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Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area

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Abstract

Global climate change is likely to affect urban infrastructure through sea level rise and increased frequency of extreme events. This paper assesses the potential impact of climate change on the system-wide performance of transportation networks using the Boston Metro Area as a case study. The methodology integrates projected changes in land use, demographic and climatic conditions into the urban transportation modeling system in order to explore the relative impacts of global warming on the system performance due to additional riverine and coastal flooding. Results indicate almost a doubling in delays and lost trips. These impacts are significant, but probably not large enough to justify a major effort for adapting the physical infrastructure to expected climatic conditions, except for some key links.

Keywords: Flooding; Climate change; Urban transportation

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1. Introduction

There is abundant knowledge of how the urban transportation sector may contribute to climate change through emissions (Intergovernmental Panel on Climate Change, 2000; Organisation for Economic Co-operation and Development/International Energy Agency, 2000). Much less attention has been given to the potential impacts of climate change on urban transportation systems. In addition to a gradual warming of ambient temperatures, climate change is expected to include increases in the frequency and severity of storms. While it is recognized that urban infrastructure is vulnerable to such an increase (Schreider et al., 2000), little is known about how flooding events affect the performance of urban transportation networks as integrated systems.

This paper addresses the potential impact of climate change on the performance of the surface transportation system in the Boston Metro Area. Our analysis of impacts is focused on transportation disruption, rather than on infrastructure damage due to floods. The literature on earthquakes, for example, indicates that in addition to direct damages caused to infrastructure, the costs associated with disrupted economic activity is a significant component of disaster impacts (Cho et al., 2001; Brookshire et al., 1997). While the effects of flooding on roads are less durable than those of earthquakes, it is important to know how much disruption in urban travel results from the intense rainfall events or coastal flooding events that are expected to become more common over the 21st century.

There has been surprisingly little research on the effects of extreme weather events on transportation systems. Of the existing studies, some focus on emergency evacuation (Church and Cova, 2000; Pisano et al., 2002) while a number of others address the effect of weather on the frequency of road accidents (Edwards, 1999; Brodsky and Hakkert, 1998). Two commuter surveys in European cities evaluate the impact of adverse weather conditions on the propensity to change travel decisions (De Palma and Rochat, 1999). In a report outlining the current state of knowledge regarding road weather conditions (National Academies Press, 2004), the Committee on Weather Research for Surface Transportation (formed at the request of the US Federal Highway Administration) recommended the development of models that assess and predict weather impacts on roadway conditions and operations.

The methodology presented in this paper makes it possible to assess the impacts of flooding on urban transportation from a systemwide performance perspective, exploring how land use conversion and climate change are likely to further increase the vulnerability of the metropolitan Boston transportation system to increased frequency of flooding. Such methodology is based on modeling and data resources that are available for most metropolitan areas in the US and many in other countries.

2. Climate change and the Boston Metro Area

The likely effects of global climate change in the coming decades include sea level rise and increased frequency of storms and hurricanes. The combined effect of sea level rise and increased frequency of storms will lead to more flooding, especially along river valleys and in coastal communities. At the same time, population and economic growth are likely to increase the pressure to

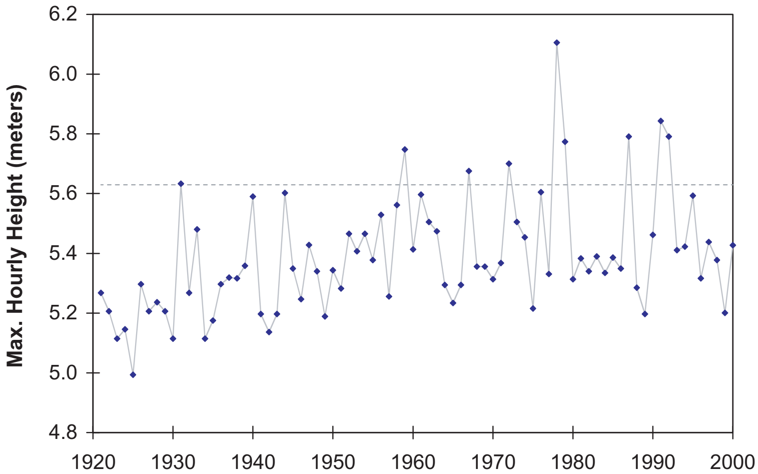

Fig. 1. Sea level at Boston harbor (1920–2000).

develop land, augmenting not only the amount of infrastructure at risk but also the runoff which must be handled by rivers, streams and stormwater systems.

There is considerable support for the idea that the frequency of extreme weather events will increase over the next century (Katz et al., 2002; Wagner, 1999; Leavesley, 1994). In particular, intense precipitation is likely to occur more frequently (Fowler and Hennessy, 1995), and consequently produce more flooding (Penning-Roswell et al., 1996; Weijers and Velinga, 1995). These perspectives are reinforced by a study conducted by Knox (1993), based on paleoflood records: the study concluded that small changes in temperature (1–2 °C) and changes in average annual rainfall can result in large changes to flood frequency and magnitude.

Fig. 1 shows the annual maximum sea level measured at Boston Harbor between 1920 and 2000 (National Oceanic and Atmospheric Administration, 2001). While sea level rise appears to be present as a slight trend upwards, a relevant fact is that high water levels associated with extreme events have increased dramatically over the second half of this period. It is estimated that a rise in sea level of 30–90 cm would increase the size of the 100-year floodplain in the US by 10,000–20,000 km^2. Fig. 2 shows the magnitude of intense precipitation events in the Boston area according to two estimates: those currently used for infrastructure design, commonly known as TP40 (Herschfield, 1961), and those from Wilks and Cember (1993), derived from more precipitation data and improved methodology. The value associated with the 100-year recurrence interval increases by about 20%.[1]

Flood damages on the coast of Massachusetts have been extensively documented (US Army Corps of Engineers, 1978; Federal Emergency Management Agency, 1997). Massachusetts has a high risk of coastal and riverine flooding because of its long coastline, numerous rivers and streams, and concentrated development in combination with high exposure to heavy rainstorms, hurricanes and 'northeasters'. As an outcome of climate change we can expect these events to

[1] This assessment is probably conservative because it does not take into account several intense events occurred during the last decade.

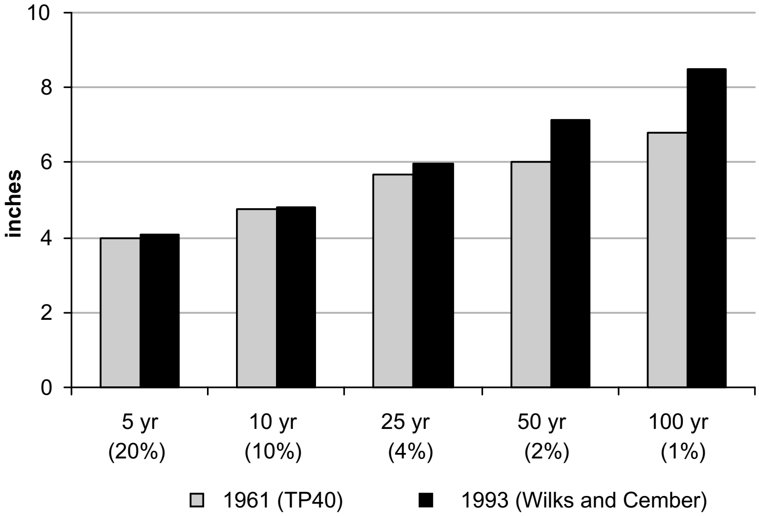

Fig. 2. Twenty-four-hour precipitation events in Boston, by recurrence interval.

become more frequent and more severe. This implies flood-related impacts on transportation systems, which are designed for environmental conditions that are very sensitive to climate-related variables such as precipitation intensity and sea level.

3. General approach to modeling flood impacts on transportation networks

Consider the example of a storm that causes significant flooding and disruptions to the transportation system because:

- Some trips will be cancelled because either the origin location or the destination location is flooded. For example, some work trips will not occur because either the employees' homes or places of work are flooded. Shopping trips may be canceled because either the shoppers' homes or the shopping center is flooded.
- Some trips will not occur because flooding of links has made it impossible for the traveler to get from origin to destination.
- Many trips that occur despite the flooding will take much longer. This may occur either because travelers are forced to take circuitous routes from origin to destination to avoid impassable links, or as a result of traffic congestion on passable links that is caused by the diversion of traffic away from impassable links.

These disruptions have economic costs because trips have value. This may be expressed in terms of lost work-days, lost sales, or lost production. Traveler's time also has value and, thus, lost time due to circuitous travel or traffic congestion has significant cost.

Our approach to estimating these impacts requires a model capable of simulating the flows of road traffic in the metropolitan area under a variety of conditions. This model is first run under normal circumstances to provide baseline values for the volume of travel and the amount of time spent in travel. Then a set of flooding scenarios is designed to identify those areas that are flooded so that no trips begin or end there, and those network links that become impassable. The model is rerun and the results are compared to the initial run to determine how many lost trips and how much extra travel time may be attributed to the weather event. This provides a basis for estimating the transportation related costs of more frequent and more extreme weather events under various climate change scenarios.

The Urban Transportation Modelling System (UTMS) is the conventional analytical framework for simulating the flows of traffic in an urban road network (Meyer and Miller, 2001). Versions of UTMS have been implemented for cities in the US and throughout the world. While they embody different levels of detail and sophistication, they all follow a common basic design. To start, the urban area is divided into a set of mutually exclusive and exhaustive zones, usually called traffic analysis zones (TAZs). Survey data are needed on the characteristics of households, businesses, and other activities in each zone as well as on the zone-to-zone trip making behaviour of the population. The UTMS breaks traffic generation into four stages: trip generation, trip distribution, modal split, and traffic assignment.

4. Simulating the effects of flooding and climate change using Boston's UTMS

The study area includes all cities and towns covered by Boston's Metropolitan Area Planning Council (MAPC) that includes the cities of Boston and Cambridge, as well as 99 municipalities within roughly 20 miles of Boston (Fig. 3). Seven zones were delineated to capture differences among municipalities in terms of density, growth patterns and influence of coastal flooding.

The UTMS used has been designed and implemented by Boston's Central Transportation Planning Staff (CTPS) and is one of the most sophisticated transportation modeling systems currently in use in the US. With 986 traffic zones, this permits a high level of geographical resolution. Its transportation network, consisting of over 22,000 links, can provide relatively detailed simulation of traffic conditions. A particular advantage of the CTPS model that it is able to make forecasts out to 2025 based on a set of projections for zonal characteristics affecting traveling patterns.

4.1. Modeling scenarios

To capture the effects of flooding of the performance of the transportation network, different flooding scenarios are defined, based on combinations of the year of simulation (2003 or 2025), area flooded (no flooding, 100-year or 500-year floodplain) and type of flooding (coastal, riverine, or both coastal and riverine combined). Independent scenarios are devised for these types of flooding because extreme rainfall may occur without coastal storm surges, and not all coastal storms result in river flooding. Some events, such as hurricanes, include all types of flooding. Thus two baseline and 12 flooding scenarios were used.

The UTMS model was run for 2003 (current) and 2025 (future). The 2003 runs reflect baseline conditions given current socioeconomic data and transport infrastructure (i.e. contemporary patterns of travel and the current state of the road network). The 2025 runs are designed to represent patterns of travel given anticipated change in the demographics of the Boston metropolitan area

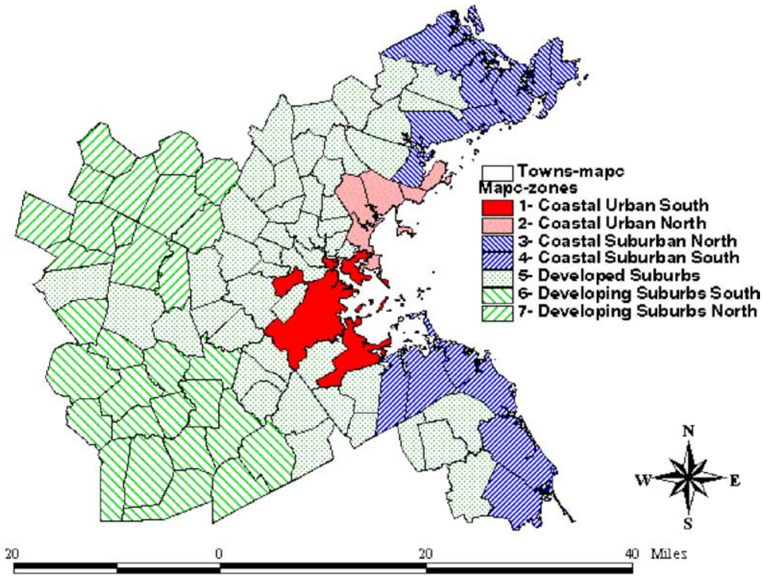

Fig. 3. Study area.

(as projected by MAPC) as well as changes in the road network such as anticipated new links and increased capacity of existing links (as projected by CTPS).

For each scenario, a number of changes need to be performed to the modeled road network and to the origin–destination matrix that assigns zone-to-zone trips. These changes are based on the following assumptions:

- A flooded road implies that the link is rendered useless, and therefore its capacity is equal to zero.
- No trips are generated from flooded residential areas.
- Commuting trips that have as destination a flooded industrial or commercial area are cancelled.
- Shopping trips that have as destination a flooded area are redirected to the closest commercial area.

By comparing the UTMS model run that incorporates these changes with the run under non-flooded conditions, the following indicators can be obtained: number of trips cancelled due to flooding of origin or destination; number of trips cancelled due to inability to go from origin to destination; difference in vehicle miles traveled, and difference in vehicle hours traveled. From this last indicator we derive the total time of delay due to increased congestion or to change in travel route caused by flooded links.

4.2. Methodology for assessing flood impacts under stable climatic conditions

Flooding processes are very place-specific. Given the complexity of the issue and the limitations in data availability, the flooding impacts estimates are based on work by the National Flood

Insurance Program (NFIP). The flood insurance studies developed under the NFIP involved the detailed modeling of coastal and riverine flooding to produce Flood Insurance Rate Maps (FIRMs). These maps show the 100-year and 500-year floodplains: areas that, on any given year under current conditions, have a probability of being flooded equal to 1% and 0.2% respectively. The shaded areas in Fig. 4 depict the 500-year floodplains in the study area.

The climate variable used for the simulation of coastal flooding is sea level, whereas the variable for riverine flooding is the 24-h rainstorm. For the current conditions, the base assumption is to associate the 24 h, 100-year storm (6.75 in.) to the 100-year riverine floodplain determined in FIRMs, and the 24-h, 500-year storm (8.22 in.) to the 500-year floodplain. This is based on the fact that the time of concentration of watersheds in the area is less than 24 h (time of concentration is a hydrologic term that refers to the travel time of water in a river basin). This assumption implies that other variables such as soil saturation and snow accumulation are not included in the model.

Even in the absence of climate change, the magnitude of stream flow, and therefore flooding, associated with a 100- or 500-year storm is likely to increase over time due to land development, whereby natural surfaces are replaced with impervious surfaces. The analysis therefore encompasses a set of development assumptions comprising spatial patterns of population, economic activities and development patterns, and a hydrologic model to estimate their effects on streamflow.

The process of defining the flood scenarios for the transportation model involves two steps. In the first, the flood maps are overlaid with the maps showing different land uses within the boundaries of each traffic analysis zone used in the model. It is assumed that the proportion of area inundated is directly related to the reduction in the number of trips generated by or attracted to the TAZ in question. If the residential land use within a certain zone is 25% flooded, for example, and it normally produces 100 trips, it is assumed that the number of trips is reduced to 75.

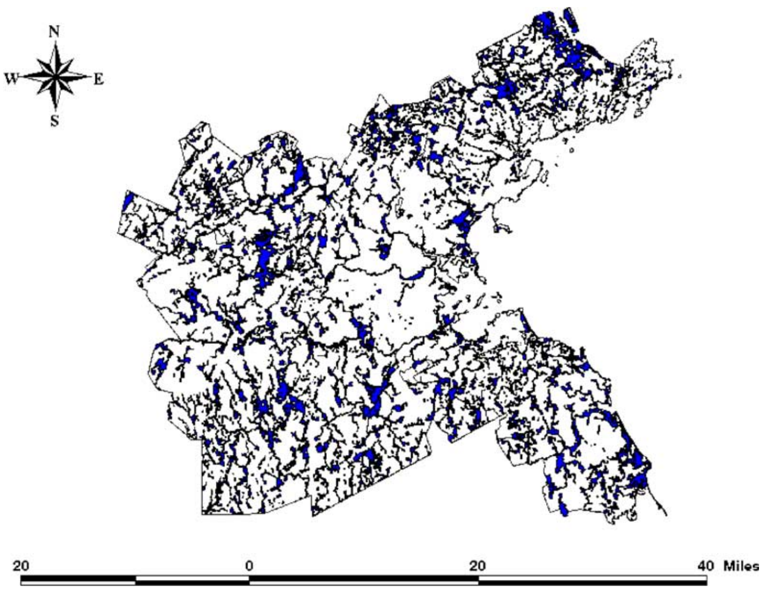

Fig. 4. Floodplains in the study area.

The second step is to overlay the flood map with a map of the road network. All road segments that intersect with flooded areas are assumed to be unavailable for travel during the flood event.[2] The outcome of this is the production of a list of links that are impassable for a period of one to two days following the extreme weather event. These links are designated as impassable in the model—operationally, their capacity will be set to zero. Because of the high degree of redundancy in Boston's transportation network (especially the road network) the flooding of links seldom makes trips impossible. More frequently trips must be diverted to more circuitous routes and therefore take longer. In the former case, the cost of the disruption is measured in terms of trips foregone, while in the latter in terms of the traveler's delay. Even travelers whose normal route is unaffected by flooding suffer some delay because the disabling of some links means that other links must carry a greater flow heightening congestion.[3]

4.3. Assessing likely effects of climate change

The next phase involves estimating the aggregate effect of climate change on delay and lost trips over 2000–2100. The first step is to estimate these aggregates under the assumption of no climate change. The occurrence of extreme events is projected according to a probability distribution derived from 50 years of rainfall and sea level data for the Boston area. Bootstrapping from this distribution allows climate inputs to be defined and used in the transportation model. Trips lost and incremental delays due to storms are aggregated over the 100 years.

To simulate the effect of climate change, the process described above is repeated with a gradual upward adjustment of the magnitude of storms, in line with available climate change predictions (Intergovernmental Panel on Climate Change, 1996). The result is an increase in the occurrence of flooding as the simulation progresses. The probability, for example, of flooding in the so-called '100-year floodplain' equalled 1% at the beginning of the 21st century, and will grow steadily as sea level rises and extreme rainfall events become more frequent. With this different set of climate inputs, the transportation model is run again for 2000–2100 to estimate delays and trips lost. The difference between the two sets of estimates of network performance may be attributed to climate change.[4]

5. Results

Table 1 shows results for 2003, indicating the change in relevant systemwide performance indicators with respect to the base scenario, shown in the last column. So, for example, there are 14,620,000 trips taken each day in the base scenario and this number is reduced by about

[2] This step presents a number of technical problems due to the fact that the geographical information systems coverages used in this process have different levels of accuracy and reliability. All intersections between highway links and flood areas were visually inspected and only those that were clearly flooded were included among the disrupted links.

[3] This effect is captured by the traffic assignment stage of the UTMS. The model was run based on typical weekday origin–destination traffic flows.

[4] The procedure is described in greater detail in Appendix A.

Table 1
Changes resulting from flood simulations—2003

	Riverine flooding		Coastal flooding		Combined		Base totals (no flood)
	100 year	500 year	100 year	500 year	100 year	500 year	
Links flooded	445	673	196	236	641	908	22,138
Trips lost (thousands)	89	151	152	170	177	206	14,620
ΔVMT (thousands)	2422	4183	29	−182	2693	4404	135,917
ΔVHT (thousands)	182	307	25	21	228	364	3862
Δavg speed (MPH)	−1.0	−1.6	−0.2	−0.24	−1.3	−2.0	35.2

89,000 in the "100-year, riverine flood" scenario. The number of trips is always expected to decline because of a flood, but the effect of the flood on the other two indicators, vehicle miles traveled (VMT) and vehicle hours traveled (VHT), is ambiguous. In the case of VMT, the value may go down because there are fewer trips. It may, however rise because the trips that are made will in some cases take more circuitous routes than in the base scenario due to the flooded links. Similarly, VHT may go down due to fewer trips or up due to greater congestion. The increased congestion is reflected in the overall reduction of average speed in the flood scenarios.

The results indicate differences between the riverine and coastal flood scenarios. Coastal floods result in greater reductions in the number of trips while riverine floods reduce in greater increases in VMT and VHT. This is probably because the transportation network in coastal areas is usually less redundant, and because coastal areas tend to be more densely populated so more people are unable to make trips because of local inundation. Riverine flooding, on the other hand, causes more circuituity and congestion because many major commuter routes are located inland and often along river valleys. Figs. 5 and 6 show the increase in VHT and VMT on a per trip basis. The percentage increases of VHT are generally about twice as high as the percentage increases in VMT. This is because VMT reflects circuituity only while VHT reflects circuituity and increased

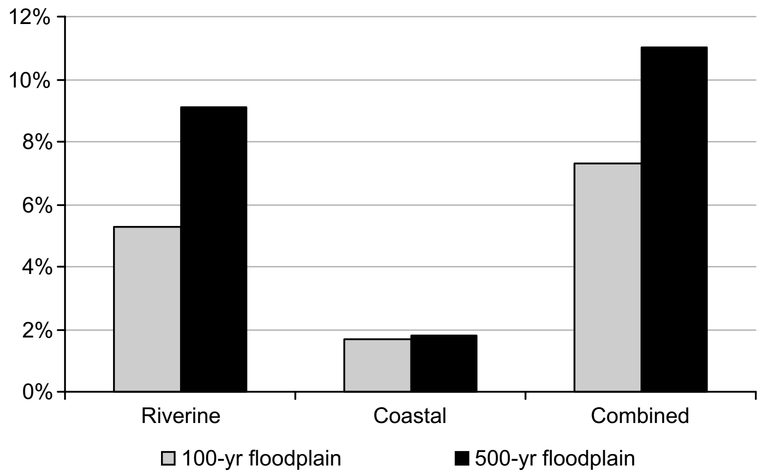

Fig. 5. Change in VHT per trip, 2003.

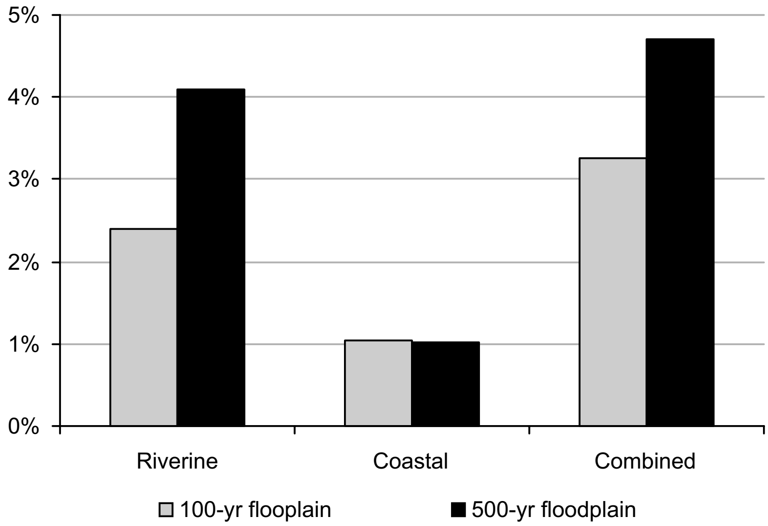

Fig. 6. Change in VMT per trip, 2003.

congestion. The travel time and miles increase more under the riverine flooding scenarios than under the coastal flooding scenarios for the reasons discussed above.

Table 2 and Figs. 7 and 8 present parallel results for 2025. The relatively modest growth of about 12.6% in the number of trips between 2003 and 2025 is consistent with the fact that Boston is a relatively mature and built out metropolitan area. The growth in VMT is significantly higher at 16.8% because most of the growth occurs at the metropolitan periphery where people are on average likely to take longer trips.

Comparing the 2003 and 2025 results suggest while the number of trips lost in all scenarios is higher in 2025, the change in VMT is lower. This is also true on a per trip basis, as one can see by comparing Figs. 6 and 8. This is due to the addition of links to the network between 2003 and 2025, allowing drivers to use less circuitous routes during flood events. The impacts on VHT per trip, however, are only slightly lower in 2025 than in 2003.

Over the period 2000–2100, the results indicate that delays and trips lost increase by 80% and 82% respectively under the climate change scenario. While this is a significant increment in percentage terms, the magnitude of the increase is not enough to justify a great deal of infrastructure improvements. Even at fairly high monetized values for lost trips and incremental delay, the total discounted

Table 2
Changes resulting from flood simulations—2025

	Riverine flooding		Coastal flooding		Combined		Base totals (no flood)
	100 year	500 year	100 year	500 year	100 year	500 year	
Links flooded	445	673	196	236	641	908	22,798
Trips lost (thousands)	97	165	165	185	193	225	16,455
ΔVMT (thousands)	1824	3359	−1711	−2080	1321	3178	158,718
ΔVHT (thousands)	198	347	−44	−54	207	381	4562
Δavg speed (MPH)	−1.1	−1.8	−.04	−.05	−1.2	−2.0	34.8

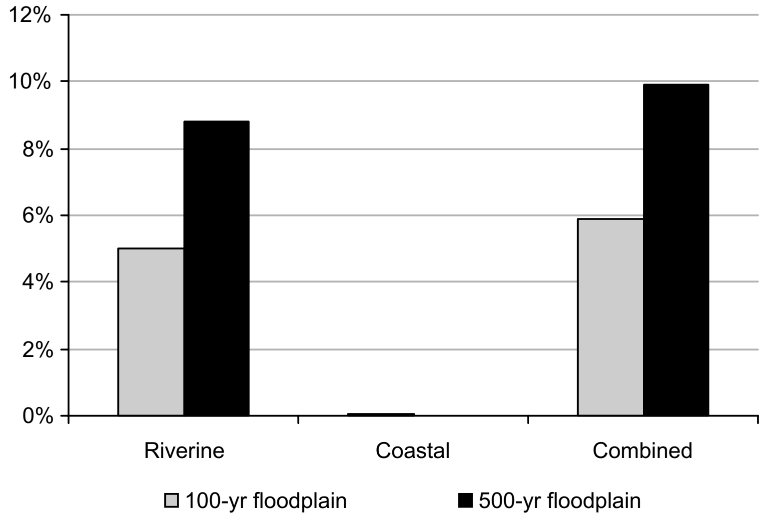

Fig. 7. Change in VHT per trip, 2025.

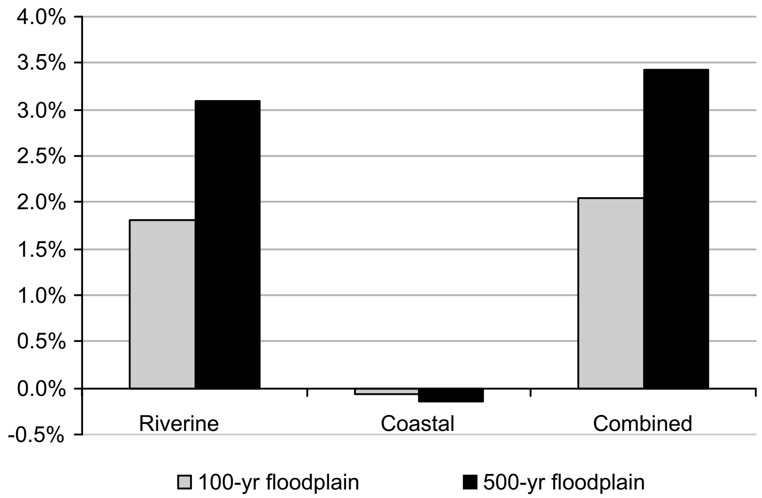

Fig. 8. Change in VMT per trip, 2025.

cost would be less than one hundred million dollars. Nevertheless, travel interruptions due to flooding are a significant nuisance that is likely to become almost twice as common due to climate change.

6. Conclusions

A methodology has been developed to assess the effects of flooding events on the performance of urban transportation networks viewed as integrated systems. This methodology incorporates projected changes in land use, demographic and climatic conditions to explore the relative impact of climate change on the delays and lost trips caused by increased coastal and riverine flooding. Given the number of assumptions required about future trends, the results should be treated as indicative rather than as specific forecasts. They do, however, provide a clear indication of a negative impact on surface transportation system performance.

The models and data used are widely available, so the general framework we have presented can be quite easily transferred to other cities. There are numerous implementations of the UTMS and commercial software available for its operation and integration with GIS. Information of flood plains is widely developed for hazard preparedness and is generally freely available. Furthermore, advances in remote sensing and GIS technologies are improving the quality of that data. While Boston is vulnerable to flooding because of its coastline and numerous river systems, it does not have as much low lying area as other US cities such as Tampa, Cincinnati and especially New Orleans. Application of the model to those cities might well generate more dramatic results.

It should be noted that the Boston Metro Area is already heavily built and therefore there will not be much change in urban infrastructure compared to other metropolitan areas in the US and worldwide. The transportation network has great redundancy and therefore it is not too vulnerable to extreme events from a systemwide perspective. Consequently, there is little margin of action in terms of modifying the existing infrastructure based on the results of this modeling effort. However, for urban areas experiencing more rapid land use conversion, or located in more hazard-prone areas, the methodology presented in this work can prove very useful for exploring choices in terms of how to guide urban growth and how to develop an integrated plan for managing transportation systems facing the threat of increased flooding.

Acknowledgments

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Appendix A. Simulation of aggregate impact of climate change 2000–2100

- A table of the largest events in Boston for every year from 1950 to 1999 is prepared to be use as a proxy for climate patterns in the area. This involves sea level for coastal flooding, and 24-h precipitation events occurring above freezing temperature for riverine flooding.
- Using the past record as a probability distribution of future extreme events, we randomly assigned one year from 50 to 1999 to each year from 2000 to 2100 to derive the values of simulated extreme events. In other words: We re-sampled the 1950–1999 data on extreme events, with replacement, to create a bootstrap sample for the 2000–2100 period.

- Based on the simulated extreme events, the hydrologic and hydraulic models compute the total area flooded for each modeled year. A functional relationship is established between total area flooded and the values of delay and lost trips for each event, for any given year. This relationship is based on linear interpolation of the results derived from the UTMS runs, allowing the model to estimate delay and lost trips for events of any size at any given time.
- Values for delay and lost trips were summed over the 100 year period.

To represent the effects of climate change on coastal flooding, the model assumes a constant rate of sea level rise equal to 0.3 cm per year (consistent with estimates by Intergovernmental Panel on Climate Change, 1996). To represent the effects of climate change on rain induced (river) flooding, the model assumes that the magnitude of extreme rainfall events increases at a rate of 0.31% per year throughout the 21st century. This is based on the results of the Canadian Global Circulation Model (CGCM1). According to these results, the ratio of the changes between the present and 2050, and between 2050 and 2090 are approximately the same, each being around 1.17. Therefore, this model assumes that the values of 24 h extreme precipitation increased by an annual value of approximately 0.0031 (1.0031^{50} equals 1.17).

Steps 1–3 are repeated under these assumptions. This allows to compare the total delay and lost trips with and without climate change. Because of the probabilistic nature of the random assignment of extreme events, a Monte Carlo approach is implemented: This entire exercise was repeated 100 times and final results are averages over those estimates.

References

Brodsky, H., Hakkert, A.S., 1998. Risk of a road accident in rainy weather. Accident Analysis and Prevention 20, 161–176.

Brookshire, D.S., Chang, S., Cochrane, H., Olson, R.A., Rose, A., Steeson, J., 1997. Direct and indirect economic losses from earthquake damage. Earthquake Spectra 13, 683–710.

Cho, S.B., Gordon, P., Moore, J.E., Richardson, H.W., Shinozuka, M., Chang, S., 2001. Integrating transportation network and regional economic models to estimate the costs of a large urban earthquake. Journal of Regional Science 41 (1), 39–65.

Church, R.L., Cova, T.J., 2000. Mapping evacuation risk on transportation networks using a spatial optimization model. Transportation Research Part C—Emerging Technologies 8, 321–336.

De Palma, A., Rochat, D., 1999. Understanding individual travel decisions: Results from a commuters survey in Geneva. Transportation 26, 263–281.

Edwards, J.B., 1999. The temporal distribution of road accidents in adverse weather. Meteorological Applications 6, 59–68.

Federal Emergency Management Agency, 1997. Interagency Hazard Mitigation Team Report covering the Counties of Essex, Middlesex, Norfolk, Plymouth and Suffolk. FEMA Region I, Boston.

Fowler, A.M., Hennessy, K.J., 1995. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. Natural Hazards 11, 283–303.

Herschfield, M., 1961. Rainfall Frequency Atlas of the Eastern United States for Duration from 30 minutes to 24 hours and Return Periods from 1 to 100 years. US Weather Bureau Technical Paper No 40, US Department of Commerce, Washington, DC.

Intergovernmental Panel on Climate Change, 1996. Technologies, Policies and Measures for Mitigating Climate Change. IPCC, Geneva.

Intergovernmental Panel on Climate Change, 2000. Special Report on Emissions Scenarios. IPCC, Geneva, Switzerland.

Katz, R.W., Parlange, M.B., Naveau, P., 2002. Statistics of extremes in hydrology. Advances in Water Resources 25, 1287–1304.

Knox, J.C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361, 430–432.

Leavesley, G.H., 1994. Modeling the effects of climate change on Water Resources: A review. Climatic Change 28, 159–177.

Meyer, M.D., Miller, E.J., 2001. Urban Transportation Planning. McGraw Hill, New York.

National Academies Press, 2004. Where the Weather meets the Road: A Research Agenda for Improving Road Weather Services. National Academies Press, Washington DC.

National Oceanic and Atmospheric Administration, 2001. Observed Water Levels and Associated Ancillary Data. Available at http://www.co-ops.nos.noaa.gov/data_res.html. Accessed December 10, 2002.

Organisation for Economic Co-operation and Development/International Energy Agency, 2000. The Road from Kyoto: Current CO_2 and Transport Policies in the IEA. OECD/IEA, Paris.

Penning-Roswell, E.C., Handmer, J., Tapsell, S., 1996. Extreme events and climate change: Floods. In: Downing, T.E., Oltshoorn, A.A., Tol, R.S.J. (Eds.), Climate Change and Extreme Events: Altered Risk, Socio-economic Impacts and Policy Responses. Institute for Environmental Studies, Vrije Universiteit, Amsterdam.

Pisano, P.L., Goodwin, X., Stern, A., 2002. Surface transportation safety and operations: The impacts of weather within the context of climate change. The Potential Impacts of Climate Change on Transportation Workshop, October 1–2, 2002. Available from: <http://climate.volpe.dot.gov/workshop1002/pisano.pdf>. Accessed November 3, 2004.

Schreider, S.Y., Smith, D.I., Jakeman, A.J., 2000. Climate change impacts on urban flooding. Climatic Change 47, 91–115.

US Army Corps of Engineers, 1978. Massachusetts Coastal Study. USACE, Boston.

Wagner, D., 1999. Assessment of the probability of extreme weather events and their potential effects in large conurbations. Atmospheric Environment 33, 4151–4155.

Weijers, E.P., Velinga, P., 1995. Climate Change and River Flooding: Changes in Rainfall Processes and Flooding Regimes Due to an Enhanced Greenhouse Effect. Vrije Universiteit, Amsterdam.

Wilks, D.S., Cember, R.P., 1993. Atlas of Precipitation Extremes for the Northeastern United States and Southeastern Canada. Northeast Regional Climate Center Research Publication RR 93-5.