2019 URBAN MOBILITY REPORT

Appendix A: Methodology

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The procedures used in the *2019 Urban Mobility Report* have been developed by the Texas A&M Transportation Institute over several years and several research projects. The congestion estimates for all study years are recalculated every time the methodology is altered to provide a consistent data trend. The estimates and methodology from this report should be used in place of any previous methodology and measures. All the measures and many of the input variables for each year and every city are provided in a spreadsheet that can be downloaded at http://mobility.tamu.edu/umr/congestion-data/.

This methodology incorporates private-sector traffic speed data from INRIX (*1*) into the calculation of the mobility performance measures. The roadway inventory data source for most of the calculations is the Highway Performance Monitoring System from the Federal Highway Administration (*2*). A detailed description of that dataset can be found at: http://www.fhwa.dot.gov/policy/ohpi/hpms/index.htm.

Methodology Changes for the *2019 Urban Mobility Report*

There are several methodology changes to the *2019 Urban Mobility Report*. The largest changes have to do with the reliability measure (Planning Time Index), estimates of daily truck volumes, and the ever-increasing INRIX speed dataset. These changes are documented in more detail in the following sections of the Methodology. Here are brief summaries of what has changed:

- Estimates of truck volume and truck travel speeds were expanded. This provides more information using the much more detailed truck speed data.
- The measure of travel time variation from day-to-day now uses a more representative trip-based process. The Planning Time Index (PTI) is based on the idea that travelers want to be on-time for an important trip 19 out of 20 times; so one would be late to work only one day per month (on-time for 19 out of the 20 work days each month). For example, a PTI value of 1.60 indicates that a traveler should allow 32 minutes to make an important trip that takes 20 minutes in low traffic volumes (1.60 x 20).
- Speeds supplied by INRIX are collected every 15-minutes from a variety of sources every day of the year on most major roads. The speeds are calculated by matching successive observations and calculating the speed using the time and distance covered between the two points. Many of the slow speeds formerly considered “too slow to be a valid observation” using instantaneous speed observations are now being retained in the INRIX dataset with more eexperience. Larger travel speed sample sizes have increased the confidence in the data.

- The average vehicle occupancy found in the American Community Survey (*3*) data has increased since the 2008/9 economic recession. The UMR adjusts to this trend by increasing the average vehicle occupancy rate from the previous value of 1.25 persons per vehicle to the new value of 1.50 over the period from 2009 to 2012.

Summary

The *Urban Mobility Report (UMR)* procedures provide estimates of mobility at the urban areawide level. The approach describes congestion in consistent ways allowing for comparisons across urban areas or groups of urban areas.

Calculation procedures use a dataset of traffic speeds from INRIX (*1*), a private company that provides travel time information to a variety of customers. INRIX's data is an annual average of traffic speed for each section of road for every 15 minutes of each day for a total of 672 day/time period cells (24 hours x 4 periods per hour x 7 days).

INRIX's speed data improves the freeway and arterial street congestion measures in the following ways:

- Measured speeds are used to estimate a range of congestion measures; speeds are obtained from vehicles moving on streets and freeways, not estimated from traffic counts.
- The 'reference speeds' were used from the INRIX dataset (*1*) as the comparison standard for travel delay. These calculated speeds are built from an improved analytical process and represent low-volume conditions. The speeds are generally slower than speeds used in previous reports, resulting in lower delay estimates; *low-volume speeds on each road section were used as the comparison standard.*
- The volume and roadway inventory data from FHWA's Highway Performance Monitoring System (HPMS) (*2*) files were used with the speeds to calculate travel delay statistics; *the best speed data are combined with the best traffic volume information to produce high-quality congestion measures.*

Congestion Measure Calculations with Speed and Volume Datasets

The following steps were used to calculate the congestion performance measures for each urban roadway section.

1. Obtain HPMS traffic volume data by road section
2. Match the HPMS road network sections with the INRIX traffic speed dataset road sections
3. Estimate traffic volumes for each 15-minute time interval from the daily volume data
4. Calculate average travel speed and total delay for each 15-minute interval
5. Establish free-flow (i.e., low volume) travel speed
6. Additional steps to estimate missing speed data (if/as needed)
7. Calculate congestion performance measures

The mobility measures require four data inputs:

1. Actual travel speed
2. Low-volume conditions travel speed
3. Vehicle volume (total vehicle and truck)
4. Vehicle occupancy (persons per vehicle) to calculate person-hours of travel delay

The INRIX traffic speed data (*1*) provides an excellent data source for the first two inputs, actual and low-volume travel time. The *UMR* analysis requires vehicle and person-volume estimates for the delay calculations; these were obtained from FHWA's HPMS dataset (*2*). The geographic referencing systems are different for the speed and volume datasets, a geographic matching process was performed to assign HPMS road section data to each traffic speed road section for the purposes of calculating the performance measures. When traffic speed data were not available for sections of road or times of day in urban areas, the speeds were estimated. This estimation process is described in more detail in Step 6.

Step 1. Identify Traffic Volume Data

The HPMS dataset from FHWA provided the source for traffic volume data, although the geographic designations in the HPMS dataset are not identical to the INRIX speed data. While there are some detailed traffic counts on major roads, the most widespread and consistent traffic counts available are average daily traffic (ADT) counts. The 15-minute traffic volumes for each section, therefore, were estimated from these ADT counts using typical time-of-day traffic volume profiles developed from continuous count locations or other data sources (see Step 3). The truck volumes were calculated using the truck traffic percentages reported in HPMS.

Step 2. Combine the Road Networks for Traffic Volume and Speed Data

The second step was to combine the road networks for the traffic volume and speed data sources, such that an estimate of traffic speed and traffic volume was available for each roadway segment in each urban area. The combination (also known as conflation) of the traffic volume and traffic speed networks was accomplished using geographic information systems (GIS) tools. The INRIX road network was chosen as the base network for the *2019 UMR*, and the volume estimates from HPMS were applied to each INRIX segment. The combined traffic count and speed data for each roadway segment were then used to develop several performance measures.

Step 3. Estimate Traffic Volumes for Shorter Time Intervals

The third step was to estimate passenger car and truck traffic volumes for 15-minute time intervals on each day of the week to match with the time periods in the speed data. A summary of the process used to divide the daily traffic volume into 15-minute time period volumes includes the following tasks (more detail is described below):

- A simple average of the 15-minute traffic speeds for the morning and evening peak periods was calculated.
- The percentage difference between the average peak period speed and the free-flow speed was calculated.
- The most congested period – morning or evening peak - was determined by the time period with the lower speeds. There is also a speed curve for locations where both peaks have approximately the same speed.
- Using the worst peak period speeds, the general level of congestion was determined by the amount of speed decline from the off-peak speeds. Road sections with little traffic congestion typically have higher percentages of daily traffic volume occurring in the peak, while higher congestion levels are usually associated with more volume in hours outside of the peak hours. The traffic volume estimates reflect this difference in volume pattern.
- Morning or evening peak; or approximately even peak speeds – The speed database has values for each direction of traffic and most roadways have one peak direction. This step identifies the time periods when the lowest speed occurs and selects the appropriate volume distribution curve (a higher volume was assigned to the peak period with the lower speed). Roadways with approximately the same congested speed in the morning and evening periods have a separate volume pattern; this pattern also has relatively high volumes in the midday hours.

- The traffic volume profiles developed from the national continuous count locations are shown in Exhibits A-1 to A-5.
- Traffic volumes were prepared for each day using an adjustment factor shown in Exhibit A-6.
- Separate 15-minute traffic volumes for trucks were created from the 15-minute traffic volume percentages shown in Exhibits A-7 to A-9.

Detailed Steps

Typical time-of-day traffic volume distribution profiles are needed to estimate 15-minute traffic flows from average daily traffic volumes. Previous analytical efforts (*4, 5*) have developed typical traffic profiles (the roadway traffic and inventory databases are used for a variety of traffic and economic studies). The 16 traffic distribution profiles shown in Exhibits A-1 through A-5 are considered to be very comprehensive, as they were developed from 713 continuous traffic monitoring locations in urban areas of 37 states. Traffic distribution profiles were developed for 16 different scenarios describing the following elements:

- Roadway class: assign using the HPMS road class
    - Freeway – access-controlled highways
    - Non-freeway – all other major roads and streets
- Day type: assign a volume profile for each day (Exhibit A-6)
    - Weekday (Monday through Friday)
    - Weekend (Saturday and Sunday)
- Traffic congestion level: assign using the peak-period speed reduction percentage calculated from the private-sector speed data. The peak-period speed reduction is calculated as follows:

  1) Calculate a simple average peak-period speed. Add all the morning and evening peak-period speeds and divide the total by the 32 15-minute periods in the eight peak hours. This is performed for each INRIX road segment (technically named a "TMC path") using speed data from 6 a.m. to 10 a.m. (morning peak period) and 3 p.m. to 7 p.m. (evening peak period).

  2) Use the INRIX reference speed as the low-volume condition baseline for congestion calculations.

  3) Calculate the peak-period speed reduction by dividing the average combined peak-period speed by the free-flow speed as shown in Equation A-1.

$$\begin{matrix}\text{Speed Reduction} \\ \text{Factor (\%)}\end{matrix} = \left(\frac{\text{Average Peak Period Speed}}{\text{Free flow Speed (10 p.m. to 5 a.m.)}}\right) \times 100 \qquad \text{(Eq. A-1)}$$

For Freeways (roads with a free-flow (baseline) speed more than 55 mph):
  - speed reduction factor ranging from 90% to 100% (no to low congestion)
  - speed reduction factor ranging from 75% to 90% (moderate congestion)
  - speed reduction factor less than 75% (severe congestion)

For Non-Freeways (roads with a free-flow (baseline) speed less than 55 mph):
  - speed reduction factor ranging from 80% to 100% (no to low congestion)
  - speed reduction factor ranging from 65% to 80% (moderate congestion)
  - speed reduction factor less than 65% (severe congestion)

- Directionality: Identify the appropriate curve in Exhibits A-1 to A-5 using the differences in peak period speed found in the INRIX speed dataset. The peak period speed differential is calculated as follows:

  1) Calculate the average morning peak period speed (6 a.m. to 10 a.m.) and the average evening peak period speed (3 p.m. to 7 p.m.)

  2) Calculate the difference between the morning and evening speeds. The lowest speed determines the "peak" direction. Any section where the difference in the morning and evening peak period speeds is 6 mph or less will be assigned to the even volume distribution in Exhibit A-5.

Exhibit A-1. Weekday Mixed-Traffic Distribution Profile for No to Low Congestion

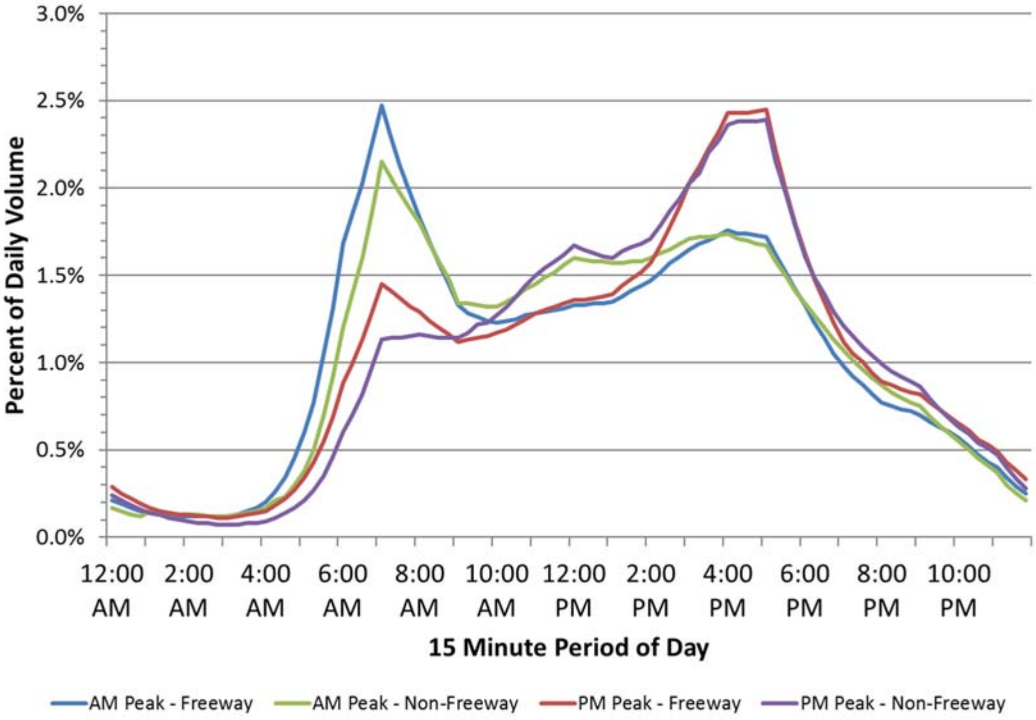


Exhibit A-2. Weekday Mixed-Traffic Distribution Profile for Moderate Congestion

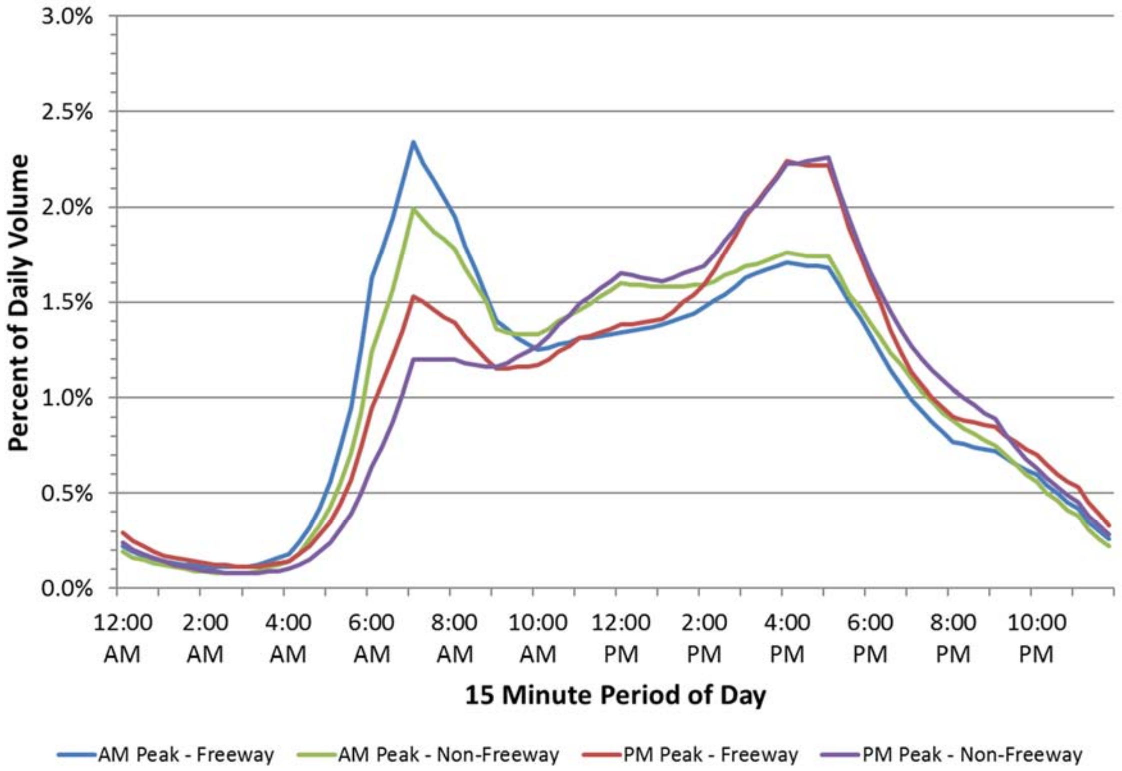


Exhibit A-3. Weekday Mixed-Traffic Distribution Profile for Severe Congestion

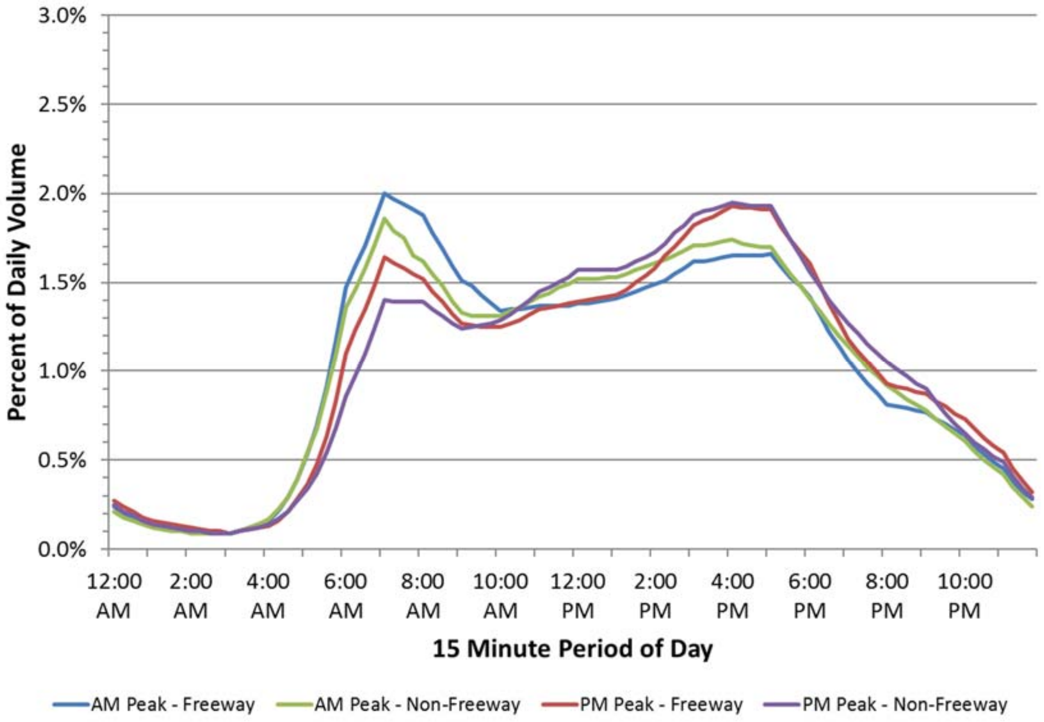


Exhibit A-4. Weekend Mixed-Traffic Distribution Profile

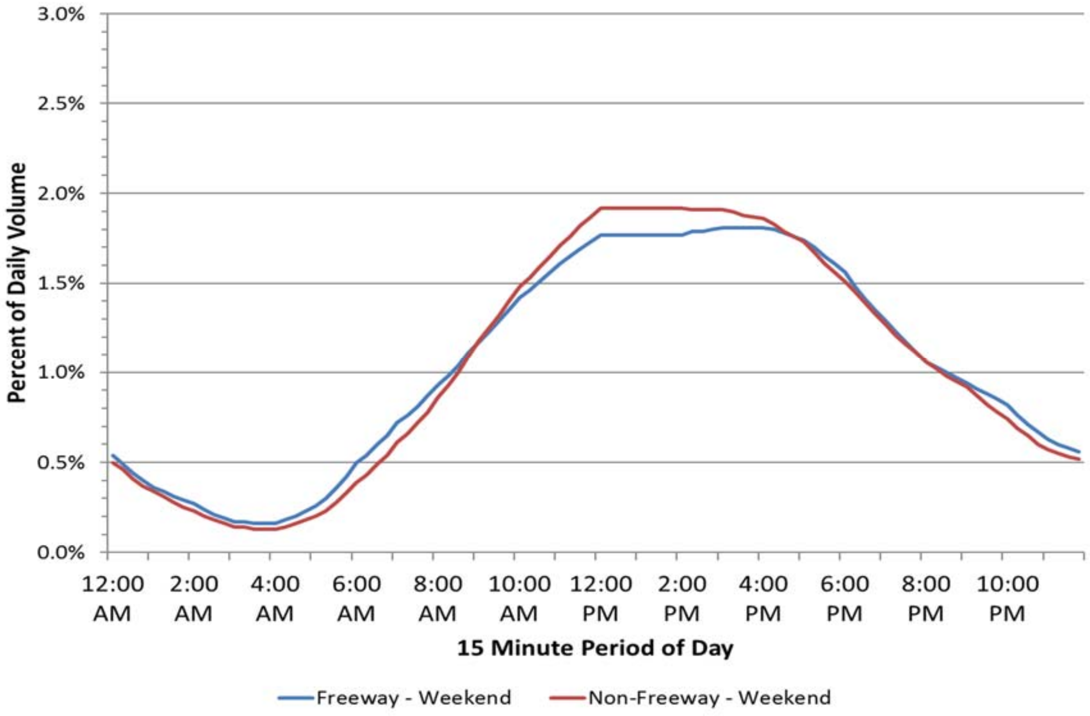
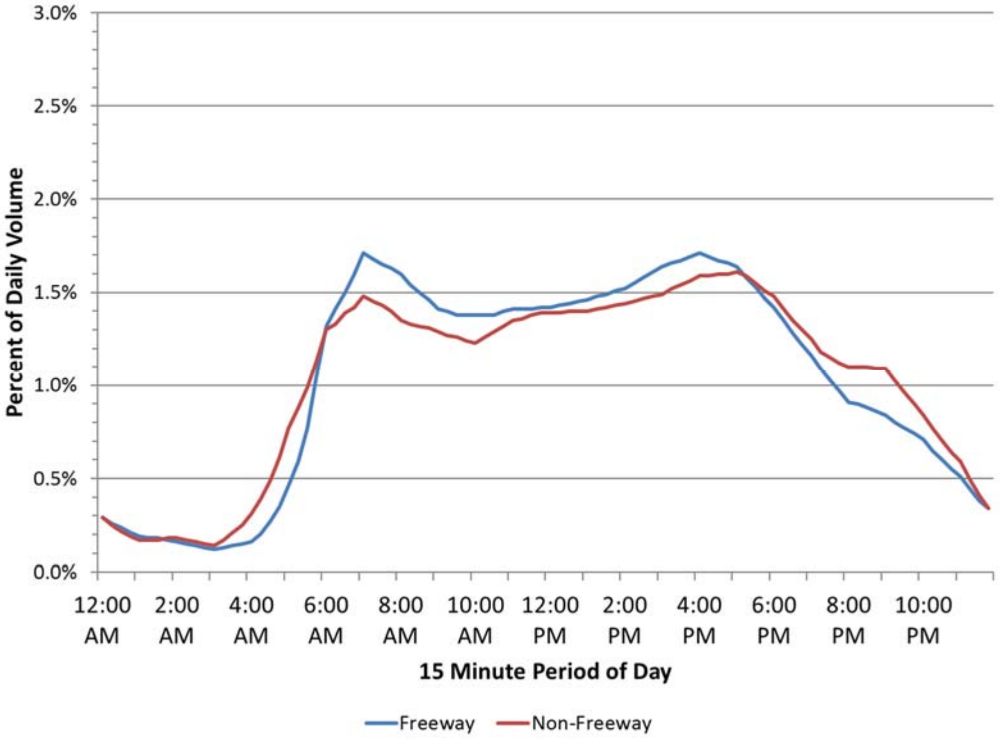


Exhibit A-5. Weekday Mixed-Traffic Distribution Profile for Severe Congestion and Similar Speeds in Each Peak Period



The final step is to apply the daily adjustment factor to the annual average volume. Exhibit A-6 illustrates the factors for the four day-of-week factors.

Exhibit A-6. Day of Week Volume Conversion Factors

Day of Week	Adjustment Factor (to convert average annual volume into day-of-week volume)
Monday to Thursday	+5%
Friday	+10%
Saturday	-10%
Sunday	-20%

Truck-Only Volume Profiles

The truck volume estimation process uses a method like the "mixed-vehicle" process to create 15-minute truck volumes from daily truck volumes. Much of the necessary information (e.g., facility type, day type, and time-of-day peaking) has already been determined in the mixed-vehicle volume process. The eight truck-only profiles used to create the 15-minute truck volumes are shown in Exhibits A-7 through A-9. The eight truck-only profiles account for the fact that truck volumes tend to peak at very different rates and times than do the mixed-vehicle traffic. Data from over 2,500 count stations in 36 states were used to develop the curves. The truck-only profiles are identical for all congestion levels. Exhibits A-7 through A-9 use the following scenarios (*6*):

- Roadway class: assign using the HPMS road class
    - Freeway – access-controlled highways
    - Non-freeway – all other major roads and streets
- Day type: assign a volume profile for each day type
    - Weekday (Monday through Friday)
    - Weekend (Saturday and Sunday)
- Directionality: peak traffic in the morning, peak traffic in the evening, approximately equal congestion in each direction

Step 4. Calculate Travel Time

The hourly speed and volume data were combined to calculate the total travel time for each 15-minute time period. The 15-minute volume for each segment was multiplied by the corresponding travel time to get a quantity of vehicle-hours; these were summed for all 24 hours for every road segment across the entire urban area.

Exhibit A-7. Weekday Freeway Truck-Traffic Distribution Profiles

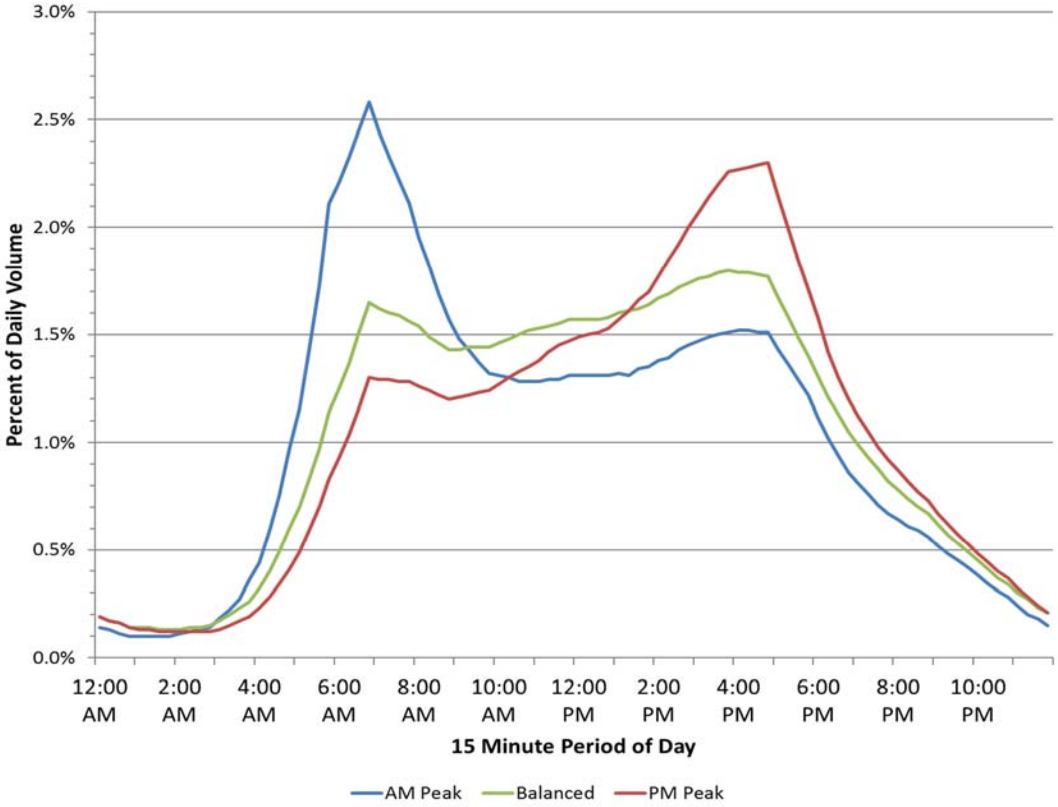


Exhibit A-8. Weekday Non-Freeway Truck-Traffic Distribution Profiles

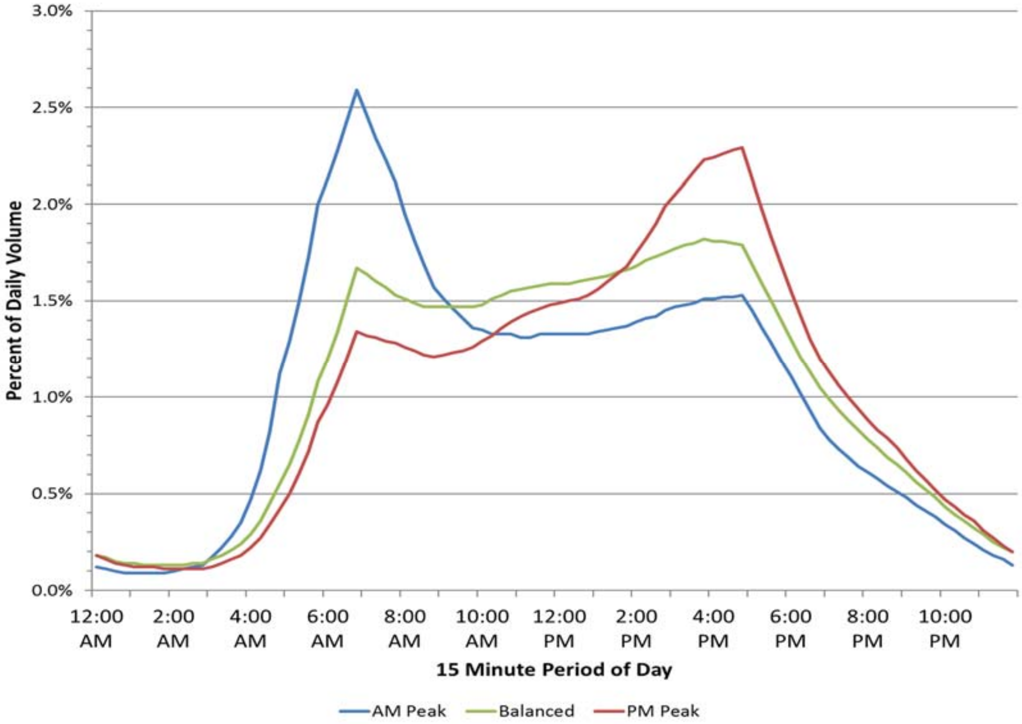
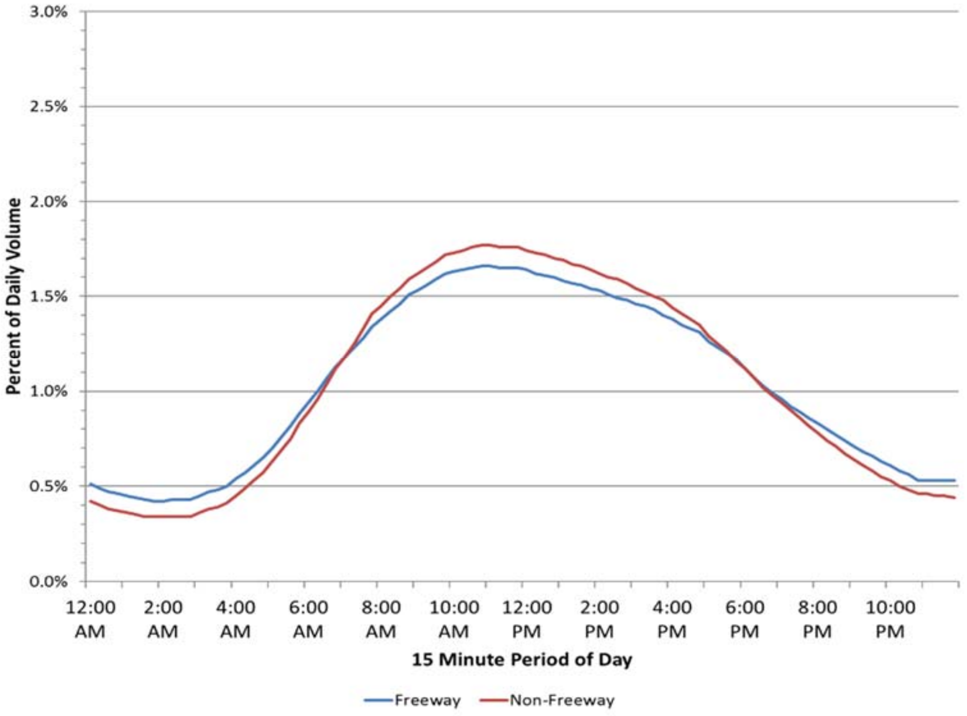


Exhibit A-9. Weekend Truck-Traffic Distribution Profiles



Step 5. Establish Free-Flow Travel Speed and Time

The calculation of congestion measures requires establishing a congestion threshold, such that delay is accumulated for any time period once the speeds are lower than, the congestion threshold. The INRIX reference speed is representative of the speed at low volume conditions (for example, 10 p.m. to 5 a.m.). This speed is relatively high, but varies according to the roadway design characteristics. An upper limit of 65 mph was placed on the freeway free-flow speed to maintain a reasonable estimate of delay; no limit was placed on the arterial street free-flow speeds.

Step 6. Estimate Speed Data Where Volume Data Had No Matched Speed Data

The *UMR* methodology analyzes travel on all freeways and arterial streets in each urban area. In some cases, the arterial streets are not maintained by the state DOTs and are not included in the roadway network GIS shapefile that is reported in HPMS (all roadway classes will eventually be added to the GIS roadway shapefiles by the state DOTs as mandated by FHWA). A technique for handling the unmatched sections of roadway was used in the *2019 UMR*. INRIX speed data covers approximately 98 percent of arterial streets across the U.S., while the freeway match percentage is more than 97 percent.

After the original conflation of the volume and speed networks in each urban area was completed, there were a small amount of unmatched volume sections of roadway and unmatched INRIX speed sections of roadway. After reviewing how much speed data were unmatched in each urban area, it was decided that unmatched data would be handled differently in urban areas over under one million in population versus areas over one million in population.

Areas Under One Million Population

The HPMS volume data records that had no matching traffic speed data were separated into freeway and arterial street sections within each urban area. The urban area HPMS road sections were organized by urban area county. If an urban area was located in two counties, the unmatched traffic volume data from each county would be analyzed separately. The volume data were then aggregated such that it was treated like one large traffic count for freeways and another for street sections.

The unmatched speed data were also separated by county. All of the speed data and free-flow speed data were then averaged together to create a speed profile for the unmatched freeway sections and unmatched street sections. The volume data and the speed data were combined (using the rank from highest volume and lowest speed sections) and Steps 1 through 5 were repeated for the unmatched data in these smaller urban areas.

Areas Over One Million Population

In urban areas with populations over one million, the unmatched data were handled in one or two steps depending on the area. The core counties of these urban areas (these include the counties with at least 15 to 20 percent of the entire urban area's vehicle-miles traveled) were treated differently because they tend to have more available unmatched speed data than some of the more suburban counties.

In the suburban counties (non-core), where less than 15 or 20 percent of the area's vehicle-miles of travel was in a particular county, the volume and speed data from those counties were treated the same as the data in smaller urban areas with populations below one million discussed earlier – Steps 1 through 5 were repeated for the non-core counties of these urban areas.

In each of the core counties, all of the unmatched HPMS sections were gathered and ranked in order of highest traffic density (vehicle-miles traveled per lane-mile) down to lowest for both freeways and arterial streets. These sections of roadway were divided into three groups. The top 25 percent of the lane-miles (highest traffic density) were grouped together into the first set. The next 25 percent were grouped into a second set and the remaining 50 percent of lane-miles were grouped into a third set.

Similar groupings were made with the unmatched speed data for each core county for both functional classes of roadway. The unmatched speed data roadway sections were ordered from most congested to least congested based on their Travel Time Index value. (The Travel Time Index was used instead of speed because the TTI is comparable across all roadway types). Since the roadway lane-miles for these sections were not available with the INRIX speed data, the listing was divided into the same splits as the traffic volume data (25/25/50 percent).

The volume data from each of the 3 groups were matched with the corresponding group of speed data and steps 1 through 5 were repeated for the unmatched data in the core counties.

Step 7. Calculate Congestion Performance Measures

Several mobility performance measures were calculated using the equations shown in the next section of this methodology once the 15-minute dataset of actual speeds, free-flow travel speeds and traffic volumes were prepared.

Calculation of the Congestion Measures

This section summarizes the methodology used to calculate many of the statistics shown in the *Urban Mobility Report* and is divided into three main sections containing information on the constant values, variables and calculation steps of the main performance measures of the mobility database. Some measures are not reported in the *2019 Urban Mobility Report*. In some cases, the measures below were last reported in the *2012 Urban Mobility Report (UMR)*; this is noted in the pages that follow.

Generally, the sections are listed in the order that they will be needed to complete all calculations.

Urban Area Definition

The Highway Performance Monitoring System dataset (2) uses urban areas as the geographic unit of study. The Census uses a general standard of 1000 persons per square mile density to determine an area within an urban area. This density standard results in areas that are more consistently urban and developed than the metropolitan statistical area, whose boundaries are always along county lines, and may include a significant amount of rural area.

National Constants

The congestion calculations utilize the values in Exhibit A-10 as national constants—values used in all urban areas to estimate the effect of congestion.

Exhibit A-10. National Congestion Constants for *2019 Urban Mobility Report*

Constant	Value
2017 Vehicle Occupancy	1.50 persons per vehicle
Average Cost of Time ($2017) (*7*)	$18.12 per person hour
Commercial Vehicle Operating Cost ($2017) (*7*)	$54.94 per vehicle hour
Total Travel Days (7x52)	364 days

Vehicle Occupancy

The average number of persons in each vehicle during peak period travel is 1.50 in 2017. This was increased from 1.25 over the period from 2009 to 2012 to reflect changes in travel behavior seen in the National Household Travel Survey (*3*).

Average Cost of Time

The 2017 value of person time is $18.29 per hour based on the national average wage rate (*7*).

Commercial Vehicle Operating Cost

Truck travel time and operating costs (excluding diesel costs) are valued at $54.94 per hour (*7*).

Working Days and Weeks

The delay from each day of the week is multiplied by 52 weeks to annualize the delay. Total delay for the year is based on 364 total travel days in the year.

Urban Area Variables

In addition to the national constants, four urbanized area or state-specific values were identified and used in the congestion cost estimate calculations.

Daily Vehicle-Miles of Travel

The daily vehicle-miles of travel (DVMT) is the average daily traffic (ADT) of a section of roadway multiplied by the length (in miles) of that roadway section. This allows the daily volume of all urban facilities to be presented in terms that can be used in cost calculations. DVMT was estimated for the freeways and arterial streets located in each urbanized study area. These estimates originate from the HPMS database and other local transportation data sources.

Population, Peak Travelers and Commuters

Population data were obtained from a combination of U.S. Census Bureau estimates and the Federal Highway Administration's Highway Performance Monitoring System (HPMS) (*2,8*). Estimates of peak-period travelers are derived from the National Household Travel Survey (NHTS) (*9*) data on the time-of-day when trips begin. *Any resident who begins a trip, by any mode, between 6 a.m. and 10 a.m. or 3 p.m. and 7 p.m. is a peak-period traveler*. Data are available for many of the major urban areas and a few of the smaller areas. Averages for areas of similar size are used in cities with no specific data. The traveler estimate for some regions (e.g., high tourism areas) may not represent all of the transportation users on an average day. The same NHTS data were also used to estimate the resident commuters who were traveling during the peak periods by private vehicle—a subset of all peak-period travelers.

Fuel Costs

Statewide average fuel cost estimates were obtained from daily fuel price data published by the American Automobile Association (AAA) (*10*). Values for gasoline and diesel are reported separately.

Truck Percentage

The percentage of passenger cars and trucks for each urban area was estimated from the Highway Performance Monitoring System dataset (*2*). The values are used to estimate congestion costs and are not used to adjust the speed, volume or roadway capacity values.

Variable and Performance Measure Calculation Descriptions

The major calculation products are described in this section. In some cases, the process requires the use of variables described elsewhere in this methodology.

Travel Delay

The best measure of the size of the congestion problem is the annual travel delay (in person-hours). This measure combines the intensity of congestion (for example, slow speeds) on any section of road with a magnitude element (the amount of people suffering that congestion). For example, a four-lane freeway can operate at the same speed as a 10-lane freeway. But the higher volume on the 10-lane freeway will mean it has more delay and, thus, is a bigger problem for the region.

Most of the basic performance measures presented in the *2019 Urban Mobility Report* are developed in the process of calculating travel delay. The travel delay calculations are greatly simplified with the INRIX speed data; annual average speed data reflects both recurring (or usual) delay and incident delay (crashes, vehicle breakdowns, etc.). The delay calculations are performed at the individual roadway section level and for each 15-minute period of the average day of the week. Depending on the application, the delay can be aggregated into summaries such as weekday peak period, weekend, weekday off-peak period, etc. Any observed speed faster than the free-flow speed is changed to the free-flow speed so that delay is zero, rather than providing a ‘delay credit’ (due to very fast average speeds) to the calculation. Equation A-2 illustrates the daily vehicle-hours of delay calculation.

$$\begin{matrix}\text{Daily Vehicle-Hours}\\ \text{of Delay}\end{matrix} = \left(\frac{\begin{matrix}\text{Daily Vehicle-Miles}\\ \text{of Travel}\end{matrix}}{\text{Speed}}\right) - \left(\frac{\begin{matrix}\text{Daily Vehicle-Miles}\\ \text{of Travel}\end{matrix}}{\text{Free-Flow Speed}}\right) \qquad \text{(Eq. A-2)}$$

Annual Person Delay

This calculation is performed to expand the daily vehicle-hours of delay estimates for freeways and arterial streets to a yearly estimate in each urban area. To calculate the annual person-hours of delay, multiply each day-of-the-week delay estimate by the average vehicle occupancy (1.50 persons per vehicle) and by 52 weeks per year (Equation A-3), and sum the totals for all seven days of the week.

$$\begin{array}{c}\text{Annual Person-Hours}\\ \text{of Delay for}\\ \text{Each Day of Week}\end{array} = \begin{array}{c}\text{Average Day Vehicle-Hours}\\ \text{of Delay on}\\ \text{Frwys and Arterial Streets}\end{array} \times \text{52 Weeks} \times \begin{array}{c}\text{1.50 Persons}\\ \text{per Vehicle}\end{array} \qquad \text{(Eq. A-3)}$$

Annual Delay per Auto Commuter

Annual delay per auto commuter is a measure of the extra travel time endured throughout the year by auto commuters who make trips during the peak period. The procedure used in the *Urban Mobility Report* applies estimates of the number of people and trip departure times during the morning and evening peak periods from the National Household Travel Survey (*9*) to the urban area population estimate to derive the average number of auto commuters during the peak periods (*11*).

The delay calculated for each commuter comes from delay during peak commute times and delay that occurs during other times of the day. All of the delay that occurs during the peak hours of the day (6:00 a.m. to 10:00 a.m. and 3:00 p.m. to 7:00 p.m.) is assigned to the pool of auto commuters. The delay that occurs outside of the peak period is assigned to the entire population of the urban area. Equation A-4 shows how the delay per auto commuter is calculated. The reason that the off-peak delay is also assigned to the commuters is that their trips are not limited to peak driving times; they also contribute to the delay that occurs during other times of the weekdays and the weekends.

$$\begin{array}{c}\text{Delay per}\\ \text{Auto Commuter}\end{array} = \left(\frac{\text{Peak Period Delay}}{\text{Auto Commuters}}\right) + \left(\frac{\text{Remaining Delay}}{\text{Population}}\right) \qquad \text{(Eq. A-4)}$$

Travel Time Index

The Travel Time Index (TTI) compares peak period travel time to low-volume travel time. The Travel Time Index includes both recurring and incident conditions and is, therefore, an estimate of the conditions faced by urban travelers. The TTI indicates the amount of extra time for any trip. For example, a TTI value of 1.40 indicates a 20-minute trip in the off-peak will take 28 minutes in the peak.

Equation A-5 illustrates the ratio used to calculate the TTI. The ratio has units of time divided by time and the Index, therefore, has no units. This “unitless” feature allows the Index to be used to compare trips of all lengths.

The Travel Time Index is calculated by comparing total travel time to the free-flow travel time (Equation A-5). The index can also be calculated by dividing the total of delay and low-volume travel time by the low volume travel time (Equation A-6).

$$\text{Travel Time Index} = \frac{\text{Peak Travel Time}}{\text{Low Volume Travel Time}} \qquad \text{(Eq. A-5)}$$

$$\text{Travel Time Index} = \frac{\text{Delay Time} + \text{Low Volume Travel Time}}{\text{Low Volume Travel Time}} \qquad \text{(Eq. A-6)}$$

Calculation Note: The change in Travel Time Index values is computed by subtracting 1.0 from all the TTI values so that the resulting values represent the change in extra travel time rather than the change in the numerical TTI values. For example, the increase in extra travel time from a TTI of 1.25 to 1.50 is 100 percent (extra travel time of 50 percent compared to 25 percent).

Commuter Stress Index

Most of the road and public transportation network operates with much more volume or ridership (and more congestion) in one direction during each peak period. Averaging the conditions for both directions in both peaks (as with the Travel Time Index) provides an accurate measure of road congestion, but does not always match the experience of the majority of commuters. The CSI measure combines the travel speed from the direction with the most congestion in each peak period to illustrate the conditions experienced by the commuters traveling in the predominant directions (for example, inbound from suburbs in the morning and outbound to the suburbs in the evening). The calculation is conducted with the Travel Time Index formula, but only for the peak directions. Thus, the CSI is more indicative of the work trip experienced by each commuter on a daily basis.

Planning Time Index (Freeway Only)

The Planning Time Index (PTI) is based on the idea that travelers want to be on-time for an important trip 19 out of 20 times; so one would be late to work only one day per month (on-time for 19 out of 20 work days each month). For example, a PTI value of 1.60 indicates that a traveler should allow 32 minutes to make an important trip that takes 20 minutes in low traffic volumes (1.60 x 20). The PTI values in Table 3 of the 2019 UMR are for freeways only.

The PTI is the 95th percentile travel time relative to the free-flow travel time as shown in Equation A-7. The PTI calculation uses trips on the INRIX average link system (the XD Network) along with a process developed to estimate corridor travel time reliability from link-level data (12).

$$\begin{matrix}\text{Planning Time} \\ \text{Index (PTI)}\end{matrix} = \frac{\begin{matrix}\text{95th Percentile Travel Time} \\ \text{(minutes)}\end{matrix}}{\begin{matrix}\text{Free-Flow Travel Time} \\ \text{(minutes)}\end{matrix}} \qquad \text{(Eq. A-7)}$$

Exhibit A-11 illustrates a distribution of travel times for a morning commute. Travel times can vary over a calendar year; the extreme cases usually have identifiable causes. It also quantifies and illustrates the relationship between the free-flow travel time, average travel time, 80th percentile travel time (e.g., the worst travel day of the week), and 95th percentile travel time.

The PTI calculation measures the trip reliability experience of a traveler; this is a slightly different approach than used with the average measures. If the analyst computes a PTI for each link as if it is an "average measure," and then combine the link values, the results show unrealistically large PTI values. This is because for many 95th percentile travel time events, a traveler will not experience this "worst day of the month" for ***every link*** that makes up the route. (A peak period crash slows traffic more than usual until a driver passes the collision spot, but then speeds are faster than typical rush hour speeds after that).

The Urban Mobility Report uses a procedure that reduces the resource-intensive roadway segmentation process (*12*).

- The speeds for each 15-minute period during the eight peak hours of the five work days are ranked from worst to best for each freeway segment (a total of 160 values).
- The 95th percentile worst value (number 152 of the 160) is chosen to represent that road segment.
- The regional average was obtained by weighting each segment's 95th percentile value by the peak period vehicle-miles of travel on that segment; national average calculations also use peak period vehicle-miles of travel.

Time of Congestion

Providing the time when congestion might be encountered is one method of explaining both the congestion problem and illustrating some of the solutions. The measure uses times of day when each road direction speed is below 75 percent of the street free-flow speed or 80 percent of the freeway free-flow speed (for example, below 48 mph on a 60 mph freeway). The times are calculated using 15-minute increments.

Wasted Fuel

This methodology uses data from the United States Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) model (*13*). MOVES is a model developed by the EPA to estimate emissions from mobile sources. Researchers primarily used the emissions estimating process in MOVES to obtain vehicle fleet composition and then estimate fuel consumption.

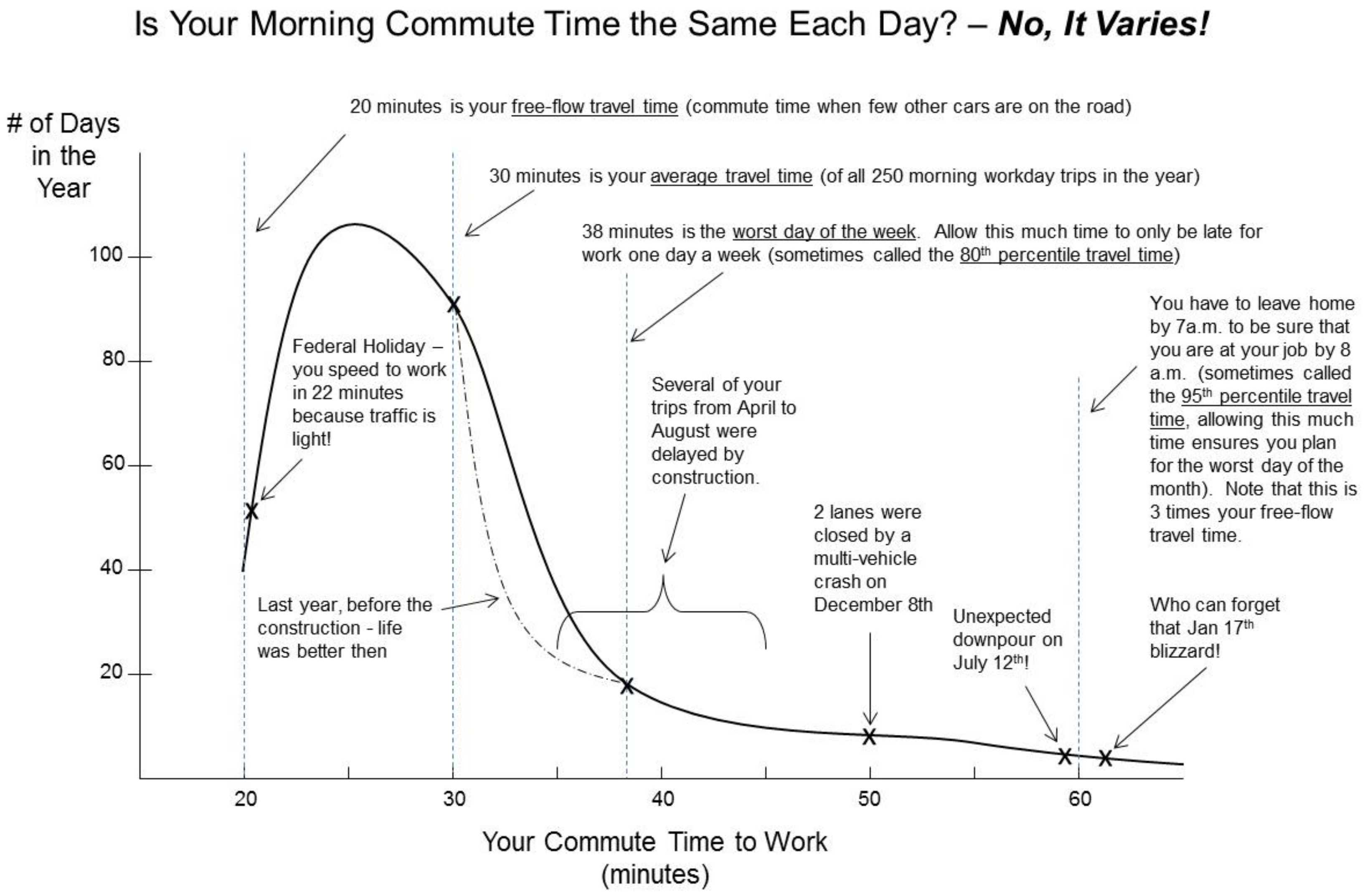
The methodology uses data from three primary data sources: 1) the FHWA's HPMS (*2*), 2) INRIX traffic speed data (*1*), and 3) EPA's MOVES model (*13*). Five steps are implemented in the methodology:

1. Group Similar Urban Areas – considers seasonal variations and the percentage of travel that occurs with the air conditioner "on," which affects fuel consumption.
2. Obtain CO_2 Emission Rates for Urban Area Group – emission rates (in grams per mile) were created for each of the 14 groups from Step #1.
3. Fit Curves to CO_2 Emission Rates – curves were created relating speed and emission rates from Step #2.
4. Calculate Fuel Consumption During Congested Conditions – The CO_2 emissions were estimated and then used, along with speed and volume data, to calculate gas and diesel fuel consumption.
5. Estimate the Fuel Consumption During Free-flow Conditions, and Estimate Wasted Fuel Due to Congestion – repeat the calculations from Step #4 using the speeds when few cars are on the road. The low-volumes condition results are subtracted from congested-condition results to obtain fuel wasted due to congestion.

Step 1. Group Similar Urban Areas

Traveling with the air conditioner turned "on" lowers fuel efficiency; locations with warmer climates typically have higher fuel consumption rates because more travel occurs with the air conditioner turned "on." It was not feasible to use individual rates for every United States county, so researchers instead created representative climate-type groups to account for the impact of climate. To create these groups, TTI researchers grouped the *UMR* urban areas based on similar seasonal "AconFraction" (ACF) values – a term used in the MOVES model 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."

Exhibit A-11. Example of Morning Commute Travel Time Distribution



Is Your Morning Commute Time the Same Each Day? – ***No, It Varies!***

20 minutes is your free-flow travel time (commute time when few other cars are on the road)

30 minutes is your average travel time (of all 250 morning workday trips in the year)

38 minutes is the worst day of the week. Allow this much time to only be late for work one day a week (sometimes called the 80th percentile travel time)

You have to leave home by 7a.m. to be sure that you are at your job by 8 a.m. (sometimes called the 95th percentile travel time, allowing this much time ensures you plan for the worst day of the month). Note that this is 3 times your free-flow travel time.

Federal Holiday – you speed to work in 22 minutes because traffic is light!

Several of your trips from April to August were delayed by construction.

2 lanes were closed by a multi-vehicle crash on December 8th

Last year, before the construction - life was better then

Unexpected downpour on July 12th!

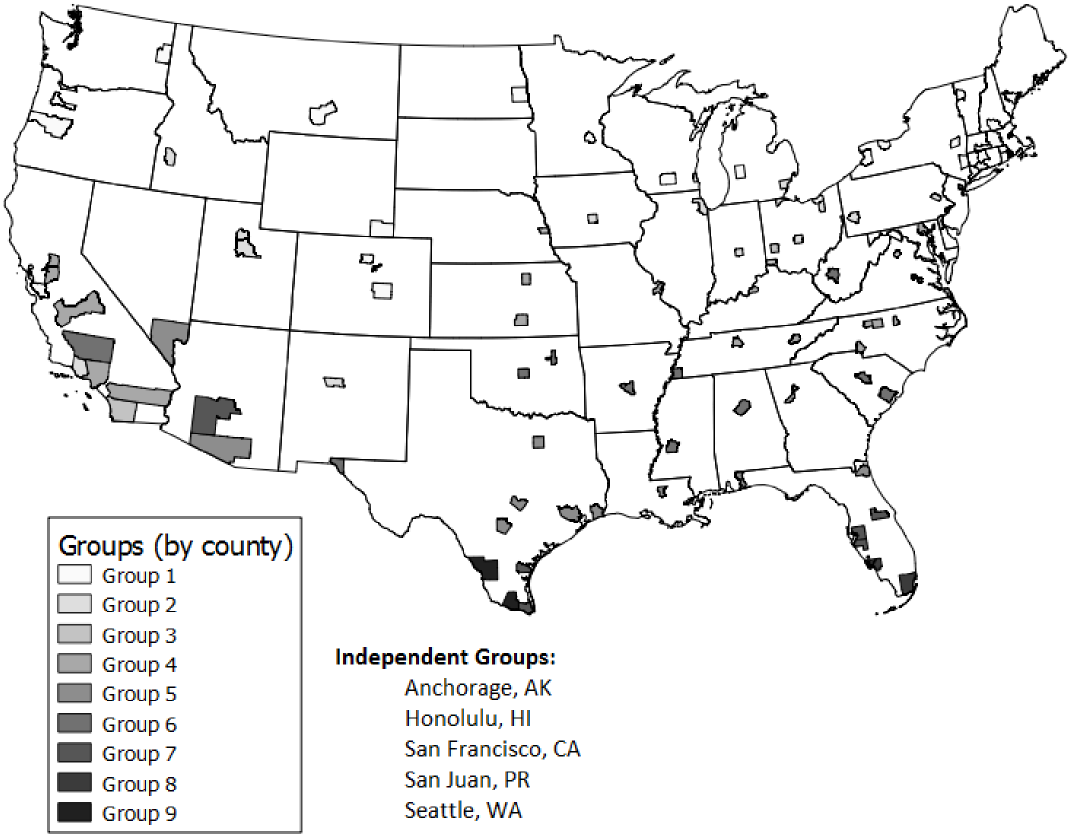
Who can forget that Jan 17th blizzard!

Because ACF is a factor of temperature and relative humidity, researchers collected hourly temperature and relative humidity data for an urban area county within TTI's *UMR* from the MOVES database. Researchers collected the climate data by county, rather than urban area (or city), because the MOVES database only has climate data available by county. For simplicity, one county per urban area (or city) was selected because the climate differences between adjacent counties were not significant.

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 hourly temperature and relative humidity data from MOVES. They used this hourly data to calculate hourly ACFs, which they then weighted by hourly traffic volume data from MOVES 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.

To group the counties (or urban areas) based on similar seasonal climates, researchers used temperature and relative humidity scatter plots to visually identify which counties had similar climates. To refine the tentative groups, researchers previewed each group's average seasonal ACF values and removed any counties that differed from the group averages. The standard to which researchers allowed a county to vary from the average was a maximum of 10 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 seasonal ACF values with any group, so they retained their original values and were calculated individually. Exhibit A-12 shows the groupings of urban areas.

Exhibit A-12. The Continental United States with Each County Shaded by Climate Group



Step 2. Obtain CO_2 Emission Rates for Urban Area Group

TTI researchers used MOVES to produce emission rates for different vehicle types and locations, and in later steps used the emissions to estimate fuel consumption. Researchers used the emission rates by combining them with volume and speed data to incorporate CO_2 emissions as described in Step 4. 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*.

MOVES has many different vehicle classifications, but TTI's *UMR* has just three broad categories: light-duty vehicles, medium-duty trucks, and heavy-duty trucks. To obtain emission rates, researchers selected MOVES vehicle types with the highest percentage of vehicle-miles of travel (VMT) within each *UMR* vehicle type.

TTI researchers used a different method for light-duty vehicles because not all "SourceTypes" within this classification have similar emission and fuel consumption rates. The light-duty vehicle classification consists of passenger cars, passenger trucks, and light commercial trucks. Researchers weighted two different "SourceTypes" – passenger cars (59%) and passenger trucks (41%) - to create one set of emission and fuel consumption rates for the light-duty vehicle type. Researchers used the passenger truck "SourceType" to supply the rates for both passenger trucks and light commercial trucks because passenger trucks account for more VMT and the rates are similar.

TTI researchers selected a fuel type for each vehicle type based on fuel usage data in MOVES. Given that light commercial trucks account for a small portion of the light-duty vehicle population, researchers used the gasoline rates to represent all light-duty vehicle fuel usage. Researchers used the diesel rates to represent fuel usage for medium-duty trucks and heavy-duty trucks.

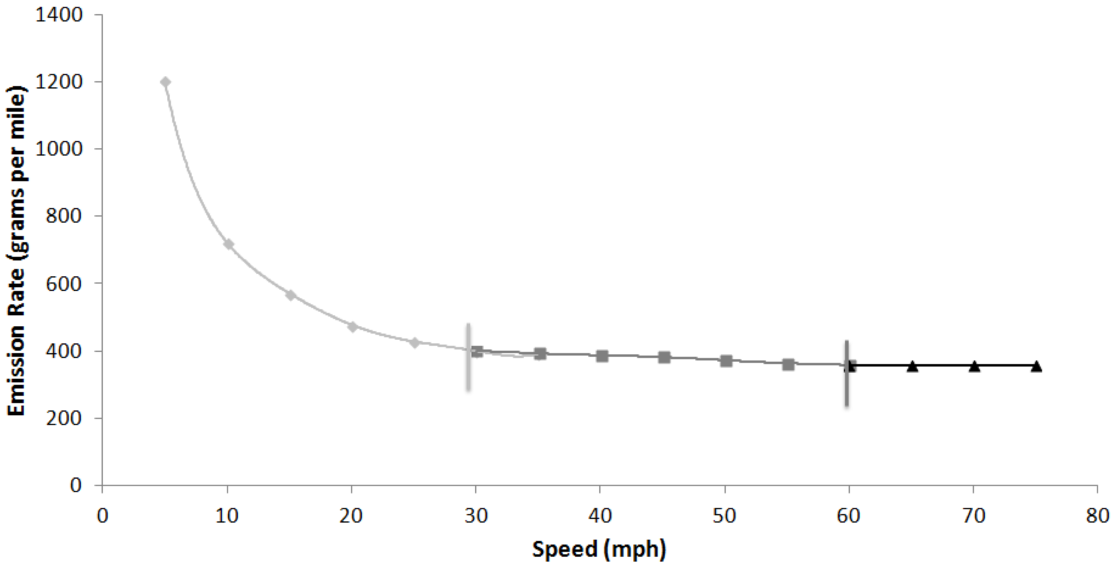
TTI researchers ran MOVES for the vehicle types, fuel types, and road types to obtain emission rates in grams per mile. Fuel consumption is calculated in Step #4.

Step 3. Fit Curves to CO2 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 and, subsequently, fuel consumption.

MOVES produces emission rates for speeds from 2.5 to 75 mph in increments of five (except for 2.5 mph). Using Microsoft Excel®, researchers initially constructed speed-dependent emission factor curves by fitting one to three polynomial curves (spline) to the emission rate data from MOVES (see Exhibit A-13 example). Researchers compared emission rates generated with the polynomial spline to the underlying MOVES-generated emission rates.

Exhibit A-13. Example Light-duty Vehicle Emission Rate Curve-set Showing Three Emission Rate Curves



The polynomial spline that was deemed sufficiently accurate by researchers was a two-segment spline using one 6th-order polynomial for the 0 to 30 mph segment and another 6th-order polynomial for the 30 to 60 mph segment. Speeds over 60 used the emission rates of the 30 to 60 mph polynomial at 60 mph. Note that these speeds are averages, and variability with speed (slope) is negligable for speeds greater than 60 mph. Lower average speeds have higher speed fluctations (i.e., more stop-and-go), which causes higher emission and fuel consumption rates. 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.

Step 4. Calculate Fuel Consumption During Congested Conditions

To calculate fuel consumption during all travel periods, researchers combined the emission rates with hourly speed data supplied by INRIX (1), hourly volume data supplied by Highway Performance Monitoring System (HPMS) (2) and relationships between emissions and fuel consumption rates.

The volume and speed data are structured for each 15-minutes for each day of the week. This means there will be a separate speed and volume value for light-duty vehicles, medium-duty trucks, and heavy-duty trucks for each 15-minutes of each day of the week. To account for the seasonal climate changes, researchers calculated separate emission rates for each season.

After calculating the emission rates, researchers combined these emission rates with the volume data to calculate emissions for each season. Lastly, researchers summed the emissions of each season, vehicle type, and day of the week to produce the annual emission estimates.

Researchers used factors that relate CO_2 emissions from a gallon of gasoline (8,887 grams CO_2 per gallon) and diesel (10,180 grams CO_2 per gallon) with the vehicle types and associated fuel types to estimate fuel consumption.

Step 5. Estimate Fuel Consumption and Wasted Fuel Due to Congestion

Researchers repeated the calculations in Step #4 using the speeds when few cars are on the road to estimate low-volume fuel consumption. To estimate wasted fuel due to congestion, researchers subtracted the fuel consumed during free-flow from the fuel used during congested conditions (Equation A-9).

$$\begin{array}{c}\text{Annual Fuel}\\\text{Wasted in Congestion}\end{array} = \begin{array}{c}\text{Annual Fuel}\\\text{Consumed in}\\\text{Congestion}\end{array} - \begin{array}{c}\text{Annual Fuel That}\\\text{Would be Consumed}\\\text{in Free-Flow Conditions}\end{array} \qquad \text{(Eq. A-9)}$$

A Word about Assumptions in the Fuel Methodology

A number of national-level assumptions are used as model inputs (e.g., volume, speed, vehicle composition, fuel types). The assumptions allow for a relatively simple and replicable methodology for each urban area. More detailed and localized inputs and analyses are conducted by local or state agencies; those are better estimates of emissions and fuel consumption.

The analysis is based upon the urban area boundaries which are a function of state and local agency updates. Localized CO_2 inventory analyses will likely include other/all roadways (including collectors and local streets) and will likely have a different area boundary (e.g., often based upon metropolitan statistical area).

Finally, Step 5 uses the difference between actual congested-condition **and** free-flow fuel consumption. According to the methodology, this difference is the “wasted” fuel due to congestion. Some may note that if the congestion were not present, speeds would be higher, vehicle throughput would increase, and this would generally result in lower fuel consumption – thus the methodology could be seen as overestimating the wasted fuel due to congestion. Similarly, if there is substantial induced travel demand due to the lack of congestion (e.g., urban residents take a different job or shop at a different store that is more easily traveled to because of lower congestion), it is possible that more fuel could be consumed than during congested conditions because of more cars traveling at free-flow. While these are notable considerations and may be true for specific corridors, the *UMR* analysis is at the areawide level and overestimating and underestimating will approximately balance out over the urban area. Therefore, the methodology provides a credible method for consistent and replicable analysis across all urban areas.

Total Congestion Cost and Truck Fuel Cost

Two cost components are associated with congestion: delay cost and fuel cost. These values are directly related to the travel speed calculations. The following sections and Equations A-10 through A-14 illustrate the calculation of the cost of delay and fuel effects of congestion.

Passenger Vehicle Delay Cost

Delay cost is an estimate of the value of lost time in passenger vehicles in congestion. Equation A-10 shows the passenger vehicle delay cost calculation.

$$\begin{array}{c}\text{Annual Psgr-Veh}\\ \text{Delay Cost}\end{array} = \begin{array}{c}\text{Daily Psgr Vehicle}\\ \text{Hours of Delay}\\ \text{(Eq. A-4)}\end{array} \times \begin{array}{c}\text{Value of}\\ \text{Person Time}\\ \text{(/hour)}\end{array} \times \begin{array}{c}\text{Vehicle}\\ \text{Occupancy}\\ \text{(1.50 pers/vehicle)}\end{array} \times \begin{array}{c}\text{Annual}\\ \text{Factor 52 weeks x 7 days}\end{array} \qquad \text{(Eq. A-10)}$$

Passenger Vehicle Fuel Cost

Fuel cost due to congestion is calculated for passenger vehicles in Equation A-11. This is done by associating the wasted fuel, the percentage of passenger vehicles in the vehicle mix, and the fuel costs.

$$\begin{array}{c}\text{Annual Psgr} - \text{Vehicle}\\ \text{Fuel Cost}\end{array} = \begin{array}{c}\text{Daily Fuel}\\ \text{Wasted}\\ \text{(Eq. A–13)}\end{array} \times \begin{array}{c}\text{Percent of}\\ \text{Passenger}\\ \text{Vehicles}\end{array} \times \begin{array}{c}\text{Gasoline}\\ \text{Cost}\end{array} \times \begin{array}{c}\text{Annual}\\ \text{Conversion Factor}\end{array} \qquad \text{(Eq. A-11)}$$

Truck or Commercial Vehicle Delay Cost

The truck delay cost is an estimate of the value of lost time in commercial vehicles and the increased operating costs of commercial vehicles in congestion. Equation A-12 shows how to calculate the commercial vehicle delay costs that result from lost time.

$$\begin{array}{c}\text{Annual Comm-Veh}\\ \text{Delay Cost}\end{array} = \begin{array}{c}\text{Daily Comm Vehicle}\\ \text{Hours of Delay}\\ \text{(Eq. A-4)}\end{array} \times \begin{array}{c}\text{Value of}\\ \text{Comm Vehicle Time}\\ \text{(\$54.94 / hour)}\end{array} \times \begin{array}{c}\text{Annual}\\ \text{Factor}\\ \text{52 weeks x 7 days}\end{array} \qquad \text{(Eq. A-12)}$$

Truck or Commercial Vehicle Fuel Cost

Fuel cost due to congestion is calculated for commercial vehicles in Equation A-13. This is done by associating the wasted fuel, the percentage of commercial vehicles in the vehicle mix, and the fuel costs.

$$\begin{array}{c}\text{Annual Commerical}\\ \text{Vehicle Fuel Cost}\end{array} = \begin{array}{c}\text{Daily Fuel}\\ \text{Wasted}\\ \text{(Eq. A–14)}\end{array} \times \begin{array}{c}\text{Percent of}\\ \text{Commercial}\\ \text{Vehicles}\end{array} \times \begin{array}{c}\text{Diesel}\\ \text{Cost}\end{array} \times \begin{array}{c}\text{Annual}\\ \text{Conversion Factor}\end{array} \qquad \text{(Eq. A-13)}$$

Total Congestion Cost

Equation A-14 combines the cost due to travel delay and wasted fuel to determine the annual cost due to congestion resulting from incident and recurring delay.

$$\begin{array}{c}\text{Annual Cost}\\ \text{Due to}\\ \text{Congestion}\end{array} = \left(\begin{array}{c}\text{Annual Passenger}\\ \text{Vehicle Delay Cost}\\ \text{(Eq. A-10)}\end{array} + \begin{array}{c}\text{Annual Passenger}\\ \text{Fuel Cost}\\ \text{(Eq. A-11)}\end{array}\right) + \begin{array}{c}\text{Annual Comm}\\ \text{Veh Delay Cost}\\ \text{(Eq. A-12)}\end{array} + \begin{array}{c}\text{Annual Comm}\\ \text{Veh Fuel Cost}\\ \text{(Eq A-13)}\end{array} \qquad \text{(Eq. A-14)}$$

Number of "Rush Hours" (Congested Hours), Congested Lane-Miles, and Congested VMT

The number of "rush hours" (congested hours) computation uses the INRIX XD Network directional roadway data. The 15-minute average speeds in each roadway travel direction during the peak eight hours are evaluated for all five weekdays. If any 15-minute speed is less than 80 percent of the uncongested speed on a freeway, or less than 75 percent of the uncongested speed on an arterial, the section of road is marked as "congested" for that 15-minute period (15). If 30 percent of the urban area freeway system is congested, the 15-minute period is considered congested (16). Similarly, if 50 percent of the arterial road sections across the urban area are congested, the associated 15-minute period is considered congested. The number of congested 15-minute periods across the urban area (freeway or arterial) are summed to determine the urban area congested hours ("rush hours").

Congested lane-miles are similarly identified – those with a speed below a congestion threshold (80 percent/75 percent of uncongested speed on freeways/arterials). These lane-miles are summed for those time periods across the urban area separately for freeways and arterials. Congested vehicle-miles of travel are also summed for each 15-minute period for urban area freeways and arterial streets. These summations of peak period vehicle-miles of travel and lane-miles are compared with the peak-period totals to determine the percent that is congested.

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