Estimating and Incorporating CO_2 Emissions and Associated Fuel Consumption into the *Urban Mobility Report*

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16. Abstract

TTI's *Urban Mobility Report (UMR)* is acknowledged as the most authoritative source of information about traffic congestion and its possible solutions. As policymakers from the local to national levels devise strategies to reduce greenhouse gas emissions and other pollutants, the level of interest in the environmental impact of congestion has increased. To this end, this research effort developed and applied a methodology for determining the emissions of carbon dioxide (CO_2) due to congestion for use in the *UMR*. The methodology also estimated fuel consumption based upon the carbon dioxide emissions estimates. Researchers at the Texas A&M Transportation Institute (TTI) collaborated with researchers at the Wisconsin Energy Institute at the University of Wisconsin-Madison to develop CO_2 estimates to include in the *UMR.* Researchers developed a five-step methodology using data from three primary data sources, 1) the Federal Highway Administration's (FHWA's) Highway Performance Monitoring System (HPMS), 2) INRIX traffic speed data, and 3) The United States Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) model. The research successfully developed and applied the methodology. Emission rates (lbs of CO_2 per mile) were validated in selected cities, with results in the range of 80 percent to 99 percent of the literature values. Researchers incorporated the new methodology for all urban areas into the *2012 Urban Mobility Report* and plan to include these same measures in future releases of the report. Researchers reported that, in 2011, 56 billion pounds of additional CO_2 were produced in all 498 urban areas during congestion only, equating to 2.9 billion gallons of "wasted" fuel. Researchers reported the amount of CO_2 produced at free-flow conditions (i.e., absent congestion) is 1.8 trillion pounds in 2011 in all 498 urban areas.

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The authors would also like to thank the sponsors of TTI's Mobility Measures in Urban Transportation FHWA pooled fund study, which provided leveraged funds for this project. The pooled fund members include 13 state departments of transportation (California, Colorado, Florida, Kentucky, Maryland, Minnesota, New York, North Carolina, Ohio, Oregon, Texas, Virginia, Washington) and two metropolitan planning organizations (Houston-Galveston Area Council, Maricopa Association of Governments), and FHWA.

In addition, we thank our project advisory committee:

- Bill Barker, Sr. Management Analyst, City of San Antonio
- Sue Cotty, Sr. Air Quality Planner, Pima Association of Governments
- Christina Ficicchia, Executive Director, New York City & Lower Hudson Valley Clean Communities
- Brian Gregor, Oregon Department of Transportation
- Jennifer Sarnecki, Wisconsin Department of Transportation

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- Tara Ramani, Program Manager, Air Quality Program
- Joe Zietsman, Division Head, Environment and Air Quality Division

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

EXECUTIVE SUMMARY

Project Summary

The *Urban Mobility Report (UMR)* is acknowledged as the most authoritative source of information about traffic congestion and its possible solutions. The *2012 Urban Mobility Report* marks the 22nd release of the report and includes 30 years of data from 1982 to 2011 (*1*). As policymakers from the local to national levels devise strategies to reduce greenhouse gas (GHG) emissions and other pollutants, the level of interest in the environmental impact of congestion has increased. To this end, this research effort developed and applied a methodology for determining the emissions of carbon dioxide (CO_2) due to congestion, which was incorporated into the *2012 Urban Mobility Report*. Fuel consumption is also estimated based upon the carbon dioxide emissions estimates.

Research Team

With funding from the National Center for Freight and Infrastructure Research and Education (CFIRE), researchers at the Texas A&M Transportation Institute (TTI) collaborated with researchers at the Wisconsin Energy Institute to develop CO_2 estimates to include in the *UMR*. Matching funds were also used from TTI's on-going Federal Highway Administration (FHWA) pooled fund study, Mobility Measures in Urban Transportation, which includes thirteen state departments of transportation (California, Colorado, Florida, Kentucky, Maryland, Minnesota, New York, North Carolina, Ohio, Oregon, Texas, Virginia, Washington) and two metropolitan planning organizations (Houston-Galveston Area Council, Maricopa Association of Governments), and FHWA.

Process

Researchers developed a five-step methodology for estimating the carbon dioxide emissions and associated fuel losses resulting from traffic congestion and incorporating this information into the *UMR*. The methodology uses data from three primary data sources: 1) the Federal Highway Administration's Highway Performance Monitoring System (HPMS), 2) INRIX traffic speed data, and 3) The United States Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES) model.

Discussion and Recommendations

The research successfully developed a methodology for estimating urban area carbon dioxide emissions due to congestion. The new methodology also computes fuel consumption based upon the emissions estimates. Emission rates (lbs of CO_2 per mile) were validated in selected cities, with results in the range of 80 percent to 99 percent of the literature values. Researchers incorporated the new methodology into the *2012 Urban Mobility Report* and plan to include it in future releases of the report. Researchers reported in the *2012 Urban Mobility Report* that 56 billion pounds of CO_2 were produced during congestion, equating to 2.9 billion gallons of "wasted" fuel.

CHAPTER 1
INTRODUCTION

Introduction

The *Urban Mobility Report (UMR)* is acknowledged as the most authoritative source of information about traffic congestion and its possible solutions. The *2012 Urban Mobility Report* marks the 22nd release of the report and includes 30 years of data from 1982 to 2011 (*1*). As policymakers from the local to national levels devise strategies to reduce greenhouse gas (GHG) emissions and other pollutants, the level of interest in the environmental impact of congestion has increased. To this end, this research effort developed and applied a methodology for determining the emissions of carbon dioxide (CO_2) due to congestion, which was incorporated into the *2012 Urban Mobility Report*. Fuel consumption is also estimated based upon the carbon dioxide emissions estimates.

Project Objectives

The objectives of this research were to create and test a methodology to incorporate emissions of carbon dioxide - a primary greenhouse gas - into the *Urban Mobility Report (UMR)* and to update and test a methodology for fuel consumption into the *UMR.* Researchers created methodologies for both carbon dioxide emissions and fuel consumption for passenger cars and freight (trucks), including medium and heavy-duty trucks.

The methodology was applied to all urban metropolitan areas included in the *UMR.*

Report Organization

This report is organized into five chapters as described below:

Chapter 1—Introduction: provides a brief introduction to the research topic and presents project objectives and report organization.

Chapter 2—Background and Project Advisory Committee: provides a brief synopsis of key literature and discusses the project advisory committee.

Chapter 3—CO_2 Emissions and Fuel Consumption Estimation Methodology: presents the methodology.

Chapter 4—CO_2 Emissions Results: describes results of the carbon dioxide emission methodology.

Chapter 5—Conclusions and Future Work: describes conclusions and future work possibilities.

CHAPTER 2
BACKGROUND AND PROJECT ADVISORY COMMITTEE

The transportation sector's sizeable contribution to greenhouse gas (GHG) emissions makes it a focal point in the ongoing effort to reduce GHG emissions. The U.S. Environmental Protection Agency (EPA) found that transportation is the second largest CO_2 emitting sector in the United States behind electricity generation, with each sector contributing 33 percent and 42 percent of total CO_2 emissions, respectively (*2*).

Improving vehicle fuel efficiency is an important component in reducing CO_2 emissions. Because gasoline and diesel are converted into CO_2 and other pollutants during combustion, reducing fuel consumption per vehicle-mile traveled can lead to significant environmental benefits. In a 2012 report that documented trends in the transportation sector, the EPA reported a 19 percent rise in CO_2 emissions from 1990 through 2010, mainly due to an increase in travel and the stagnation of fuel efficiency across the United States' vehicle fleet. The EPA also reported a slight improvement in average fuel economy from 1990 through 2010, primarily from the retirement of older and less fuel efficient vehicles. The average fuel economy among new vehicles sold from 1990 through 2004 actually declined, in large part to the increasing market share of light-duty trucks. In recent years, however, this trend has been stunted by increasing fuel prices. The average new vehicle fuel economy has improved since 2005 as the market share of passenger cars has increased (*2*).

In addition, new U.S. government standards will accelerate recent improvements in fuel economy. In 2012 the National Highway Traffic Safety Administration (NHTSA) and EPA issued new Corporate Average Fuel Economy (CAFE) standards that will increase fuel economy to the equivalent of 54.5 miles per gallon for cars and light-duty trucks by Model Year 2025—a near-doubling of CAFE standards prior to 2010 (*3*).

Despite these positive trends in vehicle fleet makeup, traffic congestion remains a significant factor in reducing fuel efficiency in urban areas, and over the past three decades congestion has become more costly in terms of time, money and fuel. The *2012 Urban Mobility Report* estimated that in 2011 congestion resulted in 2.9 billion gallons of excess fuel consumption, up from 0.5 billion gallons in 1982 (*2*). The *2012 Urban Mobility Report* also states that urban congestion cost the average auto commuter $818 in wasted time and fuel in 2011 (*2*).

As the international scientific community gains a better understanding of how GHG emissions from human activities are contributing to global climate change, local government officials are becoming more interested in strategies to mitigate the negative impacts of climate change (*4*). Since 2005, more than 1,000 city mayors have signed the U.S. Conference of Mayors Climate Protection Agreement, in which participating cities pledged to reduce CO_2 emissions by 7 percent below 1990 levels by 2012 (*5*).

The research team acknowledged this local interest in CO_2 reductions by targeting individuals from local or regional governments for its project advisory committee. Reducing congestion could be one of many strategies that these levels of government employ to reduce CO_2 emissions, and this research project is meant to document emissions estimates for each of the urban areas included in the *UMR*. Therefore, it was important to have the right perspectives to understand how the emissions estimates could be calculated and reported in a way useful to local and regional governments.

The two major groups targeted for the project advisory committee were 1) urban sustainability directors—municipal government professionals tasked with improving the natural and built environment in their cities; and 2) leaders of U.S. Department of Energy Clean Cities coalitions—regional public-private partnerships that devise and implement strategies to reduce petroleum consumption. The advisory committee is asked to review the proposed research methodology and review and comment on the draft final report.

After an invitation was sent to individuals around the country in these two groups, five individuals agreed to be members of the project advisory committee. They are:

- Bill Barker, Sr. Management Analyst, City of San Antonio
- Sue Cotty, Sr. Air Quality Planner, Pima Association of Govts.
- Christina Ficicchia, Executive Director, New York City & Lower Hudson Valley Clean Communities
- Brian Gregor, Oregon Department of Transportation
- Jennifer Sarnecki, Urban and Regional Planning Supervisor at Wisconsin Department of Transportation (former Senior Regional Planner, Southern California Association of Governments))

CHAPTER 3
CO_2 EMISSIONS AND FUEL CONSUMPTION ESTIMATION METHODOLOGY

This chapter documents the methods used to add carbon dioxide (CO_2) emissions estimates to the Texas A&M Transportation Institute's *Urban Mobility Report* to better understand the impact of congestion on CO_2. Researchers focused only on CO_2 emissions because they have accounted for over 98 percent of global warming potential-weighted emissions (a metric used to compare different greenhouse gases) for the United States transportation sector from 2007 to 2010 (*2*). Researchers hope to expand estimates to include other air pollutants in future *Urban Mobility Report* releases.

DATA SOURCES

The methodology described in this chapter uses data from three primary data sources: 1) the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS), 2) INRIX traffic speed data, and 3) The United States Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) model.

Highway Performance Monitoring System

HPMS includes national-level data used to assess the condition and performance of the highway system (*6*). The states provide HPMS data elements to FHWA on a yearly basis for use in federal aid allocation and for producing FHWA's "Conditions and Performance" reports (*7*).

HPMS data elements have historically been used in the development of the statistics in the *Urban Mobility Report.* The following are the specific HPMS "link" data elements used in the methodology:

- Average Daily Traffic (ADT) – measured in number of vehicles
- Truck percent [percent of ADT that are combination and single-unit trucks]
- Link (roadway) length

INRIX Traffic Speed Data

INRIX provides TTI with speed data for nearly every major urban roadway in the United States for use in the *Urban Mobility Report*. The detail of this speed data allows for the production of improved congestion information and measurements. The INRIX traffic speeds are collected from a variety of sources and compiled in their archived average speed database. Agreements with fleet operators who have location devices on their vehicles feed time and location data points to INRIX. Individuals who have downloaded the INRIX application to their smart phones also contribute time and location data.

MOtor Vehicle Emission Simulator (MOVES)

MOVES is a model developed by the EPA that is designed to estimate emissions from mobile sources. Researchers used MOVES 2010b extensively in the development of the CO_2 emission rates for different vehicle types at different times, which were then used to calculate overall CO_2 emissions and fuel consumption estimates for the cities in the *2012*

Urban Mobility Report. In particular, MOVES 2010b provided data and methodology for the following components of the report:

- Vehicle emission rates
- Seasonal climate data
- Vehicle fleet composition

URBAN MOBILITY REPORT CO_2 EMISSIONS AND FUEL CONSUMPTION METHODOLOGY

Researchers used the steps shown in Figure 1 to estimate CO_2 emissions and fuel consumption for each urban roadway section within an urban area. These steps are listed here, and more detail is provided in the sections that follow.

1. Group Similar Urban Areas: Group urban areas based on the percentage of travel that occurs with the air conditioner turned "on," considering seasonal variations.
2. Obtain Emission Rates for Each Group: Use MOVES to obtain emission rates for each group by the fraction of travel occurring with the air conditioner turned "on" – this fraction of travel is represented with the factor "AConFraction" or "ACF."
3. Fit Curves to Emission Rates: Fit curves to the emission rates data from Step 2, and use these curves to calculate emission rates by speed.
4. Calculate Emissions and Fuel Consumption: Combine speed, volume, and emission rates data to calculate emissions. Use the emissions estimates to calculate fuel consumption.
5. Estimate the Emissions and Fuel Consumption Due to Congestion: Repeat the calculations from Step 4 using free-flow speed. Subtract congested-conditions results from free-flow results to obtain emissions and fuel consumption due to congestion.

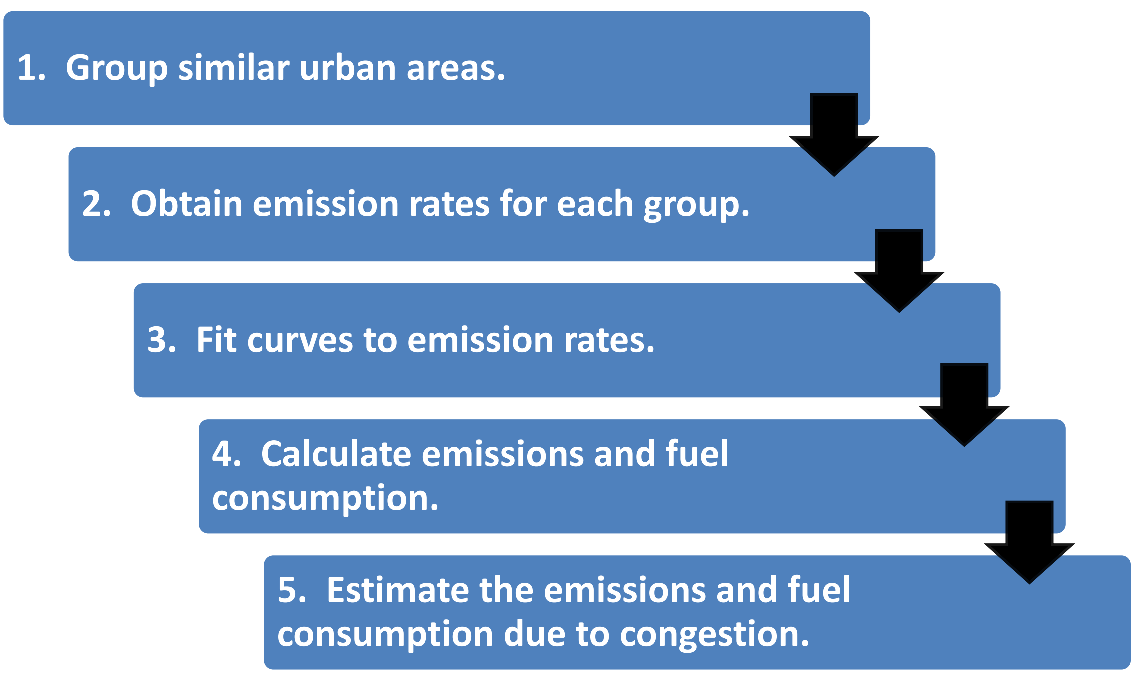

Figure 1. Steps Used to Incorporate CO_2 Emissions and Fuel Consumption into the _Urban Mobility Report_

1. Group Similar Urban Areas

For some pollutants, the influence of weather conditions causes vehicle tail-pipe emissions to vary considerably by location. Tail-pipe CO_2 emissions, however, are not directly influenced by weather conditions, although they still vary by location because they are influenced by air conditioning use. Traveling with the air conditioner turned "on" lowers fuel efficiency and increases CO_2 emission rates. Thus, locations with warmer climates typically have higher emission rates because more travel occurs with the air conditioner turned "on."

It was not feasible to use emission rates for every county in the United States, so researchers instead created representative climate-type groups to account for the impact of climate on CO_2 emission rates. To create these groups, TTI researchers grouped the urban areas based on similar seasonal "AConFraction" (ACF) values – a term used in MOVES to indicate the fraction of travel that occurs with the air conditioner turned "on." For example, a vehicle traveling 100 miles with an ACF of 11 percent would travel 11 of those 100 miles with the air conditioner turned "on." The following steps were used to group the similar urban areas.

a) Identify Appropriate County for Each Urban Area Analysis

Because ACF is a factor of temperature and relative humidity, researchers extracted default hourly temperature and relative humidity data for a county within each urban area from the MOVES database. The climate data were collected for a county because the MOVES database has climate data available by county, rather than urban area (or city).

Researchers used a city/county database (*8*) to select the appropriate counties. Only one county per urban area (or city) was selected because the climate differences between adjacent counties were not significant.

b) Calculate Seasonal "AConFraction" for Each County

TTI researchers used methods similar to those used in MOVES to calculate the seasonal "AConFraction" (ACF) for each county. Researchers developed seasonal ACFs based on default hourly temperature and relative humidity data from the MOVES database. They used this hourly data to calculate hourly ACFs, which they then weighted by hourly traffic volume distributions from the MOVES database and averaged for each month. To produce the weighted seasonal ACFs, researchers averaged these weighted monthly ACFs over three-month periods for the seasons defined by MOVES.

The first step in the process is to calculate the hourly heat index from the hourly temperature and relative humidity data. The heat index best predicts air conditioning use because it quantifies the "discomfort caused by the combined effects of temperature and relative humidity" (*9*). Researchers used an hourly analysis because traffic volumes change throughout the day. Hourly climate data allowed researchers to weight the climate data by an average volume distribution taken from MOVES. For example, an 85 degree heat index for midnight was not weighted as much as a 95 degree heat index for 5 p.m. because more volume occurs during the 5 p.m. peak hour (this is described in greater detail at the end of step 1b). Researchers used equation 1 to relate temperature and relative humidity to the heat index (*10*).

$$
\begin{aligned}
Heat\ Index = &-42.379 + 2.04901523 \times T + 10.14333127 \times RH \\
&- 0.22475541 \times T \times RH \ - 6.83783 \times 0.001 \times T^2 \\
&- 5.481717 \times 0.01 \times RH^2 + 1.22874 \times 0.001 \times T^2 \times RH \\
&+ 8.5282 \times 0.0001 \times T \times RH^2 - 1.99 \times 0.000001 \times T^2 \times RH^2
\end{aligned}
\quad \text{(Equation 1)}
$$

Where: Heat Index (degrees Fahrenheit)
T = Temperature (degrees Fahrenheit)
RH = Relative Humidity (percent)

According to the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service, the heat index equation (Equation 1) is not designed to calculate heat index if the temperature is below 80 degrees Fahrenheit or if the relative humidity is less than 40 percent (*11*). The EPA also states that, for low humidity conditions, the heat index is nearly identical to the temperature; thus, for low humidity conditions, using either the heat index or temperature to determine the ACF produces the same result (*9*).

Therefore, TTI researchers only calculated the heat index if both the temperature was above 80 degrees Fahrenheit and the relative humidity was greater than 40 percent. If either the temperature or relative humidity did not meet these requirements, researchers used only the temperature to calculate the ACF. Researchers ensured that the resulting ACFs accurately represented the ACFs within MOVES by analyzing emission rates produced for various climate conditions. More specifically, researchers compared emission rates at various levels of humidity for a given temperature. The differences in emission rates caused by changes in relative humidity for temperatures below 80 degrees are not substantial. This is consistent with the National Weather Service's data regarding this relationship, which is displayed in Figure 2. As Figure 2 shows, relative humidity impacts the heat index less as temperature decreases. Note that researchers did not analyze the impact of humidity on the heat index for temperatures below 67 degrees Fahrenheit because the ACF is zero for these temperatures, as displayed in Table 1 (*12*). Also, this methodology does not account for the use of air conditioners at low temperatures for defogging purposes because MOVES does not account for this (*13*).

NOAA's National Weather Service

Heat Index

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Figure 2. National Weather Service Chart Displaying the Relationship between Relative Humidity, Temperature, and Heat Index (Adapted from Reference *12*)

Table 1. "AConFraction" as a Function of Heat Index in Degrees Fahrenheit (Adapted from Reference *13*)

Heat Index	AC On Fraction
67.44	0.000
70	0.089
75	0.251
80	0.399
85	0.534
90	0.655
95	0.762
100	0.855
105	0.934
110	1.000

Next, researchers applied Equation 2 to the hourly heat indexes to get the hourly ACF. Equation 2 represents air conditioning demand as a function of the heat index (as shown in Figure 3 and Table 1). The coefficients used in Equation 2 are default coefficients used in MOVES that represent an average air conditioning activity demand over the course of a full day (*14*).

$$\text{AConFraction} = -0.000276\,(\text{HeatIndex})^2 + 0.072465\,(\text{HeatIndex}) - 3.63154 \qquad \text{(Equation 2)}$$

Where:

AConFraction = 0 to 1
Heat Index = Degrees Fahrenheit

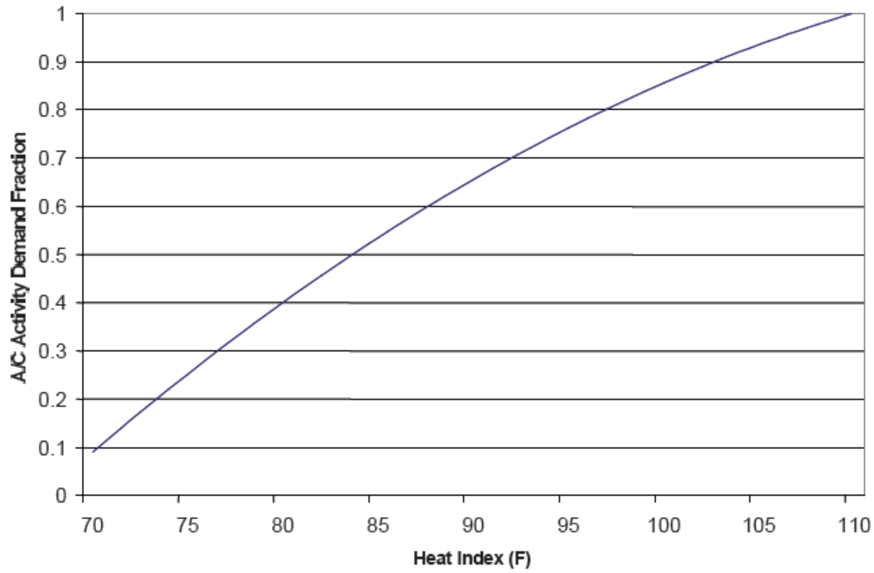

Figure 3. AC Activity Demand ("AConFraction") as a Function of Heat Index in Degrees Fahrenheit (Adapted from Reference *14*)

Figure 4 provides an example of how TTI researchers used the hourly ACF values to calculate a monthly ACF for each county. Researchers weighted the hourly ACF values by an hourly traffic volume factor from MOVES to account for volume distribution changes throughout the day. To accomplish this, researchers multiplied each hourly ACF by the fraction of daily traffic that occurred during that hour. The volume distribution factors were based on average weekday urban road type hourly volume factors used in MOVES. The EPA obtained these volume percentages from a report produced by the Office of Highway Management (*15*), and these volume percentages assume the same vehicle-miles of travel (VMT) percentages for all vehicle types (*14*). Researchers used these average volume percentages instead of the more detailed volume data used later in the methodology, because the more detailed volume data used later are for a specific urban area, and here the intent was to simply use typical hourly distributions to weight peak hours appropriately. Researchers summed the weighted hourly ACF values for each month to obtain each county's weighted monthly ACF, which is also displayed in Figure 4.

Researchers averaged the weighted monthly ACF for all the months within each season to obtain the weighted seasonal ACF values for each county. Researchers used the seasonal definitions from MOVES as Season 1 (January, February, March), Season 2 (April, May, June), Season 3 (July, August, September), and Season 4 (October, November, December). At the end of this step, researchers had estimates of seasonal ACF values for each county. The next step was to group the counties based on these values.

Hour of Day	"AConFraction" Values *(Hourly Average "AConFraction" Values for the Month)*		Volume Distribution Factors *(Average Hourly Volume Distribution — from MOVES)*		Weighted "AConFraction" *(Weighted Hourly "AConFraction")*	Month "AConFraction" *(Weighted "AConFraction" Value for the Month)*
1	0.15	×	0.010	=	0.0015	
2	0.11	×	0.006	=	0.0007	
3	0.08	×	0.005	=	0.0004	
4	0.06	×	0.005	=	0.0003	
5	0.03	×	0.007	=	0.0002	
6	0.00	×	0.018	=	0.0000	
7	0.05	×	0.046	=	0.0022	
8	0.17	×	0.070	=	0.0117	
9	0.33	×	0.061	=	0.0202	
10	0.45	×	0.050	=	0.0226	
11	0.54	×	0.050	=	0.0271	
12	0.60	×	0.054	=	0.0328	0.479
13	0.64	×	0.058	=	0.0369	
14	0.67	×	0.058	=	0.0389	
15	0.69	×	0.062	=	0.0428	
16	0.68	×	0.071	=	0.0486	
17	0.67	×	0.077	=	0.0516	
18	0.64	×	0.077	=	0.0492	
19	0.58	×	0.060	=	0.0346	
20	0.49	×	0.044	=	0.0219	
21	0.41	×	0.035	=	0.0144	
22	0.33	×	0.032	=	0.0107	
23	0.24	×	0.025	=	0.0059	
24	0.20	×	0.018	=	0.0036	

Figure 4. Example Monthly "AConFraction" Calculation Methodology

c) Group Similar Climates with the Seasonal "AConFraction" for Each County

To begin the process of grouping urban areas based on similar seasonal climates of each county, researchers used temperature and relative humidity scatter plots to visually identify which counties had similar climates. This step was performed as a precursor to forming the groups by ACF because the visual relationship between temperature and relative humidity offered an effective way of organizing the large number of counties.

Figure 5 displays a scatter plot with seasonal climate data for all of the counties. The relationship between relative humidity and temperature is plotted four times for each county – one point for each season. The visual benefit of plotting the climate data is apparent when comparing Figure 5 with Figure 6, as the temperature and relative humidity points for each season are clustered much closer to one another in Figure 6. Whereas Figure 5 has seasonal climate data for every county (over 100 counties), Figure 6 only has climate data for a group of counties with similar seasonal temperature and relative humidity averages (approximately 20 to 30 counties). Researchers organized the climate data displayed in Figure 5 into approximately ten different scatter plots of counties with similar seasonal climates comparable to Figure 6.

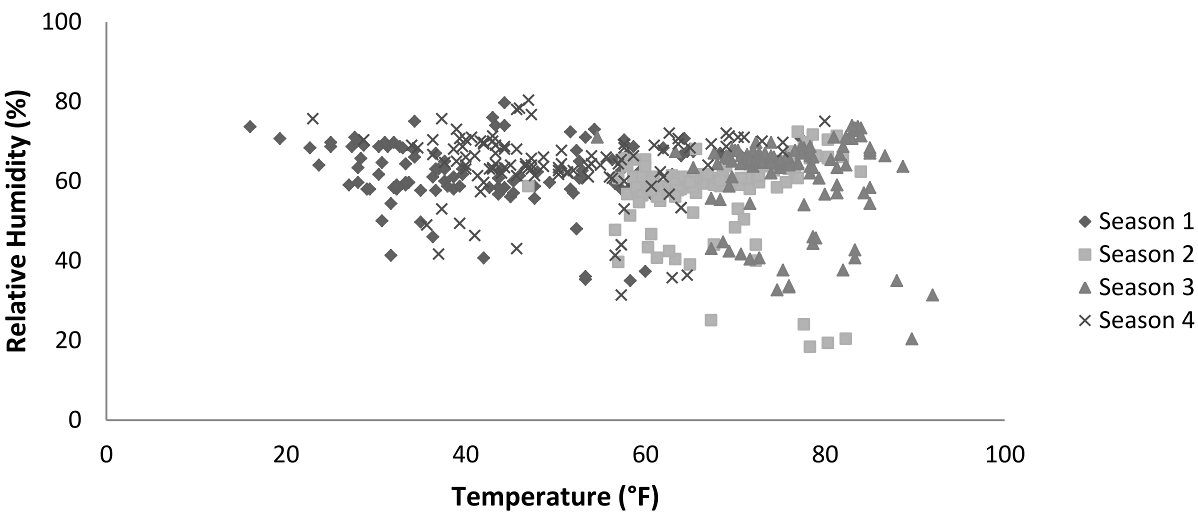

Figure 5. Seasonal Relative Humidity and Temperature for Every County

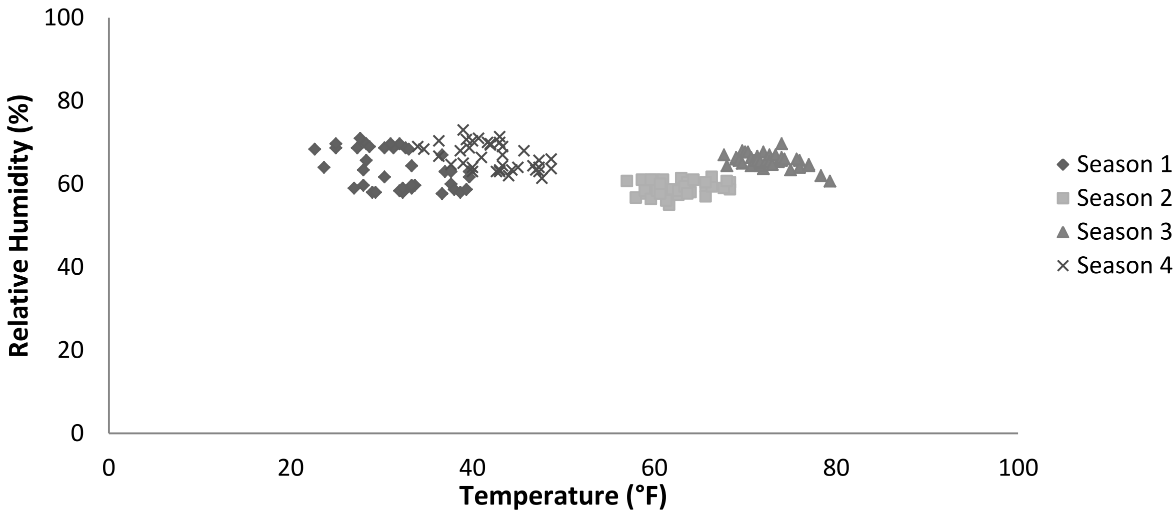

Figure 6. Seasonal Relative Humidity and Temperature for Counties with Similar Seasonal Climates

Although the counties were tentatively grouped by temperature and relative humidity, researchers also retained the weighted seasonal ACF values that were calculated for each county in Step 1b. Researchers averaged each tentative group's weighted seasonal ACF to compare the counties within each group to the group average. Researchers removed any counties that differed significantly from the group averages. The degree to which a county varied from the average was approximately no more than 10 percent and preferably no more than 5 percent. For example, group two, which is comprised of 16 urban areas with similar seasonal climates, has a weighted ACF value of 26 percent for Season 3, and for that season, most counties (or cities) in that group have a weighted ACF between 23 and 29 percent. Researchers determined this margin for error during the grouping process based on the need to create a manageable number of groups without sacrificing accuracy. Several counties did not share similar weighted seasonal ACF values with any group, so TTI researchers calculated their emissions independently.

Up to this point, the term "weighted" has indicated that each *county's* seasonal ACF was created from hourly ACF values that researchers weighted with hourly traffic volume distribution averages (described earlier in Step 1b and displayed in Figure 4). However, to account for differences in traffic volume among counties within each group, researchers weighted each *group's* weighted seasonal ACF averages with the amount of travel that occurred in each county (expressed in VMT). Here, the term weighted seasonal ACF average indicates that each group's seasonal ACF average was weighted with the VMT that occurred in each county.

TTI researchers weighted the seasonal ACF averages by VMT to ensure that each group's seasonal ACF average was weighted by traffic level. While this favored the urban areas with higher amounts of traffic, researchers continued to use the established criteria for all counties in the group (approximately no more than a 10 percent difference from the average and preferably no more than 5 percent).

To weight each group's seasonal ACF averages, researchers used MOVES to obtain the VMT for each county in 2012. To calculate the VMT for a given year, MOVES applies VMT growth factors to base year FHWA VMT data. The VMT for each county does not directly represent the total VMT for each *UMR* urban area, but researchers manually confirmed that the counties produced results sufficient for a broad comparison of the *UMR* urban areas. Researchers confirmed this by comparing the VMT totals for counties from different sized urban areas, based on *UMR* urban area size classifications. For example, Chicago is defined as a "Very Large" urban area in the *UMR*, and the county used for Chicago had significantly more VMT than the county used for Akron (defined as a "Medium" sized urban area).

After obtaining the VMT within each county, researchers needed to compare the VMT of each county within each group. Researchers first summed the VMT for every county in each group. Researchers then calculated each county's percentage of the total and multiplied each county's VMT fraction by its weighted seasonal ACF. For each group, these results were summed for each season to create the group's weighted seasonal ACF average.

Figure 7 provides an example group to demonstrate how TTI researchers weighted each group's seasonal ACF values. The example group is comprised of two counties, CountyA and CountyB, each with a seasonal ACF and VMT value. Because CountyB has a higher VMT value, CountyB's seasonal ACF value influenced the group's average more than CountyA's ACF value did.

	VMT *(from MOVES)*	**Portion of Total Group VMT**		**Original "AConFraction"**		**Weighted "AConFraction"**	**Group Seasonal "AConFraction"**
CountyA	100	16.7%	×	0.15	=	0.0250	0.183
CountyB	500	83.3%	×	0.19	=	0.1580	

Figure 7. Example of Creating the Group Weighted Seasonal "AConFraction" Average

After creating each group's weighted seasonal ACF average, researchers used the same criteria presented earlier (approximately no more than a 10 percent difference from the average and preferably no more than 5 percent) to re-evaluate the groups. Researchers removed any counties that did not satisfy the criteria. After this step, researchers repeated the process of calculating each group's seasonal weighted ACF average and re-evaluating each group until all of the groups met the criteria. Several counties did not share similar weighted seasonal ACF values with any group, so TTI researchers calculated their emissions independently.

The counties comprising the groups are displayed in Figure 8 on a map of the Continental United States. The counties for the independent groups are listed separately. Table 2 lists the urban areas for each group based on the counties displayed in Figure 8.

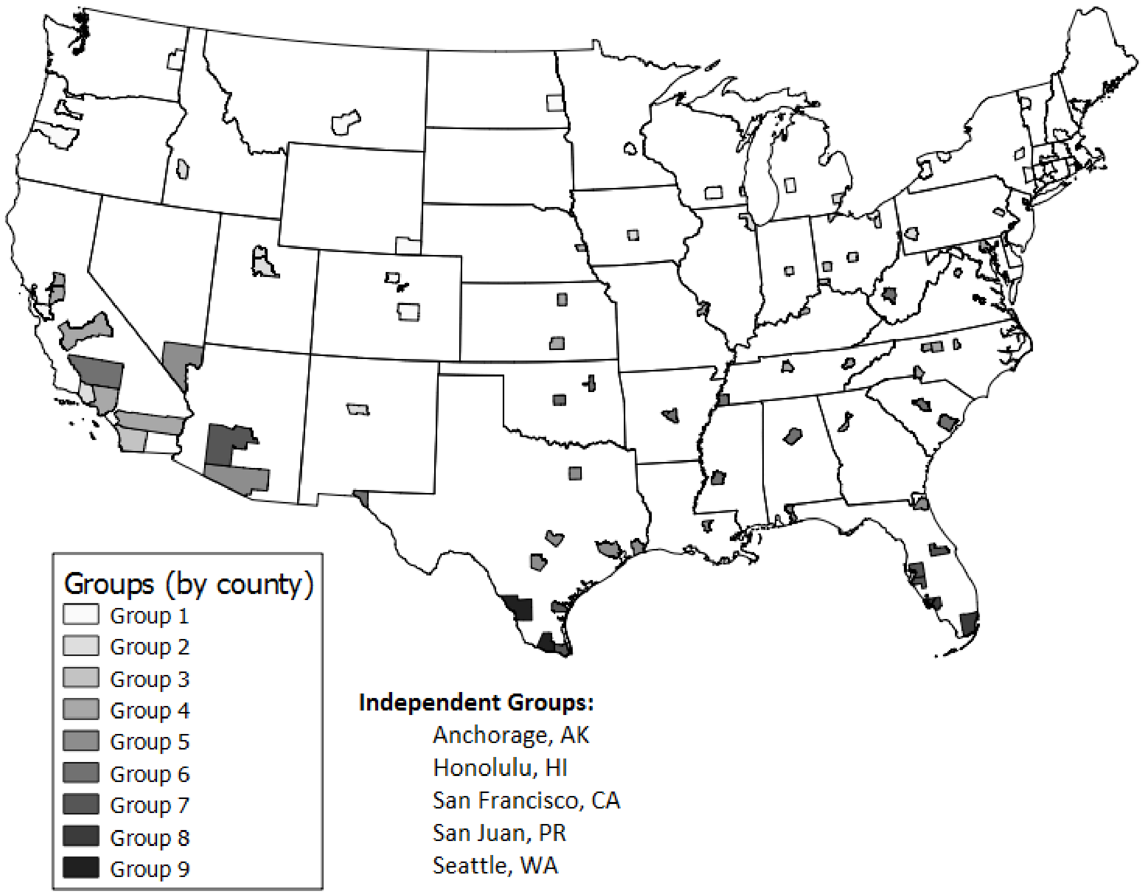

Figure 8. The Continental United States with Each County Shaded by Group

Table 2. *UMR* Urban Area Groups Based on County Groupings Shown in Figure 8

Group	Urban Area Listed by City
1	San Jose, CA / Boulder, CO / Colorado Springs, CO / Denver-Aurora, CO / Bridgeport-Stamford, CT / Hartford, CT / New Haven, CT / Boston, MA / Springfield, MA / Worcester, MA / Grand Rapids, MI / Minneapolis-St. Paul, MN / Albany-Schenectady, NY / Buffalo, NY / Poughkeepsie-Newburgh, NY / Rochester, NY / Cleveland, OH / Eugene, OR / Portland, OR / Salem, OR / Providence, RI / Spokane, WA / Madison, WI / Milwaukee, WI
2	Oxnard-Ventura, CA / Boise, ID / Chicago, IL / Indianapolis, IN / Detroit, MI / Albuquerque, NM / New York-Newark, NY / Akron, OH / Columbus, OH / Toledo, OH / Allentown-Bethlehem, PA / Pittsburgh, PA / Provo, UT / Salt Lake City, UT
3	San Diego, CA / Omaha, IA / Cincinnati, OH / Dayton, OH / Philadelphia, PA / Washington D.C.
4	Indio-Cathedral City-Palm Springs, CA / Lancaster-Palmdale, CA / Los Angeles-Long Beach-Santa Ana, CA / Riverside-San Bernardino, CA / Sacramento, CA / Stockton, CA / Atlanta, GA / Wichita, KS / Kansas City, KS/MO / Louisville, KY / Baltimore, MD / St. Louis, MO / Charlotte, NC / Greensboro, NC / Raleigh-Durham, NC / Winston-Salem, NC / Knoxville, TN / Nashville-Davidson, TN / Richmond, VA / Virginia Beach, VA
5	Tucson, AZ / Jacksonville, FL / Pensacola, FL / Baton Rouge, LA / New Orleans, LA / Las Vegas, NV / Austin, TX / Beaumont, TX / Dallas-Fort Worth-Arlington, TX / Houston, TX / San Antonio, TX
6	Birmingham, AL / Little Rock, AR / Bakersfield, CA / Jackson, MS / Oklahoma City, OK / Tulsa, OK / Charleston-North Charleston, SC / Columbia, SC / Memphis, TN / El Paso, TX
7	Phoenix, AZ / Orlando, FL / Sarasota-Bradenton, FL / Tampa-St. Petersburg, FL / Brownsville, TX / Corpus Christi, TX
8	Cape Coral, FL / Miami, FL
9	Laredo, TX / McAllen, TX
None	Anchorage, AK / San Francisco-Oakland, CA / Honolulu, HI / San Juan, PR / Seattle, WA

2. Obtain Emission Rates for Each Group

TTI researchers used MOVES to produce emission rates for different vehicle types and locations, which they would later combine with separately obtained speed and volume data to calculate emissions estimates. Researchers produced emission rates for every ACF value assigned to the groups in Step 1. For each ACF value, researchers produced emission rates for each vehicle type, fuel type, and road type used in the *UMR*, all of which are described in the following paragraphs.

a) Identify Representative "SourceTypes"

While MOVES classifies vehicles into several vehicle types, the *Urban Mobility Report* uses just three categories: light-duty vehicles, medium-duty trucks, and heavy-duty trucks. In order to apply the MOVES emission rates to the *UMR* vehicle types, researchers selected a representative vehicle type from MOVES for each of the three *UMR* categories.

Researchers based these decisions on two levels of vehicle classification from MOVES: Highway Performance Monitoring System (HPMS) vehicle classes and MOVES "SourceType." "SourceType" is a vehicle classification for which MOVES produces emission rates, and each "SourceType" is associated with an HPMS vehicle class, as shown in Table 3. Researchers used the "SourceType" primarily to provide emission rates, although they also referenced MOVES "SourceType" population data, which is described in the following paragraphs. Researchers used the HPMS vehicle classifications to calculate the composition of vehicle types for the light-duty vehicle class, which is also explained in the following paragraphs. Table 4 displays the *UMR* vehicle types with the associated "SourceType(s)" TTI researchers used to supply emission rates.

Table 3. MOVES "SourceType" and Associated HPMS Vehicle Class

MOVES "SourceType"	ID	ID	HPMS Vehicle Class
Passenger Car	21	20	Passenger Car
Passenger Truck	31	30	Other Two-Axle/Four Tire, Single Unit
Light Commercial Truck	32	30	Other Two-Axle/Four Tire, Single Unit
Refuse Truck	51	50	Single Unit
Single-Unit Short-haul Truck	52	50	Single Unit
Single-Unit Long-haul Truck	53	50	Single Unit
Motor Home	54	50	Single Unit
Combination Short-haul Truck	61	60	Combination
Combination Long-haul Truck	62	60	Combination

Table 4. Vehicle Types and Associated Information

UMR Vehicle Type	MOVES "SourceType" Selected for Emission Rates	Weighted *(based on VMT)*	MOVES "SourceType" ID	Fuel Type
Light-Duty Vehicle	Passenger Cars	59%	21	Gasoline
	Passenger Trucks	41%	31	Gasoline
Medium-Duty Truck	Single Unit Short-haul Trucks	-	52	Diesel
Heavy-Duty Truck	Combination Short-haul Trucks	-	61	Diesel

Multiple "SourceTypes" meet the description of each vehicle type used in the *Urban Mobility Report* (light-duty vehicles, medium-duty trucks, and heavy-duty trucks). For example, both the combination short-haul and combination long-haul trucks qualify as heavy-duty trucks. Rather than weighting the emission rates of every "SourceType," researchers selected a single "SourceType" to supply emission rates for each *UMR* vehicle type, because many "SourceTypes" have similar emission rates (light-duty vehicles are an exception, however).

b) Select "SourceTypes" to Supply Emission Rates

To determine which "SourceType" would supply the emission rates for a vehicle type, researchers chose the "SourceType" with the highest percentage of vehicle-miles of travel (VMT) within each *UMR* vehicle type. For both medium and heavy-duty trucks, researchers used the short-haul truck emission rates based on 1990 and 1999 MOVES VMT data, which is the most recent VMT data for the MOVES "SourceTypes." The 1990 and 1999 VMT data indicated that single-unit short-haul and combination short-haul trucks accounted for the most VMT for their vehicle types. Researchers found this data to be sufficient because the VMT distribution was similar for both 1990 and 1999, and researchers assumed that this distribution would not have drastically changed by 2012.

TTI researchers used a different method for light-duty vehicles, because not all "SourceTypes" within this classification have similar emission rates. The light-duty vehicle classification consists of passenger cars, passenger trucks, and light commercial trucks. Passenger trucks and light commercial trucks have similar emission rates, but passenger car emission rates are substantially different. To create one set of emission rates for this vehicle type (light-duty vehicles), researchers combined and weighted the emission rates of two different "SourceTypes" – passenger cars and passenger trucks, as shown in Table 4. Researchers used only the passenger truck "SourceType" to supply the emission rates for both passenger trucks and light commercial trucks because they have similar emission rates, and because passenger trucks account for more VMT (based on the 1990 and 1999 MOVES data).

After obtaining emission rates for passenger cars and passenger trucks, researchers combined and weighted them to create one set of emission rates for the light-duty vehicle class. To weight the emission rates, researchers determined the volume distribution of the "SourceTypes" in the light-duty vehicle class. Because researchers used the same emission rates for both passenger trucks and light commercial trucks, they only needed to determine the volume of two vehicle types: 1) passenger cars, and 2) passenger trucks/light commercial trucks. As shown in Table 3, this corresponded with two HPMS vehicle classifications: vehicle type 20 (passenger cars), and vehicle type 30 (passenger trucks and light commercial trucks).

To obtain 2012 VMT data for HPMS vehicle types 20 and 30, TTI researchers ran MOVES to apply VMT growth factors to HPMS VMT data from the base year of 1999. Researchers then determined that vehicle types 20 and 30 accounted for 59 and 41 percent of total light-duty VMT, respectively.

To check their vehicle type selections for accuracy, TTI researchers compared emissions rates for all of the "SourceTypes" within each *UMR* vehicle type. For the light-duty classification, passenger cars had unique emission rates, while the emission rates of passenger trucks and light commercial trucks had less than a 1 percent average difference. For the medium-duty classification, the emission rates of every "SourceType" were confined within a range of about a 5 to 6 percent average difference. Researchers determined this difference was acceptable because, based on the 1990 and 1999 VMT data, single unit short-haul trucks accounted for significantly more VMT than any other "SourceType" in the medium-duty class. For the heavy-duty classification, the combination short and long-haul trucks emission rates had about a 4 percent average difference.

c) Determine Fuel and Road Types

Emission rates also differ for specific fuel types, and TTI researchers selected a fuel type for each vehicle type based on fuel usage data in MOVES (see Table 3). In the MOVES database, over *99* percent of passenger cars use gasoline, over *97* percent of passenger trucks use gasoline, and over *89* percent of light commercial trucks use gasoline. Given the additional fact that light commercial trucks account for a small portion of the light-duty vehicle population, researchers therefore used the gasoline emission rates to represent all fuel usage for light-duty vehicles when calculating emissions. For medium-duty trucks in the MOVES database, about *70* percent use diesel and *30* percent use gasoline. To simplify, researchers used the diesel emission rates to represent all fuel usage for medium-duty trucks when estimating emissions. According to MOVES, *100* percent of all heavy-duty trucks use diesel, so researchers used the diesel emission rates to represent all fuel usage for heavy-duty trucks.

Researchers also ran MOVES for the two road types that best represented the road types (arterial and freeway) used in the *Urban Mobility Report*, as seen in Table 5.

Table 5. Road Types and Associated Information

UMR Road Type	MOVES Road Type	MOVES Road Type ID	HPMS Functional Types
Arterial	Urban Unrestricted Access	5	Urban Principal Arterial,Minor Arterial, Collector & Local
Freeway	Urban Restricted Access	4	Urban Interstate & Urban Freeway/Expressway

d) Use MOVES to Obtain Emission Rates

TTI researchers ran MOVES for the appropriate vehicle types, fuel types, and road types to obtain emission rates in grams per mile. Because researchers were only interested in obtaining CO_2 emission rates, the location selected when using MOVES was not significant. This is because the only substantial impact location has on emission rates in MOVES is the climate effects (or ACF). For example, the emission rates for a passenger car with a 30 percent ACF in Hawaii are similar to the emission rates for a passenger car with a 30 percent ACF in Texas. Researchers ran MOVES to produce emission rates for the diverse range of ACF values needed.

MOVES does not display the ACF that was used during each run because those calculations are done internally. MOVES is typically used as a standalone tool, thus it is not designed to display every internal calculation. It does display temperature and relative humidity however, so researchers calculated each county's ACF value (Step 1b) as part of estimating emission rates.

After obtaining emission rates by ACF, researchers identified all of the ACF values being used for the previously-created groups (and the cities for which researchers would calculate emissions individually). For these ACF values, researchers created emission rates tables for each vehicle type, gasoline type, and road type.

3. Fit Curves to Emission Rates

TTI researchers developed curves to calculate emission rates for a given speed. Researchers later used the equations for each curve to calculate emissions, which is detailed in Step 4. The following sub-steps identify how researchers developed the curves.

a) Fit Each Set of Emission Rates with Three Polynomial Curves

MOVES produces emission rates for speeds of 2.5 to 75 mph in increments of five (except for 2.5 mph). Using Microsoft Excel®, researchers constructed speed-dependent emission factor curves by fitting one to three polynomial curves (spline) to the emission rate data from MOVES. Figure 9 displays an example set of three emission rate curves. Researchers compared emission rates generated with the polynomial spline to the underlying MOVES-generated emission rates.

The polynomial spline that was deemed sufficiently accurate by researchers was a two-segment spline using one 6^{th}-order polynomial for the 0 – 30 mph segment and another 6^{th}-order polynomial for the 30 – 60 mph segment. Free-flow speeds are capped at 65 mph on freeways because it does not make sense to accumulate delay for speeds over 65 mph. Emission rates for speeds between 60 mph and 65 mph were fixed at the rate at 60 mph. There is a 1 percent increase in emissions from 60 mph to 65 mph for passenger cars and medium-duty trucks. There is about a 5 percent difference for heavy-duty vehicles, but they account for a much smaller portion of the areawide vehicle-miles so the overall difference is still closer to a negligible 1 percent. Also note that these speeds are averages, and variability with speed (slope) is negligible for speeds greater than 60 mph. To the contrary, lower average speeds have higher speed fluctations (or more stop-and-go), which causes higher emission rates. From a CO_2 perspective, these slower speeds are of greater concern. Because there are fewer speed fluctuations at higher speeds, which results in a more efficient system operation, it is desirable for urban areas to operate during the relatively free-flow conditions as much as possible.

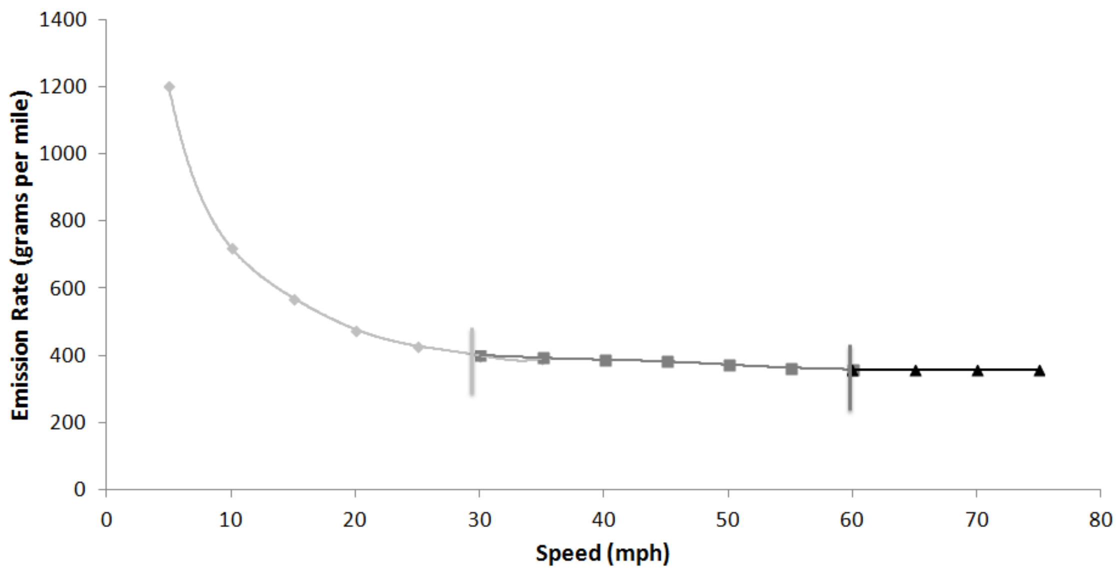

Figure 9. Example Light-duty Vehicle Emission Rate Curve-set Showing Three Emission Rate Curves

4. Calculate Emissions and Fuel Consumption

TTI researchers combined hourly speed data supplied by INRIX, hourly volume data supplied by Highway Performance Monitoring System (HPMS), and emission rates to calculate emissions. Researchers then used the results of the emissions estimates to calculate fuel consumption.

a) Estimate Emissions Using SAS®

Researchers used SAS, a statistical computer program, to automate the process of calculating emissions. The process involved selecting the appropriate emission rate equations (or curves), using the speed data to calculate emission rates, combining the volume data with the emission rates to calculate emissions, and then using the emissions estimates to calculate fuel consumption.

For each urban area, researchers used SAS to first select a set of curves from the 14 available equation-sets (the 9 groups and 5 individual cities described in Step 1 and displayed in Figure 8 and Table 2). Within each equation-set, each vehicle type has 24 curves (4 seasons × 2 road types × 3 curves per emission rate table). After researchers used SAS to select the appropriate equation-set for a corridor, they used SAS to select an arterial or freeway equation-set, dependent on the roadway type.

Each day of the week contained 24 hourly average speeds in each direction. For each hour, researchers used SAS to select the appropriate curve for each vehicle type, dependent on the season and average speed, producing 12 unique emission rates. Some seasons had identical emission rates due to identical ACF values. In fact, many curve sets had multiple seasons with an ACF of zero.

Figure 10 displays examples of hourly emission rates by vehicle type and by season. It is apparent in this figure that each vehicle type has a significantly different emission rate. In Figure 10, Season 1's emission rates are lower than Season 3's emission rates, which is consistent with each season's time of year (Season 1 includes mostly winter months, and Season 3 includes mostly summer months).

CO_2 Emission Rate (grams per mile)

		Season 1			Season 2			Season 3			Season 4		
Hour	Speed	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty
1	40	370	932	1946	380	963	1996	389	989	2038	372	939	1958
2	35	383	1014	1985	394	1049	2038	403	1078	2081	386	1022	1997
3	40	370	932	1946	380	963	1996	389	989	2038	372	939	1958
4	45	360	866	1916	370	894	1964	378	917	2004	362	872	1927
5	50	353	796	1828	362	822	1873	370	843	1911	355	802	1838

Figure 10. Example Hourly CO_2 Emission Rates

After the hourly emission rates were selected, researchers used SAS to multiply the VMT by the emission rates to get the hourly emissions. Figure 11 displays an example in which researchers multiplied emission rates (Figure 11a) by hourly VMT (Figure 11b) to get daily emissions (Figure 11c).

CO₂ Emission Rate *(grams per mile)*

Hour	Speed	Season 1 L-duty	Season 1 M-duty	Season 1 H-duty	Season 2 L-duty	Season 2 M-duty	Season 2 H-duty	Season 3 L-duty	Season 3 M-duty	Season 3 H-duty	Season 4 L-duty	Season 4 M-duty	Season 4 H-duty
1	40	370	932	1946	380	963	1996	389	989	2038	372	939	1958
2	35	383	1014	1985	394	1049	2038	403	1078	2081	386	1022	1997
3	40	370	932	1946	380	963	1996	389	989	2038	372	939	1958
4	45	360	866	1916	370	894	1964	378	917	2004	362	872	1927
5	50	353	796	1828	362	822	1873	370	843	1911	355	802	1838

(a)

VMT

Hour	Season 1 L-duty	Season 1 M-duty	Season 1 H-duty	Season 2 L-duty	Season 2 M-duty	Season 2 H-duty	Season 3 L-duty	Season 3 M-duty	Season 3 H-duty	Season 4 L-duty	Season 4 M-duty	Season 4 H-duty
1	4060	140	233	4060	140	233	4060	140	233	4060	140	233
2	5075	175	292	5075	175	292	5075	175	292	5075	175	292
3	4060	140	233	4060	140	233	4060	140	233	4060	140	233
4	3045	105	175	3045	105	175	3045	105	175	3045	105	175
5	2030	70	117	2030	70	117	2030	70	117	2030	70	117

(b)

CO_2 Emissions for One Day *(kilograms)*

Hour	Season 1 L-duty	Season 1 M-duty	Season 1 H-duty	Season 2 L-duty	Season 2 M-duty	Season 2 H-duty	Season 3 L-duty	Season 3 M-duty	Season 3 H-duty	Season 4 L-duty	Season 4 M-duty	Season 4 H-duty
1	1503	130	454	1544	135	466	1578	138	475	1512	131	457
2	1946	177	579	2001	184	594	2048	189	607	1958	179	582
3	1503	130	454	1544	135	466	1578	138	475	1512	131	457
4	1097	91	335	1126	94	344	1150	96	351	1103	92	337
5	717	56	213	735	58	219	750	59	223	721	56	214

(c)

Figure 11. Example Hourly CO_2 Emissions for one Day

b) Estimate Total Annual Emissions and Fuel Consumption

Researchers used SAS to multiply the hourly emissions for one day by the number of weeks in each season to get the hourly emissions for each season, as shown in Figure 12.

At this point in the process, researchers used SAS to compute fuel consumption, and the fuel consumption and emissions estimates were computed simultaneously for the rest of the process. Researchers used SAS to combine the hourly emissions data for each season with fuel consumption factors from MOVES to produce hourly fuel consumption for each season. For light-duty vehicles, researchers used the gasoline factor, and for heavy-duty trucks, researchers used the diesel factor. For medium-duty trucks, researchers used the factors according to the percentage of medium-duty trucks that use gasoline (30 percent) and diesel (70 percent). These data were provided by MOVES and are described in Step 2c.

Researchers converted CO_2 emissions to estimate fuel consumption using the following relationship:

Fuel Consumption (gallons) = CO_2 emission (grams) / grams CO_2 per gallon (Equation 3)

Where:
CO_2 Emissions from a gallon of gasoline: 8,887 grams CO_2/gallon
CO_2 Emissions from a gallon of diesel: 10,180 grams CO_2/gallon (*16*)

CO_2 Emissions for One Day *(kilograms)*

	Season 1			Season 2			Season 3			Season 4		
Hour	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty
1	1503	130	454	1544	135	466	1578	138	475	1512	131	457
2	1946	177	579	2001	184	594	2048	189	607	1958	179	582
3	1503	130	454	1544	135	466	1578	138	475	1512	131	457
4	1097	91	335	1126	94	344	1150	96	351	1103	92	337
5	717	56	213	735	58	219	750	59	223	721	56	214

(a)

Number of Weeks in Each Season

Season 1	Season 2	Season 3	Season 4
12.9	13	13.1	13.1

(b)

CO_2 Emissions for Each Season *(kilograms)*

	Season 1			Season 2			Season 3			Season 4		
Hour	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty	L-duty	M-duty	H-duty
1	19383	1683	5859	20070	1753	6056	20673	1814	6229	19804	1722	5984
2	25102	2289	7470	26019	2387	7727	26823	2472	7952	25654	2343	7630
3	19383	1683	5859	20070	1753	6056	20673	1814	6229	19804	1722	5984
4	14149	1172	4326	14637	1220	4468	15066	1262	4594	14454	1199	4418
5	9249	719	2751	9559	748	2841	9831	773	2920	9445	735	2809

(c)

Figure 12. Example Hourly CO_2 Emissions for Each Season

Researchers used SAS to sum the hourly seasonal totals (shown in Figure 12) for both fuel consumption and emissions to produce the hourly totals for the year. Finally, researchers used SAS to sum both the hourly fuel consumption and emissions calculations totals for the year to produce the annual totals.

5. Estimate the Emissions and Fuel Consumption Due to Congestion

To estimate the emissions and fuel consumption due to congestion, researchers repeated Step 4 with free-flow speeds and subtracted the congested-condition results from the free-flow results.

CHAPTER 4
CO_2 EMISSION RESULTS

Table 6 shows the results of the methodology application as presented in the *2012 Urban Mobility Report*. Each page of the table provides CO_2 emission results by urban area population size. For each urban area, data are presented in columns for the following:

- Pounds per auto commuter of CO_2 produced during congestion only, and associated ranking
- Pounds (millions) of CO_2 produced during congestion only, and associated ranking
- Pounds (millions) of CO_2 produced during free-flow conditions, and associated ranking
- Percent of CO_2 production during congestion relative to free-flow

These data are for freeways and principal arterials only for all-day, every day in 2011. These statistics provide an indication of the overall magnitude of the problem in urban areas in total pounds as well as an indication of what that large value means to the individual by characterizing it per auto commuter.

The 498 urban area total CO_2 produced during congested conditions only is 56 billion pounds as shown in the values summarized at the end of Table 6. For this analysis, a comparison is made of CO_2 emissions for each trip at both free-flow conditions and the reported speed under congested conditions. The amount of CO_2 produced at free-flow is 1.8 trillion pounds. The 56 billion pounds is the additional CO_2 produced because of slower speeds in congestion.

Table 6. Annual Urban Area CO_2 Production on Freeways and Arterial Streets, 2011 (Adapted from Reference *1*)

Urban Area	Pounds per Auto Commuter (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Free-flow)	Rank	Percent of CO_2 Production During Congestion Relative to Free-Flow
Very Large Average (15 areas)	**464**		**1,747**		**38,692**		**4.5**
Washington DC-VA-MD	631	1	1,703	5	29,916	9	5.7
New York-Newark NY-NJ-CT	557	2	5,146	1	76,858	2	6.7
Boston MA-NH-RI	526	3	1,338	8	26,161	12	5.1
San Francisco-Oakland CA	503	5	1,298	10	44,642	4	2.9
Miami FL	498	6	1,885	4	33,583	8	5.6
Houston TX	463	10	1,324	9	34,175	7	3.9
Atlanta GA	462	11	1,284	11	34,442	6	3.7
Philadelphia PA-NJ-DE-MD	458	12	1,520	6	28,549	10	5.3
Seattle WA	447	14	955	13	21,696	14	4.4
Los Angeles-Long Beach-Santa Ana CA	436	15	3,578	2	84,264	1	4.2
Chicago IL-IN	434	16	2,320	3	53,395	3	4.3
Dallas-Fort Worth-Arlington TX	405	20	1,505	7	39,098	5	3.8
Phoenix-Mesa AZ	401	22	944	14	25,668	13	3.7
Detroit MI	370	30	982	12	28,024	11	3.5
San Diego CA	218	76	427	25	19,905	15	2.1

Very Large Urban Areas—over 3 million population.
Large Urban Areas—over 1 million and less than 3 million population.
Medium Urban Areas—over 500,000 and less than 1 million population.
Small Urban Areas—less than 500,000 population.
A number of assumptions are in the model using national-level data as inputs. This allows for a relatively simple and replicable methodology for 498 urban areas. More detailed and localized inputs should be used where available to improve local estimates of CO_2 production.
See the CO_2 emissions estimation methodology in the appendix for further details.
Note: Please do not place too much emphasis on small differences in the rankings. There may be little difference in congestion between areas ranked (for example) 6th and 12th. The actual measure values should also be examined.
Also note: The best congestion comparisons use multi-year trends and are made between similar urban areas.

Table 6. Annual CO_2 Production due to Roadway Congestion, 2011, continued 2011 (Adapted from Reference *1*)

Urban Area	Pounds per Auto Commuter (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Free-flow)	Rank	Percent of CO_2 Production During Congestion Relative to Free-Flow
Large Average (32 areas)	**329**		**359**		**10,537**		**3.4**
Nashville-Davidson TN	491	7	377	28	10,638	29	3.5
Orlando FL	450	13	471	20	10,968	28	4.3
Las Vegas NV	417	17	429	24	9,358	34	4.6
Portland OR-WA	415	18	503	18	10,346	31	4.9
Charlotte NC-SC	412	19	296	36	9,012	38	3.3
Denver-Aurora CO	403	21	695	15	14,835	20	4.7
Austin TX	398	23	343	30	8,308	41	4.1
Indianapolis IN	393	24	340	31	11,314	25	3.0
Baltimore MD	392	25	667	16	16,029	18	4.2
Memphis TN-MS-AR	384	27	291	37	7,996	42	3.6
Virginia Beach VA	373	29	392	27	10,382	30	3.8
Tampa-St. Petersburg FL	366	32	613	17	14,924	19	4.1
Cincinnati OH-KY-IN	364	33	421	26	12,549	22	3.4
Buffalo NY	357	35	234	46	5,683	54	4.1
Pittsburgh PA	355	37	431	23	9,100	35	4.7
Columbus OH	353	39	311	34	10,153	32	3.1
Louisville KY-IN	340	40	253	40	8,311	40	3.0
San Antonio TX	323	44	336	33	11,637	24	2.9
Cleveland OH	308	46	350	29	11,079	27	3.2
San Juan PR	306	48	486	19	9,078	36	5.4
Providence RI-MA	293	51	242	43	7,506	45	3.2
St. Louis MO-IL	272	56	437	22	19,243	16	2.3
Jacksonville FL	271	57	207	51	7,777	43	2.7
New Orleans LA	270	58	190	52	4,980	57	3.8
Riverside-San Bernardino CA	257	60	339	32	13,471	21	2.5
Salt Lake City UT	257	60	185	53	5,534	55	3.3
Minneapolis-St. Paul MN	249	65	444	21	18,031	17	2.5
San Jose CA	249	65	302	35	11,113	26	2.7
Kansas City MO-KS	235	70	256	38	11,951	23	2.1
Milwaukee WI	232	74	237	45	9,046	37	2.6
Raleigh-Durham NC	217	77	170	55	6,779	47	2.5
Sacramento CA	207	84	254	39	10,047	33	2.5

Very Large Urban Areas—over 3 million population.
Large Urban Areas—over 1 million and less than 3 million population.
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A number of assumptions are in the model using national-level data as inputs. This allows for a relatively simple and replicable methodology for 498 urban areas. More detailed and localized inputs should be used where available to improve local estimates of CO_2 production.

See the CO_2 emissions estimation methodology in the appendix for further details.

Note: Please do not place too much emphasis on small differences in the rankings. There may be little difference in congestion between areas ranked (for example) 6th and 12th. The actual measure values should also be examined.

Also note: The best congestion comparisons use multi-year trends and are made between similar urban areas.

Table 6. Annual CO_2 Production due to Roadway Congestion, 2011, continued 2011 (Adapted from Reference *1*)

Urban Area	Pounds per Auto Commuter (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Free-flow)	Rank	Percent of CO_2 Production During Congestion Relative to Free-Flow
Medium Average (33 areas)	**278**		**129**		**4,533**		**2.8**
Baton Rouge LA	526	3	210	49	5,791	52	3.6
Tucson AZ	491	7	248	41	6,053	50	4.1
Honolulu HI	485	9	225	48	3,254	79	6.9
Bridgeport-Stamford CT-NY	392	25	246	42	5,879	51	4.2
Albany NY	379	28	162	56	4,399	61	3.7
Hartford CT	368	31	226	47	6,620	49	3.4
Oklahoma City OK	362	34	242	43	8,642	39	2.8
Birmingham AL	356	36	208	50	6,775	48	3.1
Knoxville TN	355	37	128	62	4,356	62	2.9
El Paso TX-NM	335	41	171	54	4,341	63	3.9
New Haven CT	327	43	139	59	4,191	67	3.3
McAllen TX	320	45	130	61	3,359	76	3.9
Tulsa OK	298	50	145	58	5,765	53	2.5
Springfield MA-CT	292	52	128	62	4,023	69	3.2
Allentown-Bethlehem PA-NJ	289	54	128	62	4,020	70	3.2
Charleston-North Charleston SC	280	55	103	67	3,690	72	2.8
Rochester NY	257	60	134	60	4,252	66	3.2
Poughkeepsie-Newburgh NY	251	64	100	70	3,628	74	2.8
Dayton OH	235	70	123	65	5,291	56	2.3
Richmond VA	234	72	159	57	7,670	44	2.1
Toledo OH-MI	234	72	84	75	3,263	78	2.6
Omaha NE-IA	217	77	95	72	4,164	68	2.3
Grand Rapids MI	216	79	92	73	4,775	60	1.9
Colorado Springs CO	214	81	83	76	3,315	77	2.5
Sarasota-Bradenton FL	212	82	107	66	3,195	81	3.3
Akron OH	195	85	83	76	3,865	71	2.1
Oxnard CA	182	88	87	74	6,891	46	1.3
Albuquerque NM	170	90	74	79	4,826	59	1.5
Wichita KS	166	91	58	83	3,253	80	1.8
Bakersfield CA	118	95	45	89	2,684	84	1.7
Fresno CA	85	97	40	92	3,684	73	1.1
Indio-Cathedral City-Palm Springs CA	61	99	25	96	2,025	93	1.2
Lancaster-Palmdale CA	50	100	21	98	1,658	95	1.3

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Table 6. Annual CO_2 Production due to Roadway Congestion, 2011, continued 2011 (Adapted from Reference *1*)

Urban Area	Pounds per Auto Commuter (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Congestion Only)	Rank	Pounds (millions) (CO_2 Produced During Free-flow)	Rank	Percent of CO_2 Production During Congestion Relative to Free-Flow
Small Average (21 areas)	**209**		**51**		**2,355**		**2.2**
Worcester MA-CT	329	42	103	67	3,504	75	2.9
Brownsville TX	308	46	46	88	919	99	5.0
Cape Coral FL	302	49	103	67	2,815	83	3.7
Columbia SC	291	53	98	71	4,289	64	2.3
Jackson MS	269	59	83	76	4,254	65	2.0
Spokane WA-ID	257	60	70	80	2,448	86	2.9
Beaumont TX	248	67	42	90	2,374	89	1.8
Greensboro NC	245	68	60	82	2,995	82	2.0
Salem OR	244	69	42	90	1,365	96	3.1
Boulder CO	229	75	24	97	563	101	4.3
Pensacola FL-AL	215	80	55	84	2,285	91	2.4
Provo-Orem UT	208	83	69	81	2,395	88	2.9
Madison WI	194	86	53	85	2,310	90	2.3
Winston-Salem NC	183	87	50	86	2,437	87	2.1
Laredo TX	171	89	29	94	1,005	98	2.9
Little Rock AR	158	92	49	87	4,877	58	1.0
Anchorage AK	144	93	31	93	732	100	4.2
Boise ID	120	94	26	95	1,953	94	1.3
Eugene OR	114	96	20	99	1,324	97	1.5
Stockton CA	67	98	19	100	2,549	85	0.7
Corpus Christi TX	39	101	9	101	2,059	92	0.4
101 Area Total			**43,043**		**1,116,603**		**3.9**
101 Area Average	**385**		**426**		**11,055**		
Remaining Area Total			**13,352**		**641,134**		**2.1**
Remaining Area Average	**366**		**34**		**1,614**		
All 498 Area Total			**56,396**		**1,757,737**		**3.2**
All 498 Area Average	**380**		**113**		**3,529**		

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A number of assumptions are in the model using national-level data as inputs. This allows for a relatively simple and replicable methodology for 498 urban areas. More detailed and localized inputs should be used where available to improve local estimates of CO_2 production. See the CO_2 emissions estimation methodology in the appendix for further details. Note: Please do not place too much emphasis on small differences in the rankings. There may be little difference in congestion between areas ranked (for example) 6th and 12th. The actual measure values should also be examined. Also note: The best congestion comparisons use multi-year trends and are made between similar urban areas.

Validation of CO_2 Results

Researchers obtained vehicle-miles of travel (VMT) and CO_2 emission estimates from the literature for selected cities to perform an "order of magnitude" validation of the results shown in Table 6.

Table 7 provides the results of the comparison for selected Texas urban areas. The data come from emissions inventories performed by TTI for the Texas Commission on Environmental Quality (TCEQ). The *2012 UMR* results are in the range of 80 percent to 99 percent of the literature values for estimated CO_2 emission rate (lbs per mile). These results appear intuitive and reasonable.

The total CO_2 estimate cannot be compared directly because there are a number of differences between how metropolitan areas are defined, which greatly affects the associated travel volumes:

- Urban area definition differences – the *2012 UMR* defines areas by the urban area boundary. The *UMR* boundary is smaller than a metropolitan statistical area and represents the urbanized (developed) area.
- Functional classes included – the *2012 UMR* includes only freeways and principal arterials. All of the references also include local and collector streets in their regional areas. This is another reason the *2012 UMR* values can be expected to be smaller.
- Simplifying assumptions – there are a number of additional simplifying assumptions made in the *2012 UMR* methodology using national-level data as inputs (volume, speed, vehicle composition, fuel types). This allows for a relatively simple and replicable methodology for 498 urban areas. More detailed and localized inputs and analyses are conducted by local or state agencies; those are better estimates of CO_2 production.

Given these assumptions in the methodology, the results in Table 7 appear intuitive. On average, the *UMR* methodology captures about 60% of the VMT and 55% of the CO_2 as the Texas emission inventories. The lower *UMR* values are intuitive because the literature references include generally-larger regional areas and more functional classifications of roadway as described above.

Table 7. Comparison of 2012 UMR and Literature References for Selected Locations for VMT and CO_2

Measure	Source	Location			
		San Antonio[1] *(17)* (2011)	Houston /Galveston[2] *(18)* (2011)	Beaumont /Port Arthur[3] *(19)* (2011)	Austin[4] *(20)* (2011)
VMT (billions)	Literature Reference	17.5	52.9	4.3	16.1
	2012 UMR	11.8	34.8	2.3	8.6
	UMR as percent of Literature	*67%*	*66%*	*53%*	*53%*
CO_2 (million tons)	Literature Reference	9.6	29.2	2.8	8.1
	2012 UMR	6.0	17.7	1.2	4.3
	UMR as percent of Literature	*63%*	*61%*	*43%*	*53%*
CO_2 rate (lbs/mile)	Literature Reference	1.10	1.10	1.30	1,01
	2012 UMR	1.02	1.02	1.04	1.00
	UMR as percent of Literature	*93%*	*92%*	*80%*	*99%*

[1]San Antonio literature reference *(17)* includes Bexar, Comal, Guadalupe, Kendall, and Wilson Counties.
[2]Houston/Galveston, Texas literature reference *(18)* includes Brazoria, Chambers, Fort, Galveston, Harris, Liberty, Montgomery, and Waller Counties.
[3]Beaumont/Port Arthur, Texas literature reference *(19)* includes Hardin, Jefferson, and Orange Counties.
[4]Austin, Texas literature reference *(20)* includes Bastrop, Caldwell, Hays, Travis, and Williamson Counties.
Note: Percentages may differ slightly due to rounding of large values.
Also note: There a number of potential causes for the differences between the literature references and the *2012 UMR* in the values presented here. These are described in detail in the text.

Estimation of the additional CO_2 emissions due to congestion provides another important element to characterize the urban congestion problem. It provides useful information for decision-making and policy makers, and it points to the importance of implementing transportation improvements to mitigate congestion. Researchers plan to incorporate other air pollutants into future editions of the *UMR*.

A Final Word about Assumptions in the CO_2 and Wasted Fuel Methodology

Step 5 of the methodology uses the difference between actual congested-condition CO_2 emissions **and** free-flow CO_2 emissions and fuel consumption. According to the methodology, this difference is the "wasted" fuel and "additional" CO_2 produced due to congestion. Some may note that if the congestion were not present, speeds would be higher, throughput would increase, and this would generally result in lower fuel consumption and CO_2 emissions – thus the methodology could be seen as overestimating the wasted fuel and additional CO_2 produced due to congestion. Similarly, if there is substantial induced demand due to the lack of congestion, it is possible that more CO_2 could be present than during congested conditions because of more cars traveling at free-flow (assuming they could). While these are notable considerations and may be true for specific corridors, the *UMR* analysis is at the area-wide level for all principal arterials and freeways and the assumption is that overestimating and underestimating will approximately balance out over the urban area. Therefore, researchers hypothesize that the methodology provides a practical method for consistent and replicable analysis across 498 urban areas.

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

This report describes the development, application and validation of a five-step methodology by TTI researchers to incorporate CO_2 into the *2012 UMR*. The methodology uses data from three primary data sources, 1) the Federal Highway Administration's (FHWA's) Highway Performance Monitoring System (HPMS), 2) INRIX traffic speed data, and 3) The United States Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) model.

There are a number of additional simplifying assumptions made in the *2012 UMR* methodology using national-level data as inputs (volume, speed, vehicle composition, fuel types). This allows for a relatively simple and replicable methodology for 498 urban areas. Emission rates (lbs of CO_2 per mile) were validated in selected cities, with results in the range of 80 percent to 99 percent of the literature values. More detailed and localized inputs and analyses are conducted by local or state agencies; those are better estimates of CO_2 production. At this local scale, some congested urban areas surely represent vibrant places with ample transportation opportunities, from which to investigate and compare approaches for reducing CO_2 emissions.
Estimation of the additional CO_2 emissions due to congestion provides another important element to characterize the urban congestion problem. It provides useful information for decision-making and policymakers, and it points to the importance of implementing transportation improvements to mitigate congestion.

Researchers will continue to improve the methodology documented in this report. The methodology will be updated with updates to EPA's MOVES model. Researchers plan to include other air quality pollutants in future releases of the *UMR*.

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