (in travel time) along the light rail alignments. Further, the light rail vehicles have engines on both ends, which allows the train to operate in either direction. Segment length data were also unavailable for bicycle lanes and multiuse paths; however, the model does indicate that routes directly parallel to the river's edge, including major multiuse pathways, are potentially at risk for flooding. Notably, many bicycle facilities are located along these open space areas vulnerable to flooding. Fortunately, nearby alternative routes (local streets) are typically available.

The majority of facilities potentially affected by landslide are in the hilly, western area of the city, where there are fewer major arterials, bicycle facilities, and rail lines. However, because there are fewer alternate routes in the event of a landslide, these routes carry greater risk. It is notable that Barbur Boulevard, identified by the model as being vulnerable to landslide, is also recommended by the regional planning agency as a future high-capacity transit corridor (*27*).

### Validation

To validate the results from the model, reports of previous landslide and flooding incidents were compared with the GIS output. City transportation staff members were also consulted for a list of locations known to have flooding or landslide problems. Overall, the results from the model were consistent with known experience, with the exception of Willamette Bridge flooding. Conveniently, much of the analysis for this study occurred during a series of heavy precipitation events in Portland during which two landslides occurred along segments of a bicycle route and a major arterial identified as vulnerable in the model (*28, 29*).

This model has been shown effective at identifying transportation system vulnerabilities to historical hazards and may be used by local planning staff to begin the process of preparing for climate change. However, while future flooding and landslide activity are likely to occur in the vicinity of known hazard areas, they also have the potential to expand to new areas based on different future climate scenarios. Thus, to strengthen the model's potential to identify new hazards, shapefiles representing a range of flood and landslide hazards under different climate scenarios need to be developed and incorporated into the model. Such shapefiles should be edited as new climate change information becomes available.

## POTENTIAL RESPONSE

This model was developed as a proof of concept to evaluate the use of GIS to identify potential transportation vulnerabilities under climate change. Although local planning staffs have expressed interest in continued development of this model, to the authors' knowledge, no new policy or project decisions have yet been made as result of these findings. However, several planning responses are recommended on the basis of the results of the model.

Once potential transportation system vulnerabilities have been identified, planners must assess the risk presented by these vulnerabilities and develop a prioritized adaptation response. As discussed earlier, the impact of a potential transportation disruption can be estimated in a number of ways, including both simple techniques based on traffic volumes along the affected segments or on the availability of alternative routes and more sophisticated analyses such as traffic modeling to estimate diversion, congestion, and associated delay (as well as the economic costs of delay). In addition to travel delay, planners must also consider the likely cost of feasible adaptation alternatives.

There are three general adaptation responses:

1. Avoidance. Planning new facilities or rerouting existing facilities outside of hazard areas. An example includes construction of a bypass around a landslide-prone area.
2. Protection. Improvements to existing facilities to increase their resilience to the impacts of climate change. Examples include increasing the height of seawalls, landslide fencing and monitoring, and bridge design that exceeds current standards.
3. Abandonment. Disuse of the facility may be the most cost-effective solution if avoidance or protection alternatives are infeasible. Examples include closure of landslide-prone segments.

A fourth adaptation response could include operational responses such as ongoing maintenance and incident response (including temporary or seasonal closure). This alternative would factor in the ongoing cost of repair and incident response on the basis of the projected frequency of events. For vulnerabilities with minimal impact or a low likelihood of occurrence, or for assets with a short life span (e.g., pavement) this approach may be an optimal response (*15*). Examples include a planned detour route in response to periodic flooding of a roadway. The City of Portland has such a plan established (including sandbag locations) for the Johnson Creek area, which is known to flood periodically. Each of these alternatives has an associated cost that must be considered in comparing response options and prioritizing among competing risks located elsewhere within the system. The results of this process may also be incorporated in the agency's overall project selection process for capital improvement and maintenance projects.

## RECOMMENDATIONS

Transportation agencies can adopt a GIS model to begin inventorying their transportation facilities for potential vulnerabilities to climate change. After locations have been identified and, ideally, validated through expert opinion or field assessments, or both, the GIS model can also be used to assess the associated impacts and to begin prioritizing an adaptation response for the system as a whole. The results of this analysis can be incorporated into an existing TAM system, or the TAM system may be adapted for this purpose. As new data become available, these should be incorporated into the model and risks and prioritization should be reassessed through an iterative process. Additional data may include new events such as flooding and landslides located outside known hazard areas. New data may also arrive as a result of advanced GIS modeling, such as revised flood estimation using digital elevation models or advanced hydrologic modeling.

Because the GIS model contains geographic location data, it can also be imported into other advanced analysis tools such as VISSIM traffic-modeling software and used to model potential traffic delays and detour effects and to estimate the potential economic effects of these impacts. Such information would provide an indication of the impact a closure (detour or congestion) would have on the system and thus serve in risk estimation and prioritization. Oregon's Department of Land Conservation and Development details additional data sources for quantifying the tangible and intangible costs of flooding or climate change required to quantify economic impacts (*30*). Economic impact analysis would be useful to evaluate a variety of future climate scenarios. However, the estimation of costs associated with the impacts of climate change may be difficult because of the lack of complete and systematic record keeping and uncertainty related to the estimation of the incremental impacts of climate change on flood event magnitudes, frequencies, and durations (*30*).

More rudimentary preliminary impact assessment and prioritization can also occur using the functional classification of the transportation system, the availability of emergency evacuation routes near the vulnerable segment, and traffic volumes along the segment. For example, the closure of a higher volume roadway would generally have a greater impact on the remainder of the system and thus would likely be prioritized for adaptation improvements ahead of lower volume roadways. Larger metropolitan areas are more likely to have the resources (both in terms of resources and of expertise) to undertake more complex risk evaluation and response prioritization. However, a simple Delphi approach may also be employed using local expert knowledge.

In addition to preliminary impact assessment and prioritization, the model may also be used to avoid potential impacts in the future. For example, the use of land use zoning data in the model may point to land use planning that can reduce risk to persons and structures in landslide hazard areas by requiring building and landscape designs that reduce the risk of soil saturation or instability during intense precipitation. Similarly, the model can be used to avoid or minimize private or public investments in potential hazard zones.

Although the proposed GIS modeling approach offers a number of advantages, there remain gaps in data that may limit full utilization of this tool. While data sets of existing hazards are frequently available, the currency of the data may vary, and the process of updating hazards can be controversial because of the increased liability incurred by property owners. For example, the Oregon Department of Land Conservation and Development indicates that of the 257 national flood insurance communities, more than 70% have flood maps that are outdated (*1*). Although GIS data sets can frequently be modified for use, as in this study, at times the data may have been collected for a specific purpose and in such a way that limits its use in other analyses. Furthermore, spatial data for future climate scenario impacts have yet to be developed, and when developed, must then be digitized and spatially referenced for use in a GIS model. In addition to uncertainty regarding the location of future impacts, there is also uncertainty regarding the magnitude and probability of these events occurring.

Not only must these data sets be developed, but their development should also be coordinated and shared with partner organizations, preferably in a central repository such as a shared GIS database. Frequently, organizations are reluctant to share available data, or a lack of communication among agencies prevents valuable information from being collected in a useful form. For example, as part of a related climate change project, data regarding thermal expansion of railroad tracks (a heat-related impact of climate change) was sought from private and public railroad operators. Private rail operators, under no obligation to share data, refused to participate in the study, referring to a federal rail authority source of this information. However, the federal source collected only data on incidents that posed a safety hazard. There are likely several reasons behind such reluctance on the part of private operators to share data, among them a concern that admission of potential risk to their operations may stifle investment. This is likely to be a concern shared by all private transportation operators, including railroads and ports.

While these factors may present obstacles in the use of GIS to identify impacts of climate change on transportation facilities, they do not necessarily prevent analysis. Instead, they are issues that practitioners should be aware of during their analyses and that they should work to address through increased coordination in the collection and sharing of GIS data.

## CONCLUSIONS

Planning for climate change in the transportation sector is no longer limited to strategies to reduce greenhouse gas emissions. Among transportation professionals, recognition is increasing that adaptation strategies for responding to the unavoidable impacts of a changing climate must also be an integral component of climate change planning. Several organizations at the national and local government levels and within the business sector have begun to work toward identifying vulnerabilities and categorizing risk. However, professionals are frequently limited in their ability to plan for adapting to climate change in local transportation networks. This limitation is due both to insufficient local data resources and to a lack of guidance on how to identify locations vulnerable to climate change and assess the risk, in terms of both infrastructure loss and operational delay.

The model presented in this report outlines a transferable method that uses GIS for preliminarily assessing potential impacts to local transportation systems from climate change. This method, which is widely accessible to a range of transportation departments because of the simple nature of the GIS analysis, can also be used as a basis for more advanced analysis, such as traffic modeling and comparative scenario testing. The results of these preliminary analyses can later be incorporated into a TAM system to assist with long-range transportation planning decisions. Although this method presents a promising first step toward vulnerability and impact assessment, it can only fulfill its promise with continued, coordinated data collection, development, and updates as climate impacts at the local level continue to be revealed.

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