APPENDIX A
Methodology for the 2009 Urban Mobility Report

The data source for most of the calculations is the Highway Performance Monitoring System from the Federal Highway Administration (*1*). A detailed description of that dataset can be found at: http://www.fhwa.dot.gov/policy/ohpi/hpms/index.htm. The procedures used in the 2009 Urban Mobility Report have been developed by the Texas 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 other previous measures. All the measures and many of the input variables for each city of every year are provided in a spreadsheet that can be downloaded at http://mobility.tamu.edu/ums/congestion_data/.

This appendix summarizes the methodology utilized to calculate many of the statistics shown in the Urban Mobility Report. The methodology 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.

1. **National Constants**
2. **Urban Area Constants and Inventory Values**
3. **Variable and Performance Measure Calculation Descriptions**
    1) Roadway Congestion Index
    2) Percent of Daily Travel in Congested Conditions
    3) Travel Speed
    4) Travel Delay
    5) Incident-Related Travel Delay
    6) Annual Person Delay
    7) Travel Time Index
    8) Fuel Economy
    9) Wasted Fuel
    10) Congestion Cost
    11) Percent of Congested Cost
    12) Lane-Miles and Passenger Trips Required to Hold Congestion Constant

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

NATIONAL CONSTANTS

The congestion calculations utilize the values in Exhibit A-1 as national constants—values used in all urban areas to estimate the effect of congestion.

Exhibit A-1. National Congestion Constants for 2009 Urban Mobility Report

Constant	Value
Vehicle Occupancy	1.25 persons per vehicle
Working Days	250 days per year
Percent of Daily Travel in Peak Periods 6 – 10 a.m. 3 -7 p.m.	50 percent
Average Cost of Time ($2007)*	$15.47 per person hour[1]
Commercial Vehicle Operating Cost ($2007)	$102.12 per vehicle hour[1, 2]

[1] Adjusted annually using the Consumer Price Index.

[2] Adjusted periodically using industry cost and logistics data.

*Source: (Reference *7,8*)

Vehicle Occupancy

The average number of persons in each vehicle during peak period travel is 1.25.

Working Days

Cost calculations were based on 250 working days per year.

Percent of Daily Travel in the Peak Period

The hours of the day outside of the peak-period are typically uncongested. Even though some sections of road in larger areas can be congested for 10 to 12 hours of the day, the Mobility Report methodology only examines the peak-periods—estimated as 6:00 to 10:00 a.m. and 3:00 to 7:00 p.m. These time periods are estimated to include 50 percent of the daily vehicle travel. The rationale for eliminating the remainder of the day is that an area's mobility statistics should not be "credited" for having an uncongested system at 3:00 a.m.

Average Cost of Time

The 2007 value of person time used in the report is $15.47 per hour based on the value of time, rather than the average or prevailing wage rate (*7*).

Commercial Vehicle Operating Cost

Truck travel time is valued at $102.12 per hour (*8*).

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 section of roadway. This allows the daily volume of all urban facilities to be presented in terms that can be utilized in cost calculations. DVMT was estimated for the freeways and principal arterial streets located in each urbanized study area. These estimates originate from the HPMS database and other local transportation data sources.

Population and Peak Travelers

Population data were obtained from a combination of U.S. Census Bureau estimates and the Federal Highway Administration's Highway Performance Monitoring System (HPMS) (*1,9*). Estimates of peak period travelers are derived from the National Household Travel Survey (*10*) 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 counted as 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, specifically high tourism areas, may not represent all of the transportation users on an average day.

Fuel Costs

Statewide average fuel cost estimates were obtained from daily fuel price data published by the American Automobile Association (AAA) (*11*). Values for different fuel types used in motor vehicles, i.e., diesel and gasoline, did not vary enough to be reported separately.

Truck Percentage

The percentage of passenger cars and trucks for each urban area was estimated from the Highway Performance Monitoring System dataset (*1*). The values are used to estimate congestion costs and are not used to adjust the capacity or vehicle speed estimating procedures.

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 Appendix A.

Roadway Congestion Index

Early versions of the Urban Mobility Report used the roadway congestion index as a primary measure. While other measures that define congestion in terms of travel time and delay have replaced the RCI, it is still used as part of the calculation of delay. The RCI measures the density of traffic across the urban area using generally available data. Urban area estimates of vehicle-miles of travel (VMT) and lane-miles of roadway (Ln-Mi) are combined in a ratio using the amount of travel on each portion of the system. The combined index measures conditions on the freeway and arterial street systems according to the amount of travel on each type of road (Eq. A-1). This variable weighting factor allows comparisons between areas that carry different percentages of regional vehicle travel on arterial streets and freeways. The resulting ratio indicates an undesirable level of areawide congestion if the index value is greater than or equal to 1.0.

The traffic density ratio (VMT per lane-mile) is divided by a value that represents congestion for a system with the same mix of freeway and street volume. The RCI is, therefore, a measure of both intensity and duration of congestion. While it may appear that the travel volume factors (e.g., freeway VMT) on the top and bottom of the equation cancel each other, a sample calculation should satisfy the reader that this is not the case.

$$\begin{matrix}\text{Roadway}\\\text{Congestion}\\\text{Index}\end{matrix} = \frac{\begin{matrix}\text{Freeway}\\\text{VMT/Ln. Mi.}\end{matrix} \times \begin{matrix}\text{Freeway}\\\text{VMT}\end{matrix} + \begin{matrix}\text{Prin Art Str}\\\text{VMT/Ln. Mi.}\end{matrix} \times \begin{matrix}\text{Prin Art Str}\\\text{VMT}\end{matrix}}{14{,}000 \times \begin{matrix}\text{Freeway}\\\text{VMT}\end{matrix} + 5{,}000 \times \begin{matrix}\text{Prin Art Str}\\\text{VMT}\end{matrix}}$$

(Eq. A-1)

An Illustration of Travel Conditions When an Urban Area RCI Equals 1.0

The congestion index is a macroscopic measure which does not account for local bottlenecks or variations in travel patterns that affect time of travel or origin-destination combinations. It also does not include the effect of improvements such as freeway entrance ramp signals, or treatments designed to give a travel speed advantage to transit and carpool riders. The urban area may see several of the following effects:

- Typical commute time 25% longer than off-peak travel time.
- Slower moving traffic during the peak period on the freeways, but not sustained stop-and-go conditions.
- Moderate congestion for 1 1/2 to 2 hours during each peak-period.
- Wait through one or two red lights at heavily traveled intersections.
- The RCI includes the effect of roadway expansion, demand management, and vehicle travel reduction programs.
- The RCI does not include the effect of operations improvements (e.g., clearing accidents quickly, regional traffic signal coordination), person movement efficiencies (e.g., bus and carpool lanes) or transit improvements (e.g., priority at traffic signals).
- The RCI does not address situations where a traffic bottleneck means much less capacity than demand over a short section of road (e.g., a narrow bridge or tunnel crossing a harbor or river), or missing capacity due to a gap in the system.
- The urban area congestion index averages all the developments within an urban area; there will be locations where congestion is much worse or much better than average.

Percent of Daily Travel in Congested Conditions

Peak travel periods in urban areas are the morning and evening "rush hours" when slow speeds are most likely to occur. The length of the peak period is held constant—essentially the most traveled four hours in the morning and evening—but the amount of the peak period that may suffer congestion is estimated separately. Large urban areas have peak periods that are typically longer than smaller or less congested areas because not all of the demand can be handled by the transportation network during a single hour. The congested times of day have increased since the start of the Urban Mobility Report. The maximum value is 50% of daily vehicle-miles of travel.

Exhibit A-2 illustrates the estimation procedure used for all urban areas. The Urban Mobility Report procedure uses the roadway congestion index (RCI)—a ratio of daily traffic volume to the number of lane-miles of arterial street and freeway—to estimate the length of the peak period. In this application, the RCI acts as an indicator of the number of hours of the day that might be affected by congested conditions (a higher RCI value means more traffic during more hours of the day). Exhibit A-2 illustrates the process used to estimate the amount of the day (and the amount of travel) when travelers might encounter congestion. Exhibit A-3 presents the results of the 2007 data analysis. Travel during the peak period, but outside these possibly congested times, is considered uncongested and is assigned a free-flow speed.

Exhibit A-2. Percent of Daily Travel in Congested Conditions

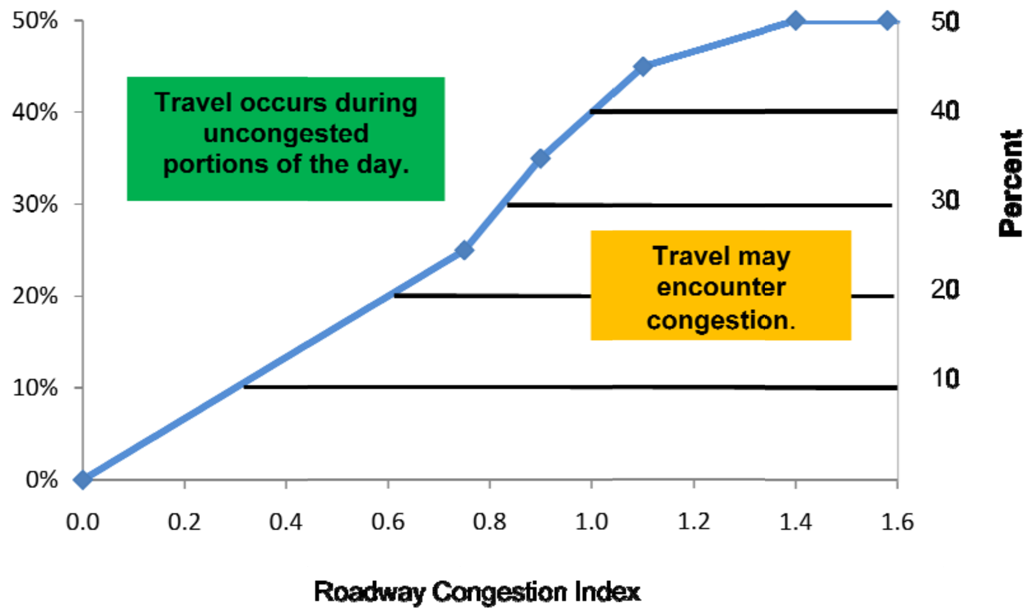


Exhibit A-3. Percentage of Daily Travel Used in Delay Estimation Procedure for 2009 Urban Mobility Report

Urban Area	2007 Roadway Congestion Index	% of Daily Travel in Congested Conditions	Urban Area	2007 Roadway Congestion Index	% of Daily Travel in Congested Conditions
Very Large			Medium		
Atlanta, GA	1.31	48.5	Akron, OH	0.88	33.6
Boston, MA-NH-RI	1.09	44.4	Albany-Schenectady, NY	0.83	30.4
Chicago, IL-IN	1.18	46.4	Albuquerque, NM	1.00	40.2
Dallas-Fort Worth-Arlington, TX	1.21	46.9	Allentown-Bethlehem, PA-NJ	0.94	37.1
Detroit, MI	1.23	47.2	Bakersfield, CA	0.83	30.2
Houston, TX	1.29	48.2	Birmingham, AL	1.02	40.8
Los Angeles-LBch-Santa Ana, CA	1.58	50.0	Bridgeport-Stamford, CT-NY	1.19	46.4
Miami, FL	1.39	49.9	Colorado Springs, CO	0.85	31.9
New York-Newark, NY-NJ-CT	1.15	45.8	Dayton, OH	0.91	35.3
Philadelphia, PA-NJ-DE-MD	1.11	45.1	El Paso, TX-NM	0.86	32.6
Phoenix, AZ	1.25	47.6	Fresno, CA	0.91	35.3
San Francisco-Oakland, CA	1.39	49.8	Grand Rapids, MI	0.87	33.1
Seattle, WA	1.12	45.4	Hartford, CT	0.97	38.3
Washington, DC-VA-MD	1.34	49.1	Honolulu, HI	1.10	45.1
			Indio-Cat. City-Palm Springs, CA	0.92	36.2
Large			Lancaster-Palmdale, CA	0.91	35.4
Austin, TX	1.19	46.5	Louisville, KY-IN	1.09	44.3
Baltimore, MD	1.21	46.8	Nashville-Davidson, TN	0.99	39.6
Buffalo, NY	0.77	26.0	New Haven, CT	1.00	39.8
Charlotte, NC-SC	1.11	45.2	Oklahoma City, OK	0.92	35.9
Cincinnati, OH-KY-IN	1.06	42.8	Omaha, NE-IA	0.96	37.8
Cleveland, OH	0.89	34.4	Oxnard-Ventura, CA	1.22	47.0
Columbus, OH	1.10	44.8	Poughkeepsie-Newburgh, NY	0.89	34.3
Denver-Aurora, CO	1.17	46.1	Richmond, VA	0.83	30.3
Indianapolis, IN	1.09	44.7	Rochester, NY	0.77	26.1
Jacksonville, FL	1.17	46.2	Salt Lake City, UT	1.06	42.9
Kansas City, MO-KS	0.79	27.5	Sarasota-Bradenton, FL	1.23	47.2
Las Vegas, NV	1.41	50.0	Springfield, MA-CT	0.83	30.1
Memphis, TN-MS-AR	0.91	35.3	Toledo, OH-MI	0.84	31.1
Milwaukee, WI	0.95	37.5	Tucson, AZ	1.15	45.9
Minneapolis-St. Paul, MN	1.17	46.1	Tulsa, OK	0.83	30.3
New Orleans, LA	0.98	39.0			
Orlando, FL	1.24	47.3	Small		
Pittsburgh, PA	0.78	26.8	Anchorage, AK	0.76	25.5
Portland, OR-WA	1.20	46.6	Beaumont, TX	0.80	28.1
Providence, RI-MA	0.95	37.3	Boulder, CO	0.89	34.3
Raleigh-Durham, NC	1.01	40.4	Brownsville, TX	0.85	31.5
Riverside-San Bernardino, CA	1.45	50.0	Cape Coral, FL	1.31	48.5
Sacramento, CA	1.33	48.9	Charleston-No. Charleston, SC	1.14	45.7
San Antonio, TX	1.16	46.0	Columbia, SC	0.94	36.8
San Diego, CA	1.37	49.5	Corpus Christi, TX	0.70	23.4
San Jose, CA	1.34	49.0	Eugene, OR	0.88	33.4
St. Louis, MO-IL	0.89	34.6	Knoxville, TN	1.08	44.0
Tampa-St. Petersburg, FL	1.29	48.2	Laredo, TX	0.82	29.6
Virginia Beach, VA	1.01	40.5	Little Rock, AR	0.94	37.1
			Pensacola, FL-AL	1.12	45.3
			Salem, OR	0.91	35.5
			Spokane, WA	0.72	18.8
			Wichita, KS	0.56	18.8

Note: 2007 data used in 2009 Urban Mobility Report.

Travel Speed

The volume and speed data that is collected by freeway operations centers in many metropolitan regions is used along with computer simulation modeling to adjust the Urban Mobility Report congestion estimation procedures. The speed functions used for the 2009 Urban Mobility Report are shown in Exhibits A-4 and A-5. More details on the supporting research are in a technical memorandum on the Urban Mobility Report website (*12*). The speed equations in Exhibit A-6 are linear within a congestion range and together the equations form a continuous line as shown in Exhibits A-4 and A-5.

Exhibit A-6. Daily Traffic Volume per Lane and Speed Estimating Used in Delay Calculation

Facility and Congestion Level	Daily Traffic Volume per Lane	Speed Estimate Equation[1]	
		Peak Direction	Off-Peak Direction
Freeway			
Uncongested	Under 15,000	60	60
Medium	15,001-17,500	70-(0.9* ADT/Lane)	67-(0.6* ADT/Lane)
Heavy	17,501-20,000	78-(1.4* ADT/Lane)	71-(0.85* ADT/Lane)
Severe	20,001-25,000	96-(2.3* ADT/Lane)	88-(1.7* ADT/Lane)
Extreme	Over 25,000	76-(1.46* ADT/Lane)	85.7-(1.6* ADT/Lane)
		Lowest speed is 35 mph	Lowest speed is 40 mph
Arterial Street			
Uncongested	Under 5,500	35	35
Medium	5,501-7,000	33.58-(0.74 ADT/Lane)	33.82-(0.59 ADT/Lane)
Heavy	7,001-8,500	33.80-(0.77 ADT/Lane)	33.90-(0.59 ADT/Lane)
Severe	8,501-10,000	31.65-(0.51 ADT/Lane)	30.10 (0.15 ADT/Lane)
Extreme	Over 10,000	32.57-(0.62 ADT/Lane)	31.23-(0.27 ADT/Lane)
		Lowest speed is 20 mph	Lowest speed is 27 mph

Note: [1]ADT/Lane in thousands.

Exhibit A-4. 2009 Urban Mobility Report – Freeway Speed Estimates

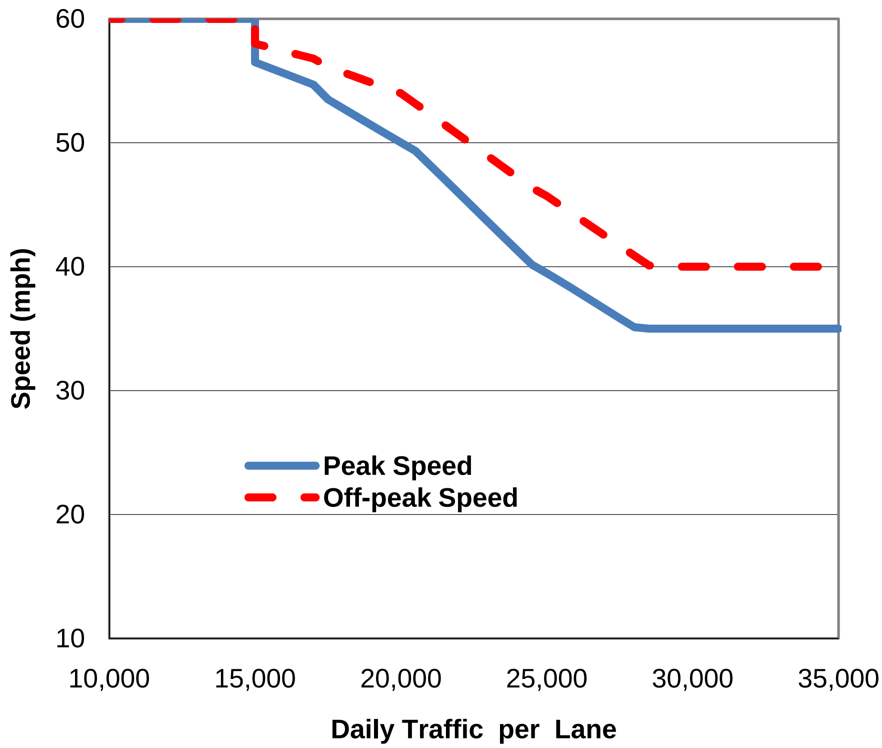
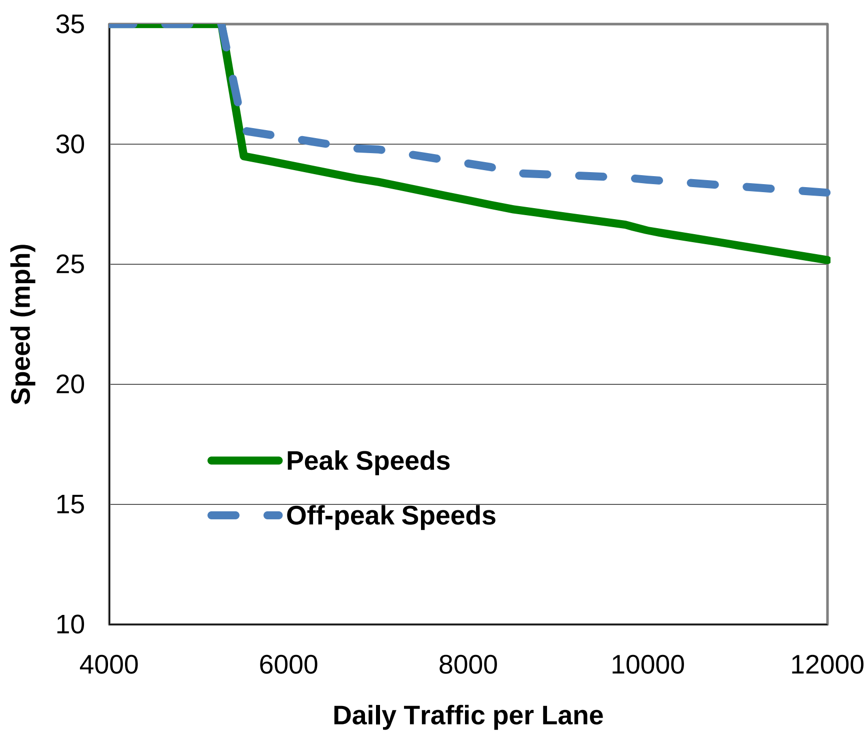


Exhibit A-5. 2009 Urban Mobility Report – Arterial Speed Estimates



The amount of travel (measured in vehicle-miles for each roadway link) is summed for each congestion level and direction. The average daily traffic volume per lane for each congestion level and direction is determined by dividing the group total VMT by the sum of lane-miles for all the links in that group. The average speed for each roadway type is obtained by weighting the speed in each congestion level by the total amount of travel at that level. The uncongested category includes travel on the uncongested portions of roadway, as well as travel during portions of the day that are estimated to rarely have congestion. The uncongested portion of the day varies for each city. The total amount of travel included in the speed averaging procedure, however, is 50 percent of the average daily vehicle-miles of travel for all urban areas.

Equation A-2 shows the calculation for a weighted average of speed. The average speed for each element of the road system is multiplied by the amount of travel on that set of roads. Using the amount of travel as a weighting factor provides a way to get an average "system experience" of travelers based on the amount of travel that occurs within each portion of the road system. This fundamental concept is used elsewhere in the Urban Mobility Report methodology. The resulting freeway and arterial speeds are shown in Exhibit A-7.

$$\underset{\text{(mph)}}{\text{Average Speed}} = \frac{\underset{\text{Freeway Speed}}{\text{Average}}\left(\underset{\text{VMT}}{\text{Freeway}}\right) + \underset{\text{Street Speed}}{\text{Average Arterial}}\left(\underset{\text{VMT}}{\text{Arterial}}\right)}{\underset{\text{VMT}}{\text{Freeway}} + \underset{\text{VMT}}{\text{Street}}} \qquad \text{(Eq. A-2)}$$

Exhibit A-7. 2007 Traffic Speed Estimates

Urban Area	Freeway	Arterial Street	Urban Area	Freeway	Arterial Street
Very Large			Medium		
Atlanta, GA	41.9	26.7	Akron, OH	56.2	32.8
Boston, MA-NH-RI	45.7	28.4	Albany-Schenectady, NY	56.3	30.7
Chicago, IL-IN	41.0	24.7	Albuquerque, NM	49.3	29.9
Dallas-Fort Worth-Arlington, TX	42.5	27.9	Allentown-Bethlehem, PA-NJ	56.3	29.0
Detroit, MI	47.5	26.4	Bakersfield, CA	55.0	31.9
Houston, TX	41.6	27.3	Birmingham, AL	53.4	29.0
Los Angeles-LBch-Santa Ana, CA	34.6	25.8	Bridgeport-Stamford, CT-NY	45.8	29.9
Miami, FL	41.6	25.5	Colorado Springs, CO	52.5	31.2
New York-Newark, NY-NJ-CT	41.5	26.1	Dayton, OH	55.9	31.5
Philadelphia, PA-NJ-DE-MD	45.2	27.6	El Paso, TX-NM	52.4	31.3
Phoenix, AZ	42.2	28.5	Fresno, CA	53.7	30.3
San Francisco-Oakland, CA	38.5	26.0	Grand Rapids, MI	58.0	30.8
Seattle, WA	43.8	27.9	Hartford, CT	53.7	30.8
Washington, DC-VA-MD	41.5	25.1	Honolulu, HI	48.8	27.3
			Indio-Cat. City-Palm Springs, CA	59.6	29.7
Large			Lancaster-Palmdale, CA	57.8	31.0
Austin, TX	46.1	26.6	Louisville, KY-IN	50.6	28.3
Baltimore, MD	43.9	27.7	Nashville-Davidson, TN	53.8	29.1
Buffalo, NY	56.2	32.5	New Haven, CT	54.2	31.1
Charlotte, NC-SC	49.6	26.7	Oklahoma City, OK	55.6	30.5
Cincinnati, OH-KY-IN	50.3	30.1	Omaha, NE-IA	51.1	29.8
Cleveland, OH	55.6	32.0	Oxnard-Ventura, CA	48.2	28.1
Columbus, OH	50.5	29.3	Poughkeepsie-Newburg, NY	58.4	30.2
Denver-Aurora, CO	45.1	26.5	Richmond, VA	55.5	31.6
Indianapolis, IN	51.6	27.7	Rochester, NY	57.2	32.4
Jacksonville, FL	50.1	26.9	Salt Lake City, UT	54.0	27.4
Kansas City, MO-KS	56.4	32.2	Sarasota-Bradenton, FL	57.5	27.8
Las Vegas, NV	44.8	27.1	Springfield, MA-CT	58.0	32.0
Memphis, TN-MS-AR	50.9	31.8	Toledo, OH-MI	55.0	32.4
Milwaukee, WI	49.6	32.2	Tucson, AZ	50.6	27.6
Minneapolis-St. Paul, MN	45.6	29.4	Tulsa, OK	58.1	30.6
New Orleans, LA	52.6	29.3			
Orlando, FL	48.6	25.2	Small		
Pittsburgh, PA	56.2	31.6	Anchorage, AK	59.8	31.2
Portland, OR-WA	44.6	27.4	Beaumont, TX	57.9	33.1
Providence, RI-MA	51.6	29.8	Boulder, CO	58.5	30.7
Raleigh-Durham, NC	53.4	28.7	Brownsville, TX	59.6	31.5
Riverside-San Bernardino, CA	39.9	28.8	Cape Coral, FL	57.7	28.7
Sacramento, CA	43.3	26.8	Charleston-No Charleston, SC	54.3	27.8
San Antonio, TX	48.8	27.7	Columbia, SC	56.9	30.4
San Diego, CA	42.1	25.7	Corpus Christi, TX	58.9	32.3
San Jose, CA	43.7	25.1	Eugene, OR	58.2	31.3
St. Louis, MO-IL	53.4	30.1	Knoxville, TN	55.6	30.3
Tampa-St. Petersburg, FL	49.4	25.3	Laredo, TX	59.3	30.4
Virginia Beach, VA	51.3	28.9	Little Rock, AR	55.9	31.3
			Pensacola, FL-AL	58.4	30.2
			Salem, OR	58.5	30.1
			Spokane, WA	58.0	33.2
			Wichita, KS	59.6	33.7

Note: 2007 data used in 2009 Urban Mobility Report.

Travel Delay

Most of the basic performance measures presented in the Urban Mobility Report are developed as part of calculating travel delay—the amount of extra time spent traveling due to congestion. An overview of the process is followed by more detailed descriptions of the individual steps.

Travel delay calculations are performed in two steps—recurring (or usual) delay and incident delay (due to crashes, vehicle breakdowns, etc.). Recurring delay estimates are developed using a process designed to identify peak period congestion due to traffic volume and capacity. Delay caused by other events is not included in the recurring delay estimate. Generally, these events can be categorized as one of the seven sources of unreliability (*13*).

- Traffic Incidents
- Work Zones
- Weather
- Fluctuation in Demand
- Special Events
- Traffic Control Devices
- Inadequate Base Capacity

The 2009 Urban Mobility Report methodology only includes estimates of travel delay from incidents, demand fluctuations and base capacity inadequacy.

Recurring Travel Delay - Summary Version

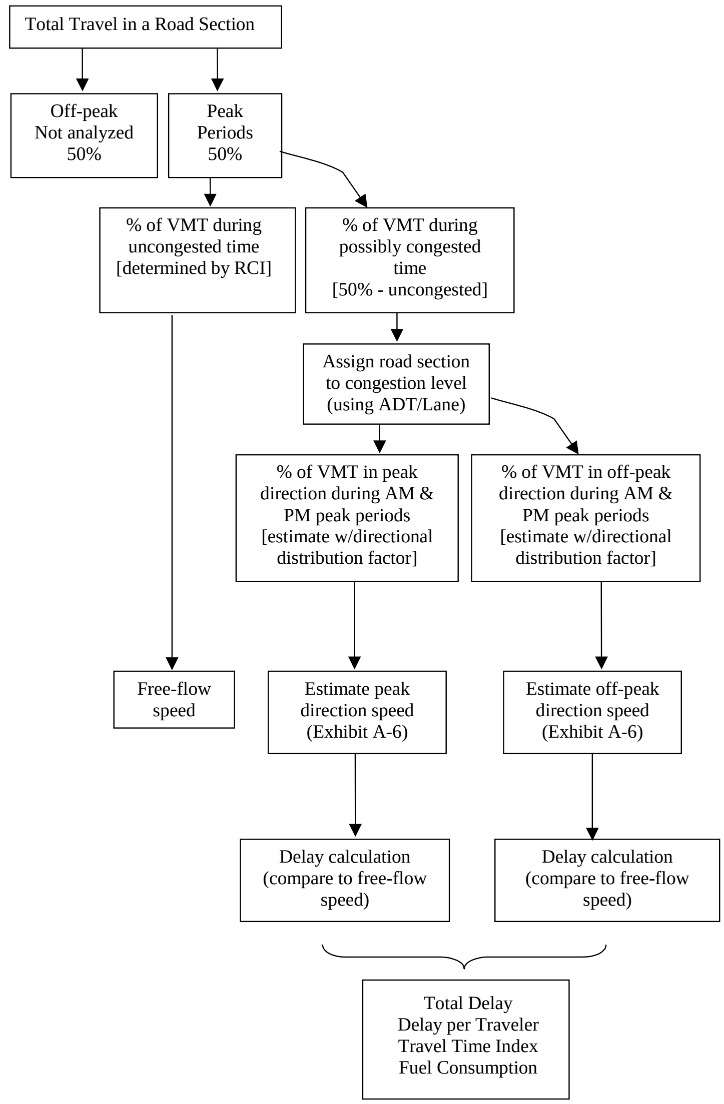
Travel delay is estimated from equations relating vehicle traffic volume per lane and traffic speed. The calculation proceeds through the following steps (displayed in Exhibit A-8):

- Estimate peak period travel miles.
- Estimate the amount of travel in times that might encounter congestion; place remainder of the travel in the uncongested group.
- Separate congested travel into peak and off-peak directions.
- Place each road section in a congestion group (one of four congestion levels for peak and off-peak or the uncongested group).
- Calculate a speed for each congestion group.
- Calculate average speed on each road type (e.g. freeways or arterial streets).

Exhibit A-8. Overview of Speed and Delay Calculation Process

Step	Why? or What
Collect travel and roadway characteristics	Get data for an average day
Isolate peak-period travel	Remove off-peak, uncongested travel (50% of day)
Identify the usually congested time of day	Varies for each area; congestion usually lasts longer in larger areas
Identify congestion level of each section of roadway	Use daily traffic/lane and Exhibit A-6
Assign travel to peak/off-peak directions	Accumulate VMT by congestion level and direction, determine average VMT per lane-mile
Apply speed estimates to each congestion level and direction	Using speed curves, determine average speed for each direction and level
Calculate delay	Compare average speeds to free-flow speeds
Calculate other measures	Use VMT, speeds and remaining methodology to determine other measures

The 'Process'



For Each Road Section

Collect Travel and Roadway Characteristics

Information for each section of roadway includes daily traffic volume, length and number of lanes.

Isolate Peak-Period and Congested Travel

Fifty percent of the daily vehicle travel occurs in the peak period and is used in the speed and delay estimates. The calculation procedure to estimate the congested portions of the peak (described previously) is used to initially distribute travel to the uncongested portions of the day and those hours that may be congested.

Separate Peak and Off-Peak Direction Travel Volume

The directional distribution factor in the Highway Performance Monitoring System database is used to divide the traffic on each link to the peak and off-peak directions. There is a different speed estimating equation for each direction (*12*). The delay reduction equation for arterial street traffic signal coordination is also different for the two directions.

Congestion Level of Each Section of Roadway

Each roadway link is assigned to one of five congestion levels—uncongested, moderate, heavy, severe or extreme, based on the daily traffic volume per lane. These assignments are used in the estimation of both the peak period travel speed and the delay reducing effects of the operational treatments.

Estimate Travel Speed in Each Congestion Group

Previous steps have separated the roadway links into freeway or arterial, congestion level, and peak or off-peak direction. The speed calculation is applied for each combination of congestion level/road type/direction for each group.

Estimate Travel Time

The travel time for each combination of road/direction/congestion level is calculated by dividing the miles traveled in each group by the average speed. The travel time at free-flow conditions is calculated by dividing the travel distance by the free-flow speed.

Estimate Travel Delay Using Speed and Travel Volume

The amount of delay incurred in the peak period is the difference between the time to travel at the average speed and the travel time at the free-flow speed, multiplied by the distance traveled in the peak period.

Estimate Travel Delay

The difference between the amount of time it takes to travel the peak-period vehicle-miles at the average speed and at free-flow speeds is termed delay.

Incident-Related Travel Delay

Another type of delay encountered by travelers is the delay that results from a collision or disabled vehicle. Incident delay is related to the frequency of crashes or vehicle breakdowns, how easily those incidents are removed from the traffic lanes and shoulders and the "normal" amount of recurring congestion. The basic procedure used to estimate incident delay in this study is to multiply the recurring delay by a ratio (Equation A-3).

$$\begin{array}{c}\text{Daily Incident}\\ \text{Vehicle - Hours of Delay}\end{array} = \begin{array}{c}\text{Daily Recurring}\\ \text{Vehicle - Hours of Delay}\end{array} \times \begin{array}{c}\text{Recurring to Incident}\\ \text{Delay Factor Ratio}\end{array} \quad \text{(Eq. A-3)}$$

The process used to develop the delay factor ratio is a detailed examination of the freeway characteristics and volumes. In addition, a methodology developed by FHWA is used to model the effect of incidents based on the design characteristics and estimated volume patterns (*14*). The procedure involves the random assignment of crashes to the roadway system based on the distribution of frequency and severity of collisions. Each type of collision has a different capacity reducing effect and depending on the traffic volume at the "time" of the collision, travel delay can increase by very little (for minor crashes during low volume conditions) to a large amount if the collision blocks a lane or lanes during high traffic volume periods. The resulting ratios are presented in Exhibit A-9.

Exhibit A-9. Incident Delay Ratios

Urban Area	Freeway Incident Delay Ratio	Arterial Street Incident Delay Ratio	Urban Area	Freeway Incident Delay Ratio	Arterial Street Incident Delay Ratio
Very Large			Medium		
Atlanta, GA	1.2	1.1	Akron, OH	1.4	1.1
Boston, MA-NH-RI	1.6	1.1	Albany-Schenectady, NY	2.3	1.1
Chicago, IL-IN	0.8	1.1	Albuquerque, NM	1.1	1.1
Dallas-Fort Worth-Arlington, TX	1.3	1.1	Allentown-Bethlehem, PA-NJ	1.6	1.1
Detroit, MI	1.2	1.1	Bakersfield, CA	1.8	1.1
Houston, TX	0.9	1.1	Birmingham, AL	2.0	1.1
Los Angeles-LBch-Santa Ana, CA	0.7	1.1	Bridgeport-Stamford, CT-NY	1.5	1.1
Miami, FL	1.0	1.1	Colorado Springs, CO	2.2	1.1
New York-Newark, NY-NJ-CT	2.5	1.1	Dayton, OH	1.4	1.1
Philadelphia, PA-NJ-DE-MD	2.2	1.1	El Paso, TX-NM	1.7	1.1
Phoenix, AZ	0.9	1.1	Fresno, CA	2.3	1.1
San Francisco-Oakland, CA	0.9	1.1	Grand Rapids, MI	2.1	1.1
Seattle, WA	1.2	1.1	Hartford, CT	2.1	1.1
Washington, DC-VA-MD	1.0	1.1	Honolulu, HI	1.3	1.1
			Indio-Cat. City-Palm Springs, CA	2.5	1.1
Large			Lancaster-Palmdale, CA	2.5	1.1
Austin, TX	1.6	1.1	Louisville, KY-IN	1.5	1.1
Baltimore, MD	1.3	1.1	Nashville-Davidson, TN	1.7	1.1
Buffalo, NY	2.1	1.1	New Haven, CT	1.4	1.1
Charlotte, NC-SC	1.2	1.1	Oklahoma City, OK	2.0	1.1
Cincinnati, OH-KY-IN	1.3	1.1	Omaha, NE-IA	2.3	1.1
Cleveland, OH	1.5	1.1	Oxnard-Ventura, CA	1.3	1.1
Columbus, OH	1.3	1.1	Poughkeepsie-Newburgh, NY	2.5	1.1
Denver-Aurora, CO	1.2	1.1	Richmond, VA	2.2	1.1
Indianapolis, IN	1.1	1.1	Rochester, NY	2.3	1.1
Jacksonville, FL	1.5	1.1	Salt Lake City, UT	1.3	1.1
Kansas City, MO-KS	2.5	1.1	Sarasota-Bradenton, FL	2.5	1.1
Las Vegas, NV	1.1	1.1	Springfield, MA-CT	1.9	1.1
Memphis, TN-MS-AR	1.6	1.1	Toledo, OH-MI	2.1	1.1
Milwaukee, WI	1.1	1.1	Tucson, AZ	1.5	1.1
Minneapolis-St. Paul, MN	1.4	1.1	Tulsa, OK	2.1	1.1
New Orleans, LA	1.4	1.1			
Orlando, FL	1.3	1.1	Small		
Pittsburgh, PA	2.5	1.1	Anchorage, AK	2.5	1.1
Portland, OR-WA	1.4	1.1	Beaumont, TX	2.5	1.1
Providence, RI-MA	2.2	1.1	Boulder, CO	2.5	1.1
Raleigh-Durham, NC	1.6	1.1	Brownsville, TX	2.5	1.1
Riverside-San Bernardino, CA	0.9	1.1	Cape Coral, FL	2.5	1.1
Sacramento, CA	1.0	1.1	Charleston-No. Charleston, SC	2.0	1.1
San Antonio, TX	1.2	1.1	Columbia, SC	1.9	1.1
San Diego, CA	0.9	1.1	Corpus Christi, TX	2.4	1.1
San Jose, CA	1.2	1.1	Eugene, OR	2.4	1.1
St. Louis, MO-IL	1.2	1.1	Knoxville, TX	2.3	1.1
Tampa-St. Petersburg, FL	1.5	1.1	Laredo, TX	2.5	1.1
Virginia Beach, VA	2.1	1.1	Little Rock, AR	1.6	1.1
			Pensacola, FL-AL	2.5	1.1
			Salem, OR	2.5	1.1
			Spokane, WA	2.4	1.1
			Wichita, KS	2.5	1.1

Incident delay occurs in different ways on streets than freeways. While there are driveways that can be used to remove incidents, the crash rate is higher and the recurring delay is lower on streets. Arterial street designs are more consistent from city to city than freeway designs. For the purpose of this study, incident delay for arterial streets is estimated as 110 percent of arterial street recurring delay.

Annual Person Delay

This calculation is performed to expand the daily recurring and incident delay estimates for freeways and arterial streets to a yearly estimate in each study area. The daily vehicle-hours of delay is the sum of the delay resulting from recurring and incident delay in all four congestion levels on both types of facilities. To calculate the annual person-hours of delay, multiply the daily delay estimates by the average vehicle occupancy (1.25 persons per vehicle) and by 250 working days per year (Equation A-4).

$$\begin{matrix}\text{Annual}\\ \text{Persons} - \text{Hours}\\ \text{of Delay}\end{matrix} = \begin{matrix}\text{Daily Vehicle} - \text{Hours of}\\ \text{Incident and Recurring}\\ \text{Delay on Frwys and Arterial Streets}\end{matrix} \times \begin{matrix}\text{250 Working Days}\\ \text{per Year}\end{matrix} \times \begin{matrix}\text{1.25 Persons}\\ \text{per Vehicle}\end{matrix} \qquad \text{(Eq. A-4)}$$

Annual delay per traveler is a measure of the extra travel time endured by persons 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 American Community Survey to the urban area population estimate to derive the average number of travelers during the peak periods (*15*). Total delay is divided by the number of travelers to get the annual delay per peak traveler.

Annual Peak Period Travel Time

Total travel time can be used as both a performance measure and as a component in other calculations. The 2009 Urban Mobility Report used travel time as a component; future reports will incorporate other information and improve on the use of total travel time as a performance measure.

Total travel time is the sum of travel delay and free-flow travel time. Both of the quantities are only calculated for freeways and arterial streets. Free-flow travel time is the amount of time needed to travel the peak period miles at the free-flow speeds (60 mph on freeways and 35 mph on streets) (Equation A-5).

$$\begin{matrix}\text{Annual Free–flow} \\ \text{Travel Time} \\ \text{(vehicle–hours)}\end{matrix} = \frac{1}{\begin{matrix}\text{Free–flow} \\ \text{Travel Speed} \\ \left(\begin{matrix}\text{60 mph–freeway} \\ \text{35 mph–arterial}\end{matrix}\right)\end{matrix}} \times \begin{matrix}\text{Peak Period} \\ \text{Vehicle–Miles} \\ \text{of Travel}\end{matrix} \times \begin{matrix}\text{250} \\ \text{Working} \\ \text{Days}\end{matrix} \qquad \text{(Eq. A-5)}$$

$$\begin{matrix}\text{Annual} \\ \text{Travel Time}\end{matrix} = \underbrace{\left(\begin{matrix}\text{Freeway} \\ \text{Delay}\end{matrix} + \begin{matrix}\text{Arterial} \\ \text{Street Delay}\end{matrix}\right)}_{\text{(Eq. A–4)}} + \underbrace{\left(\begin{matrix}\text{Freeway} \\ \text{Free–flow} \\ \text{Travel Time}\end{matrix} + \begin{matrix}\text{Arterial} \\ \text{Free–flow} \\ \text{Travel Time}\end{matrix}\right)}_{\text{(Eq. A–5)}} \qquad \text{(Eq. A-6)}$$

Travel Time Index

The Travel Time Index (TTI) illustrates the comparison of peak period travel time to free-flow travel time. The Travel Time Index includes both recurring and incident conditions and is, therefore, an estimate of the conditions faced by urban travelers. Equation A-5 illustrates the ratio used to calculate the TTI. The ratio is time divided by time and the Index, therefore, has no units. This “unitless” feature allows the Index to be used to compare trips of different lengths to estimate the travel time in excess of that experienced in free-flow conditions.

The index is calculated with a procedure consistent with the methods and data that will be used in the automated travel management centers. The free-flow travel time for each functional class is subtracted from the average travel time to estimate delay. The recurring delay is multiplied by the incident-to-recurring delay ratio to estimate incident delay. For each congestion level, the incident delay is added to the recurring delay to estimate total delay. The Travel Time Index is calculated by comparing total travel time to the free-flow travel time (Equations A-7 and A-8).

$$\text{Travel Time Index} = \frac{\text{Peak Travel Time}}{\text{Free–Flow Travel Time}} \qquad \text{(Eq. A-7)}$$

$$\text{Travel Time Index} = \frac{\text{Delay Time} + \text{Free–Flow Travel Time}}{\text{Free–Flow Travel Time}} \qquad \text{(Eq. A-8)}$$

Fuel Economy

The average fuel economy calculation is used to estimate the fuel consumption of the vehicles operating in congested and uncongested conditions. Equation A-9 is a linear regression applied to a modified version of fuel consumption reported by Raus (*16*).

$$\begin{matrix}\text{Average Fuel}\\ \text{Economy}\\ \text{in Congestion}\end{matrix} = 8.8 + 0.25\begin{pmatrix}\text{Average Peak}\\ \text{Period Congested}\\ \text{System Speed}\end{pmatrix} \qquad \text{(Eq. A-9)}$$

Wasted Fuel

The Urban Mobility Report calculates the wasted fuel due to vehicles moving at speeds slower than free-flow during peak period travel. Equation A-10 calculates the fuel wasted in recurring and incident delay conditions from Equation A-4, the average peak period speed (Equation A-2), and the average fuel economy associated with the peak speed (Equation A-9).

$$\begin{matrix}\text{Annual}\\ \text{Fuel Wasted}\end{matrix} = \begin{matrix}\text{Travel Time}\\ \text{(vehicle hours)}\\ \text{(Eq. A–5)}\end{matrix} \times \begin{matrix}\text{Average Peak Period System}\\ \text{"Congested Speed"}\\ \text{(Eq. A–2)}\end{matrix} \div \begin{matrix}\text{Average Fuel}\\ \text{Economy}\\ \text{(Eq. A–9)}\end{matrix} \times \begin{matrix}\text{250 Working}\\ \text{Days per year}\end{matrix} \qquad \text{(Eq. A-10)}$$

Equation A-11 incorporates the same factors to calculate fuel that would be consumed in free-flow conditions. The fuel that is deemed “wasted due to congestion” is the difference between the amount consumed at peak speeds and free-flow speeds (Equation A-10).

$$\begin{matrix}\text{Annual Fuel That Would}\\ \text{be Consumed in}\\ \text{Free-flow Conditions}\end{matrix} = \begin{matrix}\text{Travel Time}\\ \text{(Eq. A–6)}\end{matrix} \times \begin{matrix}\text{Free-flow Speed}\\ \text{(35 mph-arterial,}\\ \text{60 mph-freeway)}\end{matrix} \div \begin{matrix}\text{Average Fuel}\\ \text{Economy for}\\ \text{Free-flow Speeds}\\ \text{(Eq. A–9)}\end{matrix} \times \begin{matrix}\text{250 Working}\\ \text{Days per Year}\end{matrix} \qquad \text{(Eq. A-11)}$$

$$\begin{matrix}\text{Annual Fuel}\\ \text{Wasted in Congestion}\end{matrix} = \begin{matrix}\text{Annual Fuel}\\ \text{Consumed in}\\ \text{Peak Conditions}\end{matrix} - \begin{matrix}\text{Annual Fuel That}\\ \text{Would be Consumed}\\ \text{in Free-flow Conditions}\end{matrix} \qquad \text{(Eq. A-12)}$$

Congestion 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-13 through A-15 show how to calculate the cost of delay and fuel effects of congestion.

Passenger Vehicle Delay Cost

The delay cost is an estimate of the value of lost time in passenger vehicles and the increased operating costs of commercial vehicles in congestion. Equation A-13 shows how to calculate the passenger vehicle delay costs that result from lost time.

$$\begin{matrix}\text{Annual Passenger} \\ \text{Vehicle Delay Cost}\end{matrix} = \begin{matrix}\text{Daily Passenger Vehicle} \\ \text{Hours of Delay} \\ \text{(Eq. A-4)}\end{matrix} \times \begin{matrix}\text{Value of} \\ \text{Person Time} \\ \text{(\$ / hour)}\end{matrix} \times \begin{matrix}\text{Vehicle} \\ \text{Occupancy} \\ \text{(persons/vehicle)}\end{matrix} \times \begin{matrix}\text{250 Working} \\ \text{Days}\end{matrix} \qquad \text{(Eq. A-13)}$$

Passenger Vehicle Fuel Cost

Fuel cost due to congestion is calculated for passenger vehicles in Equation A-14. This is done by associating the peak period congested speeds, the average fuel economy, and the fuel costs with the vehicle-hours of delay.

$$\begin{matrix}\text{Annual} \\ \text{Fuel Cost}\end{matrix} = \begin{matrix}\text{Annual Fuel} \\ \text{Wasted} \\ \text{(Eq. A–12)}\end{matrix} \times \begin{matrix}\text{Percent of} \\ \text{Passenger} \\ \text{Vehicles}\end{matrix} \times \begin{matrix}\text{Fuel} \\ \text{Cost}\end{matrix} \times \begin{matrix}\text{250} \\ \text{Working Days}\end{matrix} \qquad \text{(Eq. A-14)}$$

Commercial Vehicle Cost

The cost of both wasted time and fuel are included in the value of commercial vehicle time ($102.12 in 2007). Thus, there is not a separate value for wasted time and fuel. The equation to calculate commercial vehicle cost is shown in Equation A-15.

$$\begin{matrix}\text{Annual} \\ \text{Commercial} \\ \text{Cost}\end{matrix} = \begin{matrix}\text{Delay Vehicle} \\ \text{Hours of Delay} \\ \text{(Eq. A–4)}\end{matrix} \times \begin{matrix}\text{Percent of} \\ \text{Commercial} \\ \text{Vehicles}\end{matrix} \times \begin{matrix}\text{Value of} \\ \text{Commercial Vehicle} \\ \text{Time (\$/hour)}\end{matrix} \times \begin{matrix}\text{250 Working} \\ \text{Days}\end{matrix} \qquad \text{(Eq. A-15)}$$

Total Congestion Cost

Equation A-16 combines the cost due to travel delay and wasted fuel to determine the annual cost due to congestion resulting from incident and recurring delay.

$$\begin{matrix}\text{Annual Cost}\\ \text{Due to}\\ \text{Congestion}\end{matrix} = \left(\begin{matrix}\text{Annual Passenger}\\ \text{Vehicle Delay Cost}\\ \text{(Eq. A–13)}\end{matrix} + \begin{matrix}\text{Annual Passenger}\\ \text{Fuel Cost}\\ \text{(Eq. A–14)}\end{matrix}\right) + \begin{matrix}\text{Annual}\\ \text{Commerical Cost}\\ \text{(Eq. A–15)}\end{matrix} \qquad \text{(Eq. A-16)}$$

Percent of Congested Travel

The percentage of travel in each urban area that is congested both for peak travel and daily travel can be calculated. The equations are very similar with the only difference being the amount of travel in the denominator. For calculations involving only the congested periods (Equations A-17 and A-18), the amount of travel used is half of the daily total since the assumption is made that only 50 percent of daily travel occurs in the peak driving times. For the daily percentage (Equation A-19), the factor in the denominator is the daily miles of travel. Exhibit A-10 shows the 2007 percent of congested travel values.

$$\begin{matrix}\text{Peak Period}\\ \text{Congested Travel}\end{matrix} = \begin{matrix}\text{Percent of Congested}\\ \text{Peak Period Travel}\end{matrix} \times \begin{matrix}\text{VMT for}\\ \text{Roadway Type}\end{matrix} \qquad \text{(Eq. A-17)}$$

$$\begin{matrix}\text{Percent Congested}\\ \text{Peak Period Travel}\end{matrix} = \begin{matrix}\text{Percent Congested}\\ \text{Daily Travel}\end{matrix} \div \text{50 percent} \qquad \text{(Eq. A-28)}$$

$$\begin{matrix}\text{Percent Congested}\\ \text{Daily Travel}\end{matrix} = \frac{\begin{matrix}\text{Freeway}\\ \text{Congested Travel}\end{matrix} + \begin{matrix}\text{Arterial}\\ \text{Congested Travel}\end{matrix}}{\text{Daily Travel}} \qquad \text{(Eq. A-39)}$$

Exhibit A-10. Percentage of Congested Travel in 2007

Urban Area	Percent of Peak Period Travel that is Congested	Percentage of Daily Travel that is Congested	Urban Area	Percent of Peak Period Travel that is Congested	Percentage of Daily Travel that is Congested
Very Large			Medium		
Atlanta, GA	75	38	Akron, OH	28	14
Boston, MA-NH-RI	58	29	Albany-Schenectady, NY	28	14
Chicago, IL-IN	79	39	Albuquerque, NM	46	23
Dallas-Fort Worth-Arlington, TX	66	33	Allentown-Bethlehem, PA-NJ	38	19
Detroit, MI	71	35	Bakersfield, CA	27	14
Houston, TX	73	36	Birmingham, AL	44	22
Los Angeles-LBch-Santa Ana, CA	86	43	Bridgeport-Stamford, CT-NY	64	32
Miami, FL	82	41	Colorado Springs, CO	32	16
New York-Newark, NY-NJ-CT	69	34	Dayton, OH	34	17
Philadelphia, PA-NJ-DE-MD	63	32	El Paso, TX-NM	34	17
Phoenix, AZ	68	34	Fresno, CA	38	19
San Francisco-Oakland, CA	82	41	Grand Rapids, MI	29	14
Seattle, WA	66	33	Hartford, CT	38	19
Washington, DC-VA-MD	81	40	Honolulu, HI	57	29
			Indio-Cat. City-Palm Springs, CA	38	19
Large			Lancaster-Palmdale, CA	30	15
Austin, TX	70	35	Louisville, KY-IN	55	27
Baltimore, MD	69	35	Nashville-Davidson, TN	41	20
Buffalo, NY	22	11	New Haven, CT	38	19
Charlotte, NC-SC	60	30	Oklahoma City, OK	36	18
Cincinnati, OH-KY-IN	51	25	Omaha, NE-IA	45	23
Cleveland, OH	28	14	Oxnard-Ventura, CA	59	29
Columbus, OH	57	29	Poughkeepsie-Newburgh, NY	27	13
Denver-Aurora, CO	67	33	Richmond, VA	29	14
Indianapolis, IN	60	30	Rochester, NY	19	10
Jacksonville, FL	64	32	Salt Lake City, UT	54	27
Kansas City, MO-KS	21	11	Sarasota-Bradenton, FL	49	25
Las Vegas, NV	72	36	Springfield, MA-CT	21	11
Memphis, TN-MS-AR	32	16	Toledo, OH-MI	25	12
Milwaukee, WI	39	20	Tucson, AZ	61	30
Minneapolis-St. Paul, MN	58	29	Tulsa, OK	26	13
New Orleans, LA	45	23			
Orlando, FL	74	37	Small		
Pittsburgh, PA	24	12	Anchorage, AK	21	10
Portland, OR-WA	68	34	Beaumont, TX	14	7
Providence, RI-MA	39	20	Boulder, CO	27	14
Raleigh-Durham, NC	51	25	Brownsville, TX	22	11
Riverside-San Bernardino, CA	78	39	Cape Coral, FL	45	23
Sacramento, CA	76	38	Charleston-No. Charleston, SC	51	25
San Antonio, TX	63	31	Columbia, SC	33	16
San Diego, CA	84	42	Corpus Christi, TX	15	8
San Jose, CA	81	40	Eugene, OR	25	12
St. Louis, MO-IL	36	18	Knoxville, TN	32	16
Tampa-St. Petersburg, FL	76	38	Laredo, TX	31	15
Virginia Beach, VA	51	25	Little Rock, AR	33	17
			Pensacola, FL-AL	35	18
			Salem, OR	29	15
			Spokane, WA	17	8
			Wichita, KS	8	4

Lane-Miles and Passenger Trips Required To Hold Congestion Constant

The lane-miles of roadway and the transit trips that would be needed every year to maintain a constant congestion level are calculated to illustrate the amount of improvement required to address growing travel needs. The average growth rate is calculated for the previous five years of growth in vehicle-miles of travel. For example, the 2007 statistics are based on the growth rate calculated from changes between 2002 and 2007. If vehicle travel grows at a higher rate than capacity (measured in lane-miles or transit trips), congestion will increase. Thus, in order to hold congestion constant, capacity must be added at the same rate as vehicle travel growth.

The following equation is used to calculate the average annual growth rate for vehicle travel and is key for calculating both the lane-miles and transit passenger trips that are needed to hold congestion constant.

$$\begin{matrix}\text{Annual Average}\\ \text{VMT Growth}\end{matrix} = \left(\frac{(2007\ \text{VMT} - 2002\ \text{VMT})}{2002\ \text{VMT}}\right) 1/5 - 1 \qquad \text{(Eq. A-20)}$$

The "needed" lane-miles are based on applying the average annual growth rate in travel during the analysis period (2002 to 2007) to the existing 2007 lane-miles. This estimates the amount of roadway lane-miles that would be needed to match the travel demand growth rate.

The calculation for the number of passenger trips needed on public transportation each year to hold congestion constant is very similar to the "needed" lane-miles. The annual average growth rate in vehicle-miles of travel is multiplied by the 2007 passenger-miles of travel on the roadways in 2007. This gives the amount of expected passenger travel growth if trends continue. To convert this annual travel mileage growth into transit trips, the person-miles of travel are divided by 9 miles, the approximate length of the average transit trip in the U.S.(*10*). This value represents the number of trips that would need to occur on public transportation to hold the congestion level constant.

It should be noted that these statistics can be calculated for any period of time. The five-year period is used in these calculations as a description of recent trends, but the same statistics could be calculated for the entire time series in the Urban Mobility Report by changing the factor (e.g., 1/5) in the equation above to one over the number of years in the time series.