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CONGESTION AND ITS EXTENT

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ABSTRACT

The objective of this chapter is to discuss current definitions of metropolitan traffic congestion and ways it is currently measured. In addition, the accuracy and reliability of these measures will be described along with a review of how congestion has been changing over the past several decades. First, the results of a survey among transportation professionals are summarized to assist in framing the issue. Most respondents linked the measurement of congestion to the increased travel time that occurs during peak periods. Roughly half of those surveyed felt that congestion measures are at least somewhat accurate, and about 80% of those surveyed feel that congestion has worsened over the past 20 years. The chapter includes a literature review of current trends in congestion definition and measurement, a discussion and short critique of one major congestion monitoring program, and presents some basic theory about how traffic parameters are often measured over time and space. A brief description of possible congestion measures over corridors and entire door-to-door trips is provided. Additional analysis of recent congestion measures for entire metropolitan area is provided, using Portland, Oregon and Minneapolis, Minnesota as case examples. Some discussion of the stability of daily travel budgets and alternative viewpoints about congestion are provided along with some conclusions and perspectives for future research.

INTRODUCTION

"You're not stuck in a traffic jam, you are the jam." - German public transport campaign (Kay, 1997)

Congestion—both in perception and in reality—impacts the movement of people and freight and is deeply tied to our history of high levels of accessibility and mobility. Along spatial and temporal dimensions, traffic congestion has been around since ancient Rome (Downs, 2004), that it wastes time and energy, causes pollution and stress, decreases productivity and imposes costs on society equal to 2-3% of our gross domestic product (GDP) (Cervero, 1998). In terms of technology, it was noted that an automobile is “a conveyance which is capable of moving 1.6 km (a mile) a minute, yet the average speed of traffic in large cities is of the order of 17.7 km/h (11 mph).” (Buchanan, 1963). For 2002, it was estimated that congestion “wasted” $63.2 billion in 75 metropolitan areas during 2002 because of extra time lost and fuel consumed, or $829 per person. (Schrank and Lomax, 2004) Some refer to these kinds of estimates as misleading since the prospect of eliminating all congestion during peak periods is “only a myth; congestion could never be eliminated completely.” (Downs, 2004).While some research emphasizes that “rush hour is longer than an hour in the morning and an hour in the evening and few people are ‘rushing’ anywhere,” others say that “gridlock is not going to happen because people change what they do long before it happens.” (Garrison and Ward, 2000) Some view congestion as a “problem” that individual drivers are subject to, while others emphasize that the users of transportation networks “not only experience congestion, they create it.” It has been shown that most people make travel decisions based on an expectation of experiencing a certain amount of congestion; while “few consider the costs their trips impose on others by adding to congestion.” (Mohring, 1999) The objective of this chapter is to discuss current definitions of metropolitan traffic congestion and ways it is currently measured. In addition, the accuracy and reliability of these measures will be described along with a review of how congestion has been changing over the past few decades.

FRAMING THE ISSUE

Congestion measurement can be thought of as focusing on system performance and measures of people’s experiences. In order to assist in framing the issues, with a focus on how people think about congestion, an unscientific survey about metropolitan area congestion was distributed by email to more than 3,500 transportation professionals and academics, and a total of 480 responses were received. The survey, conducted specifically for this chapter, asked four qualitative questions:

- How do you define congestion in metropolitan areas?
- How is congestion in metropolitan areas measured?
- How accurate or reliable are traffic congestion measurements?
- How has metropolitan traffic congestion been changing over the past two decades?

Respondents were provided with an opportunity to comment on congestion in general. The survey results are described below and are used to motivate later elements of the chapter.

Definition of Congestion

In attempting to define congestion, a total of 557 responses were provided since many responses included separate definitions for freeways and signalized intersections. As shown in Figure 1, survey respondents mentioned time, speed, volume, level of service (LOS) and traffic signal cycle failure (meaning that one has to wait through more than one cycle to clear the queue) as the primary definitions of congestion. Respondents who used the term “LOS” were not more specific; typical LOS measures include volume/capacity, density, delay, number of stops, among others. The majority of the responses included a “time” component—travel time, speed, cycle failure and LOS are all related to the fact that users experience additional travel time due to congestion. It is clear from these responses, that some definitions of congestion rely on point measures (e.g., volume and time mean speed) and some rely on spatial measures (travel time, density and space mean speed).

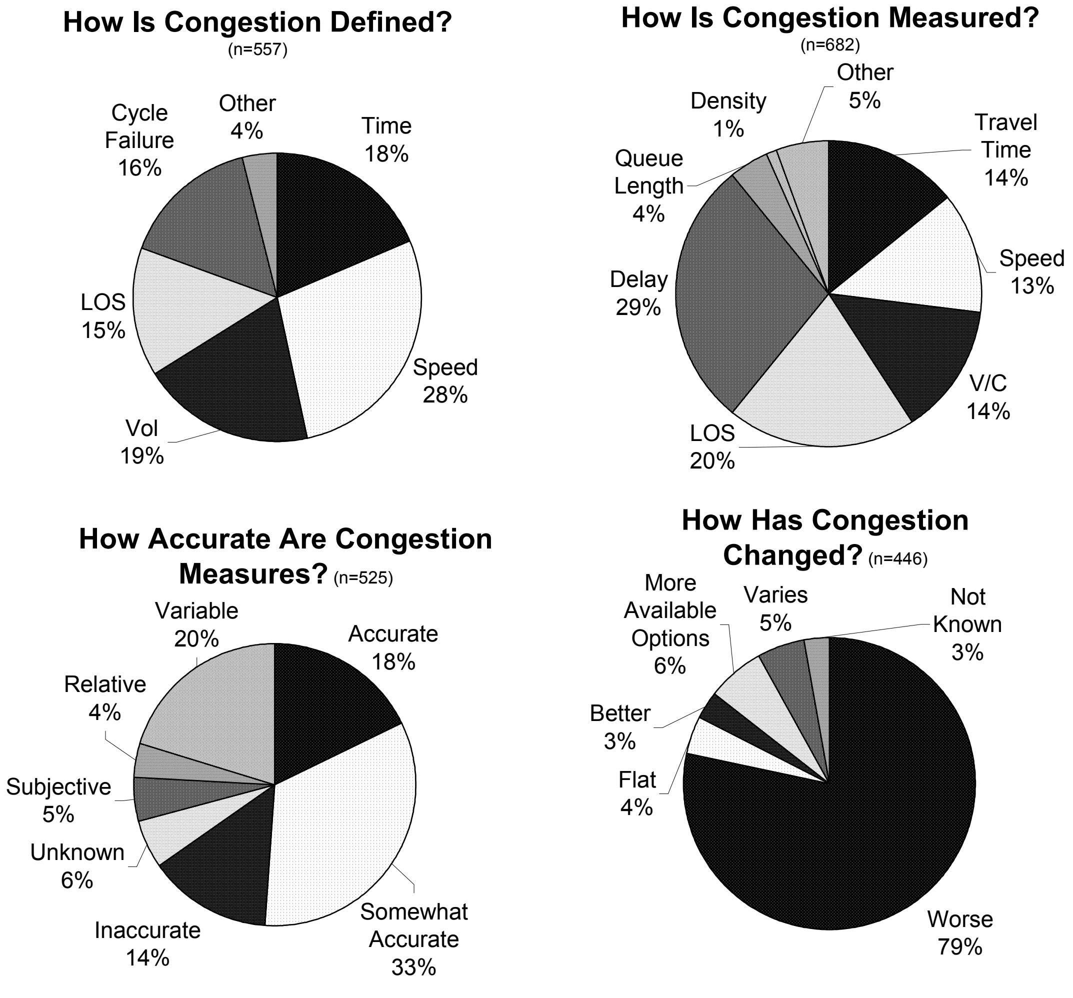


Figure 1. Congestion Survey Results

The definitions of congestion that are related to point measures include vehicle count (expressed as flows) and time mean speed extracted from point detectors (often extrapolated over a segment to estimate link travel time). A point-based travel time estimate can be compared to a free flow travel time for a link, where the difference between actual and free flow travel times is defined as the delay. The product of the number of vehicles to pass a point during a given time interval and the length of an associated segment will provide the vehicle-kilometers traveled (VKT). The product of the number of vehicles passing the point during a time interval and the travel time for the associated link results in the vehicle-hours traveled (VHT). Definitions of congestion related to spatial measures include density, queue length and actual segment travel time (recorded by a probe vehicle). Delay can be calculated as actual travel time over a segment minus the free flow travel time for that segment.

Several survey responses included important comments. It was pointed out that "if we want to reduce congestion we need to be able to define it and quantify it." Some were willing to define congestion as "anything below the posted speed limit," or below some "speed threshold (e.g., <35 mph)." Others noted that "congestion is relative," "a perception" and, "I know it when I see it." One response pointed out that congestion was not so much of a concern anymore since "fortunately we have had an economic collapse." Other surveys have found similar results. In the U.K. respondents defined congestion as stop-start conditions (38%); a traffic jam with complete stops of 5+ min at a time (24%); having to travel at less than the speed limit (19%); and moving very slowly at less than 10 mph (17%). (U.K. Department for Transport, 2001) A conference of European Transport Ministers concluded that there is no widely accepted definition of road congestion, but that an appropriate definition might be: "the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity." (European Conference of Ministers of Transport, 1998) Finally, a survey conducted by the National Associations Working Group for ITS included a response describing the difficulty in defining congestion: "you know it when you see it—and the severity of the problem should be judged by the commonly accepted community standards." (Orski, 2002)

Measurement of Congestion

There were 682 responses to the question asking how congestion is measured (multiple response). As shown in Figure 1, most responses were related to time: delay, speed, travel time and LOS, all of which include the notion that actual travel time can be a primary measure of congestion. Other measures included volume/capacity (point measure) and queue length and density (spatial measures). The small number of responses in the "Other" category included such measures as number of stops and travel time reliability. One responded summed up the issue by stating "it is never truly measured." The literature includes a wide array of possible congestion measures including: volume/capacity (disregards duration),VKT, VKT/lane km, speed, occupancy, travel time, delay, LOS and reliability. In the U.K. survey several helpful measures of congestion were identified: delay (51%); risk of delay (20%); average speed (18%); and amount of time stationary or less than 10 mph (11%).

Accuracy and Reliability of Congestion Measurements

Next, respondents were asked, "how accurate or reliable are traffic congestion measurements?" There were 525 responses to this question, indicating that respondents had mixed feelings about the accuracy/reliability of congestion measurements. As shown in Figure 1, about half of the responses indicated that the measurements are accurate or somewhat accurate, while the other half indicated that they are inaccurate or variable. Many comments indicated that congestion measurements are often based on very small sample sizes, that they are relative and variable and that they should be presented with confidence intervals rather than purely deterministic values. One comment stated that congestion measurements are "reasonably accurate despite the fact that they measure the wrong things," while another stated that "congestion perception is a personal thing based on personal experiences and anecdotes." Finally, one comment indicated that "the result is really just a snapshot in time."

Changes in Congestion

The final survey question aimed to assess the extent to which urban traffic congestion has changed over the past two decades; most respondents indicated that congestion has worsened. Some respondents indicated that more transportation options (such as transit and intelligent transportation systems) are now available and some indicated that congestion has gotten better. The response is not surprising since the U.S. population increased by 24% to 282 million from 1980-2000, the number of highway vehicles has increased 39% to 225 million and the passenger car VKT has increased 44% during the same period. Respondents commented that the impact of congestion has increased in both spatial and temporal dimensions, including the spread of peak periods. Others pointed out that change has been relative, depending on the area and on the user. For example, "western cities are experiencing increasing congestion, as both population and per capita kilometres of travel increase. Some rust belt cities, on the other hand, are experiencing decreasing population and thus are experiencing decreases in congestion." Some respondents indicated that drivers have been conditioned to tolerate more congestion, using an analogy about how to boil a frog: "... start out by putting him cold water, gradually raise the temperature, and he won't figure it out (and thus escape) so he stays 'til he's cooked! We're all gradually getting cooked!"

Several responses pointed out that the congestion will always be a by-product of a healthy, vibrant urban area. In this context, it was pointed out that traditional traffic/transportation engineering antidotes to congestion have been reactive in nature, and that roadways are not improved until there is a problem. Another comment stated that "current conceptions of congestion have more to do with preserving the world as it was, rather than preparing us for the world as it will be," and another stated that there is "too much focus on congestion, there should be more attention to accessibility. What can people get to in a reasonable period of time (20-30 minutes)?" Several respondents indicated that there has been a transformation from the mentality that you can "build your way out of congestion" to the point where other options such as HOV lanes and reversible lanes" are available.

Other Survey Comments

Survey respondents offered comments and suggestions. These included sometime conflicting suggestions to consider alternative transportation strategies such as: congestion pricing, more transit, demand management, regional/statewide approaches, more funding, higher gas taxes, more frequent systematic assessment of traffic operations, driver and citizen information and education, probe vehicles, multi-jurisdictional traffic signal operations, incident reduction, better land use policies, consideration of user vs. system goals, consideration of impacts on health and air quality, focus on moving people during the peak hour, more operations improvements, ITS improvements, more understandable measures, consideration of how trucks affect capacity and simply building more lanes. On the other hand, other respondents suggested: consider equity impacts of congestion pricing, don't build more lanes, don't waste money on ITS, don't waste money on transit and "don't spend too much time on it." Now that the input from a survey of experts has been considered, it is important to examine the literature.

LITERATURE REVIEW

The survey results motivated a comprehensive literature review in order to explore current federal, state and local efforts to define and quantify congestion.

Federal Definition and Monitoring

The Federal Highway Administration (FHWA) defines traffic congestion as: "the level at which transportation system performance is no longer acceptable due to traffic interference." Because there is a relative sense to the word "congestion," the FHWA continues their definition by stating that "the level of system performance may vary by type of transportation facility, geographic location (metropolitan area or sub-area, rural area), and/or time of day," in addition to other variations by event or season. (Lomax, Turner and Shunk, 1997) The definition of congestion is imprecise and is made more difficult since people have different perceptions and expectations of how the system should perform based on whether they are in rural or urban areas, in peak/off peak, and as a result of the history of an area.

Congestion can vary since demand (day of week, time of day, season, recreational, special events, evacuations, special events) and capacity (incidents, work zones, weather) are changing. Most researchers agree that recurrent congestion (due to demand exceeding capacity (40%) and poor signal timing (5%)) makes up about half of the total delay experienced by motorists, while nonrecurrent congestion (due to work zones (10%), incidents (30%) and weather (15%)) makes up the other half. It has been shown that four components interact in a congested system (Lomax, Turner and Shunk, 1997):

- Duration: amount of time congestion affects the travel system.
- Extent: number of people or vehicles affected by congestion, and geographic distribution of congestion.
- Intensity: severity of congestion.
- Reliability: variation of the other three elements.

Because of user expectation, one proposal is to define “unacceptable congestion” as the travel time in excess of an agreed-upon norm, which might vary by type of transportation facility, travel mode, geographic location, and time of day. (Lomax, Turner and Shunk, 1997) “A key aspect of a congestion management strategy is identifying the level of ‘acceptable’ congestion and developing plans and programs to achieve that target.” (Lomax et al., 2001) Based on U.S. Census data, an extensive analysis of commuting patterns has been conducted (Pisarski 1996). In this analysis of journey to work data, there seem to be several thresholds for unacceptable congestion occurring: if less than half of the population can commute to work in less than 20 minutes or if more than 10% of the population can commute to work in more than 60 minutes. It is apparent that several agencies use the term “acceptable congestion,” but clearly this can mean different things to different people and at different times and locations. In this context, it has been argued that individuals and firms may choose to locate in a congested area due to easier access to other individuals and firms. (Taylor, 2002) This highlights the need to consider the interaction between transportation and land use when attempting to define congestion.

The FHWA has initiated a Mobility Monitoring Program based on measured travel time in which they are trying to answer a mobility question: “how easy is it to move around?” and a reliability question: “how much does the ease of movement vary?” The measures used include (Turner, et al., 2002; Lomax, Turner and Margiotta, 2001; Jung, et al., 2004; FHWA, 2004):

- *Travel time index*: ratio of travel conditions in the peak period to free-flow conditions, indicating how much longer a trip will take during a peak time (a travel time index of 1.3 indicates that the trip will take 30 percent longer). The calculation of this index assumes a capacity of 14,000 vehicles per freeway lane per day and 5,500 vehicles per principal arterial lane per day and compares measured VKT to these assumed capacity values.
- *Average duration of congested travel per day* (hours): “How long does the peak period last?” Trips are considered across the roadway network at five-minute intervals throughout the day. At any time interval, a trip is considered congested if its duration exceeds 130% of the free-flow duration. When more than 20% of all trips in a network are congested in any five-minute time interval, the entire network is considered congested for that interval. The total number of hours in which the network is designated as congested is reported in this measure.
- *Buffer index*: this measure expresses the amount of extra time needed to be on-time 95 percent of the time (late one day per month). Travelers could multiply their average trip time by the buffer index, and then add that buffer time to their trip to ensure they will be on-time for 95 percent of all trips. An advantage of expressing the reliability (or lack thereof) in this way is that a percent value is distance and time neutral.

A recent synthesis examined more than 70 possible performance measures for monitoring highway segments and systems (NCHRP, 2003). From users’ perspectives, key measures for reporting the quantity of travel included: person-kilometers traveled, truck-kilometers traveled, VKT, persons moved, trucks moved and vehicles moved. In terms of the quality of travel, key measures included: average speed weighted by person-kilometers traveled, average door-to-door travel time, travel time predictability, travel time reliability (percent of trips that arrive in acceptable time), average delay (total, recurring and incident-based) and LOS.

Other Congestion Definitions and Monitoring

A review of the literature reveals that transportation agencies have adopted particular definitions of congestion for their purposes. INCOG, the regional council of governments in Tulsa, Oklahoma defines congestion as “travel time or delay in excess of that normally incurred under light or free-flow travel conditions.” (INCOG, 2001) INCOG applies their policy of identifying recurring congestion and documenting its magnitude. To do so, traffic counts are compared to capacity and then the ratio of volume/capacity is expressed as a level of service. Tulsa uses traffic counts (and traffic volume forecasts) as an initial screen to locate congested routes and future problems. In Rhode Island, the state DOT recognizes that “congestion can mean a lot of different things to different people.” As a result, the state attempts to use objective congestion performance measures such as percent travel under posted speed and volume/capacity ratios. In Cape Cod, Massachusetts, a traffic congestion indicator is used to track average annual daily bridge crossings over the Sagamore and Bourne bridges. (Cape Cod Center for Sustainability, 2003) This very simple measure was chosen for this island community since it is appropriate, easy to measure, and since historic data are available to monitor long-term trends. In the State of Oregon, the 1991 Transportation Planning Rule (TPR) uses VKT as a primary metric, with a goal of reducing VKT by 20% per capita in metropolitan areas by 2025.

In Minnesota, freeway congestion is defined as traffic is flowing below 45 mph for any length of time in any direction, between 6:00 a.m. and 9:00 a.m. or 2:00 p.m. and 7:00 p.m. on weekdays. Michigan defines freeway congestion in terms of LOS F, when the volume/capacity ratio is greater than or equal to one. Since the function of the transportation system is to provide transport of people and goods, and its benefits are a function of the number of trips served, in California “congestion” is defined as the state when traffic flow and the number of trips are reduced. The California Department of Transportation (Caltrans) defines congestion as occurring on a freeway when the average speed drops below 35 mph for 15 minutes or more on a typical weekday. There is currently a proposal to change the definition of congestion to be measured as the time spent driving below 60 mph, based on analysis of 3363 loop detectors at 1324 locations as part of the California Performance Measurement System (PeMS) database (Varaiya, 2002). The State of Washington DOT aims to provide congestion information (in plain English) that uses real time measurements, reports on recurrent congestion (due to inadequate capacity) separately from nonrecurrent congestion (due to incidents). This includes the measurement of volumes, speeds, congestion frequency, and geographical extent of congestion, travel time and reliability. The Washington DOT also focuses on travel time reliability and predictability by presenting a “worst case” travel time for a set of corridors such that commuters can expect to be on time for work 19 out of 20 working days a month (95 percent of trips), if they allow for the calculated travel time. (Washington State Department of Transportation, 2004)

The Urban Congestion Report

The Urban Mobility Report (UMR) (Schrank and Lomax 2004), sponsored by a consortium of state departments of transportation and several interest groups, has been conducted by the Texas Transportation Institute since 1982 (FHWA 2004). The very popular UMR (see http://mobility.tamu.edu) tracks congestion patterns in the 75 largest U.S. metropolitan areas. The main mission of the UMR is to convert traffic counts to speeds, so that delay can be computed. Since 2002, the UMR has also reported on the contributions of operational strategies (such as incident management and ramp metering) and public transportation have on reducing delay (FHWA 2004).

The UMR uses several measured variables reported as part of the Highway Performance Monitoring System (HPMS). The HPMS was developed by the FHWA and the states in 1978 to promote a systematic, national approach for identifying highway conditions, estimating capital investment needs, and measuring changes in highway conditions over time (Hill et al. 2000). In support of the HPMS, states are required to report 70 data elements on pavement condition, traffic counts, and physical design characteristics for a statistical sample of about 100,000 highway sections. For some segments, traffic count data are available from continuous (usually hourly) automatic traffic recorder systems, while on other segments these data are measured over 48 hour periods on a triennial basis. The UMR uses the following measured and reported variables for its analysis (for facilities defined in the HPMS as freeways and principal arterials):

- Population: U.S. Census data are obtained for metropolitan areas. The census definition of a metropolitan area may or may not coincide with city, county or metropolitan planning organization (MPO) limits or urban growth boundary.
- Urban Area Size: this variable is based on census definitions of metropolitan areas.
- Segment Length: length of each freeway or principal arterial segment.
- Number of Lanes: number of lanes for each freeway or principal arterial segment.
- Average Daily Traffic (ADT): total daily traffic volume of freeway or principal arterial segment.
- Directional Factor: estimate of directional split for average daily traffic volume.

The UMR takes these measured parameters and follows some well-documented procedures toward the production of the performance measures listed above. In order to complete the process, a number of assumptions and constants are used, including:

- Vehicle Occupancy: 1.25
- Working Days Per Year : 250.
- Consumer Price Index (CPI): taken from the U.S. Department of Labor.
- Value of Time: $13.45 (2002 value; adjusted using CPI).
- Commercial Vehicle Operating Cost: $71.05 (2002 value; adjusted using CPI).
- Vehicle Mix: 5% commercial vehicles.
- Fuel Cost: taken from the American Automobile Association.

- Peak Periods: assumed to be 6:00-9:30 AM and 3:30-7:00 PM.
- Percent of Daily Travel in Peak Period: assumed to be 50%.
- Uncongested "Supply" (vehicles per lane per day): assumed to be 14,000 for freeways and 5,500 for principal arterials.
- Relation between Road Congestion Index (RCI) and Percent of Daily Travel in Congested Conditions: the RCI is a ratio of daily traffic volume to the supply of roadway, and is applied using one piecewise linear relation (see Exhibit B-4 in Schrank and Lomax 2004).
- Relation between ADT and Speed for Freeway (Peak and Off Peak Direction) and Arterial (Peak and Off Peak Direction): applied using equations (see Exhibits B-7 and B-8 in Schrank and Lomax 2004).
- Free Flow Speed: assumed to be 96 km/h (60 mph) for freeways and 56 km/h (35 mph) for principal arterials.

Given the measured or estimated traffic counts, data describing the length and numbers of lanes for each freeway and principal arterial segment and the constants described above, the UMR then computes nine derived variables for each metropolitan area:

- Daily VKT by Facility Type: based on Segment Length and ADT data.
- Lane Miles by Facility Type: based on Segment Length data.
- Road Congestion Index (RCI): a ratio of daily traffic volume to the supply of roadway, based on Daily VKT and Lane Kilometer data.
- Percent of Congested Travel During Peak Period: based on RCI Relation.
- VKT by Congestion Level and Direction: based on Percent of Congested Travel and Directional Factor data.
- Segment Speed by Congestion Level and Direction: based on Relation between ADT and Speed.
- Delay: based on Speed and Free Flow Speed.
- Travel Rate (minutes/km) by Facility Type (actual and free flow): based on calculated actual Speed and Free Flow Speed.
- Travel Rate Index (TRI): based on VKT and Travel Rate.

Given the count based estimates of speed, and assuming free flow speeds by facility type, the UMR reports four primary performance measures:

- Annual Delay per Traveler: Extra travel time for peak period travel during the year for freeways and principal arterials.
- Travel Time Index (TTI): The ratio of travel time in the peak period to the travel time at free flow conditions.
- Travel Delay: Extra travel time for peak period travel above that required for travel at free flow conditions.
- Excess Fuel Consumed: Increased fuel consumption due to travel in congested conditions rather than free-flow conditions.

- Congestion Cost: Value of delay and excess fuel consumption converted to dollars for person and commercial vehicle travel.

It is clear that the UMR results are based on traffic count data that were originally collected for system monitoring. No actual traffic speeds or measures extracted from real transportation system users are included, and it should be apparent that any results from these very limited inputs should be used with extreme caution. To its credit, the UMR does leverage existing data sources (using 6 measured variables and 13 constant values or relations) and produces a document that provides a basis for drawing some limited conclusions. The annual release of the UMR results in widespread media coverage and often major headlines describing worsening congestion and comparing one metropolitan area to another. However, the UMR authors caution against comparisons between cities, emphasizing that the UMR is more appropriate for comparisons of trends for individual cities, rather than focusing on any value for a particular year. Further, the performance measures should be viewed with skepticism since in any one year, there are traffic counts that are three years old, very limited data (48 hour counts) are extrapolated over the entire freeway and principal arterial system, and the U.S. Census definitions of metropolitan area populations and areas may be at odds with a region's actual boundaries or urban growth boundary. The Census definition of "urban" may be different than that of a particular region, and traffic volumes actually accommodated in a metropolitan area may be excluded from the UMR due to boundary definition inconsistencies. It is also worth noting that there may be a lag in reporting changes to metropolitan area population and size data coupled with lags in reporting changes in the extent of the freeway and arterial system. This may result in spikes in the reported UMR performance measures.

A number of other seemingly arbitrary assumptions are also worth noting. The UMR applies uniform definitions of vehicle occupancy, vehicle mix, lengths of peak periods, amount of travel occurring during peak periods, daily capacities of freeway and principal arterial lanes, and the relations between volume and speed. It is probable that the combination of measurement error noted above plus the errors introduced by these constants end up producing results with some quantifiable error distribution—but this is not reported. The UMR also defines congestion as travel occurring at anything less than a pre-defined national value of free flow speed. As noted earlier in this chapter, there may be diverging opinions about what an appropriate speed threshold for congestion should be—again this is not included in the UMR. With this review of the literature in mind, there are some basic theoretical issues that should be explored, so that various metrics and their derivations can be better understood.

SOME BASIC THEORY

Having reviewed the literature, it is clear that many common traffic measurements are derived from the basic traffic flow parameters—flow, density and speed. This section describes how these fundamental measures can be applied at the level of the roadway segment, a corridor and over an entire door-to-door trip.

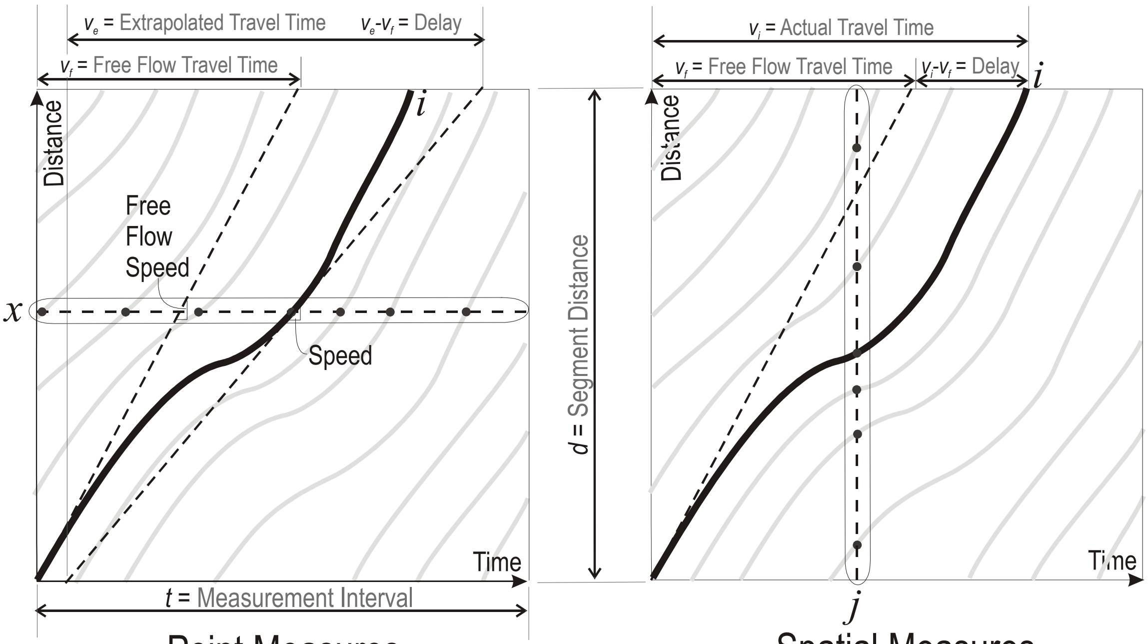
Segment Level

Figure 2 illustrates some basic points about traffic flow. In Figure 2(a), a set of vehicle trajectories on a time-space plane is shown in the context of a roadside observer (or detector) at location *x*. (Daganzo, 1997) During time interval *t*, an observer would count 7 vehicles passing point *x*. Flow, a point measure, is defined as the number of vehicles that pass a point during a particular time interval; in this case $7/t$, usually expressed in vehicles/hour. Under certain circumstances the "capacity" of the highway at point *x* might be estimated, and the actual measured volume could be compared to that theoretical capacity value in the form of a volume/capacity ratio. Speed could also be measured at point *x*, for example by a radar gun. If the arithmetic average of the speeds measured at a point is taken over a measurement interval *t*, this is called the time mean speed.

Figure 2(b), which also shows a set of vehicle trajectories on a time-space plane, illustrates that some key traffic flow parameters are measured over distance. For example at time *j*, the number of vehicles on the segment *d* at that instant would be counted as six vehicles. The density at time *j* is the number of vehicles on the section at that time divided by the section length, in this case $6/d$, usually expressed in vehicles/km. The actual travel times of vehicles can also be recorded over space; in this case for vehicle *i*, its travel time is shown as v_i. The free flow travel time for segment *d* might be assumed to be v_f. Therefore, for vehicle *i* on this roadway segment the delay is defined as v_i-v_f.

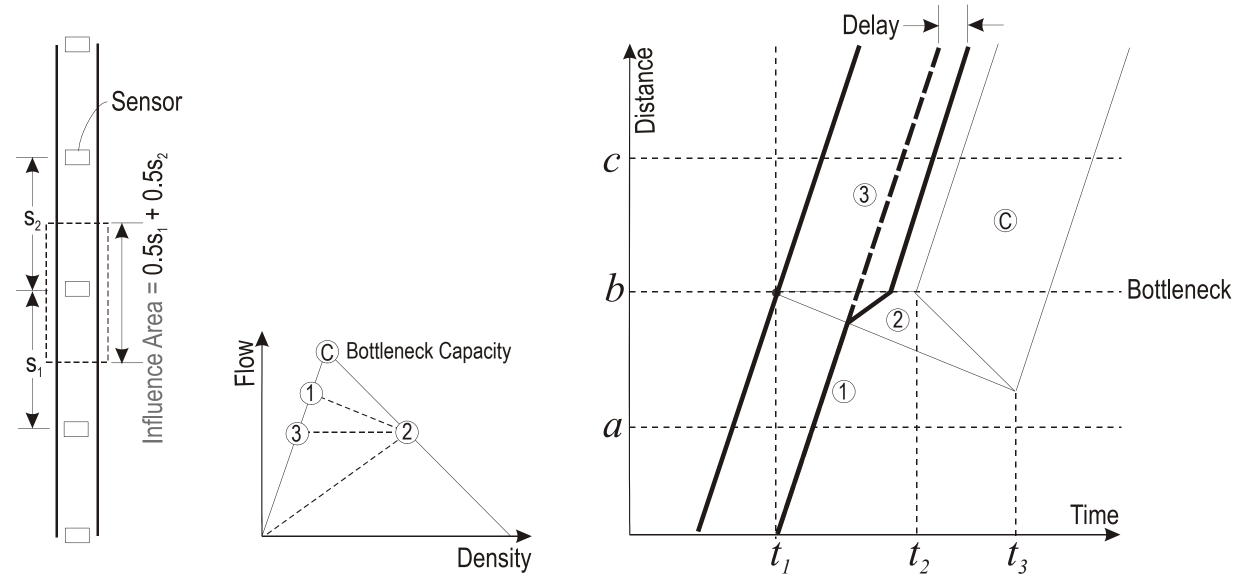
Depending on what data collection system is available, sometimes a point measure, such as speed, can be applied over a roadway segment. As shown in Figure 2(c), if a roadway is equipped with measurement sensors, a sensor's area of influence can be assumed to be the distance between the upstream and downstream midpoints between each detector pair. In Figure 2(c) this would be equal to $0.5s_1+0.5s_2$. For federal reporting purposes, as part of the HPMS, limited point-level count and speed measurements are taken on a sampling of urban roadway locations for one 48-hour period every three years and extrapolated over the entire roadway network. Figure 2(a) also shows how a point speed measured at location *x* can be extrapolated to determine segment travel time, v_e for vehicle *i*. This can be used to estimate the delay for vehicle *i*, v_e-v_f.

Figure 2(d) illustrates the basic relation between fundamental traffic flow variables on a density-flow plane for the hypothetical road segment shown in Figure 2(c). (Coifman and Mallika, 2004) The relation is approximated as a triangle, where zero flow occurs when there are no vehicles on the facility—density and flow are both zero. Zero flow also occurs when density increases to a level such that all vehicles must stop—the speed and flow are zero. (FHWA, 2003) Figure 2(d) illustrates four distinct traffic states: 1, 2, 3 and C. Traffic states 1, 3 and C fall on the unqueued branch of the flow-density relation, while state 2 falls on the queued branch. Figure 2(e) illustrates several issues related to the measurement of traffic parameters along a highway segment where an incident of some kind occurred at a bottleneck location *b* at time t_1. (Coifman and Mallika, 2004) Prior to time t_1, traffic along this



Point Measures
(a)

Spatial Measures
(b)



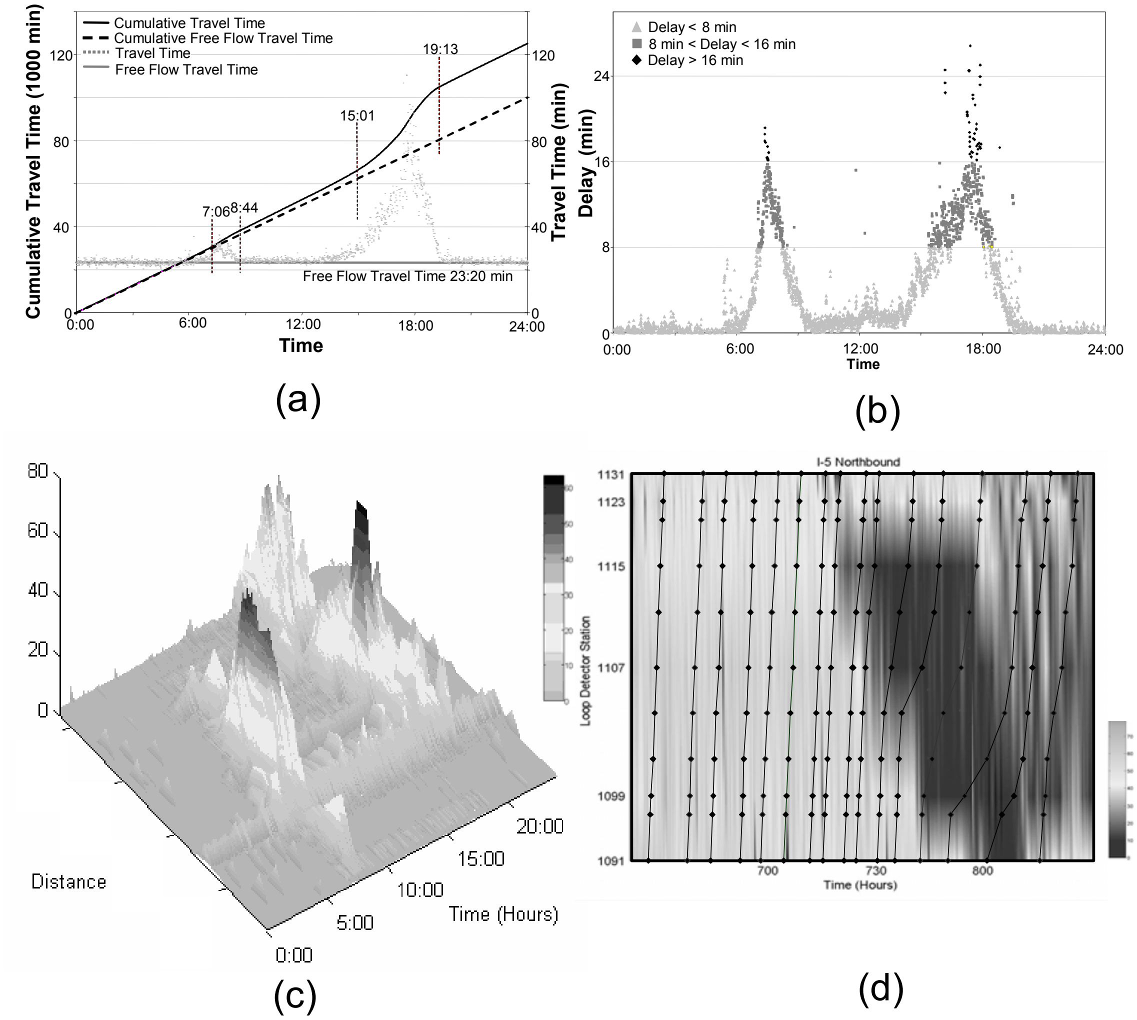
(c) (d) (e)

Figure 2. Segment Level Measures of Congestion

hypothetical road segment was in state 1. At t_1 traffic transitioned abruptly to state 2, with lower flow, lower speed and higher density. A shock passed backwards. The traffic state just downstream would be characterized by state 3. At some time t_2, the bottleneck was deactivated, so a backward moving recovery wave passed upstream until it intersected with the initial shock at time t_3. During the recovery, traffic flowed at state C until it returned to state 1. It is very important to understand how, when and where bottlenecks occur on a highway. For example, in Figure 2(e) if a detector were located at location *a*, it never would have “seen” queued traffic and furthermore if a vehicle entering the road section at time t_1 had received traffic speed information recorded at locations *a*, *b* or *c* prior to t_1 that motorist would have had no way of predicting the actual delay that was later experienced. Also, if a detector were located at point *c*, traffic speeds would remain high throughout the entire time period shown, falsely characterizing the segment conditions as unqueued. Thus, depending on where traffic conditions are monitored, it is possible to misreport actual conditions; this would adversely affect congestion measures for a segment.

Corridor Level

It is possible to compute congestion-related measures over a larger freeway corridor where more detection locations are available. Travel time can be calculated from real-time or archived freeway sensor data by extrapolating a measured speed value over an influence area



(a)

(b)

(c)

(d)

Fig

Figure 3. Corridor Level Congestion Indicators

(segment). For example, Figure 3(a) shows travel time versus time for one day on northbound Interstate 5 in Portland, Oregon. This was performed over this 35.2 km (22 mi) corridor using data from inductive loop detectors at 25 locations that recorded count, occupancy and speed at 20-sec intervals. The figure also illustrates the cumulative travel time and free-flow travel time (dashed line) throughout the day. As the cumulative line deviates from the cumulative free-flow travel time the travel time increases can be clearly observed. At 7:05 the travel time increased from 23 min. to 28 min. Similarly, at 19:42 the travel time decreased from 49 min. to 24 min. The free-flow travel time on this day was approximately 24 min.

One of the costs of congestion is delay, defined as the excess time required to traverse a section of roadway compared to the free flow travel time. As shown in Figure 3(b), the average delay was calculated for northbound Interstate 5 over five weekdays. Delay was estimated based on the difference between actual travel time and the free-flow travel time on the freeway segments. Total delay for each detector station, defined as the sum of all delay at that station throughout the day, is shown on a three-dimensional plot in Figure 3(c) for the southbound direction. For locations that indicate higher delays, as an example, a DOT can focus its incident response efforts to reduce further delays. From this plot one can see several spikes of delay that occurred at key bottlenecks along the corridor.

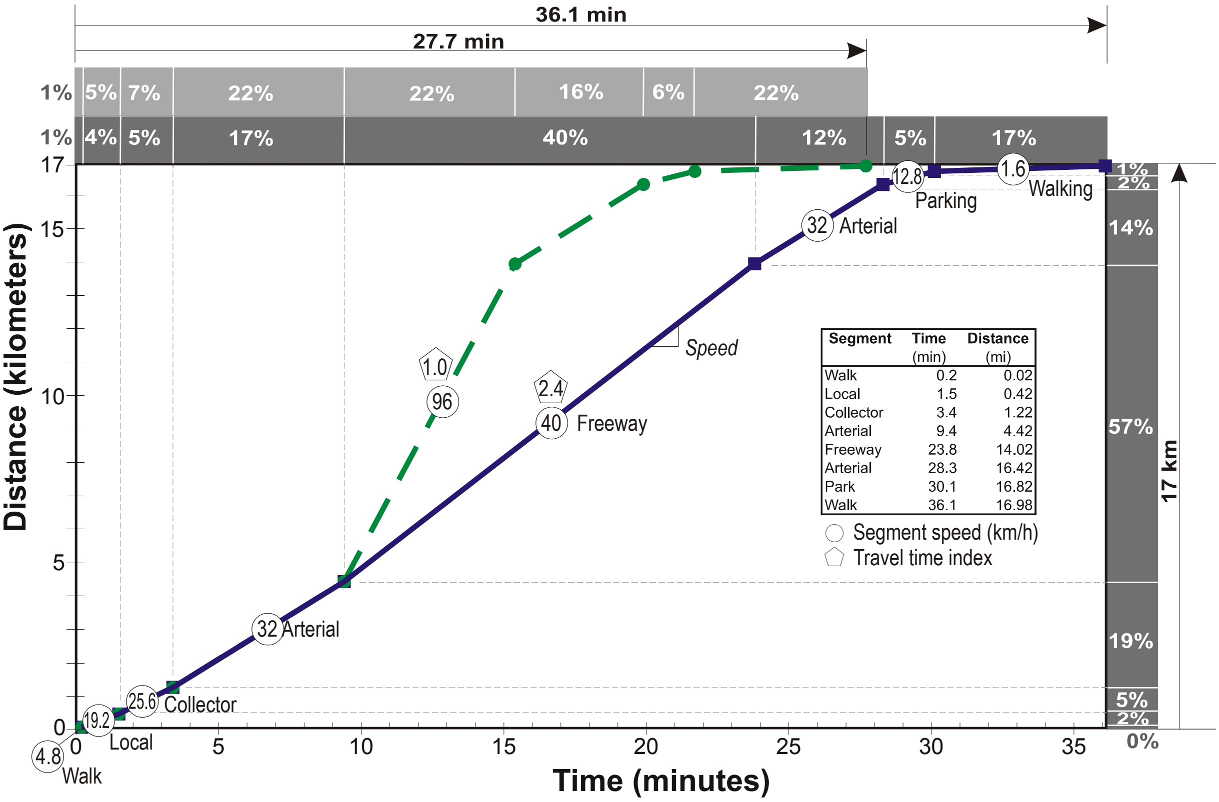
Figure 3(d) shows a speed plot for northbound Interstate 5 on one day, where the greyscale variation represents the average speeds measured at 20-second intervals at six detector stations. In addition, 20 express bus trajectories recorded from an automatic vehicle location (AVL) system have been superimposed over the speed plot, indicating that the loop detectors can provide a good indication of mean travel time for a corridor. The slopes of the trajectories changed at nearly the same locations where the freeway speed declined (darker grey). This method was used to show how accurately the speed is reported by the loop detectors. Statistical analysis was used to validate that there was no evidence of difference between the means at the 95% level of confidence.

Table 1. Percentage of U.S. Lane Kilometers and Vehicle Kilometers Traveled by Facility Type, 2000

	Total Lane Km	% Lane Km	Total VKT (Million)	% VKT
Freeway	401,400	3.0	1,353,100	30.6
Arterial	1,523,500	11.6	1,840,000	41.5
Other	11,258,400	85.4	1,234,600	27.9
Total	13,183,400	100.0	4,427,700	100.0

Consideration of Total Trip

As shown in Table 1, freeways comprise about 3% of the lane km in the U.S., but they carry more than 30% of the traffic. (FHWA, 2002) Most congestion measures are relevant for a particular link, with a focus on freeways since that is where the most traffic is located and where sensors are in place. Some researchers point out that what is relevant for the traveler is the entire door-to-door trip (Taylor, 2002). For example, Figure 4 is based on Taylor (2002) and illustrates a hypothetical vehicle trajectory (solid line) on a time-space plane. For this trip, the traveler walks to her car, travels on a local street, collector and arterial, followed by a freeway segment, an arterial, a parking lot, and finally walks from her car to her workplace. This trip took 36.1 min and traversed 17 km (10.6 mi). As shown on the *x*- and *y*-axes of Figure 4, the congested freeway component of the trip (at 40 km/h) accounted for 57% of the distance and 40% of the total travel time. On this trip 60% of the travel time occurred off of the freeway. If we focus on the freeway segment and imagine a solution that would return freeway speeds to free-flow conditions (96 km/h), the trip time would be reduced to 27.7 min, as shown by the dashed line. As shown on the *x*-axis, this would reduce the freeway segment's share to 22% of the travel time; now 78% of the trip time would occur off the freeway. It is worth noting that improving freeway conditions may impact many more trips than improvements to other links in the network.



Segment	Time (min)	Distance (mi)
Walk	0.2	0.02
Local	1.5	0.42
Collector	3.4	1.22
Arterial	9.4	4.42
Freeway	23.8	14.02
Arterial	28.3	16.42
Park	30.1	16.82
Walk	36.1	16.98

Figure 4. Door-to-Door Trip Times

METROPOLITAN LEVEL MOBILITY MEASURES

When thinking about ways to measure congestion at the metropolitan scale, it is important to remember that our current perceptions are strongly influenced by what happened during the 1960s and 1970s in the U.S. This period (within the memory of many of today's drivers) was one of relatively low congestion since the Interstate system construction era provided much greater expansion in travel capacity than the growth in travel during the same period. (Lomax, Turner and Shunk, 1997) The result was that in many large urban areas traffic congestion actually decreased. This recent experience frames the debate in that some would like to try to return mobility levels to those earlier conditions

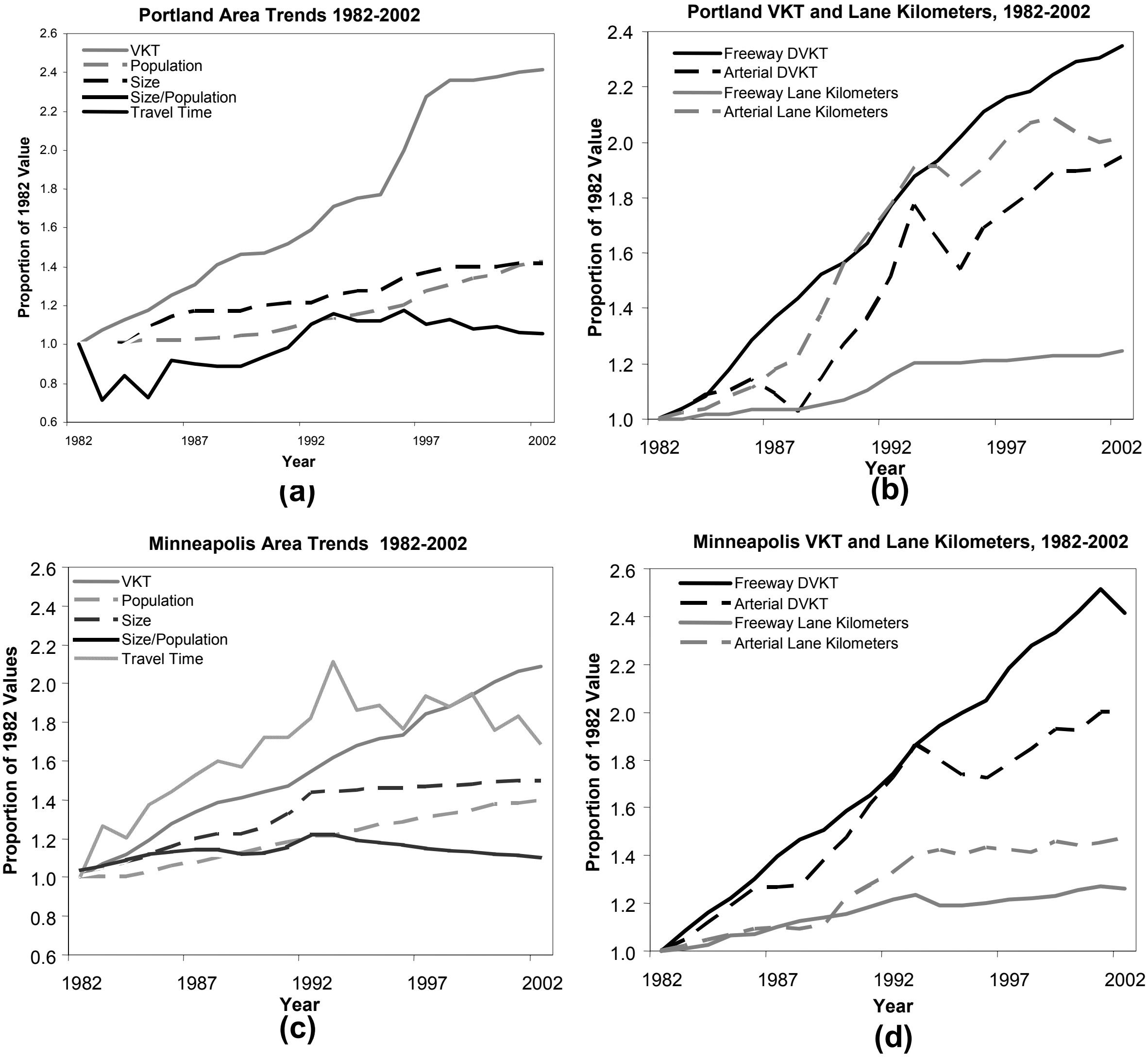
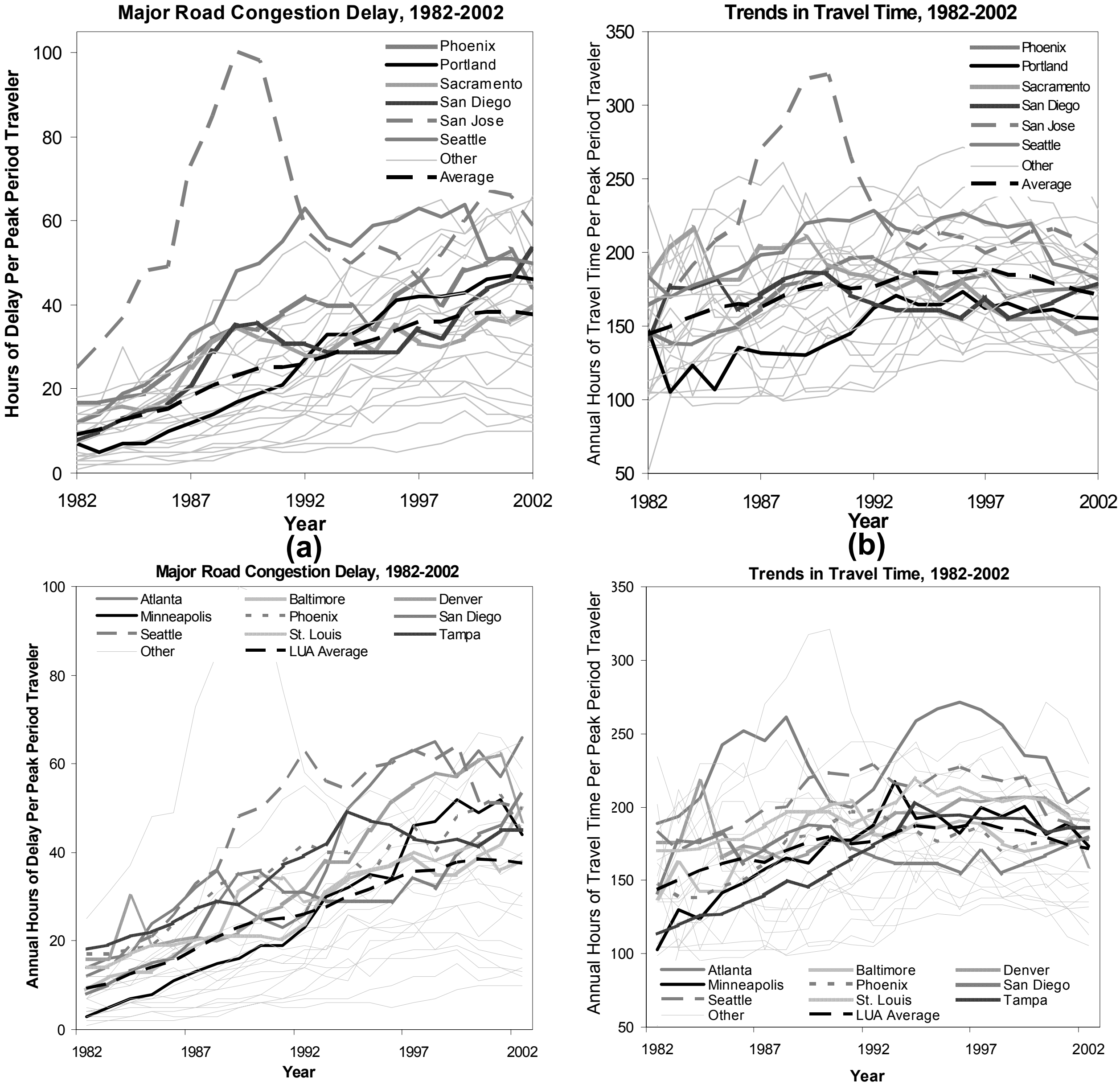


Figure 5. Portland and Minneapolis Travel Trends, 1982-2002

Using data from the 2004 UCR (Schrank and Lomax 2004), a recent study was conducted to begin tracking transportation performance in Portland, Oregon (Portland State University, 2004; Gregor, 2004) for the past 20 years. Keeping the caveats mentioned above regarding the UCR in mind, as an example, Figure 5(a) shows trends in the proportional change in VKT, population, metropolitan area size (sq. mi.), the ratio of size to population and average travel time in peak periods for the Portland, Oregon-Vancouver, Washington urbanized area since 1982. For example, the plot indicates that the VKT in 2002 was 2.4 times that recorded in 1982 while the population and size were nearly 1.4 times their 1982 values. The travel time, on the other hand is nearly the same as it was in 1982. Focusing on freeways and principal arterials, Figure 5(b) shows that daily VKT on Portland-Vancouver area freeways more than doubled between 1982 and 2002, and has also doubled on arterials. Lane km on arterials have been added at a rate greater than the increase in VKT. However, lane km on freeways have increased by only 25 percent over the past 20 years. The gap between VKT and lane km on freeways may explain the declining speeds on Portland-Vancouver freeways. Figures 5(c) and 5(d) show similar data for Minneapolis-St. Paul, Minnesota. As shown in Figure 5(c), population and metropolitan area size have increased to 1.4 times their values in 1982, while the ratio of size/population has remained constant. VKT has approximately doubled and peak period travel time has reportedly increased to more than 1.6 times its 1982 value. As shown in Figure 5(d), Minneapolis-St. Paul's freeway VKT and lane km grew at similar rates to those in Portland-Vancouver, but the notable difference is that the extent of the arterial system has not kept pace in Minneapolis-St. Paul.



(a) (b)

(c) (d)

Figure 6. Comparing Urban Area Delay and Travel Times, 1982-2002

As part of the Portland performance measures analysis, the Portland-Vancouver urbanized area was compared to 26 other urban areas with populations between 1-3 million. (Portland State University, 2004) Despite the caveats and limitations in the UMR data mentioned above, as shown in Figure 6(a), when comparing the 20-year trends for Portland-Vancouver with other urban areas, the highlighted lines are for six western peer cities: Phoenix, Sacramento, San Diego, San Jose and Seattle, plus Portland-Vancouver. The lighter grey lines are for the remaining cities the 1-3 million population category, and the dashed black line represents the average value measured across all 27 Large cities. Figure 6(a) is a comparison of the hours of delay per peak period traveller as reported by the UMR. Delay in all cities has been increasing. This figure shows that annual congestion delay estimated for peak period travelers in Portland-Vancouver reportedly increased from 7 hours per year in 1982 to 46 hours per year in 2002, and has remained close to the mean value for similarly sized cities. It had been below the average before 1992, and exceeded the average after that. Portland-Vancouver's peer cities have larger estimates of delay in 2002. In Portland-Vancouver, it appears that shorter-than-average travel distance coupled with lower-than-average travel speed has leveled off the delay actually experienced by travelers.

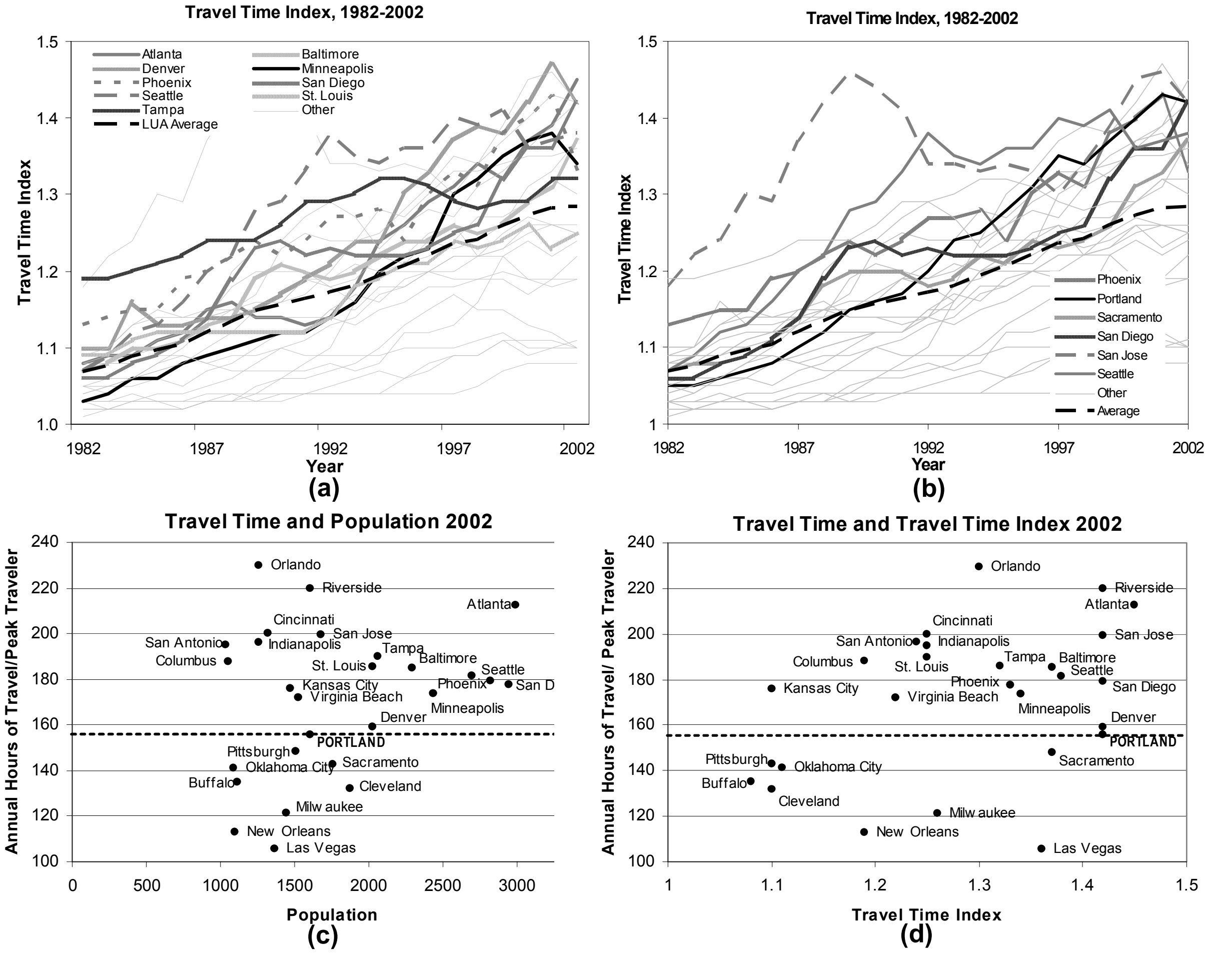
Figure 6(b) compares the average peak period freeway and major arterial travel time reported by the UMR. This figure shows that Portland-Vancouver's annual travel time per peak period traveler has remained below the average of all Large metropolitan area and has actually declined slightly in recent years. The reported mean travel time for Portland-Vancouver's peer cities also tended to be higher than average. Again, for Portland-Vancouver, shorter-than-average travel distance, coupled with operational improvements, some capacity improvements, and expansions of the public transportation system has eased the impact of congestion on travel time. It is difficult to draw conclusions from these comparisons—and some of the trends are easier to explain than others. For example, the large drop in delay and travel time for San Jose might be explained by the opening of several new freeways in the 1990s. Other fluctuations (such as for Seattle) may be explained by economic conditions.

Similarly, Figure 6(c) shows 20-year trends on delay with a focus on Minneapolis and 8 other cities with populations between 2-3 million: Atlanta, Denver, Phoenix, Seattle, Tampa, Baltimore, San Diego and St. Louis. The average trend in reported delay is shown for all 27 cities with populations between 1-3 million. As shown, Minneapolis began somewhat below average in the delay measure but now falls above average. As shown in Figure 6(d), the trend in mean travel time is similar, yet the more recent data illustrate that the travel time for Minneapolis is about average among all cities in the 1-3 million population range.

Using comparisons as in Figure 6, Figures 7(a) and 7(b) illustrate the Travel Time Index (TTI) trends between 1982-2002 for Portland and Minneapolis, respectively. As noted, based on limited traffic count data, the TTI is the ratio of travel time in the peak period to the travel time at free-flow conditions for freeways and principal arterials. A value of 1.35 would indicate that a 20-minute free-flow trip took 27 minutes in the peak. These figures show that the TTI for both cities is comparable with other peer cities in this category. Figure 7(c) shows a scatter plot of population vs. peak period travel for the 27 cities with populations between 1-

3 million. Portland's population is 13th out of the 27 large cities (25th out of all 85 cities), and the amount of travel per peak period traveler is 19th out of the 27 large cities. The population of Minneapolis is 5th out of the 27 large cities, yet the annual hours of delay per peak period traveler is only the 16th highest. Figure 7(d) shows that the annual amount of travel per peak period traveler in Portland is among the 9 lowest when compared to other large cities, while the Travel Time Index for Portland is among the top 6 out of the 27 large cities. In the case of Minneapolis, the Travel Time Index is 11th among the 27 large cities.

The presentation of comparative plots using the UCR data leads to the question of whether the measures shown are the correct measures, or whether the proper variables are actually being measured. For example, would it be better to measure actual speeds, consider reactions from actual travellers, or compute confidence intervals for the reported performance measures? This concern for considering other issues beyond traffic counts at discrete points motivates the discussion presented in the next section.



(a) (b)

(c) (d)

Figure 7. Comparing Urban Area Travel Time Index, Population and Travel Times, 1982-2002

GOING BEYOND CONGESTION MEASURES

The earlier discussion of the congestion survey results, the presentation of the literature review with a focus on understanding the UCR and other definitions of congestion, and the comparative results just described lead to more questions. Do we need to go beyond the congestion measures currently used? The comparisons just drawn are aggregate in the sense that they are derived from very general UCR measurements that were designed for one purpose and used for another. It is thus important to consider going beyond these measurements when attempting to grasp the issues related to congestion. It is also important to use caution when using these results for informing policy decisions—it is possible that performance is being measured incorrectly and that the wrong things are being measured. First, the concept of a travel time budged will be examined briefly.

Travel Time Budget

It has been mentioned above that the journey to work time has remained stable in recent years despite large increases in VKT. Some authors have stated that "average journey to work time changed little as suburban road and highway expansion has accommodated growing number of trips." (Garrison and Ward, 2000) It is said that typical commutes are actually becoming shorter. (Garreau, 1991) The concept of a "travel time budget" was conceived and has been investigated over many years. (Zahavi and Ryan, 1980; Zahavi and Talvitie, 1980; Ryan and Zahavi, 1980) When looking back at development patterns of even ancient cities, the average travel time to work locations has been relatively stable for a few thousand years, and that people have maintained a total daily travel time budget of roughly one hour over the past 5,000 years. (Lomax, et al., 2001; Ausubel and Marchetti, 2001; and Shafer and Victor, 1997) This point has been linked to an assessment of the size of cities as transportation technology has evolved. (Crawford, 2000) For example, if we consider that the maximum accepted (average) commute time is about 45 minutes, it has been reported that the city of Istanbul was approximately 9.6 km in diameter in the sixteenth century. In that case and if people walked at about 6.4 km/h it would have taken 45 minutes to walk from the city's periphery to the city center. (Garreau, 1991)

Several studies have attempted to document these phenomena more specifically. In one study it was shown that the average weekly commuting time for males and females in the U.S.S.R. between 1910-1990 ranged between 4.2 and 5.8 hours week, which would have translated to 50-70 minutes per day with a five day work week. (Grübler, 1990) Another study analyzed aggregate survey data from 1958 and 1970 in Washington, D.C. and Minneapolis-St. Paul, and found that in both cities and at both times, travelers averaged approximately 1.1 hours of travel per day. (Ryan and Zahavi, 1980) A more recent paper has provided more up to date values of travel budget for Washington, D.C. and the Minneapolis-St. Paul regions. (Levinson and Wu, 2005). The authors rejected the notion of a travel time budget, found increasing commute times in Minneapolis and concluded that commute time clearly depends on the spatial structure of an urban area.

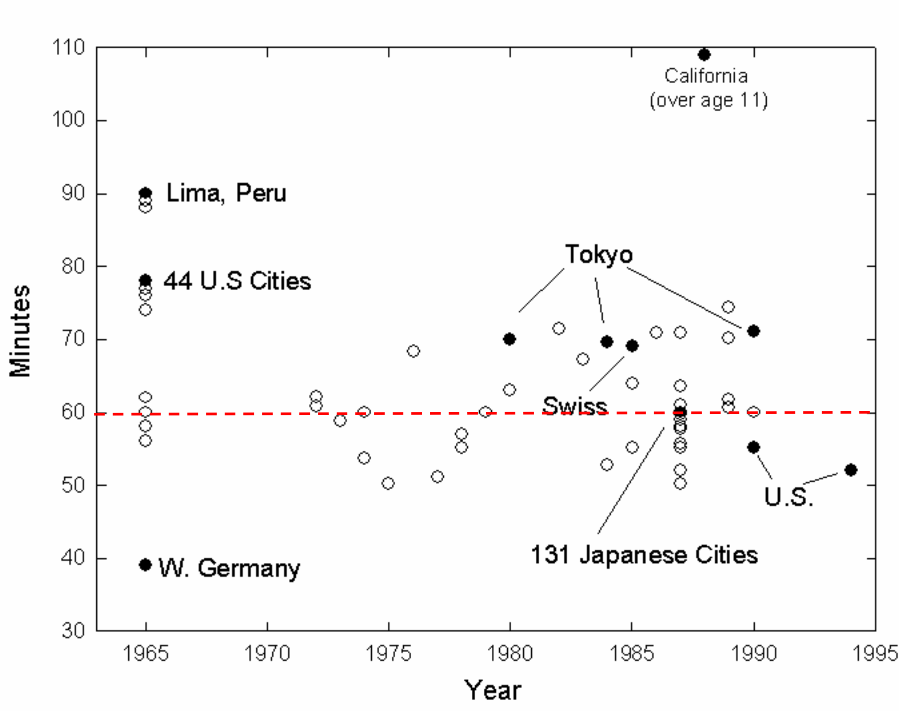


Figure 8. Travel time budget (source: Ausubel, Marchetti and Meyer)

Finally, a comprehensive analysis of daily travel between 1965-1995 in various U.S. and international cities, it has been noted that it appears that people travel about one hour per day. As technology has evolved, the distance traveled per day in the U.S. has increased approximately 2.7% per year from 4 km (walking) in 1880 to approximately 80 km per day in 1990. (Ausubel, Marchetti and Meyer, 1998) As an extract from this work, Figure 8 shows representative data for studies of the U.S. and a dozen other countries since 1965. Despite one obvious outlier from a California study, the figure does indicate that much of the available data centers on the 60 minute range. With this in mind, in order to provide some balance against the measures described up until this point, a short discussion of some other viewpoints on congestion measures will now be presented.

Other Viewpoints

A number of authors have been presenting slightly different views about traffic congestion. Some have noted that successful cities are places where economic transactions are promoted and social interactions occur, and that traffic congestion occurs where “lots of people pursue these ends simultaneously in limited space.” (Taylor, 2002; Downs, 2004) It has also been stated that congestion is not necessarily all bad, since it can be a sign that “a community has a healthy growing economy and has refrained from over-investing in roads.” (Cervero, 1998) Similarly, it has been noted that unpopular places rarely experience congestion (Garrison and Ward, 2000) and that declining cities have actually experienced reductions in congestion. (Taylor, 2002)

Given the limitations of metro level congestion indices, some alternative techniques have been proposed. For example, a congestion burden index (CBI) was proposed to account for the presence of commute options. (Surface Transportation Policy Project, 2001) The CBI is the travel rate index multiplied by the proportion of commuters who are subject to congestion by driving to work. For example, the 1999 Portland travel rate index was 1.36 (rank 8), and the transit share was 0.14. So the CBI was 1.36×(1-.143) = 1.16 (rank 14). As another indicator that the provision of transportation choices in an urban area is helpful, the transportation choice ratio was also proposed (Surface Transportation Policy Project, 2001), which is calculated by dividing the hourly km of transit service per capita by the lane km of interstates, freeways, expressways and principal arterials for each metro area. It has also been recognized that there is an interaction between personal lifestyles and traffic congestion. Some have noted that during peak periods, only one-third to one-half of all trips are work trips (Lomax, et al., 2001).

Knowing that congestion is often poorly measured, there are few standard indices and it is difficult to compare congestion across metro areas and years, a capacity adequacy (CA) has been proposed. (Boarnet, Kim and Parkany, 1999) The CA system establishes six capacity levels for highway classifications between principal arterials in rural areas to major urban expressways, based on peak hour traffic flow rather than daily VKT. The CA is calculated as 100 × (capacity/volume during present design hour). In this equation, the capacity is estimated and design hour volume is based on the 30th highest hour (rural) or 200th highest hour (urban). This analysis was performed at a county level for California counties; the CA for each highway was weighted by ADT and summed for the entire county. This measure would be in contrast to the UMR calculations, where the capacities of freeway and arterial lanes are fixed at 14,000 and 5,500 vehicles per hour per lane respectively. Given these other research efforts aimed at improving the way congestion is measured toward providing better inputs to policy makers, it is perhaps not surprising that current research is under way as well.

Current Research

With many decades of work to define and monitor congestion as a backdrop, this section discusses some current research efforts that are revealing some fundamental changes in how vehicles use the highway system. For example, very high sustained freeway flows have been measured, more than 20% greater than was once considered to be a theoretical maximum (Lomax, et al., 2001; Cassidy and Bertini, 1999). This means that drivers are accepting very short headways, such that one vehicle's hesitation can cause other vehicles to brake suddenly (Lomax, et al., 2001). This also has immense safety implications. In addition, it has been shown that under some circumstances, freeway flows drop when congestion forms. On Canadian, German and U.S. freeways, this drop is in the range of 2-11% (Cassidy and Bertini, 1999; Bertini, et al., 2004, Zhang and Levinson, 2004), while in Los Angeles, there are reports that the uncongested flows of 2,000 to 2,500 vehicles per hour per lane (vphpl) drop to about 1,400 to 1,600 vphpl. (Garrison and Ward, 2000). Finally, earlier studies have mentioned the need to protect transit vehicles from congestion (Buchanan, 1963). Recent developments in bus rapid transit and transit signal priority are taking advantage of opportunities to exploit some gains in improving person travel through congested corridors. (Byrne, et al., 2004) Finally, there is increasing evidence shows that travelers and shippers, when making travel-related choices, consider not only the absolute extent of congestion, but also its temporal variation. As one means to examine this, a regional transportation data archive has been established in Portland, Oregon, and includes systems for automatically generating system performance measures (Bertini et al. 2005). Figure 9 illustrates a sample monthly report for one freeway segment (northbound Interstate 5) for April 2005. This automatically generated plot shows the mean travel time (by 5-minute time slice), the 95th percentile travel time and the congestion frequency for each time interval (right hand axis). There is a need to continue these and other research programs in order to improve our understanding of how the transportation system operates at both microscopic and macroscopic levels.

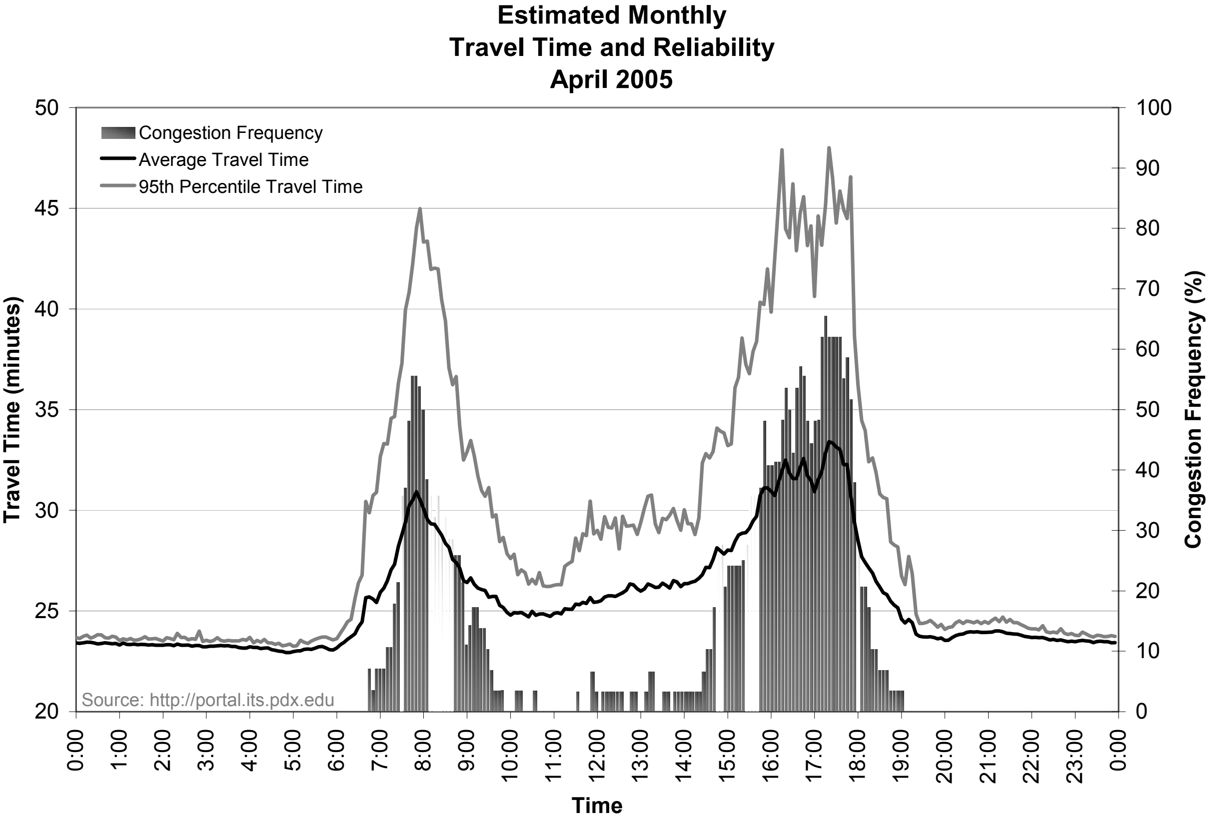


Figure 9. Travel time reliability.

FINAL REMARKS

"Congestion is people with the economic means to act on their social and economic interests getting in the way of other people with the means to act on theirs!" (Pisarski, 2005)

This chapter has covered a lot of territory, and it would be difficult to provide a definitive conclusion, since work in this area is continuing on many fronts. Instead, this section mentions a few important points that should be considered when thinking about congestion. It is generally felt that congestion on the nation's highway system continues to increase, both in reality and in people's perceptions. The notion of simply expanding capacity is limited due to constraints in transportation finance and in public acceptance because of environmental impacts. Efforts to reduce congestion and improve safety through operational means and with improved public transportation should and will continue. One implication of this situation is that since congestion cannot (and some would argue should not) be eliminated the standard methods for measuring and reporting system performance in those terms are no longer very useful. We can no longer simply evaluate the effects of road widening projects on vehicles using limited, aggregate measures such as traffic counts, VKT, the volume/capacity ratio and LOS, nor is it helpful to apply arbitrary speed or volume thresholds across all facility types. These limited measures are usually derived from simple, limited data (e.g., average volumes, number of lanes) extrapolated over large segments of the network and do not consider the impacts on different types of users. The current poor measurements may also be clouding our thinking and leading to irrational policy actions. These factors limit the specificity of performance reporting to large areas and generalized effects. Given new developments that allow for more robust data collection and demands for reporting actual system performance, we can no longer rely on the old way of system performance measurement.

Improvements or changes to the transportation system will impact different users differently—and the magnitude of that impact depends on the type of travel (e.g., freight, commute, recreation) and when their travel needs occur. Therefore, we now need to develop the ability to assess how different system users and society in general are affected by congestion and how that would change with different congestion mitigation actions. For example, reducing congestion on a highway serving a retail center might not be as beneficial as reducing congestion on a freight route because shoppers may be less sensitive to congestion delay than manufacturers and shippers, especially where just-in-time delivery is an important business practice.

In order to reliably estimate how congestion affects different travelers we need three things. First we have to know who is on the congested highway links and how and why they're traveling. Second we need to understand the trip characteristics that are important to travelers (e.g., travel time, reliability). Third, we need data that can be used to estimate these important trip characteristics. For example, if truck movements to and from a high tech manufacturing area are occurring on a congested highway segment, and if travel time reliability is an important travel characteristic, then we must be able to collect performance data that can be used to estimate travel reliability. Future efforts to define and measure traffic congestion should include these important principles. These efforts may include the development and expansion of transportation data archiving systems, the extraction of detailed travel behavior data using floating car data (probe vehicles), and the improvement of tools provided to transportation and land use decision-makers.

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