



Climate Change/Extreme Weather Vulnerability and Risk Assessment for Transportation Infrastructure in Dallas and Tarrant Counties

Report

Prepared by the University of Texas at Arlington (UTA) for submittal to

North Central Texas Council of Governments (NCTCOG)

The Metropolitan Planning Organization (MPO)
for the Dallas-Fort Worth Metropolitan Region

In fulfillment of the partnership grant between NCTCOG and UTA as obligated by the FHWA Climate Change/Extreme Weather Vulnerability Assessment Pilot Study.

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Foreword

This document has been developed by the North Central Texas Council of Governments (NCTCOG) and project partners in accordance with a grant from the Federal Highway Administration (FHWA). It presents the results of a comprehensive investigation of infrastructure vulnerability to extreme weather and climate change in the Dallas-Fort Worth (DFW) Metropolitan Area. The existing and future infrastructure assets within Dallas and Tarrant Counties, including road, rail, and aviation transportation facilities, has been aggregated together with Federal Emergency Management Agency (FEMA) flood maps. A vulnerability assessment matrix for the local transportation network has been developed to quantify the likelihood of hazards and the magnitude of adverse consequences.

Notice

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What is NCTCOG?

The North Central Texas Council of Governments (NCTCOG) is a voluntary association of cities, counties, school districts, and special districts which was established in January 1966 to assist local governments in planning for common needs, cooperating for mutual benefit, and coordinating for sound regional development.

It serves a 16-county metropolitan region centered around the two urban centers of Dallas and Fort Worth. Currently the Council has 242 members, including 16 counties, 169 cities, 22 independent school districts, and 31 special districts. The area of the region is approximately 12,800 square miles, which is larger than nine states, and the population of the region is over 6.5 million, which is larger than 38 states.

NCTCOG's structure is relatively simple; each member government appoints a voting representative from the governing body. These voting representatives make the General Assembly which annually elects a 15-member Executive Board. The Executive Board is supported by policy development, technical advisory, and study committees, as well as a professional staff of 311 persons.

NCTCOG's offices are located in Arlington in the Centerpoint Two Building at 616 Six Flags Drive (approximately one-half mile south of the main entrance to Six Flags Over Texas).

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NCTCOG's Department of Transportation

Since 1974, NCTCOG has served as the Metropolitan Planning Organization (MPO) for transportation for the Dallas-Fort Worth area. NCTCOG's Department of Transportation is responsible for the regional planning process for all modes of transportation. The department provides technical support and staff assistance to the Regional Transportation Council and its technical committees, which compose the MPO policy-making structure. In addition, the department provides technical assistance to the local governments of North Central Texas in planning, coordinating, and implementing transportation decisions.

EXECUTIVE SUMMARY

This report is an initial assessment of the vulnerability of North Central Texas (NCT) transportation infrastructure as part of the FHWA Climate Change/Extreme Weather Vulnerability Assessment Pilot Study. It summarizes the results from a sequence of meetings organized by the North Central Texas Council of Governments (NCTCOG), attended by local experts, and supported by several local government agency stakeholders to create a qualitative assessment of extreme weather and climate change impacts on infrastructure assets with a focus on Dallas and Tarrant Counties (which includes the primary cities of Dallas and Fort Worth).

The three major elements of the climate impact vulnerability assessment are the following:

1. A compilation of historical climate data and projected future climate information for the Dallas-Fort Worth (DFW) Metropolitan Area.

- The UTA climate group (A. Winguth) gathered climate and weather data from 1900 to 2010 to interpret the historic trends in extremes and variability of temperature and precipitation suggesting an increase in temperature, particularly in the summer season, and an increase in rainfall and rainfall intensity, primarily during the spring season.
- Historic weather-related disruption of transportation is mainly related to extreme events like snow and ice storms as well as damages by severe supercell-type thunderstorms.
- Future climate prediction suggests extreme temperatures of up to 125 °F by the end of 21st century, exceeding historic heat waves by 12 °F.
- By 2050, soil moisture is reduced by 10-15% in all seasons compared to historic values due to increase in temperatures. This suggests a higher risk of infrastructure damage by cracking and, together with elevated temperatures, a higher-than-present risk of fires, particularly in wooded neighborhoods.
- Higher likelihood of drought will also amplify the urban heat island, particularly during summer months, that can result in up to 10 °F temperature difference between downtown Dallas and adjacent rural locations.
- An increase in mean rainfall by up to 10% and severe thunderstorms by up to 40% in the spring season will likely lead to a higher risk of flooding affecting the infrastructure.
- Extreme flooding events exceeding historic floods are expected as a result of more tropical storm systems occurring in the fall season.

2. The NCT criticality assessment team developed an asset inventory of existing and future transportation infrastructure in Dallas and Tarrant Counties including roads, passenger rail, and aviation facilities.

- A comprehensive geographic information system (GIS) data inventory was compiled linking together Federal Emergency Management Agency (FEMA) flood maps, temperature maps produced by the UTA climate group, and location maps for current/future transportation assets.
- Projection of infrastructure expansion based on the NCTCOG long-range transportation plan (Mobility 2035: The Metropolitan Transportation Plan for North Central Texas – 2013 Amendment) was identified.
- Criticality of the current and future transportation infrastructure was determined based on the average annual daily traffic (AADT) and passenger rail ridership data.

3. The vulnerability of transportation infrastructure in Dallas and Tarrant Counties to risks from extreme weather and climate change was evaluated.

- Transportation infrastructure assets located within the FEMA 100-year floodplain were identified.
- A risk assessment matrix for transportation infrastructure was developed as a function of the criticality of the assets and high likelihood of extreme weather impacts (flooding and high temperatures).

Assessing future weather-related infrastructure disruption is important for developing adaptation strategies and prioritizing transportation planning efforts. The results of this Study provide ground evidence for developing adaptation strategies that ensure safe, effective, and efficient access and mobility into the future while also considering economic, social, and environmental needs. These goals are also part of the Texas Department of Transportation's (TxDOT's) strategic plan, as well as those of other transportation providers and local governments. Future work is required for a more accurate and comprehensive assessment of the potential vulnerability of all North Central Texas transportation assets. Such expanded efforts could be accomplished through greater incorporation of more precise forecasts of extreme precipitation and temperature (e.g. Collaborative Adaptive Sensing of Atmosphere or CASA Project), accommodation of spatially explicate analysis using three-dimensional models (e.g. Light Detention and Ranging or LiDAR) to determine runoff risks, increased monitoring/tracking of weather-related stresses and associated damage to infrastructure, and enhanced testing and application of various engineering methods and construction materials designed to improve resiliency.

List of Acronyms, Abbreviation, and Resources

CASA	Collaborative Adaptive Sensing of Atmosphere
CESM	Community Earth System Model
CIKR	Critical Infrastructure and Key Resources
CMIP	Coupled Model Intercomparison Project
DART	Dallas Area Rapid Transit
DFW	Dallas Forth Worth Metropolitan Area
DFWIA	Dallas-Fort Worth International Airport
DOT	Department of Transportation
EPA	Environmental Protection Agency
FWTA	Fort Worth Transportation Authority
FHWA	Federal Highway Administration
GIS	Graphical Information System
LiDAR	Light Detection and Ranging
IPCC	Intergovernmental Panel on Climate Change
MODIS	Moderate Resolution Imaging Spectroradiometer
NWS	National Weather Service
NOAA	National Oceanic and Atmospheric Administration
NCAR	National Center for Atmospheric Research
NCTCOG	North Central Texas Council of Governments
SST	Sea Surface Temperature
RCP	Representative Concentration Pathways
TRE	Trinity Railway Express
TxDOT	Texas Department of Transportation
UHI	Urban Heat Island
UTA	University of Texas at Arlington
WMO	World Meteorological Organization

NCT Vulnerability Assessment Team

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Metric Conversions

Temperature
1°C = 274.15 K -273.15
1°C = (33.8°F -32)*5/9

Precipitation
1 mm = 0.03937 in

Length
1 km = 0.62137 miles

Pressure
1000 hPa = 29.5334 in Mercury

1. INTRODUCTION

This Study has been developed in collaboration between the University of Texas at Arlington **(UTA**) and the North Central Texas Council of Government **(NCTCOG)** in partnership with the Public Works Department of the City of Dallas and the Fort Worth Transportation Authority (FWTA), to assess how future extremes in weather events through the end of the 21st century can affect the transportation infrastructure in Dallas and Tarrant Counties. This assessment (Fig. 1.1) will not only allow transportation planners to adapt future infrastructure demands and improvement needs to changes in extreme weather, but hereby will also enhance and protect taxpayer investments.

Extreme weather events have frequently disrupted mobility and levels of services on highway and rail networks in the Dallas-Fort Worth (DFW) Metropolitan Area, and current climate projections suggest that such disruptions may occur more often in the future. Extreme precipitation events and vulnerable infrastructure create transportation delays, particularly in locations of high traffic volume, and they also can endanger public safety across the region.

Past extreme weather events like severe thunderstorms, flooding, or ice have severely impacted the transportation infrastructure of the DFW area. Examples in the recent past include the Fort Worth tornado of March 28, 2000; the tornado outbreak of April 3, 2012; the heavy precipitation event of September 7 - 8, 2010; the heavy ice and snowfall event of February 11 - 12, 2010; the Groundhog Day Blizzard of January 31 to February 2, 2011; and the ice storms of November 22-24, 2013 and December 5-7, 2013.

NCTCOG, the region's Metropolitan Planning Organization (**MPO**), has been awarded funding by the Federal Highway Administration (**FHWA**) to conduct a ***Type I: Vulnerability Assessment Pilot*** in order to analyze the vulnerability of transportation infrastructure to climate change effects and extreme weather events in the North Central Texas (NCT) region.

In this technical study the three major tasks listed below have been addressed:

- **Task 1.** A compilation of historical climate data and projected future climate information for the Dallas-Fort Worth Metropolitan area has been provided, including surface air temperature, precipitation, evaporation, and soil moisture/water content, in order to assess the impact of climate change.
- **Task 2.** The existing infrastructure of the DFW area including road and rail has been aggregated together with flood maps. The importance of infrastructure assets has been ranked for the Dallas and Tarrant Counties using normalized traffic density maps from the Federal Highway Administration, flood plains, and other regional sources. The future expansion of the transportation infrastructure is based on the NCTCOG's Long Range

Transportation Plan, Mobility 2035: The Metropolitan Transportation Plan for North Central Texas - 2013 Amendment.

Task 3. The vulnerability of Dallas and Tarrant Counties' transportation infrastructure to extreme weather and climate change has been evaluated. A vulnerability assessment matrix for transportation has been used to estimate the likelihood of hazards and the magnitude of adverse consequences. The criticality of transportation assets is categorized into low, medium, and high vulnerability for future heat waves; low and high risk of fires; and low, medium, and high vulnerability for future floods.

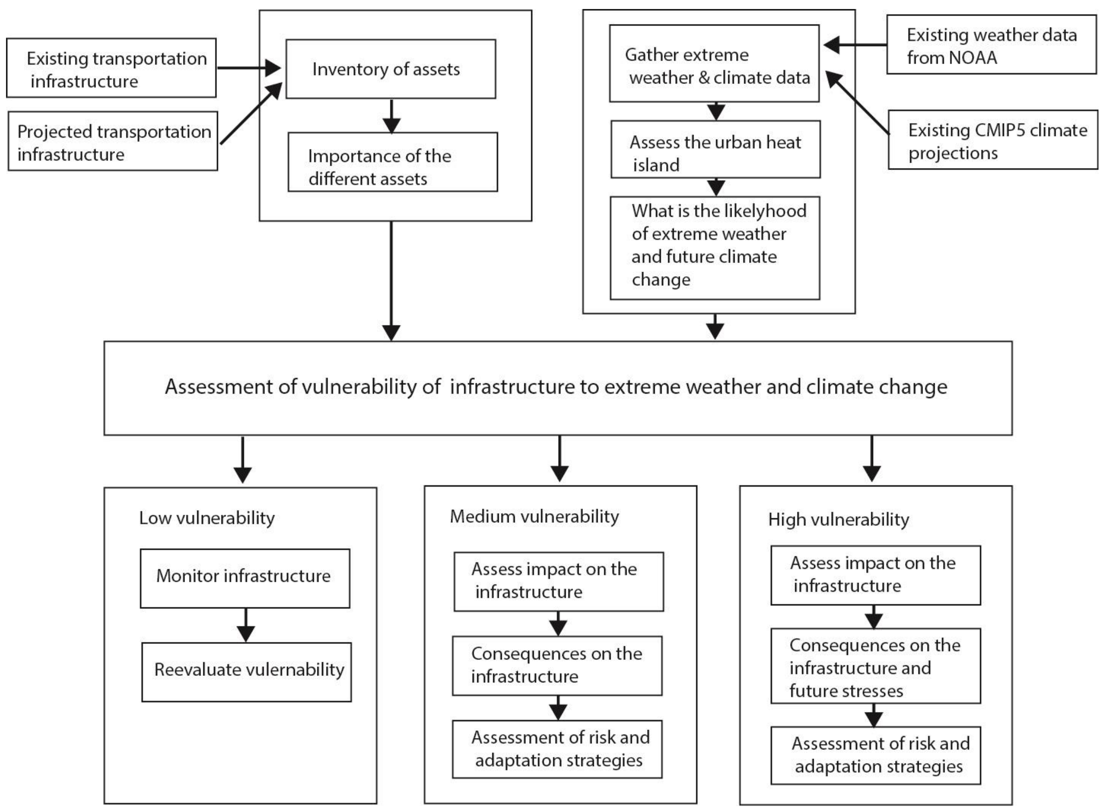

Figure 1.1. The climate change risk assessment methodology for DFW area infrastructure

2. HISTORICAL AND PROJECTED CLIMATE AND EXTREMES IN WEATHER OF NORTH-CENTRAL TEXAS

2.1. Historical Climate and Extremes in Weather

The climate of North Central Texas is classified as humid subtropical, with 8 months above 68 °F (20 °C) and dry winters (Fig. 2.1; Köppen-Geiger classification Cfa; Köppen, 1936; Peel et al., 2007). Summer temperatures are generally high with daytime extremes of up to 113 °F (Fig. 2.1a). The longest heat wave on record for North Central Texas occurred during the summer season of 2011, with 71 consecutive days exceeding 100°F or 37.8 °C (Fig. 2.2). The precipitation gradient of North Central Texas is remarkable, with a difference of about 12 in (304 mm) year^{-1} between Palo Pinto County in the west and Rockwall County in the east (Nielsen-Gammon, 2011). The largest portion of the annual precipitation results from thunderstorm activity, which occurs most frequently in the spring (Fig. 2.1b), and is characterized by occasional heavy rainfall over brief periods of time.

The annual temperature anomaly of North Central Texas with respect to the 1900-2011 average, shown in Fig. 2.3, reflects the long-term warming trend of 0.09 °F/decade. The overall warming amounts to 1.04 °F over this period, with the strongest increase of 0.25 °F from 2001 to 2011. The seasonal trends are particularly strong during the last

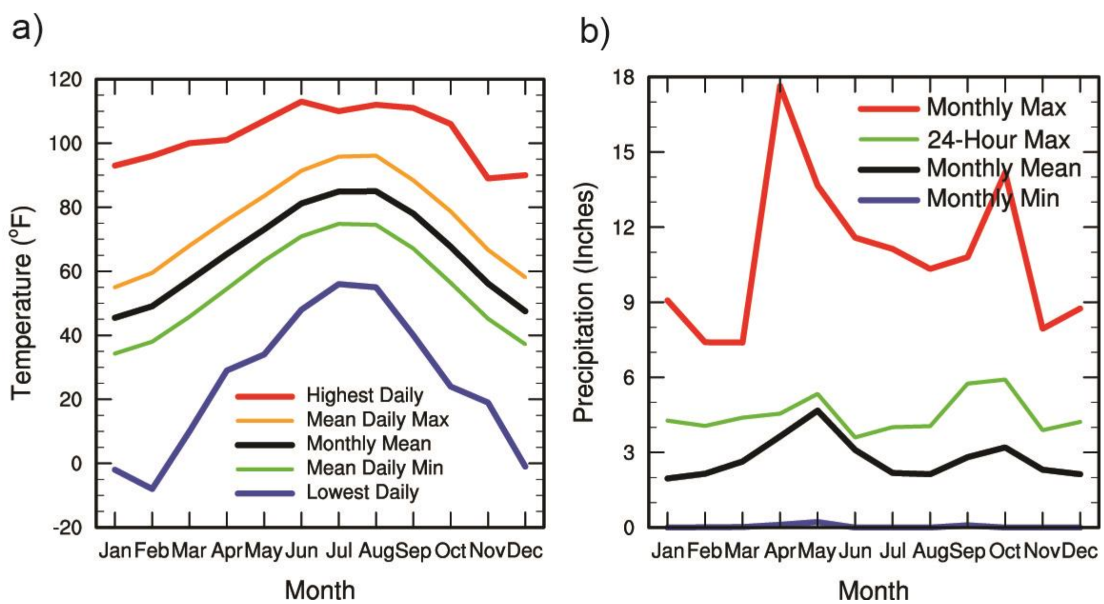

Figure 2.1. Monthly mean temperature (a) and precipitation (b) for Dallas-Fort Worth averaged from 1980 to 2010 (Source: National Weather Service, Fort Worth, 2012). Annual mean temperature is 65.4 °F (18.8°C) and annual precipitation is 33.1 in (839.91 mm) year-1 averaged over the period 1900 to 2010.

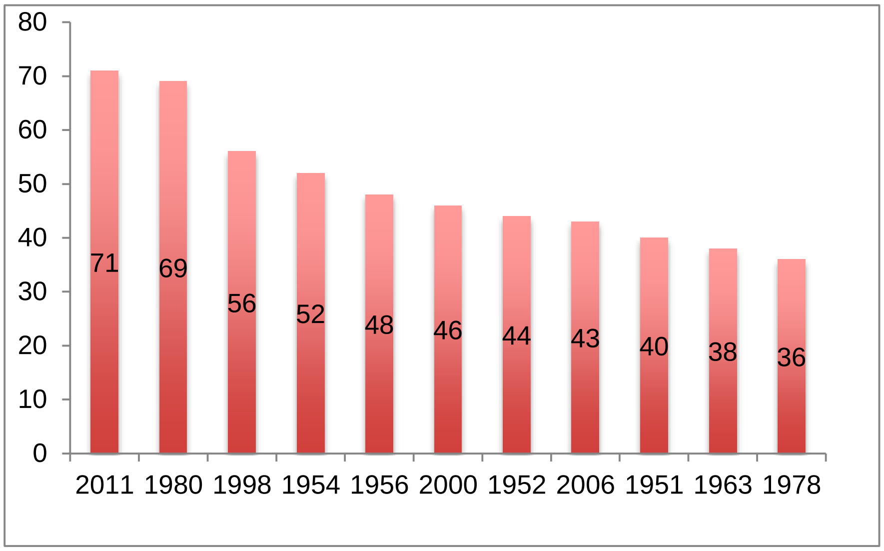

Figure 2.2. Dallas-Fort Worth annual consecutive 100° F days (NWS Dallas-Fort Worth).

decade, with an increase in temperature of 0.61 °F during summer months and 0.11 °F during winter months over this time period (Fig. 2.3 a).

Precipitation anomalies relative to the period between 1900 and 2010 (Fig. 2.3b) indicate higher amounts of rainfall the decade of the 1990's. Severe droughts of the early 1950's and in 2006 are represented in this graph by anomalously low rainfall. The long-term precipitation trend for the DFW area indicates an increase in rainfall of 4.8 in (or 15 %) over the period from 1900 to 2010. This increase occurred particularly during winter months, whereas summer season precipitation slightly declined. Increases in rainfall and snowfall is highly correlated with an increase in regional crash rates (Fig 2.5 a).

Several studies have supported the hypothesis that droughts over the Great Plains are linked to cold sea surface temperature (SST) anomalies linked to La Niña in the tropical Pacific (Trenberth et al., 1988; Trenberth and Branstator, 1992; Palmer and Brankovic, 1989; Ortegren, 2008; Seager et al., 2009). The 2010-2011 drought in Texas (Fig. 2.4) was likely amplified by strong La Niña conditions, together with a positive phase of the Atlantic Multidecadal Oscillation (McCabe et al., 2004; Mo et al., 2009; Nielsen-Gammon, 2012). Low rural soil moisture during the previous winter, also noted as a factor during the 2003 heat wave in Paris (Cassou et al., 2005; Dousset et al., 2007), may have enhanced the drought in North Central Texas (Hong and Kalnay, 2002). Anthropogenic land use changes could have further intensified the drought conditions (Cook et al., 2009). Historical trends (Fig. 2.2) suggest that droughts associated with prolonged heat waves have been more frequent in the last two decades. The risk of wildfires is significantly higher under drought conditions (Texas AM Forest Service, 2015a).

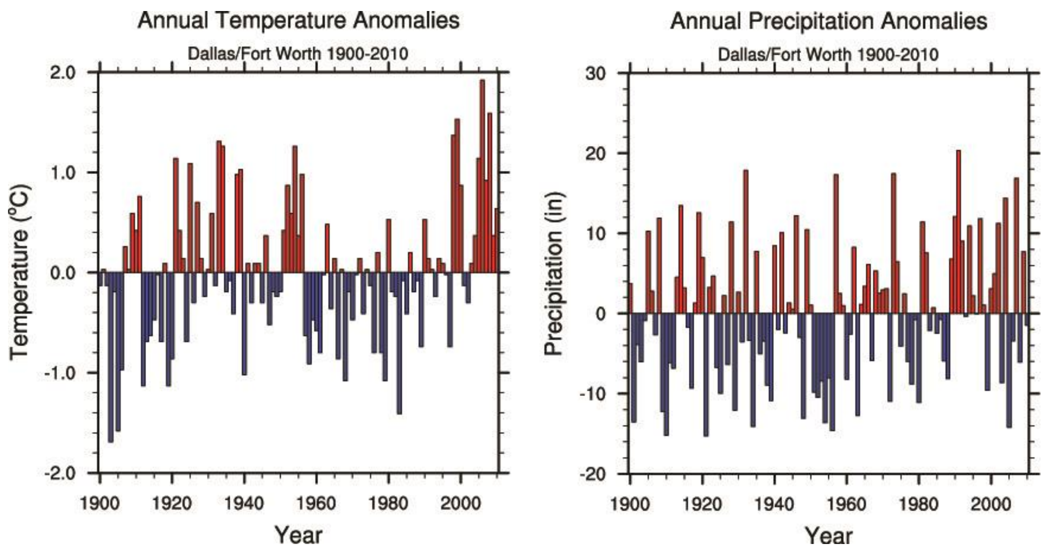

Figure 2.3. Annual average surface temperature (a) and rainfall (b) anomalies as compared to the average between 1900 and 2010, in °C from NWS COOP station 412242 (Dallas-Fort Worth International Airport).

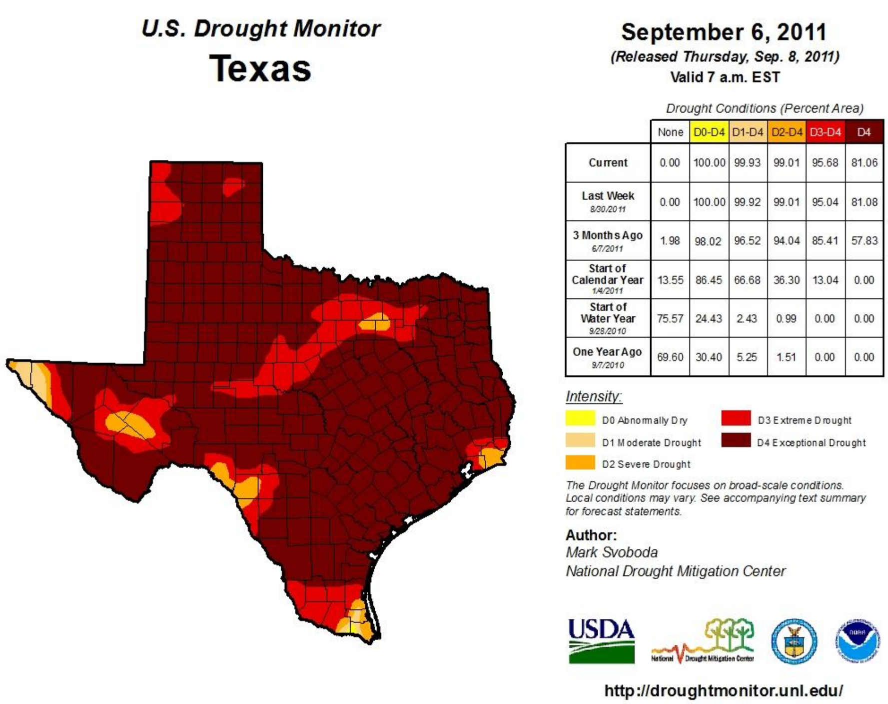

Figure 2.4. Severe 2011 drought in Texas as inferred from the U.S. Drought Monitor Texas (http://droughtmonitor.unl.edu).

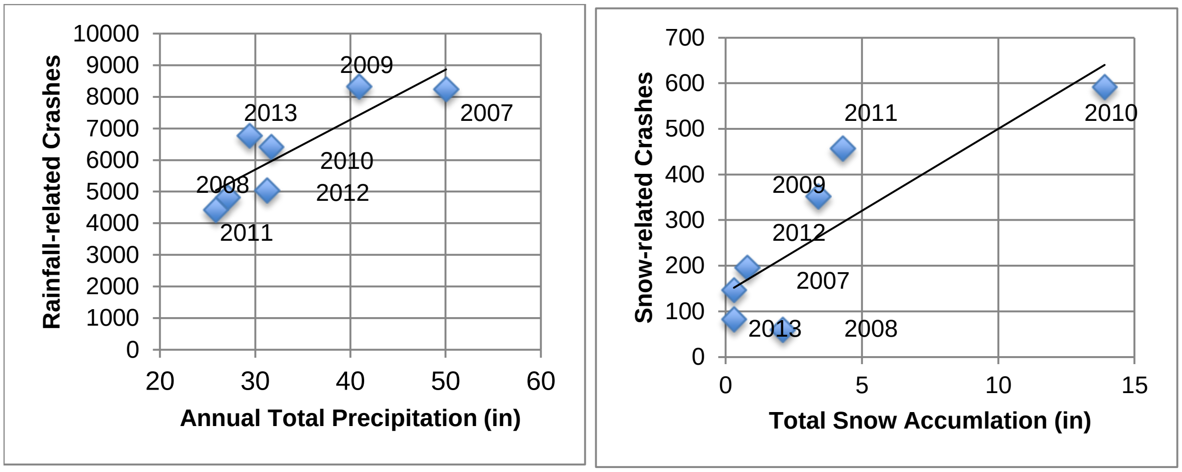

Figure 2.5. a) Annual total precipitation for the period 2007 to 2014, in inches, and rain-related crashes and b) annual snow accumulation for the period 2007 to 2014, in inches, and snow-related crashes.

The transportation infrastructure of the DFW area is highly sensitive to frozen precipitation (Fig. 2.5b, Fig. 2.6a,) because of limited plow capacity for highways, power outages for light rail signal systems, ice buildup on the light rail, and freezing switches for railroad. Extreme events like the Groundhog Day Blizzard of January 31 to February 2, 2011; the ice storm of November 22-24, 2013; and the winter storm of December 5-7, 2013, have led to significant traffic disruptions (Fig. 2.6b). In the recent decade, the cumulative snowfall increased (Fig. 2.6a) compared to the previous decades, which is consistent to the positive rainfall anomaly. Decadal variabilities such as the Atlantic Multidecadal Oscillation and the El Niño Southern Oscillation likely influence the changeability in the cumulative season snowfall.

Severe extra-tropical and tropical cyclones can also contribute to infrastructure disruption (Fig. 2.5a and 2.7a). Frontal systems associated with the extratropical cyclones can lead to tornado formation, for example the Fort Worth tornado of March 28, 2000, or the tornado outbreak of April 3, 2012. Straight-line winds (derecho) and associated microbursts (Caracena et al., 1987), e.g. the August 2, 1985 storm contributing to a crash of Delta Air Lines Flight 191 (Fujita, 1985), or the recent October 3, 2014, Fort Worth-Arlington derecho, also cause significant damage. On average, there were annually eight tornado watches and 14 severe thunderstorm warnings over the period of 1999-2008 (Fig. 2.7b, NWS Storm Prediction Center, Norman, OK). Tropical storms like Hurricane Ike in 2008 can lead to significant rainfall and flooding events. Historical surveys indicate that the increasing trend in the strength of tropical cyclone precipitation is related to the long-term rise in sea surface temperature linked to climate change (Emanuel, 2005; Zhu, 2014).

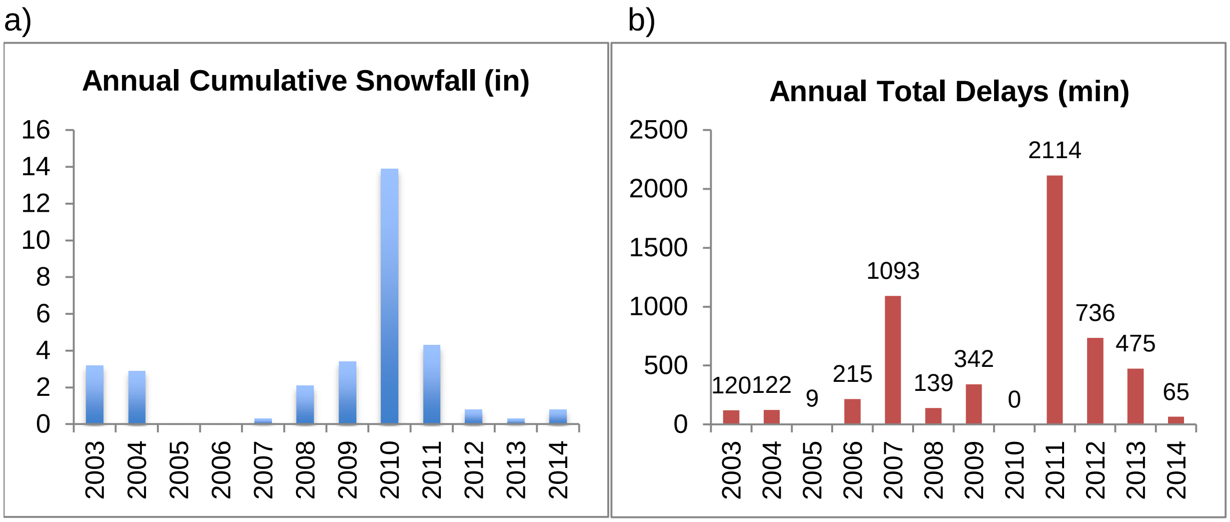

Figure 2.6. a) Annual cumulative snowfall for the period 2003 to 2014, in inches and b) service disruption in minutes of the commuter railway TRE. Note that no service data are available for 2010.

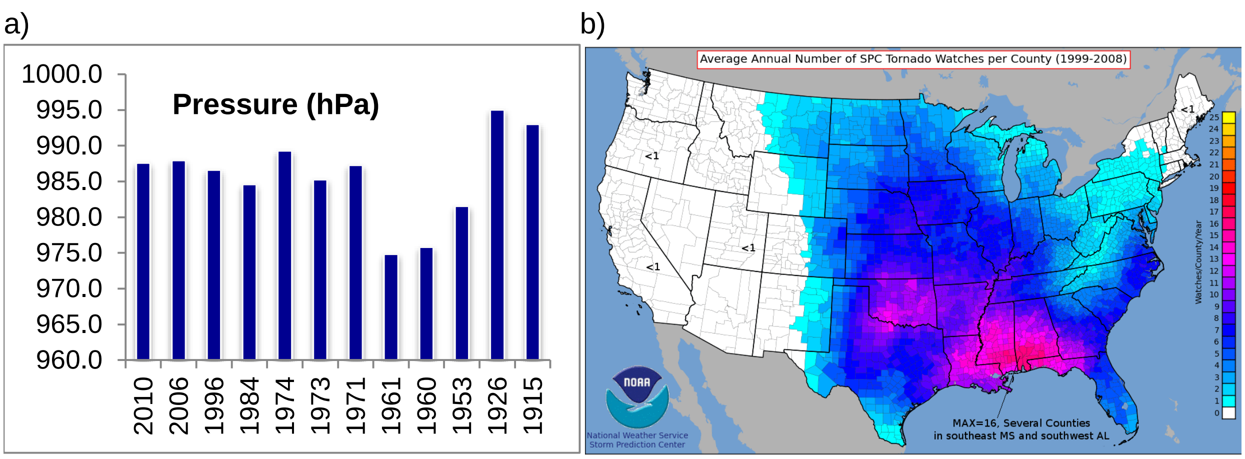

Figure 2.7. a) Surface pressure of significant storm systems (in hPa) passing the Dallas-Fort Worth area and b) average annual number of tornado watches over the period 1999-2008. Note that the Dallas-Fort Worth Metropolitan area has about 8 tornado watches per year.

2.2 Urban Heat Island of Dallas-Fort Worth

Urban areas are generally warmer than rural locations (Howard, 1833), a phenomenon known as the urban heat island (UHI) effect (Oke, 1973). The UHI is commonly estimated by the difference in temperature measurements between weather stations in urbanized areas and rural areas. In this context, rural areas are defined as landscapes that are predominantly natural and not covered with buildings, parking areas, roads, or other man-made urban surfaces (Stewart, 2011). The hourly surface temperature

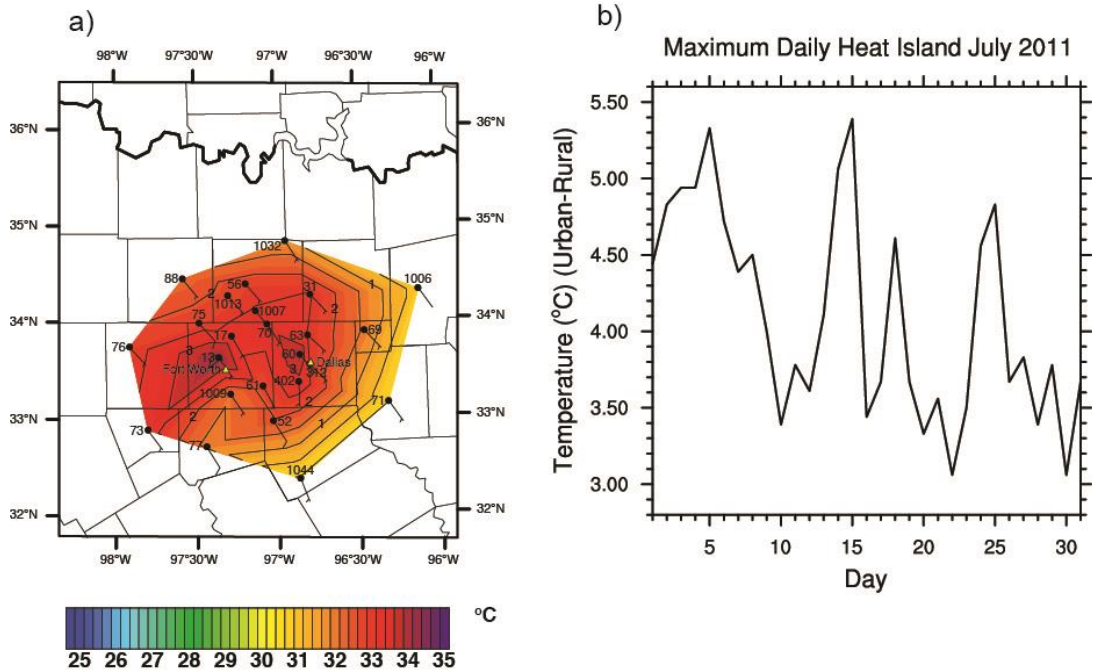

Figure 2.8. Maps of the average air temperatures (°C) at screen level at (a) 21:00, reported by TCEQ stations listed in Table II in Winguth et al. (2013). Wind barbs are in knots. Each short barb represents 5 knots and each long barb 10 knots. Contour lines show the magnitude of the urban heat island relative to the Kaufman station (CAMS 71). Contour line interval is 0.5°C. b) Daily maximum urban heat island in July 2011.

differences between DFW area urban and rural sites have been used to calculate the urban heat island from 2001 to 2011 (Winguth and Kelp, 2013). The UHI effect peaked after sunset, and was particularly strong during the drought and heat wave in July 2011, reaching a single-day instantaneous maximum value of 9.7 F° (5.4°C) and a monthly mean maximum of 6.1°F (3.4°C), compared to the 2001 to 2011 July average of 4.3 F° (2.4°C) (Fig. 2.8). The ground-based assessment of canopy air temperature at screening level has been supported by a remote-sensed surface estimate from the MODIS/Terra satellite, highlighting a dual-peak maximum heat island in the major city centers of Dallas and Fort Worth. Both ground-based and remote-sensed spatial analyses of the maximum heat island indicate a northwest shift, the result of southeast winds in July 2011 of ~4.5 mph (2 m s^{-1}) on average (Fig. 2.8). There was an overall positive trend in the UHI of 0.2 °F/decade in the DFW area from 2001-2011, due to rapid urbanization. Superimposed on this trend are significant inter-annual and decadal variations that influence the urban climate.

2.3. Projected Climatic Changes and Extremes in Weather

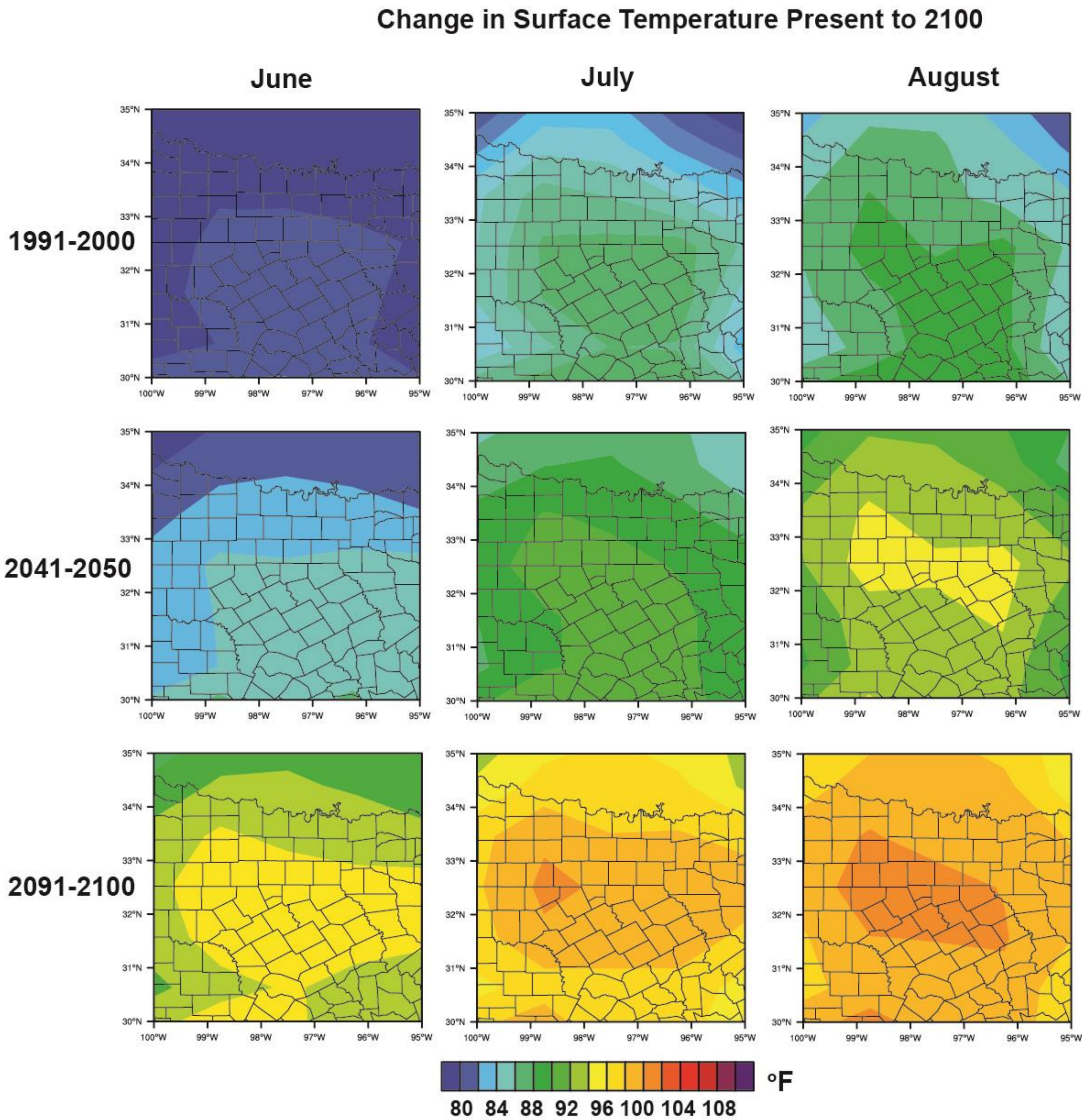

Figure 2.9. Projected summer surface air temperature until 2100 predicted by the RCP8.5 scenario from CESM1.2.

Recent reports from the Intergovernmental Panel of Climate Change support significant global and regional climate changes (IPCC, 2013). The historical trend as discussed above is already very likely influenced by these changes. For this Study, output from the Community Earth System Model (CESM) Version 1.2 from the National Center of Atmospheric Research (NCAR) is taken to assess historical and future trends until the year 2100.

The future climate scenario used is the RCP8.5 scenario, a “business as usual” scenario with the assumption that the anthropogenic radiative forcing will be 8.5 W m^{-2} by the year 2100. Radiative forcing is used to compare and assess anthropogenic and natural drivers of climate change such as solar variability, greenhouse gas concentrations, and atmospheric dust composition. The predicted changes of surface air temperature for North Central Texas under this scenario are significant with an 8.1 °F (4.5 °C) increase in summer temperature by the period 2091-2100 relative to the recent historical period of 1986 – 2005 (Fig. 2.9, IPCC, 2013).

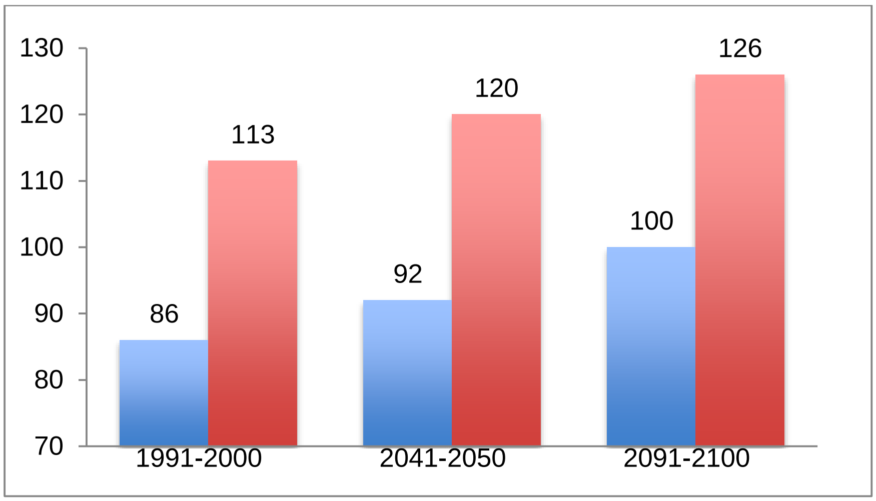

Figure 2.10. August mean temperature in °F (blue bar) and August maximum temperature (red bar) for Dallas and Tarrant Counties predicted by CESM1 and CMIP5 simulations (see text).

The analysis of the climate simulation suggests an increase in mean July temperature to ~90 °F for 2041-2050 in Dallas and Tarrant Counties compared to 85 °F for 1991-2000 (Fig. 2.9). Mean August temperatures in theses counties would reach 94 °F by 2041-2050, thus daily extremes could likely exceed 120 °F (IPCC, 2013), comparable to historical extreme temperatures of cities such as Phoenix, AZ (Western Regional Climate Center; http://www.wrcc.dri.edu). For the end of this century, the RCP8.5 simulation with CESM1.2 predicts at least 2 months of mean surface air temperatures above 100 °F, and 3 months of mean temperatures above 95 °F, with extreme temperatures exceeding 13 °F above historical extremes (Figure 12.13c in IPCC, 2013), or 126 °F (Fig. 2.10), and comparable to extreme temperatures in Furnace Creek, Death Valley, CA (WMO, http://wmo.asu.edu). The likely impacts of such predicted extreme heat waves are an increase in wildfires along paved highways, heat-induced stress on bridges and railroads, air conditioning problems in public transport vehicles, and heat-related accidents by failure of individual vehicles and heat-related stress. These impacts can be translated into substantial mobility and economic loss.

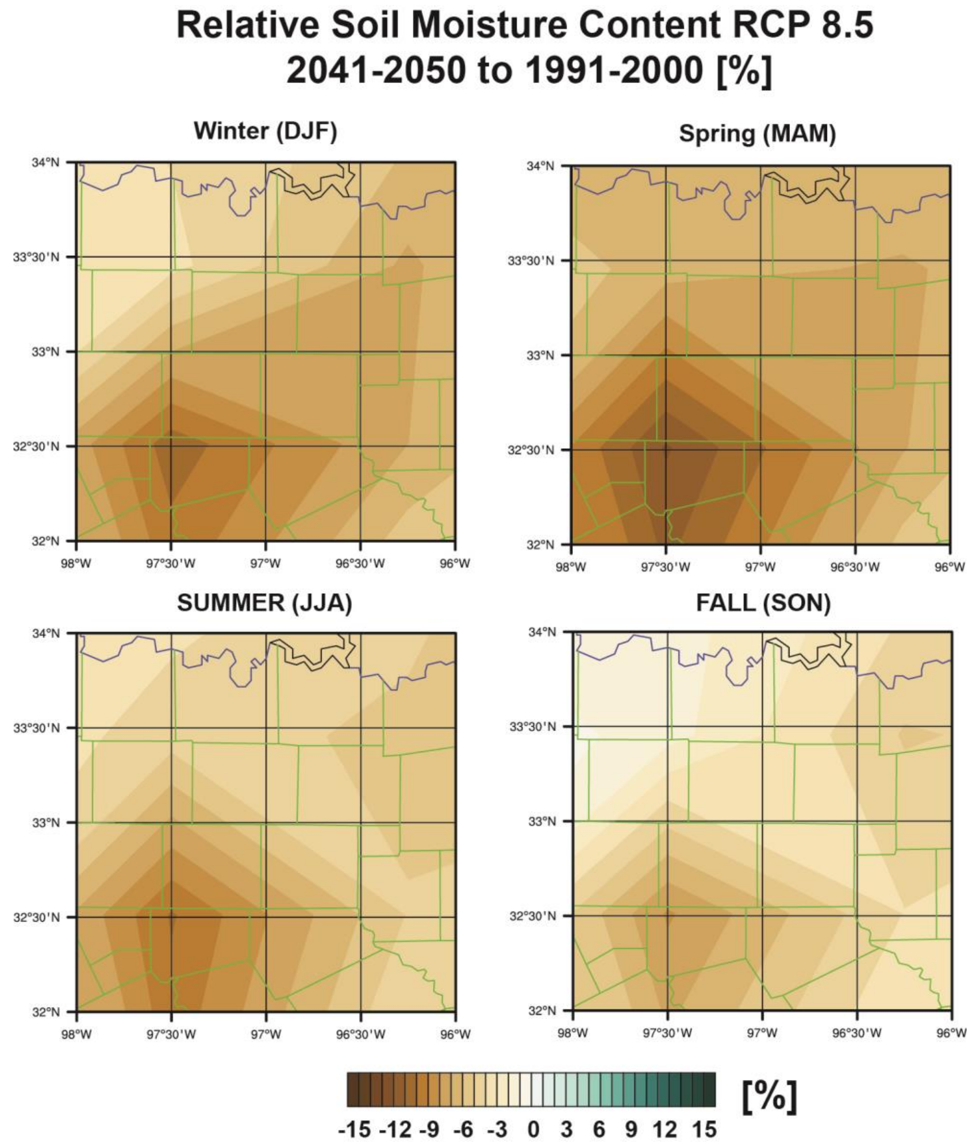

Figure. 2.11. Projected change of soil moisture until 2050, predicted by the RCP8.5 scenario from CESM1.2.

Changes in soil moisture (Fig. 2.11) and rainfall (Fig. 2.12) can have a significant impact on infrastructure. Low soil moisture accompanied with severe drought favors cracking and premature loss of road/railway serviceability, partly because of an increase in soil suction (Puppala et al., 2011). A persistent U.S. southern drought, with the cumulative effects of low soil moisture and extreme temperatures, not only impacts pavement and its sub-grade materials/soils but also creates a higher risk of wildfires in general. These effects were documented in experiences by the 2011 Possum Kingdom complex fires, a grouping of four wildfires that consumed about 148,000 acres in Palo Pinto, Stephens, and Young Counties northwest of Fort Worth, and the Bastrop County complex fire that burned nearly 34,400 acres in central Texas (Texas A&M Forest Service, 2015b).

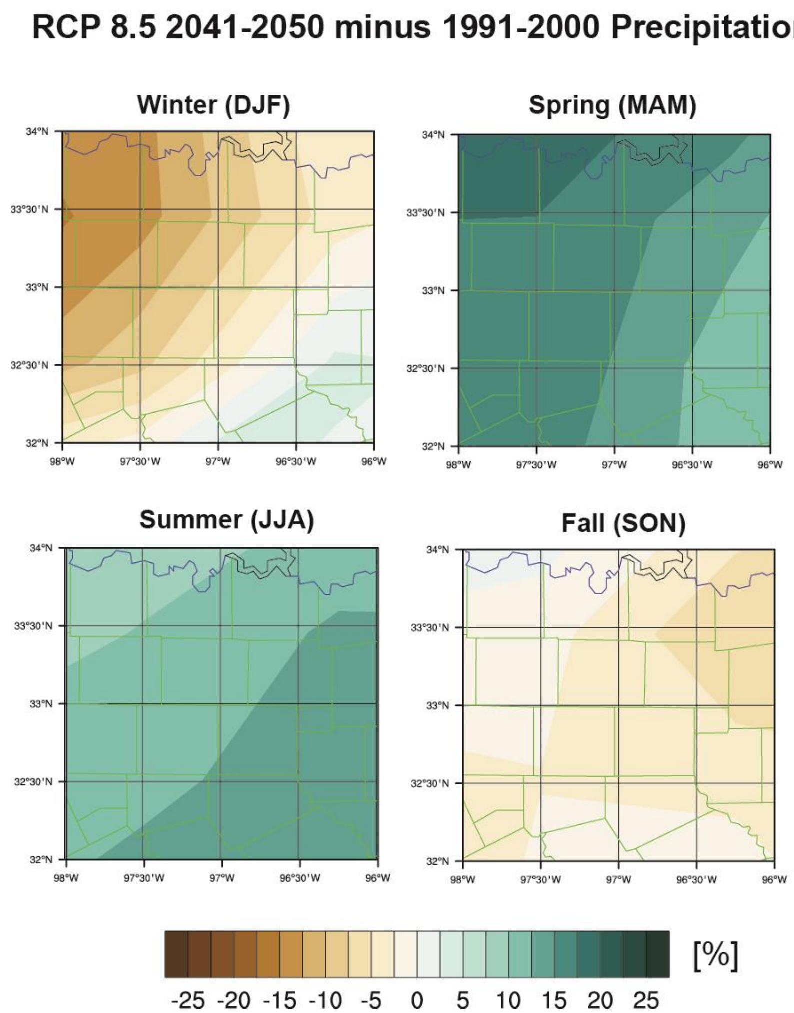

Figure. 2.12. Projected change of rainfall until 2050, predicted by the RCP8.5 scenario from CESM1.2.

The spread of wildfires is accelerated by high wind speed and dry air masses and can be amplified by firestorm or conflagration effects. Future climate prediction indicates significantly lower soil moisture for all seasons by 2050, in particular for the western counties of the DFW area (Fig. 2.11), because of the rise in temperature. Rainfall is predicted to be lower both in the winter and summer seasons; however, periods of low precipitation would be disrupted by single storm events that likely will be stronger in intensity (Fig. 2.12). An increase in rainfall would probably occur particularly during spring season, associated with the intensification of extra-tropical cyclones. There is a robust likelihood of increase in the number of days of severe thunderstorms by the end of the century (Fig 2.13, Diffenbaugh et al., 2013). Particularly during the spring season, severe thunderstorm likelihood increases to about 40% relative to historical values, leading to a heightened risk of disruption by high wind speed, hail damage, and flooding, especially in low-lying areas in or adjacent to the floodplain (see Chapter 2.1).

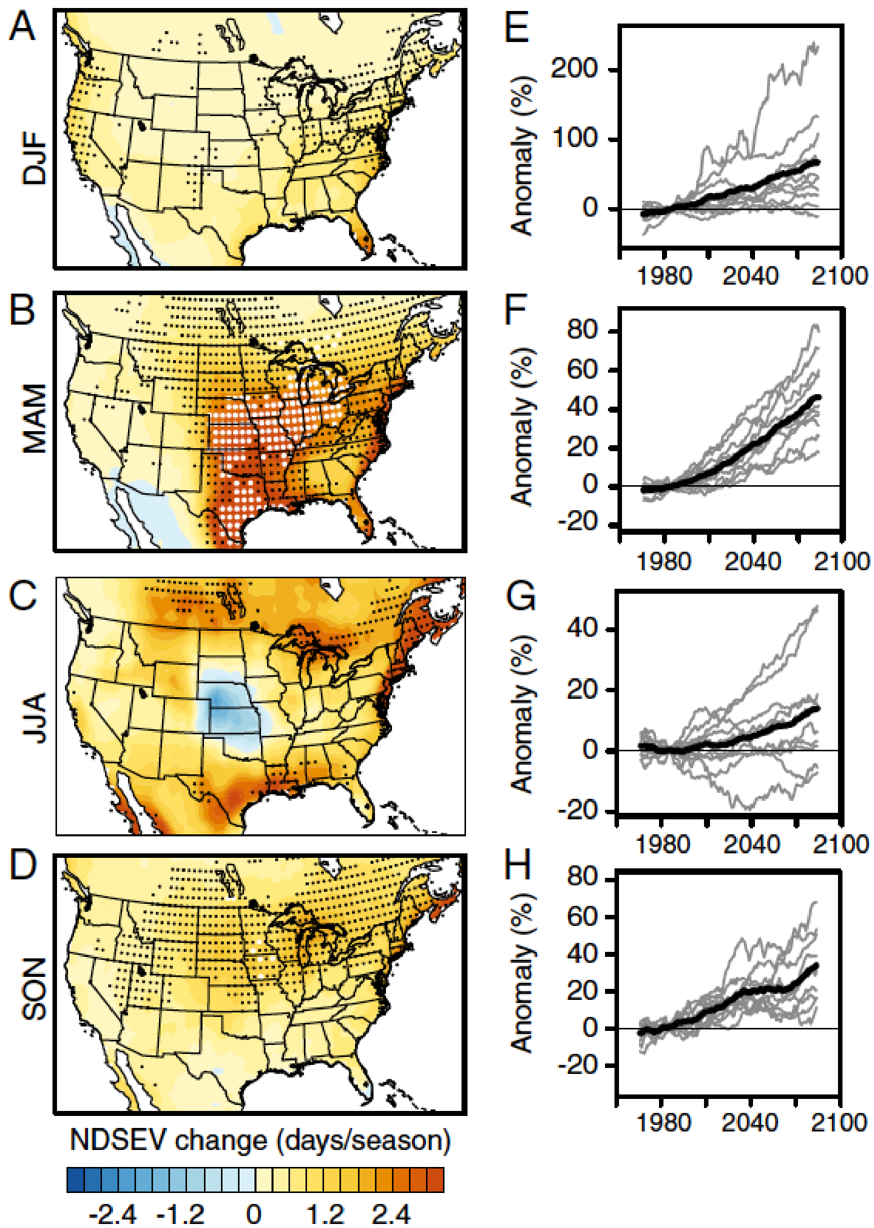

Figure. 2.13. Left column (A–D): Change in severe thunderstorm environments (NDSEV) for the last 3 decades of 21st century, predicted by CMIP RCP8.5 relative to the three last decades of the 20th century for winter (DJF), spring (MAM), summer (JJA), and autumn (SON) seasons. Black (gray) dots indicate areas where the signal from the ensemble simulations exceeds one (two) Standard deviation(s) of the ensemble noise, referred to as robust (highly robust). Right column (E–H): Anomaly of NDSEV for each year in the 21st century expressed as a percentage value relative to the 1970-1999 baseline for each individual CMIP model simulation (thin line) and ensemble mean (thick line) over the eastern United States (Figure from Diffenbaugh et al., 2013).

Enhanced rainfall by more intense tropical cyclones is likely for the summer-to-fall season (Knutson et al., 2001; Pielke et al., 2005 Emanuel, 2011). Predicted enhanced convection by more intense tropical storms will likely cause an increase in severe flooding. The flooding would exacerbate erosion and runoff characteristics in areas impacted by increased urbanization and/or drainage channelization, and put infrastructure both within and immediately adjacent to 100-year flood zones at greater risk for damage or incapacitation.

A change in the hydrological cycle also affects the strength of the UHI. Figure 2.14 illustrates the correlation between the Palmer Drought Severity Index and the maximum UHI. The calculated Pearson's linear correlation coefficient is -0.734 and the ρ value is 0.01, indicating that there is a significant correlation between the drought and maximum heat island (Winguth and Kelp, 2013). Two remarkable droughts with different characteristics occurred between 2001 and 2011, the 2005-2006 drought (Dong et al., 2011) and the 2010-2011 severe drought (Nielsen-Gammon, 2012). Predicted reduction in the soil moisture (Fig. 2.11) will lead to significant increase in the urban-to-rural temperature gradient, thus amplifying the heat stress on the infrastructure as discussed above.

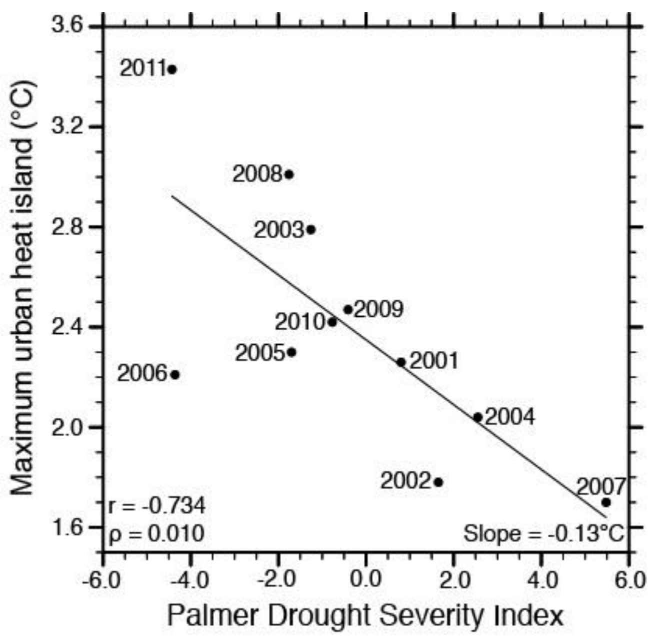

Figure 2.14. Correlation between the Palmer Drought Severity Index (PDSI) and the maximum urban heat island (UHI) with a Pearson's linear correlation coefficient of -0.734 and ρ value of 0.01 for North Central Texas for July between 2001 and 2011. Note that negative PDSI denotes drought conditions, for example, -2 is moderate drought, -3 is severe drought, -4 is extreme drought. The UHI is computed between the Dallas Hinton station (CAMS 60) and the Kaufman station (CAMS 71) (from Winguth and Kelp, 2013).

3. EXISTING AND PROJECTED INFRASTRUCTURE OF DALLAS AND TARRANT COUNTIES

3.1. Introduction

In order to complete Task 2, the Study team compiled an inventory of existing and future transportation infrastructure in Dallas and Tarrant Counties and ranked the importance of certain assets based on their capacity-based criticality. According to Mobility 2035: The Metropolitan Transportation Plan for North Central Texas – 2013 Amendment, the Dallas-Fort Worth (DFW) region is projected to grow rapidly: approximately 45% increase in population, 44% in employment, and 55% in vehicle-miles traveled from 2013 to 2035. Given this projected growth, the annual cost of congestion is expected to more than double from $4.7 billion to $10.1 billion (Table 3.1). The existing transportation infrastructure would require significant maintenance for aging and damaged structures and improvements in potential capacity to provide an adequate level of mobility/accessibility, maintain environmental quality, and prepare and/or adapt for more severe and frequent extreme weather events.

Table 3.1. Projected growth of the North Central Texas region from 2013 to 2035

Regional Performance Measures	2013	2035	% Change
Population	6,778,201	9,833,378	45%
Employment	4,292,516	6,177,016	44%
Vehicle Miles of Travel	181,516,746	281,580,581	55%
Hourly Capacity (Miles)	42,593,607	51,288,092	20%
Vehicle Hours Spent in Delay (Daily)	1,165,512	2,489,440	114%
Increase in Travel Time Due to Congestion	32.1%	44.9%	40%
Annual Cost of Congestion (Billions)	$4.7	$10.1	114%

Source: Mobility 2035 Plan – 2013 Amendment (NCTCOG, 2013)

3.2. Asset Inventory and Data Collection

An inventory of current and future transportation assets was compiled focusing on roads, passenger rail facilities, and critical bridges in Dallas and Tarrant Counties primarily using NCTCOG's existing inventories compiled from the region's various transportation providers (Table 3.2; Fig. 3.1-3.4). Future projections of transportation infrastructure location and capacity was based on the Mobility 2035 Plan – 2013 Amendment. Geospatial data for roadway arterials, collectors, and local roads with attributes of functional classification, number of lanes, and annual average daily traffic (AADT) were assembled. Rail networks include both passenger and freight rail facilities.

Geospatial data for annual passenger railridership were joined to rail lines operated by Dallas Area Rapid Transit (DART) and the Fort Worth Transportation Authority (FWTA). Lastly, locations of airports were mapped and joined with 2013 passenger boarding data.

In addition to transportation assets, FEMA 100-year floodplain maps were obtained to identify the assets that are more vulnerable to flooding in case of severe precipitation events. Likewise, temperature maps were created to identify assets that are more vulnerable to extremely high temperatures and potential wildfires, which would potential lead to increases in maintenance and repair costs. The floodplain and temperature maps were used in vulnerability and risk assessment (Chapter 4).

Table 3.2. Asset inventory and data collection

Assets	Format	Source	Information Types
Transportation Infrastructure			
Roads (2014 and 2035)	GIS	NCTCOG	AADT, functional classes, number of lanes
Critical Bridges (2014 and 2035)	GIS	NCTCOG	Location and elevation of bridges
Rail Road Lines (2014 and 2035)	GIS	NCTCOG, DART, TRE, The T	Annual passenger ridership
Airports (2007)	GIS	NCTCOG	Airport passenger boarding (2013) from the Federal Aviation Administration
Natural features			
100-yr Floodplain	GIS	FEMA	Flooded area based on 100-year floods
River data	GIS	NCTCOG, TRA, USGS	Stream flow
Temperature	GIS	NCAR, TCEQ, NWS	Meteorological stations and climate simulations

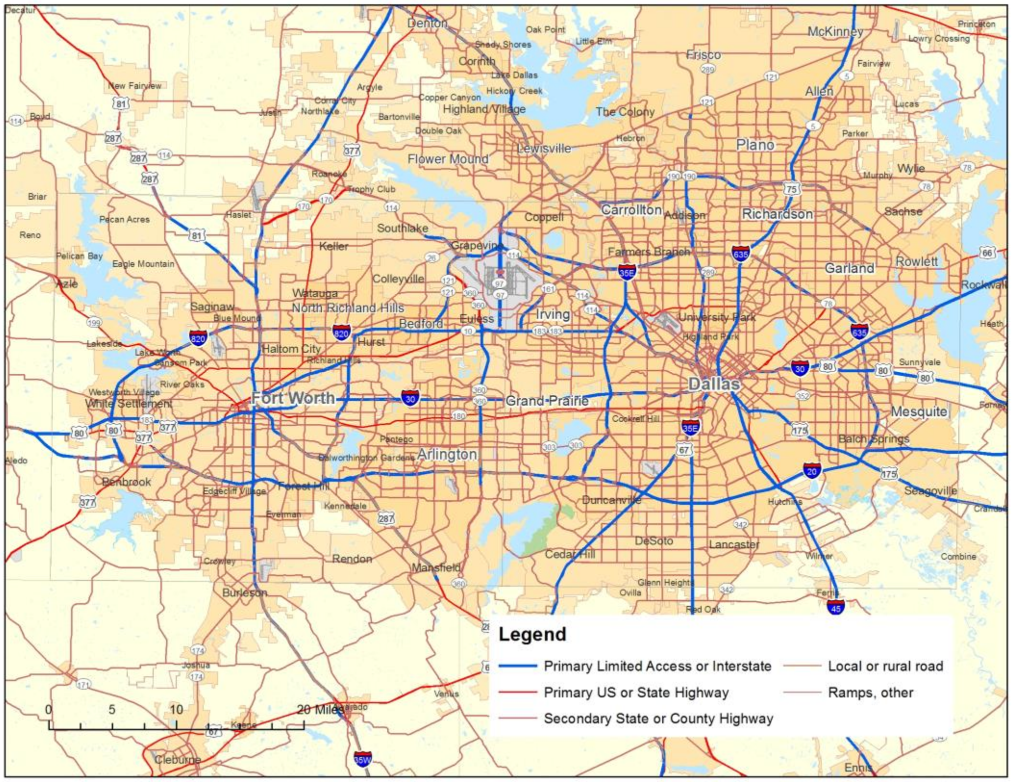

Figure 3.1. Current roadway network of Dallas and Tarrant Counties (2014).

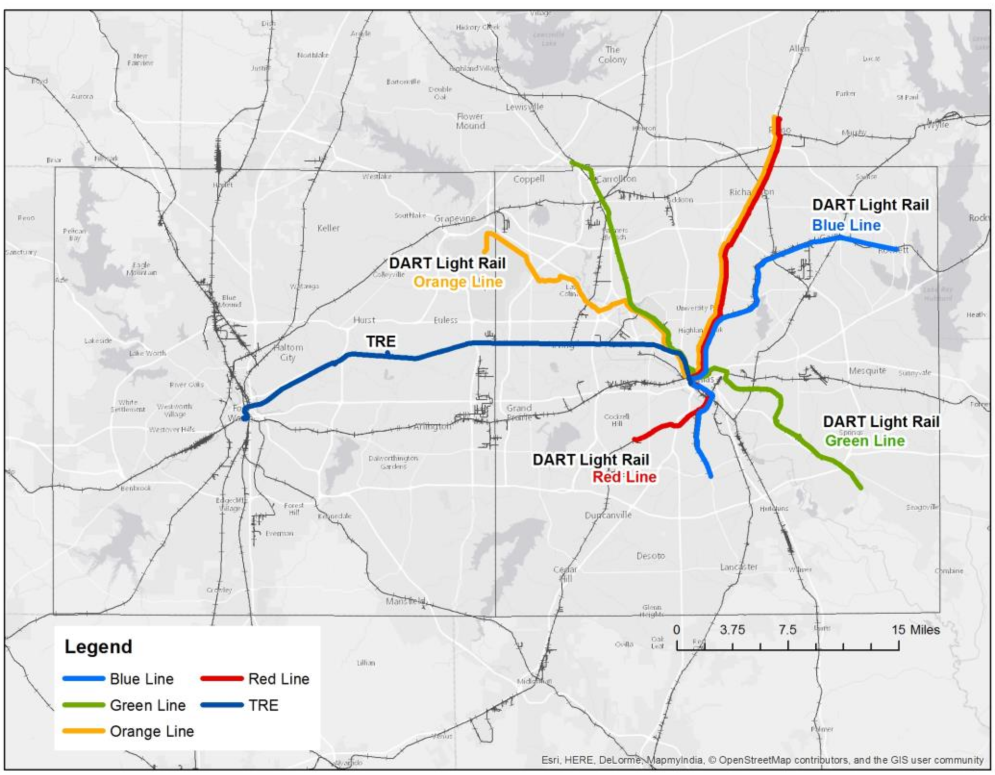

Figure 3.2. Current (2008) rail networks of Dallas and Tarrant Counties.

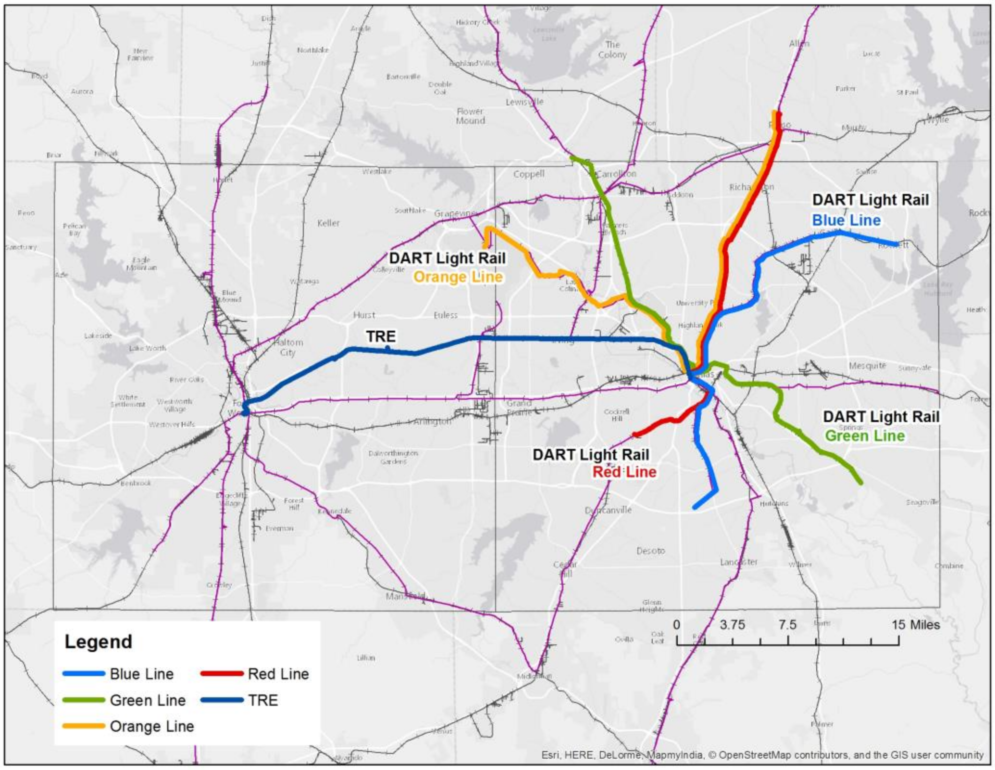

Figure 3.3. Future (2035) rail networks of Dallas and Tarrant Counties.

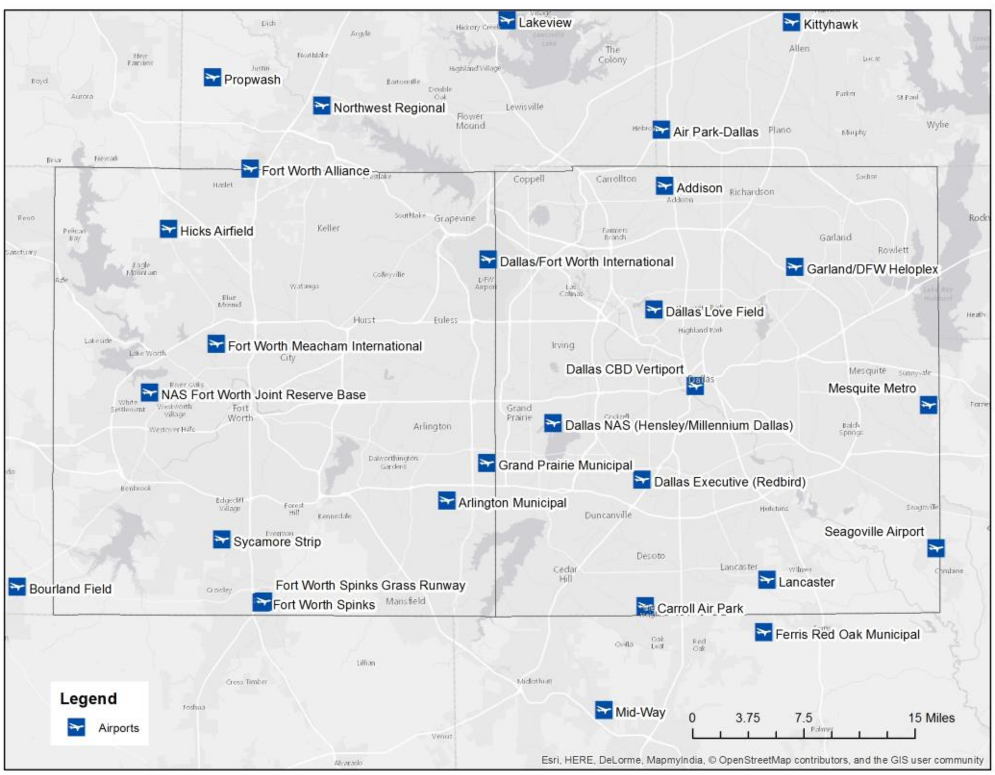

Figure 3.4. Current location of airports in Dallas and Tarrant Counties.

3.3. Criticality Assessment

Criticality was defined and assessed to prioritize each asset based on its relative importance for emergency preparedness, recovery, and maintenance. FHWA (2012) reports two major approaches used by the DHS National Critical Infrastructure Prioritization Program (NCIPP) in identifying the importance of assets: (1) consequence-based criteria including: loss of life, economic costs, ability to re-route and length of detour, and time to rebuild if damaged; and (2) capacity-based criteria, which focus on the level of usage (e.g. AADT). Several previous pilot studies conducted by the Gulf Coast, North Jersey, and the State of Washington defined and determined criticality using qualitative (e.g. opinions from the workshop participants) and/or quantitative methods (e.g. assessing multiple criteria such as socioeconomic data, level of use, and health and safety) based on their regional characteristics and data availability. In this study, the capacity-based approach using AADT for roadways, annual ridership for passenger rails, and annual passenger boarding for airports is primarily used to determine the criticality of assets.

Roadways

AADT was normalized by number of lanes to better represent the functionality of roadways (Fig. 3.5) based on consultation among the project partners assembled for this Study. Compared to using absolute values of AADT, this method captures the importance of isolated lower-capacity roadways with greater delay over time. At many locations throughout the DFW area, many of these roadways with greater traffic delays are associated with fewer alternative routes and greater need for capacity improvements. For classifying AADT per travel lane, percentile ranks were used to rank each segment based on its current traffic volume and to highlight the relative standing of each critical segment compared to all roadways. Figures 3.5 and 3.6 show the roadway segments with top 1%, 5%, 10%, 20% of total roadways, and each class was assigned to a score as below:

- 27,201- 36,350 vehicles (top 1%) was assigned a score of 5.
- 20,968 – 27,200 vehicles (top 1 – 5%) was assigned a score of 4.
- 16,034 – 20,967 vehicles (top 5 – 10%) was assigned a score of 3.
- 7,751 – 16,033 vehicles (top 10 – 20%) was assigned a score of 2.
- 0 – 7,750 vehicles (top 20 – 100%) was assigned a score of 1.

Currently, highways in the north and northeast areas of Tarrant County and broad areas throughout the northern half of Dallas County carry higher traffic volumes and experience frequent congestion throughout the day (Figure3.5). By applying the traffic classification as defined above, the 2035 projection (Figure 3.6) shows that congested roadways with high traffic volume largely expand over the entirety of both counties.

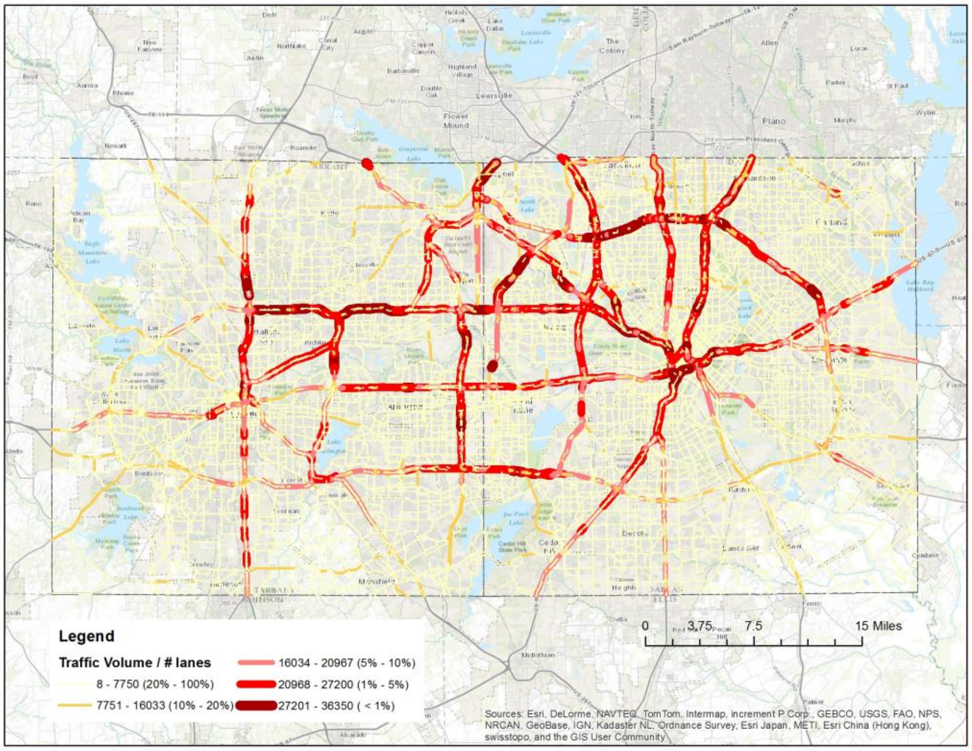

Figure 3.5. Current roadway traffic volume in Dallas and Tarrant Counties based on AADT and normalized by number of lanes.

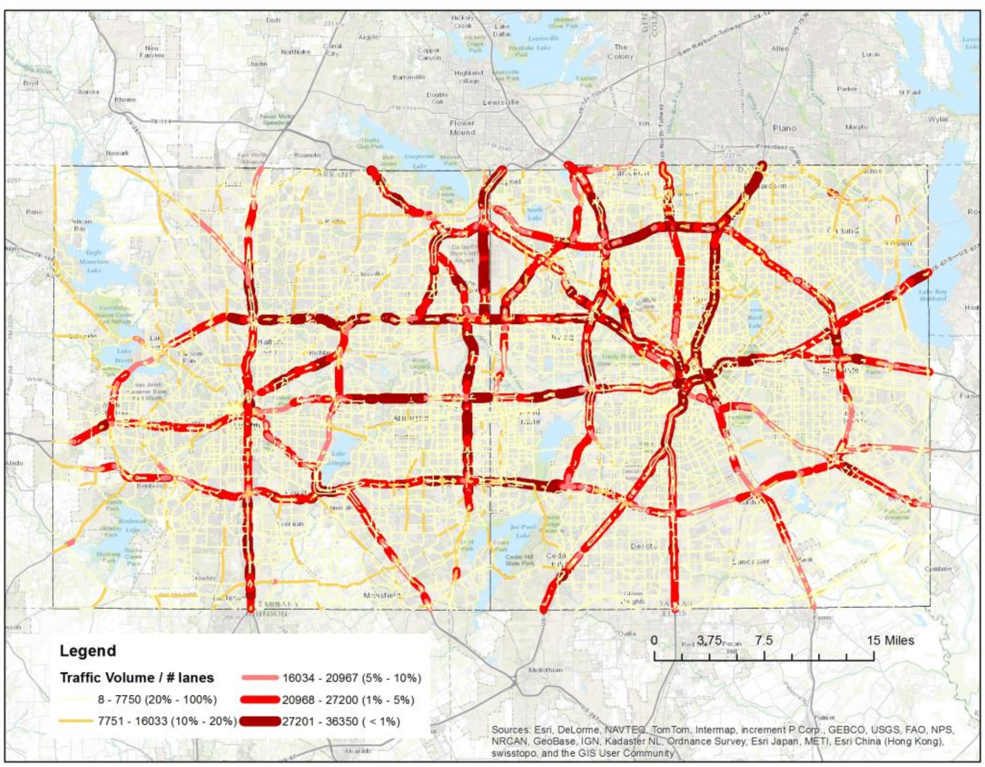

Figure 3.6. 2035 roadway traffic volume in Dallas and Tarrant Counties based on AADT and normalized by number of lanes.

Traffic volume near the middle of the two counties, particularly on highways near Dallas-Fort Worth International Airport (DFWIA) is projected to significantly increase.

Passenger Rail

Currently, Dallas and Tarrant Counties have two passenger rail operators: DART and FWTA. Operated since 1996, the DART Light Rail System consists of four major lines: Red, Orange, Blue, and Green that connect suburban areas of Dallas County (as well as portions of Collin County to the north and Denton County to the northwest) to Downtown Dallas. In 2013, annual passenger ridership of DART Light Rail was 29.5 million passengers, with 96,300 persons identified as the average weekday ridership (DART, 2014). FWTA conducts a joint operation with DART for the Trinity Railway Express (TRE), a commuter rail corridor that travels between the central business districts of Fort Worth and Dallas. The TRE also contains intermediate stops in the cities of Richland Hills, Hurst, Irving, as well as Fort Worth's Centreport Campus which provides a bus connection hub to DFWIA. The 2013 annual ridership of TRE was 2.1 million passengers, with an average weekday ridership of 7,550 persons (DART, 2014).

Current and year 2035 projected annual passenger ridership by each DART/FWTA rail line were mapped and aggregated into railway segments that carry multiple lines (Fig. 3.6 and 3.7). Year 2035 annual average daily ridership for individual railway segments was classified into five tiers using a natural break classification, a method of manual data classification that achieves to partition data into classes based on natural groups in the data distribution. Each class was assigned to a score as below:

- 74,135 – 137,239 passengers was assigned a score of 5.
- 26,327 – 74,134 passengers was assigned a score of 4.
- 11,966 – 26,326 passengers was assigned a score of 3.
- 3,807 – 11,965 passengers was assigned a score of 2.
- 0 – 3,806 passengers was assigned a score of 1.

Currently, the DART Orange and Red lines carry relatively high average daily riderships; railway segments in Downtown Dallas show the highest ridership because all four lines pass through a dedicated transit corridor. TRE lines carry the fewest passengers (Fig. 3.7). By 2035, passenger ridership for all lines is expected to grow significantly, reflecting a nearly 50% increase of population and employment compared to current figures (Fig. 3.8). In particular, the highest number of passengers are projected to be carried by the Red and Orange lines for the section between Downtown Dallas and the City of Plano in Collin County. Future projections also indicate strong ridership for several new rail corridors to be developed prior to 2035. TEX Rail, a 27-mile commuter rail line being developed by FWTA, will debut by 2018 to connect Downtown Fort Worth to the northern entrance of DFWIA along the southwest-to-northeast-oriented Cotton Belt corridor. Ultimately, extensions to either side of this line will allow uninterrupted

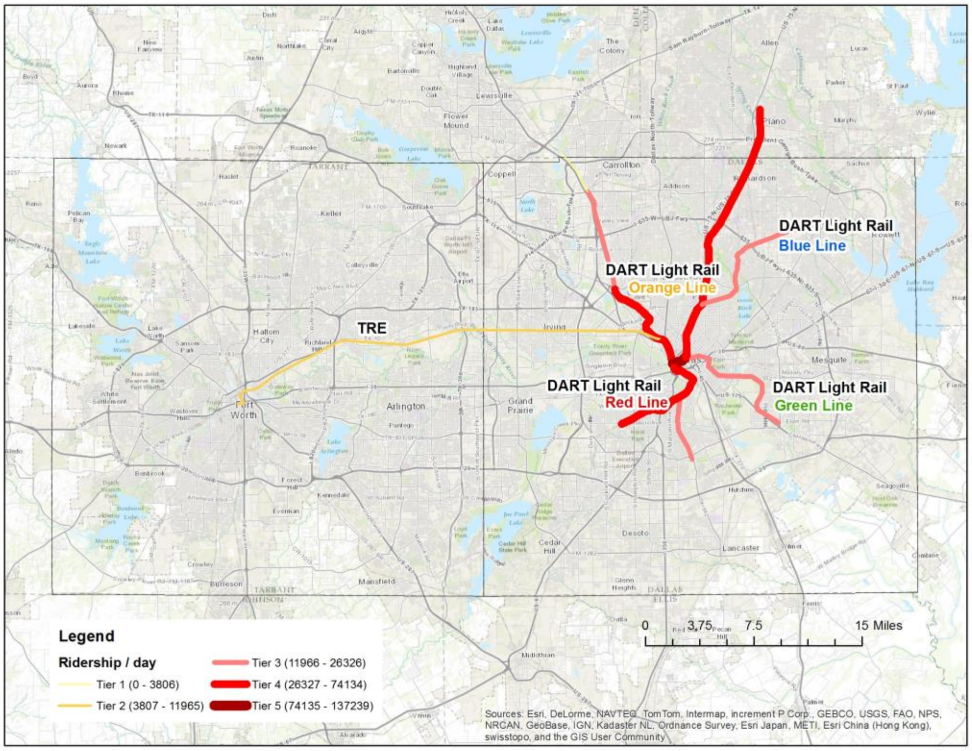

Figure 3.7. Current annual ridership of passenger rail (DART and FWTA) in Dallas and Tarrant Counties.

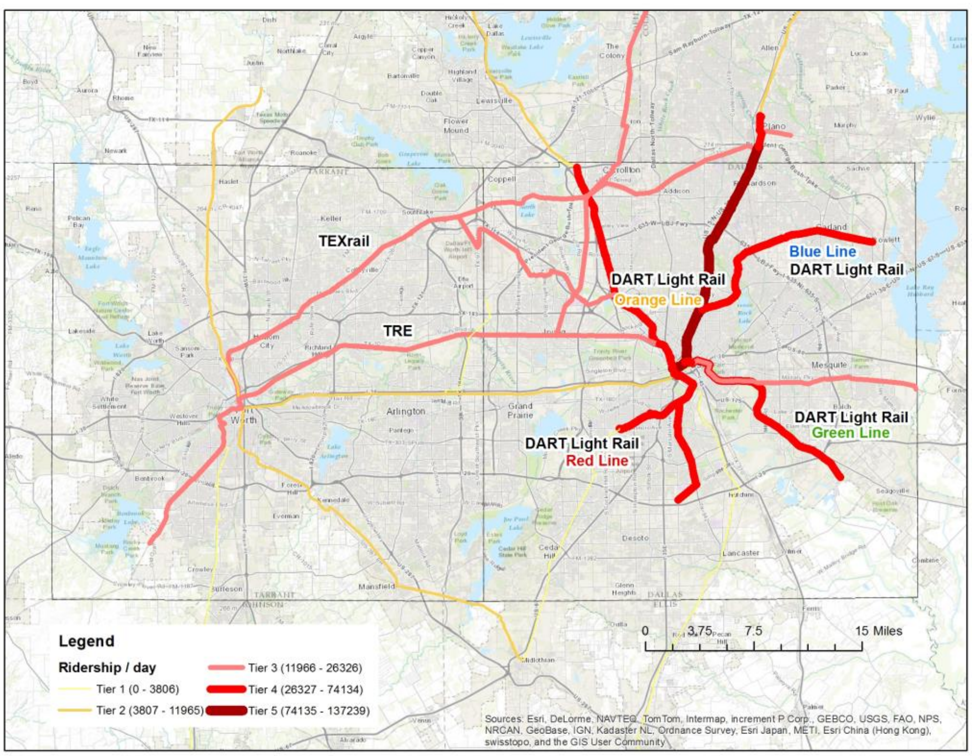

Figure 3.8. Annual ridership of passenger rail in 2035 (DART and FWTA) in Dallas and Tarrant Counties.

travel between southwest Fort Worth and the DART Red/Orange Line in the City of Plano. Another highly-traveled commuter rail service is also anticipated for development along the Burlington Northern Santa Fe (BNSF) corridor between the TRE South Irving Station and the City of Frisco in Collin County. This interconnectivity enables ridership to increase across many railway segments throughout the North Central Texas region.

Airports

Airports are important transportation assets in the DFW area that connect passengers and cargo to various domestic and international regions. Dallas and Tarrant Counties contain 19 airports, including DFWIA and Dallas Love Field Airport. According to the Federal Aviation Administration (2014), DFWIA is ranked 4th for passenger boarding (annual enplanement of 29,038,128 persons) and 10th for landed weights of cargo (3,062,528,160 lb.) among the U.S. airports in 2013. Dallas Love Field was ranked 44th for passenger boarding (annual enplanement of 4,023,779 persons). Criticality of the airports was determined based on their passenger boarding figures for 2013 (Fig. 3.9). Airports are major sources of heat island formation because of their extensive impervious coverage (Houston Advanced Research Center, 2009) and extreme heat significantly air density, which impacts the minimum runway length for planes to take off (FAA, 2014). Extreme weather events such as storms with severe wind speeds, flooding, as well as snow and ice events, can also lead to significant flight delays.

Figure 3.9. Current (2013) major airport passenger boarding (DFWIA and Love Field) in Dallas and Tarrant Counties (Source: US DOT Federal Aviation Administration, 2014).

4. VULNERABILITY OF DALLAS AND TARRANT COUNTY TRANSPORTATION INFRASTRUCTURE TO EXTREME WEATHER AND CLIMATE CHANGE

4.1. Introduction

The definition of vulnerability and risk varies for different applications (Biging et al. 2012). Climate change vulnerability is defined as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2013). In the FHWA framework, climate change vulnerability is a composite of three factors: the exposure to climate effects, sensitivity to climate effects, and adaptive capacity to climate change (FHWA, 2012).

Vulnerability = *f* (exposure, sensitivity, adaptive capacity).

Exposure is determined by whether or not assets in question are situated in an area that is directly affected by climate change and extreme weather events such as severe precipitation and heat waves. Sensitivity refers to the direct and indirect costs of potential impacts caused by climate change and extreme weather. Adaptive capacity is estimated by whether or not there are sufficient local and regional resources (physical capacity, capital/materials for construction/maintenance, etc.) and policies (emergency management, operating procedures, etc.) that allow immediate and short-term responses to climate stressors.

In assessing vulnerability to severe flooding, this Study focuses on identifying critical infrastructure located within the spatial extents of the 100-year floodplain. It should be noted that some of the critical infrastructure located within the floodplain area may not be directly exposed or sensitive to flooding as a result of elevation, local drainage/runoff characteristics, engineering factors, or other conditions. Information to verify such conditions for each facility could not be assessed for this Study due to time constraints and limited data availability from potential sources. However, it is clear that large quantities of critical infrastructure in Dallas and Tarrant Counties are present in flood-prone areas. Therefore, vulnerability due to potential exposure is likely and substantial portions of the roadway network would be sensitive to potential impacts should they occur. Criticality measures outlined in the previous chapter are incorporated into the vulnerability calculation as well. Adaptive capacity is assumed constant in this assessment due to the lack of sufficient information and complexities in quantification directly pertinent to the North Central Texas region. The presence of numerous transportation providers, local governments, and a wide range of interactions and linkages that support construction, maintenance, operations, and emergency management in the DFW area make it difficult to accurately determine adaptive capacity alternatives, as well as defining the comprehensive array of potential applications in various weather-related circumstances.

Risk assessment is defined in this study by the magnitude of impacts (consequence) and the probability (likelihood) of occurrence:

Risk = *f* (magnitude of impact, the probability of occurrence).

Vulnerability and risk to extreme heat is assessed by the following procedure: Surface air temperature maps generated from the climate simulations are overlaid upon maps of critical assets to identify infrastructure vulnerability to heat exposure. Gradients in surface air temperature are used to classify the likelihood of heat-related damage into low, medium and high classes.

It should be noted that there is a lag in the time horizon between the projected criticality of transportation assets and the climate change projections identified in this study. Most long-range metropolitan transportation plans, such as the Mobility 2035 Plan – 2013 Amendment, have a time horizon ranging from 20 to 30 years whereas climate projections cover much longer time frames of about 30 to 100 years. In this study, the year 2035 projection from the Mobility 2035 Plan – 2013 Amendment provides the longest infrastructure projection available for vehicle volumes and rail ridership. Climate projections for the horizon years 2050 and 2100 were used to determine the likelihood of extreme weather events and climate change.

4.2. Critical Infrastructure in the 100-Year Floodplain

Roadways

Critical roadways within the 100-year floodplain were identified by overlaying 100-year floodplain coverage maps over the location of facilities with high annual average daily traffic (AADT) per travel lane based on the Mobility 2035 Plan – 2013 Amendment (Fig. 4.1). The results show that 635.7 center-line miles of roads, dependent on elevation and other physical/location characteristics, will have a higher potential for flooding and associated damage and/or disruption due to extreme precipitation events with runoff comparable to a 100-year flood. Critical roadways located within the 100-year floodplain are classified as follows based on future traffic projections:

- The roadways that have a criticality score of 4 or 5 are classified as “High” criticality segments;
- The roadways that have a criticality score of 2 or 3 are classified as “Medium” criticality segments; and
- The roadways that have a criticality score of 1 are classified as “Low” criticality segments.

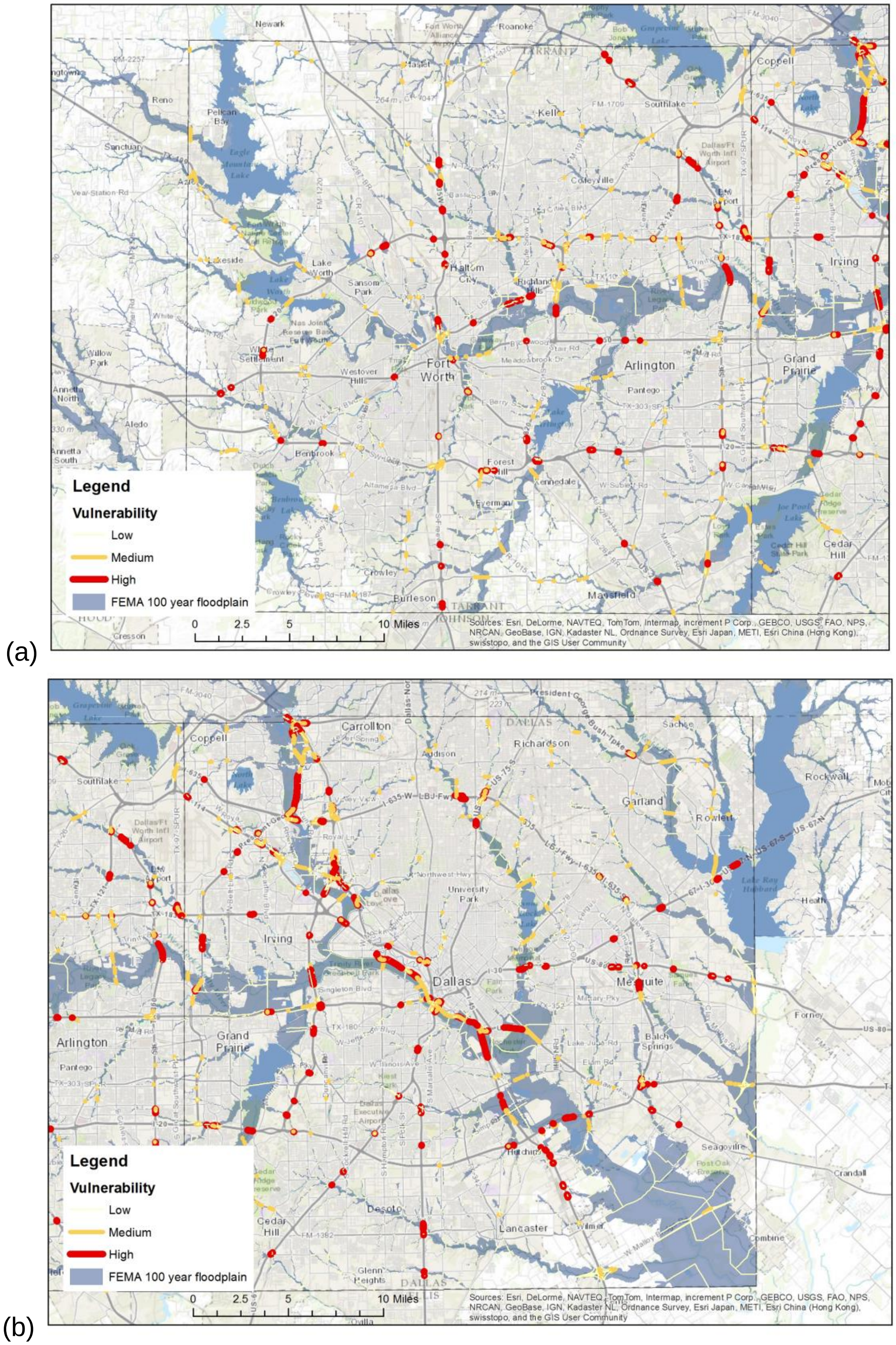

Figure 4.1. Critical roadway segments in the 100-year floodplain: (a) Tarrant County (b) Dallas County (Year: 2035)

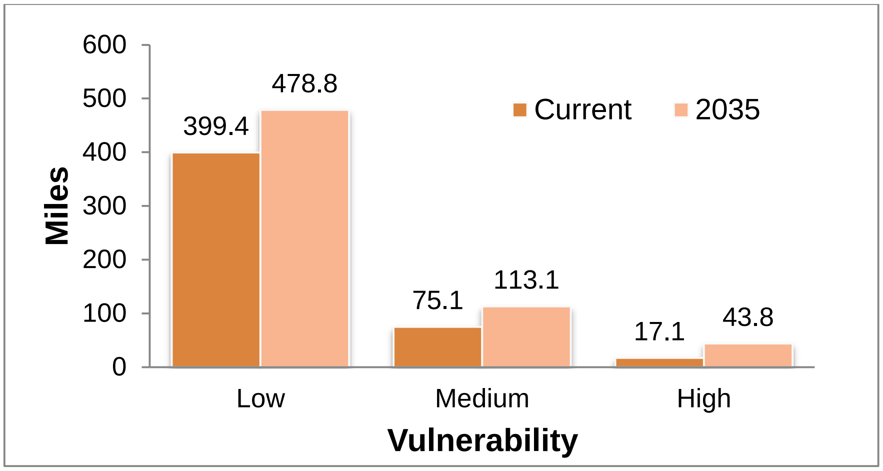

Figure 4.2. Length of critical road segments (center-line miles) in Dallas and Tarrant Counties located within the 100-year floodplain. Low criticality denotes AADT per lane < 7,751, medium criticality denotes AADT per lane range of 7,751 – 20,967, and high criticality denotes AADT per lane > 20,967.

Given the projected increases in traffic volume throughout the DFW area, the total length of "high" criticality roadway segments in the 100-year floodplain (the segments highlighted in red on the maps in Figure 4.1) increases from 17.1 miles in 2013 to 43.8 miles in 2035 (Figure 4.2). The potential consequences of inland flooding on roadways include both structural (Appendix A) and operational problems (Appendix B) as listed below:

- Affecting structural integrity of roads
- Highway and bridge scour
- Erosions of road and bridge supports
- Disruption of traffic flows
- Higher crash rates
- Increased congestion
- Delays in evacuation and emergency response

Railroads

Critical railroad segments located within the 100-year floodplain were identified using an approach similar to the one used for roadways. The spatial extent of 100-year floodplain was overlaid upon the location of critical railroad networks based on the Mobility 2035 Plan – 2013 Amendment (Fig. 4.3). The GIS analysis shows that by 2035, 39 miles of railway segments, dependent on elevation and other physical/location characteristics, are likely to be impacted by intense precipitation events that could generate a 100-year flood. Critical passenger railroad facilities in the 100-year floodplain are classified as follows based on potential ridership:

- The passenger railroads that have a criticality score of 4 or 5 are classified as "High" criticality facilities;
- The passenger railroads that have a criticality score of 2 or 3 are classified as "Medium" criticality facilities; and
- The passenger railroads that have a criticality score of 1 are classified as "Low" criticality facilities.

The potential impacts of inland flooding on railroads include the following;

- Flooding over railroads
- Disruption of traffic, delay, increased risk of hazardous material spill
- Damage to railways and track bed due to landslides and mudslides
- Increased malfunction of track or signal sensors
- Complete or partial loss of service
- Drowning of passengers by accidents

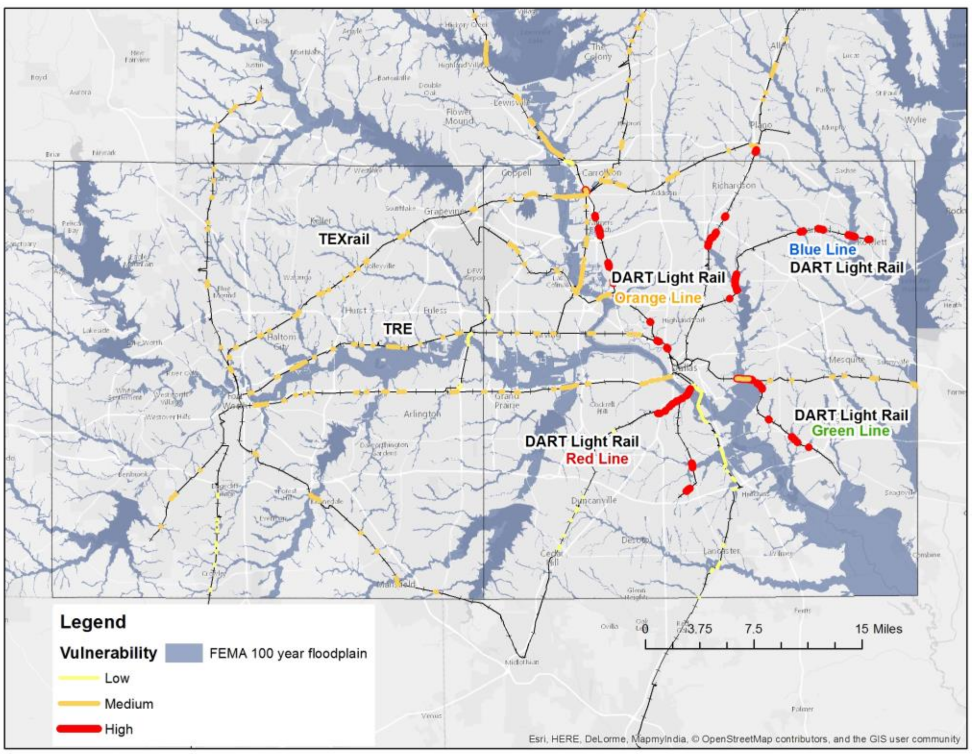

Figure 4.3. Critical railways located within the 100-year floodplain in Dallas and Tarrant Counties (Year: 2035).

Airports

A similar overlay-analysis was conducted to determine airport infrastructure located within the 100-year floodplain. The results show that the majority of the existing airports are unlikely to be inundated by extreme precipitation events that would result in a 100-

year flood. For example, DFWIA shows a very small portion (0.1%) of overlapping area within the 100-year floodplain. Service roads and terminals could be affected by flooding, but the runways are typically higher than the surrounding ground and thus are not likely to be affected by an increase in precipitation. Higher precipitation associated climate change, as predicted for spring months in the future, will lead to an increase in delays and higher risk of aviation accidents.

Although the results show that the impact of flooding on the runways would be inconsiderable, extreme precipitation and severe storms may impact airport operations such as airport closure, delays in passenger and cargo loading, and disruptions to other service-related operations. In addition, accessibility to the airports via the regional roadway and passenger rail network are also more likely to be impacted, thus influencing airport operations.

Table 4.1. Airports vulnerable to severe flooding in Dallas and Tarrant Counties (Year 2035)

Airport	Enplanement	Impacted Area (ft^2)	Airport Area (ft^2)	Impacted / total area
DFW International Airport	29,038,128	119,776	96,664,968	0.1%
Dallas Love Field	4,023,779	0	25,443,514	0.0%
Fort Worth Alliance	1,348	115,264	12,706,103	0.9%
NAS Fort Worth Joint Reserve Base	1,072	1,547,774	19,286,536	8.0%

4.3. Critical Infrastructure Vulnerable to Heat Risks

Climate simulations project a significant increase in the mean and daily extreme temperatures during the summer season (see Chapter 2.3). While changes in mean temperatures would have long-term impacts on transportation infrastructure and services, the short-term impacts would be related to temperature extremes, based on both magnitude and frequency. Temperature extremes cause severe problems on both transportation infrastructure itself (as discussed in Chapter 2.3 and Appendix A) and associated operations (Appendix B; Savonis et al., 2008).

In general, global climate simulations have a spatial resolution of 100 - 300 km; their original spatial resolution is too coarse to assess the specific climate impacts on regional/local transportation systems. In order to acquire finer resolution for mean temperature maps (e.g. 1 km), the pattern-scaling method was employed by assuming that the spatial pattern of change in climate variables would be consistent in time (Mitchell, 2003). The maps of mean summer surface air temperature for the period 1991-2010 over the NCT region was generated using the NWS COOP weather station data acquired from the National Climatic Data Center (NCDC) through Climate Data Online (CDO). Mean NWS COOP summer air temperature observations were seasonally averaged and spatially interpolated to produce a highly-resolved surface temperature map at 1 km spatial resolution. Changes in predicted surface air temperature were estimated from RCP8.5 CMIP simulations with the Community Earth System Model Version 1.2 (CESM) at ~1° x 1° horizontal resolution for the periods 2041-2050 and 2091-2100 relative to the historical period (1991-2010). These surface air temperature anomalies predicted by CESM1 (Fig. 2.9) were added to the observed temperatures to generate the downscaled predicted temperature for the NCT region. By using downscaled surface temperature maps, local temperature variances including UHI effects were superimposed on the long-term climate change to assess the potential impact of heat stress on transportation infrastructure.

Risk assessment matrix for extreme heat

The Study team assessed the temperature-related risk on transportation infrastructure using a two-dimensional matrix, which classifies risks into three categories (low, medium, high) as a function of the likelihood of failure and the various potential consequences (Fig., 4.4). Although higher temperature is likely to increase the failure of transportation assets, determining the relationship between the probability of failure and the level of summer season mean temperature is complicated and uncertain. In this report, the mean temperatures were classified into five categories: 75-80 °F, 80-85 °F, 85-90 °F, 90-95 °F, and above 95 °F to estimate the likelihood of failure.

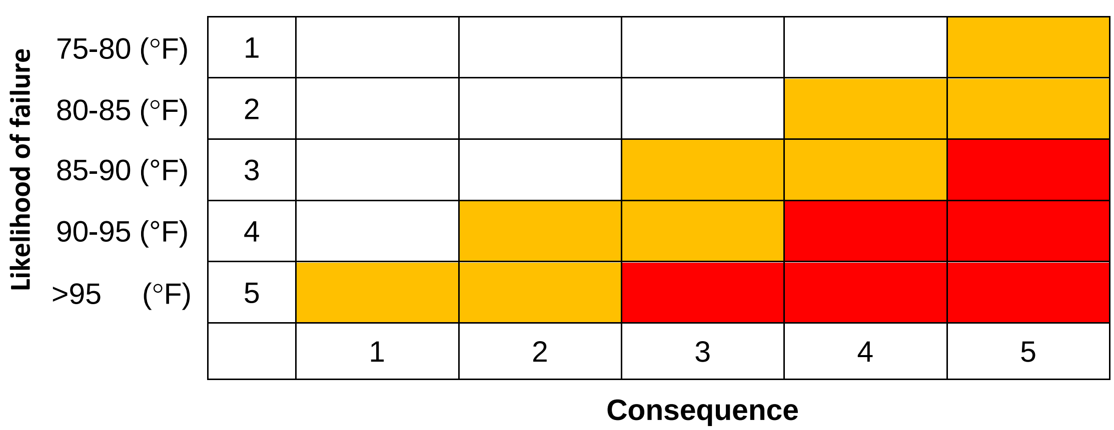

Figure 4.4. Risk assessment matrix categorized for low (white), medium (orange), and high risk (red).

Roadways

High temperature and heat risks on roadways were determined by using the above risk matrix (Fig. 4.4) considering the likelihood of failure (based on temperature class) and the potential consequences (based on criticalities of roadways). The maps of mean summer temperature for the years of 2050 (Fig. 4.5) and 2100 (Fig. 4.6) were superimposed on the network of critical roadways.

Higher temperature and extreme heats may pose the following risks to roadways:

- Pavement rutting and migration of liquid asphalt
- Buckling and/or warping at joints between pavement sections and at bridges
- Greater pavement repair needs resulting in more frequent lane closures
- Vehicle engine overheating and tire deterioration
- Exceedances in air conditioning capacity; cooling system failures
- Higher crash rates linked to mechanical failures and heat exhaustion/strokes

Pavement distress caused by the 2011 heat wave and drought cost TxDOT $26 million in additional statewide maintenance activities that year (Baglin, 2014). With future climate simulations suggesting more extreme weather events and significant temperature increases, pavement degradation rates (Appendix A) are likely to accelerate. Coupled with the projected strong traffic volume growth for most principal roadway facilities across North Central Texas, these amplified stresses on pavement performance would result in substantially decreased lifespans for both roadways and their supporting sub-grade infrastructure. This will translate into major increases in roadway maintenance and construction material costs compared to current figures.

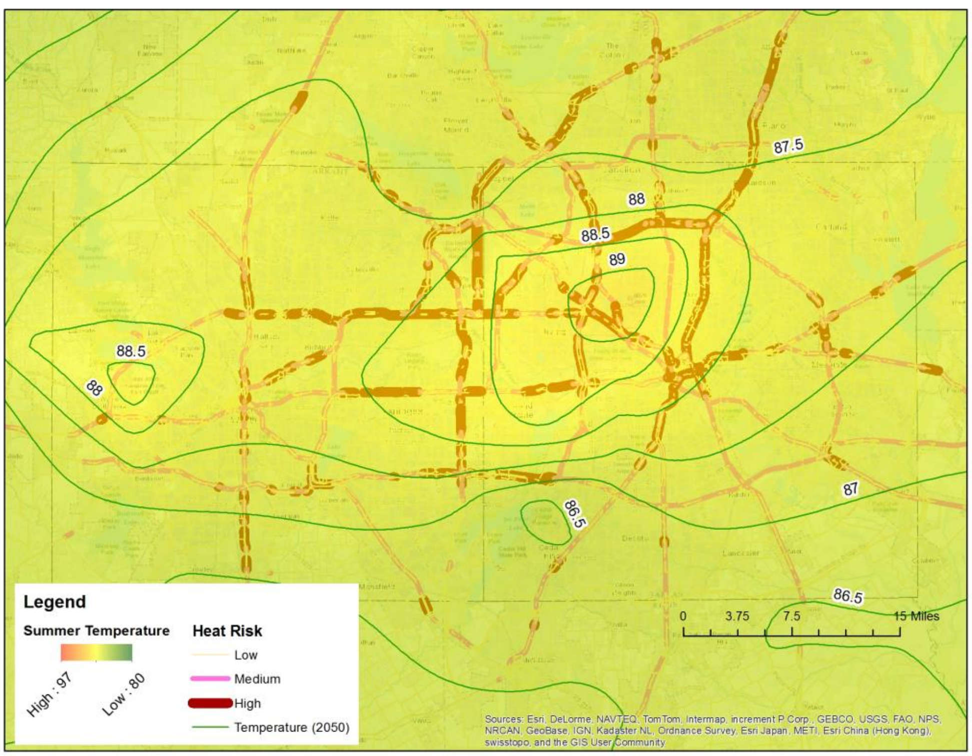

Figure 4.5. Critical roadways vulnerable to heat risks in Dallas and Tarrant Counties for the period 2041-2050.

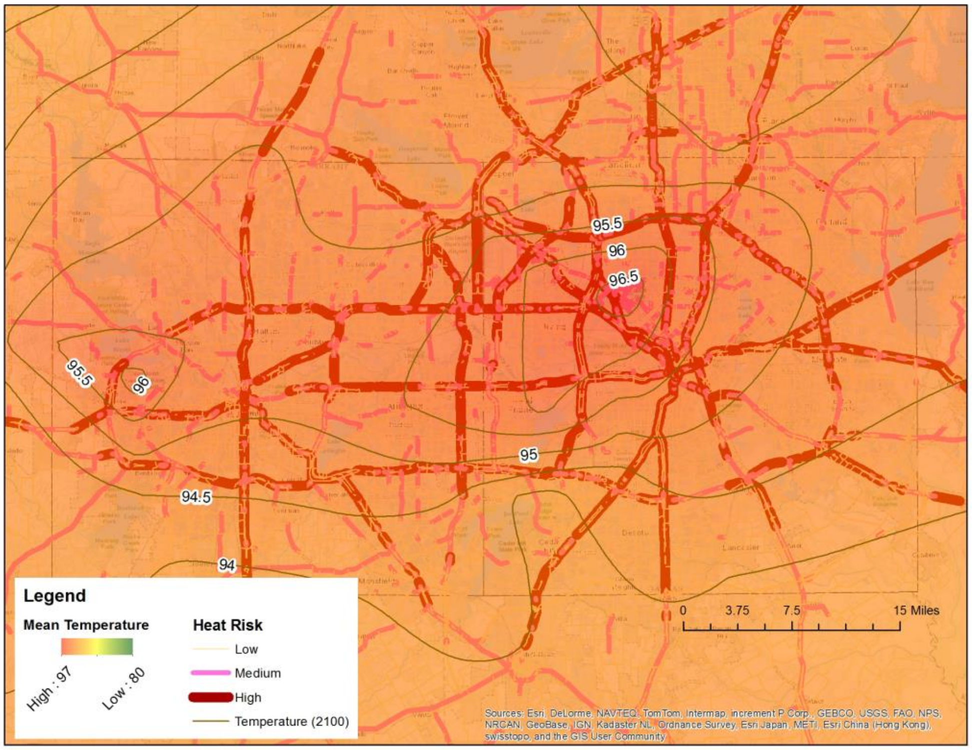

Figure 4.6. Critical roadways vulnerable to heat risks in Dallas and Tarrant Counties for the period 2091-2100.

Railroads

Passenger rail lines with higher ridership numbers are likely to experience more consequences from infrastructure failure or service disruptions by extreme heat. High temperatures and extreme heat can cause various impacts on rail tracks and rail-related transportation assets:

- Rail bucking
- Operational delay due to speed restriction
- Catenary sagging and pulley failures
- Switches and signal failures
- Exceedances in air conditioning capacity; cooling system failures
- Higher fire risk, particularly near wooded areas

These weather-related impacts are high, particularly during summer season heat waves with frequent extreme temperatures (Fig. 2.9). However, accumulated stress may cause a reduced lifespan of rail infrastructure assets; maintenance and repair costs may increase accordingly.

In 2050, the DART Red/Orange line between Downtown Dallas and the City of Plano (Collin County) is expected to be at a greater risk for impacts because of its high

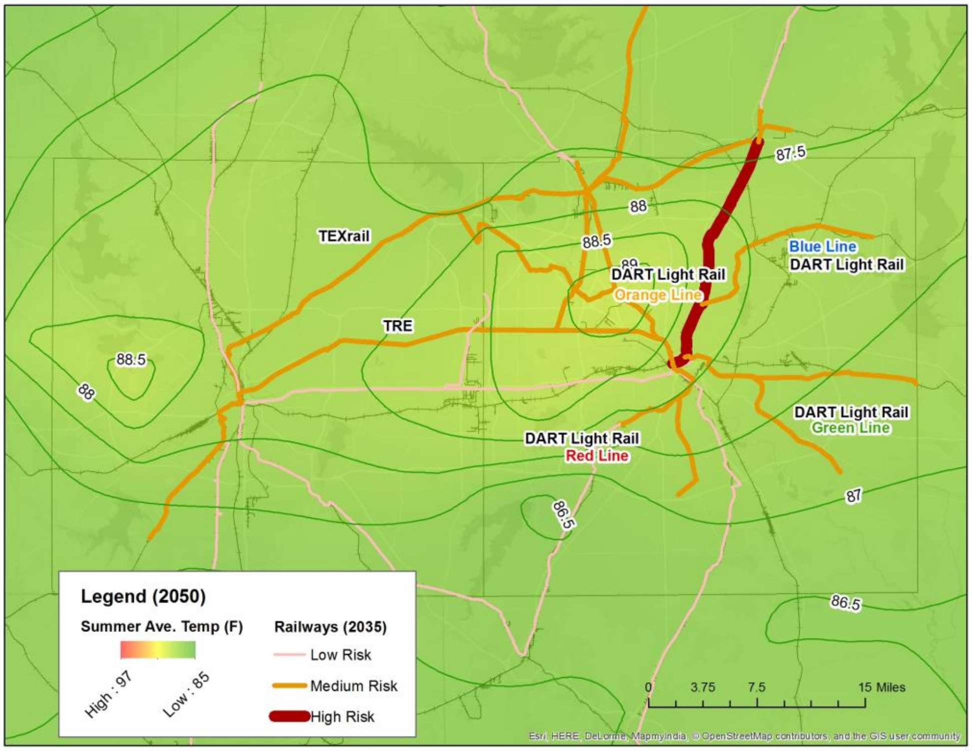

Figure 4.7. Critical railways vulnerable to heat risk in Dallas and Tarrant Counties for the period 2041-2050.

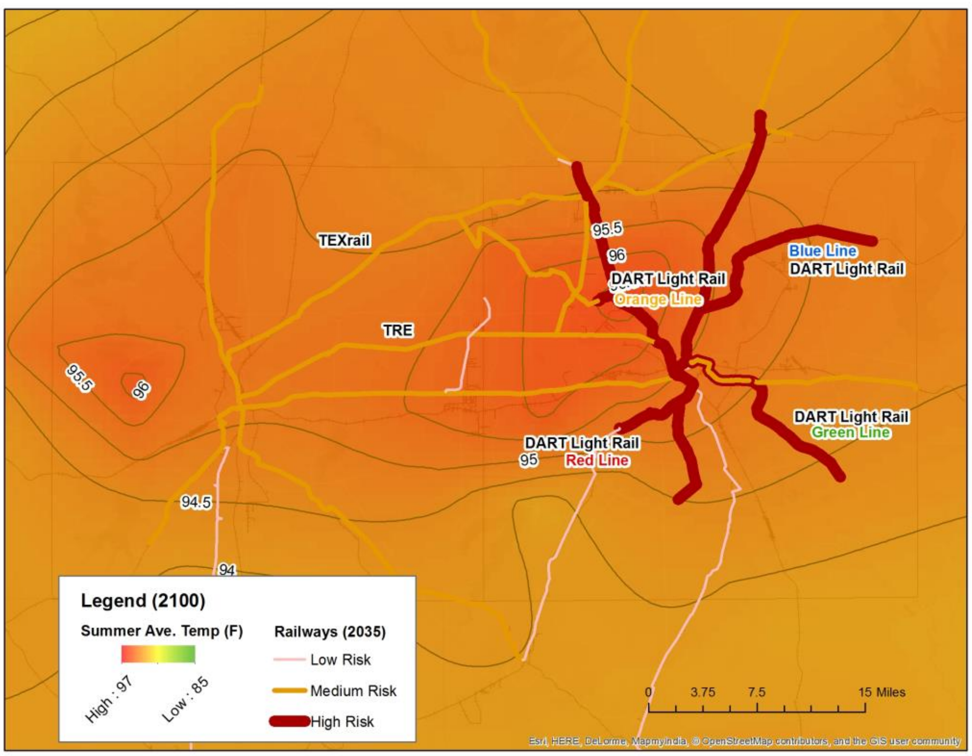

Figure 4.8. Critical railways vulnerable to heat risk in Dallas and Tarrant Counties for the period 2091-2000.

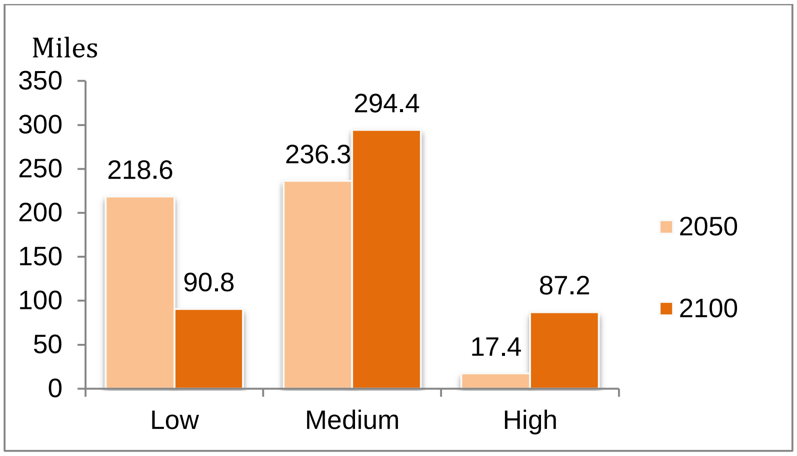

Figure 4.9. The length of railways at heat risk in Dallas and Tarrant Counties.

ridership number and higher temperatures (Fig. 4.7). In 2100, all DART lines are expected to be at high risk because of the increase in temperature. The north and the northeast areas of downtown Dallas are expected to reach average summer temperatures of 95-96˚F, which is higher than in other areas because of the UHI effect (Fig. 4.8). The results of the risk assessment show that the length of rail tracks classified as “high risk” is expected to increase from 17.4 miles to 87.2 miles from the climate projection for the year of 2050 to that of 2100 (Fig. 4.9).

Airports

The high temperature risk for airports was assessed using the projected mean summer season temperatures (for 2050 and 2100) and enplanements. For this criterion, the study team did not classify the magnitude of consequence for individual airports because the differences in passenger boarding between the major airports (DFWIA and Dallas Love Field Airport) and other airports are significant. The mean summer season temperature projection for the years 2050 and 2100 was overlaid upon the airport location map (Fig. 4.10) to determine the potential impacts. Temperature projections indicate that the airports near the urban centers (e.g. the Dallas Love Field Airport) tend to have higher mean temperatures than the airports located away from the urban centers (e.g. Fort Worth Alliance). For DFWIA, the summer season mean temperature (currently 83.7 °F) is expected to reach 88.11°F by 2050 and 95.40°F by 2100 (Table 4.2). For the Dallas Love Field Airport, the summer season mean temperature (currently 84.9 °F) is expected to increase to 89.3 F by 2050 and 96.6 °F by 2100 (Table 4.2). The greatest temperature changes are predicted for August (Fig 2.9 and 2.10) with extreme maximum temperatures likely exceeding 120 °F for the mid-century and 125 °F by the end of this century. Consequently, airports near urban centers are expected to have relatively more heat-related disruptions.

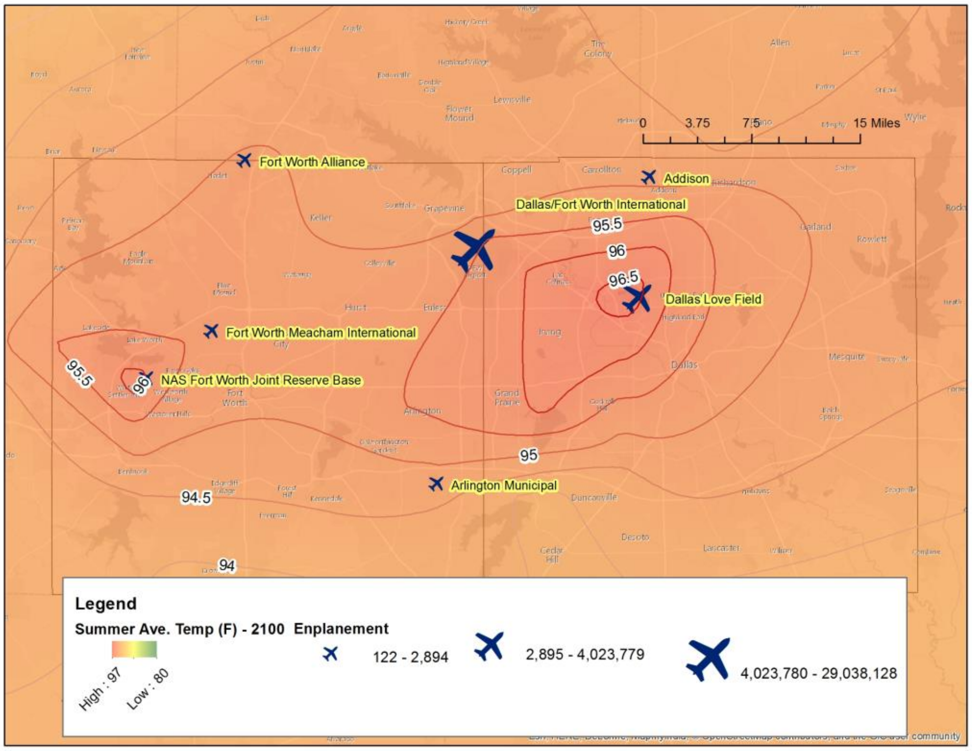

Figure 4.10. Critical airports vulnerable to heat risk in Dallas and Tarrant Counties (Year: 2100) with passenger boarding of major airports (DFWIA and Love Field; see Figure 3.9).

Table 4.2. Critical airports vulnerable to heat risk in Dallas and Tarrant Counties

Airport	Enplanement	Summer Average Temperature (°F)		
		Current	2050	2100
Dallas Love Field Airport	4,023,779	84.92	89.30	96.59
NAS Fort Worth Joint Reserve Base	1072	84.35	88.69	96.05
DFW International Airport	29,038,128	83.71	88.11	95.40
Fort Worth Meacham International	2894	83.57	87.93	95.27
Fort Worth Alliance	1,348	83.41	87.84	95.09
Addison	616	83.17	87.62	94.87
Arlington Municipal	189	83.01	87.31	94.72

Higher temperatures and extreme heat waves may pose the following risks to airports:

- Heat buckling of runways
- Effect on aircraft lift potential (by changing the surface air density)

- Payload restrictions, flight cancellations, and service disruptions
- Exceedances in air conditioning capacity; cooling system failures
- Increased pavement burdens due to longer runway take-off distances

Because airports connect a wide range of locations (on a national and global scale), the impact of climate change and weather events on aviation transportation is not restricted to local weather extremes. It should be noted that extreme weather events or climate stressors in other areas (other states or other countries) could also cause delays on airports throughout the North Central Texas region as well.

5. CONCLUSIONS

This Study provided a comprehensive assessment on the potential effects of extreme weather and climate change on transportation infrastructure in Dallas and Tarrant Counties. The vulnerability and risk of critical infrastructure assets (road, rail, and aviation) was evaluated using a risk assessment matrix. Based on the analysis conducted, it can be concluded that by the end of the 21st century:

- There is a robust likelihood of level of service disruption and damage to infrastructure assets by more extreme storms and higher precipitation leading to an increase in flooding, particularly during the spring season. Due to the projected increases in traffic volumes and passenger rail ridership, more critical roadways and railroads are expected to be in the 100-year floodplain and may be potentially vulnerable to future impacts.
- There is a high likelihood of greater heat-related risks for multiple infrastructure assets, particularly during the summer season. Due to the projected increases in both temperature and mobility needs, more critical roadways and railroads are expected to be at risk to heat-related damage and/or disruption.

To be proactive in both the preparation for and adaptation to increased weather-related effects, it is imperative to link the findings of this Study to various engineering guidelines for transportation infrastructure (range of normal operations or threshold of endurance) and incorporate potential implications into future long-range transportation plans. Based on the information provided there is a need to improve the monitoring of weather-related stresses of the infrastructure (see Appendix A), enhance existing infrastructure maintenance, and protect future infrastructure construction projects so that extreme weather events cause less impacts to safe, effective, and efficient access and mobility. As transportation network performance measures continue to be integrated into long-range transportation planning efforts, additional points of data and analysis regarding potential climate change effects/impacts will be of vital future importance to decision-makers, particularly in a fast-growing region like North Central Texas where investment choices and quality of life implications between increased maintenance and additional capacity will need to be weighed considerably. With continuing uncertainties in the availability of dedicated revenue sources for infrastructure over time, the ability for NCTCOG to assist the region in developing and implementing such an all-inclusive analysis provides greater transparency and accountability to help justify where, when, and why those choices must be made.

Future investigations are required for a more accurate assessment of asset vulnerability that can fully incorporate regionally relevant exposure, sensitivity, and adaptive capacity measures. This will be necessary to determine exclusive risks/impacts for individual facilities, identify potential mitigation strategies, and set action priorities through comparison of features with other needed projects. For example, employing the use of temperature extremes and heat wave magnitudes could improve reasonability testing to assess the vulnerability to heat risks. Precipitation can be more accurately projected by using high-resolution radar precipitation data from the CASA project. Frequent data-intensive monitoring of weather-related stresses and damages to infrastructure, and a refined highly-downscaled weather prediction system could lead to a better regional forecasting apparatus for extreme events. Proliferation in the use of three-dimensional models, e.g. LiDAR, would significantly improve the vulnerability assessment of critical infrastructure to severe flooding and make the results more spatially explicit and reliable. These actions can help ensure that asset management and comprehensive long-range transportation planning may strategically and effectively incorporate weather-related risks/impacts into decision-making (see Appendix B), enable expanded development of adaptation strategies based on priorities, and help prolong the functionality and demand accommodations of the complex and continually evolving transportation network for North Central Texas.

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APPENDIX A

A.1. Street Maintenance Plan and Pavement Deterioration from the City Of Dallas

In assessing the vulnerability of transportation infrastructure to climate change and extreme weather events, it is important to also discuss the linkages between environmental impacts and the asset management process. While comprehensive maintenance programs have long been a major component in the planning and budgetary processes for government operations from the local to the federal level, it is primarily in recent years where asset management has highlighted the significance of lifecycle maximization, particularly in the face of increasing financial constraints that have limited the scope and scale of needed infrastructure improvements (AASHTO, 2011). The City of Dallas, a primary partner in this Pilot Study, is just one of numerous local governments in the North Central Texas region, Texas, and the country, performing data collection and evaluation on a regular basis to extend and/or improve the quality and lifespan of its major capital assets. Their experience illustrates that climate change/extreme weather is just one variable of many that affects roadway system performance, and like many other management systems, the focus is centered primarily upon the data that is most readily available, calculable, and easiest to communicate in terms of where and by how much desired performance levels are or are not being maintained. This helps to address direct objectives for safety, level-of-service, and state-of-good-repair, but it does not entirely address questions regarding what impacts are most likely to affect performance levels, what severity are those potential impacts, and why they are occurring. It underscores the importance from an asset management standpoint of also attempting to achieve transportation system resiliency simultaneously with other factors, and this process in itself can affect an entity's vulnerability and responsiveness to environmental factors such as climate change.

The City of Dallas is the largest local jurisdiction by area and population of the more than 230 member governments comprising the 16-county North Central Texas Council of Governments' (NCTCOG) region. With a total area of 385.8 square miles and a 2013 population estimate of 1,257,616 (U.S. Census Bureau, 2015), the City of Dallas maintains a mature and complex roadway system to support the economic, mobility, and accessibility needs of its large size and continually growing number of inhabitants and visitors. In addition to the substantial amount of state and federally-maintained roadways that pass into and/or across the City of Dallas, the local government is responsible for approximately 11,700 lane-miles of streets (City of Dallas, 2014), including 444 lane-miles of arterials (high-capacity roads), 4,507 lane-miles of collectors (low- to moderate-capacity roads), and 5,327 lane-miles of local facilities (streets for direct residential or business access). These figures are similar in quantity to other U.S.

cities such as San Jose, Phoenix, Detroit, Indianapolis, and Miami/Dade County (City of Dallas, 2014).

Like many major cities throughout the country, the City of Dallas has built and maintained its streets to support a typical life-expectancy ranging from twenty to fifty years. Variables that can influence this range of functionality include pavement design, traffic loads, soil conditions, weather/precipitation patterns, and maintenance schedules. High travel demands and a large extent of responsibility has required the City of Dallas to make extensive investments over time in maintaining the quality and functionality of its roadway system. Beginning in 1975, the city relied primarily on routine visual inspections by trained staff to evaluate street conditions (City of Dallas, 2014). Through the years, daily ratings of streets were found to be typically subjective in nature, and by 2008 a more robust and objective system of inspections was implemented. This involved the development of a 24-month review cycle utilizing city-owned vehicles called Data Collection Vans (City of Dallas, 2014). With equipment such as recording cameras, lasers for crack detection, laser profilers for roughness detection, ground-penetrating radar to determine subsurface conditions, and use of visual surveys by a two-person team to confirm and supplement the mechanical readings, the vehicles enabled the city to record repeatable ratings for its streets consistent with the American Society for Testing and Materials (ASTM) International standards for Pavement Condition Index (PCI).

PCI ratings for streets are based on the extent and severity of pavement distress. This may consist of a variety of features such as roughness and low ride quality; longitudinal or transverse cracking within pavement blocks and/or edges, joint reflections; swelling and/or sagging which can cause rutting and/or potholes; and, patching discontinuities from actions such as utility cuts (Pierce et al., 2013). The City of Dallas uses assigned letter grades based on ranges of PCI from A (best) to E (worst) to identify the level of distress for each evaluated street section (approximately 200,000 points of direct measurement), and the data is recorded into a database system for supplementary storage and analysis (City of Dallas, 2014). The database system is then applied as a measurement tool to establish baseline settings for current street conditions, determine the effectiveness of regular maintenance operations over time, examine changes in roadway deterioration rates, and identify potential activities and quantities needed to achieve specific performance goals across defined geographic areas. This process enables elected officials and their constituents to readily evaluate constraints that can impact performance limits for street conditions and better regulate budget considerations for maintenance investments which can have a direct influence on the city’s economic vitality and quality of life.

In 2006, the Dallas City Council adopted street condition goals to set a lane-mile satisfactory rating of 87% citywide, and a minimum satisfactory rating of 80% across each of the fourteen City Council Districts (McDaniel, 2014). This goal was set as the result of completion of the city's 2006 bond program in conjunction with a recently enhanced operations and maintenance program. Information from the database system had shown the city had made significant strides throughout the 1990's and early 2000's to attain the 87% performance goal after many years below previous standards (Fig. A.1). However, several factors contributed together to create a reversal of the trend shortly after the 2006 goal was set (City of Dallas, 2014):

- The worldwide economic recession that occurred between 2008 and 2012 caused substantial budget changes for various departments throughout the city, and it led to increased amounts of deferred maintenance projects.
- Development and implementation of a more precise condition rating system beginning in 2010 identified that the overall number of street sections meeting the satisfactory rating was actually lower than previous measured.
- Despite the economic recession, the Dallas-Fort Worth Metropolitan Area (including the City of Dallas) continued to grow at faster rate than all metropolitan regions nationwide contributing to increased traffic and vehicle-miles of travel on the thoroughfare system.

In addition to observations indicating the difficulty for the City of Dallas to maintain the 87% satisfactory rating goal, comparisons with deterioration rates of various roadway

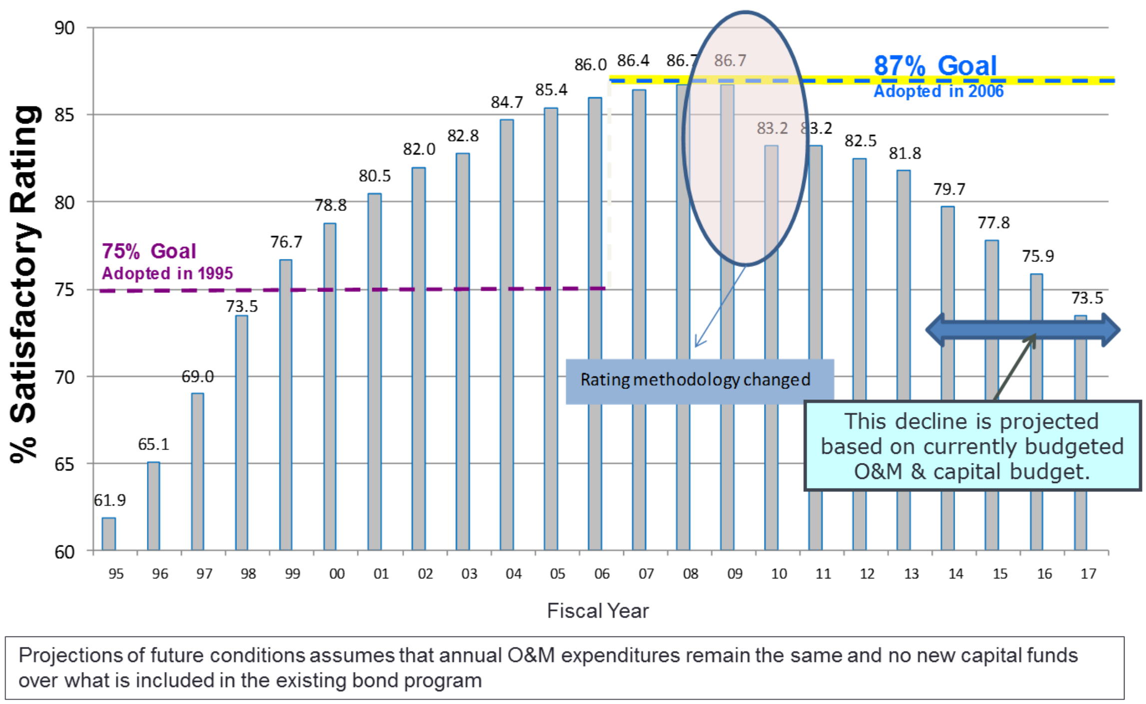
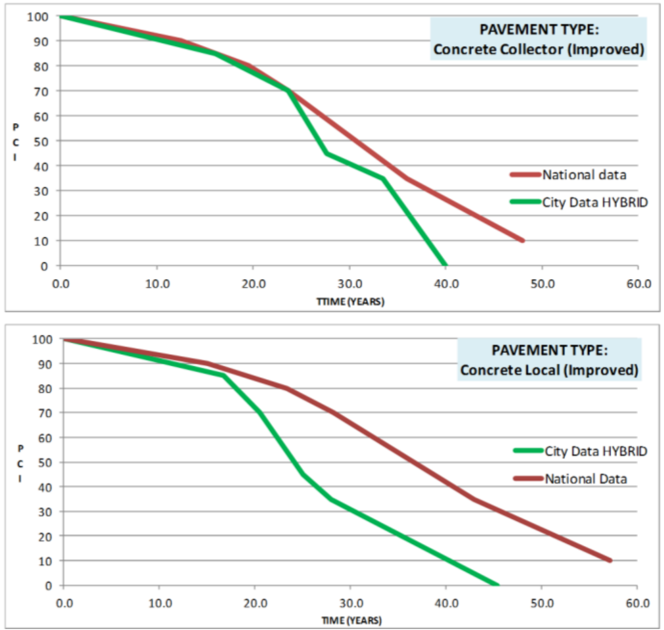


Figure A.1. Trends and projections of the City of Dallas street condition (McDaniel, 2014). Future projections are based on currently budgeted operation and maintenance budget.

a) Deterioration of Concrete Streets of the City of Dallas



b) Deterioration of Asphalt Streets of the City of Dallas

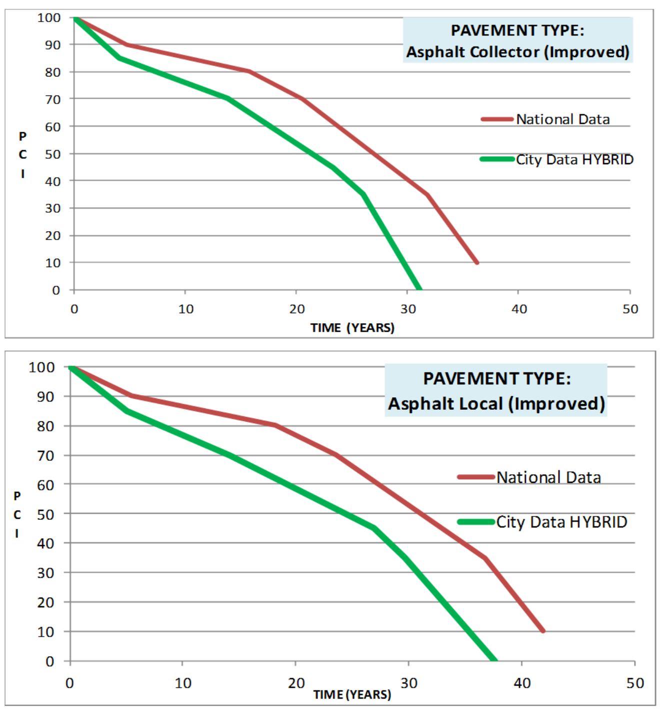


Figure A.2. Comparison of street deterioration for a) concrete and b) asphalt streets between the City of Dallas and national surveys (City of Dallas, 2014)

types from national data illustrated that the city's streets were deteriorating at a faster pace than other localities. City of Dallas PCI ratings for both concrete and asphalt-based streets diverged substantially lower than similar facilities from other cities, particularly beyond a horizon span of between fifteen to twenty-five years of age (Fig. A.2). This translated to functional lifespan for various streets ranging from five to ten years less than those of other locations. According to a presentation given to the 15th Annual S.A.M.E. Infrastructure Forum in December 2014, officials from the City of Dallas postulated that the reasons for the faster deterioration rate resulted from the following (City of Dallas, 2014):

- Decreased city spending on non-essential services, including street maintenance.
- National data that averages multi-city PCI ratings is updated on a five-year cycle, and the information may not have fully absorbed the widespread effects of the economic recession and impacts to government spending.
- Specific pavement measures and emphasis on factors that vary to some degree from city to city.
- Unique factors such as construction or maintenance practices, environmental issues, and street usage that may not be fully quantified and/or normalized for equal comparisons.

For the previous fiscal year (FY 2014), the City of Dallas determined the overall pavement rating stood at just under 80%, with projections that the rate would fall to as low as 73.5% within four years (City of Dallas, 2014). The city estimated that approximately $900 million in dedicated funds would be required over the next four years to return ratings to the 87% goal, however, the City Council only managed to approve $36 million in maintenance funds for FY 2015 (it should be noted that other City departments also allocate funds toward public works and street maintenance, but the combined resources still fall short of estimated needs). Yet, the available funds were increased by 13% over the previous year to include major maintenance for high-traffic streets, judged to be a cost-effective strategy that would defer even greater capital costs in the future for potential reconstruction (McDaniel, 2014). This situation reflects an often-repeated pattern for many municipalities nationwide who, according to the American Society for Civil Engineers' 2013 Infrastructure Report Card, are seeing increased visual and functional examples of deteriorating transportation facilities but are more greatly constrained in the financial resources necessary to make substantial improvements (ASCE, 2013).

It is plausible to conclude that a partial cause for increased street deterioration in the City of Dallas is due to some of the recent impacts of climate change, extreme weather, and urban heat island effects outlined within this report. Major events like the ongoing drought from 2010 and the extreme heat during the summer of 2011, combined with widespread extent of high-plasticity soils within the city and their enhanced effects on shifting due to changing soil moisture conditions (Fig. A.3), can certainly contribute additional stresses to roadway performance and maintenance effectiveness (USDA, 2014). Unfortunately, despite the robustness of the database system and its capabilities for the cataloging and manipulation of numerous points of data, it is currently not configured in such a way to indicate that extreme weather effects are a direct cause to specific street section degradation or failures (Jordan, 2014).

Also, some weather events can be highly localized in nature, and for a jurisdiction as large as the City of Dallas, the timely and detailed recording of explicit impacts may be difficult to achieve on a regular basis. More data collection and analysis is needed to identify particular impacts resulting from special events, examine if/when/how design and performance thresholds were exceeded based on the type of event in question, set benchmark conditions in order to validate and compare data with other municipalities, and determine measurable quantities in materials and time expended solely for weather-related maintenance compared to other work types. These are important considerations for the future to ensure that ongoing capital development and maintenance programs, both locally in the City of Dallas and nationwide among other typical government entities, can bring more resources to bear in combating all potential variables that simultaneously impact effective asset management and affect vulnerability to climate change factors.

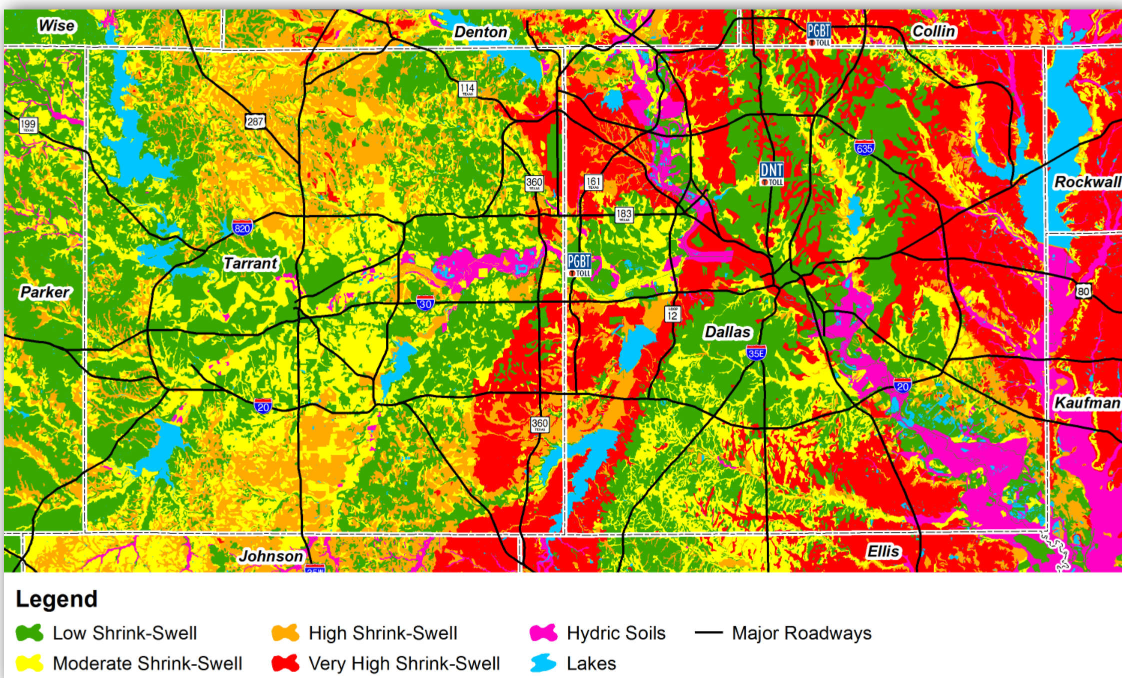


Figure A.3. Soil plasticity map for Tarrant and Dallas Counties (USDA, 2014).

A.2. References

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APPENDIX B.

B.1. Dallas Area Rapid Transit (DART) Severe Weather Action Plan

This Pilot Study has highlighted recent occurrences where extreme weather events have impacted transportation infrastructure and provider services throughout North Central Texas, and it suggests that the region will become more vulnerable to potential damage and/or disruptions under projected climate change patterns up through the end of the 21st century. The frequency and intensity of various extreme weather occurrences have prompted some local governments and transportation providers to develop dedicated mitigation and/or contingency plans to outline how appropriate operations and maintenance processes should proceed. As one of the Dallas-Fort Worth (DFW) Metropolitan Area's primary transit providers, Dallas Area Rapid Transit (DART) developed a Severe Weather Action Plan (SWAP) in February 2008 to define roles, responsibilities, equipment, and supply requirements for the agency's operating divisions essential for personnel to respond and allocate resources in the most effective manner (DART, 2015). The SWAP endured its most significant test to date during the major winter storm event of December 5-7, 2013.

This extreme weather event was unusual in that after a combination of freezing rain, sleet, and snow fell with accumulations of up to five inches in some locations during the first 24 hours, daily maximum temperatures remained continuously below the freezing point for just over 60 hours (National Weather Service, 2014). Even for five days after the onset of the storm, when daily maximum temperatures were slightly above the freezing point, daily minimum temperatures at night were still below the freezing point, so that many locations in the northern portion of the DFW area had lingering icy conditions (Fig. B.1). Some of the major regional impacts from this storm on Tarrant and Dallas County infrastructure included the following (National Weather Service, 2014):

- As many as 275,000 customers were without electricity at the peak of the storm
- Most schools, particularly in the most severe impacted areas, were closed for several days
- Thousands of local businesses were forced to close for up to two days
- Hundreds of flights were cancelled at Dallas-Fort Worth International Airport (DFWIA) and Dallas Love Field Airport leaving thousands of flyers stranded at these airports
- Seven fatalities, including four in vehicles, two from exposure, and one from a fall on the ice
- Hundreds of injuries were reported due to falls on the ice
- Over $30 million in residential insured losses according to the Insurance Council of Texas
- Recurring combination of vehicle compaction, melting/re-freezing, and various treatment applications resulted in the development of "cobblestone ice" causing

substantial damage to roads and bridges, personal property damage, and widespread traffic congestion

For DART, all light-rail service was suspended for three days, primarily due to ice build-up on power lines and catenaries (Aasen, 2013). Trinity Railway Express (TRE) service delays extended up to one hour at times for two days since maintenance crews were limited in their abilities to move quickly between rail switches for de-icing operations (Aasen, 2013). These effects occurred despite the agency's activation of SWAP and its interactions with various utility providers and emergency response entities. The experience underscored the importance of adaptation in the planning and preparation for major events, and the realization that resource mobilization and responses need to be both flexible and concentrated to deal effectively with wide-ranging weather variables. DART identified that it was appropriate to apply lessons learned from this event and right-size operations to maximize potential service and minimize risk within a defined geographic area.

In January 2015, DART prepared and released two operational scenario plans to govern how transit service could be provided under various winter weather conditions in the DFW area (DART, 2015). Operating Scenario One is developed around a partial rail

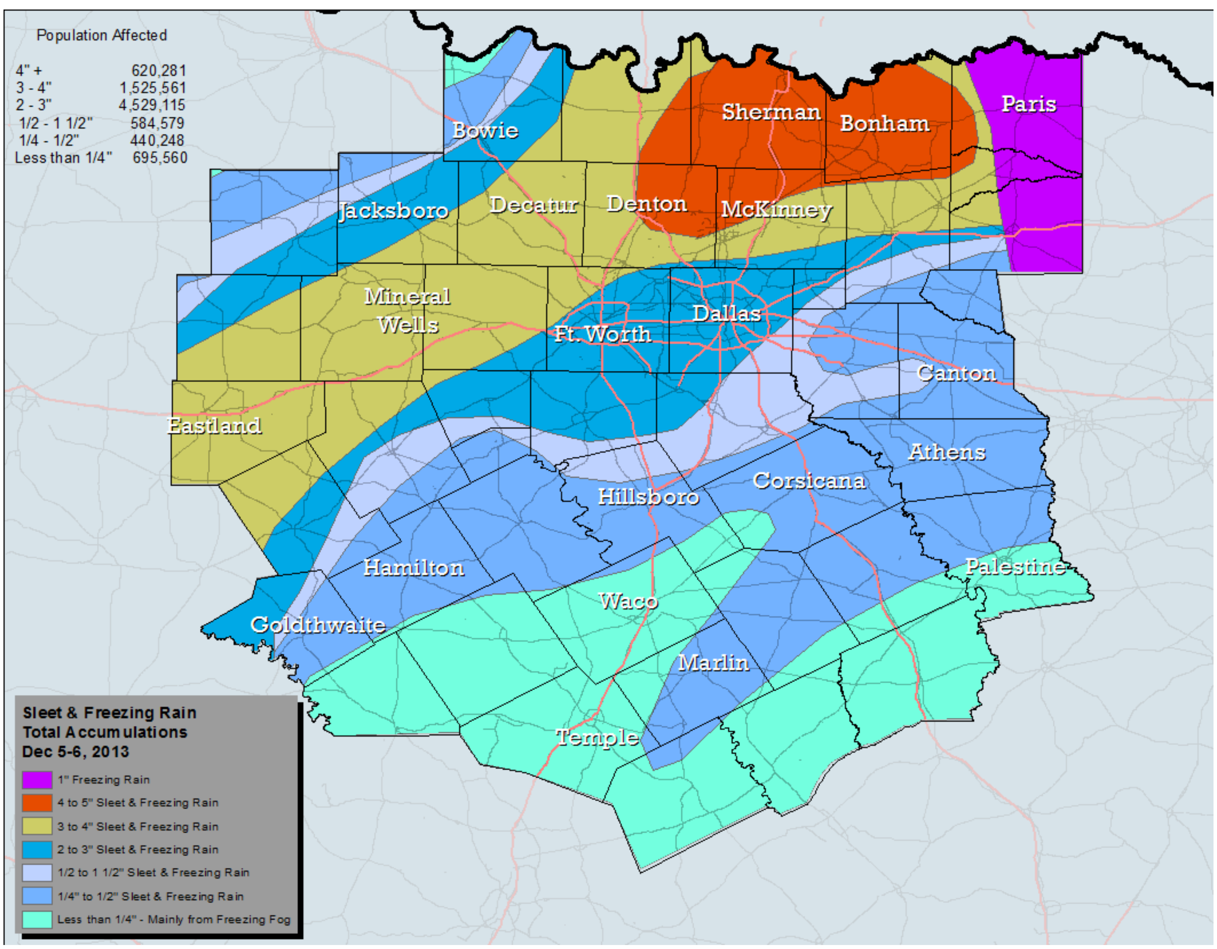

Figure B.1. Total accumulations of sleet and freezing rain during the winter storm of December 5-6 in 2013 (National Weather Service, 2014).

shutdown (Fig. B.2) allowing limited operations between rail stations inside the Interstate Highway (I.H.) 635 loop. Shuttle bus routes would operate to connect travelers between rail stations outside the loop. Operating Scenario Two describes a full rail shutdown. In that case, only bus service would be available for travel to/from all light-rail stations and park-and-ride facilities. DART has indicated that internet, social media, and conventional media outlets can be sent implementation notices of either plan as much as six to eight hours prior to the start of service for each day of potential disruption, allowing for both sufficient public awareness and a more efficient deployment of staff and resources to help simultaneously maintain service and combat potential infrastructure impacts.

Extreme weather events will continue to provide significant challenges toward infrastructure maintenance and service optimization. DART's severe weather alert plan with alternate operational scenarios in the activation of its SWAP illustrates how vulnerability and risk can be mitigated through the continuous evaluation of current extreme weather condition, thus allocating necessary resources for these events. This is a critical consideration in determining the overall level of asset exposure and sensitivity to potential extreme weather and climate change. It highlights the need to ensure that infrastructure monitoring and action planning are comprehensively linked and implemented together.

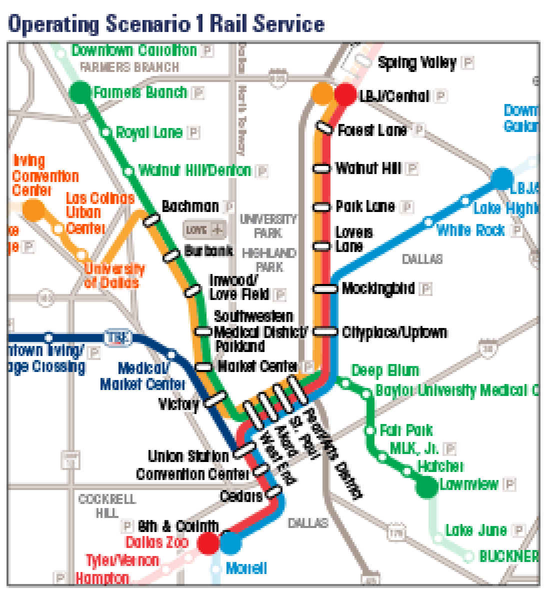

Figure B.2. Map of DART light-rail network operating under Operating Scenario One conditions (DART, 2015)

B.2. References

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