Managing a Regional Transit System in a Severe Weather Event
Case Study of the New York Region and Hurricane Irene

Report from the International Panel of the WEATHER project funded by the European Commission’s 7th framework programme

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1 The New York Region and Its Key Transportation Infrastructure

New York is the largest city in the U.S., it is densely populated, and it relies heavily on public transportation for passenger travel – 2/3 of the rail transit passengers in the U.S. are in the New York region.¹ This is a coastal region, and the central city is close to sea level, making the possibility of storm surges a real threat. Manhattan Island, the core of the region, relies on bridges and tunnels to link it to New Jersey on the west, suburban and upstate New York on the north, and Queens, Brooklyn and Long Island on the east (Figure 1). Much of the rail transit system in the center of the city is below the surface.

Figure 1: New York Metropolitan Area Showing Principal Rail Lines

2 The Event: Hurricane Irene

Hurricane Irene was a large, category 3 hurricane (wind speeds 111 to 130 mph - 179 - 209 kph) that approached the east coast of the U.S. in the last week of August of 2011. Irene made three landfalls, once at Cape Lookout, North Carolina as a Category 1 hurricane with winds at 85 miles per hour (136 kph), once just north of Atlantic City, New Jersey as a Category 1 with winds at 75 miles per hour (121 kph) and once at New York City as a tropical storm, with winds at 65 miles per hour (105 kph).

Irene brought heavy rains and high winds to much of the eastern seaboard. The storm surge associated with the hurricane damaged portions of the Outer Banks in North Carolina, a set of barrier islands that help protect the main coastline from storm surges. Downed trees and flooding contributed to power outages throughout North Carolina, Virginia, Maryland, Washington, DC, Delaware and Pennsylvania.

It is rare for hurricane-strength storms to hit New York City; although hurricane tracks do cross the region, storms are usually weakened due to an earlier landfall or travel over cooler waters. The expectations for Irene were different. At least four days in advance, it was clear that the storm was headed for New York City; strong wind and rain were major threats, and there was serious concern about storm surges. Initial winds and rains were expected on the afternoon of Saturday, August 27th, and passage over the city was predicted to occur on Sunday the 28th. At a press conference on August 27th, Mayor Michael Bloomberg stated:

We expect a strong Category 1 storm to hit us tonight ... The great danger to us here is from the storm surge, and there's no evidence that the forecast for that is changing. It is going to be a very serious thing as far as we can tell now.2

According a forecast by Dr. Jeffery Masters, Chief Meteorologist at Weather Underground:

Tree damage will be very heavy, and we can expect trees in regions with saturated soils will fall over in high winds onto power lines. Expect major river flooding throughout New Jersey, the Delmarva Peninsula, and regions near New York City, as Irene's rains run off the saturated soils directly into the rivers.3


Thus, the expectations for Irene were ominous, and the threats to transportation in the New York region were multiple and serious.
3 Public Transportation in the New York Region

Public transit in the New York region, including toll bridges and tunnels on the New York side of the Hudson River, is the responsibility of the Metropolitan Transportation Authority (MTA). The MTA is a regional agency that includes the New York City subway and bus systems, the Long Island Railroad (LIRR), Metro North Railroad (MNRR), regional buses, the Staten Island Railroad, and MTA Bridges and Tunnels (formerly the Triborough Bridge and Tunnel Authority). MTA is the largest transit authority in the U.S., serving about 8,500,000 trips each weekday in all five boroughs of New York City, the suburban counties of Dutchess, Nassau, Putnam, Suffolk and Westchester in New York state, Bergen and Passaic in New Jersey and Orange and Rockland in New York (contracted through New Jersey Transit), and southwest Connecticut counties of Fairfield and New Haven.

Transit on the west side of the Hudson River, also part of the New York metropolitan area, is the responsibility of New Jersey Transit (NJT), a state agency separate from, but coordinating with, MTA. NJT offers extensive electrified rail and bus services in the metropolitan area across the Hudson River from Manhattan, and as far south as Atlantic City and Philadelphia. System wide, in 2010, it carried over 900,000 weekday trips, and 428,000 and 286,000 on Saturdays and Sundays, respectively. Weekday NJT New York area rail carries 282,000 daily trips; weekend rail ridership is about 90,000 trips on Saturday and 70,000 on Sunday.4

Additional transportation services in the region are provided by the Port Authority of New York and New Jersey, a multi-state agency that operates the Hudson River crossings, the George Washington Bridge, the Lincoln and Holland Tunnels, and the Port Authority Trans-Hudson (PATH) Railroad, connecting Hoboken and Newark, New Jersey with Manhattan. PATH carried 282,000 weekday trips, and 141,000 and 103,000 Saturday and Sunday trips.5

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4 Vulnerability of the Transportation System

The hurricane vulnerability of the New York transit system includes these risk factors:

- Wind damage directly affects vehicles in motion on elevated structures (highways and rail lines). The region has numerous long-span bridges carrying highway traffic over shipping channels. A substantial part of the rapid transit system outside of Manhattan is on elevated structure; commuter rail lines are mainly at grade level.
- Flooding can result from rainfall that is so intensive that normal storm water drainage infrastructure cannot accommodate the flows. This threatens low lying facilities, roadways, yards, stations, and tunnels. Flooding can also be caused by storm surges, wind driven water overwhelming shoreline protection. Because New York is surrounded by water, the risk of storm surges is widespread – Hudson River shores on Staten Island; New Jersey; Manhattan; and further up river in Orange and Westchester Counties; the East River in Manhattan, Queens and Brooklyn; the Harlem River in Manhattan and The Bronx; Long Island Sound in the Bronx, Queens and Nassau County; and the Atlantic Ocean in Brooklyn, Nassau and Suffolk Counties. Highways and surface rail lines adjacent to these waterways are at risk, as are roadway and subway tunnels in lower Manhattan. Experience with highway and subway flooding in Manhattan is both real and recent (see examples below).

Parts of the New Jersey Rail system, including the Hoboken Terminal across the Hudson River from Manhattan, are subject to occasional flooding.

- Wash-outs due to heavy rains, overflowing rivers and streams, are serious risks, particularly in suburban and rural areas.
- Falling branches and downed trees can damage or destroy vehicles and infrastructure and block rights of way. Catenary power cables, used on Metro North and Amtrak railroad lines on the New Haven Line, and for many parts of the New Jersey Transit rail network, are vulnerable to disruption and damage by falling branches and trees.

Trees are an ongoing maintenance issue, particularly for the railroads, presenting risks throughout the above-ground system, but particularly on the commuter rail components in the suburbs, where tree density is higher than in the city. Although trees on railroad properties are trimmed routinely, many trees which threaten tracks and infrastructure are on private properties, requiring owner permission for access. Trees with branches that overhand railroad property can be trimmed, but in major storms, significant damage results from downed trees.
Narrow rights of way and catenary power cables exacerbate this problem on the New Haven Line in Connecticut.

- Rainfall from Hurricane Irene added more rain to a record monthly rainfall in the New York City region. Heavy summer foliage along with saturated soils meant that flooding could be worse than average for storms of this size and significant tree damage was likely.6

Thus, the vulnerability of transportation infrastructure and services to major hurricanes in the New York region transportation is substantial and widespread. This presents a particular challenge to the most populous metropolitan area in the U.S., the financial and corporate capital of the nation where so many people and high valued resources are packed into a relatively small area surrounded by water. This is a region that is more dependent on its public transit system than any other in the U.S. A threat to this system is a threat to the city and the nation. Hurricane Irene was such a threat.

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5 The Decision to Shut Down the Regional Public Transit System

Hurricane Irene was predicted to strike New York City late on Saturday (August 27th) or early Sunday (August 28th), and it looked like it would arrive as a category 3 storm, with winds from 96 to 113 kts (178-209) kph. In the face of such forecasts, New York prepared for the worst. Based on established policy, a decision was made on Friday, August 26th, to start shutting down the entire MTA mass transit system starting midday on Saturday, largely based on the wind forecasts. A similar, but independent, decision was made by New Jersey Transit. The New York decision was announced to the public by Governor Andrew Cuomo, and the action was guided by established policies defined for hurricane conditions.

The NJT decision was made by operating personnel and announced through the media by the agency and by Governor Chris Christie. The NJT decision to shut the system down was made on the basis of discussions with public safety and emergency management agencies, considering the weather forecasts that those agencies accepted. The agency did not have a specific policy on terminating service in the face of severe weather events. Port Authority Trans-Hudson rail service was to be terminated at noon on Saturday for the same reasons.

The decisions to shut down the transit system in the face of Hurricane Irene was guided by the desire to avoid putting people – riders and employees – as well as rolling stock, at risk to the forces of the storm. The New York Metropolitan Transportation Authority (MTA) hurricane policy was developed at the direction of Mayor Michael Bloomberg by MTA management in collaboration with New York State and county Offices of Emergency Management based on lessons learned from Hurricane Katrina. Katrina struck New Orleans, Louisiana, in August, 2005. There was ample warning when this hurricane approached New Orleans as a category 5 storm (sustained winds ≥ 175 mph (280 kph)); it weakened to category 3 (sustained winds ≥ 125mph – 205 kph) when it made landfall at New Orleans on August 29, 2005. Catastrophic damage resulted from high winds, rain, and primarily from massive flooding as a storm surge overwhelmed flood control infrastructure. Although the mayor of New Orleans ordered an evacuation of low lying areas (much of New Orleans is below sea level), preparations and evacuation capacity were inadequate (and known to be so for a category 3 storm based on a drill held about 12 months prior to Katrina). Evacuation was initiated too late and transportation and relocation capacity were too limited to meet the emergent need.

Over 1,800 people were killed, many more were stranded and/or displaced, and the economic cost was estimated to be more than $100 billion. Katrina was in the news for
an extended period of time, and public agencies - transportation, emergency response, and others - were vilified for inadequate preparation and response. This event was an American tragedy that provided a lesson for the nation about the importance of careful preparations for predictable weather events, and for more conservative responses to impending events.

New York MTA officials documented the lessons from Katrina in their own hurricane response plan. Details of the plan are closely held, but its major steps included these:

- The plan defines people and protocols for interagency coordination on decision making, timing, evacuation, and system shutdown.
- The plan emphasizes communicating the current situation and plans with the public – the riders and the broader community – using multiple channels: mass media through press releases, rider announcements, variable message signs in stations, and the Internet (mta.info, Twitter, Flickr, blogs). There is an underlying premise that informing riders of the condition of the transportation system and shutdown plans will encourage cooperation and reduce or eliminate the possibility of riders being stranded if and when the system closes.
- The focus of the plan is two-fold: evacuation of those living in flood-prone areas and shutting down the transit system to protect people and hard assets. Evacuation zones were pre-defined and well-publicized (see Figure 2), and classified by degree of risk so that authorities can call for stagewise evacuations based on expected flood levels.
- Specific criteria were established for closing the transit system, based on the critical threats of high winds and storm surges. The shutdown criterion was established by interagency agreement to be forecasts of sustained wind speeds of 40 miles per hour (64 kph) or more, with timing of a shutdown to be based on the time required to shut down services and secure people and equipment. Thus the shutdown decision was to be made on the basis of a prediction, rather than waiting until the criterion wind speed was reached.
- The shutdown decision was tied to forecasts of wind and water because closing the system takes an extended time period: 4 hours for rail services; 3 hours for buses, and 2 hours for bridges and tunnels. The time is consumed in notification, field implementation of closures, time to make the final runs on transit services, and time to secure rolling stock and employees.
- The wind criterion was based on vulnerability assessment, specifically the risk of damage to infrastructure, rolling stock and people from direct effects and by bringing down trees on to rights of way and vehicles. Catenary wires that supply power on electrified rail service (the Metro North New Haven Line) were vulnerable to falling trees and branches, although much of the catenary system was...
modified to auto-tensioning wires that usually yield rather than failing when struck by falling trees.

- Hurricane winds are generally correlated with flooding, but flooding risk was recognized separately for low lying yards and facilities near the waterways that surround and penetrate the New York region. These risks motivated both service termination and relocation of rolling stock to protected areas – high ground or parts of the tunnel network known to be safe from flooding.

The MTA hurricane response plan had not been implemented prior to Irene, but coordination was strong, actions were decisive, and public communication was comprehensive and effective. In the end, few if any people were stranded waiting for transit service during the shutdown. Terminating service was a draconian move, “not in our culture” said one senior transit manager, but criteria had previously been adopted to respond to the likelihood of strong winds and flooding in critical, low lying facilities.

While the hurricane response plan was a well-documented and accepted template for preparing for Irene, system managers suggested that the shutdown decision was reinforced by other, recent events that occurred in the New York region. The severe snow storm that struck New York on Sunday, December 26, 2010, the Boxing Day snow storm, was probably the most important, immediately-prior experience informing the response to Irene, because this was close to home, it was a public failure in New York, it was recent, and thus the same agency leadership was involved.

The Boxing Day 20+ inch (51 cm) snow storm, sixth largest in New York recorded weather history,7 crippled the city for more than two days. Metropolitan Transportation Authority (MTA) buses and subway systems were described as being in disarray: “...subways lost power on frozen tracks and hundreds of buses wound up stuck in snow filled streets”.8 The MTA did not issue a full alert and a call for extra crew until late Sunday morning, when snow had already accumulated. By Monday morning, December 27th, there were reports of hundreds of buses trapped on unplowed streets. Many passengers were trapped for hours on subway trains that lost power. Entire sections of rapid transit lines were knocked out by huge snowdrifts — the exact lines that the winter planning manual warned were “most vulnerable to service disruptions” in a fierce storm. One group of stranded passengers subsequently sued the MTA for damages.9

9 Huffington Post, December 27, 2011.
Some reports suggest that MTA did not adequately inform the riding public about the status of transit services immediately after the snow storm. In contrast, New Jersey Transit, which offers bus and rail service on the New Jersey side of the Hudson River, provided constant updates through official channels. New Jersey Transit’s bus service was suspended late Sunday as the winter storm became worse. Trains were operated on an abbreviated schedule on Monday, with normal service resumed only by Wednesday. According to New Jersey Transit’s press release, some crew members were prepositioned before the storm to allow for faster recovery.

After initially claiming success in response to the Boxing Day storm, New York’s Mayor Michael Bloomberg later admitted that the city’s response was “inadequate and unacceptable”\(^{10}\). The cost to the MTA was estimated to be $30m, including overtime pay ($14m) and lost revenues ($16m). In addition, there was a series of damage claims that the City of New York paid. In the Spring of 2011 the New York City Council passed a series of bills defining when to activate emergency operations, to seek help from other agencies, and to notify the public about service disruptions.\(^{11}\)

The impacts of the Boxing Day snow storm on the public transit system in New York might have been softened by better communications with riders and perhaps with a decision to shut down all or parts of the transit system. This might have prevented riders from being stranded on board vehicles and en route. The public reaction as revealed in the press and transit-related blogs was particularly negative, perhaps making it easier to close the transit system as Hurricane Irene approached.

\(^{10}\) *Huffington Post*, December 30, 2010.

Figure 2: Flooding in PATH Train Station, Hoboken, NJ, 1992 Nor'easter
(NY Department of Emergency Management)

Other, earlier events and studies may also have been influential in the decision to shut down the transit system in preparation for Irene. In December, 1992, a prototypical storm called a “nor'easter” struck New York City with hurricane-force winds ($\geq$ 75 mph – 120 kph) and rains that flooded low lying parts of the city, including subways in New York and New Jersey (see Figure 2), LaGuardia Airport, and parts of FDR Drive along the Hudson River in Manhattan. A subsequent report by the U.S. Army Corps of Engineers predicted that a Category 3 Hurricane – the rating of Irene before it struck New Jersey and New York – would flood nearly 30% of the south part of Manhattan Island. More recent modeling studies have highlighted New York City’s vulnerability to coastal flooding in major storms. Thus, the prospects for flooding underground parts of the transit system in a storm surge were known to be real and serious.

The post-Katrina hurricane plan was used to guide the preparation for and response to Irene. However, this plan was focused more on deployment of forces for evacuation than on preparing to restore service. The Katrina experience, the threat of Hurricane Irene, together with the experience of the Boxing day snow storm of 2010, led MTA

officials to put high priority on rapid service restoration after the storm. This is a logical priority given the heavy dependence of the New York region on its public transportation system. Thus, the mission became: protecting passengers and workers; securing the rolling stock and infrastructure; and positioning the resources for quick recovery and service re-start. Emphasis on service restoration seems to have made it easier to close the system to protect its assets so that those assets could be rapidly returned to service.

Addressing the factors motivating preparation for Irene by the entire community (including public officials), Benjamin Orlove wrote in Weather, Climate and Society that pre-Irene decisions were encouraged by three factors:15

- Timing of the storm, including the occurrence of severe rains in the northeastern U.S. in early August of 2011 and the unusual August 23rd earthquake in Virginia that was felt in the New York area. Orlove believes these heightened disaster awareness. He also observes that the fact that Irene was a slow moving storm (14 mph – 23 kph) gave people plenty of time to decide and act. Finally, that the hurricane hit New York City on a weekend meant people were traveling less, and so the impacts of “hunkering down,” and of shutting down the transit system, were less onerous than would have been the case if Irene arrived on a weekday (Sunday ridership on New York subways and busses is about 46% of average weekdays; for Metro North Railroad the Sunday:weekday percentage is 36%).16 In subsequent interviews, transit officials denied that they would have acted differently had Irene come on a weekday – they were following the established hurricane action plan.

- Aggressive and clear communications about the risks of Irene from public officials, including the Governors of New York and New Jersey, the Mayor of New York, and others. Leadership played a strong and clear role in describing the hazards of the approaching hurricane and the need to prepare for them.

- Social amplification – less a factor in transportation management decisions, but the large and dense population made it easy for people to see others preparing for the worst, thus providing an incentive for joining in the effort. One can theorize, wrote Orlove, that with the public willing to retreat to their homes and prepare for disaster, a decision to shut down the transit system might have seemed easier to make.


The decision to shut down the entire public transit system was made early enough to give people plenty of warning, allowing them to settle in safe places before services stopped. Advance warning was possible because the MTA hurricane guidelines defined a forecast-based shutdown criterion, and because forecasts of the track and intensity of the slow-moving hurricane were available and accepted. An early decision was necessary because of the time necessary to implement the shutdown.
6  Weather Forecasts

Like most public agencies facing risks from extreme weather, the MTA integrates weather information from multiple sources, including the U.S. National Weather Service as well as private services that can deliver customized forecasts that may be more specific in terms of temporal and spatial resolution. Facing severe weather events – and particularly in the case of Irene – transportation agency leaders within MTA, as well as emergency management personnel, collaborate in the acquisition and interpretation of weather forecasts, so that unified actions can be taken. Facing Hurricane Irene, managers felt they had reliable forecasts on which to base their actions – forecasting uncertainty did not appear to be a significant issue. This contrasts with snow events such as the December 2010 storm, when uncertainty as to the amount of snow expected was substantial. Officials reported that this uncertainty is common for snow forecasts, making it more difficult to anticipate and prepare for potentially significant snow storms.

Snow storms tend to be amorphous, while hurricanes have better-defined structure – the eye, eye-wall, and surrounding winds of known direction and measurable velocity. The major uncertainties associated with snow storms are the geographic pattern and total snow accumulation. The size and strength of hurricanes are easier to measure, and because they tend to be well-defined, hurricane track forecasts are made and published, along with information about uncertainty, in the form of a mapped cone of threatened areas (see Figure 3). While quantities of precipitation are also uncertain, forecasts give clearer expectations about the event and its impacts, at least in the extremes. Stated differently, a hurricane is a hurricane: the characteristics are broadly known based on estimates of strength; a snow storm could be larger or small, intense or mild.
Uncertainty of forecasts was not a significant obstacle in the decision process that led to shutting down the transit system. Of course there was uncertainty as to storm track and intensity, and in fact the storm had weakened substantially so that it was downgraded to a tropical storm by the time it struck New York City (wind speeds 35-64 kts (63-118 kph)). The major storm surge did not occur, but there was substantial flooding due to heavy rains, and downed trees and washouts would have interrupted service had it not been stopped earlier.

Thus, agency leadership felt that storm forecasts provided a reasonable basis for decision making, which was appropriately conservative from the perspective of protecting lives and critical system assets.
7 Evacuation

Low lying parts of the city, shown as Zone A in Figure 4, were designated for mandatory evacuation, affecting about 370,000 residents, a large group although only a small fraction of the regional population. Residents were warned in advance to evacuate, and special bus services were deployed to accommodate those who could not relocate on their own. Public relocation centers had been identified in advance and those without private relocation options could move to these centers, using their own means or public transit services. On Saturday, August 27th transit vehicles were deployed to relocate people from nursing homes, hospitals, and some high rise public housing, in anticipation of power outages and loss of elevator services.

Figure 4: Evacuation Zones in New York City, NY (New York Times, August 26, 2011)
The shutdown of the transportation system was initiated well in advance of the expected arrival of the hurricane. Vulnerable parts of the highway system – low lying roadways and exposed bridges - were included. Table 1 shows the timing of closure of various components of the transportation system. As stated above, closing some elements of the system took many hours to complete.

**Table 1: Timing of Closure of Transportation Facilities and Services**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Component Affected</th>
<th>Operator</th>
<th>Action</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturday</td>
<td>12:00</td>
<td>MTA Subway, Bus</td>
<td>MTA</td>
<td>Closed</td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>LIRR, Metro North</td>
<td>MTA</td>
<td>Closed</td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>JFK, LGA, EWR, TEB, SWF Arrivals</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>Press Release</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>PATH</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td>12:00</td>
<td>New Jersey Transit</td>
<td>NJT</td>
<td>Closure began</td>
<td>Interview</td>
</tr>
<tr>
<td></td>
<td>20:00</td>
<td>All Tolls/Fares suspended in Evacuation areas</td>
<td>MTA</td>
<td>Closed</td>
<td>NYT</td>
</tr>
<tr>
<td></td>
<td>20:53</td>
<td>George Washington Bridge, Lower Level</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>CNN</td>
</tr>
<tr>
<td></td>
<td>22:00</td>
<td>Staten Island Ferry</td>
<td>NYCDOT</td>
<td>Closed</td>
<td>NYT</td>
</tr>
<tr>
<td></td>
<td>22:00</td>
<td>JFK, LGA, EWR, TEB, SWF Airports</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>CNN</td>
</tr>
<tr>
<td>Sunday</td>
<td>0:00</td>
<td>Port of NY and Long Island</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>CNN</td>
</tr>
<tr>
<td></td>
<td>0:00</td>
<td>Palisades Interstate to GW Bridge</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>CNN</td>
</tr>
<tr>
<td></td>
<td>8:57</td>
<td>Holland Tunnel North (To NJ)</td>
<td>PANYNJ</td>
<td>Closed</td>
<td>CNN</td>
</tr>
<tr>
<td></td>
<td>9:57</td>
<td>New York State Thruway between Exits 12 (West Nyack) and 17 (Newburgh)</td>
<td>NYDOT</td>
<td>Closed</td>
<td>CNN</td>
</tr>
<tr>
<td></td>
<td>11:08</td>
<td>Holland Tunnel North (To NJ)</td>
<td>PANYNJ</td>
<td>Reopen</td>
<td>NYT</td>
</tr>
<tr>
<td></td>
<td>11:17</td>
<td>Palisades Interstate &amp; GW Bridge</td>
<td>PANYNJ</td>
<td>Reopen</td>
<td>NYT</td>
</tr>
</tbody>
</table>

To facilitate moving travelers rapidly to secure locations in advance of the storm, at 8:00 p.m. on Friday night the MTA stopped fare and toll collection on rail, bus, ferries and bridges serving evacuation zone A (Figure 4), including the barrier islands on the south side of Long Island. New Jersey Transit made all fare media acceptable on all of its modes – light rail, heavy rail, buses – starting at midnight Friday evening to help passengers complete their travel in advance of the shutdown.

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Highway authorities, and the Port Authority, which among other things operates the George Washington Bridge (GWB) crossing the Hudson River, and the New York State Thruway Authority, which operates the Tappan Zee Bridge, the next Hudson River crossing north of the GWB, all warned of the possibility of lane or facility closures. Operations on the GWB were changed, restricting traffic to the upper level – this may have been a result of vulnerability of NJ approaches along the Palisades.

Airports are particularly vulnerable to severe weather of all kinds, and so in collaboration with the Federal Aviation Administration and the airlines, the Port Authority of New York and New Jersey decided on Friday to close the commercial airports at noon on Saturday, August 27 for all arriving flights. Flight operations were officially suspended at 10:00 p.m. the same day. An advance decision on closure gave both airlines and travelers time to plan and to relocate, thus minimizing the likelihood that large numbers of passengers would be stranded in the airports. Airport vulnerability extends to staff members, many of whom depend on public transportation to get to and from work. Thus the decision to close the airports was linked to the decision to close the transit system because of uncertainty in the availability of critical staff, ranging from flight crews to air traffic controllers to security agents.

### 8.1 Communication with the Public

Transportation agencies used multiple channels to communicate service status and plans to the public. Important advances in digital communications made it possible to keep travelers informed, to reduce surprises they might encounter en route, and thereby to minimize impacts of service shutdowns. That there was ample warning of the approaching storm made this possible: operations management decisions and actions were well-planned, not precipitous, and there was plenty of time to warn travelers.

When Hurricane Katrina struck New Orleans in 2005, there was less dependence on the Internet to inform the public, smart phones were just coming into use, and the only social media platform was MySpace - Facebook was still a student-only social network and Twitter did not exist. In 2011, MTA and other agencies utilized press releases to the web, broadcast, and print media. Web communications were heavily used and MTA monitored web hits to assess whether its customers were getting the messages. MTA management believes that multi-channel distribution of information about shutdown plans led to near zero demand for transit before the official closure times posted by MTA and sister agencies.

Updates were frequent, before, during and after the storm passage. Twitter was extensively used for rapid distribution of system plans and status information. MTA person-
nel utilized cameras, especially those on smartphones, to photograph and relay storm conditions and damage back to MTA’s command center, which were then posted on Flickr and made available to the press. These photos also provided near-immediate information to system managers about conditions on the system. In the past it would have taken hours or days to get this documentation to the public. In retrospect, the decision of the agency to document damage in near-real-time provided incontrovertible justification for the decision to shut the system and probably eliminated second-guessing on the part of the public and the press.

8.2 Protecting Infrastructure and Rolling Stock

In advance of the hurricane, and as a part of the service shutdown activities, all MTA agencies and NJT relocated rail cars from low lying, flood prone yards (Coney Island and 148th Street-Lenox Avenue subway car yards) to higher ground or protected underground locations, such as Grand Central Terminal (Table 2). More than 1,000 rail transit cars (about 19% of the fleet) were relocated to storage in locations not subject to flooding. Rail cars were stored in yards and express tracks on mainlines to maintain access to almost all parts of the rail system using diesel equipment during the shutdown.

Both agencies also removed buses to protected locations in anticipation of flooding. To protect the lowest yards and under-river tunnels from storm surges, inflatable dams, wood barriers, and sandbags were installed after trains were evacuated (Figure 5 and Figure 6).
Table 2: Key Preparatory Actions\textsuperscript{18}

<table>
<thead>
<tr>
<th>Action</th>
<th>Agencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move Rolling Stock to Protected Areas</td>
<td>MNR, NJT, NYCT</td>
</tr>
<tr>
<td>Move Flood Prone Signal and Switch Equipment</td>
<td>NYCT, MNR</td>
</tr>
<tr>
<td>De-Energize tracks</td>
<td>NYCT</td>
</tr>
<tr>
<td>Removing Crossing Guards</td>
<td>MNR</td>
</tr>
<tr>
<td>Install Temporary Dams at Tunnel Entrances</td>
<td>LIRR, NYCT</td>
</tr>
<tr>
<td>Position Pump Trains at Flood Prone Locations</td>
<td>NYCT</td>
</tr>
<tr>
<td>Position Personnel overnight at Strategic Locations</td>
<td>MNR, NJT, NYCT</td>
</tr>
</tbody>
</table>

\textsuperscript{18} LIRR was not interviewed; their omission from this table should not suggest that they did not prepare for the storm.

Figure 5: Transit workers build protective dams at MTA Lenox Yard in Harlem. Photo by MTA / Leonard Wiggins: [http://www.flickr.com/photos/mtaphotos/6088568489/in/photostream/]
Figure 6: LIRR employees fill an Aqua-Barrier with water to help prevent water from flowing into tunnels to Penn Station. Photo by MTA/John Kettell
http://www.flickr.com/photos/mtaphotos/6085662147/in/photostream/

Vulnerable equipment was removed from the rail system to prevent loss and damage. Signals and other electronic equipment were taken from low lying areas, including under river tunnels, to avoid damage from salt water during storm surges. Commuter railroads removed railroad crossing gates at grade crossings to prevent wind damage. Construction equipment that could not be moved was secured.

The electrical system was powered down on lines and stations to minimize damage and danger to personnel. Emergency operations switched to diesel rail vehicles, which could then access all parts of the rail system not blocked by temporary dams or flooding.

8.3 Protecting Personnel

To ensure sufficient staffing for safe shutdown and restart, all vacations were suspended and key management and other employees (e.g., maintenance of way personnel) were warned to expect to remain on duty through the storm. It was expected that most operating personnel would be released to return home, or if necessary would be secured on site by MTA.
The major objective of the shutdown was to protect human life, both passengers and personnel. Station employees were needed to be on duty until the actual shutdown to secure the premises, remove any loose equipment that may cause damage, and inform customers of the shutdown. They then had to be relocated to safety, either sent home – which was the case for most employees – or secured on site. However, transit employees tend to travel on the very system they were shutting down. To accommodate employees, special shuttle trains and buses were operated to sweep workers from the system. Contracted car services were used to relocate some employees.

While most operating personnel went home, some employees were prepositioned at protected locations to respond quickly during and after the storm. MTA worked systematically to preserve employee energy and ensure safety by providing for basic needs for workers sheltering in place. It supplied cots, bedding, and food to their employees, who were paid even during rest cycles. The work schedule was 16 hours on, 8 hours off. This kept essential employees close at hand and enabled rapid clearance and restart of service.

8.4 Preparing to Restore Full Service

All of these elements worked in tandem to assure speedy service restoration, a primary objective from the time a decision was made to shut down the system. Personnel and customers needed to be protected so that rescue and emergency services would not block track protection and inspection. Securing rolling stock and infrastructure reduced the amount of inspection and repair needed. The shutdown was planned for an 8 hour period; this time was spent not only stopping the service, but also protecting equipment, infrastructure, and personnel. Because of these preparatory steps, less time was spent after the storm repairing infrastructure and rescuing people and trains, thereby, reducing the time to restore service to full capacity. Stopping the service was accomplished, in large measure, to be sure the assets were available for full service when the storm passed.

8.5 Command and Control

Beyond routine operations management structures, facing Hurricane Irene, the MTA established an Executive Command Center (ECC), bringing together top agency managers (President, Vice Presidents, liaison personnel, a scribe for documentation, etc.) to coordinate activities across system components – MNRR, LIRR, MTA subways and buses. The ECC was above the event-related Incident Command Center (ICC), the regular Rail Control Center (RCC), and short-term emergency storm fighting centers.
A Customer Advocate (CA) was assigned to the ECC to identify and track stranded vehicles. The CA function was created after the Boxing Day snow storm in 2010, when transit vehicles were stranded for extended periods. The sole function of the CA is to remind operating personnel of stranded vehicles so they are not forgotten as storm fighting proceeded.

In retrospect, MTA was very satisfied with the performance of the management structure, particularly the newly-created ECC.
9 The Impacts of Irene

New York City’s transit system suffered significant but recoverable damage from Hurricane Irene, summarized in Table 3. Perhaps the most widespread impact was wind damage caused by fallen trees, which blocked rail lines and surface streets and brought down some catenary power cables wires. The bulk of tree-related damage occurred in suburban areas, affecting Metro North and Long Island Railroads, as well as MTA trains, buses and motor vehicle traffic (Figure 7, Figure 8, Figure 9 and Figure 10).

Table 3: Impacts Across Systems\(^\text{19}\)

<table>
<thead>
<tr>
<th>NYCT</th>
<th>Flooding at low lying yards and lines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freshwater flooding at 149(^{th}) Street Tunnel</td>
</tr>
<tr>
<td></td>
<td>Trees Down on elevated structure</td>
</tr>
<tr>
<td>MNR</td>
<td>Washout on the Port Jervis Line</td>
</tr>
<tr>
<td></td>
<td>Flooding on Harlem Line</td>
</tr>
<tr>
<td></td>
<td>Landslides on Hudson Line</td>
</tr>
<tr>
<td></td>
<td>Trees down on Harlem, Hudson, Port Jervis and New Haven Lines</td>
</tr>
<tr>
<td>NJT</td>
<td>Flooding on Pascack Valley Line, Montecclair-Boonton Line, Main Line, Northeast Corridor Line, and Hoboken Terminal</td>
</tr>
<tr>
<td></td>
<td>Geotechnical Damage (washouts, Sinkholes, Mudslides, voids) on Coast Line, Morris &amp; Essex Line</td>
</tr>
<tr>
<td></td>
<td>Catenary Line Damage on Montecclair-Boonton Line</td>
</tr>
<tr>
<td></td>
<td>Trees Down on the Atlantic City and Morris &amp; Essex Line</td>
</tr>
</tbody>
</table>

\(^{19}\) Again, specific LIRR damages are not reported, but does not mean that they were not affected by the storm.
There was substantial flooding of rail lines in both the central city and suburbs, due to heavy rains and surface runoff rather than storm surges. Flooding in Coney Island and Lenox Avenue MTA rail yards was expected because of past experience, and rolling stock was relocated as the system was being shut down (Figure 11). This prevented damage to motors and control systems, and it reduced the need for inspections as the system was being re-started. Figure 12 shows a work crew using a portable pump to remove water from the Lenox Avenue yard. MTA also used pump trains to evacuate water from scattered sites in the tunnels and stations. In some cases pumping was delayed until water levels fell sufficiently in receiving sewers.

A critical and unexpected impact was washouts of rail roadbed and track due to heaving flooding on Metro North Lines. These were significant in size and extent, and had they occurred while trains were running, the consequences could have been severe.

Figure 7: Mudslide at Glenwood on the MNRR Hudson Line. Photo by MTA. http://www.flickr.com/photos/mtaphotos/6089986106/in/photostream/
Figure 8: Removing downed tree limbs on the MTA 2 line in the Bronx. Photo by MTA/Leonard Wiggins. http://www.flickr.com/photos/mtaphotos/6090623735/in/photostream/

Figure 9: Downed trees and power lines forced temporary bus detours. Photo by MTA / John Pillartz http://www.flickr.com/photos/mtaphotos/6092649067/in/photostream/
Figure 10:  Fallen tree blocking MNRR Hudson Line at Garrison. Photo by MTA.
http://www.flickr.com/photos/mtaphotos/6090749482/in/photostream/
Figure 11: Flooding in subway train storage yard at Coney Island. Photo by MTA / David Knights.
http://www.flickr.com/photos/mtaphotos/6089071899/in/photostream/
Figure 12: Pumping flood water out of the 148th Street / Lenox Subway Yard.
Photo by MTA / George Von Dolln.
http://www.flickr.com/photos/mtaphotos/6088662639/in/photostream/

Hardest hit of the surface commuter rail lines were the Metro North Hudson and Port Jervis Lines. Damage to Port Jervis, which is on the west side of the Hudson River and is operated by New Jersey Transit, was so extensive that the full line did not reopen until the end of November, 2011, three months after the hurricane passage.

Over some of its length the Port Jervis Line runs along the small Ramapo River, a logical choice of location because grades are normally least steep along natural waterways – roads and railroads have been built in river valleys throughout history. This is a good design principle to control construction costs, but when the river floods, major problems can arise. If the railroad is constructed to be flood-resistant, or flood-resilient (i.e., can be flooded without washing out), the interruption can be minimal. Otherwise, the risk can be substantial, and Port Jervis illustrates that.

Waters in the river swelled because of Irene’s heavy rainfall– about 12 inches of rain fell in just a few hours. After the washout damage was done, it was alleged that a nearby, small private dam failed, releasing flood waters that destroyed a long section of the roadbed. This 100 year old dam was on Echo Lake, about ¼ mile from the Port Jervis Line (and therefore outside the perspective of railroad managers), near the city of Tuxedo Park, NY. Extent of the damage is illustrated in Figure 13, Figure 14 and Figure 15.
Figure 13: Track on Metro-North Railroad's Port Jervis Line washed out by Hurricane Irene. Photo by MTA/ Hilary Ring. 
http://www.flickr.com/photos/mtaphotos/6100388249/in/photostream/
Figure 14: Washout damage on the Port Jervis Line next to the Ramapo River. Photo by MTA/ Hilary Ring
http://www.flickr.com/photos/mtaphotos/6094348128/in/photostream/
Figure 15: Roadbed on the Port Jervis Line was undermined by flood waters between Sloatsburg and Harriman, Orange County, NY. Photo by MTA/Hilary Ring.
http://www.flickr.com/photos/mtaphotos/6100372595/in/photostream/

Figure 16 shows the section of the Port Jervis Line closest to the failed dam and the Ramapo River. This section of track is adjacent to the New York Thruway, Interstate Highway 87, which was not damaged. It is newer than the railroad, and it is on a small embankment near the river, which passes under the highway in a culvert.
Damage due to washouts was not fully anticipated, and in the case of Port Jervis, risk presented by the failure of the private dam, an event not detected by Metro North until some days after the passage of the hurricane, may have been invisible to railroad managers. This dam was rated by the New York Department of Environmental Conservation as presenting low risk to the public about a year prior to the passage of Irene, which raised questions about the effectiveness of private dam safety assurance. This is becoming a serious issue across the U.S.

While the damage due to washouts seems to have been unexpected, there were anticipated events that did not occur, primarily because of the timing and intensity of the hurricane strike. Because the passage of the hurricane did not correspond to high tide, there was no storm surge, and thus under-river and other tunnels were not flooded. These events would have made the impacts much worse.

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21 For example, see http://www.damsafety.org/; and http://theinfrastructureshow.com/podcasts.
9.1 Damage Costs

A full accounting of the direct costs of Irene to the New York area transit system is complex and not yet available. The costs include at least these factors:

- Costs to prepare for the shutdown, including incremental personnel and materials costs, emergency transportation.
- Costs of operations management during the shutdown- extra personnel (including paying remaining personnel during rest periods), subsistence supplies.
- Lost revenues during preparations, when some services were operated fare-free, and during shutdowns (see next section for discussion).
- Post-storm clean-up costs – mainly tree removal and pumping flooded facilities.
- Incremental operating costs for shuttle buses replacing Port Jervis and other services.
- Post-storm repair costs, the bulk of which were for rebuilding sections of the Port Jervis Line.

Gross estimates put these costs at more than $115 million, about 40% of which was to rebuild the Port Jervis Line.

9.2 Travel Interruptions

Many trips were censored – not taken at all – or converted to different destinations and modes – as a result of the hurricane. Trips were dropped or shifted because of the impending storm, as people secured themselves for the passing of Irene. More significantly, people changed their travel in response to the announcement that the transit system would be shut down starting at noon on Saturday, August 28th. The likely shifts were cancellations; shifting in time – move trips earlier or defer until after the storm; changing destinations (e.g., shop or socialize within walking distance from home); or change activities to be less dependent on (transit) travel – visit a neighbor rather than a friend across town.

There was no timely effort to collect data on these detailed changes in travel. There is data on transit travel – number of unlinked trips – on average weekdays, Saturdays and Sundays. Table 4 shows average daily boardings by transit property for the New York area by carrier and mode for 2010. On a typical weekday regional transit services

22 An unlinked trip is a passenger boarding of a transit vehicle: every entry is counted as a trip. There are fewer true trips, origin-to-destination movements by one person, because many people transfer vehicles within a trip, from bus to train, train to bus, etc. Each transfer is counted as a trip.
carry close to 10 million trips.\textsuperscript{23} Saturday travel is just less than 60% of this, and on Sundays the regional system serves a little over 40% of the weekend market. Senior MTA managers reported that about one third of the Saturday trips, and all of the Sunday market, were lost due to the hurricane and shutdown. This is about 5.7 million trips. Assuming the average traveler takes more than 2 trips in a journey – out and back plus some transfers – between about 1.8 and almost 2.8 million travelers may have been affected.

<table>
<thead>
<tr>
<th>System Component</th>
<th>Average Daily Unlinked Trips (boardings)</th>
<th>Weekdays</th>
<th>Saturdays</th>
<th>Sundays</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTA Subway</td>
<td></td>
<td>5,156,913</td>
<td>3,031,289</td>
<td>2,335,077</td>
</tr>
<tr>
<td>MTA Buses</td>
<td></td>
<td>2,623,766</td>
<td>1,590,505</td>
<td>1,179,053</td>
</tr>
<tr>
<td>LIRR</td>
<td></td>
<td>333,683</td>
<td>135,334</td>
<td>111,531</td>
</tr>
<tr>
<td>MNRR</td>
<td></td>
<td>277,171</td>
<td>114,464</td>
<td>89,865</td>
</tr>
<tr>
<td>NJ Transit Commuter Rail</td>
<td></td>
<td>282,000</td>
<td>90,000</td>
<td>70,000</td>
</tr>
<tr>
<td>LI Buses</td>
<td></td>
<td>103,661</td>
<td>55,670</td>
<td>32,655</td>
</tr>
<tr>
<td>Staten Island RR</td>
<td></td>
<td>28,054</td>
<td>5,260</td>
<td>5,260</td>
</tr>
<tr>
<td>PATH</td>
<td></td>
<td>281,764</td>
<td>140,751</td>
<td>103,345</td>
</tr>
<tr>
<td>Staten Island Ferry</td>
<td></td>
<td>68,584</td>
<td>45,748</td>
<td>36,502</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>9,155,596</td>
<td>5,209,021</td>
<td>3,963,288</td>
</tr>
</tbody>
</table>

Source: NTD 2010 Profiles, New York City Transit Ridership Report, Kevin O’Connor, Vice President, NJ Transit

Of course not all of these lost or modified trips presented a serious problem to travelers. Some shifts were easy to make and people were probably able to satisfy their traveler needs completely. In other cases there were real losses – inability to get to work, to make an important purchase, to see a close friend or relative. And both the scale and the economic impact would have been much greater had the closure occurred on a work day.

Transit operators lost revenue, the magnitude of which is affected by the mode of fare payment. Travelers on prepaid monthly passes already contributed their revenue, and for them there was a loss of value. Travelers using stored value fare instruments simply paid for a different trip, and the transit operator already held the revenue. The major

\textsuperscript{23} National Transit Database, 2010, \url{http://www.ntdprogram.gov/ntdprogram/}. 
loss for carriers was for single payment, cash fare riders. There are more of these occasional riders on weekends, tourists and residents who might not be regular riders going to entertainment venues or visiting friends in the city. These are more likely to be discretionary trips, and fewer of them will be deferred to another time. Transit managers viewed the fares from these lost trips as true lost revenues.

Setting aside the fact that many rides are prepaid (the financial perspective), the economic perspective suggests that since the transit system is fully owned by the public, a fare not paid for a trip (benefit to the traveler) is fare revenue not received by the operator, and so the net outcome is zero. However, the vast majority of travelers gain consumer surplus from their trips, that is, the value of the trip to the traveler on average exceeds the cost paid in fares. This loss of consumer surplus – loss in the value of the trip net after fares – is the real loss to travelers. This would be reflected in the value of the activities undertaken on the trip, purchases, employment, enjoyment, etc. This is difficult to estimate but it is surely some multiple of the number of people affected. If the consumer surplus for the average trip is $10, the net loss could be on the order of $20 million. This does not account for business losses caused by inability of employees to get to work or customers unable to come to the establishment.
10 Restoring Service

Because of the decision to shut down the transit system to protect people and capital assets, restoration was rapid, with the exception of the Port Jervis commuter rail line, where substantial reconstruction was necessary (Table 4). MTA subway and bus services largely came back on line for the morning rush hour on Monday, 29 August, the day after Irene passed. New Jersey transit and the New York commuter rail lines (Long Island and Metro North Railroads) instituted limited service on Tuesday, and were moving toward full service on Wednesday, 31 August.

Table 5: Service Restoration Timeframe

<table>
<thead>
<tr>
<th></th>
<th>Monday 29 August</th>
<th>Tuesday 30 August</th>
<th>Wednesday 31 August</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New York City Transit</strong></td>
<td>Full Service with some exceptions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Long Island Railroad</strong></td>
<td>Extremely Limited Service</td>
<td>Partial service</td>
<td>Full Service with some exceptions</td>
</tr>
<tr>
<td><strong>Metro North</strong></td>
<td>No Service</td>
<td>Partial Service</td>
<td>Full Service with some exceptions</td>
</tr>
<tr>
<td><strong>New Jersey Transit</strong></td>
<td>No Service</td>
<td>Partial Service</td>
<td>Partial Service</td>
</tr>
<tr>
<td>(Except Port Jervis Line)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Rail—Except Atlantic City Line)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Repairs costs for the washed out parts of the Port Jervis Line between Harriman and Suffern, New York, were about $50 million, and service was not restored until 28 November, 2011, a full three months after the hurricane passed. In the interim, MNRR operated substitute bus service at substantial incremental costs.

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24 Port Jervis Line was severely damaged was not restored to a near full scale until months after the event. Temporary bus shuttle service was used in the interim period.

25 Atlantic City Line did not sustain damage and is outside of the New York City Metropolitan Region.
Partial or Complete Shutdown

It is logical to ask why the entire transit system – New Jersey Transit and the MTA – was shutdown, as opposed to closing only the most vulnerable components. Recall that this region is the most transit-dependent of any city in the United States, and so preserving some rudimentary service might seem highly desirable. In retrospect, senior managers were satisfied with the system-wide shutdown decision; among the reasons for this are the following factors.

- Many trips involve multiple components of the transit system – rail, bus, ferries. These strong interconnections present the risk of stranding passengers, far from their destinations and exposed to dangerous weather conditions, if only selected services are stopped.
- Informing travelers about which elements of the system were functioning and which were not would have presented a complex communications challenge, again exposing riders to the possibility of being stranded in vulnerable or isolated locations.
- It was not evident that some parts of the system were invulnerable to damage: everything was at risk. This is because the hurricane threats were multidimensional – flooding, wind, flying and falling objects, etc.

Running selected services might have benefited some travelers, but might also have put those travelers, transportation employees, and rolling stock at risk.

A complete shutdown essentially forced citizens to stay out of the path of the storm, i.e., it left no one waiting at or walking to or from stops and stations.
12 Analytic Framework for the Decision to Cancel Transit Service

This section applies decision analysis and Monte Carlo simulation to characterize the general effect of several factors on the decision to shut down transit service in the face of a severe weather event. The aim here is not to second-guess the New York decision, but to reveal insights about the tradeoffs in the decision-making situation, i.e., to identify the sources of uncertainty, the possible consequences/costs, and importantly how the scale and distribution of these parameters influence managerial decision-making.26 One of the areas of interest is to understand the impact and viability of investments intended to protect assets, and in certain cases allow for safe and reliable operations in the face of storm risk.

To accomplish this, an example or “toy” problem is formulated and an accepted decision analysis framework is used to represent the risks associated with hurricane damage, and in particular to analyze the decision to shut down public transit service in a metropolitan area in advance of the arrival of a weather event such as a hurricane. Then a parametric analysis is conducted to explore the effect of uncertainty in the decision-making situation.

12.1 Structuring the Decision to Cancel Public Transit Service

Building on Regnier and Harr27 in the context of hurricane evacuation, Figure 17 represents the decision to shut down public transit service as a decision tree. The framework provides a systematic approach to represent the sequence of decisions, sources of uncertainty, as well as the associated consequences. At a high level, in a given period, the options being considered are to continue to operate, to terminate service, or to postpone a termination decision in anticipation of updated forecasts. These decisions are presented in the first stage of the diagram presented in Figure 17, i.e., in advance of the realization of the uncertain events.

26 The significance of post-hoc analysis is unclear, in part, due to the difficulty in (meaningful) parameter estimation, as well as inherent difficulties of assigning (monetary) value to intangible criteria such as ensuring public safety, for which the importance of timely, clear and consistent messaging/information supersedes the basic economic tradeoffs. Nevertheless, this analysis can provide (or reaffirm) valuable insights to transportation researchers and policy-makers.

The periods in the decision-making situation capture intervals between forecast updates, which are approximately 6 hours for storms tracked by the National Hurricane Center (NHC) on the Atlantic Coast of the United States. The last decision-making opportunity coincides with the lead-time needed to prepare for a system shutdown.

The sources of uncertainty in the problem are the storm track, intensity, and damage potential. These events are presented in the second and third stages in Figure 17. For example, data from the National Hurricane Center show that 24 hours in advance of a storm, errors in track forecast can be on the order of 100 miles. The NHC uses the Saffir-Simpson Hurricane Scale presented in Table 5 to classify storms into 7 discrete intensity levels depending on wind-speed. The storm categories are tropical depressions, storms, and 5 categories of hurricanes. Twenty-four hours in advance of a storm, errors in sustained wind-speed forecasts can be on the order of 10 knots, which amounts to misclassification of the storm’s intensity by one of the commonly used intensity levels. However, other hurricane effects, such as storm surge, floods from rainfall and tornadoes, are not directly included in the scale; such effects are typically stronger with higher categories, but local geography and individual storms may have a stronger or weaker possibility of these hurricane characteristics.28

Table 6: Tropical Storm and Hurricane Classifications by National Hurricane Center

<table>
<thead>
<tr>
<th>Tropical Storm/Hurricane Classification29</th>
<th>Wind-Speed</th>
<th>Storm Surge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km/h (knots)</td>
<td>(m)</td>
</tr>
<tr>
<td>Tropical Depression</td>
<td>≤63 (≤35)</td>
<td></td>
</tr>
<tr>
<td>Tropical Storm</td>
<td>63-118 (35-64)</td>
<td>≤1.2</td>
</tr>
<tr>
<td>Category One</td>
<td>118-154 (64-83)</td>
<td>1.2-1.8</td>
</tr>
<tr>
<td>Category Two</td>
<td>154-178 (83-96)</td>
<td>1.8-2.7</td>
</tr>
<tr>
<td>Category Three</td>
<td>178-209 (96-</td>
<td>2.7-4.0</td>
</tr>
</tbody>
</table>


29 Ibid.
Uncertainties related to a storm’s track and intensity are exogenous. In contrast, uncertainty related to damage and its consequences, i.e., an agency’s/operator’s inherent risk profile, depends on the exposure to incidents, e.g., flooding or debris blockages, vulnerabilities of its assets, and demand served. Importantly, the consequences/costs also depend on the decision to operate or shut down in advance of a storm. Risk profiles and consequences that reflect the several transit modes in the New York City Metropolitan Area in the context of preparations for Hurricane Irene are outlined below.

12.1.1 Commuter Rail

Commuter rail lines (in New York) have significant exposure to a large number of (low probability) damage events due to their extent. These include wind downing trees or tree branches blocking tracks and damaging infrastructure; flooding and track washouts; and water damage to sensitive equipment. Wind damage is not necessarily associated with a direct strike, and thus risk can be significant even if the track forecast

| Category Four | 209-252 (113-137) | 4.0-5.5 |
| Category Five | ≥252 (≥137)        | ≥5.5    |

Figure 17: Decision Tree Model – Decision to Close the Transit System
uncertainty is large. This type of risk is driven by exposure to a very large number of low probability events, e.g., tree branches falling. The difficulty is that the probability of at least one event occurring grows significantly as a function of the exposure: one tree down along a rail line can stop operations on that line. It follows that due to their unpredictable nature, these risks are difficult to guard against in a way that permits safe operations during weather events.

12.1.2 Rail Rapid Transit Service

The greatest risk of subway system comes from flooding. This risk is driven by storm-surge, as well as heavy rains and surface water runoff. In contrast to the risks associated with commuter rail operations, this risk is predictable, that is, managers are aware of these vulnerabilities. In the case of Hurricane Irene, the storm-surge and flooding were expected to threaten operation of the subway system in low-lying rail yards and under-river tunnels, as well as some underground stations.

This type of predictable risk can, to some extent, be guarded against by making infrastructure investments, such as flood walls. Risks to stored rolling stock can be mitigated by relocating equipment to higher ground or protected underground locations.

12.1.3 Bus Service

Similar to commuter rail, bus systems have a great exposure due to the distribution of service over a large geographic area; however, unlike commuter rail, bus service is flexible, meaning that, barring a catastrophic accidents, buses are capable of avoiding obstacles by changing their trajectory/path.

12.1.4 Parametric Analysis

A parametric analysis explores the effect of uncertainty on the decision to shut down transit service during a weather event such as Hurricane Irene. The Normal Form representation of the decision-making situation is presented below, and for simplicity the uncertainty related to storm intensity is omitted.

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30 If \( N \) independent events are considered, each with probability of occurrence of \( p \), then the probability of at least 1 event is \( 1-(1-p)^N \). For \( p=0.1\% \) and \( N=100 \), the probability of at least 1 event is 10\%, which is significant. Logically, such events are positively correlated, which increases the risk further.
Table 7: Storm outcomes

<table>
<thead>
<tr>
<th>Agency Decisions</th>
<th>Storm Miss</th>
<th>Storm Strike (P(strike))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Incident (P(incidents/strike))</td>
<td>None</td>
</tr>
<tr>
<td>Operate</td>
<td>0 (reference level)</td>
<td>Base + Incidents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base + Preparation and Recovery Cost + Base</td>
</tr>
<tr>
<td></td>
<td>Preparation and Recovery Cost</td>
<td>Preparation and Recovery Cost + Base + Goodwill</td>
</tr>
</tbody>
</table>

The elements are as follows:

- The decisions (options) considered are to either continue (Operate), or shut down (Closure).
- The uncertain events are related to the realization and consequences of the weather event. Specifically, the storm outcomes are **Strike**, when the weather event realizes, or **Miss**, otherwise. **Incident** and **None** are the outcomes contingent on the realization of the weather event. The outcome **Incident** is intended to aggregate significant and likely negative outcomes stemming from the decision to operate through the weather event, e.g., damage to roadbeds, rolling-stock or other infrastructure facilities; compensation/loss of goodwill associated with accidents; etc.
- Every possible outcome requires the specification of a probability reflecting its relative likelihood of occurrence. The relevant probabilities are labeled P(strike) and P(inc/strike). Labels are omitted for their respective complements.
  - P(strike) applies to the likelihood of a weather event reaching or exceeding a critical threshold, impacting the geographic region of interest. Depending on the weather event and the situation, the critical threshold could be related to (combinations of) factors such as wind speed, precipitation (cumulative or rate), temperature (changes), etc. These probabilities are obtained from short or long-term weather forecasts depending on the objective. An agency has no control over these probabilities; however, long-term infrastructure investment decisions could have an effect on the relevant threshold.
P(incidents/strike) is the conditional probability that incidents occur given that the weather event realizes. This probability is a function of the vulnerability/exposure of each of the systems being considered to the type of weather event. It is also a function of the intensity of a weather event. This probability describes an agency's risk profile. To some extent, an agency can influence this probability by making investments in protection, e.g., floodwalls, improved drainage, etc.

Every combination of decision and outcome requires a specification of the relevant consequences, i.e., costs. In terms of notation and assumptions:

- This analysis considers incremental costs with respect to those associated with operations in the absence of a weather event (Miss). Accordingly, these costs correspond to the reference level of zero.

- Preparation and Recovery Cost represents costs associated with system closure in advance of the weather event, and reopening afterwards. This can include costs of repositioning equipment and protecting infrastructure, loss of revenue, user costs associated with inability to travel (which can be large in a transit-dependent city like New York), etc. These costs are deterministic.

- Base Costs are associated damage caused by realization of a weather event that are independent of the decision to operate. These costs are unavoidable in the short-term and are largely predictable, e.g., equipment repair costs associated with subway flooding. These costs are stochastic, though small number of points of exposure and thorough understanding of a system's vulnerabilities can make them predictable.

- Incident Costs are related to expected and unexpected incidents during operations in the event of a storm (or similar weather event). As stated earlier, these costs are a function of an agency's assets, their spatial distribution, etc. These costs can be (partially) avoided by protecting (infrastructure) assets in advance of a storm, and most importantly, by minimizing (or reducing) the exposure of agency personnel and passengers to incidents.

- Goodwill represents costs associated with (unrecovered) loss of goodwill associated with system closure and absence of the weather event. In certain situations these costs can be reflected in subsequent ridership losses, and in most, they will be manifested in complaints and critical press reports.
These costs are the political consequences of the decision to close the system unnecessarily.

The elements of the decision-making situation are presented in Figure 18 in extended form. The decision tree includes example values for the parameters defined earlier. The parameters were selected to reflect less certainty about the realization of the weather event than about the vulnerability of a system. For the given parameters system, closure, decision 2, is the action that minimizes the sum of expected costs, $10.5.

Figure 18: Shut down Decision Tree (Example)

Using this as a reference model, it is now possible to conduct a parametric analysis to reveal insights about the decision-making situation.

12.2 Value of Information

The case of perfect information is a benchmark constructed under the assumption that the uncertain events, i.e., realization of weather event and incidents, are known prior to deciding to operate or shut down. The value of perfect information is obtained by evaluating the policy for an idealized decision-maker who is aware of the outcomes of the uncertain events prior to deciding to operate or shut down. For the reference model, the realization of a weather event that causes incidents leads to a system shutdown, as was the case in New York City. In all other cases, the decision is to operate. In turn, the
expected costs of the idealized situation is $3.625,\textsuperscript{31} which means that the value of knowing the outcome of the uncertain events, i.e., the value of perfect information is 10.5-3.625 = $6.875. This information is useful to benchmark the value of tests or forecasts intended to reduce the state of uncertainty. As is shown below, this type of analysis can be used to guide the selection of the type of tests or information sources to consider, for example, whether or not to defer a decision while waiting for a forecast update.

In an analogous fashion, the value of knowing the realization of the weather event alone, i.e., strike or miss, is $6.5, which implies that the value of knowing if incidents will in fact occur is at most $0.375 (the difference between the value of perfect information and the value of only the weather information 6.875-6.5), and in turn, suggests the importance of having information regarding the weather event dominates that of having information about the system’s risk profile. The example also suggests that an idealized decision-maker can gain significantly by postponing a terminal decision as much as possible to take advantage of the most accurate weather event forecast. A corollary is that there is value to making investments/plans that allow for postponing a shutdown decision, which, among other things, would involve reducing the lead-time needed to prepare, e.g., protect infrastructure, evacuate personnel, etc. The caveat is, of course, that the values and thus the interpretation presented here depend on the structure and parameters used in this example.

### 12.3 Conclusions

This section has presented a decision analysis model of an agency’s decisions in the context of uncertain events and the subsequent consequences. In addition to structuring an inherently complex situation, the outcome of which depends both on decisions and on events with uncertain outcomes, the model leads to valuable insights about the risks borne by transit operators, which depend on the exposure of their assets, personnel and customers, as well as their ability to protect them. The simple numerical example shows how this model can be used to identify the most significant sources of uncertainty, which, in turn, can be used to understand the value of tests/forecasts, and, in the long-term, where resource allocation can have a positive impact. In this numerical example, investments that reduce the lead-time needed to prepare in advance of a

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\textsuperscript{31} These costs are far less than the expected costs of $10.5 because the idealized decision-maker deploys a policy that responds to the different realizations of the uncertain events with different actions. In the earlier situation, the decision-maker is restricted to selecting a single action.
weather event, and that allow for agencies to receive additional, more accurate weather forecasts, can lead to significant cost savings.
13 Lessons Learned

New York MTA has performed a post event audit by assembling documentation of the Hurricane Irene event, including internal communications, press releases, and photographs, and preparing preliminary notes on lessons learned. Lessons reported here are interpretations of the authors.

A primary lesson learned is that it is feasible to shut down and restore transit services over a short time interval even in this highly transit-dependent region. Here feasibility means that the shutdown and service restoration can be accomplished without massive negative response from riders, the community, and regional leadership. Of course there was substantial disruption of economic and social activities – that was unavoidable. At least three factors seem to have made this shutdown and recovery possible:

- There was ample warning of the hurricane’s track, speed, and maximum wind velocity. This provided time for decision making, planning, and preparatory action. In a no-notice event (e.g., an earthquake), circumstances would have been much different.
- A firm shutdown decision was made on the basis of forecasts well in advance. That is, a commitment was made to the shutdown based on predicted sustained wind velocities, as had been defined in the MTA hurricane response plan.
- The hurricane struck the New York region on a weekend. The arrival day was known with high confidence several days in advance. Weekends are the lightest travel days, and they are times when people’s activities and schedules are most flexible. MTA officials reported that in the face of similar weather forecasts, they would have shut the system down on a weekday if necessary. Still, the impacts and the public pushback would likely have been substantially different if Irene had arrived on a weekday.

A second lesson was that even though most damage was less severe than expected, the effects of the storm were of sufficient magnitude and extent that the wind velocity and storm surge shutdown criteria were confirmed. Under extreme circumstances, it is wise, and it is feasible, to shut down the transit system to protect human and material assets.

Third, the decision to secure people and property, to relocate rolling stock and attempt to minimize flooding, achieved the desired end. Both passengers and employees were safe through the storm, and the rolling stock and most of the infrastructure were positioned for a rapid restart of services after the storm passed. Relaxing some rules and procedures, e.g., eliminating fare collection and permitting pets, helped facilitate evacuation and shutdown.
Fourth, the success and general public acceptance of the shutdown were substantially attributable to a highly effective communications plan that informed customers, employees, and collaborating agencies about the risks of the approaching storm, and the status and plans for the transportation system. A variety of information channels, including social media tools, were used to inform the public and the press. This made it possible to sweep customers out of the system as the shutdown proceeded. Maintaining and rapidly disseminating a photographic record showed the public and their leadership the true nature of the problem, helping to explain and justify the system shutdown. The MTA communications program during Hurricane Irene benefited importantly from the latest methods for recording and disseminating information in the digital age. In terms of public information content, MTA managers emphasized the importance of under-promising and over-delivering so that performance met or exceeded expectations.

A corollary to both the first and fourth lesson learned from the experience with Hurricane Irene as a model severe weather event is that even in the New York metropolitan area, customers can tolerate short-term shutdowns with ample advance warning and explanation. Future customer tolerance is probably increased by demonstrating that recovery can be accomplished quickly.

Irene was effectively a natural probe – it tested the vulnerability of the transit system to extreme weather assaults. A fifth lesson was identification and/or confirmation of those vulnerabilities. Some were known, and responses to them were available and applied, e.g., flooding and damage to trees. More seriously, it appears that roadbed washouts were not anticipated and because they happened so rapidly, there was no immediate defense for them. But the experience with Irene, the natural probe, identified that vulnerability. Now that this risk has been exposed, there is the opportunity to rebuild in more resilient ways to prevent, or reduce the probability of, such damage in the future.32

The sixth lesson learned focused on the effectiveness of actions to protect transit system assets. Rolling stock was successfully protected by relocating it to secure areas, i.e., areas not prone to flooding. Water damage to motors and control components of electric transit vehicles – particularly salt water damage – could have been severe and might have produced long-term consequences to service. The Chicago Transit Authority chose to operate its heavy rail transit system through a massive snow storm in 1979.

32 A counter example is the Canadian National Railway derailment in Cherry Valley, Illinois in June of 2009, as a result of a storm water washout. The findings of the National Transportation Safety Board attributed the derailment to failure to address prior washouts that occurred as early as 2006. That is, the risk was known but not addressed (http://www.ntsb.gov/doclib/recletters/2012/R-12-001-002.pdf).
Resulting snow damage to electric components required rebuilding almost all of the electric motors, which was both costly and forced the carrier to operate with a reduced fleet long after the snow melted.33

Protecting infrastructure from flooding was more difficult because much of it lies at or below sea level, making it subject to flooding and storm surges. Flooding, in the case of Irene, was mainly caused by heavy rains overflowing into low and underground infrastructure. Although under-river tunnels did not flood, the risk for them was high, particularly if a storm surge poured brackish water into them. Hastily installed temporary dams, both inflatable and constructed wood and sandbag barriers provided some protection but were not entirely successful. To address potentially more frequent flooding events in the future, some more effective, and more permanent, options may be warranted. Some redesign of facilities may help – MTA has already installed low water barriers around some surface-level air vents and station entrances. Protecting subsurface and low-lying infrastructure from long-term sea level rise, in combination with storm surges, will be substantially more challenging.

A seventh lesson focuses on management in the short and long term. The command and control structure developed for Irene, the top layer Executive Command Center added above the normal Incident Command Center, worked well. Such system-wide, region-wide coordination was a valuable part of the response process. This seems to be particularly important for settings such as the New York region, where the transportation system is composed of a number of interconnected components through which passengers routinely travel. The ECC and lower level command structures facilitated quick and coordinated responses. Having a Customer Advocate in the middle of this management team reduced the likelihood of customers being stranded as the shutdown proceeded.

The overall event management process was facilitated by the existence of the hurricane response manual developed in response to Hurricane Katrina 6 years earlier. At least for the MTA, Katrina represented what may have been the most important lesson learned about preparing for large and severe weather events. The value of this guidebook, as well as the lessons learned from Irene, have led MTA to update the manual, and to extend it to cover a more general set of severe weather events, e.g., snow storms, Nor’easter, as well as hurricanes. The December 2010 snow storm was also important in strengthening the resolve to shut down the system to protect riders and preserve assets.

This process of purposeful and continuous learning should help transportation managers in New York and elsewhere sharpen their ability to respond to and prepare for future severe weather events.
14 Acknowledgements

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15 References


