Freight Performance Measure Approaches for Bottlenecks, Arterials, and Linking Volumes to Congestion Report

August 2015

U.S. Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-HOP-15-033		

4. Title and Subtitle	5. Report Date
Freight Performance Measure Approaches for Bottlenecks, Arterials, and Linking Volumes to Congestion Report	August 2015
	6. Performing Organization Code
7. Author(s) Richard Margiotta, Bill Eisele, and Jeffrey Short	8. Performing Organization Report No.
9. Performing Organization Name and Address Cambridge Systematics, Inc. 4800 Hampden Lane, Suite 800 Bethesda, MD 20814	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFH61-11-D-00012
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Freight Management and Operations 1200 New Jersey Avenue, SE Washington, DC 20590	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Section 1115 of MAP-21 ("National Freight Policy") specifically requires the development of new tools and improvement to existing tools to support the analysis and evaluation of freight transportation projects in order to more strategically target investments and improve performance of the transportation system. This report deals with three aspects of this directive:

1. Comprehensive analysis of freight bottlenecks—research and evaluation of national and state level approaches to identifying freight bottlenecks and methodologies for measuring the performance of truck freight bottlenecks;
2. Arterial mobility performance—development of methods that produce valid and reliable performance measures from truck-based probe data, speed and travel times; and
3. Linkage of truck volumes to congestion methodologies—development of methods for integrating travel times from truck probe data with truck volumes, flows, and demands.

The National Performance Management Research Data Set (NPMRDS) is being used to develop examples of the recommended analysis.

17. Key Words	18. Distribution Statement
Freight, Bottlenecks, Performance, Measures, Mobility	No restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	106	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AOG	Arrival on Green
ARC	Atlanta Regional Commission
ATRI	American Transportation Research Institute
AVC	Automatic Vehicle Classification
AVI	Automatic Vehicle Identification
BTI	Buffer Time Index
DMI	Distance Measuring Instrument
DOT	Department of Transportation
EDRG	Economic Development Research Group
ELPR	Electronic License Plate Reader
FCAT	Freight Chokepoint Analysis Tool
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GDOT	Georgia Department of Transportation
GIS	Geographic Information System
GPS	Global Positioning System
HCM	*Highway Capacity Manual*
HOS	Hours of Service
HPMS	Highway Performance Monitoring System
HSM	*Highway Safety Manual*
ID	Identification Document
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation Systems
LRTP	Long-Range Transportation Plan
MAC	Media Access Control
MAP-21	Moving Ahead for Progress in the 21st Century Act
MMUT	*Mobility Measurement in Urban Transportation*
MOE	Measures of Effectiveness
MPO	Metropolitan Planning Organization
MTTI	Mean Travel-Time Index
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
NPMRDS	National Performance Management Research Data Set
pcphpl	passenger cars per hour per lane
POG	Percent Arrivals on Green
PTI	Planning-Time Index
RHiNo	Roadway-Highway Inventory Network
SCAG	Southern California Association of Governments
SESRC	Social and Economic Sciences Research Center
SHRP 2	Strategic Highway Research Program 2
TMAS	Travel Monitoring Analysis System
TMC	Traffic Message Channel

TOPS-BC	Tool for Operations Benefit Cost Analysis
TTI	Texas A&M Transportation Institute
TWG	Technical Working Group
TxDOT	Texas Department of Transportation
VCTIR	Virginia Center for Transportation Innovation and Research
VHT	Vehicle-Hours of Travel
VMT	Vehicle-Miles of Travel
VOR	Value of Reliability
VOT	Value of Typical Time
VTRIS	Vehicle Travel Information System
WIM	Weigh-in-Motion

CHAPTER 1. INTRODUCTION

1.1 PURPOSE OF THIS GUIDE

The U.S. freight system serves the world's largest economy. The highway portion of the freight system comprises 4 million miles of paved public roads. It also involves not only transportation agencies, but also private trucking firms and shippers. Because of the strong ties to private industry and the health of the general economy, freight performance becomes a unique functional performance area. Understanding freight performance and matching solutions to performance problems is critical to improving the movement of goods in the Nation.

The Federal Highway Administration (FHWA) has developed this Guide with two purposes in mind: 1) to provide best practices and approaches on several key areas of freight performance measurement; and 2) to develop practical guidance in analyzing truck freight bottlenecks to State departments of transportation (DOT) and metropolitan planning organizations (MPO).

This Guide will assist analysts with identifying and analyzing truck performance in general and truck freight bottlenecks specifically. This Guide specifies step-by-step procedures for analysts to follow, including data assembly and manipulation. Where applicable, limitations of the data and procedures are identified.

A Technical Working Group (TWG) formed by FHWA and comprised of State and local agency personnel with a stake in analyzing freight bottlenecks, reviewed the development of this Guide. They were instrumental in ensuring that the methodology developed is comprehensive and useful to practitioners.

1.2 GUIDE ORGANIZATION

The structure of this Guide is as follows:

- **Chapter 2—**Summarizes of previous work on truck freight performance and bottleneck analysis is presented.
- **Chapter 3—**Covers the issue of matching traffic volumes to congestion data.
- **Chapter 4—**Presents data and methods for measuring congestion on signalized arterials.
- **Chapter 5—**Incorporates material from the previous chapters—along with new material—into a comprehensive methodology for analyzing truck freight bottlenecks.

1.3 SUMMARY OF PAST WORK

1.3.1 Background

A series of case studies provided documentation of the existing methodologies and practices related to truck freight bottleneck analysis, including the measurement of truck travel times on signalized arterials and the development of truck volumes to use in conjunction with travel-time data. The documentation used a matrix approach with a common template with a number of criteria:

- Reasons for conducting the analysis.
- Stakeholders/users.
- Data and models used.
- Methodology.
- Identification of bottlenecks.
- Raw data processing.
- Performance and cost measures.
- Recommended treatments.
- Scalability.
- Follow-up activities.
- Areas for methodological improvements.

There were 15 case studies that were undertaken:

1. Texas Freight Mobility Plan.
2. North Carolina I-95 Economic Impact Study.
3. Houston/Galveston Intermodal Connector Analysis.
4. American Transportation Research Institute (ATRI)/Federal Highway Administration (FHWA) Congestion and Bottleneck Analysis.
5. Georgia Department of Transportation (GDOT) Freight and Logistics Plan (Bottleneck Analysis Component).
6. Atlanta Regional Commission (ARC) Strategic Truck Route Master Plan.
7. Southern California Association of Governments (SCAG) Regional Goods Movement Project.
8. Texas Top 100 Congested Roadways.
9. 2012 Urban Mobility Report.
10. 2011 Congested Corridors Report.
11. Northwest Arkansas Congestion Analysis.
12. Twin Cities Arterial Mobility Performance.
13. Freight Chokepoint Analysis Tool (FCAT).
14. Assessment of Multi-modal Freight Bottlenecks for the Upper Midwest Region.
15. Bottleneck Performance in the I-95 Corridor.

1.3.2 Case Study Findings

The results of the case study analyses are presented in appendix A using a common template. A summary of the findings follows:

- In general, the degree of sophistication in the methods, and the ability to provide high-resolution and accurate results, depends on the quality and nature of the data that are used, regardless of the analytic method. Older studies relied on “planning-level” data—typically traffic volumes, truck percentages, and information about physical capacity. The primary performance metric of interest—travel-time or a variant of it—was developed by the use of models. Recent studies have used primarily vehicle probe travel-time data from private vendors. These data offer a great step forward in that they are actual measurements rather than modeled estimates.

- Global positioning system readings produce data from on-board or personal devices, but are heavily processed by the vendors so that any origin and destination (O/D) data are lost. This is true of the vendors that provide the data as speeds assigned to a link, usually defined by the Traffic Message Channel (TMC) standard. It also is more advantageous to have specific freight truck data rather than general traffic data, as several studies have confirmed both route and speed differences between cars (including taxis and limousines) and freight trucks. The American Transportation Research Institute (ATRI) has access to unprocessed truck data and thus has been able to develop O/D information from their data.

- Methodologies for producing performance measures from data are very similar, but would benefit from consistent/standardized processing procedures. Developing high-level performance measures from low-level data requires multiple processing steps, and there are usually multiple ways to perform each step. Default values also are often necessary, and these can vary depending on the methodology. The result is that different values can result from processing the same basic data.

- Past studies have taken the facility-based view of truck impacts but truckers and shippers are usually more concerned with the performance of the entire trip. The reason that facility performance is so prevalent is that this is the level at which the data are available; true O/D data that would define entire trips are very rare. One study explored synthesizing trip travel-time data from facility-specific data as an option. In general, incorporating the user's perspective into freight performance is a key step to advance the state of the practice. However, both perspectives provide for a comprehensive freight performance management program, especially since the majority of improvements that can be effected by transportation agencies are facility focused.

- The current methodologies do not "drill down" to identify the causes of congestion. Model-based methods have considered only recurring (physical bottleneck-related) congestion. Methods based on continuously collected travel-time data capture all potential sources of congestion, but the methods to date have not decomposed congestion into its sources.

- Bottlenecks related to the physical geometry of the roadway are the most prevalent type in these studies. While these types of bottlenecks tend to be the most severe, other types such as those created by operating policies and restrictions have not been covered. Again, we suspect that this is an artifact of the facility-based data that are used in the studies.

- Only a few studies have translated truck congestion into general economic impacts. Data on the commodities carried by trucks traversing bottlenecks is the main limitation.

- Freight bottleneck methodologies start with simple methods to "scan" for potential locations. The scans can be based on:

    - **Vehicle Probe Data—**Looking for links with a significant amount of slow vehicle speeds, especially if the links are in sequence (indicates queuing).

- **Inventory Data (e.g., Highway Performance Monitoring System (HPMS))—**Highway sections with high volume-to-capacity ratios.

- **Anecdotal Information—**Often the best information is to ask State and local engineers and planners who are usually aware of problem locations.

- Since most methodologies reviewed consider geometric (recurring) bottlenecks, physical characteristics such as interchanges, bridge crossings, and lane drops are matched against the data scans. This step is necessary to identify other causes of "links with slow speeds" such as long-term work zones or bad weather, and to give the bottleneck an identity.

- Performance measures used in the studies are the usual suite of travel-time-based measures, made truck-specific. Delay is a common metric because it can be valued.

- Arterial truck performance is very important for access to port/transfer facilities, but this has not been widely studied, perhaps because more serious truck bottlenecks occur on freeways. Data limitations are another possible reason. A few studies have used vehicle probe data in largely the same way as for studying freeway bottlenecks. While vehicle probe data should provide the necessary content, there are technical concerns (e.g., stopped delay at signals appears to be a problem).

- Even the more recent studies, which use vehicle probe data to develop detailed travel-time measures, rely on planning-level estimates of truck volumes. Short count-produced truck volumes may not be reflective of actual truck volumes on an individual facility. Further, matching the network georeferencing used for vehicle probe data with the georeferencing used by transportation agencies is a huge technical obstacle.

1.3.3 Suggestions for Final Methodology Based on Technical Working Group

1.3.3.1 Discussion

- There was much support by the TWG favoring the gathering of anecdotal data at several levels, including the initial identification of potential bottleneck locations and truck stakeholders' perceptions of the significance/severity of impact. It was suggested that the methodology provide guidance on how agencies develop anecdotal information (who to contact, what questions to ask, how to use the information, etc.). However, anecdotal information is not a substitute for data in performance analysis. For example, it is not possible to determine the percent of trucks on roadway by interviewing several shippers or analyzing a small number of supply chains.

- The issue of impacted users at freight bottlenecks was discussed. From the perspective of a supply chain, delay at a bottleneck may only account for a small portion of the total trip, and thus would not be viewed as a significant problem. In addition, if the bottleneck is related to peak weekday periods or times of inclement weather, scheduling would reduce the impact to the supply chain. The methodology should at least acknowledge this fact and offer guidance on how to decompose the different types of users affected by freight bottlenecks. The Research Plan recommended this as one of the topics for further discussion.

- The TWG suggested that part of the methodology should be identifying the causes of congestion at bottlenecks. As mentioned in the presentation, it is important for analysts to define the nature of the bottleneck, especially when reviewing system-wide scans based on travel-time data. However, no original research on this topic was conducted, as there is other recent material that can be appropriated (e.g., Strategic Highway Research Program 2 (SHRP 2) Projects L02 and L03). Additionally, National Cooperative Highway Research Program (NCHRP) Project 8-98 (*Guide for Identifying, Classifying, Evaluating, and Mitigating Truck Freight Bottlenecks*), which is being conducted simultaneously, will be exploring the congestion-by-source issue in depth.

- The methodology should be scalable to both rural and urban settings. A major issue in rural issues is the nature of the current generation of vehicle probe data: the roadway sections that vendors use for reporting travel times can be excessively long in rural areas (more than 20 miles) and long sections can mask bottlenecks. This underscores the need to have good anecdotal data on bottleneck locations, but some form of supplemental travel-time data may be required in these cases.

- An ongoing freight performance measurement program should house the methodology. One way to approach this is to consider freight bottleneck identification and analysis as a second or "drill-down" step in a system-wide freight performance measurement system. System-wide monitoring produces high-level statistics on how the system is performing. The freight bottleneck methodology is a tier lower than this as it searches for specific locations that are congestion trouble spots. How to design and maintain a freight performance measurement system is beyond the scope of this work, but recommendations on now it can be integrated with the freight bottleneck methodology will be made.

- As part of the bigger picture, an agency-wide performance management program should incorporate the freight bottleneck methodology. Here, the methodology would provide input to procedures such as agency target setting and tradeoff analyses with other functional areas such as safety, pavement, and bridges. How to conduct tradeoff analyses with other project and program types also is beyond the scope of this project, but we will ensure that the freight bottleneck methodology's usefulness is discussed.

- Recent work on bottleneck analysis has emphasized the use of vehicle probe data from private vendors as the primary data source. The reason for this that it has extremely wide coverage and is cost-effective. However, as of this writing, these data may not provide accurate performance information on signalized arterials. To a very large extent, the methodology is neutral as to how the data were collected; all that is required are travel times and volumes. Regardless of the technology, data from any source gets transformed into travel times and volumes before the analysis is started. So while the preprocessing may be different, the actual analysis stays the same.

CHAPTER 2. MATCHING TRAFFIC VOLUMES TO CONGESTION DATA

In any bottleneck analyses, there is a need to combine traffic volume data with speed (travel-time) data for performance measure calculation. This chapter discusses various travel-time and truck volume data sources and processing procedures to match these two data sources.

2.1 DATA SOURCES

2.1.1 Travel-Time Data

A number of travel-time data sources are available for truck bottleneck analysis. Several of these sources are described below.

2.1.1.1 Vehicle Probe Data from Commercial Sources

Over the last decade, and particularly in the last few years, the transportation industry has experienced increased availability of probe data sources for speed (travel-time) data. The typical arrangement is that companies who resell the speed data have agreements with fleet owners/ managers and others to obtain the probe data. Some of these companies also have probe data coming in from navigation devices or smartphone apps—all sources of travel-time information. The "value-add" of these commercial companies is that they aggregate and summarize the speed (travel-time) data based upon their multiple-source probes. Coverage is often comprehensive on higher functional classification roadways (freeways, highway, and major arterials). Typically, vehicle probe data are obtainable in annual summaries for a 15-minute or hourly time period, or more detailed data are available for every predefined time intervals ("epochs") over a long time span (e.g., continuously collected over a year). These data are commonly available at 5-minute or even 1-minute epochs. Some vendors of vehicle probe data can provide truck-specific speed (travel-time) data in a similar format.

An example of a probe data source is the Federal Highway Administration (FHWA) National Performance Management Research Data Set (NPMRDS), which provides travel-time data in 5-minute time aggregations (throughout the year) for both trucks and passenger cars on the traffic message channel (TMC) roadway network. TMC is the traveler information industry standard roadway network geography used for reporting traveler information.

2.1.1.2 Bluetooth Readers

Bluetooth readers allow for the collection of travel-time information between two points on a roadway. Bluetooth readers can identify the media access control address (MAC address) unique identifier at two locations along a roadway. Associated commercial software provides travel-time information between the two locations based on matched MAC addresses and related time stamps.

For short-term studies, Bluetooth readers can be deployed in portable weather-resistant cases with a portable battery source. For permanent continuous data collection, Bluetooth readers are most commonly installed in existing traffic signal systems cabinets. This solution provides the most cost-effective solution as the signal cabinets offer weather resistant, a power source, and in some cases, a real-time communications link.

The Texas A&M Transportation Institute (TTI) summarized a number of additional observations about Bluetooth readers as part of an FHWA Pooled Fund Project (TPF-5[198], *Mobility Measurement in Urban Transportation [MMUT]*). The observations include:[1]

- Bluetooth reader placement is somewhat dependent on whether the application is short-term data collection or permanent continuous data collection.
- For both short-term and permanent Bluetooth readers, the antenna should be placed at vehicle windshield height or higher (at least three feet) to minimize obstructions.
- In addition to antenna height, the antenna configuration (e.g., type, power level, etc.) is an important parameter that should be optimized at each installation.
- The spacing of Bluetooth readers varies based on the application, the roadway type, the level of through traffic, and Bluetooth read radius.
- The data is only available for blue tooth devices in the "discoverable" mode.

The University of Maryland has performed extensive research on outlier filtering during the post-processing of historical Bluetooth reads. The interested reader is referred elsewhere for more information on these post-processing techniques.[2,3]

2.1.1.3 Toll-Tag Readers

Another way to directly measure point-to-point travel-time information is with toll-tag readers, a form of automatic vehicle identification (AVI). Toll-tag readers detect toll-tag-equipped vehicles for tolling operations. The presence of a toll tag allows motorists to travel through a lane at highway speeds and have tolls removed from a toll-tag account. This expedites travel, as motorists do not need to go through the cash lanes. The toll-tag system inherently obtains time stamp and vehicle identification information. Travel-time information between toll-tag readers is obtainable from such a system. To protect privacy concerns, vehicle identification information is anonymized so individual (known) vehicles are not "tracked" but rather travel-time information on the general travel stream are available. Because known vehicle types are not identified, this type of system generally does not allow for obtaining truck-specific travel-time information because travel time is aggregated for all vehicles in the traffic stream.

An example of using toll-tag information for travel-time data is the Houston TranStar® Traffic Map where travel-time data are provided by AVI readers throughout the roadway network. While only selected roadways in the network are tolled, there are ample toll-tags in the Houston

---

[1] Turner, S. M. Bluetooth-Based Travel-Time Data Collection. Task 1.2 Technical Report, FHWA Mobility Measurement in Urban Transportation Pooled Fund Project, September 2010.

[2] Haghani, A., M. Hamedi, K. F. Sadabadi, S. Young, and P. Tarnoff. *Data Collection of Freeway Travel-Time Ground Truth in Bluetooth Sensors*, Transportation Research Record No. 2160, Transportation Research Board of the National Academies, Washington, D.C., 2010. Available: http://trb.metapress.com/content/4885780436228757/.

[3] Traffax, BluSTATs Operations Manual, BluSTATs Version 1.2B, February 16, 2009.

area for obtaining system-wide travel-time information. Figure 1 shows the Houston TranStar® Traffic Map powered by AVI readers, and also includes other traveler information. Again, a limitation is that the data cannot readily differentiate trucks from cars.

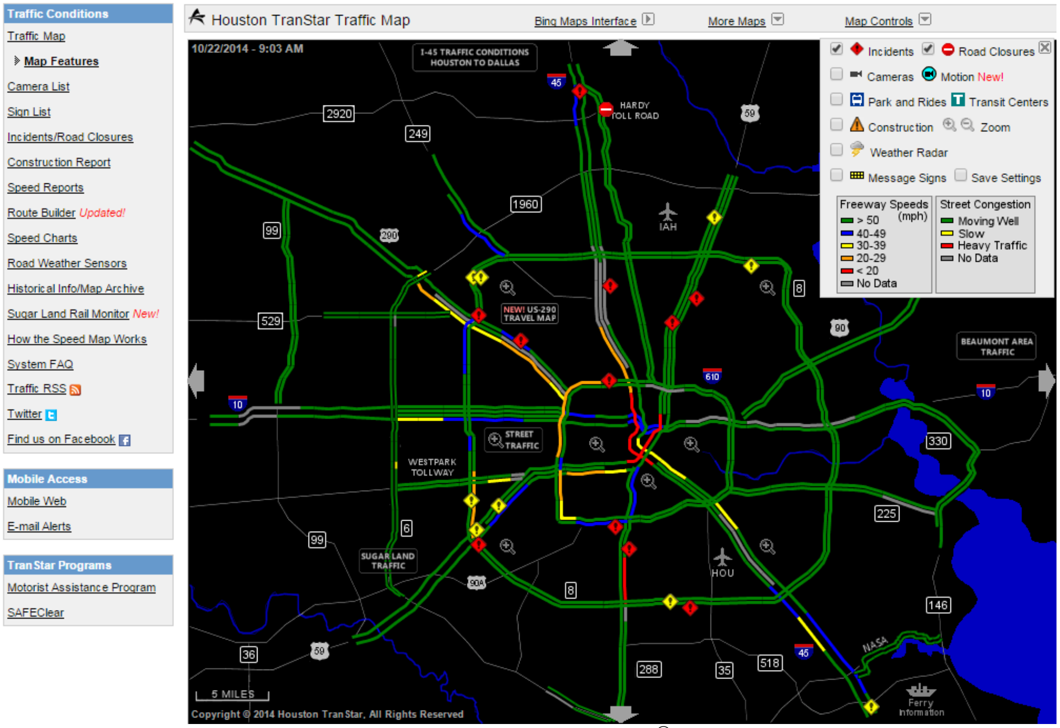


Figure 1. Map. Houston TranStar® traffic map.
(Source: Texas Department of Transportation (TxDOT)—Houston TranStar®. Last accessed October 28, 2014, http://traffic.houstontranstar.org/layers/.)

2.1.1.4 Intelligent Transportation Systems Roadway Detectors

Intelligent Transportation Systems (ITS) roadway detectors are another method of speed data collection. These detector technologies represent traditional monitoring equipment used by public agencies to monitor traffic conditions. Typical ITS detector types include:

- Inductive loops.
- Magnetometer.
- Piezoelectric or bending plates (weigh-in-motion).
- Radar.

These technologies all can provide speed, classification and speed data. Piezoelectric or bending plates also can provide weight information. Speeds can be grouped by classification with these detectors (i.e., speeds for a few length-based truck classes are available). Unlike the methods for speed data collection mentioned up to now, ITS roadway detectors may allow for the measurement of speed information by lane.

A key distinction with these technologies is that speeds are obtained "at a point" rather than direct measurement of travel time along the roadway link of interest as obtained with Bluetooth or toll-tag readers. To obtain travel time from these speeds, the analyst must convert these speeds to a travel time along the link of interest. One typical way to do this is to assume the point speed is representative across the entire link and to divide the link length by the (point) link speed to obtain a travel time along the link of interest.

More details about ITS detector technologies can be found in FHWA's *Traffic Detector Handbook.*[4, 5] Another good source for those new to the technologies is the "Equipment" section of the *Traffic Monitoring in Federal Lands* on-line training.[6]

2.1.1.5 Electronic License Plate Readers (ELPR)

License plate reader systems are another method for obtaining travel-time information between two points in the roadway network. In this method, license plates are read at one location upstream and then at another location downstream. A time stamp is obtained at both the upstream and downstream location and the difference in these times for matched license plates provide an estimate of the travel time through the link of interest. Character recognition software provides for more automated ELPR. ELPR can be performed manually using tape recorders, portable computers, or video with manual transcription. Data collection and reduction times are more significant with the manual methods.

2.1.1.6 Test-Vehicle Travel Time

In its most manual form, the test-vehicle method of obtaining travel times includes having a driver traverse a corridor while a recorder/observer operates a stopwatch to identify time stamps along particular links of interest along the roadway. Automatic data collection equipment such as a distance measuring instrument (DMI) or GPS facilitate data collection and software can facilitate data reduction and analysis from these automated collection methods.

The "floating car" test-vehicle method employs a driver that "floats" with the traffic stream and attempts to pass as many vehicles as pass the driver. Other test-vehicle methods are available depending upon the application. More information on test-vehicle travel-time data collection is available in Institute of Transportation Engineers (ITE)'s Manual of Transportation Engineering Studies.[7]

---

[4] Traffic Detector Handbook: Third Edition—Volume I. Federal Highway Administration, Publication No. FHWA-HRT-06-108, October 2006, available: http://www.fhwa.dot.gov/publications/research/operations/its/06108/06108.pdf.

[5] Traffic Detector Handbook: Third Edition—Volume II. Federal Highway Administration, Publication No. FHWA-HRT-06-139, October 2006, available: http://www.fhwa.dot.gov/publications/research/operations/its/06139/06139.pdf.

[6] Traffic Monitoring in Federal Lands. Coordinated Technology Implementation Program (CTIP), Federal Highway Administration Federal Lands Highway Office. 2013. Available: http://www.ctiponline.org/tools/traffic_monitoring/.

[7] Manual of Transportation Engineering Studies, Second Edition. Institute of Transportation Engineers, Washington, D.C., 2010.

2.1.1.7 Road Tubes

The placement of temporary road tubes with road counters can provide traffic speeds by vehicle classification. Road tubes provide a way to obtain speed (and volume) information for a short-time period (e.g., 48 hours). Speed is obtained by lane through the use of two tubes in the travel direction. Assuming equipment availability, road tubes provide a low-cost way to obtain data. The limitation is that these data are just a sample of traffic speeds and volumes and are not representative of annual conditions. The speeds are just a snapshot, and the volumes require adjustments to estimate annual volume parameters (see section 2.4.3).

2.1.2 Truck Volume Data

Truck volume data can be obtained from a number of sources, some that were described above for travel-time data collection (e.g., ITS detectors). The section below provides more detail on truck volume data sources. Many of the detector technologies for speed (travel time) data only sample vehicles in the traffic stream (e.g., vehicle probes, toll-tag readers, Bluetooth, test vehicles, license-plate readers) so they do not provide traffic volume (or volume by vehicle classification) for the entire traffic stream.

There are generally five possible sources of time-of-day volume data (by vehicle classification) to match to the travel-time data:

1. Classification data for a specific location from a detector (e.g., State department of transportation [DOT] automatic traffic recorders or weigh-in-motion stations).
2. Classification data from a short-term count at a similar and/or adjacent site.
3. Daily volumes (classification) from a roadway inventory database.
4. Classification data from national-level sources from FHWA.
5. Time-of-day volume curves created by vehicle classification.

The following sections describe each of these possible volume data sources in more detail.

2.1.2.1 Roadway Detectors Used for Traffic Monitoring

As described previously, roadway detectors can provide classification data by time-of-day, day-of-week, and/or month-of-year. State DOTs deploy these detectors as part of their routine traffic monitoring activities and include automatic vehicle classification (AVC) and weigh-in-motion (WIM) stations. Most stations are deployed at permanent locations but portable equipment also is used. The main limitation is the number of locations which number in the dozens for small States and the hundreds for large States. Essentially, these are sampling stations that used to develop factors for statewide planning and pavement design.

2.1.2.2 Short-Term Counts

In some cases, the available roadway detectors (AVC, WIM, or others) are not located near the site of the truck bottleneck. In these cases, the analyst may need to collect a short-term count using road tubes or another portable roadway detector technology. These short-term counts are then seasonally adjusted to obtain representative truck counts for the location of interest. More information on seasonal adjustments is described in section 2.4.3. Most States and many local agencies maintain a very large short-term count program but nearly all of the counts are for all vehicles combined, so vehicle classification is not possible.

2.1.2.3 Roadway Inventory Characteristics

State DOTs typically have roadway inventory databases that include geometric and operational aspects of roadways on their maintained system. Analysts can obtain annual average daily traffic (AADT) and truck percentages from these databases to estimate truck volumes for the site of interest. The AADT from these datasets can be adjusted (if necessary) to an hourly value to match the speed (travel time) dataset. The source of the traffic data in these datasets is the roadway detector network discussed immediately above. More information is in sections 2.1.2.5 and 2.4.4.

2.1.2.4 National Sources of Classification Data

National classification datasets are available from FHWA. The source of these data are the State DOT and in some cases local agency traffic monitoring activities; data resubmitted periodically to FHWA. These datasets can provide a consistent source for conducting truck bottleneck studies across States or regions and/or at an area-wide level. The possible FHWA datasets with truck classification data include:

- Highway Performance Monitoring System (HPMS).[8]
- Vehicle Travel Information System (VTRIS).[9]
- Travel Monitoring Analysis System (TMAS).[10]

2.1.2.5 Time-of-Day Truck Volume Curves

Time-of-day truck volume curves can be developed from continuous data sources (e.g., ITS roadway detectors) for planning applications. If built from roadway segments that are similar in geometric and operating characteristics to where they are ultimately applied, they can provide a useful tool. TTI's *Urban Mobility Report* uses such profiles created by functional classification, weekend/weekday, and congestion levels (using the speed data) for area-wide congestion statistics and analysis. More information about time-of-day profiles is provided in section 2.4.4.

---

[8] Highway Performance Monitoring System (HPMS), FHWA Office of Highway Policy Information, Available: https://www.fhwa.dot.gov/policyinformation/hpms.cfm.

[9] Vehicle Travel Information System (VTRIS), FHWA Office of Highway Policy Information, Available: http://www.fhwa.dot.gov/ohim/ohimvtis.cfm.

[10] Travel Monitoring Analysis System (TMAS), FHWA Office of Highway Policy Information, Available: http://www.fhwa.dot.gov/ohim/tvtw/tvtfaq.cfm#faq08.

2.2 SEGMENTATION OF ROADWAY INTO REPORTING SEGMENTS

A key element to successful truck bottleneck analysis is the determination of the appropriate segmentation of the roadway network for the desired analyses. To assess the regional nature of truck bottlenecks in an urban area, it is desirable to combine short adjacent links of the roadway network that have similar congestion patterns. By combining short but similar roadway links, one can more easily identify “big picture” urban congestion patterns and the most congested locations in the region. When looking at very detailed congestion data on short links, one can sometimes “miss the forest because of all the trees.” A more focused, follow-up analysis of the most congested locations will likely analyze these shorter links to better understand the specific causes of congestion and possible mitigation strategies.

Therefore, longer segments (composed of short, adjacent links) are recommended for the purposes of regional congestion reporting and identifying potential truck bottleneck locations. Note that this is different from using a long segment that is comprised of a single “data reporting” link; congestion patterns such long segments, common in rural areas, will be diluted by the length making it difficult to identify bottlenecks that may exist on the segment. At least in the former case, the more detailed exists for additional analysis. Traffic levels, congestion patterns, and traffic operation are relatively consistent along these congestion reporting segments (e.g., a defined segment should not include a mix of free-flowing traffic and congested traffic). Ultimately, the use and context of the congestion measures is the key determining factor in the definition of reporting segments. For example, a statewide congestion analysis geared to identifying most congested roadways and truck bottlenecks will likely have longer reporting segments than an arterial street facility-based analysis that is geared toward identifying most congested intersections. The following provides tips for roadway segmentation appropriate for truck bottleneck analyses in urban areas.[11]

The segmentation discussion that follows is especially germane for performance reporting, where it is most useful to report performance for roadway facilities. The bottleneck methodology presented in chapter 4 creates segmentation and performance measures based on observed queue lengths for those segments.

2.2.1 For All Roadways

- Short links should be combined into a reporting segment where traffic levels and resulting congestion patterns are relatively consistent.
- Reporting segments are almost always defined uniquely for each direction of travel. The possible exceptions are where: 1) both travel directions have similar congestion patterns; or 2) the scale (e.g., statewide or multi-region) of the analysis is conducive to more aggregate reporting.

[11] Hudson, J. G., N. Wood, B. Dai, and S. M. Turner, 2012 Roadway Congestion Analysis: Performance Report and Information System. Produced by the Texas A&M Transportation Institute for the Capital Area Metropolitan Planning Organization (CAMPO), Austin, Texas, September 2014.

2.2.2 Freeways and Access Controlled Highways

- In most cases, a freeway segment will include multiple entrance and exit ramps.
- Freeway segment endpoints are typically entrance or exit ramps from/to another freeway or major cross street, as this is where roadway characteristics, traffic levels, and congestion patterns are most likely to change.
- Freeway segments in dense, built-up areas typically range from 3 to 5 miles in length. These segments also are likely to have more frequent ramp access points.
- Freeway segments in less dense, suburban or exurban areas typically range from 5 to 10 miles in length. These segments are likely to have less frequent ramp access.

2.2.3 Arterial Streets

- In most cases, an arterial street segment will include multiple signalized intersections.
- Arterial street segment endpoints are typically major cross streets, as this is where roadway characteristics, traffic levels, and congestion patterns are most likely to change.
- Arterial street segments in dense, built-up areas typically range from one to three miles in length. These segments also are likely to have higher levels of intersection density.
- Arterial street segments in less dense, suburban or exurban areas typically range from three to five miles in length. These segments are likely to have lower levels of intersection density.

For identifying truck bottlenecks in rural areas, longer reporting segmentation is appropriate (e.g., intercity).

2.3 QUALITY CONTROL

Prior to data analysis, it is important that the analyst perform quality control of the datasets to ensure certain specifications are met. The quality control process typically includes one or more of the following actions:[12]

1. Reviewing the traffic data format and basic internal consistency.
2. Comparing traffic data values to specified validation criteria.
3. Marking or flagging traffic data values that do not meet the validation criteria.
4. Reviewing marked or flagged traffic data values for final resolution.
5. Imputing marked, flagged, or missing traffic data values with "best estimates" (while still retaining original data values and labeling imputed values as estimates).

The American Association of State Highway and Transportation Officials (AASHTO) *Guidelines for Traffic Data Programs*[13] describes these quality control processes in more detail. Of particular interest are the definitions for traffic data quality measures, including accuracy, completeness (also referred to as availability), validity, timeliness, coverage, and accessibility

---

[12] AASHTO Guidelines for Traffic Data Programs, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

[13] AASHTO Guidelines for Traffic Data Programs, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

(also referred to as usability). More specifically, AASHTO spells out validation criteria for vehicle count, classification, and weight data from ITS detector sources. Additional examples of quality control checks ("business rules") for ITS detector sources are described elsewhere.[14] Note that some of the prior sections in this section addressed aspects of quality control when the data types were introduced (e.g., Bluetooth).

In some cases, quality control by visual inspection is valuable. Visual inspection is helpful when it is not easy to automate the quality control with business rules. Sometimes the human eye is more adept at identifying reasonableness in data-time series. For example, graphing speed or volume plots by time for a variety of days in the month on the same graphic or looking at lane-by-lane speed and volume relationships on the same graph. Visual inspection of graphics like this allow the analyst to identify places where more "drill down" analyses may be warranted if something suspicious is found. More examples are documented elsewhere.[15]

2.3.1 Probe Speed Data Quality Control

Probe speed data are a very cost-effective source for system-wide data collection. With the increased and widespread use of probe speed data for bottleneck analysis (including truck bottleneck analyses), quality control of these data sources is of particular interest and is the focus of this section. The National Performance Management Research Data Set (NPMRDS) is used as an example in this section to illustrate quality control considerations for a probe speed dataset.

NPMRDS provides travel-time data in five-minute time aggregations. Due to the recent release of NPMRDS, there has been limited investigation of the data source and State DOT and metropolitan planning organization (MPO) practitioners are asking how the dataset can be used for performance measurement and truck analysis on freeways and arterials, and about the general quality of the data for these uses.

As part of an ongoing FHWA Pooled Fund Project (TPF-5[198], *Mobility Measurement in Urban Transportation [MMUT]*), TTI investigated several States' worth of the NPMRDS to characterize the roadway coverage, completeness (temporal and spatial), and validity of the five-minute travel-time data. Data for the 14 States in the FHWA pooled fund project at the time of the analysis were included (California, Colorado, Florida, Kentucky, Maryland, Minnesota, New York, North Carolina, Ohio, Oregon, South Carolina, Texas, Virginia, and Washington). Findings are provided here as well as additional analyses related to the truck speed data completeness and validity performed as part of this project. Completeness of the dataset included identification of missing records by traffic message channel (TMC) (the industry standard

---

[14] Margiotta, R., T. Lomax, M. Hallenbeck, S. Turner, A. Skabardonis, C. Ferrell, and W. Eisele. Guide to Effective Freeway Performance Measurement: Final Report and Guidebook, National Cooperative Highway Research Program, Washington, D.C., 2006. Available: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w97.pdf.

[15] Margiotta, R., T. Lomax, M. Hallenbeck, S. Turner, A. Skabardonis, C. Ferrell, and W. Eisele. Guide to Effective Freeway Performance Measurement: Final Report and Guidebook, National Cooperative Highway Research Program, Washington, D.C., 2006. Available: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w97.pdf.

mapping geography), and by functional classification. For the validity checks, the travel-time data were first converted to speeds, because they can be more intuitively understood and investigated in terms of speed.

Practitioners using large datasets such as NPMRDS for any analyses (such as truck bottlenecks) should understand the data set prior to performing analyses for their specific application. For planning applications, annual averages of five-minute travel-time data may be acceptable rather than day-to-day information that might be more appropriate for operational analyses. Depending upon the application, small nuances in the speeds may not matter, but systematic nuances could cause unacceptable errors.

2.3.1.1 NPMRDS Coverage

The FHWA pooled fund project analysis investigated the coverage of the NPMRDS. Aggregate findings for the United States are summarized in table 1. Analysts investigated the 2011 and 2012 Highway Performance Monitoring System (HPMS) data, and the total directional miles in 2012 on the National Highway System (NHS) increased by 42 percent over 2011 (reflecting the “enhanced NHS” in 2012). Analysts investigated the data from all 13 States in the FHWA pooled fund project, and the entire United States network. Table 1 shows that the U.S. directional-miles of coverage in the 2012 HPMS (NHS) (479,178 directional miles) compares favorably to the NPMRDS network coverage in directional miles (486,953 directional miles).

Analysts took the analysis a step further and put the NPMRDS network on a Geographic Information System (GIS) map because that is what is required to perform conflation of speeds and volumes and, again, the results are favorable (475,407 directional miles mapped). The full TMC-encoded network used by industry has approximately 80 percent more coverage (877,882 directional miles—including more arterial/collector coverage) than the NPMRDS network across the United States.

The coverage results of the individual States were generally the same as those documented in table 1 for the United States.

Table 1. United States traffic message channel—Roadway coverage in National Highway System and National Performance Management Research Data Set.

2012 HPMS NHS (Directional Miles)	NPMRDS Network (Directional Miles)	NPMRDS GIS/ Map Network (Directional Miles)	Full TMC Network (Directional Miles)
479,178	486,953	475,407	877,882

(Source: Adapted from *Information Sharing on FHWA’s NPMRDS*, Webinar. Texas A&M Transportation Institute, FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation, April 2014.)

2.3.1.2 NPMRDS Completeness

The NPMRDS is five-minute travel-time data for each day and data are present ***only*** when probe vehicles are present (i.e., data are not estimated when missing). Therefore, it is important for analysts to understand how incomplete data may affect analyses and measure calculation. The analyst should ask himself or herself what level of completeness is needed for their performance measure application. The analyst may need to impute missing values on specific days of interest. If overall performance for extended periods of time is needed, aggregated statistics to monthly, quarterly, or even annually for day of week may be acceptable.

NPMRDS provides three travel-time values for each five-minute time period and TMC: 1) mixed vehicle; 2) passenger car; and 3) truck. Analysts investigated the completeness of mixed-vehicle and truck travel-time values in the dataset. A three-month dataset from November 2013 to January 2014 was used for the analysis. Daylight hours were used for analysis (6:00 a.m. to 8:00 p.m.) because most analysis are most concerned with daytime traffic conditions, rather than overnight hours. (Nighttime travel is important for trucks, but there is less interference from passenger cars then.) Analysts looked at three aggregation-time periods of results: 1) individual day-to-day; 2) one-month average day-of-week; and 3) three months day-of-week.

Completeness in number 3 (three months day-of-week) was satisfied if any five-minute travel-time value was present for the given TMC for the given five-minute time period over the three-month period. Similarly, the one-month average day-of-week was satisfied if a travel-time value was present for the given TMC over the one-month time period. The individual day-to-day value represents the percentage of time the data were available for the specific five-minute time period of interest.

Analysts also aggregated the 5-minute data to 15-minute time periods, urban versus rural and roadway functional classification. The average completeness values for mixed traffic and trucks are shown as rows in table 2. The results in table 2 are average completeness estimates across the 13 States represented in the FHWA pooled fund project.

The above analysis is only a snapshot for a specific time period. It is important to note that the NPMRDS, as well as other commercial data sources, will continue to evolve over time. The authors expect, but cannot be absolutely certain, that data quality and completeness will improve over time. For example, starting in February 2014, an effort is underway to increase the truck data within the NPMRDS dramatically. However, users should still be cautious in using third-party data, and replicating the above quality and completeness analyses is a sound first step before embarking on analysis.

Table 2. Completeness percentages for the National Performance Management Research Data Set for mixed traffic and trucks.

Travel-Time Type	Urban/ Rural	Functional Classification	Individual Day-to-Day		One Month—Average Day-of-Week		Three Months—Average Day-of-Week	
			5 minutes	15 minutes	5 minutes	15 minutes	5 minutes	15 minutes
Mixed-Vehicle	Urban and Rural	All NHS	28%[a]	48%	58%	76%	78%	90%
Mixed-Vehicle	Urban	Class 1—Interstate	54%	76%	82%	93%	95%	98%
Mixed-Vehicle	Urban	Class 2—Other Freeway/ Expressway	36%	61%	71%	88%	91%	97%
Mixed-Vehicle	Urban	Class 3 and 4—Principal/Minor Arterial	23%	44%	55%	77%	81%	93%
Truck	Urban and Rural	All NHS	6%[b]	15%	30%	33%	48%	67%
Truck	Urban	Class 1—Interstate	19%	33%	58%	67%	81%	91%
Truck	Urban	Class 2—Other Freeway/ Expressway	6%	13%	3%	39%	60%	79%
Truck	Urban	Class 3 and 4—Principal/Minor Arterial	3%	5%	16%	21%	37%	60%

(Source: Adapted from Information Sharing on FHWA's NPMRDS, Webinar. Texas A&M Transportation Institute, FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation, April 2014 and original analysis for this report.)

Note: All NHS/NPMRDS (Daytime only, 6:00 a.m. to 8:00 p.m.); average completeness values of 14 States represented in the FHWA MMUT Pooled Fund Project; three months of data from November 2013 to January 2014.

[a] About 28 percent is based on 583,070,592 observations out of a total of 2,053,298,688.
[b] About 6 percent is based on 128,723,738 observations out of a total of 2,053,298,688.

The completeness results in table 2 lead to the following observations:

- Aggregation from individual day to monthly or quarterly increases completeness.
- Aggregation from 5-minute data to 15-minute data increases completeness.
- Truck data completeness percent is substantially less than mixed vehicle.

- Completeness decreases with decreasing functional classification.
- Completeness in urban areas is generally slightly higher than in rural areas (documented elsewhere).[16]

These NPMRDS completeness results suggest the analyst should recognize that the five-minute travel-time data are thin in some cases, particularly for the truck data and particularly on principal and minor arterials. Analysts should use caution and be careful not to "slice the data too thinly" for certain performance activities such as planning-level analysis, including many truck bottleneck studies. While analyses were conducted using the NPMRDS for this study, it is highly likely that other third-party travel-time data show similar tendencies, highlighting the need for users to scrutinize the data before conducting analyses. It should be noted that aggregation is one method for practitioners to handle missing data, and imputation is another. These observations also pertain to historical data; future data will likely show higher completeness rates. Imputation methods could look at time slices before/after the missing data and/or look at adjacent days. Imputation has been accomplished through a variety of methods, but they are all imperfect (See, for example, the SHRP Project L02 Report and Guidebook).[17] If imputation is done, analysts must clearly document: 1) the amount of data that has been imputed by time period; and 2) details of the imputation methodology.

2.3.1.3 National Performance Management Research Data Set Validity

Analysts performed a validity test of NPMRDS meant to verify how often speeds were in a specific range or how often there were notable differences between the car and truck travel-time data. As mentioned previously, the five-minute travel-time data from NPMRDS were converted to speeds and the following validity tests were investigated by functional classification:

- Percent of mixed-vehicle speeds and truck speeds less than 5 miles per hour by functional classification (table 3).
- Percent of mixed-vehicle speeds and truck speeds greater than 75 miles per hour by functional classification (table 3).
- "Car minus truck speed" difference cumulative percentage distribution by functional classification (figures 2 through 4).

---

[16] Information Sharing on FHWA's NPMRDS, Webinar. Texas A&M Transportation Institute, FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation, April 2014.

[17] http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2178.

Table 3. Mixed speed and truck speed percentage validation results by functional classification.

Validity Check	Speed Data Type	Functional Classification	Percentage
Speed <5 miles per hour	Mixed-vehicle	Interstate	0%
Speed <5 miles per hour	Mixed-vehicle	Other Freeway and Expressway	0%
Speed <5 miles per hour	Mixed-vehicle	Principal and Minor Arterials	3%
Speed <5 miles per hour	Truck	Interstate	0%
Speed <5 miles per hour	Truck	Other Freeway and Expressway	1%
Speed <5 miles per hour	Truck	Principal and Minor Arterials	2%
Speed >75 miles per hour	Mixed-vehicle	Interstate	1%
Speed >75 miles per hour	Mixed-vehicle	Other Freeway and Expressway	1%
Speed >75 miles per hour	Mixed-vehicle	Principal and Minor Arterials	0%
Speed >75 miles per hour	Truck	Interstate	0.08%[a]
Speed >75 miles per hour	Truck	Other Freeway and Expressway	0.03%[b]
Speed >75 miles per hour	Truck	Principal and Minor Arterials	0.05%[c]

(Source: Adapted from *Information Sharing on FHWA's NPMRDS*, Webinar. Texas A&M Transportation Institute, FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation, April 2014 and original analysis for this report.)

Note: All NHS/NPMRDS (Daytime only, 6:00 a.m. to 8:00 p.m.); average validity values of 14 States represented in the FHWA Pooled Fund Project; one month of data used in the analysis (January 2014).

[a] 0.08% is based on 18,510 observations out of a total of 23,474,056 observations.
[b] 0.03% is based on 1,153 observations out of a total of 4,568,560 observations.
[c] 0.05% is based on 5,526 observations out of a total of 10,542,144 observations.

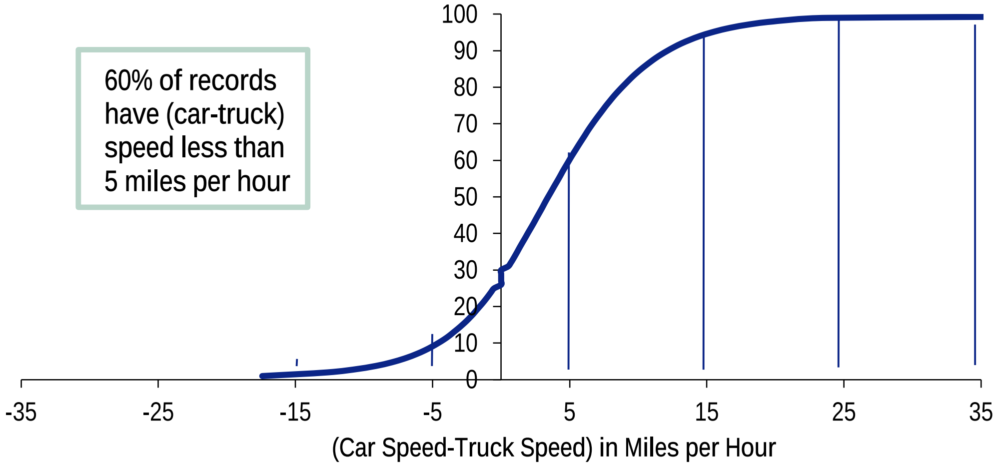


Figure 2. Graph. "Car speed minus truck speed" difference cumulative percentage distribution, *Interstates.*
(Source: Original analysis of FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation data for this report.)

Note: All NHS/NPMRDS (Daytime only, 6:00 a.m. to 8:00 p.m.); average validity values of 14 States represented in the FHWA Pooled Fund Project; one month of data used in the analysis (January 2014).

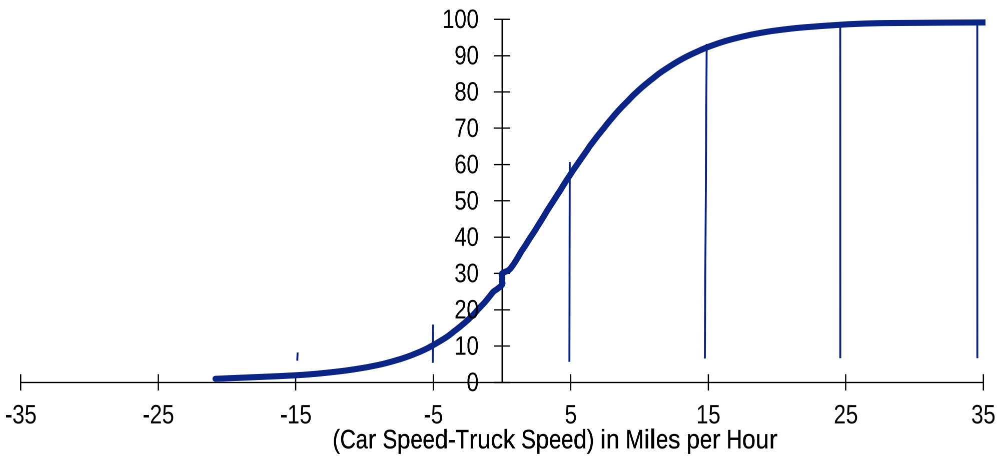


Figure 3. Graph. "Car speed minus truck speed" difference cumulative percentage distribution, *other freeway and expressway.*
(Source: Original analysis of FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation data for this report.)

Note: All NHS/NPMRDS (Daytime only, 6:00 a.m. to 8:00 p.m.); average validity values of 14 States represented in the FHWA Pooled Fund Project; one month of data used in the analysis (January 2014).

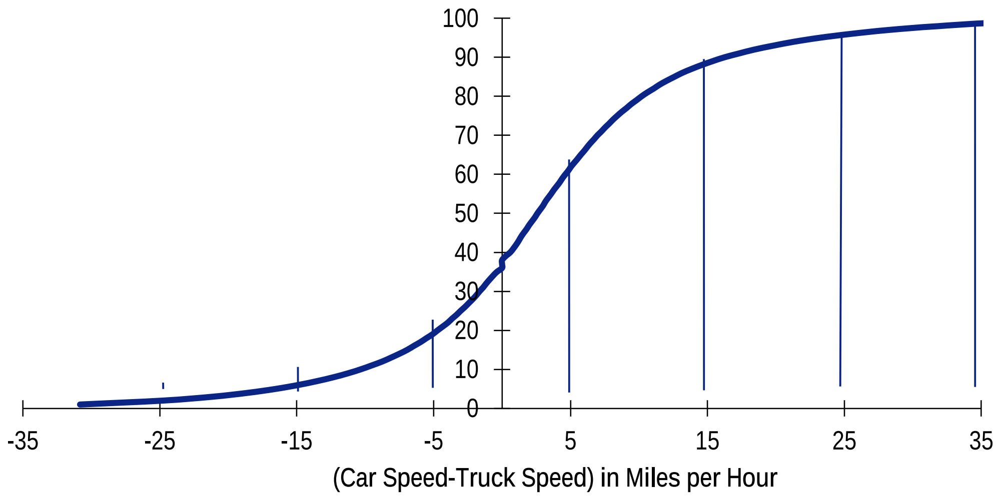


Figure 4. Graph. "Car speed minus truck speed" difference cumulative percentage distribution, *principal and minor arterials.*
(Source: Original analysis of FHWA Pooled Fund Project: Mobility Measurement in Urban Transportation data for this report.)

Note: All NHS/NPMRDS (Daytime only, 6:00 a.m. to 8:00 p.m.); average validity values of 14 States represented in the FHWA Pooled Fund Project; one month of data used in the analysis (January 2014).

The validity results in table 3 generally indicate low occurrences of the validity checks being satisfied. Other results appear less intuitive (i.e., differences between car speeds and truck speeds, particularly when trucks are faster). For example, on Interstates and other freeways and expressways (figures 2 and 3), approximately 5 percent of data have truck speeds 10 miles per hour faster or more than cars. For principal and minor arterials (figure 4), approximately 10 percent of the data have truck speeds 10 miles per hour faster or more than cars. Depending upon functional classification, between 25 percent and 35 percent of the data indicate truck speeds faster than car speeds.

The relatively low occurrences documented in table 3 and figures 2 through 4 may not impact overall results, but analysts should run such validity tests to verify if/when they do occur and whether they occur during a time period that could impact the results for their specific application (e.g., truck bottleneck analysis).

Because NPMRDS travel-time data exist at the five-minute level, the analyst should verify that adequate travel-time data sample is available for the analyses desired. As described in the prior section, in some cases the travel-time samples at five minutes are limited (particularly the truck-only travel-time data). To obtain adequate NPMRDS travel-time data sample for a particular analysis, the analyst may need to do the following (for TMCs of interest):

- Aggregate the 5-minute travel-time data to a 15-minute or hourly travel-time estimate.
- Aggregate the daily travel-time data to a monthly, seasonal, or yearly travel-time estimate.
- Impute data from adjacent-time periods and/or adjacent days.

2.3.1.4 Concluding Thoughts for Practitioners

The following are two important questions the analyst should ask himself or herself to determine the most appropriate aggregation level of the NPMRDS travel-time data:

- *What temporal aggregation is necessary for decision-makers using the results of this analysis?* For example, for a planning study, it is possible that seasonal or annual statistics summarized from 15-minute or hourly data will be adequate.

- *What spatial aggregation is necessary for decision-makers using the results of this analysis?* The travel-time data from NPMRDS begin at the TMC level. In rural areas, TMCs are typically very long while in urban areas they can be shorter (e.g., ramp-to-ramp on an Interstate). It is likely that the analyst will want to perform segmentation of their roadway network for analysis differently than the TMC level. Segmentation is described in more detail in section 2.2.

After determining the appropriate temporal and spatial aggregation of the NPMRDS travel-time data (or by imputation), it is recommended that the analyst convert the travel-time information to speeds for quality control prior to aggregation. Within the NPMRDS, there is an inventory file with TMC segment information, including length (miles), a road label (description) and GPS x-y coordinates for the start and endpoints of the TMC. The TMC length (miles) divided by the travel time (in seconds) multiplied by 3,600 (seconds in an hour) gives the speed (miles per hour) for the TMC of interest.

Reviewing speeds is more intuitive for recognizing suspicious speed data and performing quality control. The analyst may want to remove (or cap) speeds that are unreasonably high. An appropriate speed cap, if desired, should consider the functional classification of the roadway (freeway or arterial) and the speed data being investigated (“truck” or “passenger car” or “all vehicles”). After quality control of the data, average speeds are computed for the temporal and spatial aggregation levels desired.

2.4 DATA PROCESSING PROCEDURES TO MATCH TRAVEL-TIME (SPEED) AND VOLUME DATA SOURCES

2.4.1 Implications of Application

The ultimate use/application of the output from an analysis drives the data processing procedures, as well as data collection and data reduction decisions. The primary application for this methodology is the determination of truck bottlenecks for prioritizing investment decisions. While that sounds straightforward, there are still important considerations for the data analyst that will impact data collection, data reduction, and data processing steps.

Ultimately, public-sector transportation professionals are trying to make the best decisions in the most cost-effective manner possible, given the available data. It is not always possible to obtain data at the spatial and temporal granularity for the specific location(s) of interest. Table 4 illustrates the spatial and temporal data availability tradeoffs that are rather commonplace in performing truck bottleneck studies when complete data are not available.

Table 4. Speed and volume spatial and temporal data availability considerations.

	Data Availability	
	Spatially	**Temporally**
Most desirable are…	….actual data for the specific site(s) of interest…	…and/or data at desired time granularity to satisfy the application (e.g., annual, hourly, 15-minute, 1-minute).
Less desirable are…	…estimated data from similar site(s)…	…and/or data aggregated over time because desired granularity not available.

(Source: Cambridge Systematics, Inc.)

2.4.2 Use of Paired Speed-Volume Observations from Intelligent Transportation Systems Detectors

Many public transportation agencies have roadway ITS detectors to monitor traffic conditions and operate the transportation system. The benefit of these detectors is that they typically can provide very disaggregate data (lane-by-lane, minute-by-minute) for a specific location. These data are the "most desirable" as shown in table 4. If that location is the specific location for which a truck bottleneck is of interest, the analyst benefits from having very good speed and volume information for analysis and decision-making. These data are sometimes called "paired speed-volume observations" because the speed and volume data are collected and available over the same time period. The analyst can then begin to develop the bottleneck performance measures as described in more detail in section 4.4.

For truck bottleneck analysis (and prioritization), it is important to ensure that the "paired speed-volume observations" occur over a "representative" time period for the locations of interest. This ensures that they will not rank artificially higher (if measured during a highly congested month/season) or artificially lower (if measured during a relatively low-congestion month/season). Adjustment factors for factor groups and/or representative sites to the data collection site can aid in selection of the "representative" time period to target for analysis. More information on adjustment factors are described in the next section.

2.4.3 Assigning Short-Term Volume Count to Continuous Travel-Time Data

Another common data scenario is when traffic volumes are available from a short-term volume count (e.g., 48 hours) and continuous travel-time data are available from a commercial source. Continuous means that the travel-time data are available throughout the year (e.g., for each five-minute period such as NPMRDS). A short-term volume count typically implies data are obtained by road tubes or some other means.

As discussed, the application here is summarizing annual bottleneck statistics to prioritize truck bottleneck areas. In this case, there is a need to "adjust" the short-term truck volume count to the same granularity of the travel-time data, which are available throughout the year in this example.

The short-term volume count must be adjusted seasonally (hour-of-day, day-of-week, and month-of-year).

The following procedure from the *AASHTO Guidelines for Traffic Data Programs* can be used to convert a short-term volume count (with at least 24 hours of data) into an estimate of AADT:[18]

1. Summarize the count as a set of hourly counts.
2. Divide each hourly count by the appropriate seasonal traffic ratio (or multiply by the appropriate seasonal traffic factors).
3. For each hour of the day, average the results of step 2, producing 24 hourly averages; and sum the 24 hourly averages to produce estimate AADT.

This procedure assumes traffic factors are available from continuous monitoring sites that are the reference site for the segment of interest. Traffic volume by vehicle class (e.g., single-unit and combination trucks) is estimated using a similar procedure where the factors used in step 2 are those developed by vehicle classes of interest. More details about this procedure are available elsewhere.[19, 20]

2.4.4 Deriving Detailed Volume and Vehicle Class Estimates to Match the Level of Detail in the Travel-Time Dataset

In some situations, travel-time data are available for 15-minute or hourly time periods aggregated for an entire year (e.g., average speed or travel time for a roadway segment for the 52 Mondays of the year between 7:00 and 7:15 a.m.), while only an AADT and associated truck percentage are available for volumes. In these cases, there is the need to derive detailed volume and vehicle class estimates to match the level of detail in the travel-time dataset.

One approach for dividing the daily traffic count into the same-time interval as the speed dataset (5-minute, 15-minute, or hourly) has been created by the Texas A&M Transportation Institute (TTI) for the list of *100 Most Congested Roadways* produced for the Texas Department of Transportation (TxDOT).[21,22] A similar method is used in TTI's *Urban Mobility Report.*[23]

---

[18] AASHTO Guidelines for Traffic Data Programs, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

[19] AASHTO Guidelines for Traffic Data Programs, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

[20] Traffic Monitoring Guide, Federal Highway Administration, Available: http://www.fhwa.dot.gov/policyinformation/tmguide/, September 2013.

[21] 100 Most Congested Roadways, Texas Department of Transportation, Available: http://www.txdot.gov/inside-txdot/projects/100-congested-roadways.html/, August 31, 2014.

[22] Most Congested Roadways in Texas, Texas A&M Transportation Institute link http://mobility.tamu.edu/most-congested-texas/, August 31, 2014.

[23] Schrank, D. L., T. J. Lomax, and B. Eisele, 2012 Urban Mobility Report. December 2012. Available: http://mobility.tamu.edu/ums.

The following sections describe the procedural steps used to divide the daily traffic counts into the same temporal scales as the travel-time data for the *100 Most Congested Roadways* list.

2.4.4.1 Step 1—Identify Traffic Volume Data

The Roadway-Highway Inventory Network (RHiNo) dataset from TxDOT provides the source for traffic volume data, although the geographic designations in the RHiNo dataset are not identical to those used for the private-company speed data. While there are some detailed traffic counts on major roads, the most widespread and consistent traffic counts available are AADT counts. The 15-minute traffic volumes for each section, therefore, were estimated from these AADT counts using typical time-of-day traffic volume profiles developed from local continuous count locations (e.g., ITS detectors).

Truck volumes are calculated in the same way by applying the truck-only 15-minute volume profiles to the truck AADTs reported in RHiNo. These 15-minute truck volumes were split into values for combination trucks and single-unit trucks using the percentages for each from RHiNo. These truck-only profiles account for the fact that trucks volumes tend to peak at very different rates and times than do the mixed-vehicle traffic.

Volume estimates for each day of the week (to match the speed database) were created from the annual average volume data using the factors in table 5. Automated traffic recorders from the Texas metropolitan areas were reviewed and the factors in table 5 are a “best-fit” average for both freeways and major streets. Creating a 15-minute volume to be used with the traffic speed values, then, is a process of multiplying the annual average by the daily factor (table 5) and by the 15-minute factor (figures 5 and 6 described in section 2.4.4.3).

Table 5. Day-of-week volume conversion factors.

Day of Week	Adjustment Factor (to Convert Average Annual Volume into Day-of-Week Volume)
Monday to Thursday	+5%
Friday	+10%
Saturday	-10%
Sunday	-20%

(Source: Adapted from: *100 Most Congested Roadways,* Texas Department of Transportation, available: http://www.txdot.gov/inside-txdot/projects/100-congested-roadways.html, August 31, 2014; and Schrank, D. L., T. J. Lomax, and B. Eisele, *2012 Urban Mobility Report.* December 2012. Available: http://mobility.tamu.edu/ums.)

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

The second step was to combine the road networks for the traffic volume and speed data sources, such that an estimate of traffic speed and traffic volume were available for each desired roadway segment. The combination (also known as conflation) of the traffic volume and traffic speed networks was accomplished using GIS tools. See section 2.4.5 for additional information about conflation. The TxDOT traffic volume network (RHiNo) was chosen as the base network; a set of speeds from the speed network was applied to each segment of the traffic volume network. Multiple RHiNo segments make up a section in the *100 Most Congested Roadways* list.

2.4.4.3 Step 3—Estimate Traffic Volumes for Shorter-Time Intervals

The third step was to estimate passenger car and truck traffic volumes for the 15-minute time intervals. The process includes the following:

- A simple average of the 15-minute traffic speeds for the morning and evening peak periods was used to identify which of the time-of-day volume pattern curves to apply. The morning and evening congestion levels were an initial sorting factor (determined by the percentage difference between the average peak-period speed and the free-flow speed).
- The most congested period was then determined by the time period with the lower speeds (morning or evening); or if both peaks have approximately the same speed, another curve was used. Sample traffic volume profiles are shown in figure 5.
- Low, medium, or high congestion levels—The general level of congestion is determined by the amount of speed decline from the off-peak speeds. Lower congestion levels typically have higher percentages of daily traffic volume occurring in the peak, while higher congestion levels are usually associated with more volume in hours outside of the peak hours.
- Morning or evening peak; or approximately even peak speeds—The speed database has values for each direction of traffic and most roadways have one peak direction. This identifies the time periods when the lowest speed occurs and selects the appropriate volume distribution curve (the higher volume was assigned to the peak period with the lower speed). Roadways with approximately the same congested speed in the morning and evening periods have a separate volume pattern; this pattern also has relatively high volumes in the mid-day hours.
- Separate 15-minute traffic volumes for trucks and non-trucks were created from the 15-minute traffic volume percentages generated from profiles such as figure 5 (mixed traffic) and figure 6 (truck).

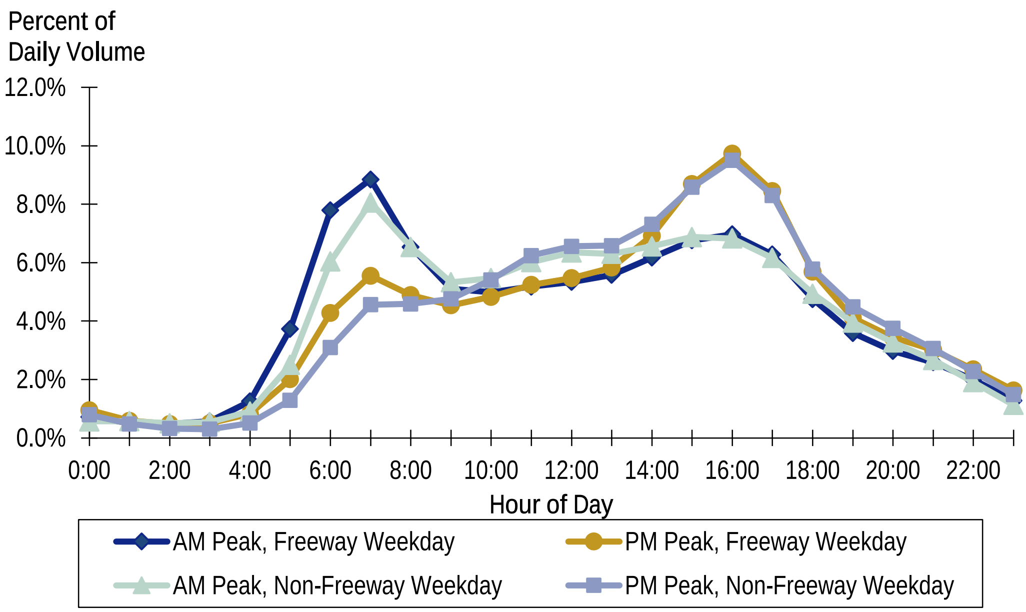


Figure 5. Graph. Weekday mixed-traffic distribution profile for no to low congestion.
(Source: Adapted from *100 Most Congested Roadways,* Texas Department of Transportation, available: http://www.txdot.gov/inside-txdot/projects/100-congested-roadways.html, August 31, 2014; and Schrank, D. L., T. J. Lomax, B. Eisele, *2012 Urban Mobility Report.* December 2012. Available: http://mobility.tamu.edu/ums.)

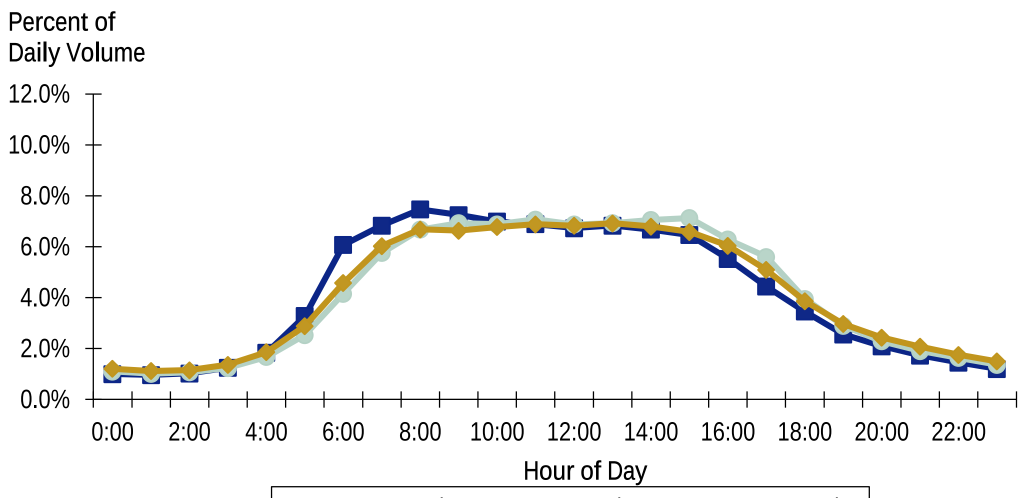


Figure 6. Graph. Weekday freeway truck-traffic distribution profiles.
(Source: Adapted from *100 Most Congested Roadways,* Texas Department of Transportation, available: http://www.txdot.gov/inside-txdot/projects/100-congested-roadways.html, August 31, 2014.)

2.4.5 Conflation Procedures

"Conflation" is the process of matching probe speed data to roadway volume data. It is necessary for computing performance measures for truck bottleneck analysis when the speed and roadway volume data are provided on different networks.

The first step in the conflation process is determining which roadway network will serve as the base network for conflation. The base network is the roadway network, which gets the attributes from the other network loaded on it. Generally, the base network should be the network that more closely aligns with the purpose for the analysis. Because datasets are large and processing time can be lengthy, it is important to consider if any records can be eliminated (i.e., by excluding some functional classes to speed processing time).

The process of conflation is facilitated by using GIS to import and compare the end points of the speed data roadway network with the traffic volume inventory. Quality control is a necessary step to ensure that the data from the speed network aligns with the volume network. More information on conflation can be found elsewhere.[24] The basic principles of conflating vehicle probe data to agency data bases are as follows.

2.4.5.1 Step 1—Build a Route System

At the center of the methodology is the need to reference both datasets segments against a common road network. As such, a base road network to which the data will be conflated and an associated route system is required. The base road network must be topologically connected (i.e., does not contain gaps at intersections) and should not contain overlaps to allow for network tracing.

2.4.5.2 Step 2—Conflate Data

The data is conflated to the base road network by snapping the end points of the polyline to the network, and then determining the logical road network link(s) that form the path between the two points. This path is output as one or more linear events giving the Route ID and the route measures at the ends of the event.

In this process, it is assumed that the polylines are digitized in the direction of travel, and the ends of the polylines must be spatially accurate enough to allow them to be snapped to the routes using a reasonable snapping tolerance.

In the snapping process:

---

[24] Schrank, D. L., "Conflation Procedure to Combine Speed and Volume Datasets for MAP-21 Performance Measurement." Presentation at the North American Travel Monitoring Exposition and Conference (NATMEC) 2014, Chicago, Illinois, available: http://onlinepubs.trb.org/onlinepubs/conferences/2014/NATMEC/Schrank.pdf.

1. If both end points snap to the same route, it is assumed this is the best path and a single linear event is generated.
2. If the end points snap to the adjacent routes, it is assumed this is the best path and two linear events are generated.
3. If there is no obvious path between the two point, network tracing is used to determine the shortest path between the points taking into account direction of travel on the network. Assuming the length of the calculated path is similar (i.e., within a defined percentage of) the length of the original polyline, it is assumed to be a match and multiple linear events are generated.

The results of this step is a linear event table referenced against the route system developed in step 1 containing (at least) the following fields:

RouteID	Unique route ID
FrMeasure	From measure
ToMeasure	To Measure
{PolylineID}	A unique ID for the polyline

2.4.5.3 Step 3—Event Overlay

To generate the many-to-many relationship table between the two datasets, the two linear event tables generated from the two datasets in step 2 must be overlaid against each other to determine the unique overlaps in the events, and for each of these overlaps the length the overlap.

The results of this event overlay step is a single linear event table containing (at least) the following fields:

RouteID	Unique route ID
FrMeasure	From measure
ToMeasure	To Measure
Length	Length, in map units, of the linear event
{Polyline1ID}	ID of the polyline from dataset 1
POverlap1	Percentage overlap, based on length, between the original polyline from dataset 1 and the linear event
{Polyline2ID}	ID of the polyline from dataset 2
POverlap2	Percentage overlap, based on length, between the original polyline from dataset 2 and the linear event

2.4.5.4 Step 4—Join

To allow data in the two datasets to be compared against each other, the two original datasets must be joined to the linear event table generated in step 3. This will produce a single linear event table containing the attributes of both datasets. Note: If any attributes need to be apportioned (e.g., travel time), this can be accomplished using the “POverlap1” and “POverlap2” event table attributes.

CHAPTER 3. MEASURING SIGNALIZED ARTERIAL CONGESTION

3.1 INTRODUCTION

Unlike freeways where there has been a fair amount of analysis activity, measuring signalized arterial performance has been elusive. Historically, agencies have had the luxury of intensive roadway data collection systems on freeways with which to track speeds and volumes at a specific point. These are useful on freeways because of uninterrupted flow and can be used for a variety of control strategies. These data, which would have to be collected mid-block on a signalized arterial, are not useful for signal control—what matters are conditions at the signal itself. However, vehicle probe and roadway-based travel-time collection systems (such as Bluetooth and toll tag readers) offer the potential for collecting arterial performance data, but several barriers still exist:

- **Sample Size—**Especially relevant when trying to measure reliability, which is based on the variability in travel times. Are there sufficient numbers of trucks to allow dependable performance metrics to be computed?

- **Truck Speeds—**Are the speeds of trucks representative of the traffic stream as a whole? Do they match well under certain flow conditions and not others? Can adjustment factors be developed?

- **Truck Operations—**Truck travel patterns can be significantly different from passenger cars which are usually studied in congestion analyses. For example, truck deliveries are concentrated during weekday mid-day periods, which are not usually studied in congestion analyses.

- **Free-Flow Speed (or Reference Speed)—**The determination of free-flow or reference speed on arterials, which determines when delay is being measured, is far from settled. (Here we use the term “reference speed” to avoid confusion because free-flow speed may have a strict definition, as in the *Highway Capacity Manual (HCM).)* Several approaches have been taken, including: examining speeds during off-peak hours (possible with continuously collected data); based on speed limit; and based on physical setting and “class” of roadway. Depending on what approach is taken, delay computation will vary significantly.

- **Arterial Performance Measures—**Many agencies have developed arterial performance measures, but a large number of measures are used to gauge signal performance rather than how users experience travel time over a section. They are primarily used as diagnostics for identifying problems with signal operations (e.g., phasing, progression). Some of these measures include queue length, failed cycles, and stopped time. These measures are understandable because they help agencies manage their system, but they are a level below hereunder-based performance, which is to measure the experience of travelers. Therefore, most, if not all, of the travel time-based measures used for freeways are appropriate for arterials as well. There may be additional ones worth considering, for example, number of stops along a signalized section resonates with travelers as a meaningful measure.

In the broader realm of ***arterial performance management***, it is desirable to construct a fully integrated set of performance measures, where higher-level performance measures (outcomes) are directly influenced by changes in lower-level measures. In the general literature on performance measurement, this is described as a ***program logic model***.[25] Figure 7 shows how this model can be adapted for arterial performance management. The distinction between "outputs" and "outcomes" is that outcomes are experienced directly be the user, while outputs are related to how signals perform (which in turn influence outcomes). Note that measures related to daily operations activities feed into a broader context, which indicates a community's overall vision and goals. In addition, as one goes higher in the structure, the influence of other factors outside of arterial performance enters the picture.

The Guide addresses these issues in the subsequent parts of this section.

[25] https://www.bja.gov/evaluation/guide/pe4.htm.

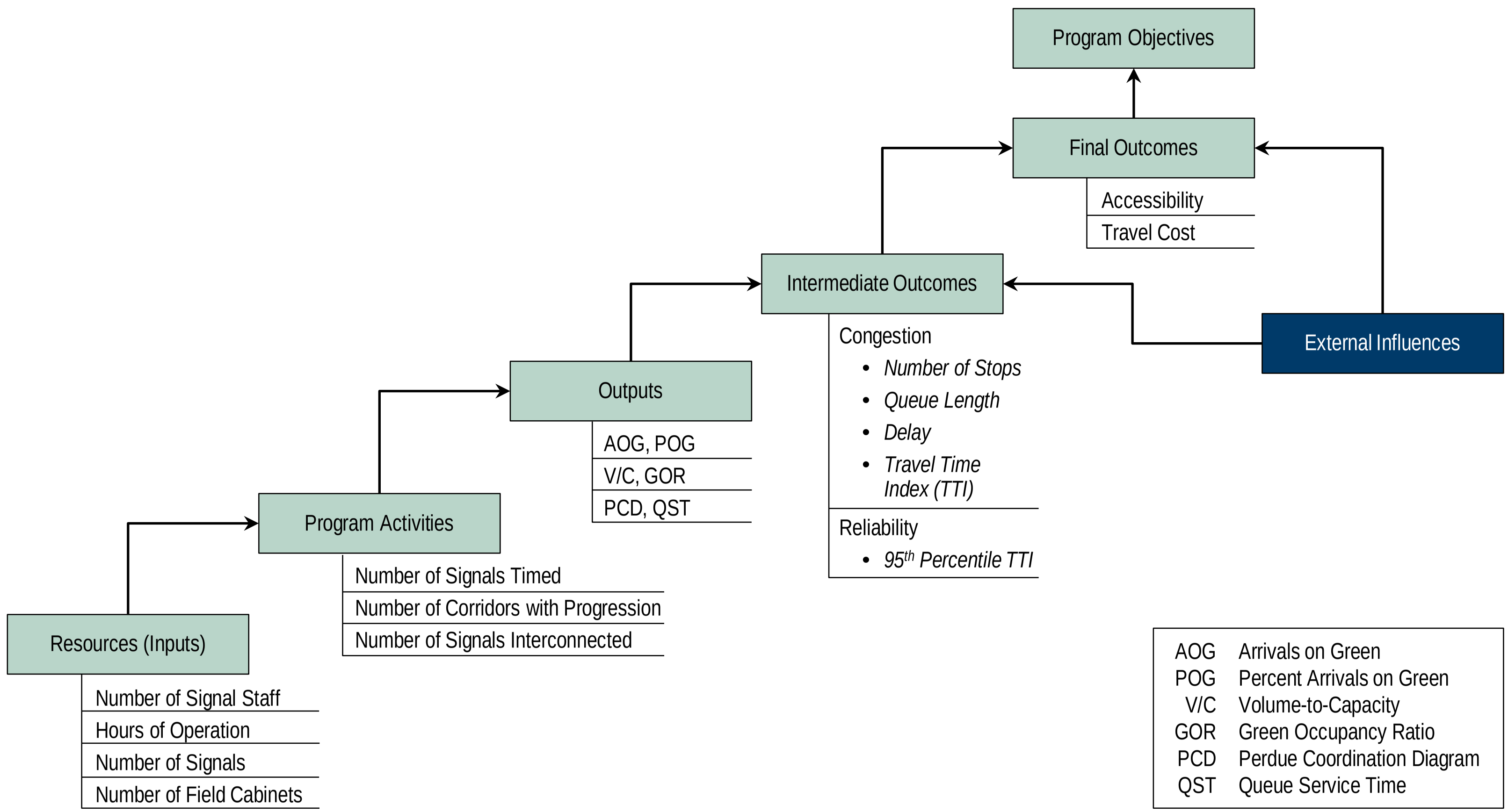


Figure 7. Flow chart. Program logic model adapted for arterial performance management.
(Source: Cambridge Systematics, Inc.)

3.2 DATA SOURCES FOR MONITORING SIGNALIZED ARTERIAL PERFORMANCE

3.2.1 Travel-Time Data

Measuring arterial travel time is challenging. Since the movement of vehicles is interrupted by signals, estimates based on average speeds from loop detectors or radar (typically placed mid-block) are inaccurate. Past approaches to arterial travel time estimation have been synthetic: Models have been used with available data to derive—rather than to measure directly—arterial travel time.[26] The data used by these procedures includes the volumes and speeds from mid-block detectors and sometimes information on signal phasing, but traffic flow models of some sort also are used to derive travel time.

All of the data sources covered in section 2.1.1 are useful in signalized environments, with the following caveats and additions.

3.2.1.1 ITS Roadway Detectors

Equipment that detects volume, speeds, and lane occupancy are of limited use on arterials where they are placed at mid-block locations; they are sometimes referred to as "system detectors." As discussed above, mid-block speeds cannot be used to derive arterial travel times because most of the delay occurs on intersection approaches.

3.2.1.2 Vehicle Signature Reidentification

This data source uses sensors that measure changes in Earth's magnetic field induced by a vehicle, and processes the measurements to detect a vehicle. Each vehicle is defined by its own unique signature. Matching individual vehicle signatures from wireless magnetic sensors placed at the two ends of a link produced travel times.[27]

3.2.1.3 Traffic Signal Control Data

In addition to using system (mid-block) detectors coupled with modeling, several researchers have developed procedures for estimating travel time from signal control data. These data are "event-based" as they relate to either the presence or absence of a vehicle at a point on or near the signal approach, or the status of the signal phasing. Liu et al. devised a "virtual probe" simulation using both vehicle-actuation and signal phase change data in a synchronized

---

[26] Kwong, K. et al., *A Practical Scheme for Arterial Travel Time Estimation Based on Vehicle Re-Identification Using Wireless Sensors*, Transportation Research Board 89th Annual Meeting, January 11 to 15, 2009, Washington, D.C.

[27] Kwong, K et al., *Arterial Performance Measurement with Wireless Magnetic Sensors*, American Society of Civil Engineers, 2011, http://ascelibrary.org/doi/abs/10.1061/41177%28415%2948.

manner.[28] These data are time-stamped allowing the reconstruction of the history of traffic signal events along the arterial street. In the simulation, the virtual probe vehicle's trajectory is traced in time and space, and its status at any point in time is dependent on the underlying data. When the vehicle "completes" its trip, total travel time is recorded. In the absence of directly measured travel times and delays, this approach would work for measuring arterial performance at the level relevant for freight bottleneck analysis, assuming that the detailed signal event data are available and the virtual probe procedures has been calibrated and is available as user-grade software. Liu et al. also developed a method for estimating queue length based on shock wave analysis.

Day et al. recently extended this approach of using high-resolution controller event data.[29] They developed a portfolio of performance measures for system maintenance and asset management; signal operations; non-vehicle modes, including pedestrians; and travel time-based performance measures for assessing arterial performance. Most of these measures relate to evaluating how well signal timing (progression) and phasing are performing and can indicate specific areas where improvement is needed. Liu reinforces this observation:[30]

> "Classical measures of effectiveness (MOE) for signal coordination include travel time, vehicle stops, arrival type, arrivals on green (AOG), percent arrivals on green (POG), and bandwidth. Although arterial travel time and vehicle stops are intuitive to drivers, AOG, POG and bandwidth are more useful from traffic operation perspective."

So, as shown back in figure 7, different levels of performance measures exist. For the purpose of freight bottlenecks analysis, travel time-based user perspective measures are the most appropriate. Adding the signal event-based measures would be a good addition if such a system already was in pace. For a State DOT, this means having access to every signal controller in the State, at least for higher order highways.

While the focus of this detailed "event-based" work is clearly on the ***signal*** operation and maintenance, several aspects are of interest to measuring ***arterial corridor*** performance.

---

[28] Liu, H. X., W. Ma, X. Wu, and H. Hu, *Development of a Real-Time Arterial Performance Monitoring System Using Traffic* Data *Available from Existing Signal Systems*, prepared for Minnesota Department of Transportation, December 2008, http://www.lrrb.org/PDF/200901.pdf.

[29] Day, C. M., E. J. Smaglik, D. M. Bullock, and J. R. Sturdevant. *Real-Time Arterial Traffic Signal Performance Measures*. Publication FHWA/IN/JTRP-2008/09. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2008. DOI: 10.5703/1288284313439.

[30] Liu, H. X., Automatic Generation of Traffic Signal Timing Plan, Research Project. Final Report 2014-38, September 2014.

First, the discussion of signal progression measures is relevant. They introduce the concept of delay at individual signals, including its components. In addition to deriving delay from models such as the Webster and *HCM* equations, Day et al. also observe that:

> "… at locations where the arrival profiles can be directly measured, it is possible to analyze the delay by calculating the area between the arrival and departure curves. This is done by directly considering the cumulative arrivals and departures over time based on vehicle detections and phase status. The departure curve can be measured either directly using departing vehicle counts or by assuming a departure profile based upon the actual green times."

Second, Day et al. present methods for calculating arterial travel time based on previous work by Remias et al.[31] They discuss five data collection methods discussed in chapter 2 but have named them differently. All of these produce estimates of travel time along some distance of the arterial:

- Agency-driven probe vehicles.
- Vehicle reidentification using pavement sensors.
- Vehicle reidentification using MAC address matching (Bluetooth).
- Crowd-sourced data (commercially available vehicle probe data).
- Virtual probe model (using high-resolution event data at each intersection along an arterial to estimate probable vehicle trajectories along the corridor).

They also present three methods for reducing the data. This assumes that travel times are available for multiple short segments within the span of an arterial corridor. Ideally, the segments are defined by signal location:

- **Origin-Based—**Data are summarized for increasing segment groupings starting at the origin. If the origin is point A and successive intersections are labeled as B on up to F (the destination), the segmentation is: A-B, A-C, A-D, A-E, and A-F.
- **Destination-Based—**Here the destination is the "anchor point," so the segmentation is: A-F, B-F, C-F, D-F, and E-F.
- **Individual Segments—**Here the segmentation is A-B, B-C, C-D, D-E, and E-F. This reduction method allows the calculation of control delay, where control delay is the travel time minus the time required to proceed through the segment at the free-flow speed. (They used the fifth percentile travel time to define the free-flow speed.)

[31] Remias, S. M., A. M. Hainen, C. M. Day; T. M. Brennan, Jr., H. Li, E. Rivera-Hernandez, J. R. Sturdevant, S. E. Young, and D. M. Bullock, *Performance Characterization of Arterial Traffic Flow with Probe Vehicle Data*, Transportation Research Record No. 2380, Transportation Research Board of the National Academies, Washington, D.C., 2013. DOI: 10.3141/2380-02.

3.2.1.4 Crowd-Sourced (Commercial Vehicle Probe) Data

Overview: Signalized arterial roadways function with far more speed variability than limited access highways, particularly those highways operating at free-flow speeds. Under normal conditions, the majority of vehicles moving on a limited access highway operate within a relatively tight speed distribution. On signalized arterials, however, it is typical for a vehicle to be moving across a wide range of speeds or to be stopped for significant amounts of time. This key difference between the two road types is demonstrated using samples of the American Transportation Research Institute's (ATRI) truck GPS data in figures 8 through 11.

Figure 8 illustrates spot speeds along a typical stretch of limited-access highway. For the most part, vehicles operate on this roadway near the speed limit (though many are equipped with speed governors).

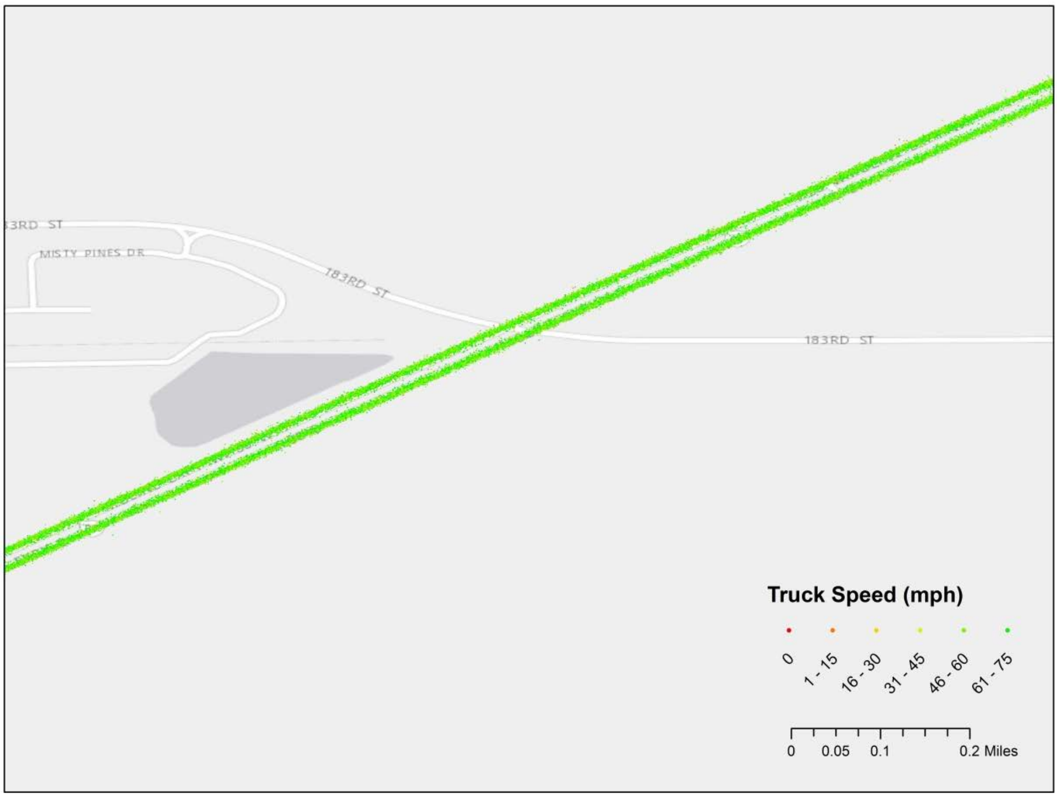


Figure 8. Map. Interstate spot speeds.
(Source: American Transportation Research Institute.)

The lack of variability among the spot speed measurements is further demonstrated in figure 9, where more than 80 percent of the measured spot speeds are between 55 and 65 miles per hour.

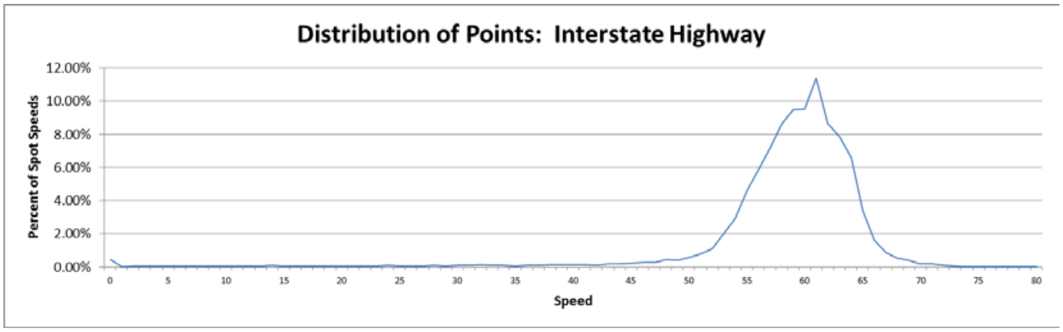


Figure 9. Graph. Distribution of sample Interstate spot speeds.
(Source: American Transportation Research Institute.)

As figure 10 shows, however, the stop-and-go nature of signalized arterials results in a variety of speeds within a small roadway segment.

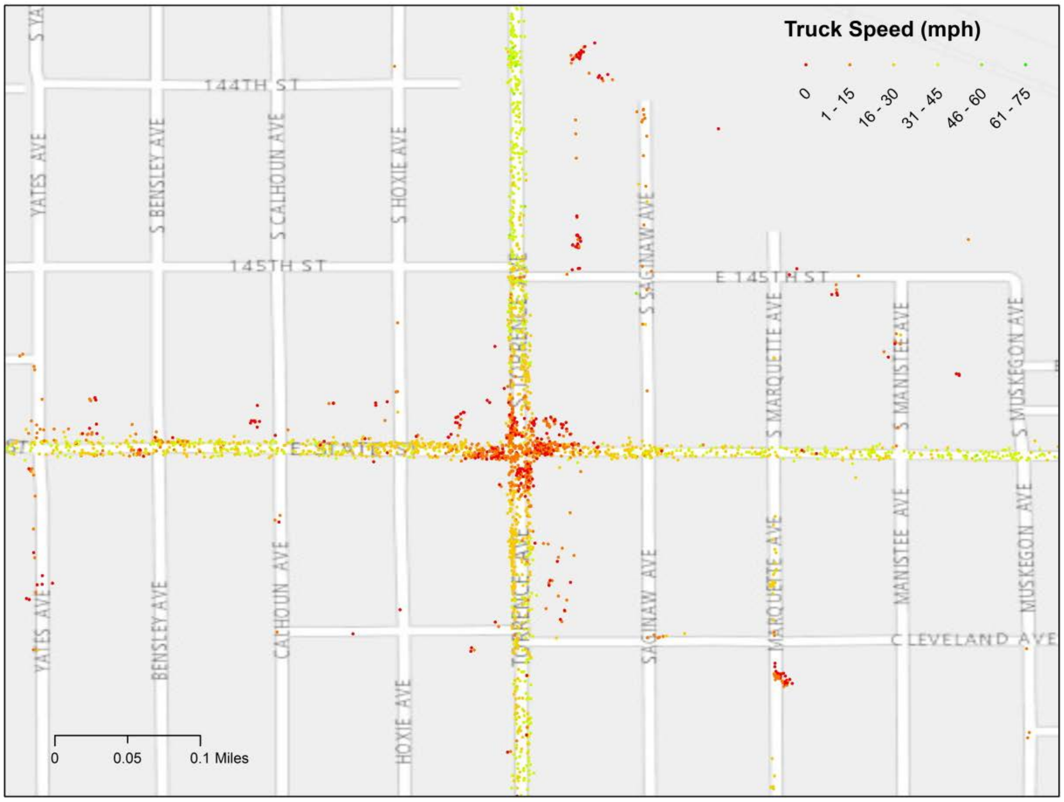


Figure 10. Map. Spot speeds along an urban signalized arterial.
(Source: American Transportation Research Institute.)

This is further demonstrated in figure 11. Nearly 9 percent of measured spot speeds are stopped, while 39 percent are operating in the 25 to 35 miles per hour range.

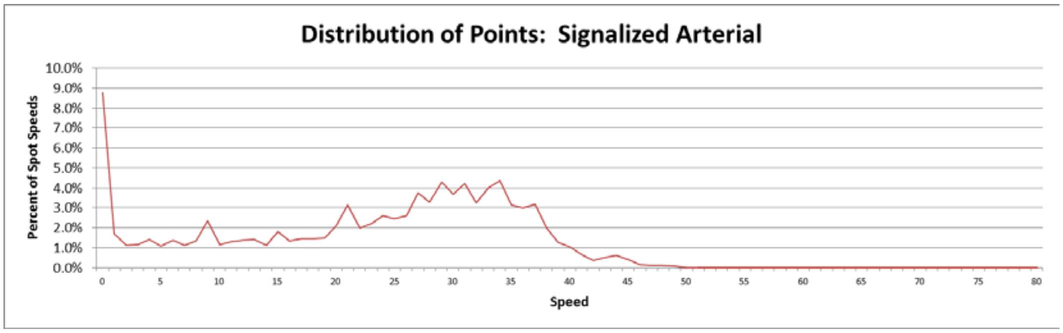


Figure 11. Graph. Distribution of sample urban signalized arterial spot speeds.
(Source: American Transportation Research Institute.)

Due to these differences, measuring performance on signalized arterials is more complex than measuring performance on limited access highways. Thus, it is likely that enhancements to standard highway measurement methodology are necessary for signalized arterials, including methodologies for identifying bottlenecks.

Approaches: Spot Speed versus Travel Time: There are two basic approaches for calculating average speed/travel times and attributing those measures to roadway segments using vehicle probe data: the spot speed approach and the travel-time approach.

Spot Speed: Spot speed calculations measure clusters of single points on a given roadway segment during a given time period. A single spot speed measurement, represented for instance as a single point in figures 8 or 10, captures the rate of travel a vehicle is moving at a certain latitude/longitude point and at a certain time. For a small stretch of rural Interstate highway (one mile, for instance), a single point may be sufficient to identify free-flow performance over a short time period.

Due to the variability of speeds within short distances, however, arterials must be approached differently. Figure 12 shows average spot speed measurements within the earlier arterial roadway example. The road has been segmented into small sections (approximately 300 feet) to show the variability of average speeds along the roadway, demonstrating that spot speed analysis might not fully capture congestion problems on signalized arterials.

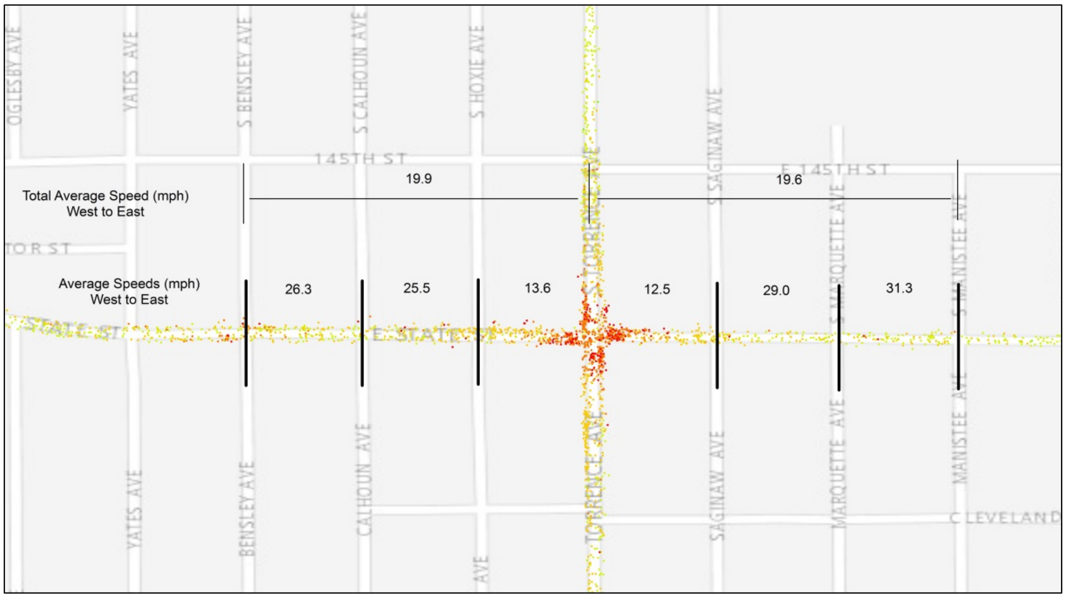


Figure 12. Map. Average spot speed measurements.
(Source: American Transportation Research Institute.)

Travel Time: Travel time calculations, on the other hand, focus on point-to-point calculations rather than a single moment in time. Such a calculation can be useful at signals in particular because it has the potential to capture the duration of a stop. Examples of these calculations are illustrated in figure 13.

Figure 13. Map. Travel time measurements along an urban arterial.
Source: American Transportation Research Institute.

The downside to this approach, however, is that vehicle probes cannot be compelled to produce a data point at two specific locations in the way a fixed traffic sensor could. Thus, individual point-to-point travel times must be layered upon or attributed to road segments that are crossed. It should also be noted that travel times, such as those in figure 13 are further complicated by direction—for an eastbound vehicle, it may take a different amount of time to turn north, south or maintain direction.

As of this writing, vehicle probe data from commercial sources are only starting to distinguish whether spot speeds or point-to-point travel times were used to calculate the data they provide, which as of now travel times (or speeds) are assigned to directional roadway "links."

3.2.1.5 Summary of Arterial Data Collection Methods for Travel Time and Delay

Table 6 provides a synopsis of the major types of data collection systems for travel time. All types except for crowd-sourced data require that agencies deploy and maintain field equipment. The ability to measure signal control delay is possible with these sources if the data segmentation coincides with signal location. Estimation of delay using signal event data synthetic, i.e., it relies on models.

Table 6. Comparison of arterial travel-time data collection technologies.

Technology	Sample Size	Characterized Distribution of Travel Times	Ability to Scale Agency-wide	Segments that Correspond to Individual Signals
Agency-driven probe vehicles	Poor	Poor	Poor	Yes
Reidentification of vehicles (ELPR, pavement sensors)	Excellent	Excellent	Poor	Yes, but depends on the ability to deploy equipment at every signal
Reidentification with MAC address matching (Bluetooth)	Good	Good	Fair	
Crowd-sourced data (commercial vehicle probe)	Fair	Fair (but improving)	Excellent	Vendor defines segmentation; may or may not coincide
Virtual probe	Excellent	Excellent (but derived)	Fair	Yes, if modeled in the simulation
Agency-driven probe vehicles	Poor	Poor	Poor	Yes

(Source: Remias et al.; "virtual probe" assessment added by Cambridge Systematics, Inc.)

The data types identified in table 7 represent those that are available as of the writing of this report. It is possible that vendors currently offering vehicle probe data based on segmentation will soon provide "traces" of individual vehicles that allow constructing travel times between origins and destinations (O/D). These O/D travel times would be directly measured rather than synthesized.

One further note on crowd-sourced (vehicle probe) data. Recent evaluations from the University of Maryland and Virginia Center for Transportation Innovation and Research (VCTIR) suggest that the accuracy of these data is questionable on streets that have very congested, oversaturated conditions (multiple-cycle failures). Accuracy problems also exist on lower-order functional classes, where probe samples are likely to be small.[32] For the purposes of arterial performance monitoring and bottleneck identification, where we are primarily interested in the relative rankings and trend analysis, the accuracy problem is not as severe as for other uses such as traveler information. As vendors gain more experience in collecting and processing travel-time data, the accuracy problem may be reduced, but there is no guarantee of that happening. For example, more direct tracking of vehicles over a facility—rather than relying on instantaneous speed readings—offer promise. For the moment, users need to be aware of the accuracy problems especially when making benefit estimates.

3.3 RECOMMENDED PROCEDURE FOR MEASURING SIGNALIZED ARTERIAL CONGESTION

3.3.1 Criteria for Developing the Measurement Procedure

As discussed above, a variety of technologies and methods can be used to calculate signalized arterial performance. The methods include direct measurement of travel time and delay, synthetic (model) derivation of travel time and delay, and a combination of direct measurement and models. The literature covers arterial performance measures extensively, but many of these relate to signal maintenance and operation, and are only indirect indicators of congestion. With that in mind, we establish several criteria that a measurement procedure should meet:

- The user's perspective, not the facility perspective, should define arterial congestion performance. Travelers experience the whole trip; isolated portions of it influence trip performance but the whole experience is important to travelers. This criterion implies that travel times be the basis for arterial performance measures for congestion. Using travel times also is consistent with freeway performance measurement and travel times resonate with the general public; they are easy to communicate.
- The best way to develop travel times is to measure them directly. Of the technologies listed in table 6, agency probe vehicles and the vehicle reidentification technologies accomplish this. Crowd-sourcing methods may or may not; these currently are used by private vendors who employ proprietary data reduction methods, and it is difficult to know if they develop travel times from tracking individual vehicles over a distance or use instantaneous vehicle

[32] http://onlinepubs.trb.org/onlinepubs/conferences/2014/NATMEC/ArterialWorkshop.pdf.

speed measurements. If vendors ever develop data based on true time-space traces for individual vehicles, then directly measured travel times will be available.

- Recognizing that the use of agency probe vehicles will result in a limited sample and the deployment of roadway-based reidentification equipment is expensive, the current generation of crowd-sourced data can be used to measure arterial performance.
- Continuously measured travel times produce distributions of travel times. Having access to the complete travel-time distribution allows the calculation of reliability and provides a more complete picture of performance.
- Measure delay at individual signals along an arterial corridor. The ability to identify specific bottlenecks along a corridor is a vital step in performance management. Once the performance of the arterial corridor is established, a “drill-down” capability will identify where problems exist.

3.3.2 Arterial Performance Measures

Travel times establish a wide variety of arterial performance measures. The following section provides the recommended minimum set of performance measures. Both corridor-wide and signal-based measures are included.

3.3.2.1 Corridor-Wide Travel-Time Data Reduction

The first step in developing corridor-wide measures is to work out the segmentation of the corridor so that the data can be properly reduced. Because of issues of “time-distance displacement” in combining data,[33] the corridor should not be excessively long: 10 miles is a reasonable maximum. Above that, care must be used in interpreting the results.

In all likelihood, the corridor of interest will be longer than the data collection segments that comprise it. Therefore, a method for combining the measurements for the data collection segments (e.g., where a reidentification detector is located or the links on which crowd-sourced travel times are reported) into the corridor is needed. Four methods can be used:

- The most direct method is simply to track the travel times of individual vehicles throughout the length of the entire corridor and develop the travel-time distribution from them. This currently is only possible with the reidentification technologies. It is the “purest” of the methods as the corridor travel time is directly measured. However, there are problems with this approach.

    - Sample sizes may be small, because of vehicles entering and leaving the corridor at different points.
    - Due to the possibility of travelers making intermediate stops at activities along the corridor, some recorded travel times will be excessively long. Statistical procedures have

[33] If travel times from multiple links are added to get the route travel time for a given time period, this will not correspond to the travel time measured from a vehicle’s perspective, which will pass over downstream links at different times.

been developed to weed out these long trips, but they are *post hoc* in nature and may result in excluding sound data.[34]

Keeping the corridors reasonably short in length minimizes problems, even for lengths shorter than the 10 miles recommended above.

- Using crowd-sourced (e.g., vendor-supplied travel-time data),[35] develop travel-time distributions for each data collection segment first, and then combine to get the corridor distribution. The moments of the distributions for the individual data collection segments are calculated. These include the following metrics for both travel time and space mean speed: minimum and maximum values; 1st, 5th, 10th, 15th, 20th, 25th, 30th, 40th, 50th, 60th, 70th, 75th, 85th, 90th, 95th, and 99th percentiles; mean; and variance. Corridor metrics are simply the sum of the data collection segment metrics. Past research has found that travel times on adjacent links are not statistically independent (i.e., they are assumed to be correlated), and hence variances and percentiles cannot be added (but means can).[36] Recent work by Isukapati et al. suggests that in practice, they can be additive.[37] However, their work is based on examining a single freeway corridor with relatively uncongested conditions—the applicability to congested and/or arterial conditions is unknown.

- Using crowd-sourced (e.g., vendor-supplied) travel-time data, develop corridor-wide travel times first, and then create the corridor distribution from them. In this approach, a corridor travel time for each time epoch (e.g., every five minutes) is created. These travel times are then the observations in the travel-time distribution from which congestion and reliability metrics are created. This method avoids any thorny statistical problems with combining distributions and most closely resembles data collected from direct observation of travel times from end to end.

- Apply the virtual probe or trajectory method to crowd-sourced data. This is not a distinct method but an extension to method 3 above, which has the problem of not precisely replicating the passage of vehicles over the facility in time and space. (Method 2 also suffers from this time-distance displacement but there is no easy way to address it for percentiles;

---

34 For example: Salek Moghaddam, Soroush and Bruce Hellinga, *Evaluating the Performance of Algorithms for the Detection of Travel Time Outliers*, Transportation Research Record No. 2338, Washington, D.C., 2013, http://trid.trb.org/view.aspx?id=1242887.

35 It is assumed that vendor-supplied travel-time data are available for short highway segments such as Traffic Message Channel segments.

36 Mahmassani, Hani et al., *Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools*, Report S2-L04-RR-1, Transportation Research Board, 2014. http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP 2_S2-L04-RR-1.pdf.

37 Isukapati, Isaac Kumar, George F. List, Billy M. Williams, and Alan F. Karr, *Synthesizing Route Travel-Time Distributions from Segment Travel-Time Distributions*, Transportation Research Record No. 2396, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 71–81. DOI: 10.3141/2396-09.

mean values could be used, however.)[38] This is less of a problem for relatively short facilities, such as the recommended 10 miles. However, as trip lengths extend, the problem becomes exacerbated.

Recommendations: Recommendations based on this assessment of arterial travel-time data reduction are:

- Using the principle that the best way to develop travel times is to directly measure them, method 1 should be the preferred method, but it has limitations for arterials because of small sample sizes and interrupted trips. It also is applicable only to the reidentification data collection technologies. Therefore, the preferred approach is method 4, especially for long corridors. Method 3 will suffice for corridors that are not longer than 10 miles.
- Adding segment distributions to obtain percentiles, which are the basis for most reliability metrics, is not recommended for facility performance. Serious theoretical questions exist that have not been adequately addressed with empirical evidence, and we see no simple way of accounting for the time-distance displacement problem with this method. Additional research may override this recommendation or develop adjustments for its application.
- If only mean travel times are desired, and then adding mean segment travel times to obtain facility travel-time is acceptable.

3.3.2.2 Treating Missing Data in the Calculations

For all of the above methods, the analyst will most likely have to deal with missing data. Because the foundation of performance measurement is to create an overall travel time for a facility as the sum of the travel times on shorter segments, missing data can influence the outcome. For example, suppose method 2 is being used. There are four short segments whose travel times need to be summed. For a given five-minute time interval, only three of the segments have travel times present.

The first step in deciding what to do is to assess the data for the occurrence of missing data for the time periods being analyzed. This analysis will provide the analyst with information on what to do next. Then, three strategies can be used to account for the missing data:

1. Discard the time interval if less than 100 percent of all segment travel times are present. The analyst may decide that the travel times on each segment are so unique that any factoring or imputation method will produce misleading results. This strategy will be adequate if there are not too many time intervals that are discarded.

2. Impute values for the missing segment travel times. Imputation creates new values based on the typical patterns of a segment. For example, the average travel time for the same time

[38] SHRP 2 Project L02 developed a Monte Carlo simulation approach to this problem but it is cumbersome to implement. See: List, George L. et al., *Establishing Monitoring Programs for Travel Time Reliability*, Report S2-LO2-RR-2, Transportation Research Board, 2014, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp? ProjectID=2178.

period for the same day of week may be used. A more detailed look at imputation can be sound in the SHRP 2 L02 Guidebook.[39] However, using overall averages cannot account for the variations in travel times caused by disruptions that may occur on a given day, so using imputation is a judgment call for the analyst.

3. Treat the existing segment travel times as a sample and expand it based on length. In this approach, the sum of the travel times for the segments with travel times is expanded based on the ratio of the facility length to sum of the lengths for the segments with travel times. As with imputation, this approach has limitations—it assumes that conditions on the segments with travel times are representative of the missing segments. If this approach is used, a minimum length for the existing segments should be established—below this threshold the data cannot be expanded. It is recommended that at least 50 percent of the facility length be present.

3.3.2.3 Signalized Arterial Performance Measures

Individual Intersections: Many performance measures have been identified for signalized intersections but most of them are to help maintain and operate signals, not for performance reporting from the user's perspective. For the purpose of the user-based performance reporting, **signal control delay** (the actual vehicle-hours minus the vehicle-hours that would be experienced to proceed through the segment at the reference speed) is the most useful measure. This is computed only for the shortest segment in the data that has a signal at the downstream end. Reference speed is defined in the next subsection.

Signalized Arterial Performance Measures: Segment and Corridor: The following measures for congestion and reliability are recommended:

- **Total Delay (Vehicle-Hours and Person-Hours)—**Actual vehicle-hours (or person-hours) experienced in the highway section minus the vehicle-hours (or person-hours) that would be experienced at the reference speed.
- **Mean Travel-Time Index (MTTI)—**The mean travel time over the highway section divided by the travel time that would occur at the reference speed.
- **Planning-Time Index (PTI)—**The 95th percentile Travel-Time Index computed as the 95th percentile travel time divided by the travel time that would occur at the reference speed.
- **80th Percentile Travel-Time Index (P80TTI)—**The 80th percentile Travel-Time Index computed as the 80th percentile travel time divided by the travel time that would occur at the reference speed.

3.3.2.4 Calculating the Reference Speed

Discussion: As noted above, performance measures require a baseline or benchmark from which to calculate them; this is based on a fixed reference speed predetermined by the user. In the literature, the free-flow speed is often used as the reference speed, but some agencies may want

[39] http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP 2_S2-L02-RR-2.pdf.

to use an alternative reference speed. The purpose of the reference speed is to determine the point at which "congestion" begins.

The biggest issue faced on signalized arterials is whether or not the presence of signals should be accounted for in establishing reference speed. Under very light traffic conditions, some delay will occur at signals in order to address side street demand. On the other hand, to assume that signals do not exist (i.e., using mid-block speeds as a basis) implies that signals on the arterial are perpetually green. The issue is to decide which of these cases is closest to ideal conditions.

Several methods exist for computing the reference speed:

- Assume a fixed-reference speed value for all facilities of a given type. Using this method a single value for all signalized arterials would be used.
- Base the reference speed on the speed limit. Some applications use the speed limit or a constant adjustment to it; the Florida DOT uses speed limit plus five miles per hour.[40]
- Base the reference speed on the speed at which maximum throughput volume occurs. Freeway analysis uses this method where it is noted that from the speed-flow curve, the maximum throughput occurs in the 45 to 54 miles per hour range. We are unaware of any application of this concept to signalized arterials as maximum throughput depends on signal timing.
- Use the speed indicative of a certain Level of Service as the reference speed, as calculated by the *HCM*. For example, Level of Service C occurs when signalized arterial speeds are 50 to 67 percent of the base free-flow speed. However, the user must select the actual value in the range.
- Use a speed that is indicative of users' "reasonable expectations." This approach is based on the observation that users acclimate to prevailing conditions, and where their travel experience is congested, do not expect to travel at the speed limit or free-flow speed. Values related to the mean or median speed are often proposed for the reference speed. A problem with this approach is that user perceptions will vary in urban versus rural areas, and can change for different facilities within an area. Moreover, selecting the reference speed is often done without scientifically determining what user expectations are.
- Use a combination of factors to set the reference speed. In the *HCM*, a number of factors determine signalized arterial free-flow speed: speed limit, median type, curb presence, access points, and signal spacing.
- Use travel-time data during off-peak hours. With the advent of continuously collected travel-time data, it is now possible to "observe" speeds under light traffic conditions. Approaches here use data from low-volume time periods, such as overnight hours between midnight and 5:00 a.m. or early morning weekend hours. The data are polled and a moment of the distribution is used as the reference speed—the 85th percentile is common. Three problems exist with this empirical approach. First, while this is a reasonable approach for freeways, signal timing during the off-peak periods may be biased toward providing green time on the mainline arterial. Second, even with freeways, if data are used periodically (e.g., every year)

---

[40] Moses, Ren and Mtoi, Enock, Evaluation of Free Flow Speeds on Interrupted Flow Facilities, Final Report, Project No. BDK83 977-18, http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_PL/FDOT-BDK83-977-18-rpt.pdf.

to update the reference speed, a constant base no longer exists, and performance trends may the result of a changing reference speed as opposed to changes in congestion level. This problem is remedied by selecting a permanent reference speed based on data.

The third problem with using field data is that there appears to be a significant difference in the free-flow speeds of passenger cars versus trucks. Data from the 2014 NPMRDS, which distinguishes the speeds of passenger cars and trucks, were analyzed for Florida and Tennessee. Free-flow (reference) speeds were computed separately for passenger cars and trucks for TMCs individually. The results are shown in table 7. The overall speed differences are dramatic: truck reference speeds on Interstates on 7.8 miles per hour lower for Tennessee and 9.6 miles per hour lower for Florida. The difference is about one-half that for non-Interstates. A closer look revealed that most truck reference speeds never get much above 65 miles per hour, probably due to speed governors and/or company driving policies.

Table 7. Reference speeds from National Performance Management Research Data Set.

		Average Reference Speed (Miles per Hour)		
State	**Roadway**	**Passenger Cars**	**Trucks**	**Combined**
Florida	Interstate	73.0	63.5	71.3
	Remainder NHS	48.3	45.3	48.0
Tennessee	Interstate	70.0	62.2	66.0
	Remainder NHS	49.9	46.5	49.0

(Source: Cambridge Systematics, Inc.)

The truck/passenger car speed differential, at least where the current NPMRDS is concerned, raises the issue of what speed measurement to use to establish reference speed. If the passenger car speeds are used, trucks will automatically be assigned some delay, even they are traveling at "their" reference speed. Using truck-only speeds would be one way to set the overall reference speed, but the number of trucks reporting speeds in any given epoch may be very low, or non-existent, especially on lower order highways. Some probe databases also do not report truck-only speeds. Finally, even under low-volume conditions, truck reference speeds could be low due to geometric conditions such as bad grades and curves. Setting the overall reference speed equal to truck reference speed would mean that these locations don't register as bottlenecks, given the way that performance measures are calculated.

A test was conducted to determine what effect different reference speed thresholds have on results. ITS detector data were used for nine highway sections in Atlanta for 2010; these have the advantage of direct volume measurements paired with speed measurements (table 8). Four thresholds were considered: the section's free-flow speed, maximum throughput speed (52 mph, based on the *HCM*'s speed-flow curve for freeways), 40 mph, and the section's median speed. Free-flow speeds were in a narrow range from 67 to 71 mph, but the median speeds varied greatly, from 31 to 66 mph, indicating that travel peaks by direction. Further, median speeds were significantly different for the AM and PM peaks for the same section. Except for delay based on median speed, delay values decreased with decreasing reference speed.

Table 8. Test of reference speeds, Atlanta, Georgia freeways.

				Annual Delay (Vehicle-Hours) Based on:			
Section	**Period**	**Median Speed**	**Free-Flow Speed**	**Free-Flow Speed**	**Maximum Throughput**	**40 mph**	**Median**
I-75 Northbound from I-285 to Roswell Road	AM PEAK	66.2	69.4	15,140	69	0	4,761
	PM PEAK	31.7		342,893	251,346	160,401	83,053
I-75 Southbound from I-285 to Roswell Road	AM PEAK	50.4	67.4	160,336	50,070	9,908	41,439
	PM PEAK	63.2		35,779	6,374	3,400	12,460
I-75 Southbound from I-20 to Brookwood	AM PEAK	63.0	69.6	17,651	6,582	240	23,394
	PM PEAK	32.3		220,267	181,181	97,336	32,711
I-285 Eastbound from Georgia-400 to I-75	AM PEAK	48.5	71.2	118,451	74,813	18,111	55,805
	PM PEAK	57.9		71,214	49,414	22,201	65,408
I-285 Westbound from Georgia-400 to I-75	AM PEAK	65.1	69.4	3,107	1,282	172	9,465
	PM PEAK	40.7		218,301	175,771	99,125	103,935
I-285 Eastbound from Georgia-400 to I-85	AM PEAK	62.9	67.6	8,670	2,153	138	13,411
	PM PEAK	30.6		309,937	271,042	195,361	117,398
I-285 Westbound from Georgia-400 to I-85	AM PEAK	42.5	67.1	160,112	107,364	25,739	40,703
	PM PEAK	57.1		59,659	36,929	15,849	50,451
I-75 Northbound from Roswell Road to Barrett Parkway	AM PEAK	66.3	69.7	16,122	368	38	8,619
	PM PEAK	37.1		229,714	149,719	75,442	57,435
I-75 Southbound from Roswell Road to Barrett Parkway	AM PEAK	39.5	70.5	195,643	119,416	53,180	50,275
	PM PEAK	66.3		18,167	3,344	1,455	9,451

(Source: Cambridge Systematics, Inc.)

For the purpose of ranking bottlenecks, any of the reference speeds, except for the median-based approach, will produce the same ranking of bottleneck locations, though the delay values will be different. If delay based on median speed is included, the ranking order is slightly different, but very close to that produced by the others. Therefore, for bottleneck analysis, we conclude that very little difference in ranking occurs due to the choice of reference speed. Although the analysis was conducted with freeway data, we expect the same pattern to hold for signalized arterials.

One other problem with using a reference speed based on median speed should be noted. The value will change over time, providing an unstable base for tracking annual trends. While it could be held fixed over time, it will tend downward in years when work zones are present, extreme weather occurs, and/or demand is unusually high. It is not clear if users' expectations are in line with degraded reference speed.

Recommendation: For congestion performance monitoring, the key outcome is the ability to track changes over time— "are things better or worse?" If that is the case, any of the above strategies are reasonable if they are held constant over time. Reiterating one of our principles for performance measures—the best way to develop travel times is to measure them directly—we prefer the data (empirical approach) for arterials. The other methods use surrogates for estimating what travelers experience. The empirical approach assumes that an adequate amount of travel-time data exists for the off-peak time period chosen, which can be either 2:00 a.m. to 5:00 a.m. on weekdays, 6:00 a.m. to 9:00 a.m. on weekends, or both. The 85^{th} percentile should be used as the reference speed from the distribution of speeds for the selected time period. Reference speed should be computed for each of the segments on the facility individually. The reference travel time is then computed as the segment length divided by the 85^{th} percentile speed, and the facility reference travel time is the sum of the individual segment reference travel times. Note that the 15^{th} percentile travel time is equivalent to the travel time that occurs at the 85^{th} percentile speed on a segment. This procedure assumes that a small amount of delay will be built into the reference speed due to signal operation, but under low traffic volumes.

The speed measurements that should be used in reference speed calculation that should be used are for all vehicles combined. This recommendation recognizes that as of this writing, some probe data bases only report this value. In the future, if speeds by vehicle type are universally reported and if reliable vehicle volume data are available, it would make sense to compute reference speeds separately for several categories of vehicle type, and subsequently to compute performance measures for each category. At this time, such a step is over-complicated and stretches the credibility of the existing data.

If sufficient measured speed data are not present, then the speed limit plus five miles per hour should be used. This should provide a reasonable approximation to field data-derived reference speed.

Users should indicate which method they have used in their documentation. Because some agencies already may have policies dictating how reference speed should be calculated, the intent here is to provide a *de facto* standard so that studies can be compared on an equal basis. Thus, where reference speed policies differ from those recommended here, agencies should compute two sets of performance measures. Their decisions will be driven by the ones based on their policies but the "standard" set will allow others to compare to their work.

3.3.2.5 Calculation Procedures for Arterial Performance Measures

Note: The methods described below can be applied to any highway type for which travel-time and volume data are available for individual segments, such as vehicle probe data. Therefore, they can be used in chapter 4 for the computation of performance measures for <u>any</u> type of freight bottleneck.

The following procedures are specified for two conditions: 1) traffic volumes have been merged into the data using procedures in chapter 2; and 2) no traffic volumes are available. It is highly recommended that traffic volumes be used in order to compute total delay and to weight aggregations properly.

The procedure assumes that in order to compute facility measures, segment measures must first be created.

If travel times are available separately for passenger cars and trucks, then the procedures are used to produce measures for passenger cars, trucks, and all vehicles.

3.3.2.6 Arterial Segments

Reidentification field equipment or by private vendors define location of the segments (e.g., traffic message channels or TMC).

No Volume Data Available

1. If travel times are not present in the data, compute them from segment speed and distance for each epoch:

$$TravelTime_{Segment} = \frac{Length_{Segment}}{Speed_{Segment}} \times 60$$

Where: $TravelTime_{Segment}$ = the travel time for the segment, minutes;
$Length_{Segment}$ is in miles; and
$Speed_{Segment}$ is in miles per hour.

Figure 14. Equation. TravelTime subscript Segment.

2. Compute reference travel time:

$$RefTravel\ Time_{Segment} = \frac{Length_{Segment}}{RefSpeed_{Segment}} \times 60$$

Where: $RefTravelTime_{Segment}$ = the reference travel time for the segment, minutes; and
$RefSpeed_{Segment}$ = the reference speed, in miles per hour (section 3.3.2.3).

Figure 15. Equation. RefTravelTime subscript Segment.

3. Compute unit delay for each epoch:

$$UnitDelay_{Segment} = RefTravelTime_{Segment} - TravelTime_{Segment}$$

Where: $UnitDelay_{Segment}$ is delay per vehicle, minutes. If *UnitDelay* is negative it should be set to zero.

Figure 16. Equation. UnitDelay subscript Segment.

4. Create travel-time distribution for the time period of interest (e.g., 6:00 to 9:00 a.m.). Each observation should represent an epoch contained in the time period. Identify the mean, 80^{th} percentile, and 95^{th} percentile (plus any other statistics that are useful for individual cases).

5. Calculate recommended performance measures for the time period of interest:

$$MTTI_{Segment} = \frac{MeanTravel\ Time_{Segment}}{RefTravelTime_{Segment}}$$

Figure 17. Equation. MTTI subscript Segment.

$$PTI_{Segment} = \frac{95th\ percentile\ Travel\ Time_{Segment}}{RefTravelTime_{Segment}}$$

Figure 18. Equation. PTI subscript Segment.

$$P80TTI_{Segment} = \frac{80th\ percentile\ Travel\ Time_{Segment}}{RefTravelTime_{Segment}}$$

Figure 19. Equation. P80TTI subscript Segment.

$$UnitDelay_{Segment} = \sum_{e} UnitDelay_{e}$$

Where: Subscript *e* refers to an individual epoch.

Figure 20. Equation. UnitDelay subscript Segment.

Volume Data Available

6. Repeat steps 1 and 2 immediately above.

7. Compute VMT (Vehicle-Miles of Travel), Vehicle-Hours of Travel (VHT), and total delay (in vehicle-hours) for each epoch.

$$VMT_{Segment} = Volume_{Segment} \times Length_{Segment}$$

Figure 21. Equation. VMT subscript Segment.

$$VHT_{Segment} = Volume_{Segment} \times TravelTime_{Segment} \times \frac{1}{60}$$

Figure 22. Equation. VHT subscript Segment.

$$TotalDelay_{Segment} = VHT_{Segment} - \left(Volume_{Segment} \times RefTravelTime_{Segment} \times \frac{1}{60}\right)$$

Figure 23. Equation. TotalDelay subscript Segment.

- Create travel-time distribution for time period of interest, using VMT as the weight on each observation. That is, the travel times in an epoch are assumed to be the average of all vehicles traveling over that segment in an epoch. Identify the mean, 80th percentile, and 95th percentile (plus any other statistics that are useful for individual cases).
- Repeat step 4 immediately above using the weighted travel-time distribution; the reference travel time is the same. Total delay is computed in the same manner as unit delay, i.e., the sum of the delay in the epochs in the time period of interest.

3.3.2.7 Arterial Facilities

No Volume Data Available

1. Create a dataset for travel times over the facility for each epoch by either: 1) using the vehicle trajectory method (discussed previously); or 2) summing the segment travel times.

- Compute the reference travel time for the facility ($RefTravelTime_{Facility}$) as the sum of the segment reference travel times.
- Compute unit delay for the facility for each epoch as the sum of *UnitDelay* for all segments on the facility for the time period of interest.
- Create travel-time distribution for time period of interest for the entire facility using the data created in step 1. Each observation should represent an epoch contained in the time period. Identify the mean, 80th percentile, and 95th percentile (plus any other statistics that are useful for individual cases).

- Calculate recommended performance measures for the time period of interest:

$$MTTI_{(Facility\ )} = \frac{MeanTravel\ Time_{Facility}}{RefTravelTime_{Facility}}$$

Figure 24. Equation. MTTI subscript (Facility).

$$PTI_{Facility} = \frac{95th\ percentile\ Travel\ Time_{Facility}}{RefTravelTime_{Facility}}$$

Figure 25. Equation. PTI subscript Facility.

$$P80TTI_{Facility} = \frac{80th\ percentile\ Travel\ Time_{Facility}}{RefTravelTime_{Facility}}$$

Figure 26. Equation. P80TTI subscript Facility.

$$UnitDelay_{Facility} = \sum_{e} UnitDelay_{e}$$

Figure 27. Equation. TotalDelay subscript Facility.

Volume Data Available

2. Repeat steps 1 and 2 immediately above.

- Compute total delay for the facility for each epoch as the sum of total delay for all segments on the facility for the time period of interest.
- Create travel-time distribution for time period of interest for the entire facility using the data created in step 1. The weight on each observation is provided by VMT. That is, the travel times in an epoch are assumed to be the average of all vehicles traveling over that segment in an epoch. Identify the mean, 80^{th} percentile, and 95^{th} percentile (plus any other statistics that are useful for individual cases).
- Repeat step 5 immediately above using the weighted travel-time distribution; the reference travel time is the same. Total delay is computed in the same manner as unit delay, i.e., the sum of the delay in the epochs in the time period of interest.

Cumulative Travel-Time Distribution Function for Arterial Facilities: In addition to the individual metrics computed above, a curative distribution function of the travel times is useful diagnostic purposes. Figure 28 shows an example of this type of plot. This is easily constructed from the travel-time distribution that is specified in the above procedures.

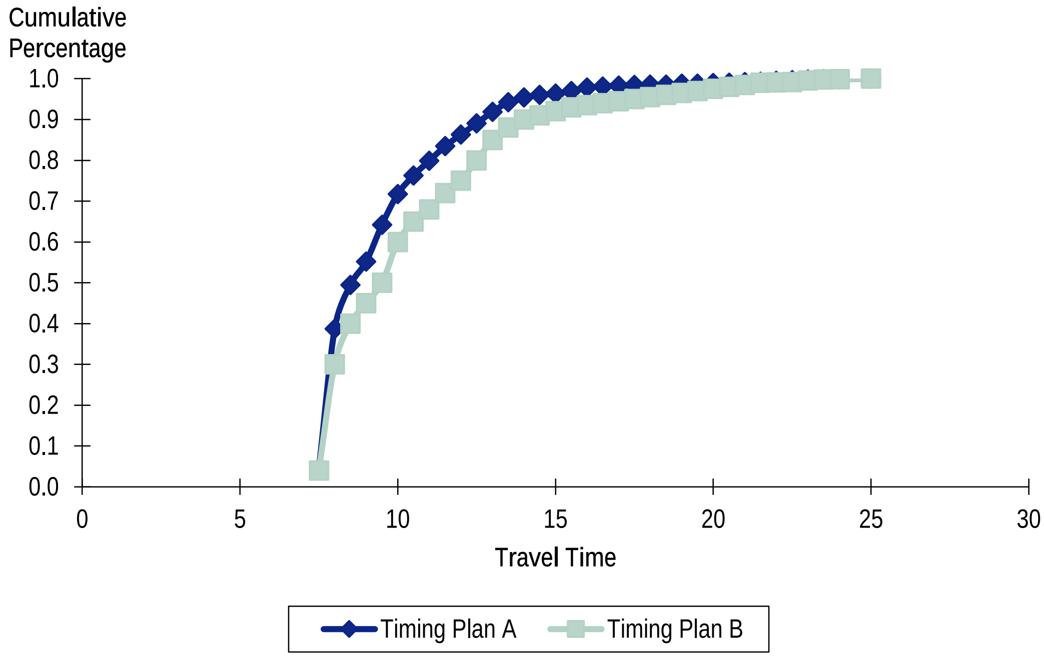


Figure 28. Graph. Example cumulative frequency distribution for travel times.
(Source: Cambridge Systematics, Inc.)

3.3.2.8 Example: Calculating Arterial Performance Measures with the NPMRDS

For this example, we chose U.S. 70, a signalized suburban arterial in Knoxville, Tennessee. It has a basic four-lane cross section with AADTs in the range of 25,000 to 30,000 vehicles per day and an overall signal density of roughly one signal every 0.4 miles. The 2014 NPMRDS was used as the source of travel times. Traffic volumes at the five-minute level are assumed not to exist for this example. The arterial section (facility) selected is the eastbound direction; it is 12 miles long and is comprised of 11 segments (TMCs, in this case). The weekday PM peak period (4:00 to 6:00 p.m.) was selected for analysis. The analysis was conducted for all vehicles, but a similar procedure can be followed if truck-only travel times are desired.

A review of the data revealed two major issues:

- About 3.0 percent of the data had speeds less than 3 miles per hour, and less than 0.2 percent had speeds higher than 55 miles per hour. Many researchers have noticed that the NPMRDS data through 2014 contains travel times that result in both low- and high-speed values. As a result, data less than 3 miles per hour or greater than 55 miles per hour were excluded from the analysis.
- The data completeness for the peak period was 31 percent. That is, only 31 percent of the possible five-minute epochs (time intervals) for the 11 TMCs had data reported.

The reference speed and performance measures for the segments appear in table 9. Even though the reference speeds were calculated from the data and include the effect of signal presence, volumes at the times used (weekends from 6:00 to 9:00 a.m.) are low and signals are likely to be mostly green on the arterial segments. This will influence the performance measures significantly. Because of the low completeness rate, the delay values severely underestimate the actual delay. One way to account for the missing data is to treat the measured delay as a sample and expand it with the ratio of the number of possible epochs to the number of epochs present.

Table 9. Segment-level performance measures, U.S. 70
PM peak.

TMC	TMC Length	Reference Speed	Annual Delay (Minute per Vehicle)	MTTI	P80_TTI	PTI
121P07054	0.259	44.4	233.5	2.250	2.714	6.476
121P07055	3.850	48.5	9,565.8	1.627	1.752	3.119
121P07056	0.449	40.4	814.1	2.066	2.600	5.900
121P07057	1.184	46.8	3,860.7	2.017	2.286	5.385
121P07058	1.315	42.3	6,701.0	2.286	2.741	5.670
121P07059	1.804	39.8	7,744.3	1.939	2.252	4.184
121P07060	0.277	38.3	685.9	2.452	3.077	6.154
121P07061	0.996	44.3	2,840.3	2.116	2.420	5.086
121P07062	0.481	38.4	1,305.5	2.234	2.667	5.889
121P07063	1.181	37.0	3,892.7	1.948	2.165	5.409
121P07064	0.161	38.5	321.9	2.516	3.200	6.867
Entire Facility	**11.955**	**43.2**	**37,965.7**	**1.958**	**2.248**	**4.656**

(Source: Cambridge Systematics, Inc.)

Because of the low completeness rate, developing a facility travel-time distribution from which to compute facility performance measures is not tenable. Therefore, the recommended procedure presented in the previous section cannot be used unless the missing data are imputed. Instead, method 2 from section 3.3.2.1 is applied (combine the travel-time distributions from the individual segments). The results appear in the bottom row of table 8. We expect completeness rates to increase as data vendors expand their coverage, but for now analysts must understand completeness patterns in their data prior to undertaking analysis.

CHAPTER 4. ANALYSIS OF FREIGHT BOTTLENECKS

4.1 INTRODUCTION

This chapter provides the details of how to conduct a truck freight bottleneck analysis. It builds on the information in chapters 2 and 3 and makes reference to their procedures. Figure 29 presents an overview of the analysis methodology presented in this chapter. The methodology is built on the basic steps of identifying potential bottlenecks, ranking bottlenecks to obtain candidate locations, and conducting detailed analysis on the candidates to obtain accurate performance characteristics and to identify specific problems causing the bottlenecks.

The methodology is focused on performance in terms of congestion and travel-time reliability, and the second order effects that result from them. The identification, ranking, and detailed analysis are based on congestion and reliability performance. The methodology does not consider safety, which is clearly a major impact area for trucks, because it was considered to be outside the scope of the project. While this is an area where future work is needed, appendix A is offered to provide some general guidance to analysts who wish to consider safety impacts.

The methodology is built on the premise that *truck freight bottleneck performance should be measured empirically* rather than estimated through the use of models. As will be discussed, models have their place in the methodology for forecasting conditions, but current year performance at individual bottleneck locations will be calculated using field measured data.

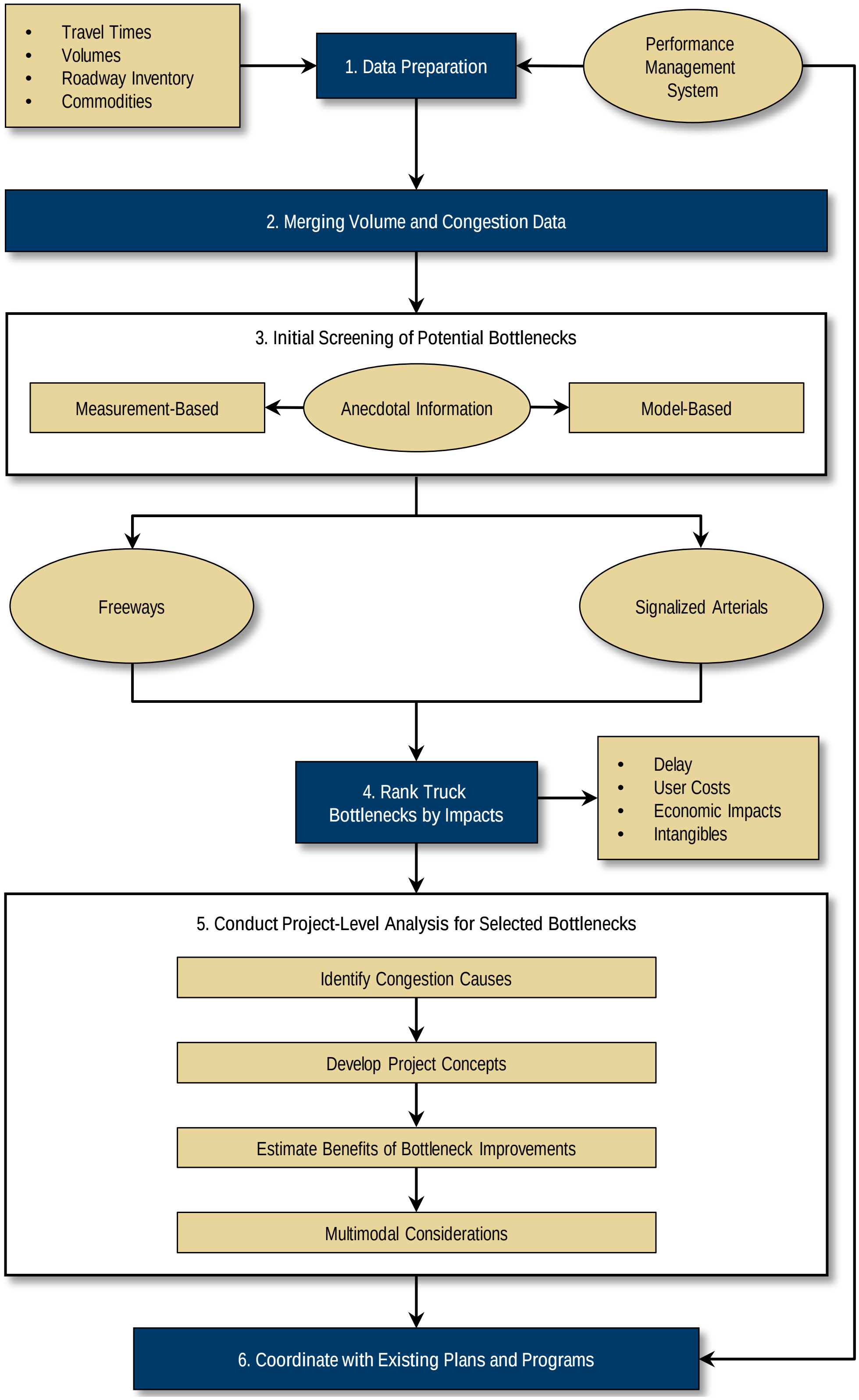


Figure 29. Flow chart. Overview of freight bottleneck analysis methodology. (Source: Cambridge Systematics, Inc.)

4.2 BOTTLENECK TYPOLOGY

Before undertaking a freight bottleneck analysis, analysts should be aware of the different types of highway freight bottlenecks that occur. It is useful to categorize bottlenecks into specific types because this aids in the analysis, and indicates which strategies are most appropriate to implement.

For the purpose of this Guide, bottlenecks are broken out into two general types based on the type of delay:

1. **Congestion-Based Delay—**These bottlenecks are defined by highway congestion, where congestion is caused by several factors. Lower speeds due to traffic flow breakdown define congestion.
2. **Non-congestion-Based Delay—**These bottlenecks are caused by policies or conditions that cause trucks to deviate from their intended route. Trucks do not necessarily enter congestion, as defined above, and their speeds may be relatively high. However, due to the deviation, truck travel times are increased over what they would have been with the deviation.

4.2.1 Congestion-Based Delay Bottlenecks

4.2.1.1 Geometric-Related Bottlenecks

These bottlenecks are caused by a reduction in roadway capacity, as compared to the prevailing capacity of the highway section. They are related to the physical characteristics of the highway and influence how it operates. Figure 30 shows the types of geometric bottlenecks that occur on freeways. From an operation standpoint, NCHRP Project 03-83 offered the following definition of geometric bottlenecks:[41]

Speeds upstream of the bottleneck are less than 30 miles per hour. Speeds at the bottleneck location range between 40 to 60 miles per hour depending of the measurement location (vehicles accelerate as they travel through the bottleneck). Traffic is free-flowing downstream with speeds at or near free-flow speeds (typically above 60 miles per hour). Detector occupancy values are generally above 30 percent upstream and less than 10 percent downstream of the bottleneck location.

[41] Kittelson Associates et al., *Low-Cost Improvements for Recurring Freeway Bottlenecks: Draft Final Report*, NCHRP Project 03-83, Transportation Research Board, November 2012. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP03-83_DraftFinalReport.pdf.

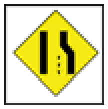
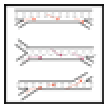
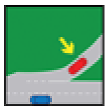
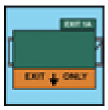
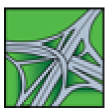
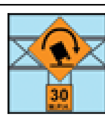
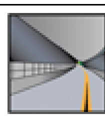
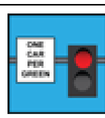
Location	Symbol	Description
Lane Drops		Bottlenecks can occur at lane drops, particularly mid-segment where one or more traffic lanes ends or at a low-volume exit ramp. They might occur at jurisdictional boundaries, just outside the metropolitan area, or at the project limits of the last megaproject. Ideally, lane drops should be located at exit ramps where there is a sufficient volume of exiting traffic.
Weaving Areas		Bottlenecks can occur at weaving areas, where traffic must merge across one or more lanes to access entry or exit ramps or enter the freeway main lanes. Bottleneck conditions are exacerbated by complex or insufficient weaving design and distance.
Freeway On-Ramps		Bottlenecks can occur at freeway on-ramps, where traffic from local streets or frontage roads merges onto a freeway. Bottleneck conditions are worsened on freeway on-ramps without auxiliary lanes, short acceleration ramps, where there are multiple on-ramps in close proximity and when peak volumes are high or large platoons of vehicles enter at the same time.
Freeway Exit Ramps		Freeway exit ramps, which are diverging areas where traffic leaves a freeway, can cause localized congestion. Bottlenecks are exacerbated on freeway exit ramps that have a short ramp length, traffic signal deficiencies at the ramp terminal intersection, or other conditions (e.g., insufficient storage length) that may cause ramp queues to back up onto freeway main lanes. Bottlenecks also could occur when a freeway exit ramp shares an auxiliary lane with an upstream on-ramp, particularly when there are large volumes of entering and exiting traffic.
Freeway-to-Freeway Interchanges		Freeway-to-freeway interchanges, which are special cases on on-ramps where flow from one freeway is directed to another. These are typically the most severe form of physical bottlenecks because of the high-traffic volumes involved.
Changes in Highway Alignment		Changes in highway alignment, which occur at sharp curves and hills and cause drivers to slow down either because of safety concerns or because their vehicles cannot maintain speed on upgrades. Another example of this type of bottleneck is in work zones where lanes may be shifted or narrowed during construction.
Tunnels/ Underpasses		Bottlenecks can occur at low-clearance structures, such as tunnels and underpasses. Drivers slow to use extra caution, or to use overload bypass routes. Even sufficiently tall clearances could cause bottlenecks if an optical illusion causes a structure to appear lower than it really is, causing drivers to slow down.
Narrow Lanes/ Lack of Shoulders		Bottlenecks can be caused by either narrow lanes or narrow or a lack of roadway shoulders. This is particularly true in locations with high volumes of oversize vehicles and large trucks.
Traffic Control Devices		Bottlenecks can be caused by traffic control devices that are necessary to manage overall system operations. Traffic signals, freeway ramp meters, and tollbooths can all contribute to disruptions in traffic flow.

Figure 30. Table. Common locations for geometric-related bottlenecks on freeways. (Source: Recurring Traffic Bottlenecks: A Primer. Focus on Low-Cost Operational Improvements, FHWA-HOP-12-012, April 2012.)

This definition implies that queuing occurs upstream of the bottleneck location (speeds less than 30 miles per hour). It also seems to have been designed for urban conditions only. There clearly will be freeway locations, especially in rural areas, where speeds are higher than 30 miles per hour but less than ideal/free-flow; grades and curves are examples. Because these types of locations are relevant for trucks, this definition is too stringent for this Guide. Therefore, we do not impose any traffic flow restrictions on what constitutes a geometric bottleneck, other than some level of delay is present.

On signalized arterials, the signal itself is a potential bottleneck. Even under light traffic, the presence of the signal will cause some vehicles to stop. However, a definition similar to one above for freeways has not been established.

4.2.1.2 Volume-Related Bottlenecks

Traffic volume (demand) can overwhelm a highway section even if there no geometric restrictions. Examples include:

- Commuter peak period traffic.
- Seasonal vacation traffic.
- Special event traffic.

The distinction between volume- and geometric-related bottlenecks is often blurred. For example, an interchange on-ramp may be poorly designed and would have reduced capacity as a result, while at the same time could add enough volume to the mainline that would cause congestion even if there was no capacity drop. Because they are so intertwined, ***it is possible to consider geometric and volume bottlenecks as a single class of bottlenecks***, but we have considered them separately because it may be helpful in developing bottleneck solutions.

4.2.1.3 Disruption-Related Bottlenecks

Here we use the term "disruption" to mean events that cause a temporary loss of capacity. This type of bottleneck is commonly labeled as "non-recurring" to distinguish them from physical bottlenecks that usually recur with a predictive frequency. Bottlenecks of this type are:

- Incidents.
- Weather.
- Construction/work zones.
- Processing delays.

Examples of processing delays are: border crossings/custom inspections, safety inspections, weighing, and terminal gate processing. With the exception of border crossing/customs, these examples are truck-specific.

4.2.2 Non-congestion-Related Bottlenecks

These bottlenecks are not related to highway operations per se but rather result from policies that delay trucks more than they otherwise would experience without the policy. They may be broken down further into subcategories:

4.2.2.1 Restrictions Requiring Rerouting

- Truck prohibitions and route restrictions.
- Bridge heights clearance issues.
- Truck size and weight limits.
- Hazardous material route restrictions.

4.2.2.2 Restrictions Requiring Changes in Timing of Trip

- Time-of-day restrictions.
- Load restrictions.

4.2.2.3 Restrictions Requiring Other Logistics Changes

- Truck size and weight limits may require lighter loads if no viable alternative routes exist).
- Loading bans.

4.3 DATA REQUIRED FOR FREIGHT BOTTLENECK ANALYSIS

Because this methodology is empirically based, the starting point for bottleneck analysis is ***travel-time data***. Sections 2.0 and 3.0 already have discussed the various forms and provided recommendations. In the ideal situation, the travel-time data has been integrated with ***traffic volume data*** (including estimates of trucks) at the lowest spatial and geographic levels of the travel-time data. In the ideal case, the integrated travel-time/volume data is available for the entire area, region, or State being analyzed. If this ideal condition cannot be achieved, the methodology allows for less detailed methods. Other data that are required are:

- **Roadway inventory data—**These data provide the geometric characteristics of roadways, including cross section (lane width, shoulder width, number, and type of lanes, median width) and the horizontal (curves) and vertical alignment (grades).
- **Commodity data—**If information on commodities carried by trucks on specific routes is available, it should be assembled. It can be used later in the benefits estimation phase.
- **Truck restriction data—**Information on where and when truck travel is restricted or banned is required for analyzing some forms of bottlenecks.

These data—especially the travel-time and volume data—already may be present in the agency's performance management system.

4.4 BOTTLENECK PERFORMANCE MEASURES

4.4.1 Congestion and Reliability Measures

For congestion and reliability, performance measures based on travel time are used. The following measures for congestion and reliability are recommended; these are to be used for all types of highways. Note that the first four measures were recommended as signalized arterial performance measures in section 3.0, which dealt with arterial performance in general. We expand the number of measures here to cover the needs of bottleneck analysis:

- **Total Delay (vehicle-hours and person-hours)—**Actual vehicle-hours (or person-hours) experienced in the highway section minus the vehicle-hours (or person-hours) that would be experienced at the reference speed. Total delay is only possible to compute if traffic volumes have been integrated. If not, unit delay (delay per vehicle) is substituted.
- **Mean Travel-Time Index (MTTI)—**The mean travel time over the highway section divided by the travel time that would occur at the reference speed.
- **Planning Time Index (PTI)—**The 95th percentile Travel-Time Index computed as the 95th percentile travel time divided by the travel time that would occur at the reference speed.
- **80th Percentile Travel-Time Index (P80TTI)—**The 80th percentile Travel-Time Index computed as the 80th percentile travel time divided by the travel time that would occur at the reference speed.
- **Hours of Congestion per Year—**Number of hours where vehicle speeds are below the following thresholds:

    - Freeways and Multi-lane highways: 50 miles per hour.
    - Rural Two-Lane Highways: 40 miles per hour.
    - Signalized Arterials: 30 miles per hour.

- **95th Percentile Queue Length—developed from a distribution of queue lengths,** the highway distance where the speeds of contiguous segments upstream of an identified bottleneck location are less than:

    - Freeways, Multi-lane, and Two-Lane Highways—30 miles per hour.
    - Signalized Highways—15 miles per hour.

- **Average Queue Length (uninterrupted flow facilities only)—**average highway distance where the speeds of contiguous segments upstream of an identified bottleneck location are less than:

    - Freeways, Multi-lane, and Two-Lane Highways—30 miles per hour.
    - Signalized Highways—15 miles per hour.

The reference speed for all highway types should be calculated using the same procedure described in chapter 3 for signalized arterials.

When bottlenecks are intersections or interchanges, it is important to develop performance measure for all approaches into the intersection of interchange. Figure 31 shows why this is necessary. In this case, the actual bottleneck point is a weaving section on the north-south roadway in the interchange. However, because of merging traffic from the east-west roadway, it also influences the performance of that roadway.

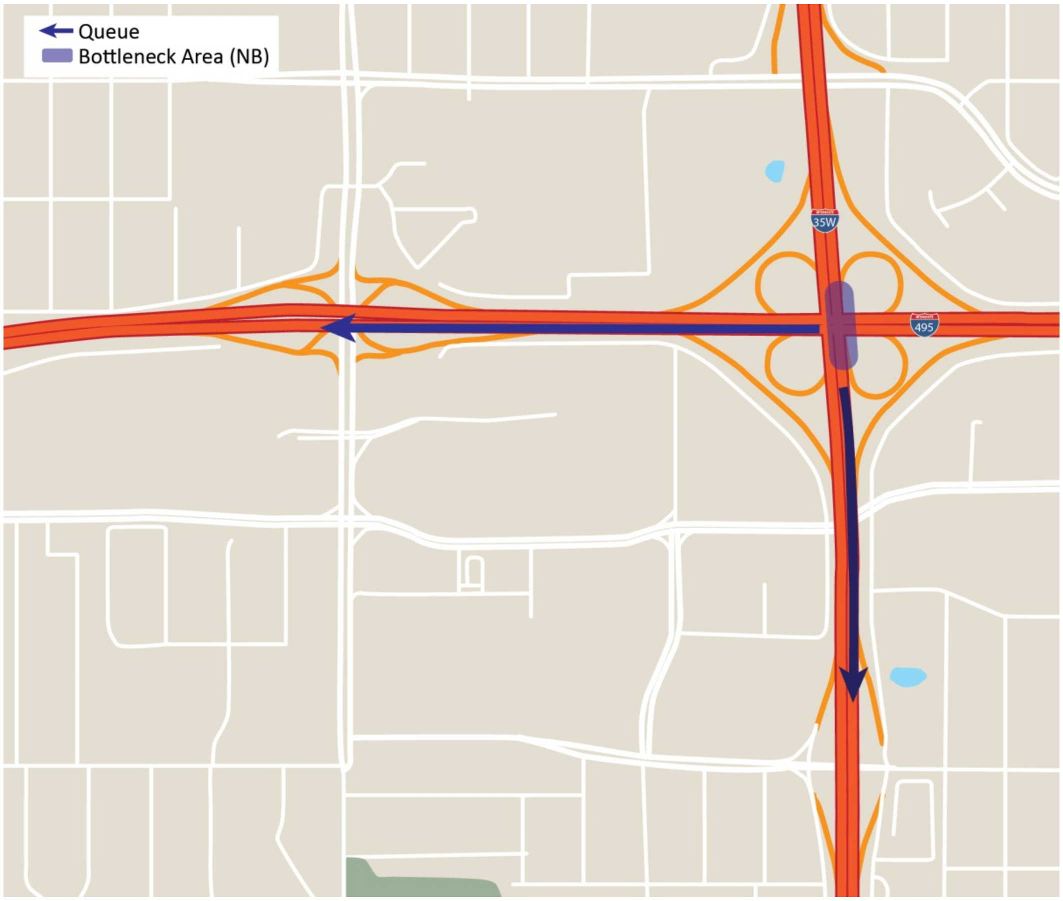


Figure 31. Map. Bottleneck at intersection or interchange.
(Source: Cambridge Systematics, Inc.)

4.4.2 Second Order Performance Measures

Second order performance measures are those that emerge as a direct result of changes in congestion and reliability. They are most commonly used to estimate impacts of bottlenecks and the benefits of improving them. The recommended measures are:

- **Delay Cost—**This is the monetized value of delay. It is computed separately for passenger cars and trucks using the following formulas.

  Annual Passenger Vehicle Delay Cost = Annual Passenger Vehicle-Hours of Delay × Value of Person Time × Vehicle Occupancy

  Figure 32. Equation. Annual passenger vehicle delay cost.

  Annual Commercial Cost = Annual Commercial Vehicle-Hours of Delay × Value of Commercial Time

  Figure 33. Equation. Annual commercial cost.

Where: the annual vehicle-hours of delay is Total Delay above, broken out by passenger and commercial (trucks).

- **Reliability Cost—**In addition to the cost of typical delay, studies have shown that highway users also value reliability, or the variability in travel conditions. The valuation of reliability is not nearly as well treated in the literature as that for typical delay. Further, reliability valuation for personal travel has been studied more than for freight travel. One recent study developed a method for computing both typical and reliability portions of congestion costs by using a “travel-time equivalent approach”:[42]

$$TTIe_{(VT)} = TTI_{50} + a * (TTI_{80} — TTI_{50})$$

Figure 34. Equation. TTI subscript e(VT).

Where:

$TTI_{e(VT)}$ is the TTI equivalent on the segment, computed separately for passenger cars (personal travel) and trucks (commercial travel);
TTI_{50} is the median TTI;
TTI_{80} is the 80th percentile TTI; and
a is the Reliability Ratio (Value of Reliability (VOR)/Value of Typical Time (VOT)).

  - = 0.8 for passenger cars
  - = 1.1 for trucks

The Reliability Ratio (VOR/VOT) of 1.1 suggests that freight interests value reliability slightly more than typical travel time.

However, this topic is still evolving. There is no agreed upon methodology for valuing reliability as of this writing. Users are free to incorporate the value of reliability in their analyses but should clearly document their assumptions. This Guide does not consider reliability costs further.

- **Fuel Cost—**Is estimated using a simple formula based on fuel efficiency. The following equation may be used separately for passenger vehicles and trucks:

Annual Fuel Cost = Annual Vehicle-Hours of Delay × Average Speed for the Time Period Being Analyzed × Average Fuel Economy of Passenger Vehicles or Commercial Vehicles × Fuel Cost

Figure 35. Equation. Annual commercial cost.

Where: average fuel economy is in gallons per mile (inverse of miles per gallon).

4.5 INITIAL SCREENING OF POTENTIAL TRUCK FREIGHT BOTTLENECKS: GEOMETRIC- AND VOLUME-RELATED BOTTLENECKS

The goal of this step is to obtain a list of potential candidate sites that will be subjected to further analysis.

---

[42] SHRP 2 Project C11, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2350.

4.5.1 Screening Based on Performance Data

If travel-time data exist for the entire area of study (e.g., region or State), analysts can perform a scan to identify highway segments where travel speeds are low. The best indication of a bottleneck is when several relatively short (about one mile) contiguous segments have high delay for the same time of day; these should be grouped together. Data should be aggregated to either 5- or 15-minute time intervals for this purpose as these levels will capture the locations that are the most serious problems. If both truck speeds and passenger car speeds are present in the data, then separate scans should be performed for each. Bottleneck locations that coincide are especially worthy of further investigation.

4.5.2 Use of Anecdotal Information

Despite the advances in data that have occurred, local knowledge is still an excellent way to identify congestion problems. Therefore, anecdotal information or the observations of field engineers can be used to verify or dismiss locations identified in the scan and to identify locations the scan may have missed. This can be done through formal or informal surveys of local engineers and planners as well as major shippers and carriers. In conducting the survey, analysts should try to distinguish between "commuter" bottlenecks (weekday peak-period bottlenecks that trucks experience as well) and primary freight bottlenecks (bottlenecks where trucks are the primary users or suffer the most delay).

A preliminary scan can be made on just truck and passenger car speeds. It is recommended that the analyst select multiple time periods for study rather than rely on single average speed value for the entire year. Weekday/non-holiday peak periods are a good starting point as is weekend mid-day (when truck volumes are heaviest). Off-peak periods also should be checked; if low truck speeds are found during both peak and off-peak periods, the likely cause is geometric in nature (e.g., steep grade, sharp curve) or work zone-related.

Table 10 shows an analysis done with NPMRDS data for 2014 for the State of Tennessee. The strategy used here is to compute average truck speeds for weekday peak periods and mid-day as well as for daylight hours on weekends. These four values are then averaged and only highway sections with a speed value less than 45 miles per hour are chosen. The color coding indicates that the sections (TMCs) are contiguous. The length of all the contiguous segments for a route is a good indication of the severity of the bottleneck. Based on small number of locations shown here, the analyst would concentrate first on I-24 southbound in Davidson County. Note that the criteria used here are only one example of those that can be used. Analysts may wish to look at different time periods and change the cutoff speed value for what to consider further.

Mapping locations that are caught in the screening process is another useful method for identifying potential bottlenecks for in-depth study. Figures 36 and 37 show truck speeds on Atlanta freeways developed from the NPMRDS for 2014. The roadways experiencing low truck speeds are roughly the same in the morning and afternoon peaks, and mostly correspond to known bottlenecks, primarily freeway-to-freeway interchanges. While the majority of delay is being caused by high passenger car demand and is not specifically truck-related, the total amount of delay to trucks is nonetheless extremely high.

On principal arterials off of the Interstate system, most of the delay is likely due to signals. Figure 38 shows the average truck speeds versus passenger car speeds for weekday daylight hours on signalized principal arterials for two urban counties in Tennessee: Davidson (Nashville) and Knox (Knoxville). For the most part, only small differences exist between the two vehicle types, indicating that the signals are controlling the traffic flow and that no trucks-specific geometric limitations exist.

If travel times have been matched to traffic volumes, then the screening should use either annual total truck delay or unit truck delay as the primary criterion. Assuming that contiguous segments are grouped together, this will give higher weight to locations with multiple “bad” segments.

Table 10. Partial list of potential truck bottleneck locations for Tennessee from National Performance Management Research Data Set scan.

					Truck Speeds				
TMC	County	Road Number	TMC Length	Direction	Weekday AM	Weekday PM	Weekday Mid-day	Daytime	Average
121N11569	Blount	I-140	1.792	Eastbound	42.1	41.0	43.4	50.7	44.3
121P10404	Blount	I-140	1.033	Westbound	43.4	44.8	43.3	42.4	43.5
121P11569	Blount	I-140	0.237	Westbound	29.3	27.7	25.9	26.2	27.3
121N04209	Davidson	I-24	1.198	Southbound	11.8	44.4	30.4	33.9	30.1
121N04222	Davidson	I-24	0.456	Southbound	49.0	20.6	51.8	53.6	43.8
121N04223	Davidson	I-24	0.195	Southbound	52.1	18.1	52.0	53.5	43.9
121N04224	Davidson	I-24	1.159	Southbound	38.5	20.8	45.4	49.4	38.6
121N04225	Davidson	I-24	0.351	Southbound	47.2	21.2	49.8	53.9	43.0
121N04226	Davidson	I-24	0.268	Southbound	49.1	22.1	50.1	53.4	43.7
121N04227	Davidson	I-24	0.262	Southbound	47.9	25.1	48.9	51.5	43.3
121P04175	Davidson	I-24	0.693	Northbound	55.8	20.0	45.5	50.4	42.9
121P04223	Davidson	I-24	0.310	Northbound	19.5	43.8	47.2	47.7	39.6
121P04224	Davidson	I-24	0.730	Northbound	42.8	38.5	45.5	44.6	42.9
121P04229	Davidson	I-24	0.243	Northbound	53.6	20.2	43.4	47.4	41.2
121N04194	Davidson	I-24/I-40	0.372	Eastbound	50.1	22.1	46.8	51.3	42.6
121N04195	Davidson	I-24/I-40	0.149	Eastbound	48.2	16.1	42.2	48.1	38.6
121P04192	Davidson	I-24/I-40	0.085	Westbound	22.2	43.2	47.8	48.1	40.3
121P04194	Davidson	I-24/I-40	0.473	Westbound	28.3	46.4	50.2	52.5	44.4
121P04195	Davidson	I-24/I-40	0.482	Westbound	28.8	42.9	48.0	49.3	42.2
121N04231	Davidson	I-24/I-65	1.040	Southbound	32.8	48.6	47.0	49.5	44.5
121N04232	Davidson	I-24/I-65	0.155	Southbound	20.9	43.2	37.2	40.9	35.5
121P04230	Davidson	I-24/I-65	0.188	Northbound	53.7	20.3	41.2	47.0	40.5
121P04231	Davidson	I-24/I-65	1.019	Northbound	51.9	24.8	40.4	45.7	40.7
121P04232	Davidson	I-24/I-65	0.775	Northbound	48.8	39.5	43.4	45.7	44.4
121N04196	Davidson	I-40	0.526	Westbound	22.7	45.8	51.0	51.2	42.7
121N04206	Davidson	I-40	0.271	Westbound	33.5	44.7	47.9	50.0	44.0
121N04207	Davidson	I-40	0.283	Westbound	25.9	38.3	44.1	47.2	38.9
121N04208	Davidson	I-40	0.226	Westbound	16.7	34.7	44.6	47.1	35.8

Table 10. Partial list of potential truck bottleneck locations for Tennessee from National Performance Management Research Data Set scan (continuation)

TMC	County	Road Number	TMC Length	Direction	Truck Speeds Weekday AM	Truck Speeds Weekday PM	Truck Speeds Weekday Mid-day	Truck Speeds Daytime	Truck Speeds Average
121P04205	Davidson	I-40	0.191	Eastbound	50.1	12.5	44.0	48.8	38.9
121P04206	Davidson	I-40	0.245	Eastbound	52.4	17.9	47.3	50.9	42.1
121P04207	Davidson	I-40	0.361	Eastbound	54.6	17.9	50.1	52.7	43.8
121P04208	Davidson	I-40	0.228	Eastbound	54.8	17.1	49.8	53.6	43.8

(Source: Cambridge Systematics, Inc. analysis of NPMRDS data.)

Figure 36. Map. Atlanta truck speeds
AM peak.
(Source: Cambridge Systematics, Inc.)

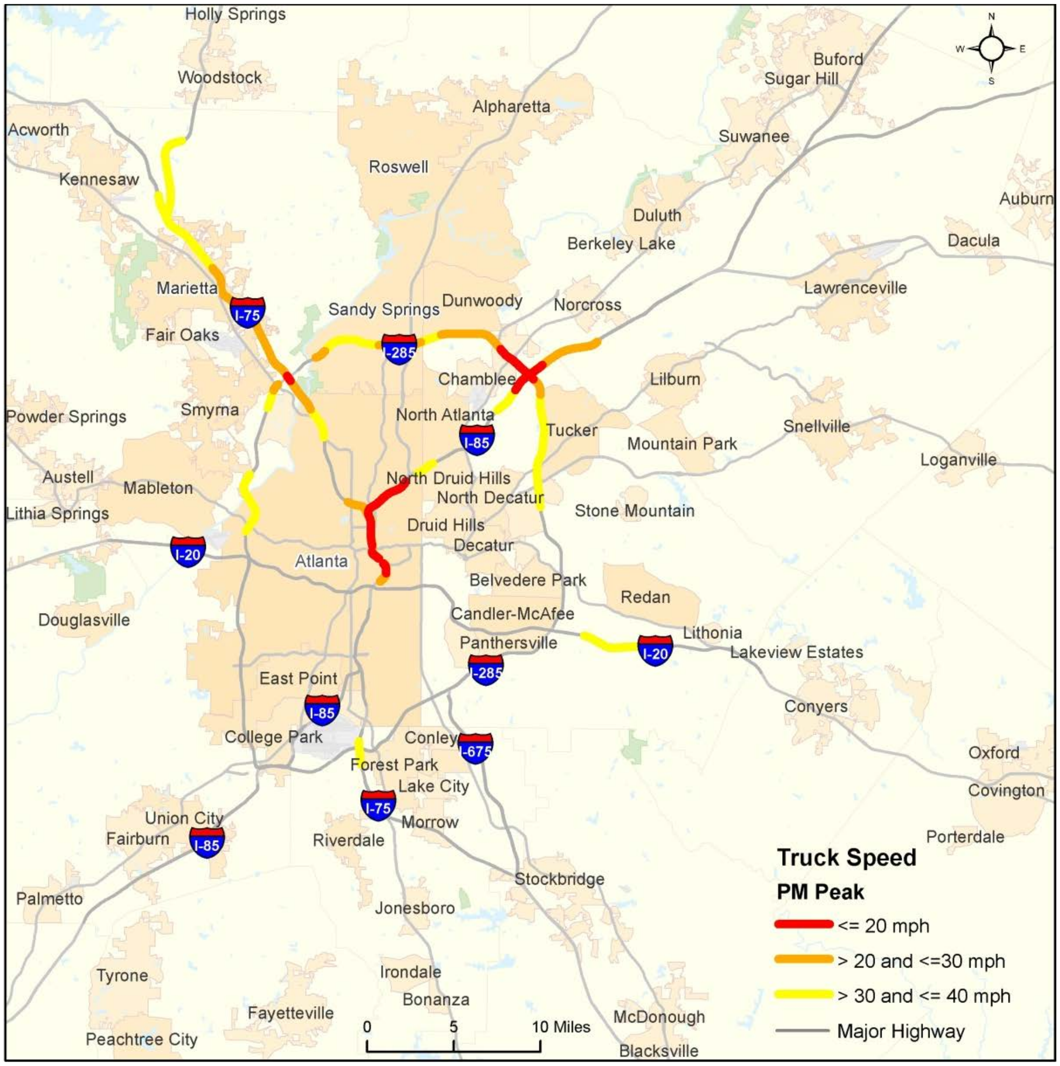


Figure 37. Map. Atlanta truck speeds
PM peak.
(Source: Cambridge Systematics, Inc.)

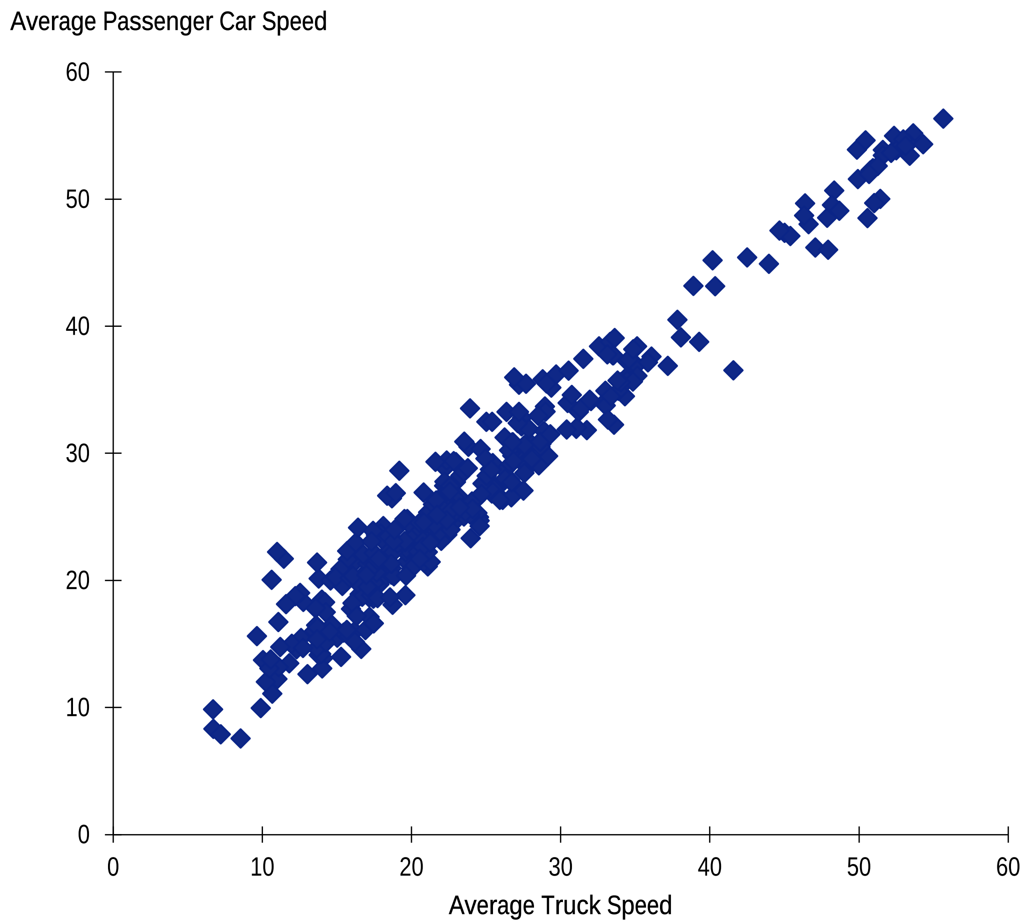


Figure 38. Graph. Vehicle speeds on primary arterials
Davidson and Knox counties, Tennessee.
(Source: Cambridge Systematics, Inc.)

4.5.3 Model and Inventory-Based Screening

If area-wide data are not available, then the bottleneck scan may be performed with models or roadway inventory data. In urban areas, travel demand forecasting models may be used. The "Full Extent" HPMS data also may be used, as can State-maintained roadway characteristics inventories. What we are looking for here are highway sections that are potential problems based on indicators of congestion rather than direct measurements. Volume-to-capacity (v/c) and AADT-to-capacity (AADT/C) ratio are the recommended indicators. The v/c ratio has a long history in transportation analysis and is based on conditions that exist for a single hour. The AADT/C ratio uses 24-hour traffic (AADT) divided by the two-way capacity. For highly congested locations where multiple hours of the day are congested, the AADT/C ratio captures more of the conditions. Table 11 indicates the AADT values implied by a range of AADT/C ratios.

Table 11. Average annual daily traffic to capacity levels and corresponding average annual daily traffic values.

AADT/C	Freeways (10% Trucks) Four-Lanes[a] AADT[d]	Freeways (10% Trucks) Six-Lanes[b] AADT[d]	Four-Lane Signalized Arterials (8% Trucks)[c] AADT[d]
9	72,000	113,000	30,000
10	80,000	126,000	33,000
11	88,000	138,000	37,000
12	96,000	151,000	40,000
13	104,000	163,000	43,000
14	112,000	176,000	47,000
15	120,000	188,000	50,000

(Source: Margiotta, Richard; Harry Cohen; and Patrick DeCorla-Souza, *Speed and Delay Prediction Models for Planning Applications*, paper presented at Sixth National Conference on Transportation Planning for Small and Medium-Sized Communities, Spokane, Washington, 1998.)

[a] Ideal Capacity = 2,200 passenger cars per hour per lane (pcphpl).
[b] Ideal Capacity = 2,300 pcphpl.
[c] Ideal Capacity = 900 pcphpl (based on a saturation flow rate of 1,800 pcphpl and 50 percent green time.
[d] Rounded to nearest 1,000.

The model-based scan is conducted the same way as the data-based scan, except that v/c, AADT/C, and truck AADT as used as the criteria. (These are indicators of the amount of delay.) These measures are computed for every link in the network of interest, paying special attention to the number of contiguous links with high values.

4.5.4 Pulling the Scan Together

The goal of the scan is to come up with a “short list” of bottleneck locations; these are the locations that will be analyzed in more detail and are candidates for improvements. The anecdotal information is reviewed against either the data-based or model-based scans. If possible, the locations should be mapped. Analysts must use their judgment in developing the reduced list of locations. In addition to the technical criteria discussed above, they also should consider:

- **Economic Impacts—**Does truck delay at a location severely limit the potential for economic growth in a region.
- **Connectivity—**Is this location a critical link in the truck highway network such as a key bridge or mountain pass?

Once all the factors have been considered, a list of 10 to 50 locations should be identified as the most significant truck bottleneck locations. Bottlenecks should be classified using the guide shown in figure 30.

4.6 CONDUCT PROJECT-LEVEL ANALYSIS FOR SELECTED BOTTLENECKS: GEOMETRIC- AND VOLUME-RELATED BOTTLENECKS

4.6.1 Basis for Analysis

The basis for project-level analysis of truck bottlenecks is empirical travel-time data; modeling is not recommended for determining the present state of the bottlenecks. Chapters 2 and 3 present a thorough discussion of travel-time data and its sources. It is assumed that volume data has been merged into travel-time data at the travel time's lowest levels of spatial and geographic resolution.

4.6.2 Determine the Physical Cause and Initial Range of Influence of the Bottleneck

The first step in project-level analysis is to identify the highway segment on which the bottleneck is located and to determine what geometric and/or volume feature is causing the bottleneck. Once this is established, detailed congestion analysis can proceed. Other than long-term work zones, it is unlikely that the bottlenecks identified during the screening process will be non-recurring in nature. Nearly all—if not all—of them will be recurring bottlenecks that also experience some non-recurring congestion (e.g., incidents, inclement weather, and short-term work zones).

For bottlenecks that primarily occur in urban areas during weekday peak periods, the most common bottleneck types on freeways are interchanges, especially freeway-to-freeway interchanges, and toll facilities. On signalized arterials, intersections especially between two major roadways are commonly the worst bottlenecks, in rural areas, grades, tunnels, and recreational traffic frequently create the worst truck bottlenecks. In rural cases, look for the days of week and times of day when delay is occurring. If most delay occurs during mid-day on most days of the year, the likely cause is a grade or tunnel. If most delay is occurring on or around weekends and holidays, recreational traffic is the likely culprit.

Once the type and location of bottleneck is identified, the initial range of influence is determined. For interchanges and intersections, segments that represent all entering legs of the location are the starting point, even if they were not identified in the scan. That is, the segments that are immediately upstream on the "inbound" direction to the bottleneck should be considered first. Because queues from the bottleneck will form upstream, we then select segments that are upstream from the bottleneck (in the inbound direction) as potential targets for analysis—a starting length of 10 miles is reasonable, it will be adjusted later. Segments on the downstream side also need to be considered because:

- If we ended the analysis at the center of an interchange, we would miss the entrance ramps' influence on the downstream side.
- Some delay will occur downstream of the last merge area as vehicles come back up to speed after being queued ("getaway" flow).

A distance of 1 mile downstream from the point of the last entrance ramp of an interchange is a reasonable place for the other endpoint of the initial range of influence of the bottleneck. Thus, we have a distance of 11 miles on each inbound route to consider. By studying each of the inbound routes, we also capture spillover effects from the bottleneck. That is, a queue formed by an entrance ramp will not only extend upstream on the mainline but on the ramp and possibly onto the intersecting route as well.

4.6.3 Performance Measure Calculation

The following steps are followed to develop performance measures for the freight bottlenecks.

1. **Adjust the Range of Influence—**For each of the entry routes into the bottleneck, the range of influence is further refined by determining the range of queuing. Speeds are used as the indicator of queuing. For each epoch in the travel-time data, speeds for each segment in the original range of influence is scanned to determine if queuing is present. The process starts on the segment at the bottleneck location and moves upstream. The idea is to identify a string of ***contiguous segments*** that meet the queuing threshold. The thresholds are as follows:

    - Freeways, Multi-lane, and Two-Lane Highways—30 miles per hour.
    - Signalized Highways—15 miles per hour.

From this analysis, a dataset is created that indicates the queue length for each epoch for each entering route. The queue length is calculated by summing up the segment lengths found to experience queuing.

Next, for each time period of interest (e.g., weekday AM/PM peaks, weekends), the mean and 95th percentile queue lengths are calculated. The range of influence is set to the 95th percentile; this is used in lieu of the maximum queue length because of possible outliers. The segments encompassed by the 95th percentile queue length are used as the highway distance over which performance measures are computed.

2. **Calculate Reference Speed—**Chapter 3 presented a method for determining the reference speed for signalized arterials based on analysis of off-peak travel-time data. The same procedure should be used for all other highway types.

3. **Calculate Performance Measures for each Bottleneck Entry Route for Each Time Period—**Likewise, the chapter 3 method for arterial facilities should be used to develop performance measures related to the bottleneck; these procedures are applicable to all highway types. The 4.5 Conduct Project-Level Analysis for Selected Bottlenecks: Geometric and "facility" in this case is the range of influence previously determined.

4. **Rank Bottlenecks by Impacts—**For truck bottlenecks, total truck delay is a strong candidate for the ranking criteria. However, as total delay will favor high-volume locations, users may wish to us an alternate criterion such as unit delay, MTTI, PTI, or queue length.

5. **Example—**I-85/I-285 Interchange, Atlanta, Georgia.

- NPMRDS data was used to analyze a well-known bottleneck in Atlanta, known locally as "Spaghetti Junction" for its complex ramp pattern (figure 39). Despite being a well-designed system-style interchange, it is still a major source of congestion due to very high (and growing) demand. The NPMRDS data were conflated with HPMS data to obtain AADT values, and the procedure given in chapter 2 was used to decompose AADT into directional 5-minute volumes on each TMC. The results are shown in table 12.

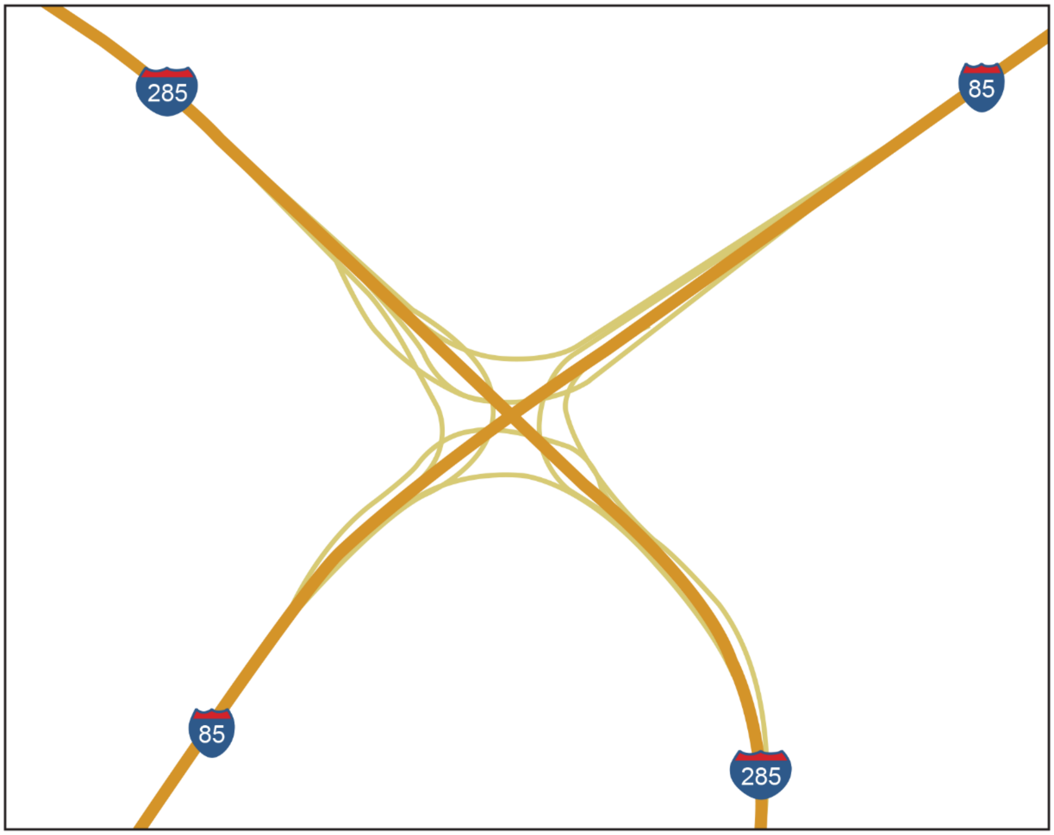


Figure 39. Map. 1-285/I-85 interchange
Atlanta, Georgia.
(Source: Cambridge Systematics, Inc.)

Table 12. Performance measures for the inbound legs of the I-85/I-285 interchange, Atlanta, Georgia, 2014.

Leg	Period	MTTI	TTIP80	PTI	VMT	Total Delay (Vehicle-Hours)	Truck Delay (Vehicle-Hours)	Hours of Congestion	95th Percentile Queue Length (miles)
I-285 Northwest	Weekday Mid-day	1.518	1.544	3.557	69,020,721	527,488	57,441		
	Weekday Peak	2.474	4.033	5.982	79,350,098	1,721,129	170,542		
	Weekend/ Off-Peak	1.267	1.187	1.828	120,538,555	481,309	44,420		
Subtotal						2,729,926	272,403	1,616	6.0
I-285 Southeast	Weekday Mid-day	1.239	1.195	1.778	67,749,891	240,140	26,427		
	Weekday Peak	1.727	2.293	3.953	75,336,398	806,557	86,991		
	Weekend/ Off-Peak	1.167	1.164	1.453	119,344,561	300,774	29,701		
Subtotal						1,347,471	143,119	1,196	2.0
I-85 Northeast	Weekday Mid-day	1.244	1.203	1.815	87,941,305	316,878	37,287		
	Weekday Peak	1.928	2.779	3.816	101,711,330	1,388,096	151,844		
	Weekend/ Off-Peak	1.157	1.157	1.525	163,979,947	383,257	42,973		
Subtotal						2,088,232	232,104	1,301	7.4
I-85 Southwest	Weekday Mid-day	1.205	1.226	1.687	78,491,014	240,005	25,972		
	Weekday Peak	1.648	2.086	3.315	86,567,552	828,151	81,796		
	Weekend/ Off-Peak	1.181	1.159	1.359	122,212,641	338,243	16,189		
Subtotal						1,406,399	123,957	1,303	5.3

(Source: Cambridge Systematics, Inc.)

4.7 CONDUCT PROJECT-LEVEL ANALYSIS FOR SELECTED BOTTLENECKS: POLICY-RELATED BOTTLENECKS

4.7.1 Overview

Policy-related bottlenecks are substantially different from other types of bottlenecks in that they result in a change in trucking operation, which then affects performance. This is difficult to emulate in an analysis because the analyst has to know—or guess—how truck operations adapt to policies. In the case of bottleneck analysis, this means the routing and/or scheduling of truck operations.

In the case of trucks being banned from certain routes, the analyst must determine the new routes being used by diverted trucks. Sometimes agencies publish guidance on detours and these should be used if available. If not, analysts will need to either interview trucking firms or make assumptions about the new routes trucks will use.

In order to analyze the effect or routing policies, truck trips—or portions of truck trips—must be defined. The endpoints of the trip should be the locations where the trucks deviate from their intended route. Travel times and the resultant performance measures are computed for both the intended trip and the rerouted trip using the same procedures as for signalized arterials from chapter 3. Because the trips or trip portions are likely to exceed 10 miles in length, travel times developed from either directly measured vehicle travel times or the virtual probe method are greatly preferred. The difference in delay between the intended route and the diversion route is the impact of the policy-related bottleneck.

Because we are interested in measuring the performance of a truck ***trip*** rather than the performance of facility, the virtual probe or trajectory method is required here. This method accounts for the temporal and spatial placement of a truck as it traverses a network, rather than simply summing up the travel times on a route for a fixed time interval. In other words, we are now interested in monitoring trip-based performance rather than facility-based performance.

With regard to defining a truck trip for studying the effects of a policy-related bottleneck, the procedure is based on synthesizing trips from a fixed origin and destination as defined by the analyst. The process proceeds as follows:

- Define the "path" of the trip as it exists now with the policy restriction as well as one or more alternative paths.
- Obtain travel-time data for the major roadways in the network.
- Create link sequences for the trips in the vendor data.
- Apply a virtual probe algorithm to create trip times by simulating the passage of a vehicle onto the network at 5-minute intervals.

Figure 40 illustrates the virtual probe (trajectory) method compared to summing the instantaneous travel times. The blue arrows represent the instantaneous method whereas the red arrows represent a travel time based on vehicle trajectory.

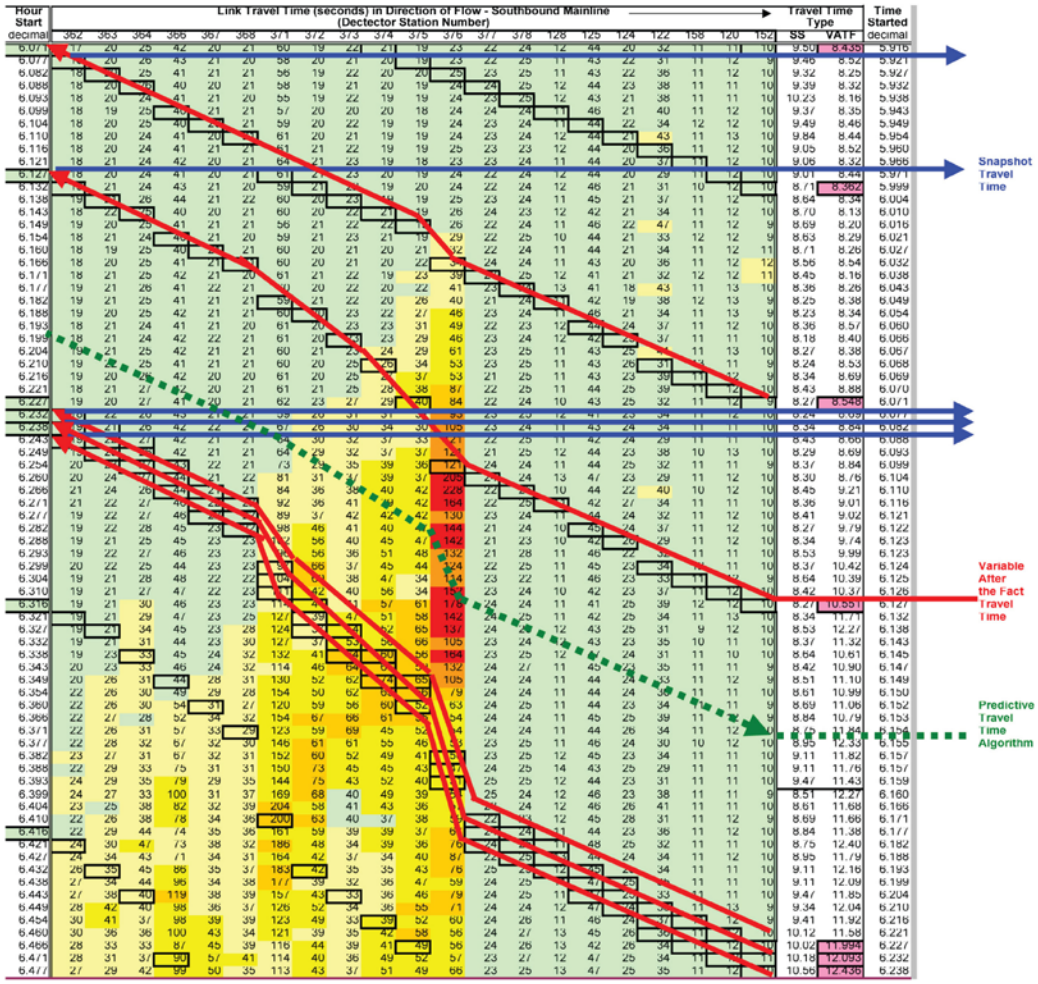


Figure 40. Figure. The instantaneous and virtual probe methods of estimating travel times from spot speeds.
(Source: Cambridge Systematics, Inc., et al., Guide to Effective Freeway Performance Measurement, Web-Only Document 97, Transportation Research Board, August 2006, http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=822.)

The virtual probe vehicle trajectory method "traces" the vehicle trip in time and applies the link travel time corresponding to the precise time in which a vehicle is expected to traverse the link. For example, a section travel time that begins at 7:00 a.m. will use a link travel time for 7:00 to 7:05 at the trip origin, but could use a link travel time from 7:05 to 7:10, or 7:10 to 7:15 at the trip destination. The virtual probe method attempts to more closely model the actual link travel times experienced by motorists as they traverse the trip.

Recent work in Florida suggests that for very long (100+ miles) trips, delay is the best measure to characterize performance.[43] Long trips routinely traverse many miles of uncongested roadway,

[43] Cambridge Systematics, Inc., *Trip-Oriented Mobility Monitoring Framework Development: Final Report*, November 5, 2014, http://www.dot.state.fl.us/PLANNING/statistics/mobilitymeasures/Task12-tommfd.pdf.

usually in rural areas, which results in the travel time indices being very low compared to pure urban conditions.

4.8 ESTIMATING THE IMPACTS OF IMPROVING TRUCK BOTTLENECKS

4.8.1 Introduction

This section presents methods for estimating the effects of making improvements to truck bottlenecks ***at the sketch-planning level***. A more in-depth treatment of problem identification and corresponding treatments are covered in NCHRP Project 08-98.

4.8.2 Sketch-Planning Methods

A variety of methods exists to assess the impacts of improvements on travel time, the key performance category considered in this Guide. FHWA has compiled a comprehensive list of these methods.[44] More recently, the SHRP 2 Program also developed several tools that can be applied (table 13). Of these, the tools developed for Projects L07 and C11 are the most appropriate for the sketch planning level.

Table 13. Reliability prediction methods developed by the Strategic Highway Research Program 2 program.

SHRP 2 Project	Analysis Scale (In Order of Increasing Complexity)
L03/C11	Sketch planning; system- or project-level
L07	Detailed sketch planning; mainly project-level
L02	Performance monitoring and project evaluations using empirical data
L10	Performance monitoring and project evaluations using empirical data
L08	Project planning using *Highway Capacity Manual* scale of analysis
C05	Project planning using mesoscopic simulation scale of analysis
C10	Regional planning using linked travel demand and mesoscopic simulation analysis
L04	Regional planning using linked travel demand and mesoscopic or microscopic simulation analysis

(Source: Cambridge Systematics, Inc.)

SHRP 2 Project C11, *Development of Improved Economic Impact Analysis Tools*, produced several modules to estimate the economic impact of transportation investments on factors not usually accounted for in transportation analyses: market access, connectivity, and travel-time reliability. It is the reliability module that should be used for sketch planning analysis of truck bottlenecks.[45] A spreadsheet was developed in SHRP 2 Project C11 to estimate the reliability impacts of highway investments. This spreadsheet can be used to estimate the future impacts of truck bottlenecks as it includes the effects of demand, capacity, and incident characteristics. It

---

44 Jeannotte, Krista, Andre Chandra, Vassili Alexiadis, and Alexander Skabardonis, *Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools*, June 2004, http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol2/sectapp_e.htm.

45 http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2350.

also produces estimates of delay and the distribution of travel-time indices, which indicate reliability performance. It also produces cost estimates for the travel-time savings affected by improvements.

The C11 procedure requires the following inputs:

- Time horizon of analysis.
- Type of highway.
- Number of lanes.
- Free-flow speed.
- Current AADT.
- Traffic growth rate.
- Percent trucks.
- Information on the value of time.

4.8.3 Identifying Potential Improvements and Their Impacts

Development of specific countermeasures for truck bottlenecks means matching problems with solutions. Potential solutions can be categorized as:

- Roadway capacity enhancements/expansion (e.g., adding more lanes, improving interchanges and intersections, and improving roadway alignment).
- Operations strategies (e.g., incident management, work zone management, weather management, traveler information, and advanced traffic control).
- Demand management (e.g., trip reduction, load consolidation, trip rescheduling, and mode shift).

Improvements must be translated into changes in the input variables to the sketch planning procedure chosen. Capacity increases can be estimated using procedures in the *Highway Capacity Manual*. The effect of operations strategies can be estimated using the assumptions built into FHWA's Tool for Operations Benefit Cost Analysis (TOPS-BC) tool.[46] Demand changes need to be estimated offline by the analyst. Either through assumptions or from a travel demand model, if the model already has been run to establish the base condition.

4.8.4 Safety Impacts

The most comprehensive procedures for conducting safety analysis are presented in the *Highway Safety Manual (HSM)*. Unfortunately, the HSM requires a wide array of inputs that are almost never available for sketch planning analysis. Therefore, the following two steps should be followed in the analysis:

---

[46] Operations Benefit/Cost Analysis TOPS-BC User's Manual—Providing Guidance to Practitioners in the Analysis of Benefits and Costs of Management and Operations Projects. In the spreadsheet tool, the relationships can be found under the "Investigate Impacts" tab. http://www.ops.fhwa.dot.gov/publications/fhwahop13041/sec1.htm.

- **Develop Base Number of Crashes (Before Improvement)—**If available, the actual number of crashes at the bottleneck location should be used. The highway limits (range of influence) are the same as was established for the travel-time analysis. If site-specific crash data are not available, statewide average crash rate for the same highway type can be used in conjunction with the VMT within the range of influence to estimate total crashes.
- **Apply Crash Reductions Due to the Improvement—**FHWA has developed crash reduction factors for a wide range of geometric improvements.[47] These can applied to estimate the number of crashes reduced due to the improvements.

4.9 MULTI-MODAL CONSIDERATIONS

Freight bottlenecks impact more than truck movements. A truck bottleneck often impacts other transportation modes—most commonly, automobiles—but no less importantly, transit buses, bicycles and pedestrians. Truck bottlenecks also impact operations of facilities that serve or are served by freight trucks, including seaports, airports, rail yards, warehousing and distribution centers, industrial manufacturers, border crossings, and trucking terminals.

In order to obtain a clear understanding of the issues and impacts of specific freight bottlenecks, it is important to review existing analyses, studies, and planning documents, as well as to reach out to stakeholders. The most useful way to obtain stakeholder feedback is to talk to them one-on-one about their specific concerns and needs in order to understand their perspectives. To carry this out in an effective manner, identify interest groups, such as private-sector goods movement organizations (shippers, carriers, and logistics service providers), businesses, environmental organizations, community and public health groups, etc. The following section provides some common issue areas for consideration when investigating the impacts of freight bottlenecks. Following the one-on-one discussions, roundtable discussions with the participants often yield additional ideas, as well as consensus on issues common to all participants. This can assist with prioritizing the issues.

4.9.1 Impacts on Intermodal Facilities

Freight bottlenecks can impact the timely delivery and efficient movement of goods over the road, as well as at intermodal facilities, such as rail yards, trucking terminals, and warehouse/ distribution centers. Delays in service often create ripple effects in the overall supply chain. To the consumer, the delay costs are not often apparent, but they tend to result in a higher cost of doing business, which finds its way to consumers through higher costs of goods.

Congestion frequently results in drayage delays of cargo to railyards or warehousing facilities (such as transloading warehouses where goods from multiple originations are repackaged and placed in domestic containers and trucked to a rail yard or over the road to their final destination). Some of the larger, higher-volume transload warehouses and distribution centers operate around

[47] Bahar, Geni, Maurice Masliah, Rhys Wolff, and Peter Park, *Desktop Reference for Crash Reduction Factors*, Report No.: FHWA-SA-08-011, 2007; http://safety.fhwa.dot.gov/tools/crf/resources/fhwasa08011/.

the clock; however, seaports and river ports typically have high labor costs, which limits the operating hours, and hence, the hours that cargo can be picked up or dropped off.

4.9.2 Impacts on Seaports and Airports

The impact of congestion on airports and seaports varies. Most air freight consists of high-value or time-sensitive goods. Congestion delays can result in missed flights, which can create a ripple of supply chain delay impacts. Congestion delays at seaports can result in additional demurrage fees if the delay is significant enough to cause goods to remain at the port beyond the "free" period. Delays in collecting cargo from the docks also add to congestion on the docks. Seaports have limited backland for storing containers. Delays in truckers picking up cargo impacts storage capabilities at both airports and seaports.[48]

4.9.3 Impacts to Consider

When investigating the impact of roadway congestion at rail yards, ports, trucking terminals, and other intermodal facilities, it is important to consider the cargo origins/destinations (port, manufacturing center, transloading facility) and types of cargo (manufactured goods, agricultural, seasonal, etc.) being moved. The impacts of congestion and delay differ across commodity types. Delay may result in a loss of perishable cargo, delays on an assembly line, or reduced productivity at a congested intermodal terminal. By reaching out to stakeholders to ask questions about the impacts, the impacts of freight roadway bottlenecks become better understood. A list of stakeholder types and sample questions are provided below.

Potential Stakeholders: Trucking companies/associations, warehouse and distribution center operators, rail operators, shippers, manufacturers, and representative associations.

Sample Questions:

1. How does congestion impact your business/operation?
2. For private businesses that require land: How has/could congestion impact your decision to locate/relocate or expand your business?
3. How do congested roadways directly impact port operations? If demurrage is charged, how much per day?

4.10 SUPPLY CHAIN CONSIDERATIONS

For the private sector, congestion drives up logistics costs and ultimately cuts into customer satisfaction and profits. With increased levels of truck traffic in the future, existing freight bottlenecks will likely be exacerbated if not addressed systematically.

[48] Leachman, Dr. Robert C., Port and Modal Elasticity Study, Phase II, Prepared for Southern California Association of Governments (2010).

4.10.1 Impacts on Trucking

Truck drivers experience the most direct impact of congestion. They operate under stringent regulations that limit the hours that they are permitted to drive. In April 2014, ATRI released its Year 2013 bottleneck analysis, which estimated that truckers had experienced 141 million hours of delay. This equated to 51,000 drivers sitting idle for a year—an industry cost of $9.2 million. This issue impacts large trucking companies, but the independent owner operators are the most vulnerable to the economic impacts of a delay.

Delay impacts truckers significantly due in part to the Federal Motor Carrier Safety Administration's (FMCSA) hours-of-service (HOS) rules. The most recent iteration of the HOS rules became effective in July 2013. (It should be noted, however, that some of the changes to this new rule were suspended by Congress in December 2014). HOS regulations contain a number of restrictions related to the amount of time a commercial motor vehicle operator may drive and be on-duty between breaks. In general, the rules limit a driver to 11 hours of driving time and 14 hours of on-duty time (which includes driving time) after 10 consecutive hours off-duty. Once this threshold is met, a driver must take another 10 consecutive hours off-duty before driving again. Drivers who reach the maximum 70 hours of on-duty time within an 8-day time period may clear their accrued on-duty hours by taking off-duty time; this can be achieved in a timely manner if 34 consecutive hours of off-duty time are taken. This "34-hour restart" acts to clear the accrued hours, and benefits drivers with the opportunity of extended off-duty time. In addition, truck drivers must take a 30-minute break during the first 8 hours of their shift if they wish to continue driving. Traffic congestion, particularly unanticipated traffic congestion, creates challenges for drivers to comply with this regulation.

Thus, reliability is important to the freight industry. Drivers will commit to a route with a longer distance or travel time if it is consistently more reliable than a shorter alternate route. The frequency of non-recurrent freight bottlenecks becomes critical in this decision-making process. Late deliveries can result in the loss of a customer. A close review of the "Buffer Time Index" (BTI) can identify non-recurrent freight bottlenecks that frequently impact the timely delivery of freight. Understanding the type of non-recurrent delay also is important. The congestion resulting from construction activity, which is classified as non-recurrent delay, can be more easily managed than other forms because closures can be broadcast to the trucking community via on-line traffic applications, as well as industry outreach. Severe weather alerts also are shared via radio, television, and Internet to alert drivers of delays, closures, and/or alternative routes. Congestion resulting from a traffic collision can be managed, but because no warning can be broadcast in advance, the impact of significant and unavoidable freight delays is high. Truck drivers often times understand which routes experience high incidents, and even if those routes are shorter when incident-free, the research indicates that drivers will take a longer, more reliable route in order to avoid the risk of delay from a major crash.

In prioritizing bottleneck improvement projects, work with the trucking community to identify both the recurrent and the non-recurrent congestion in the system. Recommended stakeholders and sample questions are as follows:

Potential Stakeholders: Trucking companies, local/State trucking associations, ATRI, law enforcement agencies (State troopers, highway patrols, etc.), and local/regional/State/Federal transportation planning agencies.

Sample Questions:

1. How do you plan for congestion (route planning, time-of-day decisions, etc.)?
2. Identify locations with high crash rates and ask the trucking community how they mitigate the risk of congestion impacts. Do they frequently use an alternate route? If so, how is that alternate route impacted by truck traffic?
3. How would improving the safety of the preferred and primary route benefit alternate routes (congestion, maintenance, air quality, noise, safety, etc.)?

4.10.2 Impacts on Freight-Dependent Industries

In a survey conducted by Washington State University Social and Economic Sciences Research Center (SESRC) in 2011, 1,062 private, freight-dependent industries provided detailed responses to questions about the impact of congestion. Respondents were asked how a 20-percent increase in congestion would impact their businesses. The responses are summarized below:

- Pass the costs on to consumers—56 percent.
- Absorb the costs—19 percent.
- Change operations or routing—16 percent.
- Forced to close their business—6 percent.
- Relocate—3 percent.

The study calculated that the cost of a 20 percent increase in congestion would equate to an increase of $14 billion of increased annual operating costs to the State's freight-dependent industries. Similar research conducted by the Economic Development Research Group (EDRG)[49] found similar results. As quoted from the EDRG report, "From the perspective of shippers and carriers, there are the day-to-day cost implications of delay and reliability as it affects supply chain management, and well as a longer-range need to assess opportunities, risks, and returns associated with location, production, and distribution decisions. Both perspectives need to be recognized when considering the full range of impacts that traffic congestion can have on the economy." Freight-dependent industry surveys conducted for this study found a wide range of behavioral responses based on the type and timing of delays and frequency, as well as recurrent versus non-recurrent delays. One common theme shared by all: the overwhelming impacts generated by unpredictability and variation in delays associated with growing congestion.

Potential Stakeholders: Talk to business supply chain managers when planning infrastructure improvements. Obtain the input of local businesses by speaking with senior managers with

[49] Weisbrod, Glen; and Stephen Fitzroy, Traffic Congestion Effects on Supply Chains: Accounting for Behavioral Elements in Planning and Economic Impact Models (2011).

transportation and logistics expertise. Find out how congestion impacts their operations, location/ relocation decisions, operating procedures, and shipping patterns.

Sample Questions: The EDRG study provides a mechanism for categorizing the impacts of congestion on the business environment and common responses, which provides a framework for engaging freight-dependent industries in a discussion about freight congestion. In speaking with local industries, finding the answers to the following seven categories can assist with prioritizing improvements:

1. What is your market/fleet size, specifically, your delivery area, market scale, fleet size/type, delivery and reliability cost, and assignment flexibility?
2. What are your delivery schedules, including delivery time shifts, truck dispatch, backhaul operations, relief drivers, and operating schedules?
3. What intermodal connections do you use, including truck, rail, seaport, and airport terminals?
4. What does your business inventory and operations management entail, such as inventory requirements, stocking costs, inventory management/control, and use of cross-docking and/or transloading?
5. What are the characteristics of worker travel, including worker time/expense to get to work, worker schedule reliability, and service delivery cost?
6. If you have recently, or are considering relocation, which case is applicable: 1) distribution from smaller, more dispersed locations; or 2) consolidation of multiple production sites into fewer or one?
7. What externalities play: land use and development shifts, costs passed onto consumers, and/or customers and workers?

4.11 COMMUNITY CONSIDERATIONS

4.11.1 Impacts on Other Transportation Modes

Truck operations impact, and are impacted by, other modes of transportation that share the public roadway network, including automobiles, bicyclists, and pedestrians. Truck and automobile traffic affect one another more heavily than the other modes due to the number of lane miles that they share on freeways, highways, arterials, and local roadways; as well as ancillary uses, such as service stations, parking, and loading zones.

Truck and automobile interactions often create safety hazards. Heavy-duty trucks in many States must operate in the far right two lanes. This requirement, particularly in congested conditions, creates difficulties for automobiles merging onto or off of freeways. Trucks accelerate much more slowly than automobiles, and they also require more braking distance. Many of the automobile/truck collisions occur due to a truck driver's limited field of site and an automobile driver's lack of understanding of a truck driver's operating parameters.

Transit buses and trucks tend to share the outside travel lane. Conflicts arise when buses stop frequently along a truck route, and also generate pedestrian traffic. To the extent feasible, truck and transit routes should be separated. When considering freight bottlenecks, identify opportunities for removing a bottleneck by shifting the route designations. Work closely with the stakeholders to identify opportunities, including transit agencies, truck drivers, industries served, and the community members. Is there a better way to serve transit and freight by designating truck routes on lower-volume transit corridors, or on corridors that do are not served by transit?

The conflicts between bicyclists and trucks occur frequently, and based on a study by University of Washington, these conflicts are "much more likely to result in severe injury or death to the bicyclist. Bicycle lane obstruction by trucks is a common problem and bicycle lane configuration can significantly affect the likelihood of bicycle lane obstruction. And most significantly, the creation of well-marked bicycle-specific facilities significantly reduces the risk of bicycle crashes and injury."[50] Like transit, trucks and bicyclists often operate in the curb lane of a roadway, whereas pedestrians are often provided with a separated sidewalk. Due to the high-seated location of a driver in a truck and the relatively low-profile position of a bicyclist or pedestrian, it is very difficult for truck drivers to see them. Conflicts do not generally occur between trucks and bicycles when a roadway offers sufficient space for the two user types; however, curbside parking poses significant risks to bicyclists, and intersections pose significant risks for both bicyclists and pedestrians, particularly when they are faced with right-turning trucks.

The intersections can be treated to improve the safety of bicyclists and pedestrians, but the safety enhancements generally conflict with truck operations. For example, reducing the crossing distance requires shorter curb turning radii, which is often impossible for a freight truck to negotiate without running over the curb or turning into opposing traffic. Increasing the pedestrian crossing time often exacerbates congestion.

When faced with these issues, it is recommended that the agency fully understand the truck and bike route operations. Physically separating truck and bike routes and creating truck routes in areas with little or no pedestrian traffic should be investigated. Importantly, feedback from both the trucking and cycling/walking communities must be taken into consideration. If segregating the modes proves undesirable, then safety improvements and education to truckers, bicyclists, and pedestrians should be implemented to reduce the risk of conflicts.

Potential Stakeholders: Talk to the trucking and bicycling communities, local residents, transit operators and riders/pedestrians, and local traffic enforcement/emergency responders.

Sample Questions:

1. Where are the high-incident locations for truck collisions?
2. What modes are served by the high-incident locations?
3. What is the primary mode involved in the collision (car, bike, pedestrian, etc.)?
4. What improvements could be implemented to reduce collisions? Segregate modes/rerouting? Signage? Better curbside management practices? Remove on-street parking? Intersection improvements? Education and outreach?

---

[50] Gelio, Kristen; Cynthia Krass; Jonathan Olds; and Maria Sandercock, *Why Can't We Be Friends? Reducing Conflicts Between Bicycles and Trucks*, University of Washington (2012).

4.11.2 Land Use Conflicts

Land use impacts freight operations in a few ways, including the designations of truck routes, weight and vehicle prohibitions on designated roadways, truck parking restrictions on public streets, development regulations for truck parking facilities, and permissible hours of operation for freight-dependent industries.

Truck parking is a growing concern across the country. Demand is increasing, and parking is particularly important for compliance with the Federal HOS regulations, but the supply of available truck parking, particularly near major freight activity areas, is not keeping up. The Los Angeles region, which ranks number one in freight congestion, provides an example of the truck parking issue. The Ports of Long Beach and Los Angeles, the Nation's busiest port complex, is situated within 30 miles of a cluster of intermodal facilities, including six Class I rail yards and millions of square feet of warehousing and distribution center uses. However, nearly all cities within close proximity to the ports prohibit on-street, overnight truck parking, and the closest major trucking terminal is located 50 miles east in Ontario. Traffic congestion on the three primary freeways between the ports and major trucking terminals often starts building at 2:00 p.m. and dissipating around 8:00 p.m. Travel time between the ports and Ontario averages more than 2 hours during peak hours. With limited truck driver hours of service and limited port hours of operations, truck drivers must carefully plan their days. Providing truck parking closer to the primary intermodal terminals could greatly improve trucking operations and reduce regional truck traffic. In some cases short-term parking can accommodate the 30-minute rest required after 8 hours of driving, but longer-term parking will be needed to accommodate the periods of longer rest, including the required 1:00 to 5:00 a.m. period. The new driver rules are resulting in drivers "timing out" without being able to find a place to park overnight. Most parking of trucks is not in the public eye because it occurs on private property and is conducted appropriately. It is when inappropriate parking occurs (such as on freeway on/off ramps or in residential areas) that community concerns are provoked. Truck drivers have four basic reasons for parking their trucks, which creates the need for temporary and long-term (greater than 10 hours) parking:

- To serve customers at the customer's site.
- To stop temporarily for personal needs and/or to await instructions as to what to do next.
- For the driver to rest during the mandated rest period.
- At the end of the day when the truck returns to its home base.

While truck drivers strive to park in designated areas in each of these situations, inappropriate parking occurs most often when local regulations prohibit parking in certain locations, sometimes including the entire local jurisdiction. While these prohibitions are often intended to preserve community quality of life amenities, they do not lessen the need for temporary or long-term truck parking in their jurisdictions, particularly in communities that have businesses and industries that rely on trucks to pick up/drop off goods. Cities, such as Oakland, have engaged multiple city departments to resolve the parking issues by identifying and developing available land for truck parking. In looking at freight bottlenecks within a region, lack of truck parking can be one of the reasons contributing to the congestion, in which one of the solutions may be creating truck parking near the areas served by trucks. This solution has the potential to improve economic efficiencies and reduce congestion, simultaneously. Other city regulations, including noise ordinances, which preclude off-peak operations of freight-dependent industries, also impact trucking operations. Truck drivers may be able to pick-up or deliver cargo from an intermodal terminal during off-peak hours, but they may not be able to deliver or pick-up cargo from the warehouse during off-peak hours.

Potential Stakeholders: Local agency staff, truckers, warehouse and distribution center operators, and manufacturers.

Sample Questions:

1. Do the current truck routes, weight and vehicle prohibitions on designated roadways make sense? Do they work? How could they be improved? What changes would you suggest, if any?
2. Is there enough truck parking? Is the truck parking conveniently located? Are there local truck parking restrictions on public streets? Is there available land for building truck parking?
3. Do regulations limit the hours of warehouse/intermodal terminal operations? If yes, what are they? Why do the restrictions exist? Could they/should they be modified? If yes, why?

4.12 EXISTING PLANS AND PROGRAMS

4.12.1 State Freight Plans

Several States have opted to develop a Moving Ahead for Progress in the 21st Century (MAP-21)-compliant State freight plan. Per the Federal guidance,[51] State Freight Plans contain an assessment of the conditions and performance of the State's Freight Transportation System, and identifies needs and improvement strategy. Reviewing the State Freight Plan should be a first step when initiating the process of prioritizing improvements.

Stakeholders: State agency staff.

Sample Questions:

1. Is a State Freight Plan available?
2. When was the most recent State Freight Plan completed?
3. Have any operational conditions changed?
4. Have any bottleneck relief projects identified in the State Freight Plan been completed?
5. Which projects are funded and moving forward shortly?

4.12.2 Regional Freight Planning

In addition, many of the regional transportation plans provide additional information about freight traffic conditions and planned projects and programs. In the Nation's key gateway regions, many of the Metropolitan Planning Organizations (MPO) have extended their understanding of goods movement by studying various aspects of it. As such, MPOs should be

[51] Interim Guidance on State Freight Plan and State Freight Advisory Committees, U.S. DOT (2012).

contacted early on in the bottleneck assessment process. For example, the Southern California Association of Governments (SCAG) has a program called FreightWorks.[52] Research has included the investigation of truck-only lanes, warehousing and distribution center development and operations, inland port concepts, U.S./Mexico border crossings, and several freight rail studies. MPOs also maintain the regional transportation model, which most of the time, provides excellent information about truck operations today and 20 years from now.

Potential Stakeholder: MPO staff.

Sample Questions:

1. Does the Long-Range Transportation Plan (LRTP) contain projects aimed at addressing freight bottlenecks?
2. Has the MPO conducted studies, research, or analysis on goods movement in the region?
3. Does the MPO aid in the coordination of truck route planning throughout the region?

4.12.3 Local Freight Planning

At a local level, counties and cities often include a discussion of goods movement, specifically truck routing, in their general plans. In addition, they designate truck routes, and also have the authority to minimize the impacts of noise, vibration, etc., on the residents of their communities. Understanding local plans, policies, and ordinances provides the context of how a community addresses goods movement.

Potential Stakeholders: Local agencies, MPO, and State DOT.

Sample Questions:

1. Are designated truck routes/weight limits consistent on interjurisdictional corridors?
2. Do the designated truck routes serve industrial uses? Do they provide connections between freight facilities? Do they cut through residential areas? Are there other routes that may better serve freight without creating additional impacts?
3. Truck parking policies—How may they be impacting/adding to an existing freight bottleneck? Is truck parking near freight facilities available? If not, why not and where are the closest places to park a truck?
4. Delivery policies—Are there delivery-hour restrictions imposed by local codes? If so, is there reason to consider changing the restrictions to support off-peak deliveries, such as, would the freight facilities accommodate off-peak deliveries?
5. How much land currently is being used for trucking, including parking, storage, and service? How much is available for future development of truck-serving uses?

[52] http://www.Freightworks.org.

U.S. Department of Transportation
Federal Highway Administration
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590

www.ops.fhwa.dot.gov

August 2015

FHWA-HOP-15-033