Technical Report

Statewide On-Road Greenhouse Gas Emissions Analysis and Climate Change Assessment

TxDOT Environmental Affairs Division
Effective Date: October 2018
725.01.RPT
Version 2

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1.0 Introduction

Consideration of greenhouse gases (GHGs) and climate change in NEPA analysis presents a unique challenge. After recognizing that Federal agencies needed assistance in determining the appropriate level of analysis for greenhouse gases and climate change in the NEPA context, the Council on Environmental Quality (CEQ) issued final guidance on greenhouse gas considerations in NEPA decisions titled, *Final Guidance for Federal Departments and Agencies on Consideration of Greenhouse Gas Emissions and the Effects of Climate Change in National Environmental Policy Act Reviews* in August of 2016. The stated goal of the guidance was to make the federal agencies' consideration of climate change impacts in NEPA documents as consistent as possible. The CEQ's greenhouse gas NEPA guidance was subsequently rescinded in March 2017.

If there was any clarity provided by the 2016 CEQ guidance, it is no longer available and the NEPA practitioner has since moved back to square one on the issue. With this lack of a clear standard, an agency NEPA decision-maker is challenged to determine what constitutes a hard look at the climate change implications of a project decision. There is a certain amount of uncertainty when estimating a proposed project's effect on climate change and the level of effort an agency should pursue when considering climate change within the NEPA context. Contributing to the difficulty is the global scope of climate change and making the causal linkage associated with any one project. The 2016 CEQ guidance recognized that inherent in NEPA and the CEQ regulations is a rule of reason which ensures that agencies are afforded the discretion, based on their expertise and experience, to determine whether and to what extent to prepare an analysis based on the availability of information, the usefulness of that information to the decision-making process and the public, and the extent of the anticipated environmental consequences. This agency deference, combined with the expectation of the NEPA process to disclose and inform, has led TxDOT to address climate change considerations for NEPA project-level decisions in this programmatic, statewide assessment. This assessment is intended to support the analysis of climate change for TxDOT projects in the NEPA context.

This report provides an analysis of: 1) available data regarding statewide greenhouse gas (GHG) emissions and on-road and fuel cycle GHG emissions,[1] 2) projected climate change for the state of Texas and 3) TxDOT's current strategies and plans for addressing the changing climate. TxDOT's goal is to provide reasonably available information regarding climate change to the public and to provide information for consideration during the environmental analysis of a project. **Appendix A** provides additional detail regarding the methodologies, data, and assumptions used for the GHG analysis and climate change assessment.

2.0 Overview of Climate Change and Greenhouse Gas Emissions

According to EPA, climate change refers to any substantial change in measures of climate (such as temperature, sea level or precipitation) lasting for an extended period (decades or longer). Climate change may result from natural factors and processes or from human activities.[2] Changes in climate have been documented by researchers, including changes in temperature, precipitation, storm activity, sea level, and wind speeds. When climate activities result in an effect on the human and/or natural environments, they are often referred to as climate "stressors." **Figure 1** provides a diagram of the climate system.

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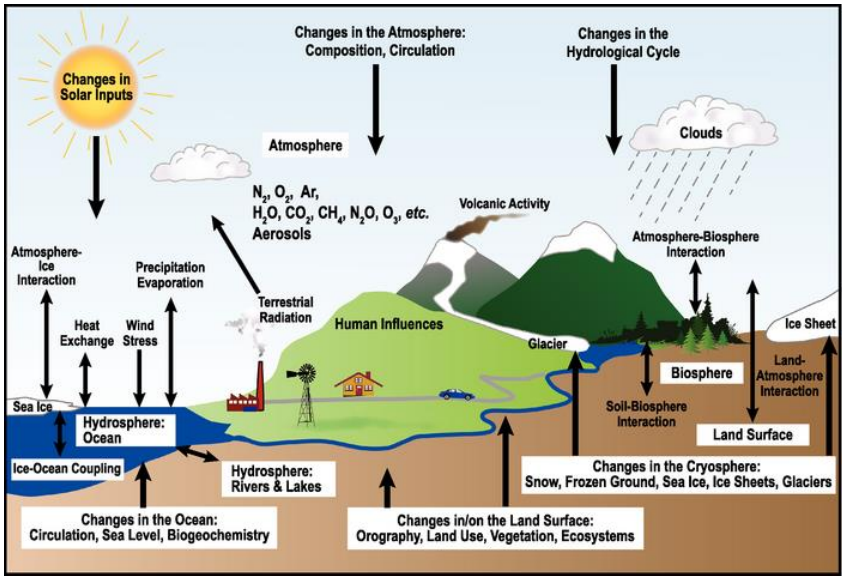
[1] Greenhouse gas (GHG) emissions consist of on-road tailpipe emissions and upstream fuel cycle emissions. For this analysis, these are measured by converting GHG emissions to CO_2-equivalent (CO_2E) emissions.

[2] (EPA, 2014)

Figure 1: Schematic View of the Components of the Climate System, Their Processes and Interactions



Source: (Solomon 2007)

Greenhouse gases were named for their ability to trap heat (energy) like a greenhouse in the lower part of the atmosphere. Atmospheric GHGs, including water vapor, carbon dioxide (CO_2), and other gases, trap some of the outgoing energy by retaining heat.

Many GHGs occur naturally and remain in the atmosphere for periods ranging from decades to centuries. Water vapor is the most abundant GHG and makes up approximately two thirds of the natural greenhouse effect. CO_2 is the second-most abundant GHG and stays in the atmosphere for approximately 30 to 95 years.[3] It is this continued persistence of CO_2 molecules in the atmosphere that scientists indicate contributes to the changing climate. CO_2 occurs naturally and is also generated through human actions.

Since the industrial revolution began in the 1700s, atmospheric concentration of GHG emissions has continued to climb, primarily due to anthropogenic[4] emissions.[5] Almost half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years[6] primarily from fossil fuel emissions[7] (e.g., coal, natural gas, gasoline, oil and/or diesel). According to the Intergovernmental Panel on Climate Change (IPCC), this increase in GHG emissions is projected to contribute to future changes in climate.

3.0 Statewide On-Road GHG Analysis

The analysis methodologies described in **Appendix A** have been applied to estimate GHG emissions for the Texas on-road transportation system and associated upstream fuel-cycle emissions. This section: 1) summarizes the GHG emissions analysis results for the system and 2) describes strategies for reducing GHG emissions.

The Texas on-road transportation system includes:

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[3] (David Archer, 2009).
[4] Anthropogenic refers to human activity.
[5] (Summary for Policymakers, IPCC Climate Change 2014 Synthesis Report, Fifth Assessment Report, 2018).
[6] (Summary for Policymakers, IPCC Climate Change 2014 Synthesis Report, Fifth Assessment Report, 2018)
[7] (Stocker, 2013)

- A total of 677,577 lane-miles in the on state[8] and off-state[9] system; and
- A total of 707.2 million average daily vehicle miles traveled (VMT) for the combination of on-state and off-state system roadways.[10]

3.1 Quantification of Emissions

On-road GHG emissions and upstream fuel-cycle emissions are ultimately dependent on: 1) the choices of individual commuters, 2) vehicle and fuel technologies regulated at the national level, and 3) characteristics of the transportation system (such as availability of transit). The emissions analysis for the GHG emissions from the Texas on-road transportation system serves as a proxy[11] for the system's potential contribution to global climate change.

The transportation and electrical energy sectors were the two largest sources of GHG emissions in the U.S. in 2015, and the state of Texas in 2014 (**Figure 2**). GHG emissions in the U.S. were 6,870.5[12] million metric tons (MMT) of CO_2E[13], and transportation's contribution was 1,810.3 MMT[14]. The majority of transportation GHG emissions result from the combustion of petroleum based products (e.g., gasoline) in personal and commercial vehicles, trains, ships, and airplanes. CO_2 is the largest component of these GHG emissions. According to the U.S. Energy Information Administration (EIA) [15], the 2014 annual CO_2 emissions in Texas were 625.3 MMT, including 211.6 MMT from the multi-modal transportation sector, which includes the on-road/non-road transportation GHG emissions related to transportation, industry, and commercial and residential construction. Additional construction related GHG emissions such as from the creation of building materials and pavements were included in the 625.3 MMT total statewide emissions. In 2014, approximately 76 percent of transportation emissions[16] were due to on-road emissions, corresponding to approximately 160.8[17] MMT CO_2 for 2014 Texas on-road emissions. This EIA data is slightly lower than the 175 MMT CO_2E estimate from the Texas Commission on Environmental Quality (TCEQ) Emission Trends Report (**Figure 3** and **Table 1**). Emission estimates vary somewhat depending upon the data sets, assumptions and analysis methods used. Three primary data sets and analysis methodologies are presented in **Appendix A**.

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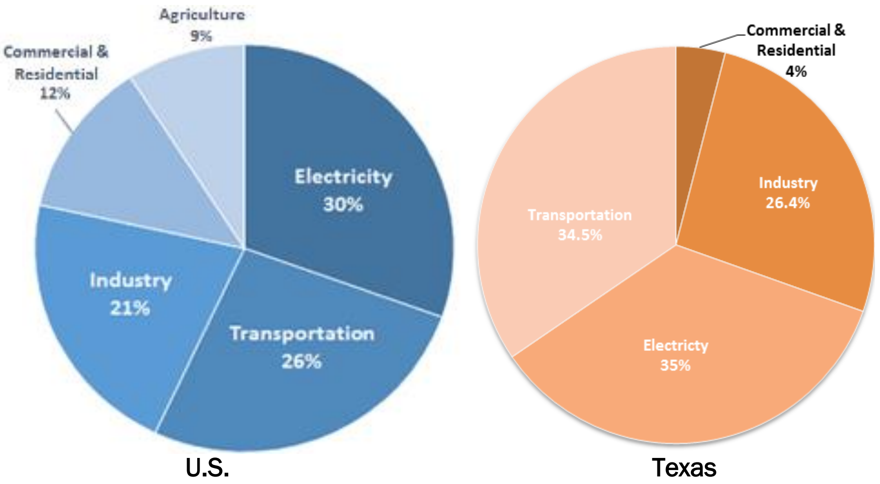
[8] An example of an on-state system roadway is an interstate, state highway, or farm-to-market road.
[9] An example of an off-state system roadway is a local city street or county road.
[10] (TxDOT 2015, Section 4.2 Historical Trend-Tables)
[11] (CEQ 2016) Pages 4 and 10 discuss using GHG emissions as a proxy for climate change.
[12] (EPA, 2016), Table ES-6, page ES-23, accessed on September 24, 2018.
[13] CO_2E stands for "carbon dioxide equivalent" and means the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas, and is calculated using Equation A-1 in 40 CFR Part 98.
[14] (EPA 2016), Table ES-6, page ES-23, accessed on September 24, 2018.
[15] (EIA, 2017).
[16] (EPA, 2017, pp. Annex 3-2)
[17] This is based on-road transportation emissions being 76% of the 211.6 MMT CO2 for multi-modal Texas transportation emissions from EIA data.

Figure 2: Total U.S. and Texas GHG Emissions by Economic Sector in 2014



U.S. Texas

Sources: U.S. graphic: (EPA, 2016); Texas data from (EIA 2016)

The historic and predicted relationship between Texas on-road VMT and tailpipe and fuel-cycle emissions is shown in **Figure 3** and **Table 1.** EPA's Motor Vehicle Emissions Simulator (MOVES, 2014 version) model was used to estimate emissions. MOVES2014 does not account for the heavy-duty diesel CAFE standards for model years 2018–2029, which would further reduce the emission projections provided in **Figure 3** and **Table 1**. The population-based VMT trend (**Figure 3** and **Table 1**) is slightly higher (261.6 billion VMT for 2015) than the VMT reported under the FHWA Highway Statistics series[18] (258.1 billion VMT for 2015) (**Table 2**), resulting in emission estimates that are slightly higher than emissions would be if based on reported VMT.

In the base year 2010, Texas on-road and fuel-cycle CO_2E emissions were estimated to be 171 MMT per year; by 2040, emissions are estimated to be 168 MMT. Emissions are predicted to peak in 2017 at 176.6 MMT and reach a low in 2032 at 161.1 MMT. The peak emission reductions would be achieved by 2032 as more of the 2012[19] and later model-year vehicles enter the Texas fleet, and older vehicles are phased out. In this situation, technology reduces emissions more than VMT increases it. This peak reduction is reached after all 2012–2025 model-year vehicles have saturated the fleet, at which point CO_2E emissions begin to increase as VMT increases. Future changes to regulations, market penetration for new vehicle and/or fuel technological advances such as electric vehicles, economics and personal decisions regarding travel options could substantially affect future CO_2E emission estimates.

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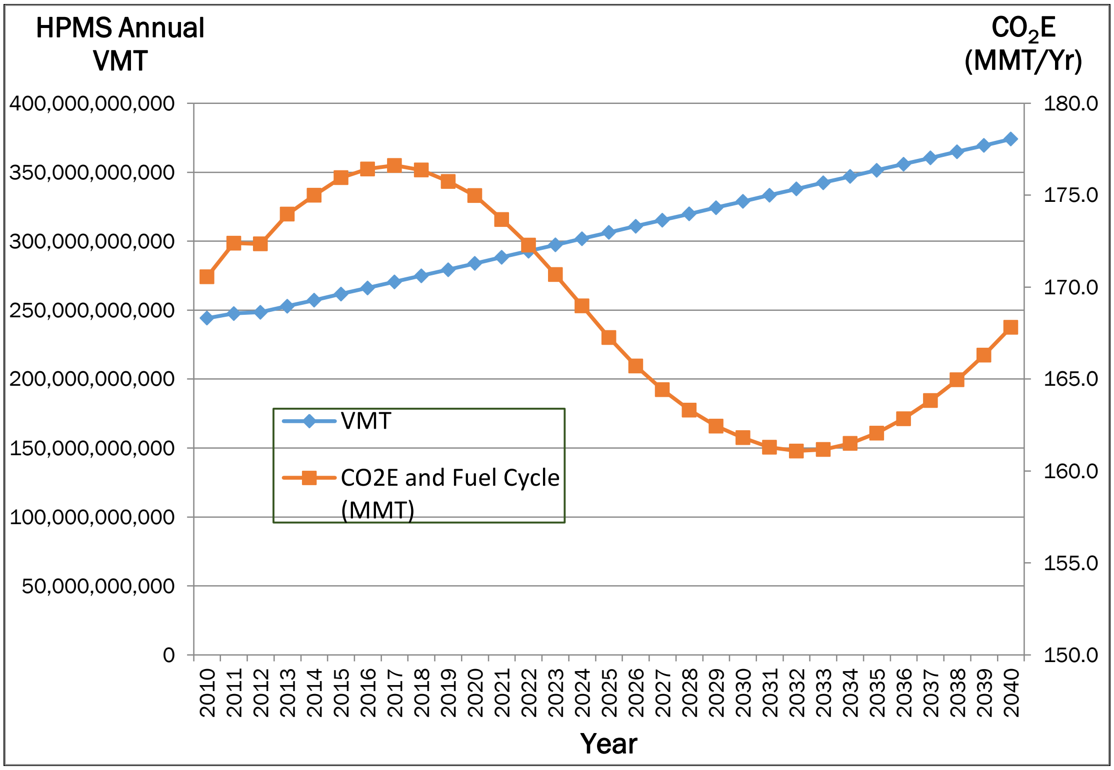
[18] The Federal Highway Statistics series consists of annual reports containing analyzed statistical information on motor fuel, motor vehicle registrations, driver licenses, highway user taxation, highway mileage, travel, and highway finance. It has been published annually since 1945.

[19] The first vehicle model year to include the combined CAFE and GHG emission standards was 2012. (Environmental Protection Agency and Department of Transportation National Highway Traffic Safety Administration , 2010).

Figure 3: Texas VMT and Annual CO_2E On-road and Fuel-Cycle Emissions Trends (in MMT)



Data Sources: For VMT, population and on-road CO_2 emissions: (TCEQ 2015)
To obtain fuel-cycle emissions, TxDOT multiplied the statewide annual emissions by 1.27 (EPA fuel-cycle factor is 27% of on-road emissions). TxDOT used the following for the million metric ton conversion (annual tons/1.10231131092 metric tons/U.S. tons)/1,000,000.

Table 1: Texas Annual VMT and Annual CO_2E On-road and Fuel-cycle Emission Trends

Year	VMT (in billions)	CO_2 On-road (MMT)	CO_2E On-road and Fuel Cycle (MMT)
2010	2.44	132	171
2014	2.57	138	175
2015	2.61	137	176
2020	2.83	136	175
2025	3.06	130	167
2030	3.28	126	162
2035	3.51	126	162
2040	3.74	130	168

Data Source for VMT and on-road CO2 emissions: (TCEQ 2015)
To obtain fuel-cycle emissions, TxDOT multiplied the statewide annual emissions by 1.27 (EPA fuel-cycle factor is 27%). TxDOT used the following for the million metric ton conversion (annual tons/1.10231131092 metric tons/U.S. tons)/1,000,000. CO_2 to CO_2E conversion is CO_2/0.986 CO_2E.

Table 2: Texas Lane Miles and Annual VMT 2011-2015

Year	Interstate and Freeways Lane Miles	Arterials, Collectors, and Local Streets Lane Miles	Total Lane Miles	Annual VMT (in billions)
2015 (1)	23,735	653,842	677,577	(2) 2.58
2014 (3)	23,734	653,841	677,575	(4) 2.43
2013 (5)	23,277	652,303	675,580	2.44
2012 (6)	23,149	652,148	675,296	(7) 2.37
2011 (8)	22,921	651,375	674,296	(9) 2.37
2015–2011 Lane Additions	813	2,468	3,281	0.20
Average Yearly Lane Additions	163	494	656	0.04

Sources: (1) (FHWA 2017)
(2) (FHWA 2016)
(3) (FHWA 2015)
(4) (FHWA 2015)
(5) This data was the result of a new TxDOT data system. Based on this information, Statewide vehicle-miles traveled (VMT) decreased 1.48% when compared to the 2013 data, contrary to an expected increase based on other economic indicators which suggest traffic growth in Texas.
(6) (FHWA 2014)
(7) (FHWA 2014)
(8) (FHWA 2013)
(9) (FHWA 2013)

As discussed in **Section 3.2**, the CAFE standards for model year 2012–2029 are estimated to reduce nationwide GHG emissions by 62,200 to 127,300 MMT. NHTSA EISs for each CAFE standard have substantial discussion of GHGs and climate change, including modeling of alternative future GHG emissions and climate stressor[20] scenarios. These large nationwide GHG reductions are estimated by year 2100 to only reduce global temperatures by small amounts (approximately 0.0005–0.027 °F) and reduce potential global sea-level rise by less than a tenth of an inch (0.008–0.06 inches) (**Table 3**).

In 2014, approximately 36,138 MMT of CO_2 emissions were released worldwide, of which less than one-half of one percent (0.48 percent or 175 MMT CO_2E) were attributed to Texas on-road and fuel-cycle emissions.[21] **Figure 4** provides an estimate of 2014 worldwide CO_2 emissions to Texas transportation-related CO_2E emissions, all sector Texas CO_2 emissions, and all sector U.S. CO_2E emissions. The purple circle in **Figure 4** represents emissions from vehicles traveling on existing and newly constructed roadways in Texas in 2014. Individually proposed TxDOT on-road projects and their alternatives represent a very small subset of the Texas transportation system emissions and even smaller portion of national and worldwide emissions. For example, the average annual lane addition in the 2017 UTP was 121 centerline miles/year, which represents a relatively tiny addition to the existing Texas transportation system, which was 677,577 lane miles. TxDOT lets more than 2,000 projects for construction per average year.

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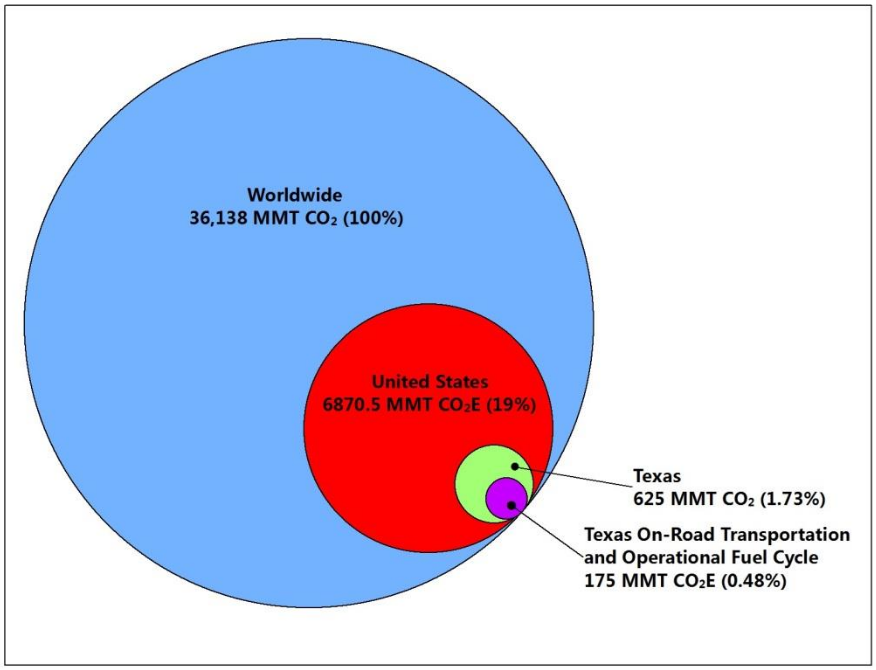
[20] A climate stressor is a condition, event, or trend related to climate variability and change that can exacerbate hazards. For example, increasing frequency and intensity of drought conditions can be a climate stressor for forests and crops. Rising sea level is another climate stressor. (NOAA).

[21] Worldwide emissions from (World Bank 2017). Different sources provide data for CO_2 and CO_2E. CO_2 is less than CO_2E. For example CO_2E worldwide according to IPCC for 2013 was 49,000 MMT.

Figure 4: Comparison of 2014 Texas, U.S., and Worldwide CO_2 Emissions



Source: TxDOT, 2017

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3.2 *Strategies that Reduce Greenhouse Gases*

Strategies to reduce on-road GHG operational emissions fall under three major categories:

- Federal engine and fuel controls under the Clean Air Act implemented jointly by EPA and U.S. Department of Transportation (USDOT), which include CAFE standards as well as other reasonably foreseeable technological advances (e.g. electric or hydrogen vehicles);
- Traffic system management (TSM), which improves the operational characteristics of the transportation network (e.g., traffic light timing, pre-staged wrecker service to clear accidents faster, or traveler information systems); and
- Travel demand management (TDM), which provides reductions in VMT (e.g., transit, rideshare, and bicycle and pedestrian facilities).

The majority of on-road tailpipe emission reductions to date have been achieved through federal vehicle and fuel controls and associated vehicle and fuel technological advancement. [22]

NHTSA and EPA jointly established new, more stringent fuel economy standards as well as the first-ever[23] EPA regulation under the Clean Air Act to regulate vehicle GHG emissions. These standards apply to model-year 2012 to 2025 passenger cars and light-duty trucks and model-year 2014 to 2029 medium- and heavy-duty

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[22] (FHWA, 2017 (website updated)).

[23] Environmental Protection Agency and Department of Transportation National Highway Traffic Safety Administration, 40 CFR Parts 85, 86, and 600; 49 CFR Parts 531, 533, 536, et al. *Light-duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule*, Federal Register, May 7, 2010, volume 75, No. 88, pp. 25324-25728. See page 25396, column 2.

vehicles. The 2021-2025 light duty vehicle GHG emission standards and the 2021-2026 CAFE standards were proposed for revision in the Federal Register on August 24, 2018.[24]

NHTSA issued EISs for the CAFE and vehicle GHG standards. Each EIS has substantial discussion of GHGs and climate change including modeling of alternative future GHG emissions and climate stressor scenarios. NHTSA estimated the impact of the CAFE standards on global GHG emissions and climate change as summarized in **Table 3**.

Table 3: Estimated Climate Impacts for the NHTSA CAFE Standards

Vehicle Model Years	Lifetime National GHG Reductions (million metric tons)	Annual GHG Reductions (million metric tons)	Lifetime Fuel Reduction (billion gallons)	Annual Fuel Reduction (billion gallons)	Reduction in Global Temperature Change in 2100 Compared to No Action	Reduction in Global Sea Level Rise in 2100, Compared to No Action (inches)
2012–2016 (1)	20,700 – 47,300 (1)	232–543 (2)	NA	25.5–59.6 (2060)	0.016°F to 0.027°F	0.02–0.06 inches
2017–2025 (2)	29,800 – 53,300 (3)	NA	200–1,767(4)	NA	0.002°F to 0.027°F	.016 to 0.06 inches
2014–2018 (3)	6,700–12,500 (5)	11–63	46.7–189.4 (6)	NA	0.0005°F to 0.0037°F	max of 0.008 inches
2018–2029 (4)	5,000 – 14,200 (7)	NA	85.9–287.1 (8)	NA	0.004°F to 0.009°F	max of 0.04 inches

Sources: (1) (NHTSA 2010, S-5, S-13, 3-85, 3-109)
(2) (NHTSA 2012, S-12, S-43, S-47, 2-41)
(3) (NHTSA 2011, S-6, S-19, S-20, 3-91, 3-114)
(4) (NHTSA 2016, S-7, S-23, S-24, S-26)

Electric Vehicle Market Projections

The assumptions used for the Texas on-road GHG and upstream fuel cycle emission projections maintain EVs in Texas at less than 1% of market share through 2040. This assumption in all likelihood is incorrect. Experts are predicting major shifts from fossil-fuel (gas/diesel/ methane/ethanol internal combustion engine-powered) passenger vehicles to passenger electric vehicles, with substantial increases beginning in 2025. For example, Bloomberg New Energy Finance (BNEF) issued "*Electric Vehicle Outlook 2017*".[25] In this report, BNEF reviewed economics, technology, policy and consumer behavior to predict electric vehicle (EV) adoption between now and 2040. These projections account for existing policy but do not anticipate any new policies to be implemented. The Bloomberg report analyzed five underlying factors likely to drive increased EV adoption:

- "Short-term regulatory support in key markets like the U.S., Europe and China;
- Falling lithium-ion battery prices;
- Increased EV commitments from automakers;
- Growing consumer acceptance, driven by competitively priced EVs across all vehicle classes; and
- The growing role of car sharing, ride hailing and autonomous driving (termed 'intelligent mobility' here)."[26]

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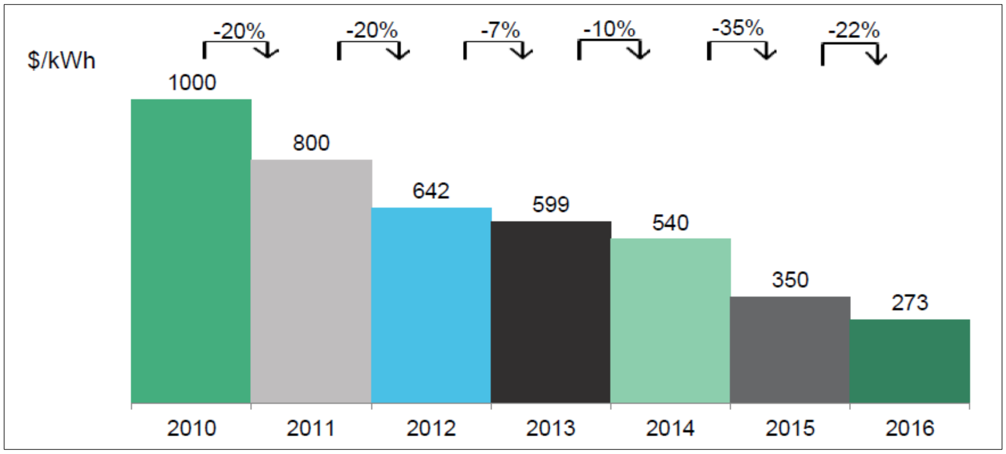
[24] (EPA and USDOT-NHTSA, 2018).
[25] (Bloomberg New Energy Finance, 2017)
[26] (BNEF 2017). Note Uber or Lyft are examples of "ride hailing" services.

BNEF projects that the cost for electric and internal combustion engines will be the same by 2025, due to reduced costs associated with electric battery manufacturing (**Figure 5**).[27] Furthermore, 2016 prices were 73% less than 2010 prices by BNEF observed values. BNEF projects prices will continue to drop and will reach $74/kilowatt hour (kWh) by 2030 (92.6% cost reduction from 2010.[28] Various news articles indicated over 100 types of electric vehicles will be available for purchase by 2022. For new vehicle sales, BNEF anticipates that electric vehicles will surpass standard internal combustion engine-powered vehicle sales by 2038. BNEF projects that electric vehicle sales will reach 54% (> 60 million electric vehicle sales/year) market share by 2040.[29]

Figure 5: Lithium Ion Battery Price Survey, 2010-2016 ($/kWh)



Source: BNEF, Lithium-Ion Battery Costs and Market, July 5, 2017

The International Energy Agency (EIA) released "*Global EV Outlook 2017 Two Million and Counting*" which revised their global market projections for electric vehicles. From 2010 to 2016 global electric vehicles have increased from 0 to 2 million. EIA projects that 60 to 200 million electric cars will be deployed world-wide by 2030.[30]

Congestion Management

Increasing congestion is both a nationwide[31] (**Figure 6**) and worldwide[32] challenge. Congested travel delays caused U.S. drivers to waste more than 3 billion gallons of fuel in 2014 (versus 0.5 billion gallons of fuel in 1982) and cost the U.S. $160 billion in 2014.[33]

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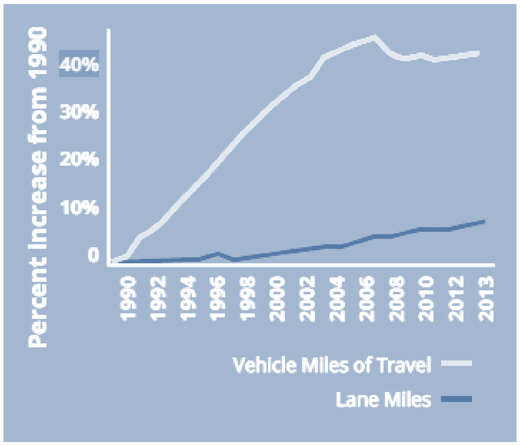
[27] (Bloomberg New Energy Finance (report by Claire Curry), 2017)
[28] (BNEF 2017)
[29] (BNEF 2017)
[30] (EIA, 2016 (website update year))
[31] (Schrank 2015)
[32] (INRIX Research 2016)
[33] (Schrank, 2015)

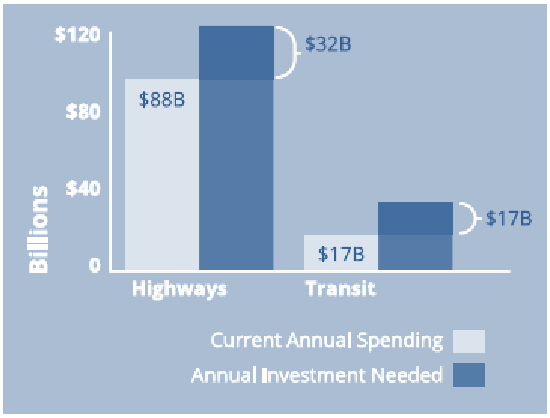
Figure 6: Percent Increase in U.S. VMT and Lane Miles



Source: (USDOT)

Increased vehicle fuel efficiency, inflation and cost increases in construction materials have reduced federal transportation funds purchasing power by nearly 40 percent (**Figure 7**),[34] resulting in increased congestion. With current available funding levels, the "rate of growth" in congestion is managed by TxDOT through the combination of system operational improvements; travel-demand reduction strategies, transit; and new roadway construction. Other options that reduce congestion include flexible work schedules, personal travel decisions, and technological advances (e.g. communication that reduces need for travel such as WebEx or transportation technologies such as automated and connected vehicles).

Figure 7: Estimated U.S. Surface Transportation Investment Gap



Source: (USDOT)

Travel speed on a roadway is an indicator for congestion. Based on EPA MOVES-generated emission rates for Texas, improvements in travel speed (reducing congestion) will provide reductions to operational GHG emissions. **Figure 8** illustrates the relationship between speed and emission rates for the 2020 and 2040 analysis years. These rates represent the average rates for all vehicle and roadway types in Texas. Rates for 2040 show an overall average decrease of 25 percent from the 2020 rates based on benefits from federal CAFE and vehicle emission standards. The most congested roadways and bottlenecks have stop-and-go traffic during peak traffic times. Stop-and-go traffic is represented in **Figure 8** at the lowest speeds (0–10 miles per

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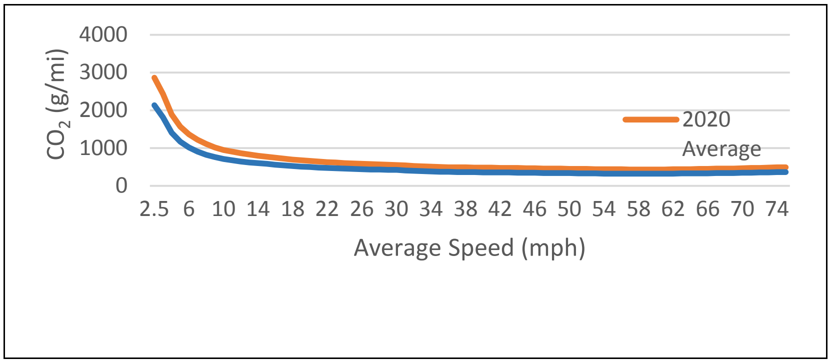
[34] (USDOT)

hour), which have the highest emission rates. For example, five mph has three times higher emissions than 20 mph. Reducing congestion on roadways reduces fuel use and congestion-related emissions.

Figure 8: Emission Rates by Speed



Source: (TxDOT, 2017) MOVES Emissions Rates for Texas

Other initiatives intended to reduce emissions include the following.

- Dallas/Fort Worth, Austin, San Antonio and Houston/Galveston participate in the U.S. Department of Energy's (DOE) Clean Cities program that supports local actions to reduce petroleum use in transportation; [35]
- Texas State Energy Conservation Office researches and assists public and private entities in securing grants to encourage the use of alternative fuels; [36]
- TxDOT is participating in the FHWA alternative fuels corridors program; [37]
- TxDOT has increased the number of alternate-fueled vehicles in the TxDOT fleet; [38]
- Texas Transportation Funding, Project Selection and TxDOT Operational Programs:
    - TxDOT provides approximately $150,000,000 per year in nonattainment areas for federally funded Congestion Mitigation Air Quality (CMAQ) improvement projects (e.g., bicycle/pedestrian facilities); [39]
    - Project selection: The Congestion management process under 23 CFR 450 encourages projects that reduce congestion (and emissions) and improve safety including but not limited to TDM and TSM; [40]
    - Transportation sector fees fund the TCEQ Texas Emission Reduction Program (TERP), a program used by many TxDOT contractors to reduce diesel on-road and construction equipment emissions. $154.8 million was appropriated to the TERP program for the 2018-2019 biennium; [41]
    - TxDOT's Recycling and Clean Construction and Operation initiatives; [42]
    - The Drive Clean Texas (DCT) program encourages driving habits that reduce vehicle emissions; [43]
    - TxDOT's Clean Air Plan encourages over 11,000 employees statewide to reduce vehicle emissions; [44]

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[35] (DOE, website year not listed).
[36] ((Texas) State Energy Conservation Office, website year not disclosed).
[37] (FHWA, 2018 (website last updated)).
[38] (TxDOT, website year not disclosed).
[39] (TxDOT, website date not disclosed).
[40] (FHWA, Rules in place as of August 30, 2018).
[41] (TCEQ, 2018 (website last updated)).
[42] (TxDOT, website date not disclosed)).
[43] (TxDOT and Drive Clean Texas, TxDOT website date not disclosed, Drive Clean Texas (copyright date 2018)).
[44] (TxDOT, website year not disclosed).

  - TxDOT Public Transportation Programs and Funding;[45] and
  - TxDOT Planning and Designing for Bicycles and Bicycle and Pedestrian Funding Programs.[46]

A few examples of these programs are provided below.

Recycling, Clean Construction and Operation

TxDOT has specifications for sustainable pavements that reduce energy consumption, increase recyclable use, and reduce air emissions including CO_2. Examples include:

- Warm Mix Asphalt (WMA);
- Recycled Asphalt Pavement (RAP);
- Recycled Asphalt Shingles (RAS);
- Coal and Other Combustion By-Products (e.g., fly ash);
- Recycled Tires;
- Recycled Concrete;
- Standard specifications for purchasing light emitting diode (LED) lighting; and
- Solar sign boards replacing diesel-powered sign boards.

In 2001, TxDOT, in partnership with the TCEQ, developed the nation's first comprehensive *statewide* public outreach and education campaign aimed at getting individual drivers to reduce tailpipe emissions by changing driving habits. TxDOT spends approximately $1.4 million annually on the campaign.

The Clean Air Plan focuses on TxDOT employee vehicle travel reduction and business operational changes in support of air quality goals for five months/year during the ozone season.

4.0 Assessment of Climate Change Stressor Projections

In this section, a background summary of potential global and national climate change projections is provided based on a variety of sources. Using the methodology disclosed in **Appendix A**, a qualitative assessment was completed to identify potential climate stressor projections for Texas for a period between 2070 and 2100, unless otherwise specified. Shorter-term projections (including for the period of the TxDOT long-range transportation plan) were not consistently available. The analysis incorporates available information on historic and projected climate change impacts for the state of Texas (**Section 4.2**). Data were reviewed from several sources, including: the 2014 National Climate Assessment (NCA); the U.S. Geological Survey (USGS) National Climate Change Viewer; the Assessments from the International Panel on Climate Change (IPCC); U.S. National Oceanic and Atmospheric Administration (NOAA) Global and Regional Sea Level Rise Scenarios; U.S. Army Corp of Engineers (USACE) Procedures to Evaluate Sea Level Change; and the four NHTSA EISs for CAFE standards.

The "climate change projections" or "climate forcing scenarios" used in this analysis were based on Representative Concentration Pathways (RCPs). RCPs are GHG concentration trajectories used for climate modeling and research and are based on assumptions relating to the level of GHG emissions now and into the future. The high and low CO_2E concentration RCP options were chosen for the TxDOT analysis. RCP8.5 (high emissions estimated to be approximately 1,370 parts per million [ppm] CO_2E in 2100) is a business as usual case with little to no additional worldwide GHG control measures. RCP4.5 (low emissions estimated to be

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[45] (TxDOT, website year not disclosed).
[46] (TxDOT, website date not disclosed).

approximately 650 ppm CO_2E in 2100) refers to a high level of GHG controls recommended to keep temperature rise below 2° C in 2100.

For transparency, several major sources of data limitations and uncertainty exist in projections regarding climate change and these are discussed in **Section 5**. The outputs of climate models are framed as potential futures or scientifically-based scenarios that reflect specific probabilities.

4.1 Overview of Global and National Climate Change Projections

Depending on international efforts, the global economy and technological advances yet to be determined, climate change is anticipated to have a potentially wide range of effects on temperature, sea level, precipitation patterns, and severe weather events. These factors in turn could affect human health and safety, infrastructure, and food and water supplies. Large elements of uncertainty within future projections[47] make it extremely difficult to reliably predict the timing and scale of future changes in climate for the state of Texas and its inhabitants (people and other organisms). In addition, a variety of studies and analyses have disclosed broad climate change predictions for the U.S. and worldwide (**Tables 4 and 5**). Climate change projections vary widely by U.S. regions, and certain predicted impacts may be more severe in certain areas. For example, according to the NCA, the Northeastern and Midwestern portions of the U.S. may experience the greatest change in heavy precipitation.

Table 4: Potential Global and U.S. Implications of a Changing Climate

Impacts to Natural Systems		Impacts to Humans	
Category	**Potential Impacts**	**Category**	**Potential Impacts**
Fresh water quality and supply	Increased irrigation needs; water shortages; variability of water supply; increased flood risk; salt water intrusion from sea level rise; increased acidity from the formation of carbonic acid when CO_2 combines with water.	Food, fiber, and forestry industries	Increased tree mortality; productivity losses in crops and livestock; changes to nutritional quality of pastures, grazelands, and food crops; impacts to fishing industry from changing marine migrations; impacts to food prices and food security.
Species and habitats	Shifts in range and migration patters of species; changes in timing of species' life-cycle events; threats to sensitive species unable to adapt to changing conditions; increased occurrence of forest fires and pest infestations; changes in habitat productivity; stimulated plant growth due to increased CO_2 in the atmosphere, depending on plant species.	Human settlements	Changes may affect services such as: • Water/energy supply • Wastewater/stormwater • Transportation • Telecommunications • Social services Changes in agricultural income; air quality changes. Vulnerable populations have higher risks, including low-income, elderly, children, and those with existing health conditions.
Oceans and coastlines	Loss of coastal areas; reduction in coral reefs and other key marine habitats; increased vulnerability to severe weather and storm surge; increased salination in estuaries and aquifers; increased acidity due to chemical reactions with excess CO_2.	Human health	Increased morbidity and mortality due to excessive heat; increases in respiratory conditions due to poor air quality and aeroallergens; increases in water and food-borne diseases; changes in seasonal patterns of vector-borne diseases; increases in malnutrition. Vulnerable populations have highest risks.
Air quality	Projected impacts on statospheric ozone recovery (large elements of uncertainty).	Security	Threats in response to adversley affected livelihoods; compromised cultures; increased and/or restricted migration; reduction in provision of adequate essential services.

Sources: (NHTSA, 2010), (NHTSA, 2011), (NHTSA, 2012), (NHTSA, 2016), (Stocker, 2013), (USGCRP, 2014), (Melillo, 2014), (NRC, 2008), (Solomon, 2007), (TRB, NCHRP, 2014), (USACE, 2014), (USGS, 2016) (United Nations, 2017), and (NOAA, 2017).

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[47] (NHTSA, 2016)

Table 5: Existing and Projected Global Sea Level Rise

Climate Variable	Source	Indicator	Existing and Projected Changes
Global Sea Level Rise	IPCC[1]	Existing	From 1901 to 2010, historical global mean sea level rise was between 6.69 to 8.27 inches (0.17 to 0.21 meters) change. Maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 16 feet (5 meters) higher than present and high confidence it did not exceed 32 feet (10 meters) above present.
		Projected	In the range 2081-2100, the likely range of global sea level rise relative to reference period of 1986 to 2005 is 1.05 to 2.07 feet (0.32 to 0.63 meters) for RCP4.5 and 1.48 to 2.69 feet (0.45 to 0.82 meters) for RCP8.5.
	NOAA[2]	Existing	Over the past 30 years global mean sea level rise has averaged approximately 0.12 inches/year (3 mm/year), based upon global tidal gauge data, or 3.54 inches over 30 years (90 mm per 30 years).
		Projected	By year 2100, 0.98 to 8.20 feet (0.3 to 2.5 meters) global sea level rise with intermediate scenario of 3.28 foot (1.0 meter). The intermediate option is slightly higher than the IPCC "likely range" scenario.
	USACE[3]	Projected	By year 2100, 0.6 to 4.9 feet (0.2 to 1.5 meters) global sea level rise.
	NCA[4]	Existing	The past century had a global average sea level rise of 8 inches.
		Projected	1 to 4 foot mean global average sea level is projected by the year 2100 with a plausible high of 3 to 4 feet. The study suggests decision-makers may wish to use a broader range of scenarios for risk based analysis within the range of 8 inches to as much as 6.6 feet.

Sources and Notes: Unless otherwise specified, Future Climate Scenarios are based upon RCP4.5 and RCP8.5. RCP4.5 = ~650 ppm CO2E in 2100 representing a high degree of CO_2 emission controls and RCP8.5 = ~1370 ppm CO_2E in 2100 representing business as usual with little to no CO_2 control measures implemented worldwide.

1 (Stocker 2013)

2 (NOAA 2017) The local sea level rise projections from the NOAA report are available for all six global sea level rise scenarios as well as low, median, and high sub-scenarios.

3 (USACE 2014).

4 (USGCRP, 2014) It projects climate data for the years 2041–2070.

4.2 Projected Impacts of Climate Stressors on the State of Texas

This section provides a qualitative summary of climate change projections for the state of Texas based upon projections of climate stressors or variables. **Table 6** shows the potential climate stressor existing data and future projections for temperature, drought, and precipitation (wet days and monthly runoff). Extreme weather events are also qualitatively discussed.

Extreme Weather Events

Though **Table 6** does not include climate stressor projections specific to extreme weather events, events such as major flooding, storm surge, and major storms have historically impacted the state's transportation system. National research studies, including reports sponsored by the Transportation Research Board (TRB), have highlighted how climate change related extreme weather events are anticipated to further impact U.S. highways and other transportation infrastructure.[48]

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[48] (TRB, NCHRP 2014, Table I.1)

Table 6: Summary of Projected Climate Change Stressors for the State of Texas

Climate Variable	Source	Indicator	Existing and Projected Changes
Temperature	NCA[1]	Existing	93.1 to 104.4 °F Temperature range of historical “7 hottest days” per year
		Projected	For RCP4.5, 0.74 to 6.08 days change and for RCP8.5 18.72 to 33.74 days in number of hottest days per year
	USGS[2]	Existing	70.6 to 85.9 °F annual mean maximum temperature
		Projected	3.08 to 4.5 °F (RCP4.5) to 4.64 to 6.25 °F (RCP8.5) change in annual mean maximum temperature
Drought	NCA[1]	Existing	18.18 to 55.19 days for the number/range of consecutive dry days
		Projected	0.74 to 6.91 days predicted increase in the number of consecutive dry days
	USGS[2]	Existing	0.056 to 4.602 inches existing mean soil storage
		Projected	0.045 to 0.008 inches (RCP4.5), 0.071 to 0.008 inches (RCP8.5) predicted change in annual mean soil storage
	USGS[2]	Existing	0.419 to 3.069 inches in monthly evaporative deficit
		Projected	0.196 to 0.419 inches (RCP4.5), -0.6228 to 0.629 inches (RCP8.5) predicted change in annual mean evaporative deficit per month
Wet	NCA[1]	Projected	Less than 1 day decrease or increase (ranging from -0.077 to 0.7029 day) in the number of wet days per year between RCP4.5 and RCP8.5
Monthly Runoff	USGS[2]	Existing	0.036 to 1.24 inches (0.91 to 31.47 mm)
		Projected	-0.094 to 0.65 inches (RCP4.5), -0.221 to 0.035 inches (RCP8.5)

Sources and Notes: 1 (USGCRP, 2014) It projects climate data for the years 2041–2070. Texas county specific data was provided by USGCRP.
2 (USGS 2016) The climate projections used were 2050–2074 compared to 1950–2005. Texas county specific data was used.

4.3 Strategies to Address a Changing Climate

Given the uncertainty and variability in range of climate stressor projections (see **Section 5**), it is important to maintain flexibility when developing strategies and programs to respond to climate change. Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. Based on the climate stressors assessed for Texas, adaptation and resiliency strategies may be considered during planning, project development, final design, construction, emergency response, asset management and/or operational and maintenance activities. This section discusses recent initiatives and TxDOT’s strategies to address a changing climate.

Recent Initiatives

In 2010, the FHWA created a sustainability resilience pilot program.[49] As of August 30, 2018, three Texas Metropolitan Planning Organizations (MPOs) have participated in this pilot program: the North Central Texas Council of Governments (NCTCOG) serving the greater Dallas-Fort Worth area, the Capital Area Metropolitan Planning Organization (CAMPO) serving greater Austin and surrounding area, and the Houston-Galveston Area Council (HGAC) serving the greater Houston and surrounding area. For further details, see the FHWA Sustainability Resilience Pilots or additional information available at each MPO’s website. The Texas Association of Metropolitan Planning Organizations (TEMPO) maintains a website that includes contact information for all MPOs in Texas.

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[49] (FHWA, 2018 (website last updated)).

Precipitation, Flooding and Sea-Level Rise

Strategies for design, operations, and emergency response activities have been developed to respond to changing conditions associated with precipitation, flooding, and sea-level rise. Stormwater management helps reduce the frequency and extent of downstream flooding, soil erosion, sedimentation, and water pollution. Consistent with FHWA guidance, designs for stormwater management seek to mitigate the potential effects of runoff rates and stormwater volumes using the latest available information. Designs typically consider 2- to 100-year flood events. In addition, some infrastructure design considers a 500-year flood event (e.g., certain bridge scour situations, which relate to the erosion of soil surrounding bridge foundations).

Should changing storm frequency and intensity alter flood event designations and their associated probabilities of occurrence, TxDOT would continue to consider that information in final design, using best available data from Federal Emergency Management Agency (FEMA) or other agencies. Due to practical and financial considerations, projects cannot be designed and built to withstand every possible storm event (i.e., 500-year or 1,000-year storm events or unusual flooding events such as Hurricane Harvey). Therefore, during such events, TxDOT implements a combination of operational practices and emergency contingencies for movement through the transportation system.

Improved data can lead to improved operational practices. For example, new research and modeling by NOAA has produced a National Water Model (NWM), which simulates both observed and forecast streamflow over the entire continental United States. For Texas, this includes flow modeling at 27,000 Texas bridges on 15,700 stream reaches and rapid flood inundation mapping. This improved blend of observations and forecasts, including flood elevation predictions and flood mapping, operationally help road crews prioritize where they are needed as well as improve emergency responders' ability to navigate safely into a flooded area and provide help where it is needed the most.

The final design process for projects occurs after completion of the environmental process in accordance with applicable design requirements. Additional design information is available on the TxDOT Design Division Hydrology/Hydraulics website and the following manuals have the procedures/specifications:

- TxDOT 2016 Hydraulic Design Manual;
- FHWA 2016 Hydraulic Engineering Circular 17: Highways in the River Environment–Floodplains, Extreme Events, Risk, and Resilience (HEC 17);
- FHWA 2014 Hydraulic Engineering Circular 25: Highways in the Coastal Environment: Assessing Extreme Events (HEC 25); and
- FHWA 2013 Urban Drainage Design Manual (HEC 22), including but not limited to Chapter 8 for stormwater detention and retention facilities.

Extreme Heat and Drought

Strategies for operational and maintenance activities have been developed to respond to changing conditions associated with extreme heat and drought. Extreme heat and drought may result in premature pavement failure. Pavement failure is addressed in the TxDOT Pavement Manual and investigated by the TxDOT Premature Distress Investigation Team. TxDOT improves and refines pavement designs to adapt to changing conditions. As needed, adjustments would be made to pavement binders and/or base design and materials.

Drought conditions, increased temperature and increased number of dry days are anticipated to increase wildfire potential. Wildfires threaten infrastructure and reduce visibility. For example, the Bastrop County Complex fire in 2011 was one of the larger recent wildfires in Texas. It resulted in minor damage to guardrails and no damage to on-road system pavement; however, roads were temporarily closed due to fire hazard and/or visibility. Strategies such as temporary closures are part of operational and emergency management activities. Damages to transportation infrastructure would be addressed through the emergency maintenance program (e.g., guard rail damage repairs).

Extreme Weather Events

TxDOT's strategies include consideration of extreme weather events in asset management, emergency response activities, project design, and maintenance operations. During these events, TxDOT implements a combination of operational practices and emergency contingencies to maintain movement through the transportation system.

TxDOT's response to Hurricane Harvey provides an example of operational strategies and practices for emergency response to an extreme weather event. Hurricane Harvey was the first Category 4 hurricane to hit Texas in 50 years and affected both coastal and inland areas of southeast Texas. It was equivalent to three major weather events in rapid succession. The first was the landfall just north of Corpus Christi that was the "traditional wind and rain event of a hurricane." The second was when it pulled back and moved eastward, accumulating up to a historic 50 inches of rain on the Houston area within several days. The third was when the storm moved again over the Gulf of Mexico and returned to the Beaumont and Port Arthur region, causing flooding there. The National Hurricane Center called the flooding "catastrophic”. It closed over 500 road segments (one road could have multiple closures). The storm also downed traffic lights, damaged roadway signs and caused highway asphalt to buckle in some areas.

Communication strategies during and after the storm were critical to carrying out such a large response effort. The TxDOT DriveTexas.org website received more than 5,000,000 visits during and immediately after the storm. The site, which includes real-time updates made by TxDOT staff in the field, provided the most accurate information possible to emergency crews and the public regarding flooding, pavement damage, and road closures. Advanced planning included having teams to ensure that TxDOT's emergency radio communications towers continued to function.

After the storm, infrastructure assessments were conducted and clean up and repairs began. TxDOT initially inspected approximately 4,300 bridges in the storm zone and identified damage to 13 bridges and 1 culvert, or less than one-half of one percent of all bridges evaluated. There were no bridge collapses or major bridge damage, which is a testament to the resiliency of bridge design, construction, and routine maintenance. As of October 2017, TxDOT had collected more than 12 million cubic feet of debris. More than 600 TxDOT employees from around the state--some of whom dealt with their own personal losses—worked to assist local jurisdictions with debris removal in the hardest-hit coastal areas from Corpus Christi to Beaumont. As of early October 2017, TxDOT's estimated costs due to this extreme weather event totaled over $150 million, including damage repair, equipment and facility costs, and the costs of mobilizing TxDOT's staff and crews.

In summary, advance preparation and practice helped TxDOT quickly respond and recover from the hurricane. Crews from across the state were pre-deployed to prepare for the storm. Staging for 2,500 crew members and more than 2,000 pieces of equipment occurred at TxDOT districts located just outside the storm zone.

5.0 Incomplete or Unavailable Information for Specific Climate Change Impacts Analysis

GHG Analysis Limitations

A level of uncertainty exists in the estimation of a state's impact on GHG emissions. This uncertainty results from limitations in travel demand forecasting, traffic operation analyses, and emission factor modeling. Travel demand estimates based on fuel use, population and/or travel models are used to forecast traffic volumes. Uncertainty surrounds the travel choices, demographic futures, and other parameters that serve as the foundation of the traffic projections. The estimation of travel speeds remains an important step in the process, as emissions vary significantly by vehicle operation; however, such data is not readily available on a statewide or national basis. In addition, average, design, or posted speed is what is typically available for most projects, with only a few of the largest projects having detailed speed data for a reasonably accurate congested and free-flow speed analysis. Travel speeds are typically estimated using statistical relationships accounting for traffic volume, the roadway capacity and free-flow speeds. These relationships may not fully represent the actual traffic conditions at specific locations in present or in future projections. Although EPA's MOVES emission factor model provides the best available tool for conducting different types of transportation GHG analyses, there is some uncertainty with many of the model's input files often based upon national defaults. Application of these rates does not fully consider detailed location-specific vehicle operations including accelerations and decelerations, the variances by specific vehicle types by model year, and the variances by different road conditions and function. Changes in the future fuel supplies, fuel costs and fuel characteristics may dramatically change emissions in ways not accounted for by EPA MOVES model. More specifically, EPA and FHWA guidance for regulatory decision analysis do not account for more recent market changes. An example of this would be the recent projections that new electric vehicles sales may exceed 50% by 2040.

Technological advances may transform societies in ways that cannot be accurately predicted today just as cell phones changed communication and internal combustion engines changed horse, buggy, bike, and rail travel in the early 1900s.

Climate Model Limitations

Climate science is highly complex and evolving, and climate models incorporate many different assumptions. Most models rely on past patterns to calibrate results; however, one of the challenges associated with climate change is that the future is not expected to follow the patterns of the past, which makes it difficult to assess the accuracy of the models. For example, it is unknown what the specific sensitivity of climate is to increased GHG concentrations, the specific rate of change in the climate system in response to changing GHG concentrations, or the potential existence of climate-tipping points or thresholds and their specific levels, all of which impact the accuracy and precision of predicted or simulated future scenarios. Additionally, the models are intended to analyze the global climate, and results must be scaled down to assess climate predictions at a more local level. The combination of assumptions, uncertainty of model results, and scaling mean that it is not possible to credibly assess climate impacts directly attributable to GHG emissions associated with individually proposed Texas on-road transportation projects.

The USGCRP[50] identifies three main sources of uncertainty within climate models:

1. Natural climate variability affects the initial conditions input into models, and variability built into the models may also affect the results. This is the dominant source of uncertainty for projecting temperature and precipitation on shorter timeframes (up to decades).
2. Results are based on the model structure and the parameters used, which are affected by the state of the science at the time the model is designed. This is the dominant source of uncertainty affecting projections of global temperature through mid-century and for regional temperature and precipitation through the end of the century.
3. Human decision making around the world will affect the level and timeframe of increased GHG emissions, and may not follow any of the scenarios modeled. It is impossible to predict which, if any, of the scenarios analyzed in the model is the most likely. This source of uncertainty affects projections of global temperatures by the end of the century.

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[50] (USGCRP (Melillo, Jerry, T.C. Richmond, and G.W. Yohe, Eds.), 2014) and Chapter 4: Climate Models, Scenarios, and Projections from (USGCRP, Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)], 2017).

6.0 Results and Conclusions

Texas on-road and fuel cycle GHG emissions are estimated to peak in 2017 at 176.6 MMT and reach a minimum in 2032 at 161.1 MMT. Data was available to compare Texas on-road and fuel cycle emissions to national and world-wide emissions for the year 2014. In 2014, Texas on-road and fuel emissions are estimated to be 0.48% of worldwide CO_2E emissions.

Future on-road GHG emissions may be affected by: 1) the results of federal policy including tailpipe and fuel controls, 2) market forces that may alter vehicle technology and purchase (such as electric vehicle manufacturing and sales), 3) individual choice decisions regarding commute options, 4) reductions that can be achieved through traffic system management operation and/or demand management, and 5) technological advancements that may alter the transportation system and associated emissions.

TxDOT has implemented programmatic strategies to reduce GHG emissions including: 1) travel demand management projects and funding to reduce VMT, such as bicycle and pedestrian facilities, 2) traffic system management projects and funding to improve the operation of the transportation system, 3) participation in the national alternative fuels corridor program, 4) clean construction activities, 5) clean fleet activities, 6) CMAQ funding, 7) transit funding, 8) two statewide campaigns to reduce tailpipe emissions, and 9) projects and operational improvements to reduce and manage congestion.

TxDOT also has strategies to address a changing climate in accordance with TxDOT and FHWA design, asset management, maintenance, emergency response, and operational policies and guidance. The flexibility and elasticity in TxDOT transportation planning, design, emergency response, maintenance, asset management, and operation and maintenance of the transportation system are intended to consider any number of changing scenarios over time.

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Appendix A: Methodology for Greenhouse Gas and Climate Change Analysis

This section identifies methodologies used for the statewide CO_2E emissions estimate (**Section 3**) and the assessment of projected climate stressors for the state of Texas (**Section 4**).

EPA MOVES (emissions model) accounts for all CAFE standards except for Phase 2 of the GHG Emissions Standards and Fuel Efficiency for Medium- and Heavy-Duty Engines and Vehicles. These standards will be incorporated in the next version of MOVES.[51]

A.1 Greenhouse Gas Analysis Methods

Three primary options exist to estimate transportation emissions, and each one produces slightly different emission results because they use different sets of data and data assumptions. The first is a fuel consumption-based method with a national average fuel economy used by EPA and EIA. The second option uses a VMT-based method obtained from a metropolitan travel demand model. The third option uses VMT based on population projections. VMT-based projections typically start with historic traffic data from state and local traffic counting equipment and apply either national fleet mix defaults or state- or local- specific fleet mix data. TxDOT is using VMT estimates based on population projections, historic traffic count data, and Texas county-specific fleet data. Texas has metropolitan-based travel demand models, but no detailed statewide travel demand model exists to conduct the emissions analysis.

A quantitative estimate of state on-road (both on- and off-system) operational emissions and upstream fuel cycle CO_2E emissions was conducted by TxDOT. The operational CO_2E emissions were calculated based on annual operational emission projections for a base year of 2010 through a design year of 2040 using TCEQ Emission Trends Report. The year 2040 is consistent with the design year (final year) of the current TxDOT statewide long-range transportation plan. **Table A-1** describes the methods employed for CO_2E emission calculations for Texas.

For the TCEQ Emission Trends Report, the Texas A&M Texas Transportation Institute (TTI) developed and produced Highway Performance Monitoring System (HPMS)-based annual emissions estimates for each of the 254 Texas counties. The level of detail in the final emissions estimates were aggregate emissions by county and vehicle class.

Table A-1: GHG Emission Methodology Matrix

Traffic Data/Inputs		
Source of Traffic Data	Texas A&M Texas Transportation Institute VMT for TCEQ Trends Report.	
Vehicle Miles Traveled (VMT)	Calculated using FHWA Highway Performance Management System (HPMS) methods.	
Emissions Activity **Type**	**Description/Assumptions**	**Tool Employed***
Operational Emissions	"Tailpipe" CO_2 emissions from vehicles using Texas roadways.	TCEQ Trends Report
Fuel Cycle	Emissions generated by extracting, shipping, refining, and delivering fuels.	EPA Multiplier of Operational Emissions (1.27 or 27%)
Conversion of CO_2 to CO_2E	EPA conversion factor for CO_2 to CO_2E, from Greenhouse Gases Equivalencies Calculator– Calculations and References for Mobile Sources	EPA Multiplier for CO_2 to CO_2E: (CO_2, CH_4, and N_2O)/0.986 CO_2

The following parameters and assumptions were used to prepare the state emissions analysis.

- Carbon dioxide (CO2) was estimated. TxDOT converted this to CO_2E and added fuel-cycle emissions by using the EPA multipliers listed in Table A-1.

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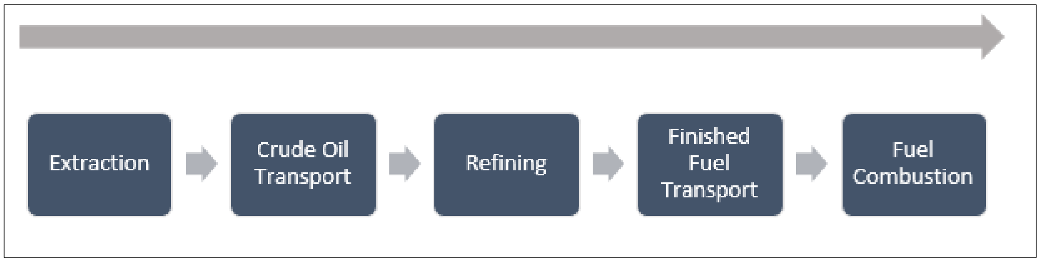
[51] (EPA, 2017) EPA email dated June 23, 2017.

- The emissions factor model used in developing inventories for this task was the most recent version of the EPA's MOVES on-road emissions model: MOVES2014.
- Emissions inventories were developed for each of the 254 Texas counties.
- The analysis years include 2010 to 2040.
- MOVES default weekday average speed distributions were used.
- Temperature and humidity inputs used were provided by TCEQ.
- The VMT mixes were consistent with the EPA MOVES source use types (SUTs).
- Locality-specific MOVES vehicle age distributions input for historical and future years were based on available and suitable local vehicle registration data in conjunction with MOVES default age distributions as needed.
- The level of detail for the development methodology in the final emissions estimates was aggregate emissions by county and vehicle class, based on 24-hour HPMS activity.
- Fuel parameter inputs were used as defined in the CFR Title 40–Protection of the Environment, Part 80–Regulation of Fuels and Fuel Additives, Section 27–Controls and Prohibitions on Gasoline Volatility. Federal- and state-regulated summer Reid Vapor Pressure (RVP) levels were modeled consistent with assumptions allowed for refiner compliance safety margins.
- The effects of the oxygenated fuel program for El Paso County were modeled.
- Federally regulated gasoline and diesel sulfur levels were modeled.
- Reformulated gasoline (RFG) was modeled for the four Dallas-Fort Worth (DFW) and the eight Houston-Galveston-Brazoria (HGB) ozone nonattainment counties, which use RFG.
- The effects of all the federal motor vehicle control programs that are included as defaults in the MOVES model were modeled.
- The Austin-Round Rock, DFW, HGB, and El Paso County inspection and maintenance (I/M) programs were modeled.
- VMT by county was forecast for future years using historical TxDOT VMT data and U.S. Census Bureau population statistics and projections, consistent with the current practice for virtual-link applications. The VMT projections vary from 1.13% to 1.76% per year.
- Year-specific Texas Low Emissions Diesel (TxLED) adjustment factors were developed using the reduction benefit information described in EPA's Memorandum on Texas Low Emission Diesel Fuel Benefits.
- The activity and fleet characterization tables included: VMT; VMT distributions (monthly, day-of-the-week, hourly); source type populations; and source type age distributions.

Population-based VMT trends, as used in this analysis, do not allow for comparison between build and no-build scenarios, so the analysis cannot fully predict emissions due to free flow or congested portions of the network. In addition, only design or average speed data is available for the vast majority of proposed projects, which prohibits the ability to accurately analyze free flow and congestion emissions of project-level build and no-build scenarios. A qualitative discussion on congestion trends is provided in the GHG analysis section.

FHWA encourages the disclosure of fuel-cycle emissions when conducting GHG analyses. Fuel-cycle GHG emissions include "well-to-pump" emissions, which are the emissions generated by extracting, shipping, refining, and delivering fuels (**Figure A-1**). These emissions represent approximately 27 percent of GHG emissions from fuel consumption on a per-vehicle-mile basis. Most roadway congestion relief projects aim to reduce fuel-cycle GHGs along with exhaust emissions. Fuel-cycle GHG emissions will also decrease if motorists make personal decisions to use less fuel. As recommended by FHWA, operational emissions were multiplied by 1.27 to account for fuel-cycle GHG emissions. This multiplier came from the EPA prorated estimates of fuel-cycle emissions based on national default fractions of VMT by vehicle type and national average fuel sales to generate one fleet-average adjustment factor for use in GHG analysis.

Figure A-1: Well-to-Wheel Process



A.2 Climate Change Assessment Methodology

A qualitative assessment was completed to evaluate the potential vulnerability of the Texas on-road transportation system to potential climate change impacts, typically projected between the years 2070 to 2100, unless otherwise specified. Shorter-term projections (including for the period of the TxDOT long-range transportation plan through 2040) were not consistently available among the data reviewed. The analysis incorporates available information on historic and projected climate change impacts for the state of Texas (**Section 4.2**). Data was reviewed from several sources, including the 2014 NCA; USGS National Climate Change Viewer; the Assessments from the IPCC; NOAA Global and Regional Sea Level Rise Scenarios; and USACE Procedures to Evaluate Sea Level Change. It should be noted that **Section 5** discusses several major sources of uncertainty inherently included in the data source projections regarding climate change, such as the effects of natural variability, future human emissions, sensitivity to GHG emissions, and natural climate drivers.

The climate change projections used herein were based on RCPs. RCPs are GHG concentration trajectories used for climate modeling and research and are based on assumptions relating to the level of GHG emissions now and into the future. The high and low CO_2E concentration RCP options were chosen for the TxDOT analysis. RCP8.5 (high emissions estimated to be approximately 1,370 parts per million [ppm] CO_2E in 2100) is a business as usual case with little to no additional worldwide GHG control measures. RCP4.5 (low emissions estimated to be approximately 650 ppm CO_2E in 2100) refers to a high level of GHG controls recommended to keep temperature rise below 2^o C in 2100.

Where information was available in the data reviewed, the current state of each climate stressor was disclosed, and then low and high future projections based upon RCP4.5 and RCP8.5 were summarized for the state of Texas (**Section 4.2**). This includes evaluating how climate stressors may impact the transportation system design, maintenance or operation and identifying the transportation system vulnerability to those stressors. Considerations of resiliency and adaptation are addressed through a combination of: existing and evolving state and local transportation activities and programs (**Section 4.3**).

Appendix B: Glossary

Anthropogenic	Resulting from or produced by human beings. (IPCC).
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium, and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio), and ozone. The atmosphere also contains water vapor, whose amount is highly variable but typically 1% volume mixing ratio. The atmosphere also contains clouds and aerosols. (IPCC).
CAFE standards	The Corporate Average Fuel Economy standards set by the National Highway Traffic Safety Administration (NHTSA). CAFE was enacted by Congress in 1975 with the purpose of reducing energy consumption by increasing the fuel economy of cars and light trucks. NHTSA has set standards to increase CAFE levels rapidly over the next several years. (NHTSA).
Carbon dioxide (CO_2)	A naturally occurring gas, also a by-product of burning fossil fuels and biomass, as well as land use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured. (IPCC).
Carbon dioxide (CO_2) equivalent (CO_2E)	Greenhouse gas emissions are often measured in carbon dioxide (CO_2) equivalent. To convert emissions of a gas into CO_2 equivalent, its emissions are multiplied by the gas's global warming potential (GWP). The GWP takes into account the fact that many gases are more effective at warming the Earth than CO_2 per unit mass. (EPA).
Cascade of uncertainty	The process whereby uncertainty accumulates throughout the process of climate change prediction and impact assessment. (IPCC).
Climate	Usually defined as the "average weather," or as the statistical description in terms of the mean and variability of relevant quantities (e.g., temperature, precipitation, and wind) over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization. (IPCC).
Climate change	A statistically significant variation in the mean state of the climate or its variability, persisting for an extended period (typically decades or longer). Climate change may be caused by natural internal processes or external forcing or by persistent anthropogenic changes in the composition of the atmosphere or land use. (IPCC).
Climate stressor	A condition, event, or trend related to climate variability and change that can exacerbate hazards. For example, increasing frequency and intensity of drought conditions can be a climate stressor for forests and crops. Rising sea level is another climate stressor. (NOAA).

Criteria pollutants	The Clean Air Act requires EPA to set National Ambient Air Quality Standards (NAAQS) for six common air pollutants (also known as “criteria air pollutants”). These pollutants are found all over the U.S. and can harm your health and the environment. These include ground-level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide. (EPA).
Emissions	The term used to describe the gases and particles which are put into the air or emitted by various sources. (EPA).
Extreme weather	A weather event that is rare at a particular place and time of year, including, for example, heat waves, cold waves, heavy rains, periods of drought and flooding, and severe storms. (USGCRP).
Fuel-cycle emissions analysis	Also referred to as lifecycle analysis or well-to-wheel analysis. Used to assess the overall greenhouse gas impacts of a fuel, including each stage of its production and use. The Environmental Protection Agency’s (EPA’s) lifecycle analysis includes significant indirect emissions as required by the Clean Air Act. (EPA).
Global warming	The observed increase in average temperature near the Earth’s surface and in the lowest layer of the atmosphere. In common usage, “global warming” often refers to the warming that has occurred as a result of increased emissions of greenhouse gases from human activities. Global warming is a type of climate change; it can also lead to other changes in climate conditions, such as changes in precipitation patterns. (USGCRP).
Greenhouse gases	The gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth’s surface, the atmosphere, and clouds. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth’s atmosphere. (IPCC).
Greenhouse gas effect	The Earth gets energy from the sun in the form of sunlight. The Earth's surface absorbs some of this energy and heats up. The Earth cools down by giving off a different form of energy, called infrared radiation. But before all this radiation can escape to outer space, greenhouse gases in the atmosphere absorb some of it, which makes the atmosphere warmer. As the atmosphere gets warmer, it makes the Earth's surface warmer, too. (EPA)
Incomplete or unavailable information	The incomplete or unavailable information provision in the Council on Environmental Quality (CEQ) regulations implementing NEPA (40 CFR § 1502.22) is recognition of the potential difficulty associated with obtaining essential and credible data necessary to complete the analysis of certain types of impacts in certain situations, especially those actions that require the preparation of an Environmental Impact Statement. (FHWA).

NEPA process	The National Environmental Policy Act (NEPA) process, also referred to as the environmental process, begins when a federal agency develops a proposal to take a major federal action as defined in 40 CFR § 1508.18. The environmental review under NEPA can involve three different levels of analysis: Categorical Exclusion (CE) determination, Environmental Assessment/Finding of No Significant Impact (EA/FONSI), and Environmental Impact Statement/Record of Decision (EIS/ROD). (EPA).
On-road transportation system	Includes both on-state roadways (e.g., interstates, state highways, farm-to-market roads) and off-state roadways (e.g., local city streets or county roads) throughout the state of Texas.
Reasonably foreseeable effects	Under NEPA, reasonably foreseeable effects include effects that are likely to occur or probable, rather than those that are merely possible. (FHWA).
Resilience	The capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption. For example, installation of backflow preventers in the stormwater systems of a coastal city increased their resilience to flooding from extreme high tides. (NOAA).

Appendix C: Abbreviations and Acronyms

CAFE	Corporate Average Fuel Economy
CAMPO	Capital Area Metropolitan Planning Organization
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
CH	Methane
CMAQ	Congestion Mitigation Air Quality
CO_2	Carbon dioxide
CO_2E	Carbon dioxide - equivalent
DCT	Drive Clean Texas
DFW	Dallas-Fort Worth
DOE	U.S. Department of Energy
DOT	Department of Transportation
EIA	U.S. Energy Information Administration
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FAST	Fixing America’s Surface Transportation Act
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GCM	General circulation model
GHG	Greenhouse gas
GWP	Global warming potential
HGAC	Houston-Galveston Area Council
HGB	Houston-Galveston-Brazoria
HPMS	Highway Performance Monitoring System
HURDAT	Atlantic Hurricane Database
IPCC	Intergovernmental Panel on Climate Change
I/M	Inspection and maintenance
JCAP	Joint Center for Artificial Photosynthesis
LED	Light emitting diode
LRTP	Long Range Transportation Plan
MAP-21	Moving Ahead for Progress in the 21st Century Act
MMT	Million metric tons
MOVES	Motor Vehicle Emissions Simulator

MPO	Metropolitan Planning Organization
NCA	National Climate Assessment
NCTCOG	North Central Texas Council of Governments
NEPA	National Environmental Policy Act
NHPP	National Highway Performance Program
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
NTRD	New Technology Research and Development
N_2O	Nitrous oxide
ppm	Parts per million
RAP	Recycled asphalt pavement
RAS	Recycled asphalt shingles
RCP	Representative Concentration Pathways
RFG	Reformulated gasoline
RVP	Reid Vapor Pressure
SUT	Source use type
TCEQ	Texas Commission on Environmental Quality
TDM	Travel demand management
TEMPO	Texas Association of Metropolitan Planning Organizations
TERP	Texas Emission Reduction Program
TRB	Transportation Research Board
TSM	Traffic system management
TTC	Texas Transportation Commission
TTI	Texas A&M Texas Transportation Institute
TxDOT	Texas Department of Transportation
TxLED	Texas Low Emissions Diesel
USACE	U.S. Army Corps of Engineers
USDOT	U.S. Department of Transportation
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
UTP	Unified Transportation Program
VMT	Vehicle miles traveled

VOC	Volatile organic compound
WMA	Warm mix asphalt