FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

An Integrated Approach to Climate Adaptation at the Chicago Transit Authority

AUGUST 2013

FTA Report No. 0070
Federal Transit Administration

PREPARED BY
Chicago Transit Authority
TranSystems

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SPONSORED BY

Federal Transit Administration
Office of Research, Demonstration and Innovation
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1200 New Jersey Avenue, SE
Washington, DC 20590

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT

CTA was selected as one of seven pilots funded by FTA to advance the state of practice for adapting transit systems to the impacts of climate change. This effort is in keeping with broader long-term goals to address state-of-good-repair needs and to enhance transit safety. The CTA pilot develops quantitative and qualitative tools that can be used by CTA and peer agencies to integrate consideration of climate impacts into operations, infrastructure planning, and standard business practices.

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ABSTRACT

The Chicago Transit Authority (CTA) was selected as one of seven pilots funded by the Federal Transit Administration (FTA) to advance the state of practice for adapting transit systems to the impacts of climate change. This effort is in keeping with broader long-term goals to address state-of-good-repair needs and to enhance transit safety. The CTA pilot develops quantitative and qualitative tools that can be used by CTA and peer agencies to integrate consideration of climate impacts into operations, infrastructure planning, and standard business practices.

EXECUTIVE SUMMARY

Introduction

The Chicago Transit Authority (CTA) was selected as one of seven pilots funded by the Federal Transit Administration (FTA) to advance the state of practice for adapting transit systems to the impacts of climate change. This effort is in keeping with broader long-term goals to address state-of-good-repair needs and to enhance transit safety. The CTA pilot develops quantitative and qualitative tools that can be used by CTA and peer agencies to integrate consideration of climate impacts into operations, infrastructure planning, and standard business practices.

Overview

Climate research and modeling show that the Chicago area is expected to encounter more extreme heat and more intense precipitation events in future years. These events have already caused significant impacts to CTA operations and infrastructure, resulting in service delays, loss of ridership revenue, and additional maintenance costs, which are likely to increase over time.

The CTA climate adaptation pilot develops quantitative tools to help assess future impacts of extreme weather on operations and infrastructure. CTA's pilot consisted of three primary tasks:

Task 1 – Survey of System Vulnerabilities

- Collected operational data and insights from CTA subject matter experts to identify general relationships between extreme weather events and CTA system disruptions.
- Produced a regression analysis of severe weather and ridership data to assess statistical relationships between climate impacts and customer behavior.
- Identified and prioritized areas of interest (e.g., infrastructure enhancements, operational impacts) for more in-depth investigation under Task 2 and Task 3.

Task 2 – Adaptation Implementation Strategies

- Developed framework to assess costs and benefits of selected adaptation strategies using a life-cycle cost assessment (LCCA) model.
- Compared alternative no-build and build scenarios in three issue areas, which include right-of-way (ROW) flooding, rail heat kinks, and signal house overheating.
- Performed sensitivity analyses to identify thresholds for inputs (e.g., severe weather events) at which proposed improvements provide a positive return on investment.

Task 3 – Integrating Adaptation Strategies into Standard Business Practices

- Defined high-level strategies to integrate climate adaptation into CTA's enterprise asset management (EAM) system in concert with ongoing refinement of the EAM framework.
- Developed a framework tool to assess financial and operational impacts of extreme weather, which can be extended to additional data sets and functionality over time.

Summary Findings

Task 1 – Survey of System Vulnerabilities

Historical climate data and projected increases in extreme heat and precipitation are likely to have significant impacts on CTA infrastructure, transit operations, and customer experience.

Extreme Heat Impacts

- Climate models project that prolonged heat events (e.g., three or more days exceeding 90°) will increase in the Chicago area under both low- and high-emissions scenarios.
- Extreme heat increases capital costs due to ROW damage and signal failures (e.g., CTA experienced nearly 40 heat kinks between 2008 and 2012).
- Extreme heat increases vehicle energy consumption (e.g., diesel fuel consumption and rail traction power increase during prolonged heat periods).

Extreme Precipitation Impacts

- Flooding incidents have inflicted significant capital, operating, and maintenance cost impacts (e.g., FEMA flooding claims in September 2008 totaled more than $3 million).
- CTA service disruptions due to flooding incur significant secondary costs due to replacement transit service, reduced system reliability, and lost ridership revenue.

Task 2 and 3 Topic Prioritization

- CTA stakeholder input yielded a risk matrix capturing severity and frequency of climate impacts, which was used to prioritize areas for further study under Tasks 2 and 3.
- Task 2 recommendations are to explore three rail-focused project areas, and Task 3 recommendations are to focus on financial and operational impacts to CTA's bus fleet.

Task 2 – Adaptation Implementation Strategies

Methodology

- Applied LCCA frameworks from the U.S. Department of Transportation (USDOT) and other agencies to three CTA project areas, with the target of achieving a positive net present value (NPV) by 2050.
- Established no-build baselines of asset performance without capital improvements, including projected increases in operating/maintenance costs due to extreme weather.
- Compared various build scenarios (i.e., design solutions) with no-build scenarios; conducted sensitivity analyses based on frequency of severe weather events.

Right-of-Way Flooding

- Water intrusion into subway portals has a high potential for service disruptions and infrastructure impacts. Vent shaft intrusion was reviewed and deemed to be a secondary issue.
- The no-build scenario assumes an increase in frequency and severity of flooding incidents, requiring additional bus shuttles and impacting ridership revenue.
- The proposed build scenario is to install drainage structures to capture and detain stormwater at portal entrances, to be released to municipal drainage systems over time.
- LCCA model runs revealed a moderate degree of sensitivity to varying input assumptions (e.g., doubling capital costs, removing passenger value of time), as shown in Table ES-1.

Table ES-1

Right-of-Way Flooding Model Runs

ROW Flooding Model Runs			Base	Double Capital Cost	No Passenger Value of Time
Results	Multiplier	Events / Year	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	0.04	$ (58,836)	$ (337,039)	$ (203,163)
Frequency 1	1.5	0.06	$ 79,467	$ (198,736)	$ (137,023)
Frequency 2	2.0	0.08	$ 217,770	$ (60,433)	$ (70,883)
Frequency 3	3.0	0.12	$ 494,376	$ 216,173	$ 61,398

Rail Heat Kinks

- Under excessive heat, steel rails can buckle, triggering slow zones and affecting service. Two build scenarios were considered for a section of Orange Line track susceptible to heat kinks.

- Upgrade existing ballasted track structure with improved materials and installation methods. This option is less costly to construct, but requires more annual maintenance.
- Replace existing track structure by fixing running rail to a structural concrete base (direct fixation). This option is more costly to construct, but requires less annual maintenance.
- LCCA model runs revealed a moderate degree of sensitivity to varying input assumptions (e.g., ballasted vs. direct fixation track, duration of slow zones), as shown in Table ES-2.

Table ES-2

Rail Heat Kink Model Runs

Rail Kink Model Runs			Ballasted (Base)	Direct Fixation (Base)	Ballasted (30 Day Impact)	Ballasted (No PVT)
Results	Frequency Increase	Events / Year	2050 NPV	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	2	$ 7,728,387	$ 7,008,659	$ 902,723	$ (2,248,200)
Frequency 1	1.5	3	$ 13,216,997	$ 12,497,268	$ 4,014,823	$ (1,747,883)
Frequency 2	2.0	4	$ 18,705,607	$ 17,985,878	$ 7,126,924	$ (1,247,567)
Frequency 3	3.0	6	$ 29,682,826	$ 28,963,098	$ 13,351,125	$ (246,934)

Signal House Overheating

- Many CTA signal houses contain a single air conditioning (A/C) unit and no back-up power source. When signal houses overheat, trains operate at restricted speeds. Two build alternatives were developed:
  - Install a second parallel A/C unit in each signal house to increase overall cooling capacity and provide redundancy in the case of failure of the primary A/C unit.
  - Provide secondary power sources to signal houses by installing switch gear or traction power inverters to connect to the Commonwealth Edison (ComEd) electrical grid.
- LCCA model runs revealed a moderate degree of sensitivity to varying input assumptions (e.g., relative levels of capital investment, ridership of rail branch), as shown in Table ES-3.

Table ES-3

Signal House Overheating Model Runs

Signal House Overheating Model Runs			Low Capital Cost	High Capital Cost	Low Capital Cost (Low Ridership)	Low Capital Cost (No PVT)
Results	Multiplier	Events / Year	2050 NPV	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	1	$ 228,084	$ 175,910	$ 111,311	$ (5,461)
Frequency 1	1.5	1.5	$ 356,619	$ 304,445	$ 181,460	$ 6,301
Frequency 2	2.0	2	$ 485,154	$ 432,980	$ 251,608	$ 18,063
Frequency 3	3.0	3	$ 742,223	$ 690,049	$ 391,905	$ 41,588

Task 3 – Integrating Adaptation Strategies into Standard Business Practices

Task 3 proposes integration of adaptation strategies into CTA's standard business practices.

Incorporation of Climate Effects into Enterprise Asset Management (EAM) Framework

- Two approaches are proposed to incorporate climate impacts into the EAM system, in concert with the build-out of the EAM framework and ongoing engineering condition assessments:
  - Develop qualitative risk assessment tables for major asset groups driven by severe weather impacts (e.g., intense precipitation increases vulnerability of rolling stock).
  - Incorporate fields in the EAM database to indicate the climate vulnerability of a given asset, as a function of three criteria: exposure, sensitivity, and adaptive capacity.

Operational Impact/Financial Cost Model

- A framework model has been developed for forecasting operational and budgetary impacts. The model has been used to correlate temperature with bus HVAC defects and fuel consumption.
- Bus HVAC defects showed a significant correlation with extreme temperatures, with more than 75 percent of failures occurring at temperatures 80°F and higher.
- Bus diesel fuel consumption showed a greater increase at higher temperatures (above 70°F), and a more modest increase at lower temperatures (below 40°F).

Next Steps

The following tasks are recommended to extend the CTA adaptation pilot to future needs:

- Task 1:
  - Modify data collection and accounting strategies to facilitate forthcoming correlations of severe weather impacts and service disruptions.
  - Continue monitoring and development of climate forecasting models to allow better integration of long-term climate projections with available CTA data.
- Task 2:
  - Refine LCCA methodology with improved forecasting of short- and long-term severe weather event frequencies, and other input assumptions.

- Identify strategies to extend project-specific findings to systemwide impacts, using appropriate methodologies and order-of-magnitude cost estimates.

- Task 3:
  - Continue development of tools to be used to understand the short- and long-term impacts of severe weather on useful life of agency assets within the EAM framework.
  - Extend model to include secondary impacts (e.g., station-specific climate-related ridership shifts, impacts of more frequent bus shuttles on mainline transit service)

SECTION 1

Task 1—Survey of System Vulnerabilities

Introduction

This report describes the efforts of the Chicago Transit Authority (CTA) in conducting a transit climate change adaptation assessment pilot in cooperation with the Federal Transit Administration (FTA) to adapt transit systems to projected impacts of climate change. The FTA pilot projects are intended to assess the vulnerability of transit agency assets and operations to anticipated climate change impacts, such as prolonged heat and intense precipitation, and to develop initial adaptation strategies consistent with agency operating environments.

Task 1, the initial phase of this study, included the quantification of extreme weather costs and impacts observed to date and the anticipation of potential future impacts based on Chicago-area climate modeling data. This was accomplished by quantifying financial costs of severe weather events (e.g., damage and labor costs from severe rainfall and snowfall), examining recent patterns in extreme weather-related CTA service disruptions (e.g., heat kinks and signal failures during prolonged heat), assessing impacts to transit ridership during extreme weather conditions (e.g., sensitivities due to weather and day type), and exploring potential system vulnerabilities based on recent weather trends and projected climate impacts (e.g., urban heat islands, freeze-thaw cycles).

Task 1 output is being used to guide forthcoming project tasks and phases. Using the results of the Task 1 baseline study, a risk matrix was developed, based on the probability and severity of agency weather impacts, to guide subsequent project tasks. Selection criteria identified in an internal workshop with a broad range of agency stakeholders helped filter risk matrix impacts to prioritize Task 2 and 3 areas of investigation. Task 2 applied a life-cycle cost analysis to three specific implementation projects, to serve as a basis for future implementation opportunities. Task 3 incorporated severe weather adaptation strategies into long-term standard business practices, to increase system resilience, and, in turn, increase the capacity of the CTA system to mitigate further climate change impacts.

Literature Review/Previous Studies

Adaptation to severe weather in the transportation sector is still an emerging field, but initial forays have been made in a number of areas, including roadway, maritime, aviation, and transit infrastructure and ridership.

Several studies have explored climate adaptation efforts for roadway networks and infrastructure, within the Federal Highway Administration (FHWA) funded climate vulnerability pilot program. Nguyen explored potential risks to shoreline assets in the San Francisco Bay Area [1]. Perlman assessed sensitivity of transportation to coastal and inland flooding in New Jersey [2]. Maurer leveraged expertise of USDOT researchers and maintenance staff through workshop formats in Washington State [3]. Similar studies have been conducted for maritime impacts in Long Beach [4], and aviation impacts along the Gulf Coast [5]. Climate adaptation strategies have also been explored in state-level plans such as Oregon Department of Transportation [6].

In the transit sector, FTA produced an overview of best practices and case studies from around the U.S. and has proposed frameworks for addressing projected climate risks [7]. The New York Metropolitan Transit Authority (NYMTA) produced a preliminary survey of severe weather impacts to its operations and infrastructure and established a roadmap for responding to anticipated future impacts [8]. NJ Transit conducted similar research on the impacts of severe weather on critical assets [9]. Transport for London (TfL) produced a defined set of vulnerabilities and planned responses in the context of a UK national adaptation plan for infrastructure resilience [10, 11].

Chicago-specific references include the Chicago Climate Action Plan research referenced in the following section and Nelson's study of rail service disruptions [12]. Guo et al. explored the relationship between weather and transit ridership in Chicago by contrasting sensitivity across different weather types, transit modes, and travel periods [13]; the current study builds directly upon this research.

Study Background

In September 2008, the City of Chicago unveiled the Chicago Climate Action Plan (CCAP) [14], which outlines the city's strategy to reduce Chicago's greenhouse gas emissions to 25 percent below 1990 levels by 2020. CCAP is composed of five strategies, including "Improved Transportation Options," which further defines 14 actions to reduce emissions from the transportation sector, to account for 23 percent of the total CCAP reduction target. CCAP's stated goal to increase Chicago transit ridership by 30 percent by 2020 would reduce regional emissions by a projected 0.83 MMT CO2e, nearly one quarter of the total transportation sector goal. The core goals of CCAP have been further enhanced with the release of the complementary Sustainable Chicago 2015 plan in September 2012 [15].

In addition to its greenhouse gas (GHG) mitigation targets, CCAP also addresses the anticipated impacts of climate change by adapting in three primary areas: Chicago's built environment, natural environment, and human population. CTA plays a critical role in the built environment area, as the agency must ultimately ensure that its infrastructure is resilient to climate impacts to maximize the carbon mitigation potential of public transit.

CCAP has advanced its climate adaptation planning focus through research and risk evaluation. In 2007, the City partnered with climate scientists, Dr. Katharine Hayhoe (Texas Tech University) and Dr. Donald Wuebbles (University of Illinois, Urbana-Champaign), along with a team of research experts convened through the Chicago Climate Task Force to create a climate impacts analysis for Chicago [16]. The Task Force also engaged Oliver Wyman, an international risk management firm, to complete almost $1 million in *pro bono* work to assess City-specific costs of climate-related impacts [17], which has laid the foundation for CCAP's adaptation framework.

Climate modeling research such as Hayhoe et al. [16] indicates that intense weather events are likely to increase in the Chicago area in both the short and long terms, as summarized in Table 1-1. Figure 1-1 shows a sample of the predicted occurrence of prolonged heat events across several time periods, and Figure 1-2 gives a sample of the predicted occurrence of intense precipitation events, differentiated for seasonal variation.

Table 1-1 *Projected Chicago-Area Severe Weather Trends*

Annual Average of Extreme Weather Events	1961 1990	1997 2006		2010 2039		2040 2069		2070 2099	
	Observed Value	*Low Emission*	*High Emission*	*Low Emission*	*High Emission*	*Low Emission*	*High Emission*	*Low Emission*	*High Emission*
Days of precipitation > 2 in.	0.68	0.92	1.23	0.99	1.02	0.87	1.20	1.21	1.74
Days of precipitation > 4 in.	0.03	0.00	0.10	0.03	0.04	0.05	0.05	0.04	0.01
Days of temperatures over 90°F	14.8	17.3	18.2	25.4	26.3	32.6	50.7	36.3	72.2
Days of temperatures over 100°F	2.0	2.1	2.5	5.1	4.7	6.7	16.1	8.4	30.5

Figure 1-1

Projected Average Occurrence of 3- and 7-Day Periods above 90°F

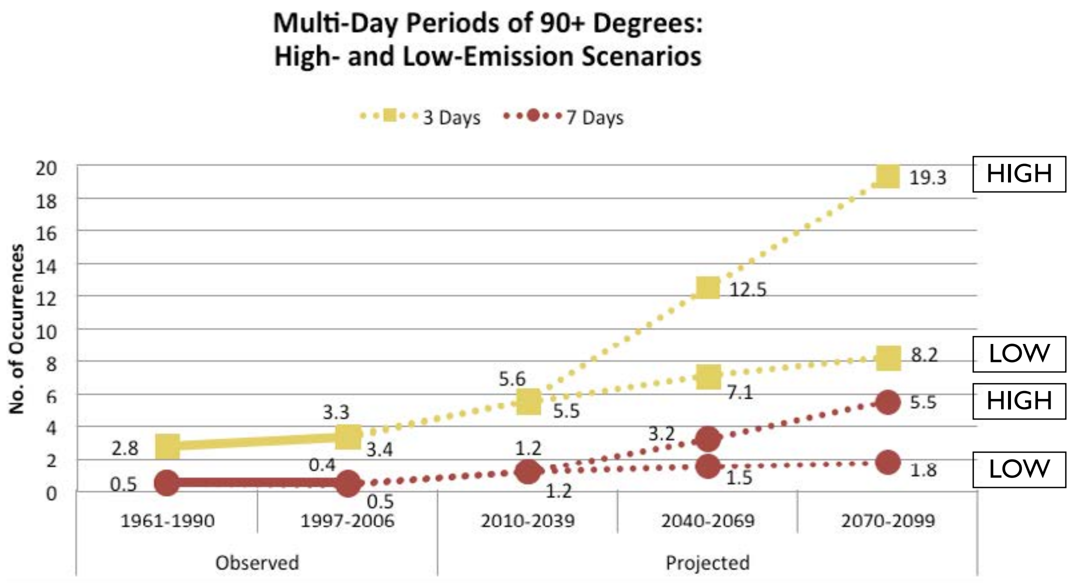
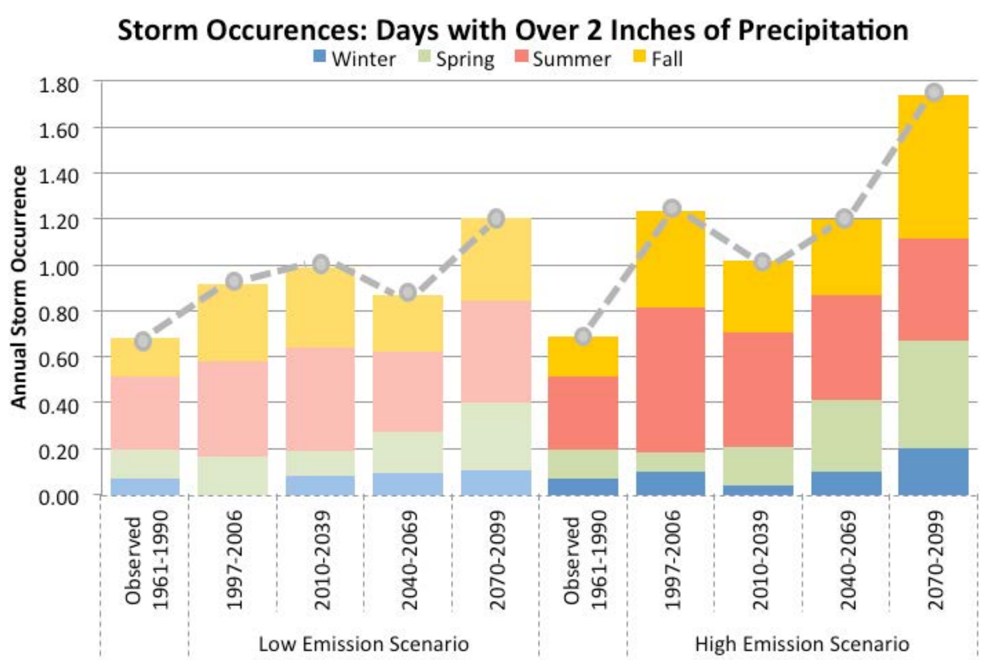


Figure 1-2

Projected Chicago-area Intense Precipitation Events



Given the magnitude of the impacts experienced in the recent past, projected future changes in extreme heat and heavy rainfall events are likely to have significant effects on many aspects of life in Chicago. Hayhoe et al. [16] developed and applied a quantitative modeling framework to assess the potential impacts and economic costs of changes in mean and extreme climate on Chicago's energy use, peak electricity demand, transportation, and built environment; this framework is used in the current study to anticipate impacts to CTA operations and infrastructure.

Research Methodology

Research methodology consists of three parts: expert interviews, data collection, and data synthesis/analysis, as described in the following sections.

Expert Interviews

At the beginning of the study, the CTA project team conducted group interviews with CTA staff and City of Chicago stakeholders to gather background information on observed and potential vulnerabilities of the CTA bus and rail systems to extreme weather. The interviews captured input from roughly 30 subject matter experts from across CTA departments, including Transit Operations, Infrastructure, Planning, Safety & Security, and Capital Investment, as well as public-sector partners including the former Chicago Department of Environment,[1] the Chicago Department of Transportation, and the Office of Emergency Management and Communication.

The interviews identified seven primary areas of severe weather concerns for further investigation: (1) intense precipitation, (2) prolonged heat, (3) heavy snowfall, (4) extreme cold, (5) rapid temperature swings, (6) storm-related impacts, and (7) emergency-related impacts. Stakeholder departments discussed potential impacts in greater detail and identified potential data sources to help quantify severe-weather impacts to CTA, as described in the following section.

Data Collection

The areas of interest identified during expert interviews span a broad number of initial data sets, which were subsequently narrowed based on criteria such as data quality and probability/severity of potential impacts. Available data sets for the study were found to have varying timescales and degrees of robustness, as summarized below:

- *Meteorological Data*
  Meteorological data were provided by the National Oceanic and Atmospheric Administration (NOAA), based on readings at Chicago Midway Airport [18]. Daily temperature data were used for 2005–2012, and hourly temperature data for 2001–2004 were aggregated into daily data for the purposes of this analysis (daily data were not available from NOAA for this time period) [19].

- *Diesel Consumption Data*
  Diesel consumption data were provided by CTA's Budget, IT, and Bus Engineering departments. These data were collected by individual bus garages and compiled to estimate and budget for these energy costs. Diesel

[1] The Chicago Department of Environment was disbanded and a reduced staff was integrated into other City departments in December 2011.

data were provided on a monthly basis beginning in FY2004 and on a daily basis beginning in 2008.

- *Rail Traction Power Data*
  Rail power data was provided by Commonwealth Edison (ComEd), the electricity provider for CTA and much of the Chicago region. Electricity consumption and demand data were compiled from 2001 through 2012 and filtered to compare extreme weather periods with baseline conditions. Traction power data are accurate at a monthly scale, but are potentially less reliable on a daily basis due to a monitoring algorithm currently under revision.

- *Service Disruption Data*
  The CTA Control Center compiles service disruption and incident data among separate databases for bus, rail, traction power, and rail station events. The data are often narrative in nature and are not directly correlated to weather-related events, although some filters exist to narrow queries. Control Center databases were phased in between 2007 and 2009, depending on subject area.

- *Financial Cost Data*
  CTA Grant Accounting maintains billing codes for outlier storm events (e.g., "September 2008 flooding," "February 2011 blizzard"), but does not track costs for general categories of extreme weather events (e.g., "flooding," "blizzard"). This CTA department also compiles detailed federal (Federal Emergency Management Agency, FEMA) and state (Illinois Emergency Management Agency, IEMA) reimbursement claims for select 100-year storm events.

- *Rolling Stock Maintenance Data*
  Bus and rail vehicle maintenance data are tracked by CTA's Maintenance Management Information System (MMIS), which was phased in across CTA vehicle storage and maintenance facilities from 2007–2008. MMIS data considered in this study ranged from 2007 to 2012.

- *Ridership Data*
  Ridership data were supplied by CTA Data Analytics, which has maintained automated data collection systems since 1998 on rail and 2001 on bus. Data ranged from January 2001 to December 2012 and were divided by mode, date, and day type (i.e., weekday, Saturday, Sunday).

- *Systems Vulnerability Data*
  The City of Chicago and partnering agencies provided a number of complementary data sets to better assess vulnerability of CTA assets and operations, including urban heat island (UHI) data layers, flooding data

layers (e.g., floodplains, troubled viaducts, contour maps), and current and projected freeze-thaw cycles.

Data Synthesis

The data sets described above were subsequently analyzed in four principal areas: cost impacts, service disruptions, ridership impacts, and system vulnerabilities, as described in the following sections.

Analysis and Results

Cost Impacts of Extreme Weather Events

This section of the analysis examines recent extreme weather events in the Chicago area that have had direct impacts on CTA infrastructure and operations, and quantifies the costs to CTA of responding to and recovering from those events. To date, analyses have been performed for case studies for each of the following severe weather event types:

- Flooding: damage due to heavy rainfall (9 inches in 10 days, September 5–15, 2008)
- Heavy snowfall: labor costs due to clearing snow and maintaining service (20 inches in three days, January 31–February 2, 2011)
- Heavy wind: power outages/debris clearance from wind/rain (3 inches in two days, August 23–24, 2007)

Table 1-2 summarizes CTA's costs associated with flooding that occurred across the CTA system during September 2008 (due to secondary impacts of Hurricane Ike). The information in this table was developed from documentation submitted by CTA to FEMA and/or IEMA for cost reimbursement and is organized according to individual projects funded to restore the CTA bus and rail system to full functionality.

The most significant cost element is to repair damage to stations and infrastructure at the O'Hare and Rosemont stations, which comprises nearly 90 percent of the total cost of more than $3 million.

Table 1-2

Costs for September 2008 Flooding

Description	Cost
Emergency protective measures	$278,250
Temporary wood canopy	$16,690
Debris removal	$58,002
Station and infrastructure repair	$2,705,203
Total	**$3,058,145**

In a separate flooding incident, CTA reported extra labor costs of $133,570 associated with responding to flooding that occurred on July 23, 2011. This incident resulted from a new all-time record rainfall when 6.86 inches fell in slightly over 3 hours (for context, the 100-year, 3-hour storm for the Chicago area is 4.85 inches).

Tables 1-3 and 1-4 show the estimated costs of two additional extreme precipitation events. Table 1-3 depicts the February 2011 blizzard, which dropped 20 inches of snow in two days (as measured at Midway Airport), marking the largest snowfall event in decades (the largest recorded single storm snowfall in Chicago measured 23 inches in 1967). Most of the CTA cost for this storm was associated with CTA labor and contract costs for track clearing and snow removal, which accounted for 88 percent of the total incident cost of $671,000.

Table 1-3

Costs for February 2011 Blizzard

Description	Cost
Labor	$458,744
Equipment	$44,440
Materials	$35,511
Contract Costs	$129,840
Administrative Costs	$2,076
Total	**$670,610**

Table 1-4 depicts CTA costs associated with heavy winds and rainfall that occurred during August 23–24, 2007. Major costs are for clearance of tree limbs and other debris and for CTA to operate 10 portable generators and one fixed generator due to power failures in the ComEd grid system. Combined labor, equipment, and fuel costs for this response exceeded $50,000, with labor costs and debris removal accounting for more than 60 percent of the total.

Table 1-4

Costs for August 2007 Rainstorms

Description	Cost
Debris clearance	$2,991
Emergency generator equipment	$15,792
Labor	$28,863
Fuel	$2,560
Total	**$50,206**

While it is difficult to predict the frequency of discrete severe weather events of this magnitude, Task 3 proposes a framework to project operational and financial impacts of more continuous weather impacts (as projected by CCAP data) to help inform periodic budget cycles.

Service Disruptions due to Extreme Weather Events

Heat Kinks

Under periods of prolonged heat, kinks can develop in steel rails when elevated temperatures cause the tracks to warp, bend, or buckle. Heat kinks (or sun kinks) have the potential to cause serious service disruptions or derailments. Many transit authorities reduce train speeds on very hot days to reduce the risks from kinked rail; unfortunately, this practice can also lead to short-term service delays and long-term ridership revenue loss.

Figure 1-3 shows approximately 39 heat kink events recorded on the CTA rail system in the five-year period from 2008–2012 (based on available CTA Control Center data). Approximately 30 percent of these heat kink events occurred during or between multi-day heat events, suggesting cumulative impacts over prolonged heat periods. The figure shows that more than 50 percent of heat kink events occurred on only two rail branches (Red and Orange), highlighting particular vulnerabilities of this infrastructure (e.g., age of track, operation in highway medians, location within urban heat islands).

Heat Kink Events (2008-2012)		
Year	Number of Events	Avg. Maximum Temperature
2008	6	79-90°F
2009	6	80-86°F
2010	12	83-94°F
2011	7	81-101°F
2012	7	85-104°F

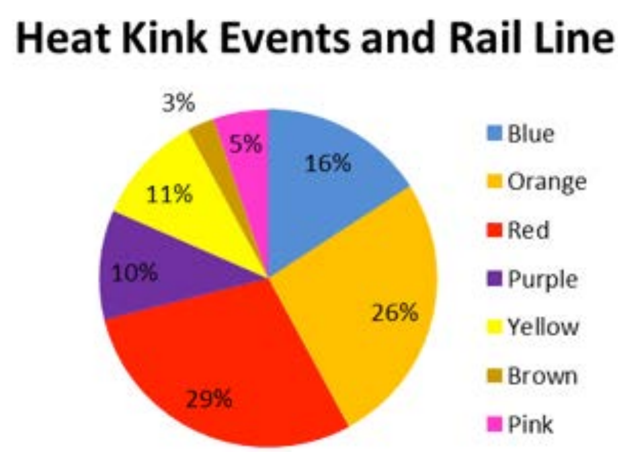


Figure 1-3 *CTA Rail Heat Kink Events*

Rolling Stock Repairs and Maintenance

This analysis uses MMIS data to compare frequency of general repair calls between extreme weather periods and parallel control periods. Although the MMIS data do not indicate which repairs are directly weather-related, repairs during, preceding and following both extreme heat and precipitation events markedly higher than during control periods, as shown in Table 1-5.

Table 1-5

Rolling Stock Repairs Following Extreme Weather Events

Dates	Event Type	Repairs Recorded	% Increase
September 2008	Heavy rain: 9 inches in 10 days	743	18%
September 2009	Control period	629	–
July 2010	Extreme heat: 5 days of 100+ Humidex	583	37%
July 2009	Control period	425	–

This relatively small sample size shows that repairs may increase significantly following adverse weather events, suggesting that repair demands on the CTA system could increase with more frequent future extreme weather events. Further investigation of MMIS data in Task 3 establishes correlations between extreme weather and specific operational and financial impacts.

Energy Consumption

ComEd delivers electricity to CTA's substations, which, in turn, provide traction power for CTA's heavy rail system. Within the CTA system, key indicators for power disruptions include traction substations, facilities, and signal equipment. CTA currently experiences outage rates of about one per year among the agency's 61 substations. The frequency of facility outages is approximately one per week, and these are normally the result of aging equipment or supply cable failures. Other equipment affected by high temperatures includes communications, railway signaling, and rail car equipment (signal house overheating is explored in depth in Task 2).

Another area of investigation is CTA's consumption of rail traction power during extreme heat. A comparison of average consumption for periods of prolonged heat, based on available ComEd data for 2001–2011, shows that rail traction power use increased by more than 10 percent on average (and more than 20% at maximum) during periods of prolonged heat, suggesting that future budgetary impacts based on CCAP projections could be significant. CTA has been in communication with ComEd to enhance reliability of traction power readings at a substation level to ensure that budget projections are in line with consumption data.

The CTA bus fleet consumes diesel fuel to provide both vehicle propulsion and on-board temperature control. Variation in diesel fuel consumption relative to ambient temperature is explored in depth in Task 3.

Rail Signal Equipment Failures

Rail signal houses are maintained at temperatures necessary for the effective functioning of electrical communications components through the use of air conditioning (A/C) units powered by feeds from the ComEd grid. Signal equipment can be damaged when A/C units fail, and while the CTA rail system has a redundant power supply, there are no current backup systems for power failures to signal house A/C units.

Available Control Center data do not directly correlate signal failures to overheating impacts (which happen at a range of ambient temperatures), but signal house A/C units are likely to be more susceptible to failure during periods of prolonged heat. Signal house overheating is explored in greater depth in Task 2.

Ridership Impacts from Extreme Weather

This section of the analysis considers the impact of various severe weather events on system-wide CTA bus and rail ridership between 2001 and 2012. Linear regressions were performed to show the relationship between daily system ridership and extreme weather patterns. The study considers four extreme weather events: high heat/humidity, heavy rainfall, extreme cold, and heavy snowfall.[2]

High Heat/Humidity Events

High heat and high humidity days in this analysis were estimated using the Humidex index, which combines both temperature and dew point data, since daily temperature data for Midway Airport did not include a separate measure for humidity.[3] This estimate is meant to provide a better measure of perceived heat, which is likely to be a determining factor in people's transportation decision making. The formula for Humidex is as follows:

$$\text{Humidex} = \text{Air temperature} + 0.5555 \times (6.11 \times e^{-5417.7530 \times (\frac{1}{273.16} - \frac{1}{\text{dewpoint in kelvins}})} - 10)$$

Based on the study data, there is a somewhat weak relationship (i.e., less than 20%) between rail ridership and temperature for all temperatures and time periods. In addition, for the less hot days (i.e., 80+ Humidex index), temperature shows a positive correlation with weekend ridership, albeit a very weak one. The correlation is strongest on the hottest days, which do see a consistent decline in ridership as temperatures increase for all time periods.

Table 1-6 shows that the negative correlation between transit ridership and high temperatures is more pronounced for bus than rail. There is little change between the set of 80˚F+ and 90˚F+ days, but for 100˚F+ days, the negative

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[2] This research builds upon an earlier study by Guo et al., published in Transportation Research Record in 2007 [13]. Weather data come from NOAA, and ridership data are provided by CTA Data Analytics, as described above. Only days that show a certain weather event are included in a given data set (e.g., days with a high of 30˚F), and holidays have been removed due to atypical travel patterns.

[3] For example, a temperature of 30˚C (86˚F) with a dew point of 15˚C (59˚F) would have a Humidex value of 34˚C (93˚F).

correlation is striking, especially on Sundays, likely due to a higher percentage of discretionary trips.

Table 1-6

Changes in Ridership and Humidex Index with an Increase of 1°F

	Rail			Bus		
	Ridership Change	Percent Change	Correlation	Ridership Change	Percent Change	Correlation
Weekday	-6	-0.01%	-0.063	-3	-0.00%	-0.015
Saturday	-1,508	-0.30%	-0.107	-4,109	-0.38%	-0.255
Sunday	-1,170	-0.32%	-0.108	-2,964	-0.39%	-0.408

CCAP data project significant increases in high heat days, particularly under a high-emissions scenario, which may have more significant implications for future long-term ridership trends.

Heavy Rainfall Events

Heavy rainfall days are defined by rainfall greater than 0.6 inches per day [13]. It was found that days with very heavy rainfall did yield reduced bus and rail ridership on weekends, while on weekdays, heavy rainfall actually resulted in a slight ridership increase. For both rail and bus, Saturday and Sunday had few occurrences and were, therefore, combined into a single category, which showed decreases with an increase in rainfall (though the correlation for both day types is fairly weak (see Table 1-7). Since CCAP data project seasonal fluctuations in extreme precipitation events, potential ridership impacts are likely to be seasonal as well.

Table 1-7

Changes in Ridership and Rainfall with an Increase of 0.1 Inch of Precipitation

	Rail			Bus		
	Ridership Change	Percent Change	Correlation	Ridership Change	Percent Change	Correlation
Weekday	1,421	0.27%	0.129	1,910	0.20%	0.091
Saturday/Sunday	-3,040	-1.01%	-0.224	-3,699	-0.67%	-0.154

Extreme Cold Events

Extremely cold days were defined by a daily high of 30˚F or lower. Table 1-8 depicts the findings that colder weather did result in a decrease in ridership for all time periods, with bus ridership more sensitive than rail ridership (although ridership decreased on both modes as temperatures dropped). Weekend ridership was also more sensitive to temperature changes than weekday ridership, likely due to a greater percentage of discretionary trips. Since CCAP data show an overall trend of increasing temperatures with a proportionally greater increase in winter, these adverse ridership impacts are likely to be reduced in future decades.

Table 1-8

Changes in Ridership and Temperature with a Decrease of 1°F

	Rail			Bus		
	Ridership Change	Percent Change	Correlation	Ridership Change	Percent Change	Correlation
Weekday	-2,585	-0.50%	0.217	-6,227	-0.65%	0.293
Saturday	-3,795	-1.29%	0.334	-7,029	-1.13%	0.498
Sunday	-637	-0.30%	0.136	-4,106	-0.96%	0.593

Heavy Snowfall Events

Available meteorological data did not reflect enough occurrences of heavy snowfall events (i.e., more than 8 inches in a calendar day) in the 2001–2012 period to determine its meaningful impact on ridership (the hourly data for 2001–2004 did not include any instances of snowfall, which may be due to limitations in the empirical data). For 2005–2012, there were only four instances of snowfall of more than 8 inches in a single day, which is insufficient to assess the impacts of heavy snowfall on transit ridership. Further analysis could be undertaken with additional snowfall data and a regression methodology that considers multi-day storm events and/or total snow accumulation.

Ridership and Revenue Impacts

This analysis suggests that any future increase in extreme heat and precipitation events may also have an impact on CTA in terms of lost ridership revenue. Assuming an average CTA revenue of approximately $1.00 per trip [20], a Humidex increase of 10˚F on a hot Sunday will result in approximately 9,030 fewer passengers on both bus and rail, or a daily revenue loss of nearly $10,000. On a very cold weekday, a temperature decline of 10˚F yields a decrease of roughly 88,120 passengers on bus and rail, with lost daily revenue of nearly $90,000.

Further research in this area could explore the net impacts of increased ridership in mild winters compared to the decreased ridership in extremely hot summers, which are projected in a warming climate. Additional research may explore the relative impacts of severe weather on individual rail branches/stations and bus routes/stops, depending on varying degrees of exposure and weather protection.

System Vulnerability Data

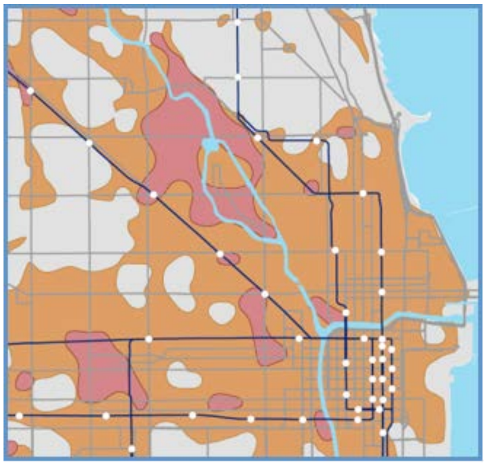
This section of the study explores several factors that may yield direct and indirect vulnerabilities to the CTA system, including urban heat islands, right-of-way flooding, and freeze-thaw cycles.

Urban Heat Islands

Urban heat islands (UHIs) refer to increased temperatures due to intense urban development, which can elevate ambient air temperature by 2–8°F. In a study conducted by the City of Chicago, two Landsat 7 satellite images were used to capture both day and night images in Chicago [21]. Each image was processed to indicate the warmest 10 percent of the pixels, and both data sets were combined to indicate Tier 1 areas, which indicate the warmest 10 percent in both day and night images, and Tier 2 areas, which indicate the warmest 10 percent of either day or night images.

Figure 1-4

Urban Heat Islands Map and Percentages of Rail Branches Affected



Rail Branch Name	UHI Tier 1	UHI Tier 2	Total
Loop Elevated	0%	100%	100%
Red Line Dan Ryan	0%	87%	87%
Blue Line O'Hare	12%	72%	83%
Blue Line Forest Park	5%	71%	75%
Pink Line	5%	59%	64%
Orange Line	10%	48%	58%
Green Line Lake Street	8%	50%	58%
Green Line South	0%	36%	36%
Red Line North Side	1%	30%	32%
Brown Line	0%	27%	27%
Purple Line	0%	0%	0%

The map detail and table indicate that some CTA rail branches are disproportionately affected by UHIs (see Figure A-3 for full UHI map). For example, the Red Line Dan Ryan branch and the Blue Line O'Hare and Forest Park branches are disproportionately affected by UHIs, most likely because they operate in highway medians.

As an additional indicator, the signal system may be more vulnerable to extreme heat than the tracks themselves. Since many pieces of signal equipment require controlled temperature, they are vulnerable to secondary failures when associated air conditioners fail. Potential correlation among signal failures to UHIs, prolonged heat and other factors require further investigation, and this topic is explored initially in Task 2.

Right-of-Way Flooding

Right-of-way (ROW) flooding is an ongoing challenge for CTA operations, as demonstrated by ongoing service disruptions along at-grade and subway branches. An acute example of flooding vulnerability is observed along the Blue Line O'Hare branch between Rosemont and Cumberland, which has been impacted by flooding events nine times in the last five years.

Vulnerability is also evident in CTA's bus service due to more than 1,500 roadway viaducts in the city of Chicago, of which roughly 10 percent are considered "troubled" by frequent flooding (see Figure 1-5).

Viaduct Location	Frequency	Bus Routes Affected
W. 47th & Shields	6	47, 24
W. Ogden & Claremont	4	18, 49
N. Sacramento & Carroll	4	65
W. 51st & Dan Ryan	3	192, 24
S. State & 63rd	3	29, 63
E. 79th & Avalon	3	79, 28
E. 95th & Cottage Grove	3	100, 111, 4

Figure 1-5 *CTA ROW Flooding Events for Roadway Viaducts and Affected CTA Bus Routes*

The map detail and table reveal disproportionate vulnerabilities among viaducts, which, in some cases, affect CTA's higher ridership routes (e.g., #79 79th, #49 Western, and #4 Cottage Grove), as shown in the enumeration of flooding events from 2010–2012. An ongoing analysis of bus and rail ROW vulnerabilities will enable CTA to define more proactive and cost-effective approaches to addressing flooding issues, in conjunction with CCAP projection data. See Figure A-2 for a complete map of City of Chicago troubled viaducts.

Freeze-Thaw Cycles

Freeze-thaw cycles increase wear-and-tear on transit infrastructure due to expansion and contraction characteristics of water; Chicago is subjected to frequent freeze-thaw cycles during winter months. Table 1-9 shows simulated values averaged from four global climate model simulations, downscaled to three historic Chicago weather stations [22]; the number of predicted freeze-thaw events varies by ±30 annually for any given time period.

Table 1-9

Freeze-Thaw Cycles for Lower- and Higher-Emissions Scenarios

	Lower Emissions Scenario	Higher Emissions Scenario
1960–1999	139	139
2010–2039	122	122
2040–2069	125	117
2070–2099	127	103

Since the projected change in freeze-thaw cycles falls within the margin of error (even under a higher-emissions scenario), this variable is less likely to have a significant future impact on CTA operations and infrastructure than other factors, such as extreme heat and precipitation.

Prioritizing Task 2 and 3 Areas of Investigation

The primary purpose of Task 1 is to determine areas of further investigation for Tasks 2 and 3. These areas of interest were identified through a CTA stakeholder workshop, subsequent project team analyses, and follow-up interviews with CTA department leads.

CTA Stakeholder Workshop

At the conclusion of Task 1, a workshop was conducted with a broad array of CTA stakeholders to prioritize potential areas for further investigation under Tasks 2 and 3, centered around the following three components:

- **Presentation** – A short presentation gave background on preliminary correlations between CTA service disruption and observed extreme weather events. Historic data were extrapolated to provide quantitative information about the expected change in the frequency of such events, based on available data from CTA and external sources.
- **Individual Surveys** – Workshop participants completed a survey to select priority issues for a number of severe weather event categories (e.g., prolonged heat, intense precipitation), providing numerical rankings to assess the frequency and severity of these impacts based on empirical data and institutional experience.
- **Risk Matrix Development** – Top-ranked issues from the survey were used to develop in real-time a risk matrix capturing frequency and severity of impacts to CTA infrastructure and operations (see Figure A-1). The resultant matrix was used to elicit group input on a set of consensus issues for further exploration.

The patterns revealed in the risk matrix led to the compilation of twelve potential issues for further study. Since rankings were tightly clustered and no single issue received the highest possible scores for both severity and frequency, the risk matrix findings were subject to further interpretation. Potential groupings are displayed in Table 1-10, prioritized by severity of impacts.

Table 1-10

Impacts Considered for Task 2 and 3 Investigation

Weather Impact	High Severity	Moderate Severity and Frequency
Failure of infrastructure components	X	X
Damage to subway track: heat kinks	X	X
Subway track fires	X	
Flooding of rail tunnels and at-grade locations	X	
A/C equipment failure		X
Emergency communications needed		X
Vehicle accidents		X
Increased loads on electrical and diesel systems		X
Viaduct flooding		X
Safety hazards at uncovered subway entrances		X
Salt erosion shortens equipment life		X
Demand for cooling and heating buses		X

The project team then grouped the remaining items according to their common elements, resulting in four general clusters of impacts due to severe weather impacts:

- Flooding – inundation of subway tunnels and at-grade locations (rail), viaducts (bus)
- Extreme heat – damage to subway track (heat kinks), track fires
- Electrical – substation performance, increased loads on electrical and diesel systems, A/C equipment failure
- Customer impacts – safety hazards, customer comfort/protection, emergency communication

Table 1-11 contains selection criteria used to determine which of the general issues prioritized above should be distributed to each of Tasks 2 and 3.

Table 1-11

Selection Criteria for Tasks 2 and 3 Areas of Investigation

Selection Criteria	
Task 2	*Task 3*
Severity of events (safety issues)	Frequency of events
Capital cost increases	Operating cost increases
Project- and site-specific issues	Process-specific issues
Assets under CTA control	Assets under other jurisdiction

The following sections describe the process of converting broad Task 1 subject areas into specific Task 2 and 3 areas of investigation.

Task 2 Topics: Implementation Strategies

Rail ROW Flooding (topic advanced)

This sub-task focuses on adaptation strategies to address flooding in subway tunnels and at-grade locations along the CTA rail system, based on costs incurred for recent extreme rainfall events in the Chicago area, and climate models indicate that intense precipitation events are likely to increase over the forecast horizon of interest.

In conversations with CTA's Chief Engineer, the project team identified flooding at a number of at-risk subway portals and ventilation shafts. Potential build and no-build scenarios were assessed, and designs for future facilities were considered for drainage solutions to accommodate increased flooding events. Roadway flooding impacts to bus operations were also explored, but were not advanced because this topic falls largely outside CTA's operational control.

Rail Heat Kinks (topic advanced)

Instances of heat kinks incidents on the CTA system and urban heat island maps have illustrated potential rail line vulnerabilities (see Figure A-3). Slow zones have been initiated to reduce train speeds during high heat days when rail buckling is more likely to occur. Strategies to resolve heat kinks include evaluation of the costs and benefits of changing the rail infrastructure specifications to align with the expected temperature ranges, in addition to improved rail track inspections and maintenance practices.

Discussions with CTA Power & Way helped to solidify heat kinks as a primary topic of investigation for climate-related impacts. Rail lines located within the medians of highway experience higher temperatures, and curves in rail line are more susceptible to buckling or pull-aparts; thus, heat kinks were advanced as a topic for further investigation in Task 2.

Rail Signal Overheating (topic advanced)

Failure of vulnerable electrical equipment becomes more frequent during high heat days or multi-day high heat periods. Existing CTA monitoring procedures are used to track equipment performance, assess reliability of key equipment groups, and identify replacement cycles. Specific signal locations may have a higher failure rate than others, which has been considered in identifying case studies.

CTA Signals shared electrical equipment vulnerabilities specific to the CTA system. The lack of reliability of signal house A/C units that run on power fed from an exterior source was identified as a hazard. While the CTA rail system has a redundant power supply, signal house A/C units have no such redundancy. Due to the criticality of these systems, this topic was advanced to Task 2.

Customer Comfort/Weather Protection (topic not advanced)

Passenger safety and comfort are compromised during extreme temperature and precipitation events, and long-term measures are needed to maintain customer satisfaction and sustain transit ridership. Existing safety hazards that will worsen with more frequent extreme weather events may be assessed with alternatives to improve passenger safety and comfort.

While this topic is highly relevant to the goals of this research, available funding prevented its inclusion in the scope of the CTA climate adaptation pilot; this topic is to be pursued under a separate study with an academic partner.

Task 3 Topics: Standard Business Practices

Capital Asset Management (topic advanced)

The CTA climate adaptation project presents a general framework for long-term integration of climate change impacts into existing and planned enterprise asset management (EAM) systems. CTA maintains a mature enterprise asset management system for rail assets and is developing a parallel asset management system for bus assets, in conjunction with an FTA State of Good Repair grant award received in 2011. This study outlines key parameters for future integration in the EAM database to indicate the climate vulnerability of a given asset, as a function of three criteria: exposure, sensitivity, and adaptive capacity.

Operational and Financial Impact Modeling (topic advanced)

Task 3 addresses potential climate impacts to capital and operating costs in CTA's annual budget development process. This task develops a framework model to correlate financial and operating impacts with extreme heat and precipitation (focusing initially on bus HVAC defects and diesel fuel consumption) and incorporates climate projection models to anticipate long-range labor, materials, and budgeting requirements. The model facilitates the incorporation of extreme weather impacts in future CTA budget cycles and can be expanded to additional data sets (e.g., rail fleet impacts).

Safety, Security and Risk Compliance (topic not advanced)

Climate adaptation is an area that overlaps with CTA's current hazard management process, which assesses potential hazards (e.g., cracked rail, ROW flooding, wet platform surfaces) in terms of likelihood/severity and determines appropriate mitigation strategies. While this subtask was not ultimately advanced to Task 3 as a standalone area of investigation, the quantitative analyses of climate change impacts in Task 2 will aid in projecting risks and defining long-term strategies to bring hazards to acceptable levels. Outcomes of Task 2 and 3 project areas are also intended to facilitate collaboration with the Chicago Department of Transportation (CDOT) and the Office of Emergency Management and Communications (OEMC) in forthcoming efforts concerning emergency management planning efforts, heat-related power outages, and evacuation routes during natural/human disasters.

SECTION

2

Task 2—Analysis of Adaptation Strategies

Background and Specific Study Areas

Based on the Task 1 analysis, the following areas are identified for further study in Task 2:

- ROW Flooding
- Rail Heat Kinks
- Signal House Overheating

Work conducted in this task focuses on the development of case studies to incorporate climate adaptation considerations into capital project planning.

A life-cycle cost analysis (LCCA) methodology was developed to identify if proposed solutions provide positive financial benefits over the lifetime of the asset. To perform this work, a framework was developed that correlates to similar methodologies used by USDOT and other federal agencies in evaluating the costs and benefits of performing projects. This methodology establishes a no-build[4] baseline of the performance of the asset without any improvements. In this case, the no-build scenario considers the impacts to the agency and their customers by climatic impacts on infrastructure which will affect service. In contrast, build scenarios (engineered solutions) were developed to place a capital cost on the proposed improvements. The no-build and build scenarios were compared in the life-cycle cost analysis to see how the capital investment compared to taking no action.

Given the specific nature of the study areas that result in defined operating impacts and construction costs, it is not feasible to directly apply the results to other locations within the CTA and other agencies without adjustment. Instead, this task develops a tool to assist the CTA and other agencies in future analysis of additional case studies and background assumptions.

This section is structured as follows:

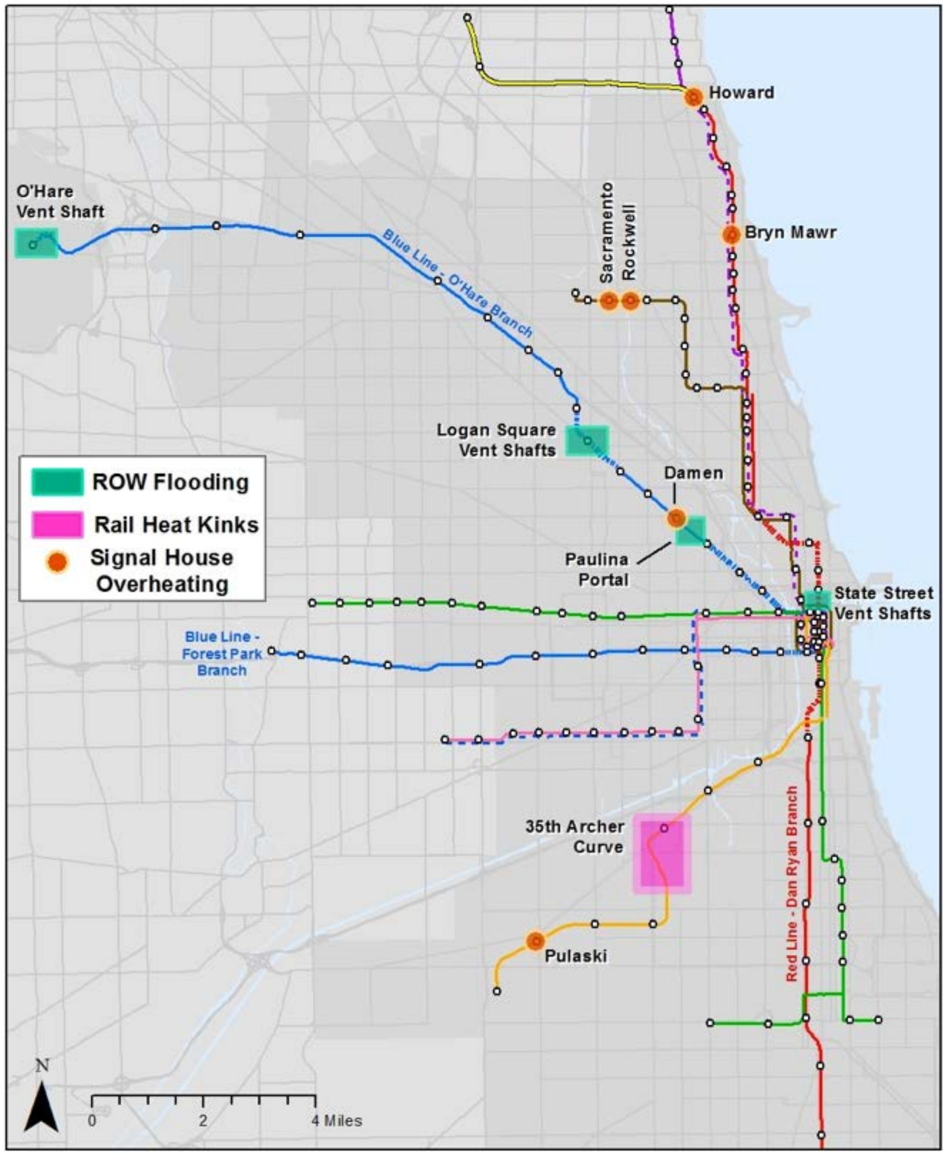
- Background information for each area of investigation
- Assumptions used in no-build scenarios
- Description of build scenarios
- Application and outcomes of LCCA model
- Potential next steps

[4] The terms "no-build scenario" and "build-scenario" are used for consistency with FTA Alternatives Analysis terminology (e.g., http://www.fta.dot.gov/12304_9717.html#251_The_No-Build_Alternative).

Geographic locations of Task 2 areas of investigation are shown in Figure 2-1.

Figure 2-1

Task 2 Areas of Investigation



Issue 1: ROW Flooding

For Issue 1, the analysis considers two flooding concerns against proposed solutions. Where applicable, these recommended solutions are compared to the costs of a no-build scenario.

Background

Flooding is of primary concern in below-grade track areas. The CTA Red and Blue lines include stretches of subway and offer high-frequency 24-hour service; thus, the following issues have a high potential for service disruption to a large number of passengers.

- Water intrusion into ventilation shafts (assuming representative ventilation shafts from both the Blue and Red lines as examples)
- Water intrusion into subway portals (using Blue Line Paulina portal as an example)

No-Build Scenario

The no-build scenario assumes an escalation in flooding incidents in frequency and severity. Data from the CCAP, the Metropolitan Water Reclamation District (MWRD), and other sources from Task 1 were used to support the evaluation. The flood map in Figure B-1 shows several CTA rail lines crossing the 100-year floodplain, including the Blue Line-O'Hare Branch and the Blue Line-Forest Park Branch. For purposes of this analysis, the potential climate impact of flooding in two situations is described here:

- Flooding events of a severity that downtown areas will become inundated, causing water to infiltrate the ventilation shafts into the subway system. This situation has the potential to overwhelm the pump system, causing service disruptions and significant damage to signal, electrical, and other communications components.
- Flooding events of increased frequency that will cause more occurrences of infiltration into the subway portals due to constraints of municipal drainage systems. This situation has the potential to cause more frequent slow zones or service disruptions.

Build Scenarios

One build scenario is presented for each of the flooding situations described above:

- Install barrier devices around ventilation shafts to prevent water infiltration. Ventilation shaft locations are selected to varying conditions across the CTA subway system.
- Install a system of drainage structures to capture and detain stormwater at a portal entrance. Structures would be tied to an underground storage cistern to allow for water to be stored and released to municipal drainage systems as capacity becomes available.

Issue 2: Increased Rail Kinks

For Issue 2, the analysis considers a single location and proposes multiple solutions.

Background

The subject location is the section of northbound Orange Line track, called the 35th Archer Curve, between 43rd Interlocking and 35th/Archer Station. It is at the top of a moderate ascending grade for northbound trains in the middle of a gentle right-hand curve with a speed limit of 35 mph. Track structure in the area is typical 115-pound continuously-welded running rail supported by treated wooden crossties. At the top of the grade and in the middle of the curve, the running rail has periodically shifted outward of the curve, occasionally requiring a slow zone. Experience over 20 years of operation has resulted in the CTA Track Department regularly modifying the track structure in the area.

No-Build Scenario:

Increased temperatures and intensified UHI effects will increase the potential for rail heat kinks, which can lead both to slow zones and total service disruption. CCAP and UHI data were used in the evaluation.

Build Scenario:

Two build scenarios are proposed:

- Upgrade track support structure with tighter tie spacing, granite ballast, sub-ballast, drainage improvements, and potentially different anchoring system.
- Replace overpass with concrete direct fixation track.

Issue 3: Signal House Overheating

For Issue 3, the analysis considers two overheating issues and proposes two recommended solutions.

Background

Signal houses are maintained at temperatures necessary for the effective functioning of electrical communications components through the use of air conditioning (A/C) units powered by feeds from the ComEd grid. Signal equipment can be damaged when A/C units fail, and while the CTA rail system has a redundant power supply, there are no current backup systems for power failures to signal house A/C units.

Failure of vulnerable electrical equipment becomes more frequent during periods of prolonged heat, which is projected to become more frequent; thus, the occurrence of service delivery impacts is likely to increase over time. Additionally, more prolonged heat events will cause increased strain on the ComEd system, resulting in more frequent system brownouts.

No-Build Scenarios

This assumes an increase in the duration of cooling season and intensity of heat during the summer months. CCAP and UHI data were used in this analysis, and additional brownout data will be sought to establish the baseline.

- Increased number of 90°F+ days will place a higher strain on malfunctioning A/C units. The frequency of service delivery impacts from overheated signal components will increase.
- Increased number of 90°F+ days will increase overall demand on the ComEd system. This may result in overall system brownouts that will affect the ability of A/C units to cool the signal substations, thus increasing slow orders and maintenance costs.

Build Scenarios

Two distinct build scenarios were explored to reduce the potential for A/C unit failure and rail signal disruptions:

- Scenario 1: Install backup A/C system to maintain temperatures in case of failure of primary unit.
- Scenario 2: Install dual A/C system and connect to source of backup power (e.g., traction power, generator unit)

No-Build Scenario Assumptions

Introduction

To establish a baseline for the build alternatives, a no-build scenario was developed for each of the issues described above. These costs are based on input from CTA and projected against the number of future occurrences of the issue related to severe weather if no capital investment is made. Climate forecasts are based upon research developed and presented in Task 1, Table 1-1.

Climate Forecasts

Table 1-1 lists the estimated forecast changes in different climate conditions for the Chicago area, based on data downscaled from global climate models. These data reveal that there is either a significant range in the projected number of future incidents, or a discrepancy between baseline projections and recent observed data. Therefore, all Task 2 model runs include a baseline frequency and three multiplier frequencies to evaluate the sensitivity of outputs to severe weather event frequencies.

Issue 1: ROW Flooding

The CCAP data shows that flooding events in the Chicago area are generally associated with 2.5 inches or more of rainfall in a 24-hour period. The closest indicator to this in the CCAP climate forecasts is precipitation events of greater than 2 inches in 24 hours. The number of these storms is predicted to increase by less than one event a year in the higher-emissions estimate and to remain relatively constant in the lower-emissions scenario. CCAP data do not suggest an increase in more intense storms (i.e., more than 4 inches in a 24-hour period).

However, these projections do not sufficiently capture three situations that cause the concern with any increased flooding caused by higher storm intensities.

- Multi-day storm events (e.g., 9 inches of rain in 10 days in September 2008) are expected to increase over time and are not captured in Table 1-1. Storms that last several days stress municipal stormwater systems, which are generally designed for 24-hour rain events.
- Existing municipal sewers into which most CTA track drainage connects were designed 30 to 70 years ago. Hydraulic modeling associated with these sewers and the drainage capacity required has advanced from the original design timeframe, reducing an already limited capacity for major storm events. Increased impermeable surface area has also increased strain on legacy stormwater systems.
- The current design guideline of five-year storm events[5] for most municipal and state storm sewer systems reduces construction costs while hedging on infrequent flooding, acknowledging that in most situations there are travel alternatives to flooded roadways.

Therefore, most older systems (and even some more modern systems) on which CTA relies to convey stormwater are not designed to handle heavy storm events. Since CTA trains cannot generally be diverted to other routes, excess stormwater has the potential to harm vital signal equipment, traction power elements, and track beds.

Issue 2: Rail Heat Kinks

CCAP climate projections provide three possible options for associating heat kinks with high temperatures: 90˚F+ days, 100˚F+ days, and occurrences of three consecutive 90˚F+ days. In all three cases, high heat events are expected to increase above the historical norm in the near term (2010–2039), and in the long-term forecast (2070–2100), both low- and high-emissions estimates show high temperature events increasing dramatically from the current average.

In general, the UHI effect produces a general increase in temperatures by 2–6˚F for much of Chicago. This will contribute to increased stress on the system as a result of elevated temperatures. For purposes of the life-cycle cost analysis, the UHI effect is minimal as the analysis considers the frequency of change over the base situation, which incorporates UHI effects. UHI data are critical in identification of locations that are more prone to rail kinks and/or signal house failures and thus should be prioritized for capital improvements.

[5] A five-year storm does not mean it occurs every five years. Rather, it indicates a 1-in-5 chance that a storm of this magnitude will occur in any given year.

Issue 3: Signal House Overheating

Cooling degree days[6] are a possible indicator of the frequency by which signal house A/C failures are likely to occur. The historical period shows a typical year having 925 cooling degree days; this figure is expected to increase by 24 percent in the short-term, and by 38–138 percent the intermediate and long terms, depending on low- or high-emissions scenarios [16].

The increase in cooling degree days will place higher loads on existing equipment, increasing the need for routine maintenance and repairs. In addition, the higher loads may cause the equipment to fail more often, potentially causing damage to signal components located within the houses. It may also lead to more frequent ComEd failures, depending upon the ability of grid operators to adapt power infrastructure to climate change impacts. ComEd is in the process of modernizing its infrastructure to create a more reliable smart grid, as part of a 10-year, $2.6 billion investment plan to strengthen the Illinois electric system [23, 24].

Since the correlation of higher temperatures to failures is influenced by many factors (including age and maintenance of equipment), it is useful to consider a range of scenarios based on different event frequencies to account for effects of extreme heat on signal house A/C units.

Service Disruptions

Service disruptions can be categorized into four levels:

- *Slow zones (slow orders)* – restrictions on train speeds due to sub-optimal track conditions, which impact on-time performance. When slow orders are consistent, the schedule is adjusted for additional time, which increases vehicle requirements.[7]
- *Single tracks* – running on only one track in an area to avoid a system failure or to make repairs. Single tracks increase run time, causing on-time performance issues. Similar to slow zones, extending single tracking requires additional trains and running time.
- *Bus shuttles (bus bridges)* – when a section of rail is taken out of service, transit service is maintained using bus shuttles, which are costly to the agency as they require a significant number of buses, operators, and service management staff. In many cases, buses are pulled from regular revenue service, causing service disruptions throughout the system. In the event of a planned line cut (e.g., 2013 Red Line Dan Ryan track renewal), required service levels can be accommodated with less system impacts.

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[6] Cooling degree days represent days with a high temperature above a baseline of 65˚F. For example, one 10-day period of 75˚F temperatures would result in 100 cooling degree days.

[7] CTA added trains to the Orange Line in the summer of 2012 to account for the number of slow orders associated with heat.

- *Total suspension of service* – in a catastrophic event that either shuts down the power grid or floods the downtown area (e.g., Hurricane Sandy in New York/New Jersey region), there is the potential to cause a total suspension of transit service. This level of disruption is beyond the scope of elements analyzed in this project.

There are three principle no-build costs associated with the service disruptions described:[8]

- No-build service costs
  - Internal service costs – resources required to provide additional trains or bus shuttles to maintain passenger service in the face of slow zones, single tracks, and bus shuttles
  - Lost ridership revenue – ridership loss associated with passengers choosing alternative travel options during service disruptions[9]
  - Passenger time value – time forgone due to service disruptions, based on the annual average income for both business and personal purposes[10]
- No-build repair costs
  - Costs associated with replacing damaged infrastructure due to extreme weather events (e.g., electronics in flooded subways; kinked track structures; signal house A/C equipment)
- No-build maintenance costs
  - Ongoing costs are associated with cumulative problems, if build scenarios are not implemented; these are separate from non-routine repair costs due to extreme weather events.

No-Build Service Costs

Internal service costs were estimated using vehicle revenue hour (VRH) costs from the 2011 National Transit Database (NTD) and inflated 5 percent for the current year. VRH incorporates all costs for bus or rail operation (e.g., labor, energy, maintenance) excluding depreciation.

- $136.34 VRH for bus hour
- $144.11 VRH for train hour (average of all trains, regardless of train lengths)

For the individual scenarios tested, the costs were estimated as follows.

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[8] The calculations in this section are based on a set of described assumptions. In the LCCA model, any of these values can be modified as CTA develops the model and its application further.

[9] Lost ridership percentage was based on professional experience by CTA service planners.

[10] Using the Memorandum Table 5 (Revision 2) from the USDOT Guidance, it blends a rate for all purposes of between $8.90 and $14.90 per hour [25].

Portal Flooding – Blue Line

This scenario assumes a bus shuttle from Blue Line Damen to Blue Line Chicago while the portal is shut down due to flooding. The total cost is a weekday estimate for the shutdown based upon the estimated number of buses required to perform the bus shuttle.

Table 2-1 *Blue Line Damen – Blue Line Chicago Bus Shuttle Cost*

Time Period (at Chicago)	Rail Trips	Cars per Train	Riders per Train	Buses per Rail Trip	Bus Trips	Bus Run Time (Min)	Bus VRH	Cost per VRH	Weekday Cost
00:01-05:00	18	4	50	1	18	45	13.5	$136.34	$1,841
05:00-06:30	15	8	150	2	30	50	25	$136.34	$3,409
06:30-09:00	31	8	300	4	124	55	113.7	$136.34	$15,498
09:00-14:00	34	8	150	2	68	50	56.67	$136.34	$7,726
14:00-16:00	14	8	200	3	42	60	42	$136.34	$5,726
16:00-18:00	25	8	300	4	100	60	100	$136.34	$13,634
18:00-20:00	18	8	150	3	54	55	49.5	$136.34	$6,749
20:00-24:00	23	4	150	2	46	45	34.5	$136.34	$4,704
Total							**434.8**	**$136.34**	**$59,286**

Data on rail trips and cars per train is provided by CTA Transit Operations. The remaining information is estimated by professional transit planners based on typical average passenger loads and bus travel times. The portal flooding scenarios did not assume any slow zones or single tracks, as the line would be completely out of service when flooded.

Rail Kink – Orange Line

This scenario assumed a bus shuttle from Orange Line Western to Orange Line 35th/Archer for when the line was shut down due to rail kinks. The total weekday cost for the shutdown based upon the estimated number of buses to perform the bus shuttle while the rail kink is repaired.

Table 2-2 *Orange Line Western – 35th/Archer Bus Shuttle Cost*

Time Period (at 35th/Archer)	Rail Trips	Cars per Train	Riders per Train	Buses per Rail Trip	Bus Trips	Bus Run Time (Min)	Bus VRH	Cost per VRH	Weekday Cost
04:10-05:35	7	4	120	2	14	25	5.833	$136.34	$795
05:35-06:30	7	8	200	3	21	25	8.75	$136.34	$1,193
06:30-07:10	8	8	300	4	32	35	18.67	$136.34	$2,545
07:10-08:50	15	8	250	4	60	30	30	$136.34	$4,090
08:50-15:20	47	8	200	3	141	25	58.75	$136.34	$8,010
16:00-17:35	14	8	300	4	56	35	32.67	$136.34	$4,454
17:35-19:45	15	8	250	4	60	30	30	$136.34	$4,090
19:45-22:00	13	4	200	3	39	25	16.25	$136.34	$2,216
22:00-01:45	17	4	70	1	17	25	7.083	$136.34	$966
Total							**208**	**$136.34**	**$28,359**

Data references are the same as for Table 2-1. In addition, there will be costs associated with slow zones until the kink can be repaired. This was estimated in additional running time by adding a single train at all times and two trains during the peak hour in both AM and PM rush periods. This frequency was based upon communication with CTA Operations for previous Orange Line slow zones at 35th/Archer, and may vary depending upon the specific location.

Signal House Overheating

When a signal house overheats, it typically causes a slow zone to be implemented as the equipment goes into a fail-safe mode. This fail-safe mode allows for train operations but slows all trains to visual line of sight speed, or approximately 15 mph, through the area where signals are not operating properly. The effects of the slow order are sensitive to the duration and service frequency.

The cost per overheating incident varies depending upon the location of the slow zone within the system and the duration of the event. As the cost-benefit analysis for Task 2 generalized from a typical signal improvement, the Orange Line slow zone cost estimate (Table 2-3) is used. This estimate represents a longer slow zone on a less frequent line, or a shorter slow zone in on a more frequent line (or in the downtown Loop, where multiple lines intersect).

Table 2-3

Orange Line Slow Zone Cost

Time Period	Train VRH	Cost per VRH	Weekday Cost
All times (one add'l train)	21	$144.11	$3,026
Peak periods (two add'l trains)	2	$144.11	$288
Total	23	$144.11	$3,315

Reduced CTA Ridership Revenue

The regression analysis established in Phase 1 did not show a strong correlation between ridership loss and extreme weather at a system-wide level; therefore, weather-related revenue loss is not currently included in this phase of the analysis. This analysis does, however, consider ridership loss associated with passengers choosing alternative travel options during bus shuttle events.

An assumption of 40 percent ridership loss was based on professional service planning experience. The CTA's average fare of $1.00 is based on reductions from a full fare for senior citizen discount, transfers, and monthly passes, as published in CTA's 2012 budget recommendations [20].

Portal Flooding – Blue Line

This assumed a bus shuttle from Blue Line Damen to Blue Line Chicago for when the portal was shut down due to flooding. Reduced revenue is based upon the reduction in round trip service during an average weekday.

Table 2-4

Blue Line Damen – Blue Line Chicago Bus Shuttle Reduced Revenue

Description	Cost
Weekday riders boarding at stations north of Damen	$61,231
Portion traveling to stations south of Damen (est.60%)	$36,739
Portion of these that would stop riding CTA (est. 40%)	$14,695
Assumed average fare (one-way)	$1.00
Weekday lost revenue per Blue Line bus shuttle (round trip)	$29,391

Ridership numbers are from CTA system data for rail station boardings. The number of passengers estimated to be heading south of Damen is based upon knowledge of the CTA system and load variances. These numbers can be adjusted with future scenarios with alternate counts applied to passenger distribution.

Rail Kink – Orange Line

This scenario assumes a bus shuttle from Orange Line Western to Orange Line 35th/Archer when the line is shut down due to rail kinks. Reduced revenue is based upon the reduction in round trip service during an average weekday.

Table 2-5

Orange Line Western – 35th/ Archer Bus Shuttle Reduced Revenue

Description	Cost
Weekday riders boarding at stations west of Western	$11,978
Portion travelling to station north of 35th (est. 80%)	$9,582
Portion of these that would stop riding CTA (est. 40%)	$3,833
Assumed average fare (one-way)	$1.00
Weekday lost revenue per Orange Line bus shuttle (round trip)	$7,666

Ridership numbers are estimated with the same methodology as for the Blue Line, as described in the previous section.

Signal House Overheating

No bus shuttles were assumed for any signal overheating issues. Therefore, no reduced CTA revenue is assumed.

Passenger Value-of-Time

The value of passenger travel time is an important factor when completing life-cycle cost analyses. Reduction in travel time adds personal value when translated to more available time for work or pleasure. USDOT publishes guidance on the values to be assigned for transportation-related analyses [25].

Time is considered based on the annual average income for both business and personal purposes. In general, personal purposes are weighted to approximately half of business purposes. For this analysis, the median value of $11.90 per hour was used [25].

Portal Flooding – Blue Line

This scenario assumes a bus shuttle from Blue Line Damen to Blue Line Chicago when the portal is shut down due to flooding. Passenger value-of-time is estimated for those riders who would remain on the system and use the bus shuttle, with lost time calculated as the difference in the time on a normal running train to using the bus shuttle.

Table 2-6

Blue Line Damen – Blue Line Chicago Bus Shuttle Passenger Value-of-time

Description	Cost
Weekday riders boarding at stations north of Damen	$61,231
Weekday riders travelling to stations south of Damen (est. 60%)	36,739
Portion of these riders seeking other travel options (est. 40%)	14,695
Riders remaining on system	22,043
Riders lost time (hrs) per incident, assuming 20 mins/direction	7,274
Passenger value-of-time (per hr)	1.90
Weekday value of lost rider time, per bus shuttle (round trip)	$173,127

Rail Kink – Orange Line

This scenario assumes a bus shuttle from Orange Line Western to Orange Line 35th/Archer, when the line is shut down due to rail kinks. Passenger value-of-time is estimated for those riders who would remain on the system and use the bus shuttle, with lost time calculated as the difference in the time on a normal running train to using the bus shuttle.

Table 2-7

Orange Line Western – 35th/ Archer Bus Shuttle Passenger Value-of-Time

Description	Cost
Weekday riders boarding at stations west of Western	$11,978
Weekday riders traveling to stations north of 35th/Archer (est. 80%)	9,582
Portion of these riders seeking other travel options (est. 40%)	3,833
Riders remaining on system	5,749
Riders lost time (hrs) per incident (time difference between bus and train run)	1,897
Passenger value-of-time (per hr)	$11.90
Weekday value of lost rider time, per bus shuttle (round trip)	$45,156

Signal House Overheating

Passenger value-of-time for signal house overheating relates to the extra time a passenger would spend on the train due to a slow zone being implemented. This number will vary greatly based upon the location within the system. For illustrative purposes, the estimate is based upon an outage affecting the Chicago station on the O'Hare branch of the Blue Line. This is a high ridership segment of the system and reflects an area of greatest impact.

Two timeframes were included to match the life cycle cost scenarios. The first considered an outage for six hours, which was assigned from 12:00 noon to 6:00 PM. The second considered a full day (24 hours) outage.[11] An estimated length of delay of one mile of track was used, equating to the distance between from the two adjacent stations minus the station acceleration/deceleration zones. Operating speeds were assumed to be reduced from 35 to 15 mph. This equated to an approximate two-minute delay per passenger.

Table 2-8

Blue Line Slow Zone Passenger Value-of-Time (Six Hours)

Description	Cost
Weekday riders through Chicago/Blue: 12:00–6:00 PM	$28,250
Rider lost time in hrs (2 min per rider)	942
Value per hr	11.90
Weekday value of lost rider time	$11,206

Table 2-9

Blue Line Slow Zone Passenger Value-of-Time (24 Hours)

Description	Cost
Weekday riders through Chicago/Blue: all day	$73,563
Rider lost time in hrs (2 min per rider)	$2,452
Value per hr	$11.90
Weekday value of lost rider time	$29,180

No-Build Maintenance Costs

No-build maintenance costs include the ongoing expense associated with issues that accumulate over time if proposed build scenarios are not implemented. These are separate costs from the non-routine repairs caused by the climate event. Additional maintenance items include more frequent surfacing of rail rights-of-way to help prevent and address rail heat kinks.

Increased Surfacing Frequency

Rail kinks are due to high stresses being placed on the rail system with thermal forces[12] and indicate areas where the track needs more attention to maintain alignment and section. Surfacing the track involves using rail maintenance equipment to bring the track back into alignment and to resist the forces placed upon the track structure by temperature variances and operating equipment. Regular surfacing is a routine preventative maintenance activity that is performed on all tracks to ensure proper functioning.

[11] Ridership data thru the station is from 2011 CTA system leaving load data as received from CTA for a CDOT study.

[12] Similar to all metallic structures, a piece of rail will expand with increased temperatures. If the rail is not properly fastened to ties that are securely bedded in stone to prevent the movement, the track will move, causing rail kinks or other alignment issues. Surfacing adds stone and reinserts the ties back into the stone at the proper alignment.

For the purpose of this analysis, it is assumed that CTA's current fleet of track maintenance machinery and qualified manpower is sufficient to perform required surfacing tasks, without having an adverse effect on other portions of the railroad. If additional manpower or equipment is required, added labor, capital and operating maintenance budget must also be assumed.

Based on experience with similar situations of track structure instability, it is assumed that the CTA would be required to surface the track back into alignment and section two additional times annually. If the build scenario was implemented, these additional costs would be avoided.

Table 2-10

Cost per Surfacing Activity, Orange Line at 35th/Archer

Description	Unit	Quantity	Unit Cost	Total Cost
Surfacing event	tf	12770	$5.36	$68,447
Total				$68,500

Thus, the estimated two additional events per year will incur a total annual cost of $137,000.

No-Build Repair Costs

No-build repair costs are those associated with replacing the damaged infrastructure caused by an extreme weather event. Example repairs include the following:

- ROW Flooding: Repairs to signals, traction power, and electronic components
- Rail Heat Kinks: Repairs to damaged track structure
- Signal House Overheating: Repairs to A/C units

ROW Flooding

When subway tunnels flood, existing equipment typically is not damaged; however, labor is required to dry out systems, check vital circuits, and restore service. For instance, when the Blue Line O'Hare portal flooded in 2008, a cost of roughly $70,000 was incurred to make repairs and restore the system. It is estimated that the Blue Line Paulina portal would require comparable labor costs to restore the line to service after portal flooding.

Rail Heat Kinks

When a rail kink occurs, repairs typically involve cutting out a section of rail, installing a new section, re-securing ties, replacing disturbed ballast, and surfacing/tamping the affected area. It is assumed that a minimum 39-ft section of track (the typical length of a preassembled wreck panel) would be removed and reinstalled; cost assumptions are shown in Table 2-11.

Table 2-11

Cost per Rail Kink Repair Orange Line at 35th/Archer

Description	Unit	Quantity	Unit Cost	Total Cost
Track removal & disposal	tf	39	$106.28	$4,144.92
Ballast removal	cy	5	$5.21	$26.05
New ballast	cy	8.6	$54.74	$470.76
New track	tf	39	$162.96	$6,355.44
New ties	ea	20	$136.00	$2,720.00
Initial tamping	tf	100	$7.36	$736.00
Final tamping	tf	100	$5.36	$536.00
Total				$15,000

Signal House Overheating

A/C unit repairs were estimated at $300/incident for labor only, assuming an average repair time of three hours (e.g., defrost unit/add refrigerant; replace failed compressor) at a cost of $100/hour per work crew (noting that repairs on the CTA rail ROW require two technicians).

Build Scenarios

ROW Flooding

The 2012 flooding of the New York/New Jersey area by Hurricane Sandy illustrates the catastrophic effects on transit systems that can be caused by major storm events. Rail transit is dependent upon the right-of-way (ROW) staying dry to maintain service, especially subway or below-grade areas. Unlike bus service or autos, trains cannot be easily diverted to higher ground. The result of ROW flooding is maintaining service temporarily with bus shuttles until the ROW can be dewatered and repairs to signal and traction power components completed.

The Chicago area is not immune to large storm events. In September 2008, the remnants of Hurricane Ike dropped 6.45 inches of rain in a single day, causing massive flooding in the region and closing the O'Hare tunnel on the Blue Line. In July 2011, 6.86 inches of rain fell as part of another storm event, flooding the Dan Ryan Expressway and closing the CTA Red Line. The Blue Line and Pink Line also experienced flooding, causing extensive delays.

Flooding has occurred in the CTA system in the subway tunnels, highway median rights-of-way, or low underpasses.[13]

[13] Flooding has also occurred in rail yards; however, these areas have been fixed with smaller capital construction programs. Stations do not tend to have major flooding problems. Substations may be prone to flooding in the basements, but this has not proven a significant problem in the past.

- The CTA has five major subway tunnels on the Red and Blue Lines. These tunnels are subject to flooding by water entering from portal entrances or ventilation shafts. The downtown tunnels along State Street and Dearborn Street have large pumps that have been designed for reliability and robustness to accommodate most situations except total power failure. Other tunnels (e.g., Milwaukee Blue Line tunnel) have pumps at the portal entrances to convey any water that enters the tunnels back to the surfaces.
- The Dan Ryan Red Line branch and Forest Park Blue Line branches run in the median of Illinois Department of Transportation (IDOT) freeways. The drainage system for the track bed ties into the IDOT system. In some cases, the CTA drainage has been disconnected in conjunction with freeway improvements. The 2013 Red Line Dan Ryan track improvement construction restores drainage connections to the IDOT system.
- There are some circumstances where one rail line goes under another rail line, such as the Pink Line at the Kilbourn railroad bridge. Depending on the quality of the adjacent municipal drainage systems, these areas can be prone to flooding.

This study focuses on subway tunnel flooding for several reasons. First, these scenarios have the greatest impact to the overall operations when they occur, as they impact the Red and Blue Lines with the highest system ridership and 24-hour service. Second, the median rights-of-way can only be corrected with complete line reconstruction and are very dependent upon the capacity of the IDOT drainage system. Finally, as a generally elevated network, the CTA rail system has very few low underpasses like the Pink Line at the Kilbourn railroad bridge.

Ventilation Shaft Flooding

Subway systems incorporate ventilation systems to both provide intakes for fresh air and exhausts for the compressed air at the front of the trains for pressure relief. These shafts are large cast concrete tunnels that lead up to the surface, which are typically covered with a grating system that is flush with the surface context.

The Dearborn, State, and Milwaukee subway tunnels have no recent evidence of ventilation shaft flooding from major storms. There may be some localized water intrusion beyond the amount that enters from the downfall; however, these volumes lie within the capacity of existing pumping systems. The outlier is the O'Hare tunnel, which has been recently improved to eliminate water problems caused by the neighboring expressway ramps, as discussed below.

Three representative locations were selected to evaluate how to prevent future inundation of water through subway ventilation shafts, as illustrated in Figure 2-2:

- O'Hare Subway (OE-1) – ventilation shaft within freeway median area
- Logan Square Subway (K-4) – two separate ventilation shafts, respectively in median area of Kedzie Avenue and pocket park south of Milwaukee Avenue
- State Street Subway (S-9B) – multiple ventilation shafts integrated into sidewalks on either side of State Street north of Hubbard Street

Figure 2-2 *Examples of Ventilation Shafts: O'Hare Highway Median (top left), Logan Square Pocket Park (top right), Logan Square Street Median (bottom left), State Street Sidewalk (bottom right).*

Completed and Proposed Improvements

The O'Hare Subway Shaft illustrates a straightforward improvement to a ventilation shaft that is located in a roadway median, and thus separated from foot traffic. CTA installed an overflow barrier around the shaft to prevent future flooding after recent tunnel inundation. The barrier was completed in 2011 at a cost of approximately $1,000, providing an example of a basic, low-cost solution that could be incorporated in similar contexts across the CTA system.

The two Logan Square ventilation shafts have different considerations. The shaft contained within the pocket park would need to integrate with the park setting;

however, pedestrian access over the ventilation shaft is not a requirement. The shaft in the roadway median would need to consider design requirements for placement of permanent structure with regard to sight obstructions, distance from auto travel lanes, and potential loading impacts.

Figure 2-3 depicts the design improvements that could be made involving the extension of the two existing Logan Square ventilation shafts; a similar treatment could be applied to other applicable ventilation shafts throughout the CTA system that are subject to flooding impacts.

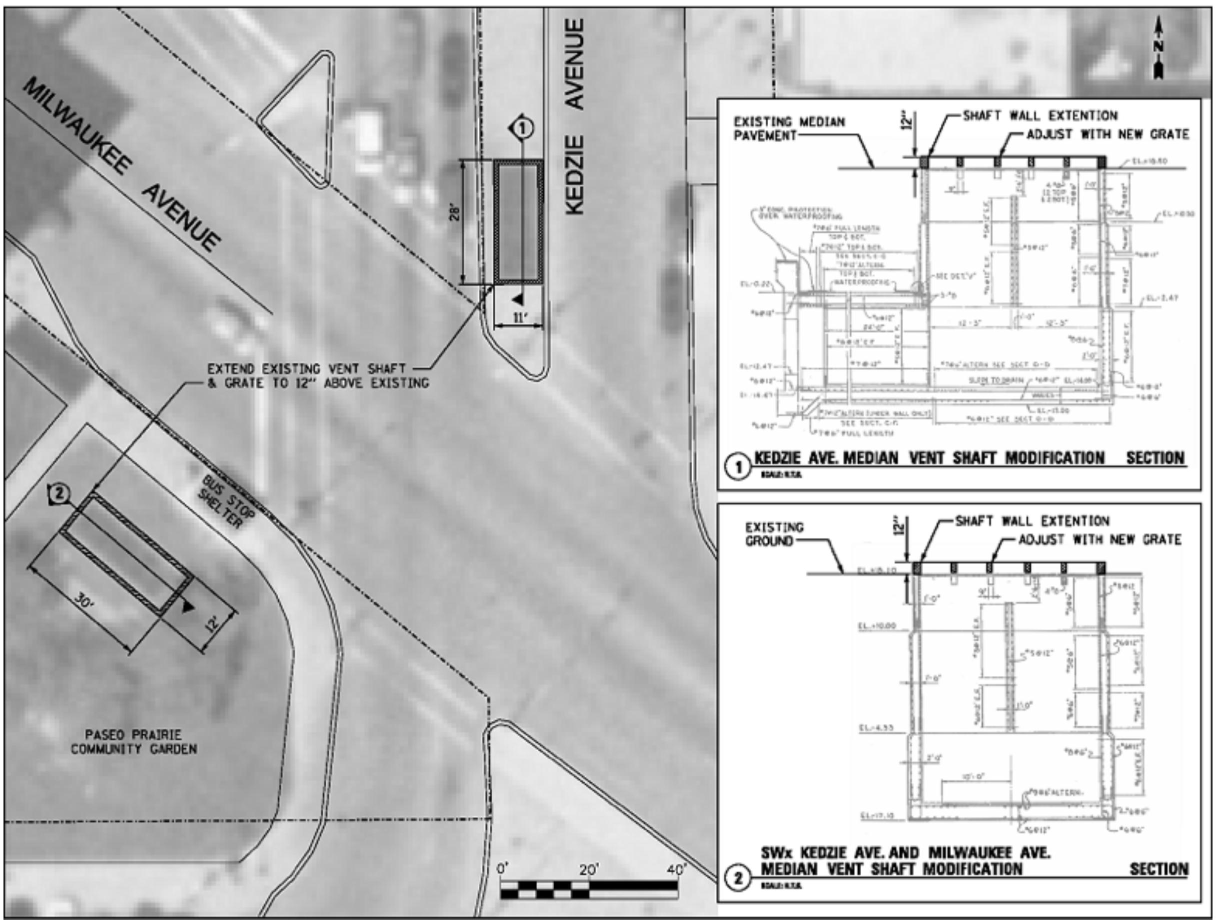

Figure 2-3 *Logan Square Ventilation Shaft Construction Diagram*

State Street ventilation shafts are located within a narrow 8ft sidewalk. The solution in this situation involves relocating the ventilation area into the parking lane and elevating the perimeter to maintain ADA sidewalk clearance. This context is common to most shafts downtown and along Milwaukee Avenue. Potential solutions should be coordinated with future CDOT street improvements. Figure 2-4 provides a suggested design improvement to the ventilation shaft at State Street that could be applied to similar designs throughout the CTA system.

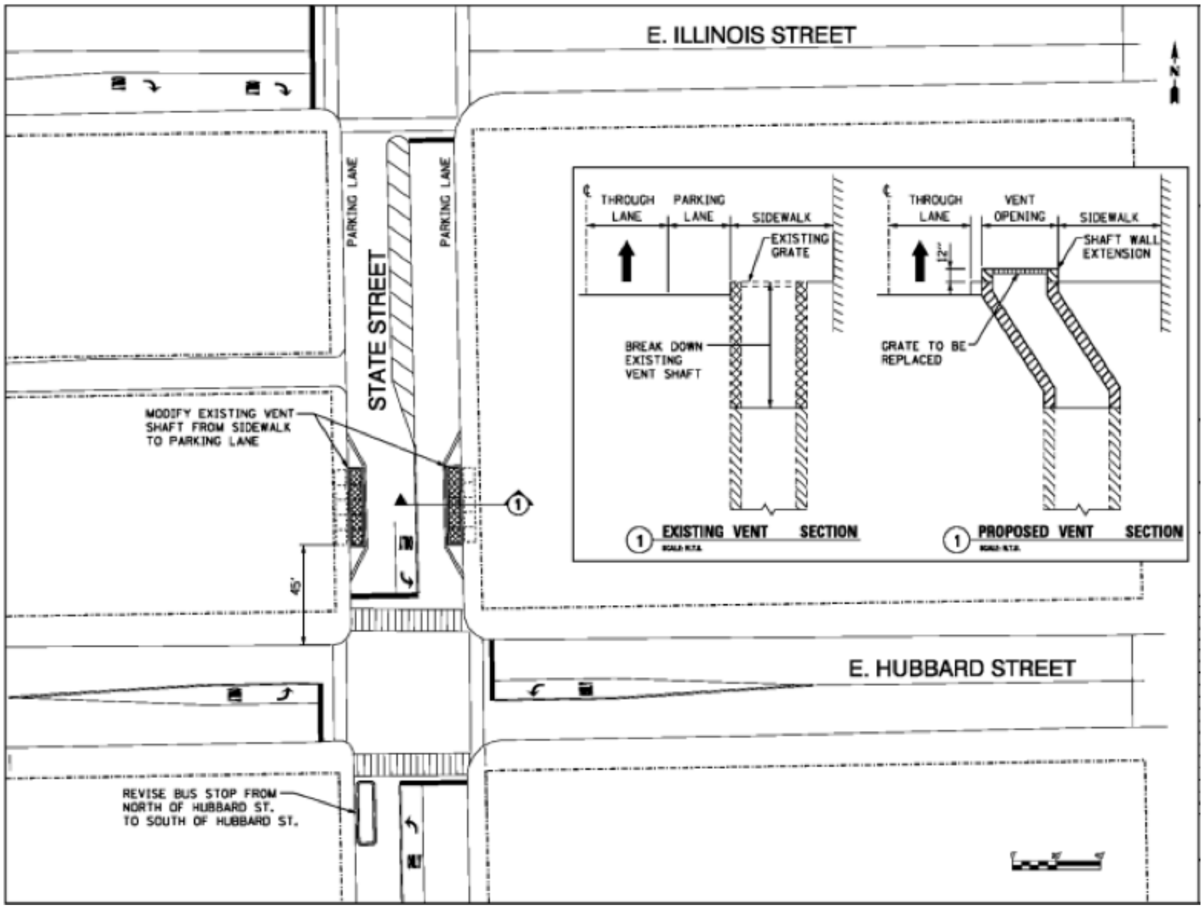

Figure 2-4 *State Street Ventilation Shaft Construction Diagram*

Estimated Capital Costs

Capital costs were not developed for the O'Hare shaft as the improvement has been completed. For Logan Square, the estimated cost is shown in Table 2-12. This is for two grates in one location. A single grate would be approximately half the cost listed below.

Table 2-12

Estimated Cost for Logan Square Ventilation Shaft Modification

Description	Unit	Quantity	Unit Cost	Total Cost
Mobilization	L sum	1	$3,000.00	$3,000.00
Traffic control protection	L sum	1	$2,900.00	$2,900.00
Temporary security fencing	foot	350	$20.00	$7,000.00
Break down existing vent shaft	foot	168	$10.00	$1,680.00
Raise vent shaft (reinforced concrete)	cu yd	6	$1,000.00	$6,000.00
Vent grate	each	2	$6,000.00	$12,000.00
Median/sidewalk restoration	sq ft	640	$6.00	$3,840.00
Topsoil furnish and place (4 in.)	sq yd	336	$5.00	$1,680.00
Sodding and salt tolerant	sq yd	336	$10.00	$3,360.00
Subtotal				$41,460
Design, permitting, construction management (20% Capital Costs)				$8,290
Contingency (25%)				$12,438
Total				$62,190

For State Street shafts, the costs included the associated roadway improvements to move the ventilation shaft into the parking lane to maintain adequate sidewalk space. Once again, two grate modifications are proposed in a single location. A representative cost for a typical two-grate installation in a downtown constrained sidewalk location where roadway improvements are required would be $188,520; this estimate would vary based on the size and degree of roadway improvements.

Table 2-13

Estimated Cost for State Street Ventilation Shaft Modification

Description	Unit	Quantity	Unit Cost	Total Cost
Mobilization	L sum	1	$3,000	$3,000
Traffic control protection	L sum	1	$10,800	$10,800
Temporary security fencing	foot	240	$20	$4,800
Break down existing vent shaft	foot	156	$100	$15,600
Raise vent shaft (reinforced concrete)	cu yd	58	$1,000	$58,000
Vent grate	ea	2	$4,500	$9,000
Curb and gutter removal	foot	126	$7	$882
Combination concrete curb and gutter	foot	126	$25	$3,150
Pavement removal	sq yd	96	$25	$2,400
Excavation for modified shaft location	cu yd	130	$25	$3,250
Sidewalk removal	sq ft	400	$2	$800
Sidewalk (5-in.)	sq ft	800	$10	$8,000
Inlets	ea	2	$1,500	$3,000
Storm sewer	foot	60	$50	$3,000
Subtotal				$125,682
Design, permitting, construction management (20% Capital Costs)				$25,140
Contingency (25%)				$37,700
Total				$188,520

Summary

Overall, flooding through ventilation shafts is not problematic except in a few select areas. The O'Hare Tunnel shaft was one of the most vulnerable shafts until CTA installed perimeter barriers. In the downtown area, where improvements are most difficult and costly to implement, little flooding has historically occurred through ventilation shafts, and the long-range probability of a major flooding event that would affect shafts is minimal (in such an event, the main concern would be station entrances, rather than ventilation shafts).

Since the impact of downtown flooding would be a total shutdown of the system, it is not feasible to accurately determine no-build costs; furthermore, it would be inaccurate to assume that improving ventilation shafts alone would suffice to address subway flooding. For these reasons, a life-cycle cost analysis for ventilation shaft flooding is determined not to be beneficial.

Subway Portal Flooding

Subway tunnel flooding typically occurs when surface water enters subway portal openings at a higher rate than existing drainage systems can capture or discharge. The three main locations for portal flooding include the following:

- Blue Line O'Hare Portal – stormwater from the O'Hare Tunnel is pumped up to a storm drainage line that is part of the Chicago Department of Aviation's (CDA) drainage system. Recently, back-ups into the CTA tunnel have increased in frequency due to indeterminate causes; resolution of this issue is being coordinated between CTA and CDA.
- Blue Line Forest Park Portal – stormwater enters the portal entrance from the Blue Line Forest Park branch. The area is in the median portion of the Eisenhower Expressway (I-290), and the primary causes of portal flooding are tied to general IDOT drainage issues. The Circle Interchange reconstruction project, launched in July 2013, is expected to significantly upgrade all systems at the junction of I-290 and I-90/94 and allow for better drainage connections adjacent to the portal.
- Blue Line Paulina Portal – stormwater enters the portal entrance to the Blue Line near Paulina Street, where the line transitions from the above-grade Milwaukee elevated section to the below-grade Dearborn subway section. Flooding issues are commonly due to constrained capacity of the municipal drainage system during major storm events, which may cause excess stormwater to flow into the tunnel where it is absorbed by CTA pumping system.

All of the above situations are related in that CTA is dependent upon other drainage systems (i.e., CDA, IDOT, City of Chicago). Since the O'Hare portal is currently under investigation, and the Congress Portal is to be incorporated into broader Circle Interchange work, the scenario selected for the evaluation in the context of this study is the Blue Line Paulina portal.

Build Scenarios

The recommendation to address the Paulina portal (and similar locations with external drainage constraints) is to provide the necessary capacity to detain stormwater until it can be released to outside systems. Capturing the water prior to entering the tunnel and causing potential damage is preferred. Where space is available, open detention ponds are the most economical solution; given that space is constrained in this area, underground detention in storage vaults would be required. To avoid disturbing retaining wall foundations under the track area, it is proposed that the vaults be placed under a street-level parkway adjacent to the portal that is currently used as a parking area (based on tax maps, this location falls within the CTA ROW).

A concrete foundation connecting the two retaining walls outside of the portal is only 14 inches below the tracks and limits the options for a catchment system. To minimize impacts to the existing structure, the system would include a series of trench drains to divert water into sump structures with pumps, and the pumps would push the water up to near street level and into the storage vault, where it would be released into the City system after detention. It is critical that the vaults be large enough to handle all storm events to avoid stormwater surging back onto the right-of-way.

Figure 2-5 shows recommended design improvements at the Paulina portal, which could also be applied to similar contexts in the CTA rail system.

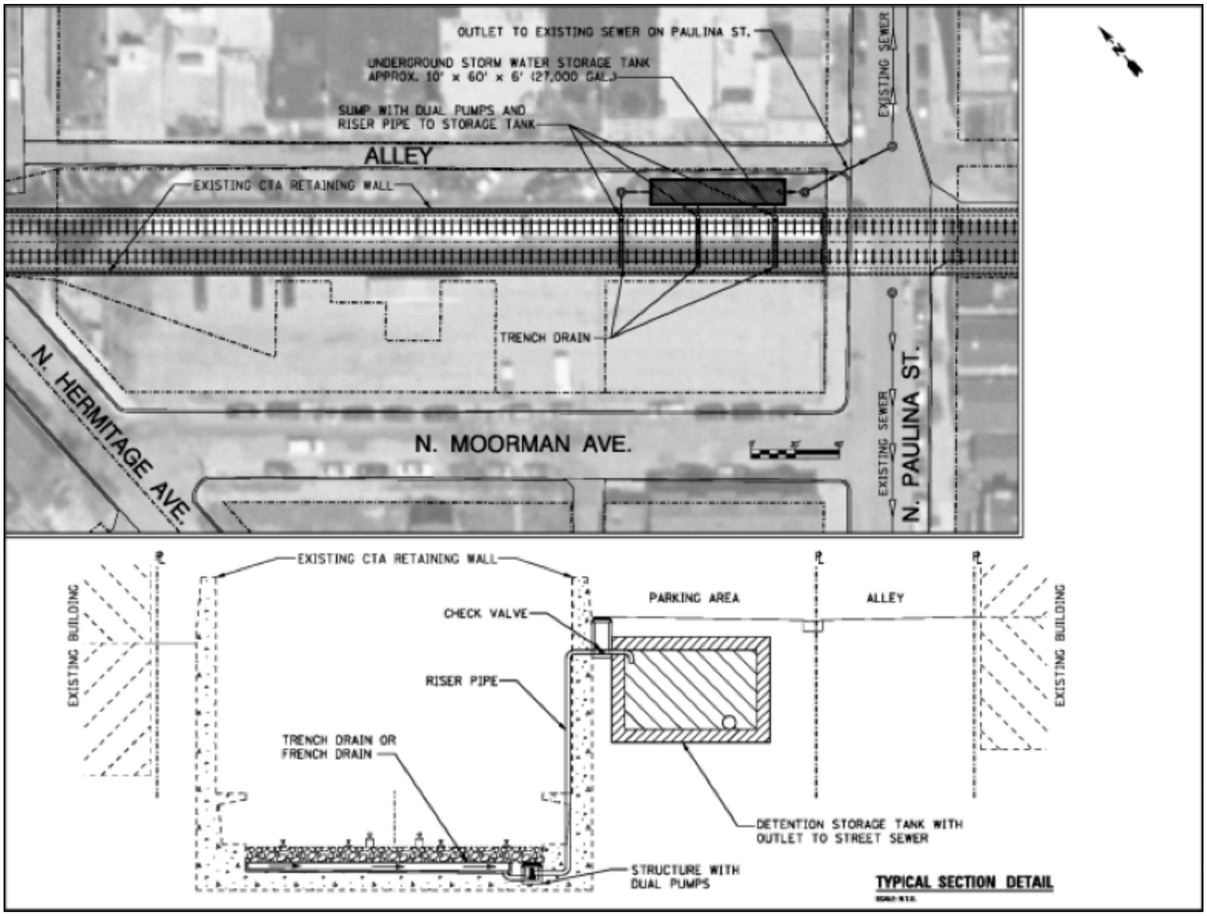

Figure 2-5 *Paulina Portal Proposed Improvements*

Estimated Capital Costs

Estimated capital costs for the Paulina portal implementation are calculated in Table 2-14.

Table 2-14

Estimated Costs for Paulina Portal Water Detention System

Description	Unit	Quantity	Unit Cost	Total Cost
Mobilization	L sum	1	$10,000	$10,000
Traffic control protection	L sum	1	$16,600	$16,600
Trench drain	ft	90	$300	$27,000
Sump structure with dual pumps & controller	ea	3	$20,000	$60,000
Service connection and power to pumps	ea	3	$2,000	$6,000
Riser pipe with heat tracing	ft	60	$85	$5,100
Sidewalk removal	sq ft	980	$2	$1,960
Sidewalk 5 inch	sq ft	980	$10	$9,800
Underground storage tank – 10'×60'×6'	each	1	$40,000	$40,000
Excavation for tank	cu yd	400	$25	$10,000
Storm sewer	ft	50	$50	$2,500
Manhole with restrictor plate	ea	1	$3,000	$3,000
Subtotal				$191,960
Design, permitting, construction management (20% Capital Costs)				$38,390
Contingency (25%)				$57,590
Total				$287,940

In addition to initial capital costs, ongoing costs for pump preventative maintenance are estimated at $2,880/year.

Summary

Estimated costs for reducing flooding risks at the Blue Line Paulina portal can be used a starting point for preliminary analysis, but this figure may be relatively lower than other CTA portal locations, since an area outside the track structure was identified for the storage vault. However, this cost may be representative of incorporating a stormwater retention system into a larger reconstruction project, such as the Circle Interchange project, as previously described. Proposed drainage improvements at additional CTA locations would require additional analysis of engineering requirements and projected implementation costs.

Rail Heat Kinks

One of the most serious problems faced by a transit agency is rail heat kinks, or the sudden deformation of the rail caused by excessive heat.[14] This problem occurs within areas of continuously welded rail (CWR), which is welded together into one long segment to eliminate joints to provide a smoother ride. Track rail

[14] A similar situation is observed with pull-aparts, where the rail separates at joint locations due to excessive contraction in cold weather.

is made primarily of steel, and like any metal material, it expands when heated and contracts when cooled. CTA's track system contains rail lengths more than a quarter mile long, which can expand and contract over 30 inches between temperature variations. Steel track is anchored in place using rail fasteners to ties at a neutral temperature based on historic average highs and lows; this system relies on the stability of the rail fasteners holding rails to the ties, and the ties biting into the ballast to hold the significant forces that develop when the rail expands or contracts. Therefore, proper installation and maintenance are critical in CWR sections of track, in the face of thermal stresses.[15]

Several areas of the CTA rail system have experienced heat kinks in recent years. Common locations have been on the Dan Ryan branch of the Red Line, the Foster station area on the Purple Line, and the 35th/Archer curve on the Orange Line, as described here:

- The 2013 Dan Ryan track reconstruction project is intended to replace the entire rail structure, including subgrade, drainage, signals, traction power, and track structure. This major intervention will correct ongoing issues with heat kinks (in particular, at 74th Street), which are primarily caused by the track structure reaching the end of its useful lifespan.
- The Foster station area of the Purple Line is a location where the track structure transitions from CWR to special trackwork for the interlocking. Transitions in the track structure, either from CWR to special trackwork, or from ballasted track to open structure/fixed rail tend to concentrate thermal stress at a specific location. These areas tend to be unique and require specific analysis to determine a proper solution.[16]
- The Orange Line curve at 35th/Archer is an area where the rail alignment transitions from CN Joliet Subdivision to the CSX Blue Island Subdivision. This results in a curve at grade to go over the CSX tracks. The rail tends to push out in the curve in the summer, causing slow zones to be put into effect during high temperatures. Since the track is still relatively new, the problem is more systemic rather than an issue of useful life.

For the purposes of the LCCA, this report focuses on the Orange Line as a representative project. This location has known operating impacts associated with slow orders because of rail movement in excessive heat. In addition, it provides a case study in which routine maintenance has not successfully alleviated the problem. The different scenarios developed to fix the Orange Line can be applied to other specific areas with additional analysis.

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[15] CTA uses CWR in ballasted sections. Elevated areas use jointed rail, and subways are direct fixation, where common practice is not to stress rail.

[16] The Purple Line, a CTA rail line that extends from downtown to Evanston, a community north of Chicago, is expected to be reconstructed with the proposed Red/Purple Modernization project. This will repair the issue at Foster, which is exacerbated by track components beyond their useful lifespan.

Summary of Current Conditions

Since being placed in service in 1993, the section of northbound Orange Line track between 43rd Interlocking and 35th/Archer station has presented CTA with track maintenance challenges. The subject location is at the top of an ascending grade for northbound trains in the middle of a gentle right-hand curve (with a speed limit of 35 mph). Track structure in the area is typical 115-pound continuously-welded running rail supported by standard creosote-treated wooden crossties. At the top of the grade and in the middle of the curve, the running rail has periodically shifted outward of the curve, occasionally requiring a slow zone. Experience over almost 20 years of operation has resulted in the CTA Track Department regularly modifying the track structure in the area. Solutions have ranged from inserting spacer ties extending from the concrete structure wall to the crossties, to removing short sections of running rail.

Areas where there is a change in track stiffness may show signs of rail running or bunching due to compressive stress accumulating in the rails. This can occur when there is a predominant direction of traffic or consistent braking applications in a location where there is stiffer portion of track structure. Trains enter the grade approaching this location at 55 mph and receive a cab signal speed reduction approaching the curve. This regular braking action by every train accumulated over time can result in the rail running toward the curve. A change in track stiffness may be caused by a change in the track structure, such as the transition from ballasted at-grade to ballasted deck, or between ballasted deck bridge sections.

It is not known how many rail anchors are installed in the vicinity. Given the track alignment and profile, it is possible that additional anchors or an alteration to the existing pattern of anchor installation approaching and within the subject area would help mitigate rail running.

Build Scenarios

Two possible build scenarios are considered here. The first scenario upgrades the existing ballasted track structure with improved materials and installation methods. The second scenario replaces the track structure with a direct fixation concrete track bed. Both offer trade-offs between initial capital costs and ongoing maintenance costs, as described in the following sections.

Upgrade Ballasted Track Structure

Improving durability of the track structure with better components and construction can offer benefits over simply increasing the frequency of surfacing. Potential strategies include higher-quality ballast, tighter tie spacing, different rail fasteners and additional rail anchors surrounding trouble spots (Figure 2-6).

Figure 2-6

Ballasted Track Structure Construction

For instance, granite ballast, as a harder aggregate than commonly-used limestone ballast, can help maintain the track profile through an improved tie interface. Installing more ties at trouble spots and within 1500 feet on either side of the recurring kink (approximately the length of the bridge) can have the effect of making the track structure less flexible and more resilient. Anchors provide the first line of defense to rail running that can lead to kinks or pull-aparts; CTA can also increase resilience by verifying the appropriate application of anchors on either side of the recurring kink, and checking the running rail/tie plate interface for wear patterns. Anchors added to both sides of more closely-spaced crossties would contribute to the cumulative effect of better ballast and more ties. Finally, using a different fastener system may add to the benefits of an improved traditional track structure.

All of these alternatives to upgrade ballast require at least as frequent surfacing as the CTA maintenance plan currently specifies. This is estimated to cost approximately $68,500 per year as an ongoing capital improvement cost. This is included in the life-cycle cost model, in contrast to the direct fixation scenario, which does not require annual surfacing.

Table 2-15

Estimated Cost for Upgraded Ballasted Track System

Description	Unit	Quantity	Unit cost	Total Cost
Track removal & disposal	tf	12770	$106.28	$1,357,196
Ballast removal	cy	19864.4	$5.21	$103,494
New ballast	cy	8513.3	$54.74	$466,018
New sub-ballast	cy	11351.1	$29.91	$339,511
New track	tf	12770	$162.96	$2,080,999
New ties	ea	7981.25	$136	$1,085,450
Drainage - elevated	lf	3056	$23.31	$71,235
Drainage - at grade	lf	3329	$30.21	$100,569
Initial tamping	tf	12770	$7.36	$93,987
Final tamping	tf	12770	$5.36	$68,447
Bus shuttles	ea	5	$28,359	$141,795
Slow zones/single tracks	ea	10	$3,315	$33,150
Passenger value-of-time	ea	5	$45,156	$225,780
Subtotal				$6,205,642
Design, permitting, construction management (20% Capital Costs)				$1,153,000
Contingency (25%)				$1,840,000
Total				$9,199,000

Replace with Direct Fixation Track Structure

Replacing the existing ballasted concrete deck at Archer overpass with direct fixation offers the most permanent solution and the best long-term reduction in annual maintenance costs. Doing so would eliminate the need for tamping, ballasting, changing worn ties and spacing the track structure, and would offer the benefit of consistent alignment and super-elevation. In turn, all of these benefits would add up to an improved ride quality for Orange Line riders. Conversely, it may introduce added track maintenance challenges at transition points between direct fixation and standard ballasted track-work. Compounding maintenance challenges could surface in the form of structural shift of the overpass members, which could introduce other kinks at or near connection points.

While constructing direct fixation structure is regarded as a standard solution, doing so while maintaining a level of revenue service may be challenging. If this option were pursued, CTA would have to determine how to stage the work to offer the least impact to revenue service while balancing the needs of the project with those of the customers. CTA has some recent experience in converting ballasted track structure to direct fixation in the Blue Line Dearborn Subway between Clinton station and the south portal. In this case, work was staged so that weekday peak period traffic operated normally, with all disruptive work consolidated on weekends.

One advantage to direct fixation is it eliminates ongoing maintenance costs except for standard annual inspections. These are not included as they are standard across all build scenarios (see calculations in Table 2-16).

Table 2-16

Estimated Costs for Direct Fixation Track System

Description	Unit	Quantity	Unit cost	Total Cost
Track removal & disposal	tf	12770	$106.28	$1,357,196
Ballast removal	cy	19864.4	$5.21	$103,494
New ballast	cy	4256.65	$54.74	$233,009
New sub-ballast	cy	5675.55	$29.91	$169,756
New track	tf	6658	$162.96	$1,084,988
New ties	ea	3329	$136	$452,744
Direct fixation	tf	6112	$430	$2,628,160
Drainage - direct fixation	lf	3056	$23.31	$71,235
Drainage - ballasted	lf	3329	$30.21	$100,569
Initial tamping	tf	6658	$7.36	$49,003
Final tamping	tf	6658	$5.36	$35,687
Bus shuttles	ea	19	$28,359	$538,821
Slow zones/single tracks	ea	20	$3,315	$66,300
Passenger value-of-time	ea	19	$45,156	$857,964
Subtotal				$7,824,945
Design, permitting, construction management (20% Capital Costs)				$1,257,000
Contingency (25%)				$2,271,000
Total				$11,353,000

Summary

Overall, initial capital costs for a new ballasted track structure and a direct fixation track structure are not dramatically different. The main consideration between the two is the operating impact for installation and ongoing maintenance. It was estimated that the ballasted track could be replaced during a long weekend outage; by contrast, for the direct fixation option, a 19-day outage is assumed, which would involve using high early strength concrete to restore service.

Signal House Overheating

Signal houses are inherently heat-sensitive, as they are essentially small metal boxes with heat-generating equipment inside. In many cases, only a single A/C unit is provided for cooling, which is powered by a house circuit connection to the ComEd network. This design has proven to have two weaknesses in context of climate model projections of more prolonged heat waves.

The first and primary weakness is that some existing A/C units are insufficient to counter the heat gain in the summer caused by high ambient air temperatures and heat release from the signal equipment. This situation is exacerbated by the waterless fire prevention system that is designed to flood the signal house with a chemical agent that will not damage electronic equipment. To work properly, the house must be sealed tight, not allowing for louvers or other traditional passive ventilation systems. Even if an A/C unit is properly sized, there is limited redundancy in the system.

The second weakness is that the system does not have a backup for ComEd power disruptions, which tend to occur during prolonged heat events. If appropriate switch gears were installed and portable generators purchased, or if A/C units were tied into signal power, CTA could power the A/C units independently during ComEd disruptions.

Summary of Current Conditions

In reviewing existing drawings and conducting field investigations, it was determined that most the signal houses have one of these possible power source configurations:

- One or two sources of electrical power for A/C units, with regular electric service backed up by a generator or third rail inverter
- Inverter input from DC rail system power, which transfers the energy source from a regular electrical feed to a stand-by generator or other alternative power source
- Automatic transfer switch (ATS), which automatically switches from one power feed to another to increase reliability when the mechanism senses a loss of power from a primary feed
- Generator tap box, which facilitates easy connection between generator and signal house; commonly used at critical facilities with smaller current loads (e.g., gate houses)

One general observation is that the A/C units do not trigger any notification system when they fail. When a signal house overheats following an A/C failure, the signal equipment will shut down and default to fail-safe mode, triggering alarms in the signal system at that point in time, although the A/C unit failure may have occurred hours, days or weeks earlier.

Some of the signal houses are equipped with an exhaust fan with a motorized damper at the intake opening that operates when the A/C has failed. This will vent some air, but may not effectively control the temperature.

Information on six signal house facilities was collected to evaluate both the effectiveness of their A/C units and their electrical configurations for backup power. Field visits to the sites were conducted to assess conditions:

Damen Station – Blue Line

This signal house was installed around 2008, thus making this a fairly current facility, with newer electronics that are somewhat heat sensitive (see Figure 2-7). This signal house structure consists of stainless steel sheets with insulation with an R-value of 21, sandwiched within the walls. This is a very good insulation factor for a building of this type. CTA has stated that the only time this type of signal house has heat issues is when the power fails and when the A/C unit fails.

Figure 2-7

Signal House at Damen Station on Blue Line

The existing A/C unit is a two-ton Bard model that is attached to and penetrates the wall. There is no remote or local monitoring of the heating and cooling equipment controlling temperatures within these buildings. There is an exhaust fan and motorized damper intake opening.

The electrical system consists of one AC power source with an inverter. The inverter input is DC power from the rail system.

Pulaski Station – Orange Line

This signal house was installed around 1993, and similarly to the Damen signal house, the signal equipment is somewhat heat sensitive. The signal house consists of a fiberglass structure (Figure 2-8).

Figure 2-8 *Examples of Signal Houses: Orange Line Pulaski Station (top left), Red Line Bryn Mawr Station (top right), Brown Line Rockwell Station (bottom left), Brown Line Sacramento Station (bottom right)*

This facility has two separate A/C units installed, both ductless split systems. One obvious issue was these units are sized differently, one was 1.5 tons (Friedrich), and the other was a ¾-ton unit (Sanyo). They are set up in a lead/lag configuration, with the 1.5-ton unit leading, and if that unit cannot maintain temperature the second unit comes on. There is an exhaust fan and motorized damper at the intake opening.

During the site visit, the two A/C units were running, as was the exhaust fan, which was set at a lower temperature then the second A/C unit. Once the exhaust fan was engaged, it was impossible for the A/C to keep up with the amount of heat the exhaust was drawing through this space.

The electrical system consists of two AC power sources with an automatic transfer switch (ATS) with generator disconnect located inside. There does not appear to be a generator tap box.

Bryn Mawr Station – Red Line

This signal house was installed in the early 1970s and is not similar to the previous two signal houses. The signal equipment is not very heat sensitive, and the signal house structure is a steel panel structure with a fiberboard interior surface (see Figure 2-8).

This facility has no A/C units installed. CTA indicated that the only time the facility needs cooling is when servicing is needed within the building in the summer months. This is for the service personnel's comfort cooling not for the equipment. There is no remote or local monitoring of the heating and cooling equipment controlling temperatures within these buildings.

The electrical system consists of two AC power sources with an automatic transfer switch.

Rockwell Station – Brown Line Crossing Gate and Signal House

This signal house was installed around 2006, thus making this a fairly current facility, with newer electronics that are somewhat heat sensitive, but less so than in the Damen signal house. The signal house is constructed of stainless steel sheets with insulation (Figure 2-8). CTA indicated that the only time this type of signal house has heat issues is when the power fails and when the A/C unit fails.

There are two existing A/C units in this building. The primary unit is a one-ton Bard model that penetrates the wall; the backup unit is a Comfort Aire ¾-ton ductless split system. There is also an exhaust fan and motorized damper intake opening. There is no remote or local monitoring of the heating and cooling equipment controlling temperatures within these buildings.

The electrical system consists of one AC power source with an inverter and a generator tap box. The inverter input is DC power from the rail system.

Sacramento Station – Brown Line Crossing Gate House

This gate house was installed around 2006, making this a fairly current facility, with newer electronics that are somewhat heat sensitive, but less so than the Damen signal house (Figure 2-8). The signal house is constructed of stainless steel sheets with insulation. CTA indicated that the only time this type of signal house has heat issues is when the power fails and when the A/C unit fails.

There are two existing A/C units in this building. The primary unit is a Friedrich window model that penetrates the wall; the backup unit is a Comfort Aire ¾-ton ductless split system that was recently replaced. An exhaust fan and motorized damper intake opening were operating as designed. There is no remote or local monitoring of the heating and cooling equipment controlling temperatures within these buildings.

The electrical system consists of one AC power source and a generator tap box on the outside which connects to the lugs of the signal panel.

Howard Station – Red Line Signal Tower

This is a modern facility with new electronics, at a key rail transfer point. Signal equipment at this location is housed in a brick building and is extremely sensitive to heat. The space is controlled by two Trane six-ton units mounted on the roof, which are relatively new and in good working order.

Build Scenarios

Possible solutions to this recurring situation include the following concepts.

- Replace and improve A/C units (e.g., install backup units, right-size dual units).
- Provide alternative power sources (e.g., inverters, generator switch gear).
- For both of these conditions, two different scenarios were considered that could be implemented depending on the existing condition of the signal house and location within the rail system. Houses located within the downtown Loop and on heavier-operating lines that show a higher tendency to overheat would warrant consideration of the highest level of improvements.

Replace and Improve A/C Units

A recommendation for each type of signal house investigated is described in the summary of existing conditions below.

- Add backup A/C unit to primary unit in good operating condition (Damen)
  - Add a backup unit with a higher thermostat setting, alternate units with routine maintenance
  - Provide signal relay to notify when second system engages
  - Cost: $30,000 per signal house
- New dual two-ton A/C system (Pulaski, Rockwell, Sacramento)
  - Install two new two-ton systems for appropriate capacity
  - Second unit has a higher thermostat setting, alternate units with routine maintenance
  - Provide signal relay to notify when second system engages
  - Cost: $54,000 per signal house
- No work required (Bryn Mawr, Howard)
  - Signal components not in danger of overheating and causing service disruptions

  - Conditioning for technician comfort only (Bryn Mawr); new A/C equipment (Howard)

For all improvements, the thermostat on one of the units should be set 3–5 degrees warmer than the other A/C unit. When any unit fails, a signal should indicate such failure at the closest customer service kiosk, or at the main signal relay office, and should notify appropriate staff that there is a need for service at this location. In the meantime, the secondary unit would keep the space cool and maintain operation of the signal equipment.

These units should be alternated as the primary unit at each regular maintenance visit, and a log should be kept to ensure that both units are in proper operating condition. Existing exhaust fans can be left in place and set at an even higher temperature than the second A/C unit to provide an additional level of redundancy.

Provide Alternate Power Sources

Every signal house contains both a signal panel and a "hotel panel":

- The signal panel provides power for all signal-related equipment. The back-up power system backs up only the signal panel and equipment in most cases. A/C units are not connected to the signal panel, since the startup of the A/C unit (i.e., inrush of motor) can interrupt the signal equipment if connected to the same panel.
- The hotel panel provides power for all other house loads (e.g., lighting, air conditioning, electrical receptacles, exhaust fans, heating, fire alarms). The hotel panel is not backed up by another service, an inverter or a generator tap box. Consequently, A/C units are not backed up by another power source or non-utility source in most cases.

The following are recommendations for providing back-up power for A/C units:

- Scenario 1: Connect A/C units to the signal panel
  - Assumes the existing signal panel can accommodate the loads of the A/C units
  - Install a system to allow for the soft start up for the A/C units to avoid interference with the signal system
  - Cost: $10,000 per signal house

- Scenario 2: Install generator tap box to back up hotel panel which feeds the A/C units
  - Includes intercepting the existing hotel feed and installing a generator tap box and transfer switch
  - Cost: $30,000 per signal house

Summary

Summary of capital costs per signal house to retrofit for climatic conditions are shown in Table 2-17.

Table 2-17
Costs for Signal House Retrofits

Signal House Retrofits	Cost
Install backup A/C system	$30,000
Install backup A/C system & connect to signal power	$40,000
Install backup A/C system & generator tap box	$60,000
Install new dual A/C system	$54,000
Install new dual A/C system & connect to signal power	$64,000
Install new dual A/C system & generator tap box	$84,000

Thus, depending on signal house condition and needs, costs range from $30,000 to $84,000 per site improvement. Each individual location should be analyzed to determine the optimal level of improvement based on signal house context, past performance, and current condition.

Life-Cycle Cost Model

Description of Model

A life-cycle cost analysis (LCCA) model was constructed to compare the infrastructure investment costs (i.e., build scenarios) against the costs of no action (no-build scenarios) for each of the three issues described above. The model was developed in a manner to provide flexibility to allow for different weather event frequencies and cost assumptions to be tested to determine the sensitivity of the model to inputs for a given scenario. This flexibility also allows for future modification of inputs by CTA or peer agencies to support additional case studies.

Principles of Good Practice

Principles of good practice are based upon the application of an LCCA to various infrastructure projects as promoted by the USDOT and the Office of Management and Budget.

The LCCA level of detail should be consistent with the level of detail of investment. LCCA need only consider differential costs among alternatives, as costs common to all alternatives are effectively canceled out. However, all LCCA factors and assumptions should be addressed, even if limited to an explanation of the rationale for not including eliminated factors in detail. Sunk costs should not be included.

The LCCA time horizon should be sufficient to reflect long-term cost differences associated with reasonable design strategies. For this project, a time horizon of

2050 was used, which is the equivalent to the general lifespan of proposed capital improvements before major repairs or upgrades would be required.

Net present value (NPV) is the economic efficiency indicator of choice as it compares the value of money today to money in the future, allowing for an accurate comparison of the value of an initial capital cost against future operating costs. Future cost and benefit streams are be estimated in constant dollars and discounted to the present using a real discount rate.

Discount rates employed in LCCA should reflect historical trends. Although long-term trends for real discount rates hover around 4 percent, with 3–5 percent considered an acceptable range. For public agencies, a 3–3.5 percent discount rate is typically applied; this analysis applied a 3.5 percent discount rate for a more conservative estimate of future benefits.[17]

Routine annual maintenance costs have only a marginal effect on NPV and should be equivalent across the alternatives. For these analyses, the maintenance costs that would be incurred above the basic preventative maintenance procedures are included to evaluate the effectiveness of different alternatives over the lifespan of the improvement.

Basic Model Architecture

The basic model architecture was developed an Excel spreadsheet format to allow adjustment of input assumptions as cost information and climate projections are refined. The model run template shown in Table 2-19 consists of four main input areas:

- Results
  - Inputs are given for baseline and multiple frequencies for severe weather events
  - Outputs are given as 2050 NPV values based on different event frequencies
- Model No-Build Cost Assumptions
  - No-Build Service Costs
    - CTA Service Costs are the operating costs calculated for slow zones, single tracks, and bus shuttles.
    - CTA Revenue Costs is the lost revenue from passengers opting for other modes of transportation during service disruptions.
    - Passenger Value-of-time is the value of passenger time for the delays associated with bus shuttles and slow zones.

[17] This is consistent with values historically reported from the Office of Management and Budget (OMB) [26].

  - No-Build Maintenance Costs are costs beyond routine preventative maintenance that would be necessary in the absence of proposed capital improvements.
  - No-Build Repair Costs are the costs of repairs due to a severe weather event that would be necessary in the absence of proposed capital improvements.
- Model Capital Cost Assumptions
  - One-Time Capital Improvement Costs are the costs developed as part of the engineering analysis necessary to adapt infrastructure to severe weather events.
  - Ongoing Capital Improvement Costs are maintenance costs incurred after construction are complete; used only if there is a difference among build scenarios.
- Model Base Assumptions
  - Discount rate assumed to calculate NPV
  - Baseline year to be used as basis for NPV cost analysis

Subsequent tabs of the LCCA model calculate the "savings" and "costs" for each given year of the model run, and final "NPV" column indicated when the return on investment turns from negative to positive (see Tables A-2 and A-3). The model run template is given in Table 2-18; elements highlighted in green are inputs, elements highlighted in blue are calculations, and elements highlighted in yellow are outputs.

Table 2-18

Model Run Template (Illustrative)

Model Run - Template			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	2	$ 8,631,090
Frequency 1	1.5	3	$ 10,350,480
Frequency 2	2.0	4	$ 12,069,870
Frequency 3	3.0	6	$ 15,508,649
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident*
CTA Service Costs			
Slow Zones	$ 2,500	120	$ 300,000
Bus Bridges	$ 250,000	0.25	$ 62,500
CTA Revenue Costs	$ 10,000	0.25	$ 2,500
Passenger Value of Time	$ 10,000	0.25	$ 2,500
Total			$ 367,500
No-Build Maintenance Costs	Cost / Year		
Work Involved	$ 20,000		
No-Build Repair Costs	Cost / Incident		
Work Involved	$ 15,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Work involved	$ 500,000		
On-Going Capital Improvement Costs			
Work involved	$ 50,000		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

After each base model run was completed, sensitivity testing was performed on no-build and build inputs (as defined earlier in this report) to determine the variability of the outputs. With each model run, a single test variable is altered, while all other variables are held constant.

Results of LCCA Model Runs

ROW Flooding

The baseline model run for right-of-way flooding is shown in Table 2-19.

Table 2-19

ROW Flooding Baseline Model

Model Run - ROW Flooding (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	0.04	$ (58,836)
Frequency 1	1.5	0.06	$ 79,467
Frequency 2	2.0	0.08	$ 217,770
Frequency 3	3.0	0.12	$ 494,376
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 2,600	0	$ -
Bus Bridges	$ 59,286	1.00	$ 59,286
CTA Revenue Costs	$ 29,391	1.00	$ 29,391
Passenger Value of Time	$ 173,127	1.00	$ 173,127
Total			$ 261,804
No-Build Maintenance Costs	Cost / Year		
None	$ -		
No-Build Repair Costs	Cost / Incident		
Labor to dry out and restore systems	$ 70,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Construction of drainage retention system	$ 287,940		
On-Going Capital Improvement Costs			
Pump annualized maintenance	$ 2,880		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Flooding Event Frequency Sensitivity

Using the baseline value of one event of four inches of rain in a single day every 25 years (= 0.04 events/year) from the CCAP projection data results in a negative return on investment over the specified time horizon. By increasing the anticipated frequency by 1.5 times (one event every 16.7 years), the model yields a positive return by 2050 Looking at the highest modeled frequency of a severe precipitation event every 8.33 years yields significant positive return. In recent decades, storm events of this magnitude have been occurring less than every eight years, so it is feasible that observed flooding events will exceed CCAP projections and trend toward the higher end of the frequency range.

No-Build Cost Sensitivity

For the No-Build Service Costs, the highest value is the passenger value-of-time. While this cost is a common input to LCCA and cost-benefit analyses, it is instructive to test sensitivity from removing this less tangible variable. Table

2-21, Column 5 shows the impact of removing the passenger value-of-time from the model, which results in a positive return on investment only for the highest flooding frequency.

Capital Cost Sensitivity

Another model run illustrates a scenario in which the proposed improvement required twice the capital costs originally estimated, with results shown in Table 2-20, Column 3. In this scenario, the return is positive only for the highest frequency.

Table 2-20

ROW Flooding: Base Case, No Passenger Value-of-Time and Double Construction Cost

ROW Flooding Model Runs			Base	Double Capital Cost	No Passenger Value of Time
Results	Multiplier	Events / Year	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	0.04	$ (58,836)	$ (337,039)	$ (203,163)
Frequency 1	1.5	0.06	$ 79,467	$ (198,736)	$ (137,023)
Frequency 2	2.0	0.08	$ 217,770	$ (60,433)	$ (70,883)
Frequency 3	3.0	0.12	$ 494,376	$ 216,173	$ 61,398

Summary

Event frequency has a significant sensitivity impact on the model runs to quantify potential flooding impacts. None of the model runs displayed a positive return on investment by 2050 using the CCAP baseline flooding event frequency; however, all scenarios displayed a positive return at the high end of the frequency scale. Thus, it is necessary to closely monitor frequency trends for flooding events to determine cost-effectiveness of the proposed improvements.

The passenger value of time resulted in the largest impact to the cost-effectiveness of the project. While this factor may be less tangible than other variables, it is critical to the core mission of a transit agency, and thus should be appropriately reflected in the analysis. Doubling capital costs has a less significant impact than removing passenger value of time, but careful estimation of capital costs is still required to ensure that the project is cost-effective.

Rail Heat Kinks

Two model templates were developed for the rail heat kink analysis reflecting the two different build scenarios: upgraded ballasted track (Table 2-21) or direct fixation track (Table 2-22). Both templates shared common data values, with the exception of initial capital costs, and the lack of ongoing maintenance costs for the direct fixation scenario.

Table 2-21

Rail Heat Kinks – Ballasted Baseline Model

Model Run - Rail Kinks Ballasted Construction (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	2	$ 7,728,387
Frequency 1	1.5	3	$ 13,216,997
Frequency 2	2.0	4	$ 18,705,607
Frequency 3	3.0	6	$ 29,682,826
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident*
CTA Service Costs			
Slow Zones	$ 3,315	60	$ 198,900
Bus Bridges	$ 28,359	0.25	$ 7,090
CTA Revenue Costs	$ 7,666	0.25	$ 1,917
Passenger Value of Time			
Slow Zones	$ 3,801	60	$ 228,060
Bus Bridges	$ 45,156	0.25	$ 11,289
Total			$ 447,255
No-Build Maintenance Costs	Cost / Year		
Additional surfacing	$ 137,000		
No-Build Repair Costs	Cost / Incident		
Repairing damaged rail	$ 15,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
New ballasted track structure	$ 9,199,000		
On-Going Capital Improvement Costs			
Annual surfacing	$ 68,500		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

* For slow zones, the cost is per year

Table 2-22

Rail Heat Kinks – Direct Fixation Baseline Model

Model Run - Rail Kinks Direct Fixation Construction (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	2	$ 7,008,659
Frequency 1	1.5	3	$ 12,497,268
Frequency 2	2.0	4	$ 17,985,878
Frequency 3	3.0	6	$ 28,963,098
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 3,315	60	$ 198,900
Bus Bridges	$ 28,359	0.25	$ 7,090
CTA Revenue Costs	$ 7,666	0.25	$ 1,917
Passenger Value of Time			
Slow Zones	$ 3,801	60	$ 228,060
Bus Bridges	$ 45,156	0.25	$ 11,289
Total			$ 447,255
No-Build Maintenance Costs	Cost / Year		
Additional surfacing	$ 137,000		
No-Build Repair Costs	Cost / Incident		
Repairing damaged rail	$ 15,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
New ballasted track structure	$ 11,353,000		
On-Going Capital Improvement Costs			
None	$ -		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

* For slow zones, the cost is per year

Frequency Sensitivity

Available CTA Control Center data showed that in 2011 there were seven heat kink incidents on the CTA rail system, with two slow orders implemented on the Orange Line. It is assumed that the heat related incidents were grouped into the two slow-order areas, based on data provided by CTA Infrastructure. For this analysis, the baseline assumes two heat kinks impacting operations per year, and according to CCAP data, the frequency of consecutive days over 90° is predicted to double. Therefore, for purposes of this analysis, the baseline was set at 2 incidents per year, and additional scenarios of 1.5, 2, and 3 times baseline frequencies were examined to determine the sensitivity due to projected increases in prolonged heat events.

Capital Cost Sensitivity

Columns 2 and 3 of Table 2-23 compare returns on investment for the upgraded ballasted track solution and the novel direct-fixation solution. Despite lower initial capital costs for the former and lower annual maintenance costs for the latter, returns on investment within the time horizon are nearly identical; thus, capital cost sensitivity under this scenario is extremely low.

No-Build Cost Sensitivity

Slow zones in 2011 lasted for a total of four months each, but a slow-zone service cost accumulation at higher frequencies would exceed the total days per year. Therefore, the base model assumes 60 days as a baseline duration for all slow zones. Bus shuttles were limited to 0.25 days per incident, as these repairs are typically performed under traffic (or in the case of the Orange Line, after service hours).

An alternative model run compares results if the average slow zone duration is reduced to 30 days (Table 2-23, Column 4); this scenario reduces overall benefits, as adverse impacts are also reduced. A final model run illustrates the effect of removing passenger value-of-time from consideration; this scenario yields a negative return on investment for all event frequencies, underscoring the passenger impacts of a combined service disruption and prolonged slow zone.

Table 2-23

Rail Heat Kinks: Ballasted Construction, Direct Fixation, Ballasted Construction with 30-Day Service Impact, No Passenger Value of Time

Rail Kink Model Runs			Ballasted (Base)	Direct Fixation (Base)	Ballasted (30 Day Impact)	Ballasted (No PVT)
Results	Frequency Increase	Events / Year	2050 NPV	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	2	$ 7,728,387	$ 7,008,659	$ 902,723	$ (2,248,200)
Frequency 1	1.5	3	$ 13,216,997	$ 12,497,268	$ 4,014,823	$ (1,747,883)
Frequency 2	2.0	4	$ 18,705,607	$ 17,985,878	$ 7,126,924	$ (1,247,567)
Frequency 3	3.0	6	$ 29,682,826	$ 28,963,098	$ 13,351,125	$ (246,934)

Summary

The rail kink build scenarios show potential significant returns on investment due to the high costs incurred by CTA for each rail buckling incident. A subsequent sensitivity analysis reveals a low sensitivity to capital costs (i.e., ballasted vs. direct fixation scenarios), a moderate sensitivity to slow zone duration, and a high sensitivity to passenger value of time, due to extended slow zone durations.

Signal House Overheating

Signal house overheating build scenarios have the lowest capital costs of the three situations analyzed, and also pose the lowest operation costs, since slow zones imposed by signal failures do not cause a total disruption of service.

Base case assumptions include a lower-end capital cost estimate of $30,000, a quarter-day slow zone (including one rush period) required to resolve the signal house failure, and passenger value of time incurred for the duration of the slow zone (see Table 2-24).

Table 2-24

Signal House Overheating – Baseline Model

Model Run - Signal House Overheating ($30,000 Capital Cost)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	1	$ 228,084
Frequency 1	1.5	1.5	$ 356,619
Frequency 2	2.0	2	$ 485,154
Frequency 3	3.0	3	$ 742,223
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 3,315	0.25	$ 829
Bus Bridges	$ -	0.00	$ -
CTA Revenue Costs	$ -	0.00	$ -
Passenger Value of Time (Noon - 6pm)	$ 11,206	1.00	$ 11,206
Total			$ 12,035
No-Build Maintenance Costs	Cost / Year		
None	$ -		
No-Build Repair Costs	Cost / Incident		
Labor to fix A/C unit	$ 300		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
New A/C only (low)	$ 30,000		
On-Going Capital Improvement Costs			
None	$ -		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Sensitivity to Severe Weather Event Frequency

Based on available CTA Control Center data, failures were either linked to A/C units not working due to deferred maintenance or to disruptions in ComEd service. The data as currently aggregated are not specific enough to reliably correlate signal failures and severe weather events; thus, for purposes of the current analysis, it is assumed that there is one failure per cooling season per signal house.

The projected increase in temperatures will place a larger load on individual A/C units and the broader ComEd system, with a prediction that the number of cooling degree days will increase by 1.25 times. Given the uncertainty of the base data, the same relative frequency multiplies are used as with the previous two case studies.

Capital Cost Sensitivity

Capital cost sensitivity was tested by comparing the lowest capital cost assumption (i.e., install backup A/C system) against the highest capital cost assumption (i.e., install new dual A/C system & generator tap box) for signal house improvements, as illustrated in Table 2-25, Columns 2 and 3, which yields a very slight margin for 2050 NPV in each of these cases.

No-Build Cost Sensitivity

Passenger loads are a major factor for the signal house overheating analysis. The base model run represents ridership for a high-ridership segment of the Blue Line. If the number of riders were reduced by 50 percent, as reflective of some lower volume rail branches (e.g., CTA Yellow, Pink, Orange, and Green Lines), the model run shows a moderately reduced return on investment, as shown in Table 2-25, Column 4.

Finally, as for previous cases, an additional model run illustrates 2050 NPV without incorporating passenger value of time (Table 2-25, Column 5). This run yields a positive return for all but the baseline frequency, revealing relatively lower sensitivity for this variable than rail heat kinks.

Table 2-25

Signal House Overheating: Low Capital Cost, High Capital Cost, Low-Ridership Rail Branch, No Passenger Value of Time

Signal House Overheating Model Runs			Low Capital Cost	High Capital Cost	Low Capital Cost (Low Ridership)	Low Capital Cost (No PVT)
Results	Multiplier	Events / Year	2050 NPV	2050 NPV	2050 NPV	2050 NPV
Baseline	1.0	1	$ 228,084	$ 175,910	$ 111,311	$ (5,461)
Frequency 1	1.5	1.5	$ 356,619	$ 304,445	$ 181,460	$ 6,301
Frequency 2	2.0	2	$ 485,154	$ 432,980	$ 251,608	$ 18,063
Frequency 3	3.0	3	$ 742,223	$ 690,049	$ 391,905	$ 41,588

Summary

Signal house overheating model runs reveals a low sensitivity to capital costs (i.e., ballasted vs. direct fixation scenarios), and a moderate sensitivity to passenger loads and passenger value of time. By selecting a specific signal house location for investigation, this analysis necessarily generalizes variables that are to be modified for other signal house locations to determine the appropriate level of capital investment.

CTA should monitor individual signal houses for A/C-related service disruptions. Any signal house showing more than two failures per year should be evaluated for appropriate capital improvements based on relative capital costs and expected level of service impacts.

Summary of Life-Cycle Cost Analysis

This research presents a life-cycle cost analysis (LCCA) model and evaluates alternative solutions to three different climate adaptation strategies, providing a flexible tool and a high level of customization of inputs to allow multiple scenarios to be tested. The following table summarizes results for each of the three project areas investigated above.

Table 2-26 *Summary of LCCA Model Runs and Payback Periods*

	No Build Scenario		Build 1 Scenario			Build 2 Scenario		
	Capital Costs (cost per event)	*Ongoing Costs (annual cost)*		*2050 NPV (by frequency)*	*Break Even (from 2013)*		*2050 NPV (by frequency)*	*Break Even (from 2013)*
ROW Flooding	$332,000	-	**Base**	-$59,000	2089 (76 years)	**Base**	-$337,000	n/a
ROW Flooding			**High**	+$494,000	2021 (8 years)	**High**	+$216,000	2034 (21 yrs)
ROW Flooding			Install storage system to capture & detain storm-water at portal entrance			Install storage system with double base construction costs		
Rail Heat Kinks	$462,000	$137,000	**Base**	+$7,700,000		**Base**	+$7,700,000	2030 (17 yrs)
Rail Heat Kinks			**High**	+$29,700,000		**High**	+$29,700,000	2019 (6 yrs)
Rail Heat Kinks			Replace with tighter tie spacing, granite ballast & new anchoring system			Replace the entire structure with concrete direct fixation track		
Signal House Overheating	$12,000	-	**Base**	+$228,000	2015 (2 years)	**Base**	+$176,000	2020 (7 yrs)
Signal House Overheating			**High**	+$742,000	2013 (immediate)	**High**	+$690,000	2015 (2 yrs)
Signal House Overheating			Install single backup A/C unit to provide redundancy for primary unit failure ($30,000 capital cost)			Install dual A/C units & connect to traction power in case of grid failure ($84,000 capital cost)		

The LCCA demonstrated a positive return on investment for all model runs at the higher event frequencies than have been predicted in the baseline climate models. Many did not show a positive return for the baseline climate prediction scenario. Downscaling global climate models to local conditions is a complex task, and thus it is necessary to revise event frequencies as more sophisticated climate forecasting tools are developed.

All model runs demonstrated sensitivity to various input assumptions. This indicates that extrapolation to other locations must be done carefully and all inputs correctly calculated for each unique situation. Changes in location of a potential project would dramatically affect CTA service costs.[18] Overall, the variables tested in this report did not take any of the model runs to all negative return on investment scenarios, which indicates that as a general rule, the capital investment scenarios selected can be justified in the context of other key decision variables.

The LCCA analysis demonstrates that certain investments made today are projected to offset the future costs associated with climate change, given the appropriate assumptions for frequency, no-build costs, and capital costs for a specific scenario. However, prioritization of the improvements should not be performed exclusively from an LCCA analysis; additional factors (as outlined in the following section) must be considered to ultimately prioritize climate-adaptive capital improvements based on historical performance and available projection data.

Task 2 Potential Next Steps

Task 2 offers a methodology for evaluating the life-cycle costs of specific climate adaptation strategies. As CTA moves forward in evaluating climate adaptation responses, it is important to be able to put these life-cycle costs analyses in a broader context. Potential next steps include the following:

- Refinement of data inputs through agency-specific data collection
- Incorporation of risk identification to assist in prioritization of projects
- Coordination of projects within the established capital improvement program
- Establishment of enhanced design criteria that incorporate climate adaptation
- Identification of potential funding streams for identified improvements

Refinement of Data Inputs

CTA and peer agencies can more comprehensively track operating impacts associated with climate-related events to guarantee reliable outputs from the LCCA model. Qualitative correlations can be backed up with quantitative data through dedicated fields to capture severe-weather impacts within service disruption databases. This process may also include introducing novel operating cost billing codes to track spending on extreme weather event responses.

[18] For example, a disruption to the downtown Loop or on the central-running Red and Blue lines is likely to have a higher impact than a disruption to the Yellow Line, a peripheral line connecting to the north Red and Purple lines.

Risk Identification and Prioritization

Risk identification is a component that can be used to assign climate-impacted infrastructure into categories of greatest to least risk (e.g., heat kinks can cause derailments, while signal house overheating triggers fail-safe slow zones; impacts in heavy-used revenue operating area is a higher risk profile than one within a non-revenue yard). Identification of these risks, with the support of CTA Safety and Operations, can assist in prioritizing climate-impacted assets, and in turn, influence general capital prioritization. This topic is addressed further in the Task 3 section on asset management.

Coordination within Capital Improvement Program

Many of the improvements identified can be tied to other projects in the CTA capital improvement program (e.g., Purple Line rail kinks could be addressed with the planned Red-Purple Modernization; drainage improvements to Blue Line portals could be tied to the future line renovations; signal house A/C upgrades could be coordinated with relevant right-of-way improvement projects). By integrating climate-adaptive enhancements with other major capital investments, overall project costs can be reduced.

Climate-Adaptive Design Criteria

CTA staff expressed agreement in the need to consider development of revised infrastructure design criteria that incorporate climate adaptation principles (e.g., increased drainage retention standards, modified track construction requirements, more robust specifications for signal house cooling). CTA and peer agencies should continue to update design and operation requirements to best meet anticipated climate impacts under FTA leadership and coordination.

Identification of Non-Traditional Funding Streams

Climate adaptation strategies, including LCCA analysis, may provide leverage to tap into non-traditional revenue streams (e.g., economic stimulus, homeland security or sustainability-focused grants) or to better leverage existing funding options. While it is difficult to predict the nature forthcoming transportation funding reauthorizations, the recent trend is to revitalize current systems to achieve state-of-good-repair rather than to prioritize system expansions, and climate adaptation strategies are consistent with this general approach.

SECTION

3

Task 3—Integrating Adaptation Strategies into Standard Business Practices

Introduction

T Task 3 provides a high-level look at how climate adaptation strategies can be integrated into CTA's standard business practices. This task is divided into two principle objectives; first, it addresses potential interactions between climate impacts and CTA's enterprise asset management system. Second, it describes a framework model to assess operational and financial impacts of extreme weather events. Both elements of this task provide flexible framework tools that can be used as a foundation for further development to suit agency needs.

Relationship to Asset Management Process

CTA maintains a mature enterprise asset management (EAM) system for rail assets, and a $5.4 million FTA State of Good Repair award received in May 2011 is funding the development of a parallel EAM system for additional bus and rail system assets.

CTA is currently conducting a set of detailed engineering condition assessments to provide input to the EAM, which is expected to be fully integrated with the maintenance work order system. This will provide a solid ability to track assets, manage maintenance efforts, and understand future expected maintenance and capital replacement needs.

As climate change has the potential to affect asset useful life and/or maintenance needs, identifying ways to incorporate climate impact information into an EAM system can provide significant value to the capital planning process.

Considerations for Incorporating Climate Impacts into EAM Process

A key element of FTA's climate change adaptation assessment pilot program is linking adaptation strategies to the organizational structure and activities of transit agencies. This section addresses how climate adaptation issues may integrated with CTA's EAM process.

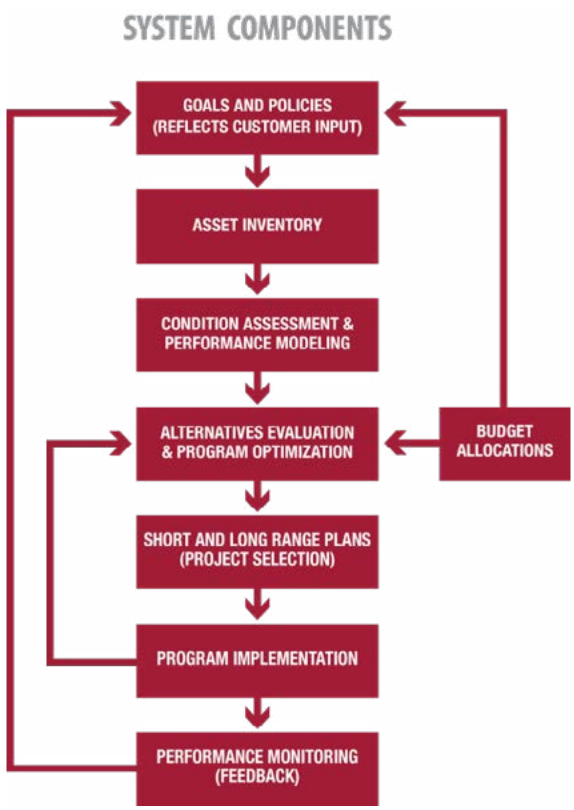
Effective asset management systems have a number of common characteristics, including the following:[19]

- Strategic, not tactical: take a long-term view of current and projected agency needs and resources
- Broadly-focused: seek to balance competing needs of operations, maintenance, reinvestment, and system expansion
- Organization-wide: seek to integrate perspectives from Infrastructure, Planning, Budget, Technology, and other departments
- Resourceful: seek to make informed decisions regarding the use of scarce resources based on reliable data in support of clear organizational objectives

Figure 3-1 shows a diagram of a generic asset management system. At the center of this process is the asset inventory and condition assessment, which can be used to establish priorities for short- and long-term capital budgets.

Figure 3-1

Components of an Asset Management System[20]



[19] FTA Rail Modernization Study Report to Congress, April 2009.

[20] Federal Highway Administration, Office of Asset Management, "Asset Management Primer," Washington DC, 1999.

The development of an EAM system is complex, requiring a high level of supporting data which must be integrated into standard CTA business practices to be useful and relevant. CTA's current EAM effort consists of four stages of work:

1. Incorporation of assets into existing database
2. Engineering condition assessment to re-baseline information
3. Reporting from multiple sources and incorporation with modeling tools
4. Development of plan to maintain asset information over time[21]

As climate change has the potential to impact the lifespan, reliability, and maintenance needs of agency assets, CTA will need to determine how climate adaptation considerations will be integrated into the EAM system. This section of the report seeks to identify a range of ways to integrate potential climate impacts into the EAM at appropriate levels of granularity. Throughout this section, the concept of asset vulnerability is described as a function of the following three elements:[22]

- Exposure – the nature and degree of exposure to climate impacts
- Sensitivity – the degree to which materials and systems are affected by exposure
- Adaptive capacity – ability of a system to respond to climate impacts

This framework can be translated into two approaches to incorporating climate adaptation into an EAM system: a top-down approach focusing on general climatic impacts, and a bottom-up approach focusing on specific agency assets.

Impact-Focused Approach (Top-Down)

An impact-focused approach can be achieved by developing a series of risk assessment tables for major asset groups. Table 3-1 presents a framework for organizing the following set of climate impact indicators, taking rolling stock as an illustrative example:[23]

- Climate Impacts – severe-weather events with potential to impact assets (e.g., intense precipitation, extreme heat)
- (Rolling Stock) Impacts – description of issues that might arise as a result of the weather-related impacts described above

[21] CTA presentation at 3rd State of Good Repair Roundtable, "Transit Asset Management System," July 2011.

[22] Rob Hyman, FHWA, "Performing a Climate Vulnerability Assessment for Mobile, Alabama," April 2013.

[23] Tables for additional sets of asset classes (e.g., buildings, stations, right-of-way, rolling stock) are presented in the appendices.

- Assets Affected – listing of categories of assets that are likely to be affected (e.g., vehicles, vehicle components, supporting equipment)
- Severity and Frequency Impacts – qualitative assessment of the magnitude of observed and projected impacts to at-risk assets
- Customer Impacts – qualitative assessment of the impact to CTA's customer experience and agency reputation
- Vulnerability Index – a qualitative index which combines severity, frequency and customer impacts captured in previous columns

Table 3-1 *Climate Impacts to Rolling Stock (Top-Down Approach)*

Climate Impact	Impacts to Rolling Stock (Bus and Rail	Assets Affected	Severity Impact	Frequency Impact	Customer Impact	Vulnerability Index
Intense Precipitation	Accelerated wear of vehicle components with exposure to water	Low-floor buses, rail equipment	2	4	2	3
	Increased vehicle accidents	All rolling stock	5	1	5	4
	Salt erosion of equipment	Buses, rail cars operating in highway medians	3	2	2	2
Extreme Heat	Electronic equipment vulnerable to temperature extremes	Bus/rail A/C components, on-board electronics	2	3	3	3
	Vehicle breakdowns more common at temperature extremes	Revenue and non-revenue equipment	4	2	4	2

Potential benefits to a top-down approach include the following:

- It provides a defined set of assets on which to focus adaptation efforts.
- It can be developed quickly through the institutional knowledge of CTA staff.
- It incorporates severity, frequency, and customer impacts into a vulnerability index.

Potential drawbacks to this approach include the following:

- It is qualitative, not quantitative.
- It is not directly integrated with other CTA standard business practices.

Asset-Focused Approach (Bottom-Up)

Another approach to integrate climate adaptation considerations within the EAM is to incorporate additional fields in the database to capture the climate vulnerability of individual assets as a function of exposure, sensitivity, and adaptive capacity. Criteria may include internal data sets (e.g., CTA Control Center data, Task 1 stakeholder input), external data sets (e.g., GIS layers representing urban heat islands and floodplains), and industry specifications of asset material type (e.g., relative sensitivity of wood vs. concrete platforms to sunlight exposure).

Illustrative examples of the asset-focused approach are presented in Table 3-2, which gives a qualitative evaluation of the vulnerability of various rail line branches and operating profiles.

Table 3-2 *Asset Vulnerability Evaluation (Bottom-Up Approach)*

Asset	Exposure			Sensitivity		Adaptive Capacity		Vulnerability
	Shade Coverage	*Urban Heat Island*	*Floodplain Proximity*	*Extreme Heat*	*Extreme Precip/ Flooding*	*CTA Jurisdiction*	*Cost of Adaptation*	*Vulnerability Rating*
Blue Line Subway	5	2	4	2	5	5	4	4
Blue Line Portal	3	3	4	1	5	1	3	3
Red Line Median	1	4	3	3	4	5	3	3
Brown Elevated	2	3	1	3	1	5	3	3
Purple Embankment	1	2	2	3	1	5	3	2

Potential benefits to this approach include the following:

- Climate vulnerability assessment provides a way for other analyses to identify susceptible assets for evaluation in scarce resource scenario planning.
- Climate vulnerability assessment can be handled offline and imported to the EAM system, if preferable.
- Application of the vulnerability function can shift from qualitative to quantitative as more data becomes available to support the analysis .

Potential drawbacks to this approach include the following:

- Requires coordination of multiple departments and information streams.
- Usefulness requires simple methods of updating asset vulnerability in conjunction with maintenance and capital projects.

While ultimately this assessment would be applied to all assets, it can start with an initial manual screening by asset type and become more automated and structured over time, with additional levels of vulnerability assessment applied as more information is made available.

Ultimately, an EAM serves an agency best when the system is able to project asset needs and replacement in future years. Currently, assessments of expected asset life are based on general industry experience and assumed to be equal for all similar assets. Over time, climate-vulnerability indices can provide a basis for adjusting expected useful life of specific assets, and this information can be considered in prioritizing future asset replacement cycles.

Integration of Climate Adaptation into EAM at Other Agencies

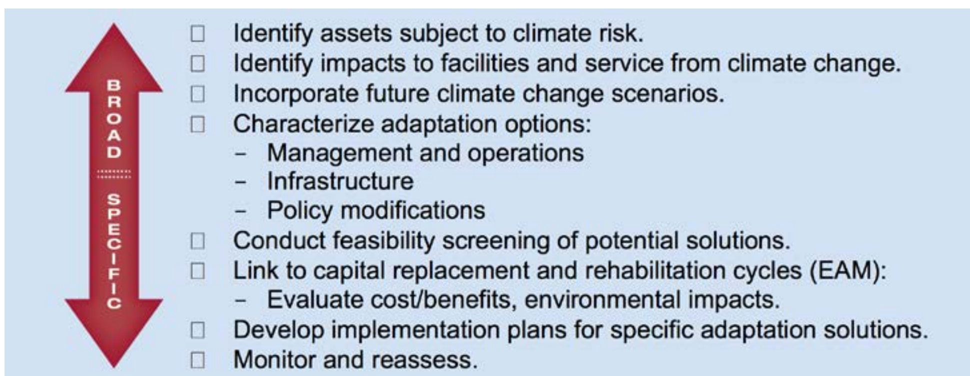
Climate adaptation is a growing concern for many transit agencies. Severe storm activity over recent decades has heightened awareness and accelerated strategic planning for resilience to major weather events. Storm damage to transit systems in the Northeast and along the Gulf Coast has prompted many agencies to adopt strategies to address storm surge and sea-level rise.

At the same time, FTA is encouraging transit agencies to improve asset management practices, and the current focus on state-of-good-repair efforts is accelerating the move to develop asset management systems at transit agencies of all sizes. Asset management systems and climate adaptation have many potential points of interaction, both at technical and policy-making levels.

Climate adaptation efforts across agencies can also be seen as having similar stages of application. NYMTA's approach to climate-adaptive asset management captures a common set of steps in the climate adaptation literature, as shown in Figure 3-2 [27].

Figure 3-2

Continuum of Climate-Adaptive Asset Management Activities



In addition to common approaches, is also apparent that different agencies take different paths to climate adaptation based on local climate conditions and agency contexts, as shown in the following examples:

- **Transport for London**: Climate adaptation efforts at Transport for London (TfL) are in response to a London-wide mandate to incorporate climate adaptation strategies into the capital improvement process. This external mandate has prompted an aggressive implementation of resiliency planning.

  Each TfL department conducted a risk assessment of relative likelihood and impact of severe weather events to prioritize high-level adaptation strategies, which were studied in more detail to identify implementation options. This risk assessment process also involved development of emergency plans, updating of standards to support changes to the built environment, and refinement of asset management plans.

- **NJ TRANSIT**: Following Hurricane Irene in 2011, NJ TRANSIT (NJT) conducted a study to look at the resilience of its assets to climate impacts [28]. The report laid out climate projections, identified high-level asset impacts, and recommended that NJT conduct a criticality assessment for resilience planning.

  Subsequent impacts from Hurricane Sandy in 2012 have increased efforts to enhance resilience of key assets in the NJT system. Sea-level rise and storm surges are the most prominent climate risks being addressed, and anticipated temperature increases will likely require adaptation measures as well.

- **MBTA**: The Massachusetts Bay Transportation Authority (MBTA) has a well-developed state-of-good-repair database, and like CTA, MBTA continues to advance condition assessments to support and expand this database. As for many transit agencies, MBTA's annual capital needs exceed available funding; thus, MBTA uses a planning model as one input into capital project prioritization. Current variables in this model include the following:
  - Asset age (relative to useful life)
  - Operational impact (a yes/no flag)
  - Measure of cost-effectiveness

MBTA is currently extending these analytic tools related to its state-of-good repair database, and evaluating the introduction of additional criteria that will be represented by scalar values, which will be added to current evaluation measures.

Operational/Financial Impact Framework Model

CTA's climate adaptation pilot provides a framework model for long-range forecasting of climate impacts to allow CTA Operations and Finance to anticipate future labor, materials, and budgeting needs. This model can be used to correlate key climate drivers (e.g., temperature, precipitation) and operational and financial factors (e.g., equipment failure, energy costs).

For illustrative purposes, the framework model was used initially to focus on two operational factors, bus fleet component defects and diesel fuel consumption, as correlated with temperature. This analysis is described in the following sections:

Bus Defect Analysis

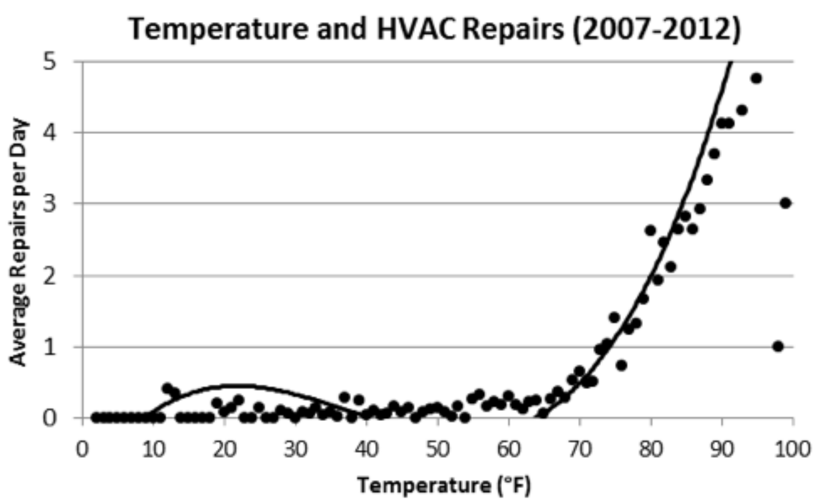
CTA's Maintenance Management Information System (MMIS) database contains a record of bus and rail vehicle maintenance issues.[24] MMIS was phased in across CTA's eight bus garages from 2007–2008, allowing for the compilation of five years of defect data. Five categories of bus defects were flagged by CTA Bus Engineering as having potential climate-related impacts:

- Heating/ventilation/air-conditioning (HVAC) systems
- Brakes
- Suspension
- Doors
- Tires and wheels

The following analysis correlates MMIS repair data and NOAA temperature data for Chicago's Midway Airport.[25] The regression analysis shown in Figure 3-3 reveals a significant correlation between temperature and HVAC repairs.

Figure 3-3

Temperature and HVAC Repairs



This graph shows a dramatic rise in average daily repairs at temperatures above 65°F, in comparison to the modest rise in daily HVAC repairs at temperatures below 40°F. Daily fleet-wide HVAC repairs averaged 2.6 at 80°F, 4.1 repairs at 90°F and 21 repairs at 100°F. Average daily repairs between 10°F and 40°F were considerably lower (less than 0.5 repairs per day).

Other bus repair data sets considered reveal less significant correlations with temperature, as shown in Figure 3-4.

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[24] MMIS also includes rail data, but bus data were the focus of the development of the framework model.

[25] Based on available MMIS data.

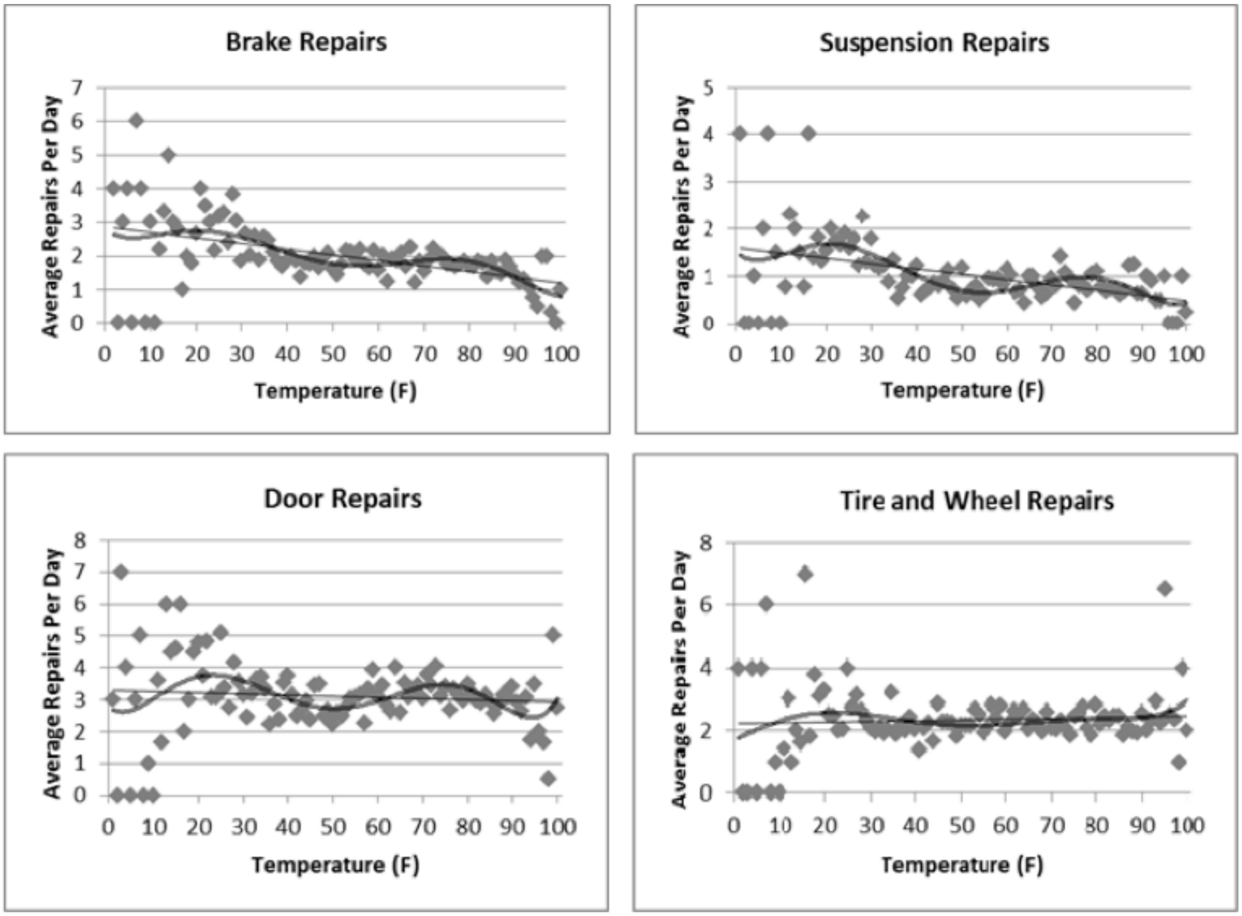


Figure 3-4 *Temperature and Brake, Suspension, Door, and Tire/Wheel Repairs*

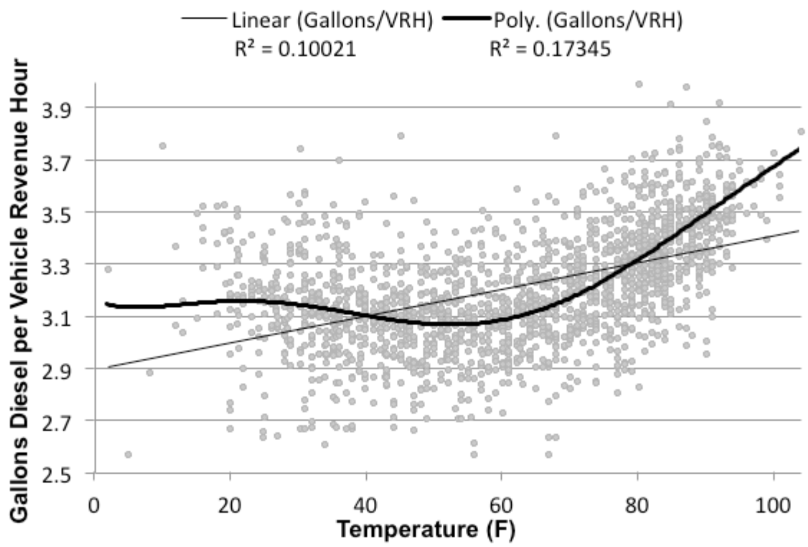
Equations for trend lines and significance-of-fit statistics for correlations in Figures 3-3 and 3-4 are presented in the appendices.

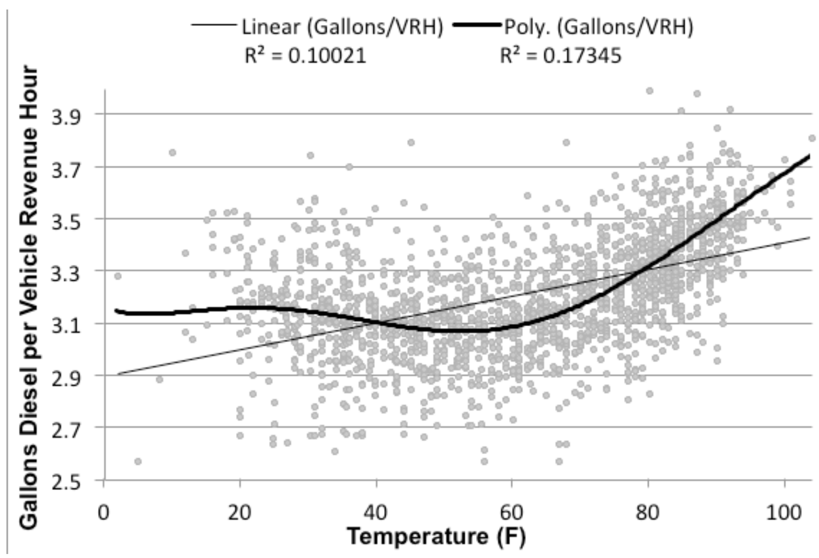
Energy Consumption Analysis

Figure 3-5 illustrates the relationship between temperature and diesel fuel consumption, normalized by vehicle revenue hour.

Figure 3-5

Temperature and Diesel Fuel Consumption





Although the relationship between temperature and diesel consumption is less significant than for HVAC repairs, this graph depicts a pattern of increased fuel consumption at temperatures below 40°F and above 70°F, which skews more heavily to the higher end of the range.

The trends described above are extrapolated to future time periods in Table 3-3, which quantifies projected changes in HVAC failures and diesel consumption with other variables held constant. Coupling the above regressions with climate projection models reveals that in the long term, HVAC failures could increase more than 50 percent and diesel consumption may rise more than 30 percent due to climate change alone.

Table 3-3

Operational/Financial Model Output – HVAC and Fuel Consumption

	Annual Days with Temperatures over 80°F		Annual HVAC Repairs		Diesel Fuel Consumption (g/VHR)	
Observed Baseline	1961–1990: 72		2007–2012: 387		2008–2012: 3.21	
Projected Time Periods:	**Average Days/Year (% Change)**		**Average Repairs/Year (% Change)**		**Average Gallons/VRH (% Change)**	
	Low Emissions	*High Emissions*	*Low Emissions*	*High Emissions*	*Low Emissions*	*High Emissions*
2010-2039	85 (18%)	86 (19%)	435 (12%)	437 (13%)	3.46 (8%)	3.47 (8%)
2040-2069	97 (35%)	111 (54%)	477 (23%)	531 (37%)	3.68 (15%)	3.96 (23%)
2070-2099	101 (40%)	131 (82%)	495 (28%)	603 (56%)	3.77 (18%)	4.33 (35%)

The framework model underlying this analysis provides the ability to modify unit costs for different input variables, as described in Appendix 3, Table A-8. The model can be extended to correlate extreme weather events to other areas (e.g., rail vehicle failures, traction power consumption).

Task 3 Summary and Next Steps

Task 3 describes the initial development of framework tools that can be used further by CTA and peer agencies to incorporate climate adaptation considerations into standard business practices. This work identified potential connections between climate impacts within the EAM system, as well as the development of a framework model to evaluate potential operational and financial impacts due to extreme weather.

Alternative methods to connect climate vulnerability assessments to the EAM system were identified, and further development will require coordination among CTA departments to assess asset vulnerability and useful life based on exposure, sensitivity, and adaptive capacity. The framework model is a first step toward projecting long-term costs of climate impacts.

Report Summary and Next Steps

CTA's climate adaptation pilot yielded the following general findings.

Task 1

Historical climate data observations and projected future increases in extreme heat and precipitation events are likely to have significant impacts on CTA's infrastructure, transit operations, and customer experience.

Localized climate models predict that prolonged heat events (e.g., 3 or more days exceeding 90˚F) will increase in the Chicago area under both low- and high-emissions scenarios. Extreme heat increases rates of rail buckling and signal equipment failures (e.g., CTA experienced nearly 40 heat kinks between 2008 and 2012), and increases vehicle energy consumption (e.g., diesel fuel consumption and rail traction power use increase during periods of extended heat).

CTA service disruptions due to extreme precipitation and flooding incur significant secondary costs due to replacement service, reduced reliability, and lost ridership revenue. Flooding incidents have inflicted significant capital, operating, and maintenance cost impacts (e.g., FEMA) claims after heavy rains in September 2008 totaled more than $3 million).

Task 2

Task 2 conducted an LCCA model to evaluate proposed adaptation solutions for three different CTA rail system vulnerabilities: ROW flooding, rail heat kinks, and signal house overheating. The LCCA demonstrated a positive return on investment for the majority of model runs at higher weather event frequencies than have been predicted in the baseline climate models.

All model runs demonstrated a moderate degree of sensitivity to input variables, which indicates that extrapolation to other locations must be done carefully and all inputs correctly calculated for each project context. The majority of model runs generated a positive return on investment within a defined range of severe weather event frequencies, indicating that as a general rule, the capital investments proposed can be justified in the context of other key decision variables.

The LCCA analysis demonstrates that certain investments made today are projected to offset the future costs associated with climate change, given appropriate assumptions for frequency, no-build costs, and capital costs for each specific scenario. However, prioritization of the improvements should not be performed exclusively from an LCCA analysis; additional factors must be considered to ultimately prioritize climate-adaptive improvements based on historical performance and available projection data.

Task 3

Integration of climate adaptation into CTA standard business practices is broken into two discrete tasks.

Two alternative approaches are proposed to incorporate climate impacts into CTA's EAM system, in concert with the ongoing build-out of the EAM framework and ongoing engineering condition assessments. The first is to develop qualitative risk assessment tables for major asset groups driven by severe weather impacts (e.g., intense precipitation increases vulnerability of rolling stock), and the second is to incorporate fields in the EAM database to indicate the climate vulnerability of a given asset, which is defined as a function of three criteria: exposure, sensitivity, and adaptive capacity.

A framework model has been developed for forecasting operational and budgetary impacts. The model has initially been used to correlate temperature with bus HVAC defects and diesel fuel consumption. Bus HVAC defects showed a significant correlation with high temperatures, with more than 75 percent of failures occurring with temperatures above 80 degrees Fahrenheit. Bus diesel fuel consumption showed a greater increase at higher temperatures (above 70°F), and a slighter increase at lower temperatures (below 20°F).

Next Steps

The following tasks are recommended to extend the CTA adaptation pilot to future needs:

- Task 1:
  - Modify data collection and accounting strategies to facilitate forthcoming correlations of severe weather impacts and service disruptions.
  - Continue monitoring and development of climate forecasting models to allow better integration of long-term climate projections with available CTA data.
- Task 2:
  - Refine LCCA methodology with improved forecasting of short- and long-term severe weather event frequencies, and other input assumptions.
  - Identify strategies to extend project-specific findings to systemwide impacts, using appropriate methodologies and order-of-magnitude cost estimates.
- Task 3:
  - Continue development of tools to be used to understand the short- and long-term impacts of severe weather on useful life of agency assets within the EAM framework.
  - Extend model to include secondary impacts (e.g., station-specific climate-related ridership shifts, impacts of more frequent bus shuttles on mainline transit service)

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APPENDIX

A

Task 1—Survey of System Vulnerabilities

Table A-1 *Matrix of Comments from Expert Interviews*

Impacts	Result of Impacts	Sponsor*					
Intense Precipitation	Flooding of viaducts	O			S	C	E
	Flooding of subway tunnels and at grade locations	O	P	I	S	C	E
	Low floor bus have key components that are being damaged by water because they are closer to the ground	O					
	Increased canopy/weather protection desired by customers, but increase maintenance and can make access difficult		P	I			
	More bad weather leads to more vehicle accidents		P				
	Flooding has more impact on rail than bus since buses can reroute		P				
Very Hot Days/ Heat Waves	Weather extremes increase loads on electrical and diesel systems	O				C	
	Extreme heat causes expansion problems with track (heat kinks)	O					
	Electronic equipment on vehicles and controlling systems vulnerable to temp extremes	O	P	I			
	Concern about some substations being substandard and overloaded and A/C related spikes in usage can cause failure or slow zones	O	P				
	Increased demand for cooling buses to support city emergency efforts	O			S	C	E
	Since most equipment is stored outside, high heat requires garage staff to idle buses overnight		P				
	Inadequate air exchange in subway is worse in hot weather		P				
	Most customer assistant booths do not have air conditioning		P				
	Increased canopy/weather protection desired by customers, but increase maintenance and can make access difficult		P	I			
	More robust A/C equipment might be needed if high temperatures continue to be more frequent		P				
	Increase in violence on hot days		P				
	Escalator and elevator reliability might be affected by temperature extremes		P				
	Transformers and rectifies at substations designed to be air cooled. If air getting hotter, what are the impacts?			I			

Impacts	Result of Impacts	Sponsor*					
Very Hot Days/ Heat Waves	Infrastructure components most affected by temperature extremes and rapid high/low swings			I			
	High temperatures create frequent "trips" of equipment sensors			I			
	Track wear is accelerated by temperature extremes and swings in temperatures			I			
	Does the track "neutral" temperature have to be adjusted?			I			
	Footwalks and platforms (wood and concrete) should be monitored for performance related to expansion and contraction			I			
	Extended heat leads to track fires and heat kinks in rail				S		
	Vehicle breakdowns more common at temperature extremes				S		
Snowfall	Weather affects exposed rail, switch and junctions with big impacts on yard operations		P				
	Snow events make system access more difficult for everyone, especially people with disabilities		P				
	At grade rail sections experience drifting problems		P				
	Increased canopy/weather protection desired by customers		P				
	Snow and ice related issues on uncovered subway entrances		P				
	More bad weather leads to more vehicle accidents		P				
	Salt erosion of equipment			I			
	Snow removal is a key issue that the City and the CTA share. Streets and San has a robust removal plan with Lake Shore Drive (LSD) and arterials being top priorities; probably overlaps well with CTA needs for moving buses						E
Extreme Cold	Weather extremes increase loads on electrical and diesel systems	O					
	Electronic equipment on vehicles and controlling systems vulnerable to temp extremes	O	P	I			
	Since most equipment is stored outside, severe cold requires garage staff to idle buses overnight	O	P				
	Weather affects exposed rail, switch and junctions with big impacts on yard operations		P				
	Increased canopy/weather protection desired by customers, but increase maintenance and can make access difficult		P	I			
	Track components, such as rail grease, cannot withstand long periods of cold			I			
	Infrastructure components most affected by temperature extremes and rapid high/low swings			I			
	Track wear is accelerated by temperature extremes and swings in temperatures			I			

Impacts	Result of Impacts	Sponsor*					
Extreme Cold	Does the track "neutral" temperature have to be adjusted?			I			
	Footwalks and platforms (wood and concrete) should be monitored for performance related to expansion and contraction			I			
	Heaters desired by customers, difficult to maintain			I			
	City emergency operations using heating buses for displaced residents				S		E
	Vehicle breakdowns more common at temperature extremes				S		
Rapid Temperature Swings	Electronic equipment on vehicles and controlling systems vulnerable to temp extremes	O					
	Road conditions deteriorate with more frequent freeze/thaw cycles decreasing ride quality and increasing vehicle wear and tear		P				
	Escalator and elevator reliability might be affected by temperature extremes		P				
	Infrastructure components most affected by temperature extremes and rapid high/low swings			I			
	Standard start-up/shut-down of boilers and seasonal equipment may need to be modified			I			
	Track wear is accelerated by temperature extremes and swings in temperatures			I			
	Repeated freeze/thaw cycles can result in cracked rail, ballasted track heaving				S		
Storm-Related Impacts	Trees down blocking tracks and roads from high wind events	O	P		S		
	Lake Shore Drive, main bus artery, can have significant impacts from storms (surge, drifting, etc.)		P				
	Potential passenger hazards for waiting rail passengers with extreme wind (tornado)				S		
	Should develop plan to communicate with passengers at above ground rail stations for severe storms and tornados						E
Emergency Issues	More cooling buses being requested/warming buses for displaced residents - some planned (esp. cooling buses), but increasingly used for emergency events that can affect CTA service delivery	O	P			C	E
Other	Disruptions to travel way (fire, downed trees, floods) seem to be increasing	O					
	As development gets closer to the tracks throughout the system, track access for maintenance becomes more difficult (physically and due to needing to have concern for neighbors)	O					
	Special events cause operations impacts	O					
	Operators have trouble getting to work in bad weather (like everyone else), which affects service reliability		P				

Impacts	Result of Impacts	Sponsor*					
Other	Design process aiming for 100-year infrastructure life			I			
	Increased ridership (a good thing) and increased service can increase the stress on the system			I			
	CTA power reliability dependent on ComEd reliability			I			
	Important to continue to improve communication with staff and customers under extreme weather conditions				S		
	City sewer infrastructure has impact on CTA operations				S		

* C = City Reps, E = OEMC, I = Infrastructure, O = Operations, P = Planning, S = Safety/Finance

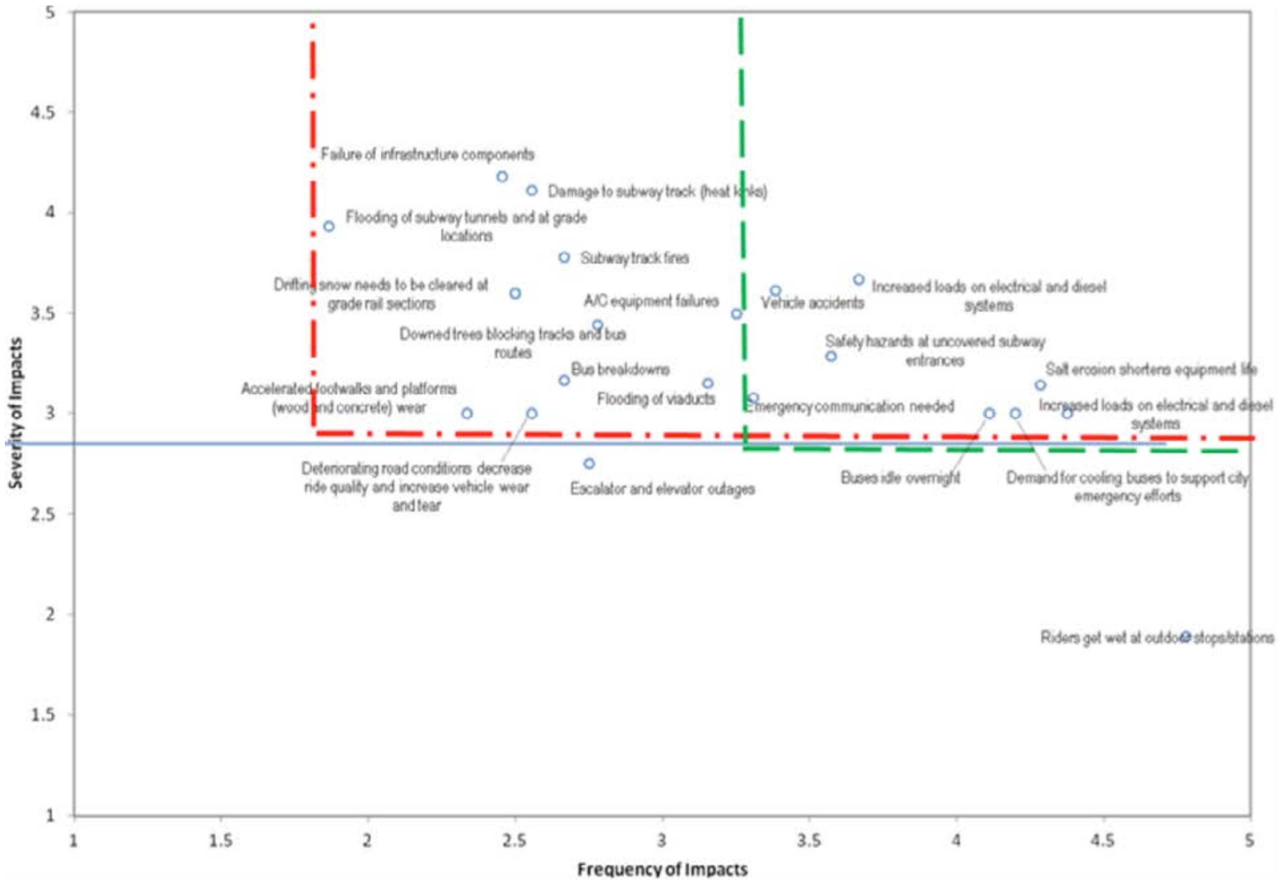


Figure A-1 *Risk Matrix*

Figure A-2

CTA Bus Routes and Affected Viaducts

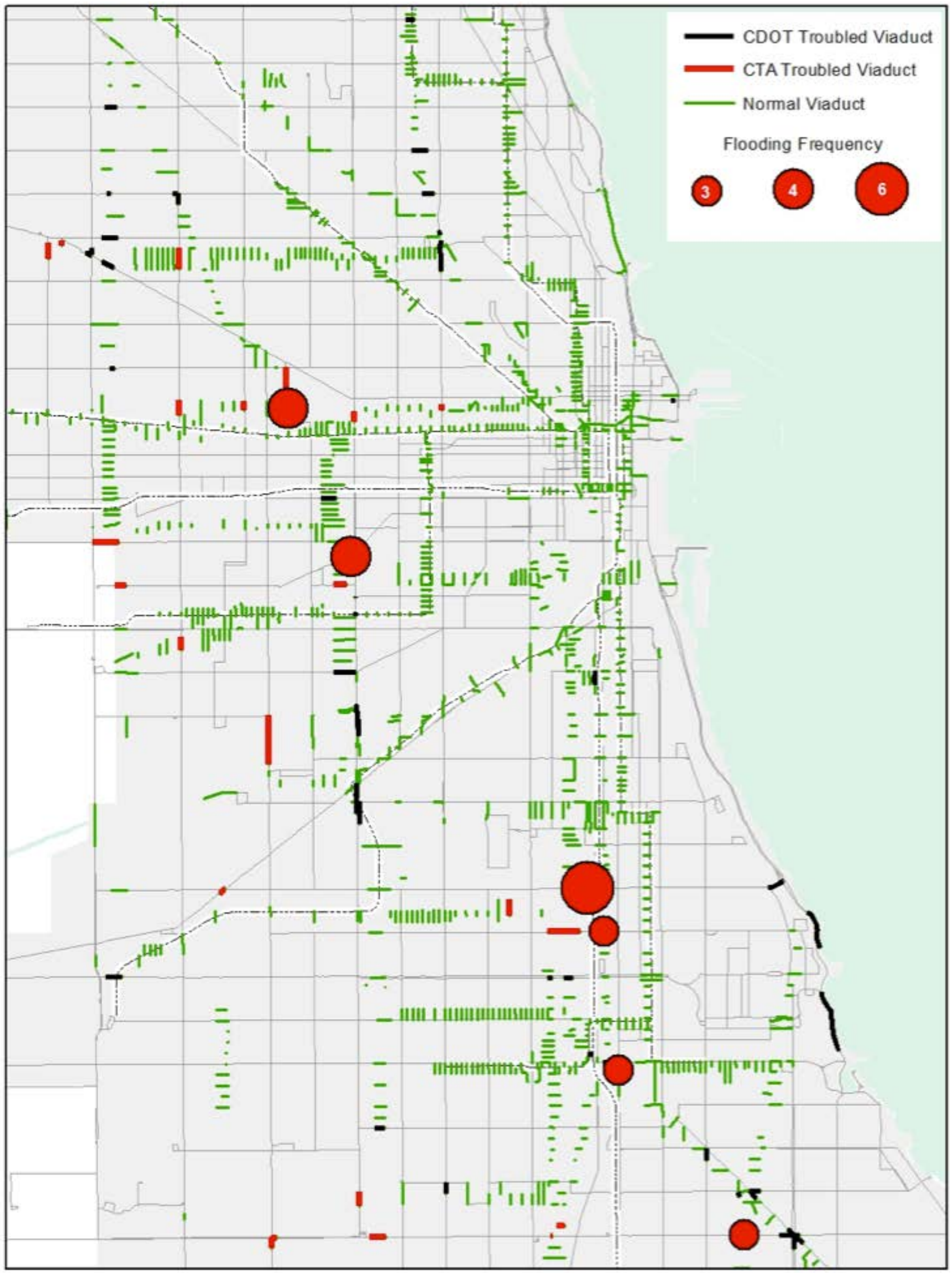
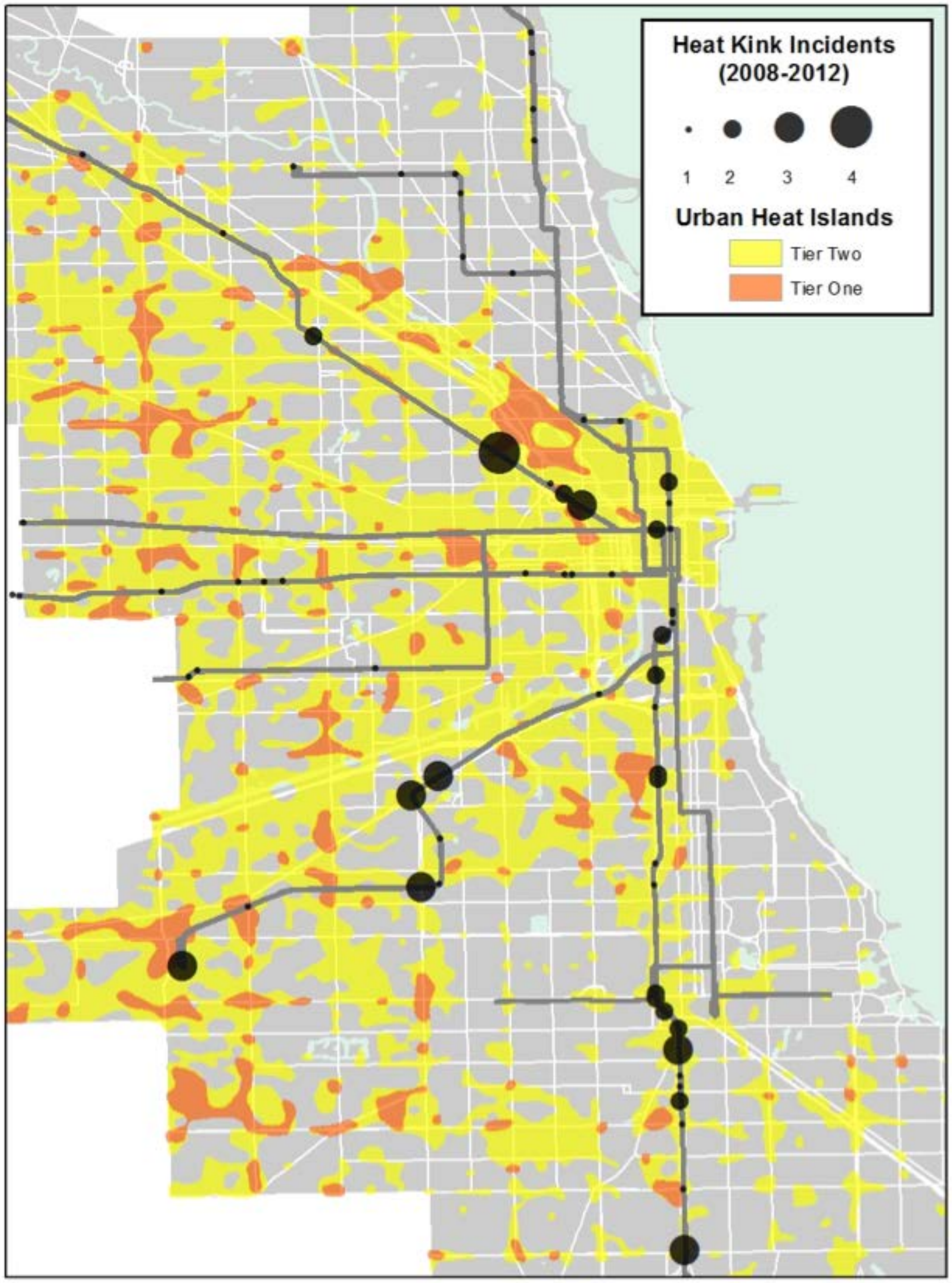


Figure A-3
Urban Heat Islands and Heat Kink Incidents (2008–2012)



APPENDIX

B

Task 2—Analysis of Adaptation Strategies

Figure B-1 *CTA Flooding Hazard Areas – Floodplain Map*

Table B-1

Basic Model Template

Model Run – Template			
Results	Frequency Increase	Events/Year	2050 NPV
Baseline	1.0	2	$8,631,090
Frequency 1	1.5	3	$10,350,480
Frequency 2	2.0	4	$12,069,870
Frequency 3	3.0	6	$15,508,649

Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost/ Day	Days	Cost/ Incident*
CTA Service Costs			
Slow Zones	$2,500	120	$300,000
Bus Bridges	$250,000	0.25	$62,500
CTA Revenue Costs	$10,000	0.25	$2,500
Passenger Value of Time	$10,000	0.25	$2,500
Total			$367,500

No-Build Maintenance Costs	Cost/Year		
Work Involved	$20,000		

No-Build Repair Costs	Cost/Incident		
Work Involved	$15,000		

Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Work Involved	$500,000		

On-Going Capital Improvement Costs			
Work Involved	$ 50,000		

Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Three different model runs were completed for the ROW Flooding scenario:

- Baseline testing frequency sensitivity
- Double capital construction cost testing capital cost sensitivity
- Removal of passenger value-of-time testing operating cost sensitivity

Table B-2

Model Run – ROW Flooding (Base)

Model Run - ROW Flooding (Base)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	0.04	$ (58,836)
Frequency 1	1.5	0.06	$ 79,467
Frequency 2	2.0	0.08	$ 217,770
Frequency 3	3.0	0.12	$ 494,376
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 2,600	0	$ -
Bus Bridges	$ 59,286	1.00	$ 59,286
CTA Revenue Costs	$ 29,391	1.00	$ 29,391
Passenger Value of Time	$ 173,127	1.00	$ 173,127
Total			$ 261,804
No-Build Maintenance Costs	Cost / Year		
None	$ -		
No-Build Repair Costs	Cost / Incident		
Labor to dry out and restore systems	$ 70,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Construction of drainage retention system	$ 287,940		
On-Going Capital Improvement Costs			
Pump annualized maintenance	$ 2,880		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Model Run - Flooding (Base)							
Baseline							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 10,472.16	$ -	$ 2,800.00	$ (287,940.00)		$ (274,667.84)	$ (265,379.56)
2014	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (255,678.36)
2015	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (246,305.23)
2016	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (237,249.06)
2017	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (228,499.14)
2018	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (220,045.11)
2019	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (211,876.97)
2020	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (203,985.04)
2021	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (196,359.99)
2022	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (188,992.80)
2023	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (181,874.73)
2024	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (174,997.37)
2025	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (168,352.58)
2026	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (161,932.50)
2027	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (155,729.51)
2028	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (149,736.29)
2029	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (143,945.74)
2030	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (138,351.01)
2031	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (132,945.47)
2032	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (127,722.72)
2033	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (122,676.59)
2034	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (117,801.10)
2035	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (113,090.48)
2036	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (108,539.16)
2037	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (104,141.75)
2038	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (99,893.05)
2039	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (95,788.02)
2040	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (91,821.80)
2041	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (87,989.71)
2042	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (84,287.21)
2043	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (80,709.91)
2044	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (77,253.59)
2045	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (73,914.14)
2046	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (70,687.63)
2047	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (67,570.22)
2048	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (64,558.23)
2049	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (61,648.10)
2050	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (58,836.38)

Model Run - Flooding (Base)							
Frequency 1							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 15,708.24	$ -	$ 4,200.00	$ (287,940.00)		$ (268,031.76)	$ (258,967.88)
2014	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (243,071.84)
2015	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (227,713.34)
2016	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (212,874.22)
2017	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (198,536.89)
2018	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (184,684.41)
2019	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (171,300.37)
2020	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (158,368.93)
2021	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (145,874.78)
2022	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (133,803.14)
2023	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (122,139.72)
2024	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (110,870.71)
2025	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (99,982.79)
2026	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (89,463.05)
2027	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (79,299.05)
2028	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (69,478.77)
2029	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (59,990.57)
2030	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (50,823.22)
2031	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (41,965.89)
2032	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (33,408.08)
2033	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (25,139.66)
2034	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (17,150.85)
2035	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (9,432.19)
2036	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (1,974.55)
2037	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 5,230.90
2038	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 12,192.68
2039	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 18,919.05
2040	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 25,417.95
2041	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 31,697.08
2042	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 37,763.87
2043	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 43,625.51
2044	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 49,288.93
2045	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 54,760.83
2046	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 60,047.69
2047	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 65,155.77
2048	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 70,091.11
2049	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 74,859.55
2050	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ 79,466.75

Model Run - Flooding (Base)							
Frequency 2							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 20,944.32	$ -	$ 5,600.00	$ (287,940.00)		$ (261,395.68)	$ (252,556.21)
2014	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (230,465.32)
2015	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (209,121.46)
2016	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (188,499.37)
2017	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (168,574.65)
2018	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (149,323.71)
2019	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (130,723.76)
2020	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (112,752.81)
2021	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (95,389.56)
2022	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (78,613.48)
2023	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (62,404.71)
2024	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (46,744.05)
2025	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (31,612.99)
2026	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (16,993.60)
2027	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (2,868.59)
2028	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 10,778.76
2029	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 23,964.61
2030	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 36,704.56
2031	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 49,013.69
2032	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 60,906.57
2033	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 72,397.28
2034	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 83,499.41
2035	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 94,226.10
2036	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 104,590.06
2037	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 114,603.55
2038	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 124,278.41
2039	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 133,626.11
2040	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 142,657.70
2041	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 151,383.87
2042	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 159,814.96
2043	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 167,960.94
2044	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 175,831.44
2045	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 183,435.80
2046	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 190,783.01
2047	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 197,881.75
2048	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 204,740.45
2049	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 211,367.21
2050	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ 217,769.87

Model Run - Flooding (Base)							
Frequency 3							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 31,416.48	$ -	$ 8,400.00	$ (287,940.00)		$ (248,123.52)	$ (239,732.87)
2014	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (205,252.27)
2015	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (171,937.68)
2016	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (139,749.67)
2017	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (108,650.15)
2018	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (78,602.30)
2019	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (49,570.56)
2020	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (21,520.57)
2021	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 5,580.87
2022	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 31,765.84
2023	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 57,065.32
2024	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 81,509.27
2025	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 105,126.60
2026	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 127,945.29
2027	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 149,992.33
2028	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 171,293.81
2029	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 191,874.96
2030	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 211,760.13
2031	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 230,972.85
2032	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 249,535.86
2033	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 267,471.14
2034	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 284,799.91
2035	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 301,542.69
2036	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 317,719.28
2037	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 333,348.84
2038	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 348,449.87
2039	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 363,040.23
2040	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 377,137.20
2041	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 390,757.46
2042	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 403,917.13
2043	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 416,631.79
2044	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 428,916.48
2045	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 440,785.75
2046	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 452,253.64
2047	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 463,333.73
2048	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 474,039.13
2049	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 484,382.51
2050	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 494,376.12

Table B-3

Model Run – Flooding (Double Construction Cost)

Model Run – Template			
Results	Frequency Increase	Events/Year	2050 NPV
Baseline	1.0	0.04	$(337,039)
Frequency 1	1.5	0.06	$(198,736)
Frequency 2	2.0	0.08	$(60,433)
Frequency 3	3.0	0.12	$216,173

Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost/ Day	Days	Cost/ Incident*
CTA Service Costs			
Slow Zones	$2,600	0	$ -
Bus Bridges	$59,286	1.00	$59,286
CTA Revenue Costs	$29,391	1.00	$29,391
Passenger Value of Time	$173,127	1.00	$173,127
Total			$261,804

No-Build Maintenance Costs	Cost/Year		
None	$ -		

No-Build Repair Costs	Cost/Incident		
Labor to dry out and restore systems	$70,000		

Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Construction of drainage retention system	$575, 880		

On-Going Capital Improvement Costs			
Pump annualized maintenance	$ 2,880		

Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Model Run - Flooding (Double Construction Cost)							
Baseline							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 10,472.16	$ -	$ 2,800.00	$ (575,880.00)		$ (562,607.84)	$ (543,582.45)
2014	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (533,881.26)
2015	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (524,508.13)
2016	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (515,451.96)
2017	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (506,702.04)
2018	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (498,248.01)
2019	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (490,079.87)
2020	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (482,187.94)
2021	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (474,562.89)
2022	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (467,195.70)
2023	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (460,077.63)
2024	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (453,200.27)
2025	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (446,555.48)
2026	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (440,135.39)
2027	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (433,932.41)
2028	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (427,939.19)
2029	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (422,148.64)
2030	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (416,553.91)
2031	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (411,148.36)
2032	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (405,925.62)
2033	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (400,879.49)
2034	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (396,004.00)
2035	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (391,293.38)
2036	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (386,742.06)
2037	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (382,344.65)
2038	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (378,095.95)
2039	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (373,990.91)
2040	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (370,024.70)
2041	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (366,192.61)
2042	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (362,490.11)
2043	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (358,912.81)
2044	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (355,456.49)
2045	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (352,117.04)
2046	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (348,890.53)
2047	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (345,773.12)
2048	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (342,761.13)
2049	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (339,851.00)
2050	$ 10,472.16	$ -	$ 2,800.00		$ (2,880.00)	$ 10,392.16	$ (337,039.27)

Model Run - Flooding (Double Construction Cost)							
Frequency 1							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 15,708.24	$ -	$ 4,200.00	$ (575,880.00)		$ (555,971.76)	$ (537,170.78)
2014	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (521,274.74)
2015	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (505,916.24)
2016	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (491,077.11)
2017	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (476,739.79)
2018	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (462,887.31)
2019	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (449,503.27)
2020	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (436,571.82)
2021	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (424,077.68)
2022	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (412,006.04)
2023	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (400,342.62)
2024	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (389,073.61)
2025	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (378,185.68)
2026	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (367,665.95)
2027	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (357,501.95)
2028	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (347,681.66)
2029	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (338,193.47)
2030	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (329,026.12)
2031	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (320,168.79)
2032	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (311,610.97)
2033	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (303,342.56)
2034	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (295,353.75)
2035	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (287,635.09)
2036	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (280,177.45)
2037	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (272,972.00)
2038	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (266,010.22)
2039	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (259,283.85)
2040	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (252,784.95)
2041	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (246,505.82)
2042	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (240,439.03)
2043	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (234,577.39)
2044	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (228,913.97)
2045	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (223,442.07)
2046	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (218,155.21)
2047	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (213,047.13)
2048	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (208,111.79)
2049	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (203,343.34)
2050	$ 15,708.24	$ -	$ 4,200.00		$ (2,880.00)	$ 17,028.24	$ (198,736.15)

Model Run - Flooding (Double Construction Cost)							
Frequency 2							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 20,944.32	$ -	$ 5,600.00	$ (575,880.00)		$ (549,335.68)	$ (530,759.11)
2014	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (508,668.22)
2015	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (487,324.35)
2016	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (466,702.27)
2017	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (446,777.54)
2018	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (427,526.60)
2019	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (408,926.66)
2020	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (390,955.70)
2021	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (373,592.46)
2022	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (356,816.38)
2023	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (340,607.60)
2024	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (324,946.95)
2025	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (309,815.89)
2026	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (295,196.50)
2027	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (281,071.49)
2028	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (267,424.14)
2029	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (254,238.29)
2030	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (241,498.34)
2031	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (229,189.21)
2032	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (217,296.33)
2033	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (205,805.62)
2034	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (194,703.49)
2035	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (183,976.80)
2036	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (173,612.84)
2037	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (163,599.35)
2038	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (153,924.49)
2039	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (144,576.79)
2040	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (135,545.20)
2041	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (126,819.03)
2042	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (118,387.94)
2043	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (110,241.96)
2044	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (102,371.45)
2045	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (94,767.10)
2046	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (87,419.89)
2047	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (80,321.14)
2048	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (73,462.45)
2049	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (66,835.69)
2050	$ 20,944.32	$ -	$ 5,600.00		$ (2,880.00)	$ 23,664.32	$ (60,433.03)

Model Run - Flooding (Double Construction Cost)							
Frequency 3							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 31,416.48	$ -	$ 8,400.00	$ (575,880.00)		$ (536,063.52)	$ (517,935.77)
2014	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (483,455.17)
2015	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (450,140.58)
2016	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (417,952.57)
2017	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (386,853.05)
2018	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (356,805.20)
2019	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (327,773.46)
2020	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (299,723.47)
2021	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (272,622.03)
2022	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (246,437.06)
2023	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (221,137.58)
2024	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (196,693.63)
2025	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (173,076.29)
2026	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (150,257.61)
2027	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (128,210.57)
2028	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (106,909.08)
2029	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (86,327.94)
2030	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (66,442.77)
2031	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (47,230.05)
2032	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (28,667.04)
2033	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ (10,731.76)
2034	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 6,597.01
2035	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 23,339.79
2036	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 39,516.39
2037	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 55,145.95
2038	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 70,246.97
2039	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 84,837.33
2040	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 98,934.30
2041	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 112,554.56
2042	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 125,714.23
2043	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 138,428.89
2044	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 150,713.58
2045	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 162,582.85
2046	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 174,050.74
2047	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 185,130.83
2048	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 195,836.23
2049	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 206,179.61
2050	$ 31,416.48	$ -	$ 8,400.00		$ (2,880.00)	$ 36,936.48	$ 216,173.22

Table B-4

Model Run – Flooding (No Passenger Value of Time)

Model Run - Flooding (No Passenger Value of Time)			
Results	Frequency Increase	Events / Year	2050 NPV
Baseline	1.0	0.04	$ (203,163)
Frequency 1	1.5	0.06	$ (137,023)
Frequency 2	2.0	0.08	$ (70,883)
Frequency 3	3.0	0.12	$ 61,398
Model No Build Cost Assumptions			
No-Build Service Costs	Weekday Cost / Day	Days	Cost / Incident
CTA Service Costs			
Slow Zones	$ 2,600	0	$ -
Bus Bridges	$ 59,286	1.00	$ 59,286
CTA Revenue Costs	$ 29,391	1.00	$ 29,391
Passenger Value of Time	$ 173,127	0.00	$ -
Total			$ 88,677
No-Build Maintenance Costs	Cost / Year		
None	$ -		
No-Build Repair Costs	Cost / Incident		
Labor to dry out and restore systems	$ 70,000		
Model Capital Cost Assumptions			
One-Time Capital Improvement Costs			
Construction of drainage retention system	$ 287,940		
On-Going Capital Improvement Costs			
Pump annualized maintenance	$ 2,880		
Model Assumptions			
Discount Rate	3.5%		
Baseline Year	2013		

Model Run - Flooding (No Passenger Value of Time)							
Baseline							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 3,547.08	$ -	$ 2,800.00	$ (287,940.00)		$ (281,592.92)	$ (272,070.45)
2014	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (268,833.90)
2015	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (265,706.79)
2016	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (262,685.43)
2017	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (259,766.24)
2018	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (256,945.77)
2019	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (254,220.68)
2020	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (251,587.74)
2021	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (249,043.83)
2022	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (246,585.95)
2023	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (244,211.19)
2024	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (241,916.74)
2025	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (239,699.87)
2026	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (237,557.97)
2027	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (235,488.50)
2028	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (233,489.02)
2029	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (231,557.15)
2030	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (229,690.61)
2031	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (227,887.19)
2032	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (226,144.75)
2033	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (224,461.24)
2034	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (222,834.65)
2035	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (221,263.08)
2036	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (219,744.64)
2037	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (218,277.56)
2038	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (216,860.09)
2039	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (215,490.55)
2040	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (214,167.32)
2041	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (212,888.84)
2042	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (211,653.60)
2043	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (210,460.12)
2044	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (209,307.01)
2045	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (208,192.89)
2046	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (207,116.44)
2047	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (206,076.40)
2048	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (205,071.52)
2049	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (204,100.63)
2050	$ 3,547.08	$ -	$ 2,800.00		$ (2,880.00)	$ 3,467.08	$ (203,162.57)

Model Run - Flooding (No Passenger Value of Time)							
Frequency 1							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 5,320.62	$ -	$ 4,200.00	$ (287,940.00)		$ (278,419.38)	$ (269,004.23)
2014	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (262,805.14)
2015	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (256,815.68)
2016	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (251,028.77)
2017	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (245,437.54)
2018	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (240,035.39)
2019	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (234,815.93)
2020	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (229,772.96)
2021	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (224,900.53)
2022	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (220,192.87)
2023	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (215,644.41)
2024	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (211,249.76)
2025	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (207,003.72)
2026	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (202,901.26)
2027	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (198,937.54)
2028	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (195,107.86)
2029	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (191,407.68)
2030	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (187,832.63)
2031	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (184,378.47)
2032	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (181,041.12)
2033	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (177,816.63)
2034	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (174,701.18)
2035	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (171,691.08)
2036	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (168,782.77)
2037	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (165,972.81)
2038	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (163,257.88)
2039	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (160,634.75)
2040	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (158,100.33)
2041	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (155,651.61)
2042	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (153,285.71)
2043	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (150,999.80)
2044	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (148,791.20)
2045	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (146,657.29)
2046	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (144,595.53)
2047	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (142,603.50)
2048	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (140,678.83)
2049	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (138,819.25)
2050	$ 5,320.62	$ -	$ 4,200.00		$ (2,880.00)	$ 6,640.62	$ (137,022.55)

Model Run - Flooding (No Passenger Value of Time)							
Frequency 2							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 7,094.16	$ -	$ 5,600.00	$ (287,940.00)		$ (275,245.84)	$ (265,938.01)
2014	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (256,776.39)
2015	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (247,924.58)
2016	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (239,372.10)
2017	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (231,108.84)
2018	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (223,125.02)
2019	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (215,411.18)
2020	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (207,958.19)
2021	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (200,757.24)
2022	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (193,799.79)
2023	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (187,077.63)
2024	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (180,582.78)
2025	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (174,307.57)
2026	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (168,244.56)
2027	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (162,386.58)
2028	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (156,726.69)
2029	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (151,258.21)
2030	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (145,974.64)
2031	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (140,869.75)
2032	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (135,937.49)
2033	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (131,172.02)
2034	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (126,567.70)
2035	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (122,119.08)
2036	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (117,820.90)
2037	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (113,668.07)
2038	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (109,655.67)
2039	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (105,778.96)
2040	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (102,033.34)
2041	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (98,414.39)
2042	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (94,917.81)
2043	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (91,539.48)
2044	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (88,275.39)
2045	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (85,121.68)
2046	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (82,074.62)
2047	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (79,130.60)
2048	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (76,286.14)
2049	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (73,537.86)
2050	$ 7,094.16	$ -	$ 5,600.00		$ (2,880.00)	$ 9,814.16	$ (70,882.52)

Model Run - Flooding (No Passenger Value of Time)							
Frequency 3							
	Savings (No-Build Costs)			Costs (Build Costs)		Totals	
Year	Service Costs	Maintenance Costs	Repair Costs	One-Time	On-Going	Annual Total	NPV
2013	$ 10,641.24	$ -	$ 8,400.00	$ (287,940.00)		$ (268,898.76)	$ (259,805.57)
2014	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (244,718.87)
2015	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (230,142.36)
2016	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (216,058.78)
2017	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (202,451.44)
2018	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (189,304.27)
2019	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (176,601.68)
2020	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (164,328.64)
2021	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (152,470.64)
2022	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (141,013.64)
2023	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (129,944.06)
2024	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (119,248.82)
2025	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (108,915.26)
2026	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (98,931.14)
2027	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (89,284.65)
2028	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (79,964.37)
2029	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (70,959.26)
2030	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (62,258.68)
2031	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (53,852.32)
2032	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (45,730.23)
2033	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (37,882.80)
2034	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (30,300.75)
2035	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (22,975.09)
2036	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (15,897.16)
2037	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (9,058.58)
2038	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ (2,451.25)
2039	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 3,932.63
2040	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 10,100.64
2041	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 16,060.07
2042	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 21,817.97
2043	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 27,381.16
2044	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 32,756.22
2045	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 37,949.52
2046	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 42,967.20
2047	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 47,815.19
2048	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 52,499.25
2049	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 57,024.91
2050	$ 10,641.24	$ -	$ 8,400.00		$ (2,880.00)	$ 16,161.24	$ 61,397.52

APPENDIX

C

Task 3 – Integrating Adaptation Strategies into Standard Business Practices

Table C-1 *Asset Type Assessments*

	Climate Impacts	Effect on Stations	Assets at Risk	Severity Impact	Frequency Impact	Customer Impact	Vulnerability Impact
Stations	Intense Precipitation/ Storms	Passenger hazards for waiting rail passengers with extreme wild (tornado)	Station design	4	3	2	3
		Need to establish means to communicate with passengers at above ground rail stations for severe weather	Communication equipment	1	3	1	2
		Need for increased canopy/weather protection for customers	Canopies, shelter	3	4	4	4
		Snow and ice related issues on uncovered subway entrances	Station stairways	3	4	2	3
	Very Hot Days/Heat Waves	Air exchange in subway is worse in hot weather	Ventilation system	3	4	3	3
		Cooling required for Customer Assistant booths	Increased air conditioning	1	3	1	2
		Escalator and elevator reliability affected by high temps and temperature extremes	Elevators, escalators	3	1	4	3
		Platform and footwalk surfaces should be monitored for expansion	Station platforms and footwalks	2	3	3	3
Buildings	Intense Precipitation/ Storms	Storm damage to buildings	Garages, terminals, substations	2	4	1	2
	Very Hot Days/Heat Waves	Power supply	Electrical Systems and Distribution	4	2	3	3
		A/C becomes more important to be in place and operational	HVAC systems	3	1	1	2
Track/ Right-of-Way	Intense Precipitation/ Storms	Flooding of viaducts/blockage of roads, track	Vehicles from water damage, track (from debris)	3	3	2	3
		Flooding of subway tunnels and at-grade locations	Signals, traction power, station equipment, track bed	4	2	5	4
		Exposed rail, switch and junctions can have big effects on yard operation	Switches, junctions	3	2	4	3
	Very Hot Days/Heat Waves	Infrastructure components affected by heat and temperature savings, including rail kinks	Track and road bed	5	2	5	4
		Frequent 'trips' of equipment sensors	Substations, signals, vehicles	3	3	4	3
		Track fire increase	All track elements	5	3	3	4

Table C-2 *London's Climate Change Adaptation Programme – Risk Assessment Methodology*

Measure	Probability	Cost	Time	Customer	Reputation
Risk	% likelihood occurrence this financial year or numbers of events in terms of year(s)	Decrease in revenue increase in cost in financial year	Delay of achievement to key milestone	Reduction in customer service	Level or type of media coverage impact on relationship with stakeholders
Very High	> or = 75% Once or more per year	> £250m		Catastrophic asset loss for several weeks/months, affecting several lines. Repair timescales in months with total loss of service during that time Example: Major inundation of several lines from river tidal surge flooding	Prolonged and targeted hostile media campaign lasting at least 1-5 years – aimed at decreasing net advocacy amongst external stakeholders • challenging organizational competence in key public safety areas Example: sustained media campaign against Railtrack following various safety incidents
High	50% - 75% More than once in 2 years	£175-250M	36-52 weeks delay	Major adverse impact such as: • disruption/loss of customer service on more than one line for several weeks • major event resulting in injuries and fatalities Example: Kings Cross Fire	• Continuous hostile media coverage of up to 1 year • Significant decrease in net advocacy amongst external stakeholders • Major organizational changes resulting from an event e.g. removal of accountable individuals from post
Medium	20% - 50% Between once in 2 to once in 5 years	£100-175M	24-36 weeks delay	Adverse impact such as: • Loss of train service on one line for several weeks • Loss of a single-ended train depot/ train staff depot/station • No injuries or fatalities • Significant and ongoing disruption to core business services Example: Chancery Lane Derailment Moorgate accident	• Ongoing critical and aggressive media campaign coverage lasting the duration of an event • Decrease in net advocacy amongst external stakeholders • Significant challenge by regulators and stakeholders into relation to management of organization • Targeted and critical parliamentary questions being asked • Severe and ongoing disruption actions taken by internal stakeholders (employees, unions, equality groups, etc.)
Low	5% - 20% Less than once in 5 years	£50-100M	12-24 weeks	Disruption to customer service for several days, or series of days Example: • Series of network-wide 1 day strikes • Loss of train service on one line for several days	• Sporadic media coverage triggered by related events e.g. in print for several days over a period of time • Regulators and stakeholder intrusion is heightened by the event • Greater scrutiny by regulators and stakeholders in relation to management of organization • Internal stakeholders (employees, unions, equality groups, etc.) carrying out limited industrial action e.g. series of 1 day strikes

Table C-2 *London's Climate Change Adaptation Programme – Risk Assessment Methodology (continued)*

Measure	Probability	Cost	Time	Customer	Reputation
Very Low	< or = 5% Less than once in 20 years	Increase revenue/ decrease costs by less than £250K in one financial year	Milestone would be achieved less than 13 weeks early	Improvements to customer service e.g.: • Improved ambience/information • Minor improvement to journey times • Small increases in satisfaction	• Positive word of mouth by customers • Positive public awareness
Low	5% - 20% Less than once in 5 years	Increase revenue/ decrease costs by between £250K-1M in one financial year	Milestone would be achieved more than 13 weeks but less than 26 weeks early	Improvements to customer service as above	• Minor/short-term positive local media coverage • Improved relations with regulators and stakeholders
Medium	20% - 50% Between once in 5 years and once in 2 years	Increase revenue/ decrease costs by between £1-5M in one financial year	Milestone would be achieved more than 26 weeks but less than 39 weeks early	Improvements to customer service Permanently improved customer satisfaction ratings (between 1-5% improvement on current scores)	Positive media coverage and enhanced relations with regulators and stakeholders e.g. headline television coverage or front page in Evening Standard for one day
High	50% - 75% More than once in 2 years	Increase revenue/ decrease costs by between £5-10M in one financial year	Milestone would be achieved more than 39 weeks but less than 52 weeks early	Noticeable and permanent improvement in customer service resulting in significantly improved customer satisfaction ratings (a > or = 5% improvement on current scores)	Significant positive media coverage and enhanced relations with regulators & stakeholders for more than a week
V. High	> or = 75% Once or more per year	Increase revenue/ decrease costs by more than £10M in one financial year	Milestone would be achieved over 52 weeks early	Major and permanent improvement in customer service resulting in significantly improved customer satisfaction ratings (a > or = 10% improvement on current scores	Significant positive media coverage and enhanced relations with regulators and stakeholders for a period of weeks

Table C-3 *London's Climate Change Adaptation Programme – Risk Assessment with Map*

Track and Civils Climate Change Risk Identification				
Weather Type	**Potential Change**	**Asset**	**Description**	**Consequence**
Extreme Hot Weather	Higher temperatures and increased frequency of hot weather	Track	Buckling Points move, detection system can't cope Lubrication – range of operation – change viscosity	Derailments, remove from service, TSR/ Suspension increased cost of maintenance More signaling failures Increased friction = higher maintenance. Increase treatment orders due to wheel screech
Drought	Longer periods of drought and increased frequency of drought	Track	Shrinkage of timber sleepers (current 30-40%)	Loss of rail support – tight gauge = inc wheel wear wheel scratch
Rain/Flooding	Heavier rain and increased frequency of high rainfall	Track (3rd party impact over current drainage is main issue) – known high risk areas	Drainage (change in frequency and rainfall patterns) – back surges into our systems General track drainage Loss of access to track due to extreme wet or heat conditions Track flooded Ballast wash out Wheel rail interface loss	Legal and financial impacts Increased cost of discharge into 3rd party drainage systems, issues over capacity enabled to discharge which could lead to need to store water Increased SPADs
Cold/Freeze	Lower temperatures and increased frequency of cold/freezing weather	Track	Increase rail breaks in woldo and joints	Loss of service and potential derailment
Snow	Heavier snow and increased		Track covered, increased point failures, difficult	

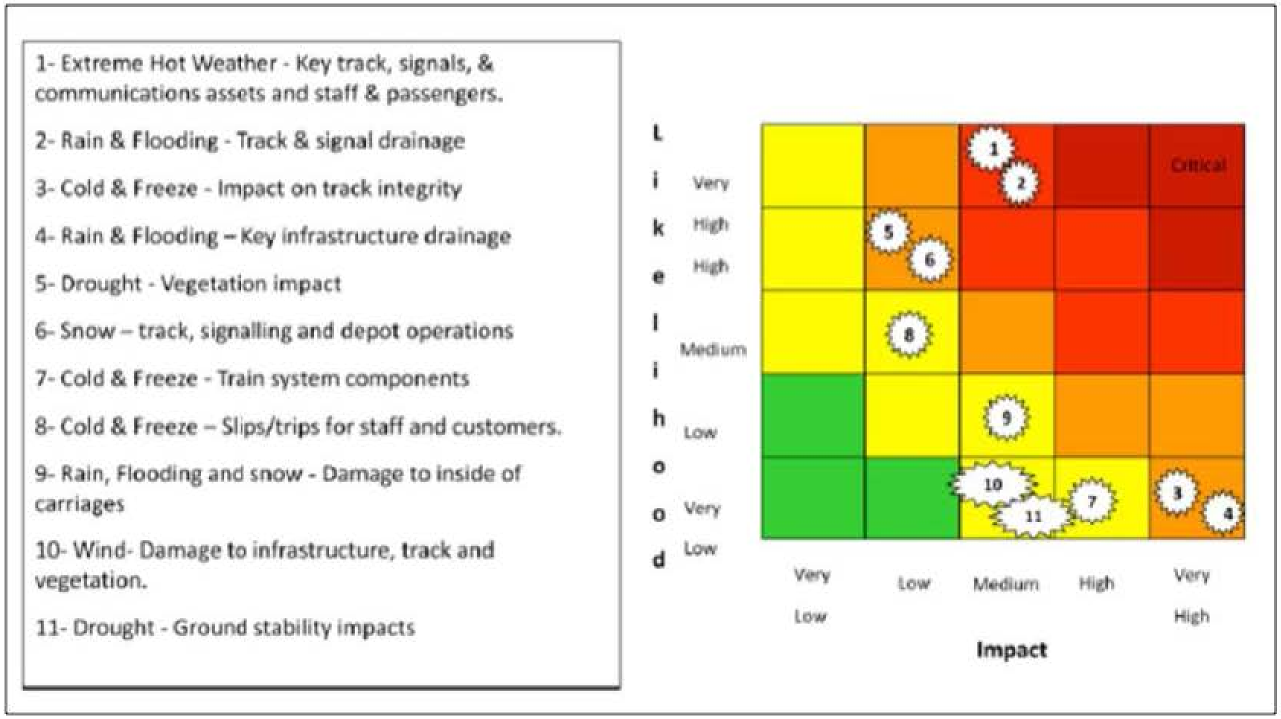

1- Extreme Hot Weather - Key track, signals, & communications assets and staff & passengers.
2- Rain & Flooding - Track & signal drainage
3- Cold & Freeze - Impact on track integrity
4- Rain & Flooding – Key infrastructure drainage
5- Drought - Vegetation impact
6- Snow – track, signalling and depot operations
7- Cold & Freeze - Train system components
8- Cold & Freeze – Slips/trips for staff and customers.
9- Rain, Flooding and snow - Damage to inside of carriages
10- Wind- Damage to infrastructure, track and vegetation.
11- Drought - Ground stability impacts
Likelihood
Very High
High
Medium
Low
Very Low
Critical
Very Low
Low
Medium
High
Very High
Impact

Table C-4 *New Jersey Transit Assets of Climate Change*

				Planning Horizon Timeframe (yrs)						Implementation Cost Estimates per Unit	
ASSET CATEGORY	Climate Impact	Effect on Buildings	Assets at Risk	1 to 5	6 to 10	11 to 20	20-50	Short-term Operational Impacts	Potential Asset Management Strategies	Low	High
Buildings	*3.2 increased rain frequency and rainfall per event*	N/A	N/A	X	X	X	X				
	3.3 increased lightning	Damage to rooftop or adjacent electrical equipment	All Stations and Depots	X	X	X	X	Possible slowed service	Verify electrical equipment, wiring, and associated facilities are protected	No cost besides equipment replacement anticipated	
	3.4 increased snow levels per event	Inaccessible stations, platforms, depots, buildings and maintenance	All Stations and platforms	X	X	X	X	Cancelled or delayed service	Additional snow removal and Roof Replacement and/or Reinforcements	$10,000	$1,300,000
	3.5 more frequent icing events	Increased road salt corrosion of station platforms	All station platforms	X	X	X	X	N/A	Increased maintenance/ cleaning and coating of exposed steel due to de-icing salt corrosion, concrete spall repair	$25,000 each	$100,000 each
		Inaccessible stations, platforms, depots, buildings and maintenance	All platforms	X	X	X	X	Cancelled or delayed service	Increased maintenance	Additional Maintenance	
	3.6 increased flooding frequency and levels	Damage or destruction to building	Flood zone buildings	X	X	X	X		Repair or replace structure	$10,000	$10,000,000
		Increased debris clogging station drainage	Flood zone stations	X	X	X	X	Delayed or slowed service	Clean drainage systems and consider installing additional drainage	$10,000	$157,000

Planning Horizon Timeframe (yrs)										Implementation Cost Estimates per Unit	
ASSET CATEGORY	Climate Impact	Effect on Buildings	Assets at Risk	1 to 5	6 to 10	11 to 20	20-50	Short-term Operational Impacts	Potential Asset Management Strategies	Low	High
Rails	*1. Increased Temperature*	Thermal expansion and buckling of rails. Warp and misalignment of tracks due to uneven thermal expansion (when shade cools adjacent sections)	All rails	X	X	X	X	Slowed service or watering of track	Installation of expansion joints/additional expansion joints in frequently buckled areas. Another possible remedy is the installation of anchors and ties to secure the track and prevent buckling	$15,000 per mile	$20,000 per mile
		Sagging and snapping of catenary lines	Electrified catenary lines	X	X	X	X	Cancelled and substitute service (bus)	Setting higher rail neutral temperature in now rail lines	Equip maintenance personnel with neutral temperature monitoring devices and perform periodic inspections (possible short-term adaptation). It is also important to not set the neutral rail temperature too high to the point where it becomes vulnerable to breaking during colder weather.	
		Damage to electrical equipment (switches, gates, signals)	All electrical equipment	X	X	X	X	Upgrade/ replace current electrical equipment and install additional ventilation	Revise specifications for equipment (such as transformers and signals) to withstand higher ambient temperatures	5% increase in electrical equipment costs	$1,300,000
		Sagging and snapping of catenary lines	Electrified catenary lines	X	X	X	X	Cancelled and substitute service (bus)	Replacement of existing catenary line tensioners	TBD	TBD
		Electric utility brownouts and outages associated with grid demand	All electrical equipment on grid	X	X	X	X	Slowed, cancelled and substitute service (bus)	Reduce electric demand of rail operations or provide supplemental power feeds	NJ Transit coordination with PJM to increase electric service reliability. May result in additional cost directly but most likely a utility cost.	

										Implementation Cost Estimates per Unit	
		Planning Horizon Timeframe (yrs)								**Implementation Cost Estimates per Unit**	
ASSET CATEGORY	Climate Impact	Effect on Buildings	Assets at Risk	1 to 5	6 to 10	11 to 20	20-50	Short-term Operational Impacts	Potential Asset Management Strategies	Low	High
Rails	*2. Sea Level Rise*	Rail systems or components no longer above sea level	NJ Coastal zone, Delaware Bay, and tidal Delaware River assets				X	N/A	Replacement of existing track above sea level (if feasible or seawall)	$225,000 per mile	$1,800,000 per mile
	2.1 Higher storm surge	Rail and rail bed destruction	NJ Coastal zone, Delaware Bay, and tidal Delaware River rail assets	X	X	X	X	Cancelled and substitute service (bus)	Repair rail, rail bed and embankments	$1,500,000 per event	$3,000,000 per event
		Flooded rails	NJ Coastal zone, Delaware Bay, and tidal Delaware River rail assets	X	X	X	X	Cancelled and substitute service (bus)	Cancelled services	Costs included in debris cleanup and electric repair numbers	
		Damage (corrosion) to electrical equipment (switches, gates, signals) due to contact with salt water	NJ Coastal zone, Delaware Bay, and tidal Delaware River electrical equipment assets	X	X	X	X	Slowed service	Repair of electric equipment, wiring and associated facilities	$115,000 per event	$230,000 per event
		Debris on rails	NJ Coastal zone, Delaware Bay, and tidal Delaware River rail assets	X	X	X	X	Cancelled and substitute service (bus)	Cleanup of storm debris from rail tracks and right of way	$415,000 per event	$830,000 per event

										Implementation Cost Estimates per Unit	
Planning Horizon Timeframe (yrs)											
ASSET CATEGORY	Climate Impact	Effect on Buildings	Assets at Risk	1 to 5	6 to 10	11 to 20	20-50	Short-term Operational Impacts	Potential Asset Management Strategies	Low	High
Structures	3. Storm Intensity and Frequency										
	3.1 Higher Wind Velocities *3.2 Increased rain frequency and rainfall per year* *3.3 Increased lightning*	Increased pressure/ forces on bridge stability	All bridges	X	X	X	X	Reduced and cancelled service	Evaluate adequacy of structures and implement remedies as required/increased maintenance	$250,000	$2,000,000
		Inadequate culvert capacity	All culverts	X	X	X	X		Install additional culverts	$10,000 each	$25,000 each
		Increased scouring of retaining walls, abutments, and foundations	All flood zone bridges and retaining walls	X	X	X	X	Reduced and cancelled service	Increased maintenance and scour mitigation measures	$15,200 per mile	$2,000,000 per mile
		N/A	N/A					N/A			
	3.4 Increased snow levels per event	Impassable Bridges	All Bridges	X	X	X	X	Cancelled or substitute service	Increased maintenance of snow removal	Additional Maintenance	
	3.5 More frequent icing events	Increased corrosion of bridges, tunnels and culverts due to road salt	All bridges, tunnels and culverts	X	X	X	X	Shortened maintenance schedule	Increased maintenance/ cleaning and coating of structures/substructure concrete spall repairs	$180,000 each	$550,500 each
	3.6 Increased flooding frequency and levels	Damage or destruction of structure	NJ coastal zone, Delaware Bay, and Tidal Delaware River structures	X	X	X	X	Cancelled or substitute service	Evaluate adequacy of structures and implement remedies or replacement as required	$250,000	$2,000,000
		Increased scouring of retaining walls, abutments, and foundations	NJ coastal zone, Delaware Bay, and Tidal Delaware River retaining walls and bridges	X	X	X	X	Reduced and cancelled service	Increased maintenance and scour mitigation measures	$180,000	$550,500 each

Table C-5

Statistics for Trend Lines

Vehicle Repair Type	Trend Line
Heat and Air Conditioning	• Straight Line: y = 0.054x - 1.5788 (R^2 = 0.3306) • Polynomial: y = 9E-10x6 - 2E-07x5 + 3E-05x4 - 0.0013x3 + 0.032x2 - 0.314x + 0.8822 (R^2 = 0.684)
Brakes	• Straight Line: y = -0.0165x + 2.8598 (R^2 = 0.2319) • Polynomial: y = 3E-10x6 - 1E-07x5 + 1E-05x4 - 0.0006x3 + 0.0131x2 - 0.1039x + 2.8029 (R^2 = 0.2761)
Suspension	• Straight Line: y = -0.011x + 1.5954 (R^2 = 0.1922) • Polynomial: y = 3E-10x6 - 1E-07x5 + 1E-05x4 - 0.0006x3 + 0.0123x2 - 0.0797x + 1.5049 (R^2 = 0.2725)
Doors	• Straight Line: y = -0.0039x + 3.3026 (R^2 = 0.0097) • Polynomial: y = 7E-10x6 - 2E-07x5 + 2E-05x4 - 0.0012x3 + 0.0231x2 - 0.1104x + 2.7646 (R^2 = 0.1104)
Tires and Wheels	• Straight Line: y = 0.0021x + 2.2468 (R^2 = 0.0031) • Polynomial: y = 2E-10x6 - 4E-08x5 + 4E-06x4 - 0.0002x3 + 0.0007x2 + 0.0654x + 1.7106 (R^2 = 0.032)
Diesel Fuel Use	• Straight Line: y = 0.0049x + 2.7894 (R^2 = 0.093) • Polynomial: y = 2E-11x6 - 8E-09x5 + 1E-06x4 - 7E-05x3 + 0.0019x2 - 0.0175x + 3.0587 (R^2 = 0.182)

Table C-6

Financial Impact Model Details

Model Design	Framework consists of Excel workbook for function transparency for user
Instruction	Overall function of model and model functions for each worksheet
User Inputs/Results	Allows user to enter values for projected temperature changes and observe expected impact on bus defects, diesel fuel use, and costs
Temperature	Historical high temperature results for Midway Airport
MMIS Database	Record of all bus maintenance by both date and problem type. Five categories of bus defects were analyzed: • B11 Bus repair requests that were labeled hot bus, no A/C or other • B13 Requests regarding brakes • B16 Requests regarding the suspension • B19 Requests regarding the doors • B27 Requests involving the tires or wheels
Repair Data Analysis	Analysis of MMIS data based on temperature
Fuel Consumption	Data provided by CTA on diesel fuel use and number of bus trips per day

User Inputs and Results

Tab	Function
Instructions	This spreadsheet models the impacts that forecast temperature increases in Chicago will have on CTA's bus system. The user inputs the expected increase in temperature from the baseline, and the model output is the expected increase in bus maintenance costs and fuel consumption. Maintenance costs are modeled based on the number of MMIS maintenance repair requests under codes B11 (AC/Heating), B13 (brakes), B16 (suspension), B19 (doors) and B27 (tires and wheels). For some of these categories, repairs occur at a much higher rate on hot days, and as temperatures increase during Chicago summers, these repair requests are modeled to increase. The change in repair requests on freezing days is also modeled for these categories. Fuel consumption is also modeled, by comparing fuel consumption on above average and below average temperature days in Chicago. In the winter months, above average temperature days have slightly lower fuel consumption. But in summer months, fuel consumption is significantly higher on warmer days. Days with a temperature above 90 degrees also have higher fuel consumption, and the model estimates the impact of an increase of these particularly hot days. The overall impact of higher
User Inputs and Results	Here the user provides inputs on the expected increase in temperatures from the baseline (2001-2012 temperatures) for the time periods of 2013-2025 and 2025-2040. The user should also input the average cost per bus repair, once that information is available. All user inputs are contained in this tab. This tab also provides all results, so that they can be compared easily with the climate inputs. The outputs provided are the estimated number of temperature related bus repairs, the costs of completing these repairs, and the increase fuel consumption from higher temperatures.
Temperature	This tab contains the historical temperature records for Chicago's Midway Airport for 2001-1012. It also provides a monthly average temperature estimate for the Chicago area.
Heat Issues – MMIS data	This tab includes the MMIS Data. The Repair Requests included are as follows: B11 Bus Repair Requests that were labeled Hot Bus, No A/C or Other. B13 Requests regarding Brakes, B16 Requests regarding the suspension, B19 Requests regarding the doors and B27 Requests involving the tires or wheels.
Repairs Data Analysis	This tab correlates the bus repair requests with temperature to see how repairs increase with temperature increases.

User Input Tab

Enter Data in Colorad Cells

Costs in Constant Dollars (Placeholder values)					
Average Cost Per Repair					Cost of Diesel Fuel
B11	B13	B16	B19	B27	
$1,000	$1,000	$1,000	$1,000	$1,000	$4

CCAP Average Annual days			Time Period	Enter Values for Following Metrics Regarding the Expected Increase in Temp
25.88	75%	0.748	2010-2039	% increase from Baseline (1961-1990) in 90+ Days, 2010-2039
41.63	181%	1.812	2040-2069	% increase from Baseline (1961-1990) in 90+ Days, 2040-2069
54.27	267%	2.665	2070-2099	% increase from Baseline (1961-1990) in 90+ Days, 2070-2099
85.23	19%	0.187	2010-2039	% increase from Baseline (1961-1990) in 80+ Days, 2010-2039 (Avg)
103.77	45%	0.446	2040-2069	% increase from Baseline (1961-1990) in 80+ Days, 2040-2069 (Avg)
116.00	62%	0.616	2070-2099	% increase from Baseline (1961-1990) in 80+ Days, 2070-2099 (Avg)
85.49	19%	0.191	2010-2039	% increase from Baseline (1961-1990) in 80+ Days, 2010-2039 (High)
111.01	55%	0.547	2040-2069	% increase from Baseline (1961-1990) in 80+ Days, 2040-2069 (High)
130.68	82%	0.821	2070-2099	% increase from Baseline (1961-1990) in 80+ Days, 2070-2099 (High)
84.97	18%	0.184	2010-2039	% increase from Baseline (1961-1990) in 80+ Days, 2010-2039 (Low)
96.54	34%	0.345	2040-2069	% increase from Baseline (1961-1990) in 80+ Days, 2040-2069 (Low)
101.31	41%	0.411	2070-2099	% increase from Baseline (1961-1990) in 80+ Days, 2070-2099 (Low)
118.01	-5%	-0.049	2010-2039	% Decrease from Baseline (1961-1990) in Below 33 Days, 2010-2039 (Avg)
109.62	-12%	-0.116	2040-2069	% Decrease from Baseline (1961-1990) in Below 33 Days, 2040-2069 (Avg)
96.62	-22%	-0.221	2070-2099	% Decrease from Baseline (1961-1990) in Below 33 Days, 2070-2099 (Avg)
117.14	-6%	-0.056	2010-2039	% Decrease from Baseline (1961-1990) in Below 33 Days, 2010-2039 (High)
104.84	-15%	-0.155	2040-2069	% Decrease from Baseline (1961-1990) in Below 33 Days, 2040-2069 (High)
85.94	-31%	-0.307	2070-2099	% Decrease from Baseline (1961-1990) in Below 33 Days, 2070-2099 (High)
118.87	-4%	-0.042	2010-2039	% Decrease from Baseline (1961-1990) in Below 33 Days, 2010-2039 (Low)
114.41	-8%	-0.078	2040-2069	% Decrease from Baseline (1961-1990) in Below 33 Days, 2040-2069 (Low)
107.30	-13%	-0.135	2070-2099	% Decrease from Baseline (1961-1990) in Below 33 Days, 2070-2099 (Low)

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