APPLYING TRAVEL TIME RELIABILITY MEASURES IN IDENTIFYING AND RANKING FREEWAY BOTTLENECKS AT THE NETWORK LEVEL

by

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ABSTRACT

LINFENG GONG. Applying travel time reliability measures in identifying and ranking freeway bottlenecks at the network level. (Under the direction of DR. WEI (DAVID) FAN)

The continuing growth of traffic congestion on U.S. roadways has become an increasing concern for both travelers and transportation agencies. According to the Texas Transportation Institute's estimate, the total financial cost of congestion in the U.S. in 2014 was $160 million, or $960 per commuter. In North Carolina, demand for highway travel continues to grow as population increases, particularly in metropolitan areas. Construction of new highway capacity to accommodate this growth in travel has not kept pace. As a matter of fact, it is now well accepted that we cannot build our way out of congestion. Congestion is largely thought of as a big city problem, but delays are becoming increasingly common in small cities and some rural areas as well. As such, developing a system approach to improving bottleneck analysis in North Carolina is essential for reducing traffic congestion, and improving the overall traveling experience for all North Carolinians.

The purpose of this dissertation is to develop a holistic bottleneck analysis approach to assist NCDOT in identifying, examining, modeling and mitigating freeway bottlenecks at a system level compared to focusing on local bottlenecks only. This will enable NCDOT to identify, manage and reduce traffic congestion statewide in a systematic, efficient and effective manner.

Traditional bottleneck identification methods are developed based on performance measures collected from stationary loop detectors (or Bluetooth sensors). However, the

applications of such local sensor based methods are usually restricted by the geographical coverage and the density of embedded detectors on the road. In recent years, the coverage and fidelity of vehicle probe data (VPD) have been greatly improved. The possibility of obtaining extensive, continuous, and dynamic VPD from private sectors such as HERE and INRIX offers a great opportunity to identify and assess freeway bottlenecks at the network level.

A number of measures of effectiveness (MOEs) can be derived from VPD and be used for bottleneck identification and evaluation, such as the planning time index (PTI), frequency of congestion (FOC), and travel time index (TTI). In this dissertation, various MOEs were analyzed in terms of their feasibility for freeway bottleneck identification and ranking. The results indicate that using travel time reliability (TTR) measures (such as FOC or PTI) can reveal only a specific facet of the travel time distribution, but are not be able to quantify the intensity dimension of the traffic congestion caused by the bottlenecks. As a consequence, a comprehensive bottleneck identification method which integrates both PTI and TTI is developed. Since both PTI and TTI are dimensionless travel time-based performance measures and are developed using the same benchmark for each roadway segment (i.e., free-flow travel time), it is reasonable to integrate both measures into the bottleneck identification and ranking framework. By doing so, both dimensions of traffic congestion on each roadway segment can be accounted for. A case study is performed to illustrate the proposed methodology, using a total of approximately 34 million speed records collected in INRIX for four major interstate corridors in Mecklenburg County, NC, in 2015. Freeway bottlenecks are identified and prioritized for a.m., p.m., both a.m. and p.m. peak periods, respectively.

The potential causes of each bottleneck group are carefully examined by synthesizing the following information: (1) bottleneck identification and ranking results, (2) geometric characteristics around the bottleneck, (3) operational analysis results obtained from the Highway Capacity Software (HCS), and (4) field trip observations. Based on them, a total of 59 scenarios aiming at alleviating bottleneck congestion are designed and evaluated in this study, which include 26 lane-addition scenarios, 15 road pricing scenarios, and 18 combined scenarios (i.e., lane addition and road pricing). Since improved traffic conditions and new infrastructure can directly affect traveler's route-choice behavior and will lead to a new regional traffic flow pattern, which may either mitigate or exacerbate existing system bottlenecks, a mesoscopic DTA modeling tool is employed in this dissertation to assess the impact of various candidate bottleneck mitigation strategies at the network level. The findings suggest that under certain conditions, simply adding one more lane at the bottleneck may deteriorate traffic performances. Such counterintuitive results have been widely reported in the literature, and such phenomenon is known as the Braess's paradox. In addition to that, this study also observe the existence of hidden bottlenecks while evaluating candidate bottleneck mitigation projects. Because the causes of bottlenecks can be highly complex and if one is ameliorated, one or more unexpected bottlenecks can quickly emerge downstream. As such, the decision makers must be very careful to ensure that informed decisions are made as to where to apply the bottleneck mitigation countermeasures.

A performance-based framework is developed to assist in assessing and prioritizing candidate bottleneck mitigation alternatives. The general project ranking framework includes five components: (1) developing candidate bottleneck mitigation projects, (2) evaluating each project, (3) screening of projects, (4) benefit-cost analysis (BCA), and (5) sensitivity analysis. It is envisioned that the proposed framework can provide insightful and objective information for traffic engineers and decision-makers in choosing effective mobility improvement strategies.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
BTI	Buffer Time Index
CV	Coefficient of Variation
DOT	Department of Transportation
DTA	Dynamic Traffic Assignment
FHWA	Federal Highway Administration
FOC	Frequency of Congestion
HCM	Highway Capacity Manual
LOS	Level of Service
MOE	Measures of Effectiveness
NCDOT	North Carolina Department of Transportation
PeMS	Performance Measurement System
PTI	Planning Time Index
SHRP 2	second Strategic Highway Research Program
TMC	Traffic Message Channel
TTI	Travel Time Index
TTR	Travel Time Reliability
USDOT	US Department of Transportation
VMT	Vehicle Miles Traveled
VPD	Vehicle Probe Data

CHAPTER 1: INTRODUCTION

1.1 Background

Demand for highway travel by North Carolinians continues to grow as population increases, particularly in metropolitan areas. Construction of new highway capacity to accommodate this growth in travel has not kept pace. As a matter of fact, it is now well accepted that we cannot build our way out of congestion. Congestion is largely thought of as a big city problem, but delays are becoming increasingly common in small cities and some rural areas as well.

Congestion results when traffic demand approaches or exceeds the available capacity of the system. As shown in Figure 1-1, according to the Federal Highway Administration (FHWA) report *Traffic Congestion and Reliability: Linking Solutions to Problems*, nearly 40% of all on-road congestion nationwide can be attributed to physical bottlenecks (Cambridge Systematics and Texas Transportation Institute, 2004). The growth of traffic congestion and bottlenecks on North Carolina's freeways, arterials, and streets is a major concern to travelers, administrators, merchants, developers and to the community at large. Its detrimental impacts in longer journey times, higher fuel consumption, increased emissions of air pollutants, greater transport and other affected costs, and changing investment decisions are increasingly recognized and felt across the state of North Carolina. Congestion and bottlenecks reduce the effective accessibility of residents, activities, and jobs and result in lost opportunities for both the public and business.

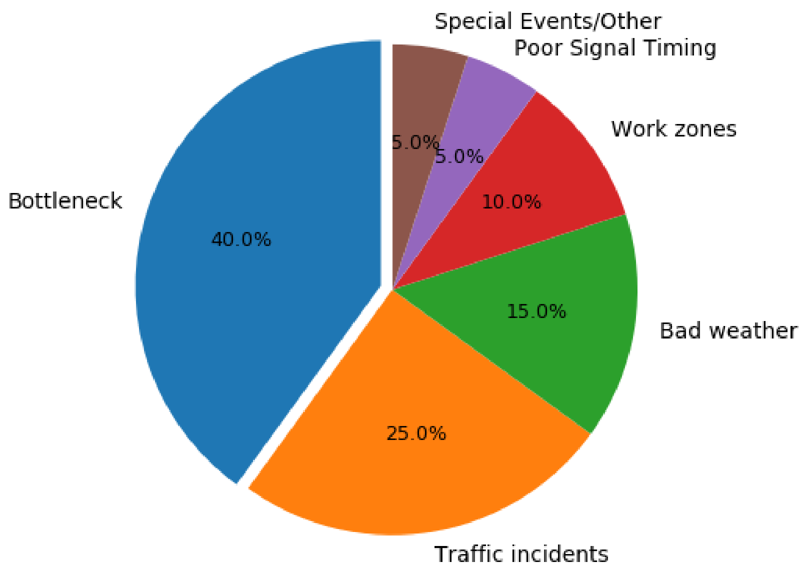


Figure 1-1 The Sources of Congestion (National Summary)

(Source: FHWA report - *Traffic Congestion and Reliability: Linking Solutions to Problems*)

Mitigating congestion and eliminating bottlenecks by managing traffic better, expanding transportation capacity, managing travel demands, or modifying land use requires basic information on *how*, *where*, *why* and *to what extent* congestion and bottlenecks occur. However, bottleneck mitigation is by no means a trivial exercise. The causes of bottlenecks can be highly complex and if one is ameliorated, one or more unexpected bottlenecks can quickly emerge elsewhere. Traditional transportation modeling approaches that can be applied to examine the bottlenecks can be classified as either operational or planning in nature. Unfortunately, neither approach is well-suited for a comprehensive analysis and treatment of bottlenecks. Operational models lack the regional scope and travel behavior capabilities and thus cannot be used to holistically treat bottleneck mitigation's unexpected consequences. Planning models cannot represent traffic flow accurately enough to enable the capturing of the intricacies of vehicular dynamics. A new and systematic approach needs to be developed to improving bottleneck analysis at the network level.

1.2 Research Objectives

The primary research goal of this dissertation is to develop a systematic approach to improving bottleneck analysis which can assist North Carolina Department of Transportation (NCDOT) in holistically identifying, examining, modeling and mitigating bottlenecks at a system level compared to focusing on local bottlenecks only. This will enable NCDOT to identify, manage and reduce traffic congestion statewide in a systematic, efficient and effective manner. To achieve this goal, this study entails the following objectives:

- To review and synthesize past experiences in freeway bottleneck analysis; particular attention will be given to existing applications of the mesoscopic dynamic traffic assignment (DTA) tools to bottleneck analysis;
- To define a set of measures of effectiveness (MOEs) to evaluate an existing freeway network, locate the most severe chokepoints in the network and quantify the impact of candidate strategies on system bottleneck mitigation and travel conditions;
- To develop a methodology to identify and prioritize freeway bottlenecks;
- To develop several DTA models for regional scale bottleneck analysis; and
- To develop a framework for ranking bottleneck mitigation projects by comparing their impacts on system-wide bottleneck mitigation and travel conditions.

1.3 Report Organization

This report consists of the following chapters:

- Chapter 1 – Introduction: provides background on the need for a systematic bottleneck analysis approach and outlines the research scope and objectives.
- Chapter 2 – Literature Review: summarizes the current state-of-the-art and state-of-the-practice of bottleneck identification methods, mitigation measures and assessing tools.
- Chapter 3 – Defining Performance Measures: presents previous experience in selecting MOEs for bottleneck analyses and synthesizes the principles employed for selecting MOEs in this study.
- Chapter 4 – Developing a Methodology to Identify Bottlenecks on Freeways: offers a systematic approach to identify and rank freeway bottlenecks, including data examination and cleaning, extracting performance measures, and result interpretation.
- Chapter 5 – Examining the Identified Test Bed Bottleneck Sites: analyzes the potential causes of each bottleneck as previously identified, and develops engineering judgement based countermeasures that are aimed at mitigating bottlenecks.
- Chapter 6 – Calibrating and Validating a Base DTA Model: calibrates a DTA model to accurately represent the base year traffic conditions for the test bed bottleneck sites.
- Chapter 7 – Comparing the Impact of Various Candidate Improvement Projects on System-wide Bottleneck Mitigation and Travel Conditions using DTA: evaluates and quantifies the impact of various candidate bottleneck mitigation projects on system-wide performance.

- Chapter 8 – Developing a Framework to Rank Potential Improvement Projects: develops a framework and uses it to design a performance-based project ranking procedure to evaluate and rank candidate bottleneck mitigation alternatives.
- Chapter 9 – Summary and Conclusions: summarizes the research and makes the conclusions achieved in this study.

Finally, a list of references is provided at the end of the report.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a comprehensive review of various aspects related to freeway bottleneck study, including bottleneck definitions, common causes, existing bottleneck identification methods, bottleneck alleviation strategies, evaluation tools (at the micro-, meso-, and macroscopic levels), and previous experience with using DTA models for bottleneck analyses. This should give a clear picture of existing bottleneck identification methods, candidate mitigation measures, and available tools for mitigation project evaluation.

2.1 Bottleneck and Congestion Definitions

2.1.1 Bottleneck Definitions

Many congestion-related issues that negatively impact North Carolina drivers on a daily basis can be traced back to a bottleneck, be it stationary or moving. Prior to accurately identifying bottlenecks along NC freeways and proposing potential bottleneck mitigation strategies, it is necessary to clearly define what a bottleneck is and understand its features.

Freeway bottlenecks have a myriad of definitions. The FHWA report *Recurring Traffic Bottlenecks: A Primer, Focus on Low-cost Operational Improvements* listed a group of commonly-used definitions of a bottleneck: (1) a critical point on the road which separates upstream queued traffic and downstream free-flowing traffic; (2) a location on a highway where there is loss of physical capacity, surges in demand, or both; (3) a point where traffic demand exceeds the normal capacity; and (4) a location where highway demand periodically exceeds the section's physical ability to handle it, and is independent of traffic-disrupting events that can occur on the roadway (Margiotta and

Spiller, 2012). Among the four definitions described above, the first one defined a bottleneck by characterizing the traffic conditions in the vicinity of the bottleneck; while the last three highlighted the imbalance between traffic demand and roadway capacity.

In practical application, however, it is not easy to directly observe travel demand or physical capacity along a roadway segment. This is because: (1) capacity is stochastic in nature (Hall and Agyemang-Duah, 1991); and (2) the vehicle counts reported from stationary loop detectors may not be able to reflect traffic demand accurately, especially under congested conditions. Thus, researchers are more interested in defining a bottleneck through the characterization of traffic condition variations around the bottleneck, such as the emergence of traffic congestion and reductions in vehicles speeds at adjacent roadway segments. Chen et al. (2004) defined (recurring) bottlenecks as "certain freeway locations that experience congestion at nearly the same time almost every day". The Cambridge Systematics report *Bottleneck Performance in the I-95 Corridor: Baseline Analysis Using Vehicle Probe Data* described a bottleneck as "a specific highway feature that causes routine congestion because of a capacity drop, volume surges, or both" (Cambridge Systematics, 2011). In the Florida *Strategic Intermodal System (SIS) Bottleneck Study,* a bottleneck is defined as "a localized highway section that experiences reduced speeds and inherent delays due to a recurring operational influence or a nonrecurring impacting event" (Florida Department of Transportation, 2011). INRIX (2015) discerned freeway bottlenecks by comparing the reported speed with the reference speed (the 85th percentile speed during all time periods) of each road segment. Specifically, a bottleneck was flagged if the reported speed stayed below 60 percent of the reference speed for more than 5 minutes.

In short, various definitions of bottlenecks have been proposed and can be classified into two categories. (1) The first category reveals the root-cause of freeway bottlenecks, i.e., the imbalance between traffic demand and roadway capacity. (2) The second category mainly focuses on variations in traffic conditions around the bottleneck - such as reductions in travel speeds or the emergence of traffic congestion. Compared to the first, in practice, the second category is better suited for quantifying, measuring and identifying freeway bottlenecks at a large spatiotemporal scope. Table 2-1 provides a summary of existing bottleneck definitions in chronological order.

Table 2-1 Summary of Existing Bottleneck Definitions

Year	**Author**	**Bottleneck Definition**
1997	Daganzo	A restriction that separates upstream queued traffic and downstream free-flowing traffic.
2004	Chen et al.	A freeway location experiences congestion at nearly the same time almost every day.
2005	Bertini and Myton	A point upstream of which there is a queue and downstream of which there is freely flowing traffic.
2007	Ban et al.	A section of the roadway which has either capacity less than or demand greater than other sections.
2011	Cambridge Systematics, Inc.	A specific highway feature that causes routine congestion because of a capacity drop, volume surges, or both.
2011	Florida DOT	A localized section of highway that experiences reduced speeds and inherent delays due to a recurring operational influence or a nonrecurring impacting event.
2012	Rouphail et al.	A critical roadway section with queues upstream and freely flowing traffic downstream.
2015	INRIX	Roadway speed stays below 60 percent of the reference speed for more than 5 minutes.

2.1.2 Congestion Definitions

The FHWA report *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation* defines congestion as an excess of vehicles on a roadway at a particular time resulting in speeds that are slower - sometimes much slower - than normal or free-flow speeds (Cambridge Systematics, 2005). Since the report did not assign a specific value to “slow”, different criteria were proposed for determining congested traffic conditions. For example, the *Travel Time Based Oklahoma Congestion Analysis: Pilot Study* specified two different threshold values (i.e., 75 and 85 percent of the free-flow speed) when quantifying traffic congestion (CDM Smith, 2014). In the *2013-2014 Indiana Mobility Report (Summary Version)*, a fixed congestion speed threshold value (45 mph) was used to distinguish congested traffic from non-congested traffic (Day et al., 2014).

It is worth mentioning that, aside from speed indices, researchers also utilized travel time reliability (TTR)-related measures to determine congested traffic conditions. Wolniak and Mahapatra (2014) categorized traffic conditions into several levels using the travel time index (TTI), which was defined as the ratio of the 50th percentile travel time of a trip during the peak period to the free-flow travel time in this study. The levels defined include: (1) uncongested (TTI<1.15); (2) light congestion (1.15<TTI<1.3); (3) heavy congestion (1.3<TTI<2.0); and (4) severe congestion (TTI>2.0). In the Florida DOT *SIS Bottleneck Study* report, congested freeway segments were declared when the planning time index (PTI) was greater than 3.0 or the frequency of congestion (FOC) was greater than 40 percent. More details about the threshold values used for defining traffic congestion will be discussed and presented in Section 2.3.2.

2.1.3 Relationship between Bottlenecks and Congestion

The defining characteristic of a bottleneck is congestion, while congestion is often more than just a bottleneck. FHWA’s research has shown that congestion is the result of six root causes often interacting with one another. The six contributing factors are: poor traffic signal timing, restricted roadway capacity, traffic incidents, inclement weather conditions, work zones, and special events. Only the first and second sources contribute to the recurring congestion; the remaining sources of congestion are nonrecurring and random (Cambridge Systematics, 2004).

In addition to that, congested traffic can propagate along the entire roadway segment or even several segments. This does not mean the entire roadway segment (or several segments) is a bottleneck. A bottleneck refers to a subordinate segment of a parent facility, which, as described earlier, separates upstream queued traffic and downstream free-flowing traffic. Bottlenecks typically occur at freeway decision points, such as on- and off- ramps, weave sections, and lane drops. Previous research has shown that freeway bottlenecks are the dominant cause of recurring congestion and that nonrecurring congestion becomes more severe when recurring congestion already exists (Cambridge Systematics, 2013).

2.2 Classification and Common Causes of Bottlenecks

2.2.1 Classification of Bottlenecks

(1) Recurring vs. non-recurring bottlenecks

Recurring bottlenecks typically occur due to the routine surges in traffic demand and/or a restriction in the roadway capacity. Recurring bottlenecks have an identifiable cause, resulting in recurring delays and generally predictable travel times. Non-recurring bottlenecks are induced by random disruptions to the traffic flow, such as traffic accidents, short-term roadway construction work, inclement weather, and special events (sports games, concerts, etc.).

(2) Moving vs. stationary bottlenecks

A moving bottleneck accounts for the impact of a slow-moving obstruction that diminishes road capacity, such as truck platoons (Daganzo, 1997). In contrast, stationary bottlenecks happen at roadway facilities with constrained capacities, such as lane drops, steep grades, on- and off-ramps, and freeway interchanges. The location of a stationary bottleneck usually remains immobile for a relatively long time.

(3) Active, inactive and hidden bottlenecks

Bottlenecks are considered to be active when queued conditions persist upstream and free-flow conditions prevail downstream, and to be inactive when there is a decrease in demand or a spillover from a downstream bottleneck (Banks, 2009). At times, the queue formed by a critical bottleneck masks potential problems downstream of it. A hidden bottleneck occurs when traffic demand is metered by an upstream bottleneck (Rouphail et al., 2012). It does not appear until a more critical, upstream bottleneck is treated.

In this study, we mainly focus on stationary, recurring freeway bottlenecks. Unless otherwise specified, we use the term “bottleneck” to indicate stationary, recurring freeway bottlenecks.

2.2.2 Common Causes of Bottlenecks

The causes of freeway bottlenecks can be summarized as either demand-related or capacity-related. From the demand perspective, in nature, travel demand varies by time of the day, day of the week, and month of the year. Thus, traffic bottlenecks are more likely to be active during peak periods on weekdays while on the same roadway segments they may remain inactive during off-peak periods. Note that some travel demand management policies, such as encouraging the public to choose the Park and Ride (P&R) travel mode and implementing congestion pricing, may also affect the occurrence of freeway bottlenecks.

Bottlenecks can be the result of physical or operational restrictions on the roadways as well. Common locations for localized bottlenecks include lane drops areas, weaving segments, on- and off- ramps, freeway-to-freeway interchanges, changes in highway alignment (such as sharp curves and steep gradients), tunnels/underpasses, and narrow lanes.

By combining the two aspects as mentioned above, it can be envisioned that, a restricted freeway facility with heavy traffic flow is very likely to be an active bottleneck during peak periods.

2.3 Bottleneck Identification and Examination Methods

Past research has sought better understanding of where freeway bottlenecks form and how and when they are activated. Existing bottleneck identification methods can be classified into the following two fundamental categories based on the data types and methods used during the identification process.

(1) Bottleneck identification using local sensors

These methods mainly used changes in traffic flow counts or vehicle speeds at consecutive fixed sensors (e.g., loop detectors) to identify the occurrence of freeway bottlenecks. Depending on the extent of user intervention, these methods can be further divided into manual and automatic identification methods. Overall, these methods are mainly developed for operational purposes and are able to capture detailed characteristics of traffic conditions immediately before and after the activation and deactivation of freeway bottlenecks. However, the spatial coverage of detectors may limit the applications of these methods.

(2) Bottleneck identification using vehicle probe data

Bottlenecks can be determined at a much broader geographical area (e.g., at the regional or network level) using travel time reliability (TTR)-related measures extracted from vehicle probe data as well. Generally speaking, TTR-related measures contain a series of indicators that are capable of describing different dimensions of traffic congestion. For example, the travel time index (TTI), typically defined as the ratio of average travel time to the ideal travel time under free-flow travel conditions, is able to denote the intensity dimension of traffic congestion - higher TTI corresponds to lower travel speed and hence implies a more severe gridlock. Alternatively, the planning time index (PTI), represented by the ratio of 90th or 95th percentile travel time to the free-flow travel time, reflects the reliability dimension of traffic congestion. Recently, the use of travel time reliability measures has been increasingly encouraged by FHWA for use as a measure for managing and operating transportation systems.

The following sections present a careful examination of both types of bottleneck identification methods.

2.3.1 Bottleneck identification using local sensors

2.3.1.1 *Cambridge Systematics' research work*

In the past several decades, the vast majority of traffic data is captured using static and point detection sensors such as inductive loops. The volume-to-capacity (V/C) ratio is a traditional and commonly used performance measure that can be derived from vehicle counts collected from stationary loop detectors. Cambridge Systematics (2005) made an effort to locate highway truck bottlenecks by scanning the FHWA Highway Performance Monitoring System (HPMS) database for highway sections that were highly congested as indicated by using the V/C ratios.

2.3.1.2 *Cassidy and Bertini's research work*

Cassidy and Bertini (1999) examined the operational features of traffic flow at freeway bottlenecks by comparing the transformed curves of cumulative vehicle arrival numbers versus time and cumulative occupancy versus time measured at consecutive loop detectors. This method was able to provide a relatively accurate identification of the activation and deactivation time of freeway bottlenecks, as well as their locations. Due to this advantage, several studies utilized this method to discern freeway bottlenecks and the results were used as the ground truth data while evaluating the efficiency of other bottleneck identification methods, including Bertini et al. (2008), Wieczorek et al. (2010), and Li and Bertini (2010). However, this method also involves a great deal of user intervention during the coordinate transformation process and hence is not suitable for identifying freeway bottlenecks in large-scale transportation networks.

2.3.1.3 *Chen, Skabardonis and Varaiya's research work*

Chen et al. (2004) developed a systematic approach to automatically identify freeway bottlenecks using 5-minute speed data from loop detectors. In their algorithm, the researchers calculated and used speed differences at adjacent detectors to identify the occurrence of congestion – that is, a bottleneck was declared if the upstream speed dropped below 40 mph and the downstream traffic was at least 20 mph faster than the upstream traffic. Additional criteria about the duration of activation time were added to distinguish recurring from non-recurring bottlenecks. The severity of bottlenecks was ranked according to the FOC values and travel delays imposed on the freeway segments. By locating freeway bottlenecks and quantifying their impacts on traffic delays, this method was able to determine the locations where bottleneck remediation measures were likely to provide the greatest benefit. However, since the algorithm was designed based on archived loop detector data, the efficiency of the algorithm was limited by the detector numbers and spacing - it was difficult to detect the speed changes and determine whether the bottleneck was active when the detectors were widely spaced in the network.

2.3.1.4 *Ban, Chu, and Benouar's research work*

Ban et al. (2007) proposed an automatic bottleneck identification method based on percentile speeds extracted from loop detectors across multiple days. Compared to average speed, Ban et al. pointed out that using percentile speeds was able to distinguish recurring traffic congestion from occasional traffic events. Also, through employing different percentile speed threshold values, it allowed one to flexibly consider bottlenecks either aggressively or conservatively. For instance, an aggressive approach may use a lower percentile (e.g., 15%), which would result in more bottlenecks, while a conservative approach may use a higher percentile, resulting in fewer bottlenecks. The queue length and time duration of a bottleneck were extracted based on the binary speed contour maps constructed by comparing percentile speeds with the threshold speed values.

2.3.1.5 *Banks's research work*

Banks (2009) described an automated approach to identifying the magnitudes and periods of queue discharge flow (QDF) and pre-queue flow (PQF) around the bottleneck. In this study, an active bottleneck was defined as a roadway section with congested traffic upstream and free-flowing traffic downstream. The congested traffic condition was declared when the average speed dropped below a pre-defined value (50 mph) and remained there for a user-specified amount of time (5 minutes). In order to reduce the impact of noisy data, a piecewise linear approximation technique was employed to smooth the cumulative curves of traffic speed and flow. Note that the main purpose of this study was to assess the operational characteristics of traffic flows nearby freeway bottlenecks, such as the activation and deactivation times of the QDFs and PQFs, and the prioritization process of the bottleneck severities was not considered herein. Besides, the proposed routine was incapable of screening out anomalous flows that resulted from incidents occurred in the bottleneck or immediately upstream.

2.3.1.6 *Jin, Yu, Fan and Ran's research work*

Jin et al. (2010) designed a robust bottleneck identification algorithm to better accommodate noisy and inconsistent data at fixed loop detectors. The authors clearly pointed out that the key for bottleneck identification was the detection of traffic congestion. The algorithm started with coordinate transformation - all data points in the flow-occupancy diagram were transformed into the URS-PUS (uncongested regime shift - perpendicular to uncongested regime shift) system. Then, the PUS values were compared to a site-specific threshold value to identify whether congestion had occurred or not. In the last step, a bottleneck was declared and reported if the FOC value at a location was greater than a pre-defined frequency. The effectiveness and robustness of the proposed algorithm were examined using three loop detector datasets collected at the city of Madison and the city of Milwaukee, WI.

2.3.1.7 *Wieczorek, Fernandez-Moctezuma, and Bertini's research work*

Wieczorek et al. (2010) conducted a rigorous evaluation of the bottleneck identification method proposed by Chen et al. (2004). Based on the fact that the freeway network configurations, weather conditions, and driver characteristics all varied from one city to another, the three parameters in Chen's model (MaxUpstreamSpeed, MinSpeedDifferential, and Aggregation Interval) may need to be adjusted to achieve the best model performance. Using the sensitivity analysis (SA) technique, five values of each parameter, for a total of 125 combinations, were tested using the archived dataset of the northbound I-5 corridor in Portland, Oregon. For comparison purpose, 91 bottlenecks over 24 days were extracted manually using the oblique-curve method (Cassidy and Bertini, 1999) and were set as the benchmark for evaluating the outcomes of Chen's approach. The results implied that the parameter values in Chen's model which were applied to the San Diego data (20 mph minimum speed differential, 40 mph maximum upstream speed, and 5-minute aggregation) were close to, but not the same as, the optimal settings for this Portland freeway (15 mph differential, 35 mph maximum upstream speed, and 3-min aggregation). The authors also recommended that, for researchers and transportation operations analysts in other cities wishing to implement a system using the Chen's algorithm, it is necessary to perform a similar SA procedure to adjust the parameters for their own network.

2.3.1.8 *Saberi and Bertini's research work*

Saberi and Bertini (2010) utilized a combination of TTR-related measures, including buffer time index (BTI), coefficient of variation (CV), PTI, TTI, and FOC, to identify and prioritize unreliable segments along the Interstate-5 freeway in Portland, Oregon. The entire northbound I-5 freeway corridor was broken into 22 segments between milepost 283.93 and milepost 307.9, and several TTR measures were computed for each segment using archived loop detector data extracted from the Portland Oregon Regional Transportation Archive Listing (PORTAL) database. Specifically, for each 5-minute interval, the indicators were calculated for each segment by aggregating all travel times that occurred during that interval across all weekdays in February and March 2007. Thus, a 22 (segments) by 288 (time intervals) matrix was created and further used to construct the time-space map for each indicator. The consistencies across different travel time reliability were examined and it was found that, for most of the day, the BTI and CV have a higher consistency than other measures. Also, the PTI and FOC seem to follow similar trends. However, both inferences were based on qualitative comparison, and more quantitative analyses are required to achieve rigorous conclusions.

The key parameters elicited from the studies reviewed above are summarized in Table 2-2 below. It provides a quick scan of bottleneck identification methods using local sensors, in terms of detailed identification methods, data sources, and indicators used for ranking bottleneck severities.

2.3.2 Bottleneck identification using vehicle probe data

2.3.2.1 *Cambridge Systematics' research work*

Cambridge Systematics (2011) established a set of procedures to monitor bottleneck performances along the I-95 Corridor using vehicle probe data. In this study, potential bottleneck locations along the I-95 Corridor were initially filtered based on the method proposed by Chen et al. (2004) and were further verified by comparing the average speed at each Traffic Message Channel (TMC) segment with a pre-defined threshold value (40 mph). Bottleneck severities were ranked using the ratio of the time identified as congested conditions to the entire observation period. In addition to that, bottleneck performances were evaluated using the following indices: queue length, delay, TTI, PTI and BTI.

The roadway sections selected for case study were those covered by the Vehicle Probe Project through December 2009. This study selected data at five-minute intervals during two different peak commute hours (non-holiday weekdays, 6 a.m. to 9 a.m. and 4 p.m. to 7 p.m.) for bottleneck identification and performance evaluation. Realizing that the free-flow speed may vary from link to link, the study used two threshold values of free-flow speed: (1) the 85th percentile speed that was extracted from the link's previous historical data, capped at 65 mph (this value was provided by INRIX); and (2) a free-flow speed of 60 mph that was assumed for all freeway links. Finally, a total of 29 bottlenecks along the I-95 Corridor were identified and their performances were evaluated as well. The main limitation associated with such method is that it cannot distinguish moving bottlenecks from stationary bottlenecks.

Table 2-2 Summary of Bottleneck Identification Methods Using Local Sensors

Year	Author	Identification Method	Data Source	Other Data	Severity Ranking Indicators
1999	Cassidy and Bertini	Comparing transformed curves of cumulative vehicle arrival numbers (or occupancy) vs time at neighboring detectors	Loop detector data collected from two freeway sites located in metropolitan Toronto, Canada	None	None
2004	Chen et al.	(1) Upstream speed≥40 mph (2) Speed diff. between consecutive detectors	Speed-flow data from PeMS	None	(1) FOC (2) Delay
2005	Cambridge Systematics	V/C ratio ≥ a pre-defined threshold value	Data from FHWA HPMS and FAF databases		Truck hours of delay
2007	Ban et al.	(1) Compare 50th percentile speed with a reference value (2) Construct binary SCMs	(1) Speed-flow data from PeMS (2) Travel time data from floating car runs	None	None
2009	Banks	(1) Upstream speed ≥ a pre-defined threshold value (2) Duration ≥ a user-specified amount of time	Volume counts and occupancies collected at a total of 21 sites in the metropolitan areas of Minneapolis–St. Paul, MN; San Diego, CA; and Seattle, WA,	None	None
2010	Jin et al.	(1) Coordinate transformation (2) Compare PUS value to a threshold value (3) Compare FOC o a threshold value	Loop data (1-min and 5 min speed data from WisDOT)	Incident log	(1) FOC (2) Bottleneck Duration
2010	Wieczorek et al.	(1) Upstream speed ≥ a pre-defined threshold value (2) Speed diff. between consecutive detectors	Loop data (1-, 3-, 5- and 15-min speed data from PORTAL)	None	FOC
2010	Saberi and Bertini	Using BTI, PTI, TTI, CV, and FOC to identify and prioritize unreliable segments	Time mean speed data from the Portland Oregon Regional Transportation Archive Listing (PORTAL) database	None	BTI, PTI, TTI, CV, FOC

2.3.2.2 *Florida DOT's research work*

Florida DOT (2011) conducted a bottleneck study on Florida's SIS network. Traffic congestion levels along roadway segments were evaluated using average speed (*intensity dimension*), PTI (*reliability dimension*), and FOC (i.e., the percentage of time a roadway experiencing congested conditions throughout the analysis period) (*duration dimension*). A roadway segment would be flagged as "congested condition" based on two criteria - either the average speed dropped below 75 percent of the free-flow speed or the PTI was greater than a predefined threshold (3.0 for freeways, 2.0 for arterials). Bottlenecks were determined and prioritized using a combination of FOC and PTI.

Vehicle probe data, provided by INRIX, along Florida's SIS network from July 2010 to June 2011 were used. A total of 293,372,069 records were extracted from the original dataset. Each record provided the average speed of a roadway segment at a five-minute interval. For each roadway segment, the free-flow speed was defined as the 85th percentile speed during overnight hours (10 p.m. to 5 a.m.). Instead of focusing on peak periods only, traffic performance measures, such as PTI and FOC, were determined for all valid weekday daytimes (6 a.m. to 7 p.m.) throughout the entire year.

2.3.2.3 *Wolniak and Mahapatra's research work*

Wolniak and Mahapatra (2014) identified and prioritized the most congested highway segments in Maryland using both vehicle probe speed data and volume data. In this research, a bottleneck was declared when "the speeds observed for a roadway segment dropped below 60% of the free-flow speed for a period greater than 5 minutes". The queue length at a bottleneck area was determined by summing the length of adjacent roadway segments that met such criteria. Bottleneck severities were ranked using a combination of average bottleneck duration, average maximum queue length and the frequency of bottleneck occurrence.

TTI, defined as "the ratio of the 50^{th} percentile travel time of a trip during the peak period to the free-flow travel time" in this study, was used to quantify central tendency of traffic congestion. It was further split into four levels to reflect various congestion severities: (1) uncongested ($TTI<1.15$); (2) light congestion ($1.15<TTI<1.3$); (3) heavy congestion ($1.3<TTI<2.0$); and (4) severe congestion ($TTI>2.0$). To account for travelers' concerns about trip reliability, the PTI was calculated as well and was classified into three levels: (1) reliable ($PTI<1.5$); (2) moderately to heavily unreliable ($1.5<PTI<2.5$); and (3) extremely unreliable ($PTI>2.5$).

The 2012 INRIX real-time dataset with more than 525,000 data points for each of roadway segment were analyzed. The original 1-minute travel speed data were aggregated to hourly intervals. Traffic volume data were collected from the Maryland State Highway Administration (SHA) on a daily basis and were factored on an hourly basis to match with the intervals of the speed data using the time-of-day profiles from Maryland's continuous traffic count stations. The TTI and PTI of each segment were calculated for both morning and evening peak hours (8 a.m. to 9 a.m. and 5 p.m. to 6 p.m.) on an annual basis. The final results exhibited 30 locations as the worst bottlenecks (based on the definition of bottleneck), the 30 most congested segments (based on TTI values) and 30 most unreliable segments (based on PTI values) in Maryland.

2.3.2.4 *CDM Smith's research work*

CDM Smith (2014) conducted a travel time-based congestion analysis to assist Oklahoma Department of Transportation (ODOT) in monitoring, evaluating, and addressing congestion problems. As a part of ODOT's 2015 - 2040 Long Range Transportation Plan (LRTP), this study utilized vehicle probe data extracted from FHWA's National Performance Measure Research Data Set (NPMRDS) to assess congestion levels along two corridors in Oklahoma (I-40 and U.S. 69).

The pilot study used several travel time-based measures to quantify traffic congestion and trip reliability, including FOC, congested vehicle miles traveled, annual hours of delay, the $80^{th}/90^{th}$ percentile travel time divided by an agency-determined threshold travel time. In order to understand the influence of different congestion threshold values on performance evaluations, this study performed two separate analyses with two distinct threshold values (i.e., 75- and 85- percent of the free-flow speed). Additionally, congestion measures were calculated for both peak period times (6 a.m. to 9 a.m. and 4 p.m. to 7 p.m.) and daytime travel conditions (6 a.m. to 7 p.m.).

2.3.2.5 *Day et al.'s research work*

The *2013-2014 Indiana Mobility Report (Summary Version)* presented an overview of the mobility performances of the Indiana State highway network using a series of speed- and travel time-based performance measures (Day et al., 2014). The study area covered the full extent of the interstate system operated by Indiana Department of Transportation (INDOT) and some selected arterial highway sections within Indiana. Traffic volume data, obtained from previous INDOT annual average daily traffic (AADT) counts, were also integrated into the performance metrics framework. This process enabled the speed- and travel time-based performance measures to be scaled to the network level, thus, adding another dimension to the analysis.

For the interstate system, the mobility performances were mainly evaluated using speed-related indices: 15-minute speed, congestion hours, distance-weighted congestion hours, speed profiles, 45 mph delay ($Delay_{45}$), total delay, and delta speed (i.e., the speed differences at neighboring sections). A 15-minute aggregation interval was used to cover longer time periods of analysis. While determining congested traffic conditions, rather than choosing a percentage of the free-flow speed as the threshold value, a fixed speed value - 45 mph - was selected in this study. Congestion levels of the interstate system were ranked using $Delay_{45}$ and total delay.

For arterial highways, this study primarily concentrated on TTR-related measures, such as the average travel time, normalized average travel time (i.e., TTI), normalized travel time reliability index and composite travel time index. It is noteworthy that, unlike many other studies which used PTI as the reliability indicator, this study employed the variance of travel times to denote the reliability dimension of congestion. Travel time data from an 18-month period during 2013-2014 were separated into different time-of-day (TOD) cohorts where similar operating conditions prevailed: morning peak period (6 a.m. to 9 a.m.), midday (9 a.m. to 3 p.m.), and evening peak period (3 p.m. to 7 p.m.). Then, within each TOD cohort, the travel time characteristics were aggregated across the two directions by taking the maximum value in both directions. The reason for using this approach was to avoid masking an unfavorable condition in one direction by taking their average in both directions. Finally, the most congested and most unreliable arterial segments within the study area were prioritized based on the TTI values and the normalized variance of travel times (computed as the standard deviation of the travel times over the analysis period divided by the travel times when driving at speed limits).

2.3.2.6 *Peterson's research work*

The Washington State Department of Transportation (WSDOT)'s *Handbook for Corridor Capacity Evaluation* presented how WSDOT performed its annual corridor analysis of congestion due to capacity constraints in Washington State, and whether it had grown on state highways (Peterson, 2014). By using real-time traffic data collected from embedded loop detectors and vehicle probe data purchased from the private sector, a variety of congestion performance measures were calculated and presented. These measures covered various aspects of the transportation system in Washington State, which included, but are not limited to: (1) delay metrics; (2) travel and lane miles metrics; (3) throughput metrics; and (4) travel time metrics. Washington State employed the maximum throughput speed (about 70 - 85 percent of the posted speed limit) as the reference speed for freeway analyses. While evaluating travel time trends of daily commute trips, WSDOT defined peak time period separately for each state region based on specific regional traffic characteristics. For instance, in the central and south Puget Sound areas, peak periods were defined as 5 a.m. to 10 a.m. and 2 p.m. to 8 p.m.; while in Spokane and Vancouver areas, peak periods were defined as 7 a.m. to 10 a.m. and 3 p.m. to 6 p.m.

WSDOT used the 95th percentile travel time as its key reliability metric for commute trips, even though the average, median, 80th and 90th travel time percentiles were calculated as well. Instead of focusing on a single congestion threshold value, WSDOT selected two different percentile speed values (i.e., 60 and 75 percent of the free-flow speed) to reflect different levels of congestion (e.g., severe congestion vs. congestion). The final results exhibited significant changes in some commute routes while some others showed less variation. For example, from 2012 to 2014, the I-5 corridor in the south Puget Sound region experienced an increase in delay from 473,500 to 939,500 vehicle hours; and travel times from Federal Way to Tacoma increased by nine minutes while travel times on other south Puget Sound commute routes remained nearly unchanged.

2.3.2.7 *USDOT and FHWA's research work*

The FHWA's report: *2014 Urban Congestion Trends: Improved Data for Operations Decision Making* documented the current state of congestion and reliability in the largest urban areas across the country (USDOT and FHWA, 2015). Transportation system performance measures were quantified and presented on a quarterly basis at both the national and city levels. Three performance metrics were extracted and reported based on the National Performance Management Research Data Set (NPMRDS) database: hours of congestion (*duration dimension*), TTI (*intensity dimension*), and PTI (*reliability dimension*). The NPMRDS dataset includes average travel times in 5-minute intervals for the National Highway System (NHS) and is available for use by state DOTs and metropolitan planning organizations (MPOs) for their performance management activities. To report and track congestion trends at a greater scale, the original 5-minute travel times were aggregated into 15-minute monthly average travel times by day of week (e.g., each TMC path had a travel time value for 6:00 a.m. to 6:15 a.m. for Mondays in January, 6:00 a.m. to 6:15 a.m. for Tuesdays in January, etc.). Therefore, the result of these summary calculations was a 96 (which was the number of 15-minute intervals in a day) by 7 (the number of days of the week) matrix for each month and TMC path.

In this study, traffic congestion was declared when the average speeds fell below 90 percent of the free-flow speed. Congested hours of each TMC path were determined by summing up all congested periods within 6 a.m. to 10 p.m. on weekdays throughout the entire analysis period. The TTI/PTI was calculated as the ratio of the average/95th percentile travel time to the free-flow travel time. Both measures were computed for the a.m. and p.m. peak periods. Note that all three performance measure values were weighted by vehicle-miles of travel (VMT) when combining different TMC paths and time periods. The results indicated that aggregated congestion, measured across all 52 metropolitan areas, had increased from 2013 to 2014.

2.3.2.8 *Schrank, Eisele, Lomax and Bak's research work*

The *2015 Urban Mobility Scorecard (UMS)* provided congestion estimates for each of the 471 U.S. urban areas using the procedures developed by the Texas Transportation Institute and INRIX (Schrank et al., 2015). In this study, the free-flow speeds were established under low volume conditions (10 p.m. to 5 a.m.) but capped at 65 mph. Both the average travel time and the 95th percentile travel time were compared to the free-flow travel time during peak periods (6 a.m. to 10 a.m. and 3 p.m. to 7 p.m.). Travel delay on an individual roadway section was calculated on an hourly basis. Other indicators, such as total peak period travel time and number of rush hours, were computed and presented as well.

Based on the literature review as presented above, Table 2-3 shows a summary of existing bottleneck identification methods using TTR-related measures. Note that the following notations are introduced to facilitate the presentations.

- LD: loop data

- VPD: vehicle probe data
- N/A: not applicable
- V_p: value of the posted speed limit
- FFS: free-flow speed
- $FFTT$: free-flow travel time
- $T_{95}/T_{90}/T_{80}/T_{50}$: the 95th/90th/80th/50th percentile travel time, respectively
- V_{up}/V_{dn}: traffic speeds measures at upstream/downstream detectors
- NPMRDS: National Performance Measure Research Data Set (FHWA)
- HPMS: FHWA's Highway Performance Monitoring System
- S_T: variance of a set of travel times
- $Index_T$: a combination of TTI and S_T, computed as $100\sqrt{max\{0, TTI - 1\}^2 + S_T^2}$

Table 2-3 Summary of Bottleneck Identification Methods Using Vehicle Probe Data

Year	Author	Data Type	Data Agg.	Data Source	Low Volume Hours (LVH)	Reference Speed	Study Periods	TTR Indexes: Reliability Dimension	TTR Indexes: Central Tendency	TTR Indexes: Other TTR Measures	Congested Condition (CC)	Ranking Index
2011	Cambridge Systematics	VPD	5-min	INRIX	N/A	min{V_{85} for all time periods, 65 mph}	6 - 9 a.m. 4 - 7 p.m.	$PTI = \frac{T_{95}}{FFTT}$	$TTI = \frac{\overline{TT}}{FFTT}$	$BTI = \frac{T_{95}-\overline{TT}}{\overline{TT}}$	$V_{up} \leq 40mph$ & $V_{dn} - V_{up} \geq 20mph$	% of CC
2011	FDOT	VPD	5-min	INRIX	10 p.m. - 5 a.m.	V_{85} during LVH	6 a.m. - 7p.m.	$PTI = \frac{T_{90}}{FFTT}$	N/A	N/A	$PTI \geq 3$ or $v \leq 75\% * FFS$	PTI, % of CC
2014	CDM Smith	VPD	15-min	NPMRDS	10 p.m. - 5 a.m.	V_{85} during LVH	6 a.m. - 7p.m. 6 - 9 a.m. 4 - 7 p.m.	$PTI = \frac{T_{80}}{FFTT}$	N/A	$PTI = \frac{T_{90}}{FFTT}$	$v \leq 75\% * FFS$ $v \leq 85\% * FFS$[1]	PTI, Duration of CC
2014	Day et al.	VPD	15-min	Private Sector	N/A	V_p	6 - 9 a.m. 9 a.m. - 3p.m. 3 - 7 p.m.	S_T	$TTI = \frac{\overline{TT}}{FFTT}$	$Index_T$	$v \leq 45\ mph$	Delay, TTI, S_T
2014	Peterson	LD & VPD	5-min	WSDOT & Private Sector	N/A	70-85% of V_p (~ 42-51 mph)	5 - 10 a.m. 2 - 8 p.m.[2] 7 - 10 a.m. 3 - 6 p.m.[2]	T_{95}	$\overline{TT}$	T_{50}, T_{80}, T_{90}	$v \leq 75\% * FFS$ $v \leq 60\% * FFS$[3]	Duration of CC
2014	Wolniak and Mahapatra	VPD	1-hr	INRIX	10 p.m. - 5a.m.	N/A	8 - 9 a.m. 5 - 6 p.m.	$PTI = \frac{T_{95}}{FFTT}$	$TTI = \frac{T_{50}}{FFTT}$	N/A	$PTI \geq 2.5$ or $PTI \geq 2.0$	PTI or TTI
2015	Schrank et al.	LD & VPD	15-min	HPMS & INRIX	10 p.m. - 5a.m.	min{V_{85} for all time periods, 65 mph}	6 - 10 a.m. 3 - 7 p.m.	$PTI = \frac{T_{95}}{FFTT}$	$TTI = \frac{\overline{TT}}{FFTT}$	N/A	N/A	% of CC, Duration of CC
2015	USDOT and FHWA	VPD	5-min	NPMRDS	9 a.m. - 4 p.m. & 7 - 10p.m.	min{V_{85} during LVH, V_p}	6 - 9 a.m. 4 - 7 p.m.	$PTI = \frac{T_{95}}{FFTT}$	$TTI = \frac{\overline{TT}}{FFTT}$	$BTI = \frac{T_{95}-\overline{TT}}{\overline{TT}}$	$v \leq 90\% * FFS$	Duration of CC

Note: [1] This study performed two separate analyses with two distinct threshold values.
[2] In the central and south Puget Sound areas peak periods were defined as 5 - 10 a.m. and 2 - 8 p.m., while in Spokane and Vancouver peak periods were defined as 7 - 10 a.m. and 3 - 6 p.m..
[3] Conditions under two congestion levels were specified in this study: (1) congestion: $v \leq 75\% * FFS$; (2) severe congestion: $v \leq 60\% * FFS$.

2.4 Bottleneck Mitigation Measures

A wide range of measures have been developed and applied in mitigating bottlenecks along freeway segments. Since the root-cause of freeway bottlenecks is the imbalance between traffic demand and roadway capacity, bottleneck mitigation measures can be generally classified into the following three categories: (1) managing travel demands; (2) increasing operational efficiency on existing roadway segments; and (3) expanding roadway capacities.

2.4.1 Travel Demand Management

Managing both the growth of and periodic shifts in traffic demand are necessary elements of managing traffic congestion. If traffic demand is not well-managed, the performance of the transportation system will be adversely affected. Managing traffic demand today is about providing travelers with choices, including the destination, route, departure time, and mode choices. In a FHWA report *Mitigating Traffic Congestion: The Role of Demand-Side Strategies*, Luten et al. (2004) listed several strategies associated with travel demand management:

- Mode strategies: Providing shared vehicles, encouraging transit or bicycle ridership, etc.
- Departure-time strategies: Encouraging flexible work hours, coordinated event scheduling, etc.
- Route strategies: Providing real-time route information, in-vehicle navigation, web-based route-planning tools, road pricing, etc.
- Trip reduction strategies: Providing employer telecommuting programs and policies, compressed work week programs, etc.

- Location/Design strategies: Encouraging transit-oriented development (TOD), living near your work, proximate commuting, etc.

For more information related to demand-side congestion mitigation measures, readers are referred to http://www.ops.fhwa.dot.gov/tdm/ref_material.htm.

2.4.2 Operational Efficiency Improvement

Instead of directly building the roadway out of congestion, operation efficiency improvement strategies can be viewed as an indirect way to reduce congestion by getting more out of existing roadway system. The FHWA's *Congestion Reduction Toolbox* (USDOT and FHWA, 2015) provided several tools that can be used to improve the level of service (LOS) on existing roads, including:

- Traffic incident management
- Freeway management and traffic operations, such as variable speed management (i.e., VSL, sometime also referred as speed harmonization), metering or closing entrance ramps, High Occupancy Vehicle (HOV) lanes or reversible lanes, and work zone management, etc.
- Road weather management
- Traveler information service: 511 traveler information telephone services, travel time message signs for travelers, national traffic and road closure information, and freight shipper congestion information, etc.

2.4.3 Roadway Construction and Capacity Expansion

Adding more lanes to existing highways and building new highways have been the traditional ways to mitigate traffic congestion. In some metropolitan areas, however, it has become difficult to undertake major highway expansions due to the financial constraints, increased right-of-way and construction costs, and adverse social and environmental effects. A previous report, *Traffic Bottlenecks: A Primer - Focus on Low-Cost Operational Improvements* (USDOT and FHWA, 2007), presented a suite of short-term, low-cost strategies to help ameliorate localized bottlenecks, including:

- Shoulder conversions
- Re-striping merge or diverge areas
- Reducing lane widths to add a travel and/or auxiliary lane
- Modifying weaving areas
- Minor interchange modifications (such as adding a new auxiliary lane to connect closely spaced interchanges)

While many of the nation's bottlenecks can only be addressed through costly and major construction projects, there is a significant opportunity for the applications of operational and low-cost infrastructure solutions to bring about relief at these chokepoints (Margiotta et al., 2012). Cooner and his colleagues' research (Cooner et al., 2009) has shown that the implementation of lower-cost improvements is a cost-effective way to improve mobility at freeway bottlenecks.

2.5 Tools for Assessing Bottleneck Mitigation Measures

There are numerous types of analytical and simulation tools that can be deployed to reasonably assess the effectiveness of the candidate bottleneck mitigation measures. In a FHWA report *Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools*, Jeannotte et al. (2004) synthesized and categorized these tools into the following groups: (1) sketch planning tools; (2) travel demand models; (3) traffic signal optimization tools; (4) analytical/deterministic tools (HCM-based); (5)

macroscopic simulation tools; (6) mesoscopic simulation tools; and (7) microscopic simulation tools. The first three types of tools are designed for specific application purposes:

- The sketch planning tools provide order-of-magnitude estimates of travel demand, operations and delay and are mainly designed for budget preparation purpose.
- The travel demand models are able to forecast future travel demand based on current travel surveys and future projections of household and employment characteristics. These models, however, are incapable of evaluating operational traffic management strategies, such as managed lanes, VSL, or hard shoulder running (HSR), etc.
- Traffic optimization tools are primarily used for developing optimal signal timing plans for isolated signal intersections, arterial streets, or signal networks.

Since the focus of this study is on estimating the operational impacts of bottleneck mitigation measures at both local and network levels, the last four groups of evaluation tools will be carefully examined in subsequent sections in terms of their functionalities, level of fidelity, methodology, input data requirements, output performance measures, computation time and storage requirements.

2.5.1 Analytical/Deterministic tools (HCM-Based)

Most analytical/deterministic tools utilize static analytical procedures presented in the *Highway Capacity Manual (HCM) 2010* (TRB, 2010) to compute traffic performance measures (e.g., speed, density, volume-to-capacity (V/C) ratio) to determine the LOS of a freeway facility. Generally speaking, the HCM procedures are macroscopic (in that their input and output deal with aggregated/average performance during a 15-minute interval within the peak hour analytical period), deterministic (identical inputs will always lead to the same outputs), and static (they estimate average operating conditions over a fixed time interval and do not account for transitions between system states over time). Examples of some most frequently used analytical tools include the Highway Capacity Software (HCS) and SIDRA (software for evaluating and designing roundabouts). In contrast to stochastic analysis tools, these analytical tools have less input data, computation time and storage requirement. For instance, while performing operational analysis for basic freeway segments, the HCS 2010 only demands basic information about traffic flow (volume, peak-hour factor, etc.), speed (basic free-flow speed), and geometric characteristics (number of lanes, land width, lateral clearance, etc.). Depending on the specific application scenario (basic freeway segments, weaving section, or on-/off-ramps), the output performance measures in HCS 2010 may include the V/C ratio, LOS, estimated capacity, speed, delay, and queue length.

In a nutshell, analytical/deterministic tools are appropriate for analyzing the performance of localized facilities such as a single intersection or a freeway section; however, they are limited in their ability to analyze network or system effects.

2.5.2 Macroscopic Simulation Tools

Macroscopic simulation tools can be used to describe aggregated traffic behaviors at a regional level. Instead of tracking individual vehicles, the simulation in a macroscopic model takes place on a section-by-section basis. Traffic flow features (such as link travel time, and link density) are determined using the traditional static traffic assignment (STA) method and aggregate speed-volume relationship. Examples of the frequently used macroscopic traffic simulation models are TransCAD and VISUM.

The widely recognized advantages of macroscopic simulation models include their ability to solve large-scale problems, to converge to precise equilibriums and to provide consistent solutions (if a proper algorithm is used with a sufficient number of iterations). Compared to micro- or meso-scopic simulation models, macroscopic models have less input data and computational resource requirements. Typical input data incorporate static origin-destination (O-D) matrix (*demand side*) obtained from regional travel surveys and a geographic representation of the study network (*supply side*). Due to these features, they have been widely used by planning agencies and traffic management centers for decades.

However, macroscopic simulation models also have some limitations in terms of accounting for the time-varying travel conditions and capturing vehicular dynamics. According to Chiu et al., (2011), the main limitations of macroscopic planning models include: (1) the volume on a link may increase indefinitely and exceed the physical capacity of the link (i.e., the V/C ratio > 1); (2) the conventional STA method assumes that the inflow to a link is always equal to the outflow, and hence there is no accumulation of traffic on the link. As a result, it is unable to model the queue formation, congestion, bottleneck, and spillovers in a network; (3) since the STA model does not distinguish between different lanes on a roadway, those lane-based effects, such as HOV lanes and high occupancy toll (HOT) lanes, cannot be modeled; and (4) most intelligent transportation systems (ITS)-related applications, such as traveler information systems and advanced network control schemes, are beyond the modeling capabilities of macroscopic simulation models.

2.5.3 Microscopic Simulation Tools

Microscopic operational models are capable of simulating the movement of individual vehicles and representing roadway geometric characteristics at a finer resolution. Individual vehicle behaviors are modeled based on the car-following, lane-changing and gap-acceptance theories. Detailed representation of roadway geometry enables an explicit analysis of the impacts of traffic control schemes (e.g., actuated traffic control and signal priority) and special lane utilization activities (e.g., shared lanes and HOV/HOT lanes). In microscopic simulation models, vehicles are assigned to a link based on some statistical distribution (e.g., the Poisson distribution) and are tracked through the network at a relatively high resolution. Upon entry, each vehicle is assigned a destination, a vehicle type, and a driver type. In many microscopic simulation models, such as VISSIM and CORSIM, the operational characteristics of each vehicle are influenced by traffic controls, roadway geometric characteristics, and the interactions among vehicles. Link performance measures (e.g., speed, density, queue length), vehicle trajectories and emission data can be collected during the simulation process (Jeannotte et al., 2004).

To accurately describe traffic patterns at a higher fidelity, microscopic simulation models typically require more input data than macroscopic models for model developments and calibration purposes. In addition to that, computation time and storage restrictions usually limit the network size that can be modeled and the number of simulation runs that can be completed. Route choice behaviors at the regional or network level cannot be modeled in microscopic simulation models either.

2.5.4 Mesoscopic Simulation Tools

Mesoscopic DTA models combine some properties of both microscopic and macroscopic simulation models. On the one hand, mesoscopic simulation models share some common features with microscopic models - individual vehicle behaviors and dynamic traffic states are simulated and tracked through simplified car-following or traffic flow theories without describing detailed interactions between vehicles (e.g., lane changing or gap acceptance) (Chiu et al., 2011). DTA models are able to produce spatiotemporal vehicular trajectories which can further be used to determine all other variables characterizing the condition of the transportation system. On the other hand, many simulation-based DTA models adopt more computationally efficient traffic simulation logic (at the price of losing some simulation fidelity or detail) in order to be able to describe traffic flow behaviors at a larger geographical scope (from a corridor up to a region) and over a longer time period (from peak hours only to 24 hours). Due to these extensions, the DTA models can dynamically model traffic operations at a very fine time scale (a few seconds) over a large geographic area. Some critical travel behaviors, such as route choice behaviors and the formation of bottlenecks, can be investigated using DTA models. Duthie et al. (2013) synthesized that DTA models are capable of capturing many realistic traffic dynamics in the transportation network that static techniques cannot capture, including:

- vehicle trajectories for every O-D pair within each time interval;
- detailed information characterizing the spatial and temporal dynamics of travel times, traffic counts at specified detector locations, time-varying speeds and travel time profiles on links; and

- congestion indices such as queue length, average density and volume, and time-dependent density and volume profiles.

It is worth mentioning that DTA models typically require a number of inputs and parameters that need to be specified prior to the model development which can be categorized as demand-side and network-side features. The demand-side data include, at a minimum, time-dependent O-D matrices or trip tables and traveler behavior parameters. The network characteristics include roadway capacities, link performance functions, traffic control information and strategy information such as incident impact parameters or ITS elements (Chiu et al., 2011). Examples of widely used simulation-based DTA models include DTALite, DYNASMART, and DynaMIT. Detailed information about the main characteristics of each mesoscopic DTA model will be presented in subsequent sections.

2.5.4.1 *DTALite*

DTALite is an open-source and agent-based DTA software. It allows transportation practitioners and researchers to freely modify, enhance and release the source code to meet various application needs. Based on a mesoscopic simulation-assignment framework, DTALite employs a computationally simple but theoretically rigorous traffic queuing model in its lightweight mesoscopic simulation engine and, thus, is capable of tracking congestion dynamics at typical bottleneck areas (Zhou and Taylor, 2014). DTALite can directly import existing static traffic assignment data from major planning software packages (e.g. TransCAD and VISUM), with additional time-dependent O-D demand patterns, to build a DTA dataset for a regional network. The parallel computing technique was integrated into the software package to speed-up the simulation process.

DTALite has been used in the second Strategic Highway Research Program (SHRP 2) C05 project to simulate day-to-day variations on the Portland metropolitan network. It demonstrated excellent computational performance on a number of large-scale regional networks: the DTALite model converged to the dynamic traffic equilibrium solution for the Portland metropolitan network (with more than 2,000 traffic analysis zones and 1.2 million vehicles in a 6-hour planning horizon) in a little over 2 hours on a regular 32-bit dual-core laptop (Kittelson & Associates, 2014). Enhanced by a graphical user interface (GUI), NEXTA (Network Explorer for Traffic Analysis), DTALite is able to (1) reasonably and realistically model traffic dynamics on a regional network; (2) evaluate the effectiveness of different congestion improvement strategies according to their impacts at the point, link, corridor, and network levels; and (3) export and visualize a rich set of simulation outputs generated over an extended period of time (several days) and therefore provide insightful information for resource allocation and investment planning purpose (DTALite, 2015).

DTALite is being used in designing, planning, and operation of a long-term work zone in I-40/I-440 at Raleigh, NC. In the first phase of the project, the tool was used to decide the number of lanes to be remained open during the construction period. DTALite was also used to get diversion from the affected route to the alternative routes. Simulated travel time on the alternative routes with the work zone in effect was useful in scheduling transit service frequency, school bus services, and arterial route signal timing. Sensitivity of simulated travel times with different levels of dynamic traffic assignment model parameters were investigated. Guidance regarding selection of appropriate network extent and details, and validation of simulation results with on-line sensors were provided as a part of the work (Tanvir et al., 2016).

2.5.4.2 *DYNASMART-P*

DYNASMART-P (DYnamic Network Assignment Simulation Model for Advanced Roadway Telematics: Planning version) is a simulation-based DTA model which supports transportation network planning and traffic operation decisions. The tool combines (1) dynamic network assignment models, used primarily in conjunction with demand forecasting procedures for planning applications, and (2) traffic simulation models, used primarily for traffic operational studies. Although traffic flow movements in DYNASMART-P are determined based on a modified version of the Greenshield's macroscopic speed-density relationship, the tool is capable of tracking and recording trajectories of each individual vehicle (Duthie et al., 2013). Since the model takes the time-varying nature of traffic flows into account, it can provide estimates of state variables such as travel times, speeds, queue lengths, delays, and congestion effects to assess the functional and environmental impacts of a variety of traditional and emerging transportation planning measures (such as lane additions and reversible lanes).

DYNASMART-P requires input data commonly used by the traditional traffic assignment and simulation models, such as geometric representation of the network and spatial demand loading patterns. The input data vary with the network being analyzed and the level of detail required by the user. Complexity of the network could range from a linear freeway corridor to an integrated network with HOV/HOT lanes, ramp metering, transit services, incidents and signal controlled intersections on surface streets. Applications to date have included metropolitan and regional networks with up to 35,000 nodes and 100,000 links, with nearly one million vehicles simulated over horizons of several hours (DYNASMART-P, 2015).

2.5.4.3 *DynaMIT*

DynaMIT (Dynamic Network Assignment for the Management of Information to Travelers) is a simulation-based DTA system that estimates and predicts traffic conditions (Ben-Akiva et al., 1998). The system is designed to interface with a real-time surveillance system and mainly comprises the following two types of core models.

- **Demand models.** DynaMIT employs a disaggregate demand representation to model individual driver's pre-trip and en-route decisions, including their response to real-time route guidance information (Ben-Akiva et al., 2010). Based on the historical O-D matrices, each agent in the model is assigned a vector of socioeconomic characteristics using the Monte Carlo method.
- **Supply models.** DynaMIT considers the physical characteristics of the road, incidents and control devices at intersections while determining the capacity restraints on roadway facilities. A deterministic queuing model and a macroscopic speed-density relationship are used to update traffic flow dynamics at freeway bottlenecks and uninterrupted facilities, respectively.

DynaMIT is able to handle a variety of real-time situations such as incidents, special events, weather conditions, and highway construction works (DynaMIT, 2015). In contrast to other mesoscopic DTA models, DynaMIT requires a huge amount of real-time traffic surveillance data and incident information to generate accurate model outputs. Additionally, static topology information about the network and historical O-D matrices is required as well. DynaMIT can visualize a group of performance measures through the

GUI, such as link speed, volume, density; other system outputs include accident reports (location, duration, severity) and traffic messages disseminated to the drivers (e.g., through variable message signs (VMS) or highway advisory radio). Most applications of DynaMIT are centered on its predictive abilities and the model has been successfully applied to small networks such as Southampton, Lower Westchester County, and Irvine, CA to study various traffic-related problems.

2.5.4.4 *Dynameq*

Dynameq, which stands for "*dynamic equilibrium*", is a mesoscopic DTA model that can account for various types of driver behaviors. The tool consists of two main components: a traffic simulation component and a routing component (Mahut and Florian, 2010). Specifically, the simulation module determines individual vehicle movements based on car-following models, gap-acceptance theories and explicit signal timing plans (the simulation process in Dynameq is performed at the microscopic level). The routing module imitates how drivers choose their routes through the network to their desired destinations (INRO, 2015). It is worth mentioning that, in Dynameq, to improve computational efficiency and to allow for modeling a regional network, traffic dynamics are updated each time when an event occurs (event-based).

To develop and calibrate a simulation model in Dynameq, it requires the following input data: (1) network description and traffic signal timings; (2) empirical traffic data (volumes, queue lengths, and travel times, etc.); and (3) time-varying O-D tables. Model outputs include animated plots and time-series charts. The animated plots in Dynameq can be easily customized to display average values of traffic measurements (flows, densities, speeds, travel times and queues) at the node, link, and path level (Snelder, 2009).

2.5.4.5 *DynusT*

DynusT (Dynamic Urban Systems in Transportation) is a dynamic traffic simulation and assignment software designed to assist engineers and planners in estimating the evolution of system-wide traffic flow patterns. To account for various types of driver response behaviors, the tool considers multiple user classes including the following (DynusT Online User's Manual, 2015):

- Class 1 - Habitual: This class of users does not respond to any information about quickest path. The driver continues on the same path assigned to them unless there is a Detour (DMS type 2) that all cars must take.
- Class 2 - System Optimal: Travel path assignments are based on optimal system perspective, not on the individual driver's.
- Class 3 - User Equilibrium: This class of users are assigned the paths that will reduce the travel time for the driver.
- Class 4 - En-Route Info: Two types of information are considered for this class: (1) radio type of information in which the incident or disaster location is disseminated to drivers at the pre-defined frequency; and (2) GPS navigation devices that presents new routes based on updated travel time information.
- Class 5 - Pre-trip Info: Pre-trip best path information in modeling is equivalent to what drivers know in advance that there is a road construction work or a lane closure before leaving.

In DynusT, vehicle movements are simulated based on the anisotropic mesoscopic simulation (AMS) model proposed by Chiu et al. (2010) and can be accelerated through adopting the multi-threaded simulation technique. DynusT can model various application scenarios, such as congestion pricing, work zone activities, incidents, variable message signs, and ramp metering. According to Schoen and Nguyen (2012), however, DynusT provides greater accuracy for corridor level analysis while its regional model was not fully developed.

In order to present a convenient way for engineers and researchers to compare and determine an appropriate tool for bottleneck analysis, a brief summary of existing tools that can be used for assessing various bottleneck mitigation strategies is provided in Table 2-4, in terms of model functionalities, level of fidelity, output performance measures, and the major limitation associated with each type of tool.

Table 2-4 Characteristics of Different Tool Types for Freeway Bottleneck Analysis

Characteristic	Analytical/ Deterministic Tools	Simulation Tools		
		Macroscopic	**Microscopic**	**Mesoscopic**
Model functionalities	Mainly used for analyzing the performances of localized areas (a single intersection or a freeway section)	Designed for modeling traffic conditions at corridor level, or network/regional level for planning purposes	Evaluating operational strategies (e.g., VSL), traffic control schemes (e.g., signal priority) and special lane utilization activities (e.g., HOV/HOT lanes) at a finer resolution	Capable of modeling regional or network-level traffic situations, such as route choice, and formation of bottlenecks
Level of fidelity	(1) Static, 15-min within the peak hour (2) Section level	(1) Static, peak-hour (2) Section level	(1) Dynamic, ≤1 second (2) Detailed geometric representation (3) Individual vehicles	(1) Dynamic, a few seconds; (2) Resolution of traffic movement are finer than macroscopic tools, but coarser than microscopic tools; (3) Individual vehicles
Methodology	HCM Procedures	Traditional 4-step model	Car-following, lane-changing and gap-acceptance theories	Time-dependent shortest path algorithm; dynamic user equilibrium theory
Input data requirements	Volume, speed, geometric layout	Static O-D matrix, geographic representation of the roadway network	Vehicle types and counts, speed distributions, driver behavior parameters (e.g., stop distance, headway time), roadway geometric layout, signal timing plan, path choice information	Demand-side: time-dependent O-D matrix, traveler behavior parameters Network-side: capacities, link performance functions, traffic control information
Performance measures	V/C, LOS, capacity, speed, delay, queue length	Volumes, LOS, link travel time, path travel time	Link performances (e.g., speed, density, queue length, etc), trajectories, emission data	Vehicle trajectories for each O-D pair and each time interval; Time-varying speed profiles; Congestion indices (queue lengths; time-varying density and flow information)
Computer time and storage requirements	Less	Medium	Significant	Significant
Major Limitations	(1) Unable to analyze network/system effects (2) Cannot describe dynamic traffic conditions	(1) Assigned volume may exceed capacity; (2) Unable to model the queue formation, congestion, bottleneck, or spillover; (3) Cannot model lane-based effects (e.g., HOV)	(1) Requires a lot of calibration work; (2) Limited network size and number of simulation runs; (3) Route choice behaviors at regional or network level cannot be modeled	(1) Requires a lot of data preparation and model calibration work; (2) Computational intensive
Examples	HCS, SIDRA	TransCAD, VISUM	VISSIM, CORSIM	DTALite, DynaMIT

2.6 Previous Case Studies Using DTA for Bottleneck Analysis

Based on the literature review as previously discussed, it is very clear that DTA models are effective tools which can be used to capture the impacts of different bottleneck mitigation measures at both the local and network levels. To get a better understanding of the feasibility and capability of the DTA models, this section presents several previous case studies using DTA models to assess various congestion mitigation strategies. Particular attention will be given to the following aspects associated with DTA model applications: (1) model platforms; (2) study periods; (3) input data requirements; and (4) output performance measures.

2.6.1 Raleigh, North Carolina

NCDOT previously conducted a research to evaluate the impact of a pavement rehabilitation project on interstates I-40 and I-440, both of which are major urban freeways in the Triangle region of North Carolina (Schroeder et al., 2014). In order to evaluate the potential impacts of distinct work zone closure configurations on alternative routes and other chokepoints in the network, two mesoscopic simulation-based DTA software packages, DynusT and DTALite, were employed in this study. The research team developed two separate models to simulate traffic conditions during the a.m. peak hour (7 a.m. to 8 a.m.) and p.m. peak hour (4:30 p.m. to 5:30 p.m.), respectively. The baseline network model used in this project was obtained from a prior NCDOT research project (Williams et al., 2011) with several modifications. Also, a calibration and validation process was performed using three key performance measures: travel time along several critical network routes, traffic volumes and speed estimates at critical locations. For each construction scenario, model outputs, such as route diversion rates, variations of traffic volumes and travel time along critical routes, were recorded and compared with the base scenario.

The results of this study indicated that both DTA tools yielded reasonable outputs for the baseline scenario and the higher-capacity work zone scenarios. However, for low capacity (more severe) work zone scenarios, DynusT presented unrealistically high traffic densities in the segments upstream of the work zone; in contrast, the DTALite tool performed more reasonably. Therefore, while both tools proved useful in this project, the DTALite results were thought to provide a more realistic assessment of the expected work zone impacts in this study.

2.6.2 Portland, Oregon

The SHRP 2 C05 project (Kittelson & Associates, 2014) tested the overall impact of several highway improvement alternatives, such as expanding an existing five-lane cross section to a seven-lane cross section, refining signal timings, and increasing the availability of pre-trip traffic information, on a subarea of the Portland network. This study area consisted of 208 traffic analysis zones (TAZs), 857 nodes and more than 200,000 originating vehicle trips during the 4-hour weekday period (3 p.m. to 7 p.m.). Two mesoscopic tools, DTALite and DYNASMART-P, were used together as the simulation execution platform. In particular, DTALite was used to model the entire Portland metropolitan area network for a period of 50 simulation days and its outputs were used to create an O-D matrix for a much smaller subarea network which became the basis for the subsequent DYNASMART-P modeling work. An initial version of the Portland metropolitan area network was provided to the research team in VISUM model format which was used by the Metro staff for their current travel demand forecasting activities. Additional input data consisted of signal control information, detailed configurations of approach lanes, and the location and length of turn pockets. All these data items were examined, rectified (when necessary) and transformed into a standard format that was used by multiple DTA programs (including DTALite, DYNASMART-P, and DynusT). Several performance measures were monitored and aggregated on a link, corridor, O-D pair, and/or network basis, depending on the nature of the performance measures, including:

- Peak hour volume (vph) (5 p.m. to 6 p.m.) at both the link and corridor levels;
- Total travel time (minutes) for links, corridors, and the entire network;
- Average travel time (minutes/veh) for links, corridors, and the entire network;
- Vehicle miles traveled (VMT) during the peak hour for each corridor and the network;
- Average speed (mph) for each corridor and the network;
- Density (veh/mi/lane) for each corridor; and
- Breakdown frequency for each corridor.

2.6.3 El Paso, Texas

In some cases, construction of additional lanes is an option to alleviate congestion. Unfortunately, the road-construction project itself could incur congestion problems as well - at least until the new lanes are available for use. To quantify and evaluate the impacts of multiple concurrent road construction activities in the El Paso area, a DTA tool was deployed to predict how traffic patterns change in response to various construction scenarios. The core part of the DTA-based model was a calibrated DynusT network and the O-D matrix of the El Paso region. Input to the model also included the construction data (location, duration, and capacity reduction of each construction project). The output performance measures from the simulation model included several metrics for each link in the network, such as average speed, density, link volume, and the percentage of queued links during the simulation period. Based on these outputs, the LOS of each link was computed and used to determine how traffic conditions changed in response to construction activities in the roadway network.

Since the most detrimental impacts of construction activities were expected to happen during peak periods, the simulations were performed using the O-D matrix for the morning peak periods (6 a.m. to 11 a.m.). Based on the analysis results, recommendations were made as to which construction scenario was preferable (Pesti et al., 2010).

2.6.4 San Francisco, California

The San Francisco County Transportation Authority conducted a project, known as “DTA Anyway”, to examine the impacts of two demand reduction strategies using the DTA tool: (1) adding a center-running bus rapid transit (BRT) lane in the downtown area of San Francisco; and (2) implementing cordon-based congestion pricing. The authority expected that the DTA model can provide answers to the following questions:

- Which streets will experience speed improvements with the implementation of congestion pricing policy and how will transit perform compared to autos?
- Where is downtown congestion coming from and going to? Where are people on this corridor going from and going to? How many of them have origins or destinations outside of the corridor and are thus easily divertible?
- Where does traffic divert to after the implementation of these strategies?

A Python module was developed by the research team to assist in automatically generating the DTA model network (Dynameq format) using various input data sources, such as the static network files and transit lines from Cube format, O-D demand tables from SF-CHAMP (San Francisco's activity-based travel demand model), and signal timing cards used by the San Francisco Municipal Transportation Agency (SFMTA).

This study focused on evaluating traffic conditions operating during evening peak periods (3:30 p.m. to 6:30 p.m.). The results suggested that (1) while applying congestion pricing strategy, the DTA model, compared to static models, can capture a clearer diversion to paths outside the cordon; and (2) the DTA model showed that adding a new BRT lane would have greater impact on vehicle speeds where link flows were highly variable (Brinckerhoff and SFCTA, 2012).

2.6.5 Seattle, Washington

Wellander et al. (2013) developed a DTA model in Dynameq to assess the feasibility and effects of various toll scenarios of the Alaskan Way Viaduct Replacement Tunnel Project in Seattle, Washington. Toll scenarios varied primarily by toll rates, direction and time of day.

The DTA model relied on the regional demand static assignment model for the 2010 base year and future demand matrices for the study area. Intersection locations and signal timing plans were collected through previous studies. To account for traffic conditions during the p.m. peak hours, the simulation period covered five hours from 1 p.m. to 6 p.m. and was sliced into multiple 15-minute intervals. Model outputs included travel times, percent changes in route choice, and toll revenue. Based on these outputs, the research group were able to determine the effectiveness of each pricing strategy and to provide candidate preventive actions to the tolling committee to mitigate the impact of toll scenarios on city streets.

2.6.6 Minneapolis, Minnesota

Chiu et al. (2010) developed a regional DTA model, based on DynusT, along the I-394 corridor in Minneapolis, Minnesota, to assist local transportation agencies in efficiently and proactively managing the movement of people and goods along major transportation corridors. The modeling framework for the I-394 corridor was developed by following a three-step procedure: (1) setting up the baseline model, (2) model validation and calibration, and (3) before-and-after scenario analyses. Networks, trip tables, and other pertinent data were migrated from the regional travel demand model maintained by the Metropolitan Council serving the Twin Cities area.

In this study, the simulation period was defined as 5:00 a.m. to 11:30 a.m., during which the first hour was used as the "warm-up" period. The analysis period (period of interest), during which the results were collected and analyzed, lasted from 6 a.m. to 11 a.m. (5 hours). The results indicated that DynusT can reasonably replicate traffic conditions on the I-394 corridor of the base year, as validated by the comparisons between observed and modeled volumes, travel times, and speed contours on I-394. In addition to that, the simulated traffic conditions under incident situations exhibited consistent traffic diversions, speed reductions, and queue propagation with the actual data (Chiu et al., 2010).

2.6.7 Austin, Texas

Duthie et al. (2013) employed a mesoscopic DTA model to evaluate the network level influences of bottleneck mitigation measures on the MoPac Expressway in the downtown area of Austin, TX. The impacts of geometric reconfigurations of northbound MoPac Expressway were simulated using the DTA tool - VISTA. The following data was utilized for calibrating pre- and post-improvement conditions:

- PM peak period demand matrix (2010) obtained from the Capital Area Metropolitan Planning Organization (CAMPO)
- The 2010 CAMPO network
- Turning movement counts at selected intersections
- Speed and travel times between each street crossing the MoPac Expressway
- 15-minute counts on MoPac entrance and exit ramps
- 15-minute downtown cordon counts (2009)

Output performance measures from the DTA model, such as travel times, vehicular flows, and route choice behavior of travelers, were collected to estimate the network-wide impacts before and after the implementation of the bottleneck alleviation measures. The final results indicated that the geometric reconfigurations of northbound MoPac Expressway resulted in a small improvement in travel times during evening peak periods (4 p.m. to 6 p.m.). The 1st/6th Street entrance ramps to northbound MoPac Expressway experienced a small increase in volume towards the end of the simulation period, but there were no major shifts in travel patterns of the commuters leaving downtown in the evening. Overall, no major route switching behavior was observed in the network. A decision-making framework to prioritize potential future improvements alternatives was presented as well.

In summary, DTA models are capable of evaluating the impacts of various types of bottleneck mitigation strategies, such as roadway capacity expansion activities, congestion pricing, and bottleneck mitigation strategies, at both the local and network levels. A variety of simulation-based DTA tools can be employed to achieve this goal, including DTALite, Dynameq, and DynusT. Input data requirements and output performance measures are specific to each platform. Table 2-5 exhibits a summary of the DTA applications reviewed in this section.

Table 2-5 Analysis Summary of Existing Practice of DTA Models

No.	Author, Year	Project Purpose	Location Scope	Study Period	Model Platform	Input Data	Output Performances
1	Schroeder et al., 2014	Evaluation of construction activities	Raleigh, NC	AM peak hour (7 a.m. - 8 a.m.) and PM peak hour (4:30 p.m. - 5:30 p.m.)	DTALite, DynusT	Road network, time-dependent O-D matrices, construction data of different scenarios, volume, speed and travel time data	Route diversion rates, traffic volumes and travel times variations along critical routes
2	Kittelson & Associates, 2014	Evaluation of alternative improvement strategies	Portland, OR	PM peak period (3 p.m. - 7 p.m.)	DTALite, DYNASMART-P	Road network, time-dependent O-D matrices, signal timing info., approach lane configurations, and the location and length of turn pockets	Peak hour volume (link/corridor), travel time (link/corridor/network), VMT (corridor/network), average speed (corridor/network), density (corridor); breakdown frequency (corridor)
3	Pesti, 2010	Evaluation of construction activities	El Paso, TX	AM peak period (6 a.m. - 11 a.m.)	DynusT	Road network and time-dependent O-D matrices, construction data (e.g., location, capacity reduction, beginning and end time)	Average speed, density, link volume, percent of queued links, LOS
4	Parsons Brinckerhoff & San Francisco County Transportation Authority, 2012	Assessing cordon-based congestion pricing & bus rapid transit (BRT)	San Francisco, CA	PM peak period (3:30 p.m. - 6:30 p.m.)[1]	Dynameq	Road network, time-dependent O-D matrices, transit lines, signal data, stop sign info., traffic counts (for validation purpose)	Link volume, speed, travel time, route shift
5	Wellander et al., 2013	Tolling analysis	Seattle, WA	Two Time Periods (6 a.m. - 9 a.m. 1 p.m. - 6 p.m.)	Dynameq	Road network, time-dependent O-D matrices, signal timing/phasing info., travel time data (for validation purpose)	Link volume, travel time, route shift, toll revenue
6	Chiu et al, 2010	Testing corridor management strategies	Minneapolis, MN	6 a.m. - 11a.m.[2]	DynusT	Road network, time-dependent O-D matrices, travel times, volumes, transit network, transit O-D matrices	Volume, travel time, speed contours, traffic diversion, speed reductions, duration, and queue propagation
7	Duthie et al., 2013	Evaluating bottleneck elimination work	Austin, TX	PM peak period (4 p.m. - 6 p.m.)	VISTA	Road network, time-dependent O-D matrices, turning movement counts at intersections, speed and travel times, on-/off-ramp counts	Travel times, vehicular flows, route choice behavior, density, and spillback

Note: [1] The entire DTA simulation period lasted from 2:30 p.m. - 7:30 p.m. It included a 1-hr warm up period and a 1-hr cool-down period.
[2] The entire DTA simulation period was 5 a.m. to 11:30 a.m., in which 5 a.m. to 6 a.m. was the warm-up period.

2.7 Summary

A comprehensive review and synthesis of the current and historical research related to bottleneck definitions, identification methods, mitigation strategies, and assessment tools have been discussed and presented in this chapter. This is intended to provide a solid reference for and assistance in formulating bottleneck identification methods and developing effective mitigation strategies for future tasks.

CHAPTER 3: DEFINING PERFORMANCE MEASURES

Mobility performance measures play important roles in performance-based transportation analysis procedures, such as assessing an existing highway network, locating the most severe chokepoints in the network and comparing candidate mitigation alternatives. In this research, the significance of performance measures is threefold:

- **Identifying bottlenecks.** It is necessary to choose an appropriate combination of measures of effectiveness (MOEs) to identify freeway bottlenecks in an efficient and effective manner. Examples of the candidate MOEs that can be used for bottleneck identification may include TTI, PTI, FOC, or a combination of them.
- **Ranking bottlenecks.** Prior to determining the best strategy of allocating resources and planning investments to improve the productivity of the network, it is necessary to define a set of MOEs in advance for use to accurately quantify and prioritize the bottlenecks. The impacts of each bottleneck can be quantified both spatially (at the link, corridor/route, or network level) and temporally (e.g., the average duration of congested conditions resulting from a bottleneck).
- **Comparing bottleneck mitigation alternatives.** The MOEs are also useful in evaluating the impacts of various candidate improvement strategies on system-wide bottleneck mitigation and travel conditions in the close vicinity of the selected bottleneck site(s). Since new construction activities or operational improvements can directly affect route-choice behavior of travelers and will lead to a new regional traffic flow pattern, a comprehensive system-wide evaluation of each candidate project is imperative.

In subsequent sections, previous experience in determining performance metrics at both the federal and state levels will be examined first, followed by summarizing the basic principles used for MOE selection. On the basis of the synthesized principles, a combination of ten performance measures were chosen to meet the goals of developing three analytical procedures in this study: bottleneck identification, bottleneck ranking, and bottleneck mitigation alternatives evaluation. Detailed discussion about each selected MOE, including their definitions, calculation methods used, geographic scales involved, and congestion dimensions represented, are also provided.

3.1 Previous Experience in Determining MOEs

3.1.1 Federal Experience

3.1.1.1 *NCHRP Report 398: Quantifying Congestion: Volume 1*

In *NCHRP Report 398: Quantifying Congestion: Volume 1*, Lomax et al. (1997) noted that it is impossible to describe all of the traveler's concerns about congestion with a single value. Instead, employing multiple performance metrics to quantify traffic congestion from the following four dimensions is recommended: duration, extent, intensity and reliability. Each dimension of congestion may vary from place to place. Large metropolitan areas, for instance, tend to have higher congestion intensities and longer congestion durations than small cities.

- **Duration** - Defined as the amount of time that congestion affects the transportation system (*how long*);
- **Extent -** Defined as the number of people or vehicles affected by congestion (*how many people/vehicles*) and by the geographic scale of congestion (*how many lane miles*);

- **Intensity** – Defined as the severity of congestion that affects travel and is typically used to distinguish between different levels of congestion (e.g., lightly congested vs. heavily congested); and
- **Reliability** - Represents the variations in the other three elements (i.e., duration, extent, and intensity).

The report clearly stated that travel time and delays are the foundations of congestion measurement, but many different performance metrics can also be very useful depending on the research needs. Table 3-1, which was excerpted from this report, shows several metrics that can be used to gauge various dimensions of traffic congestion.

Table 3-1 Overview of Methods to Measure Congestion

Congestion Aspect	**System Type**		
	Single Roadway	**Corridor**	**Area-wide Network**
Duration (e.g., amount of time system is congested)	Hours facility operates below acceptable speed	Hours facility operates below acceptable speed	Set of travel time contour maps; "bandwidth" maps showing amount of congested time for system sections
Extent (e.g., number of people affected or geographic distribution)	% or amount of congested VMT[1] or PMT[2]; % or lane-miles of congested road	% of VMT or PMT in congestion; % or miles of congested road	% of trips in congestion; person-miles or person-hours of congestion; % or lane-miles of congested road
Intensity (e.g., level or total amount of congestion	Travel rate; delay rate; relative delay rate; minute-miles; lane-mile hours	Average speed or travel rate; delay per PMT; delay ratio	Accessibility; total delay in person-hours; delay per person; delay per PMT
Reliability (e.g., variation in the amount of congestion)	Average travel rate or speed ± standard deviation; delay ± standard deviation	Average travel rate or speed ± standard deviation; delay ± standard deviation	Travel time contour maps with variation lines; average travel time ± standard deviation; delay ± standard deviation

Note: [1] VMT - vehicle miles traveled
[2] PMT - person-miles traveled
(Source: *NCHRP Report 398: Quantifying Congestion: Volume1*, page 7)

3.1.1.2 *NCHRP Web-Only Document 97: Guide to Effective Freeway Performance Measurement: Final report and Guidebook*

The purpose of the *NCHRP Web-Only Document 97: Guide to Effective Freeway Performance Measurement: Final report and Guidebook* was to develop a guide on the effective use of performance measures in operating and managing a freeway system and in meeting the information needs of a large spectrum of potential local, regional, and national users (Margiotta et al., 2006). To gain a better understanding of the current utilization of performance measures in freeway management, the research team undertook a series of interviews with transportation agencies in ten areas including the Minnesota Department of Transportation (MnDOT), Washington State Department of Transportation (WSDOT), Virginia Department of Transportation (VDOT) and others. The final report synthesized four key motivations that drive state and local transportation agencies to perform freeway performance measurement, including: legislative mandates, agency-wide performance measurement initiatives, formal business planning (particularly for operations), and quantification of benefits for freeway programs (particularly for operations). In addition to that, the research team also developed a set of basic principles that need to be considered in monitoring freeway performance. Some of the guiding principles of this study are listed below:

- Multiple metrics should be used to report freeway performance, especially for mobility.
- In most cases, traditional HCM-based performance measures for mobility (V/C ratio and LOS) should not be ignored but should serve as supplementary measures of performance.

- The measurement of travel time reliability is a key aspect of freeway performance assessment, and reliability measures should be developed and applied.
- Three dimensions of freeway mobility/congestion should be tracked with mobility performance measures: source of congestion, temporal aspects (which has also been referred to as the duration dimension of congestion in some literature), and spatial details (similar to the extent dimension of congestion in some previous studies).
- Communication of freeway performance measurement should be done with graphics that resonate with various technical and nontechnical audiences.

Note that except for congestion/mobility metrics, performance measures related to other aspects of freeway performance monitoring (such as environment and safety measures) were also included in the *NCHRP Web-Only Document 97*. Table 3-2 shows a list of MOEs related to freeway congestion/mobility measurement.

Table 3-2 Recommended Core Freeway Performance Measures

Performance Metric	**Definition**	**Units**	**Geographic Scale**	**Time Scale**
Average (Typical) Congestion Conditions				
Travel Time	The average time consumed by vehicles traversing a fixed distance of freeway	Minutes	Specific points on a section or a representative trip only; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak periods, midday, daily
Travel Time Index	The ratio of the actual travel rate to the ideal travel rate	None; minimum value = 1.0	Section and area-wide as a minimum; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak periods, midday, daily

Table 3-2 (*continued*)

Performance Metric	**Definition**	**Units**	**Geographic Scale**	**Time Scale**
Average (Typical) Congestion Conditions				
Total Delay, Vehicles	The excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions	Vehicle-hours	Section and area-wide as a minimum; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak periods, midday, daily
Total Delay, Persons	The excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions	Person-hours	Section and area-wide as a minimum; separately for GP and HOV lanes	Peak hour, a.m./p.m. peak periods, midday, daily
Delay per Vehicle	Total freeway delay divided by the number of vehicles using the freeway	Hours (vehicle-hours per vehicle)	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Spatial Extent of Congestion No. 1	Percent of freeway VMT with average section speeds <50 mph	Percent	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Spatial Extent of Congestion No. 2	Percent of freeway VMT with average section speeds <30 mph	Percent	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Temporal Extent of Congestion No. 1	Percent of day with average freeway section speeds <50 mph	Percent	Section and area-wide	Daily
Temporal Extent of Congestion No. 2	Percent of day with average freeway section speeds <30 mph	Percent	Section and area-wide	Daily
Density	Number of vehicles occupying a length of freeway	Vehicles per lane-mile	Section	Peak hour/periods for weekday/weekend
Reliability				
Buffer Time Index	The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time	Percent	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Planning Time Index	The 95th percentile travel time index	None; minimum value = 1.0	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily

Table 3-2 (*continued*)

Performance Metric	**Definition**	**Units**	**Geographic Scale**	**Time Scale**
Capacity Bottlenecks				
Geometric Deficiencies Related to Traffic Flow (Potential Bottlenecks)	Count of potential bottleneck locations by type	Number	Section and area-wide	N/A
Major Traffic-Influencing Bottlenecks	Count of locations that are the primary cause of traffic flow breakdown on a highway section, by type	Number	Section and area-wide	N/A
Throughput				
Throughput - Vehicle	Number of vehicles traversing a freeway in vehicles	Vehicles per unit time	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Throughout - Persons	Number of persons traversing a freeway	Persons per unit time	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Vehicle-Miles of Travel	The product of the number of vehicles traveling over a length of freeway, times the length of the freeway	Vehicle-miles	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Truck Vehicle-Miles of Travel	The product of the number of trucks traveling over a length of freeway, times the length of the freeway	Vehicle-miles	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily
Lost Highway Productivity	Lost capacity due to flow breakdown – the difference between measured volumes on a freeway segment under congested flow versus the maximum capacity for that segment	Vehicles per hour	Section and area-wide	Peak hour, a.m./p.m. peak periods, midday, daily

(Source: *NCHRP Web-Only Document 97: Guide to Effective Freeway Performance Measurement: Final report and Guidebook*, page 23)

3.1.1.3 *FHWA Report: Traffic Analysis Toolbox Volume VI: Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness*

In *FHWA Report: Traffic Analysis Toolbox Volume VI: Definition, Interpretation, and Calculation of Measures of Effectiveness*, Dowling (2007) examined the current practice regarding the use and interpretation of commonly used performance metrics in traffic operations and capacity improvements. The study indicated that most existing performance measures are able to quantify uncongested traffic conditions in a satisfactory manner. Speed, though, is less insensitive to changing traffic flow rates when volumes are less than capacity. Under extremely congested conditions, most of the MOEs tend to break down. For example, speed and density are invariant under "parking lot" conditions. The only MOEs that continue to function under "parking lot" conditions are travel time and delay, which continue to increase over the length of the study period. This implies that incorporating performance metrics that can quantify the extent and duration of traffic congestion is essential. Seven basic performance measures, considered as the "building blocks" in most applications related to highway system performance evaluation, were summarized and presented. They are as follows: travel time, speed, delay, queue, stops, density and travel time variance. This report also confirmed the argument that incorporating multiple indicators in evaluating highway performance is necessary. Examples showing how to calculate and interpret the recommended system-wide MOEs for a freeway and an urban arterial street were also provided in the report.

3.1.1.4 *NCHRP Report 618: Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability*

NCHRP Report 618: Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability discussed the importance of incorporating travel time-based (TT-based) measures in evaluating transportation system mobility and reliability (Cambridge Systematics et al., 2008). The authors underlined the fact that TT-based measures are of special interests to the traveling public and elected decision-makers due to the following reasons: (1) TT-based measures are directly linked to travelers' route choice behavior; (2) TT-based performance measures can be easily related to everyday commuting experience and thus are readily understandable to the traveling public; and (3) By measuring TT-based system metrics, agencies will be able to plan and operate their systems to achieve the best result for a given level of investment.

The report also revealed the factors that may have significant influence on the selection of performance metrics, which include the purpose of the research program (e.g., problem identification vs. alternative comparison), time and budget restraints of the project, potential congestion solutions, and the types and formats of the available data set. A checklist, which specifies the factors that need to be considered during the process of metric selection, was presented as well. Finally, a total of eleven TT-based performance measures were listed and discussed in terms of the geographical scope they addressed (e.g., region, subarea, corridor, or section) and the congestion dimension they accounted for (duration, extent, intensity or reliability), as presented in Table 3-3. It is noteworthy that when evaluating the potential impacts of candidate bottleneck mitigation measures, performance measures related to route changes should be considered as well.

Table 3-3 Key Characteristics of Mobility and Reliability Measures

Performance Measure	Congestion Component Addressed	Geographic Area Addressed
Delay per Traveler	Intensity	Region, Subarea, Section, Corridor
Travel-Time Index	Intensity	Region, Subarea, Section, Corridor
Buffer Time Index	Intensity, Variability	Region, Subarea, Section, Corridor
Planning Time Index, Percent Variation	Intensity, Variability	Region, Subarea, Section, Corridor
Percent On-Time Arrival	Variability	Facility, Corridor, System
Total Delay	Intensity	Region, Subarea, Section, Corridor
Congested Travel	Extent, Intensity	Region, Subarea
Percent of Congested Travel	Duration, Extent, Intensity	Region, Subarea
Congested Roadway	Extent, Intensity	Region, Subarea
Misery Index	Intensity, Variability	Region, Subarea, Corridor
Accessibility	Extent, Intensity	Region, Subarea

(Source: *NCHRP Report 618: Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability*, page 18)

3.1.2 State DOTs' Experience

3.1.2.1 *Arizona*

Arizona DOT utilized TTI, PTI, percentage of congested corridor miles, and percentage of congested times (same as FOC in this report) to assess the performance levels along a freeway corridor of interest (AZTech™, 2012).

- TTI was defined as the ratio of the actual travel time to the free-flow travel time along a freeway corridor and was computed for both morning (6 a.m. to 9 a.m.) and evening peak periods (3 p.m. to 7 p.m.).
- PTI was defined as the ratio of the 95th percentile travel time to the free-flow travel time. This measure complements additional information about the degree of variability in travel time measures.

- Percentage of corridor miles congested was used to evaluate the extent of congestion by counting the number of congested freeway corridors during peak periods. A corridor segment was regarded as congested when the average vehicle speed dropped below 50 percent of the free-flow speed for more than four hours in a week.
- Percentage of time congested allowed researchers to gauge the duration dimension of traffic congestion.

3.1.2.2 *California*

The Caltrans *Mobility Performance Report (MPR) 2011* revealed the performance of the transportation system at both the district and state levels. The report presented congestion levels using archived volume and occupancy data extracted from the Caltrans Performance Measurement System (PeMS) database.

The main congestion measure reported by Caltrans was the vehicle hours of delay (VHD), which was defined as the additional travel time spent in traffic beyond what people would experience if they were traveling at a pre-defined benchmark speed. Two threshold speed values, 35 mph and 60 mph, which represent the speeds under heavy and light congestion conditions respectively, were selected as the benchmark values. In addition to that, vehicle miles of travel (VMT) and cost of congestion were also reported (Caltrans, 2014).

3.1.2.3 *Florida*

McLeod and Morgan (2012) presented a total of fifteen key mobility performance measures reported by Florida DOT. These metrics depicted operational performance of

Florida highways from four dimensions: quantity of travel, quality of service, accessibility, and capacity utilization.

- **Quantity dimension:** vehicle miles traveled, person miles traveled, truck miles traveled, and transit ridership;
- **Quality dimension:** average travel speed, vehicle delay, person delay, LOS, and travel time reliability;
- **Accessibility dimension:** proximity to major transportation hubs, percent of urban miles with sidewalks, and percent of urban miles with paved shoulders/bicycle lanes;
- **Capacity utilization:** vehicles per lane mile, percent of miles heavily congested, percent of travels heavily congested, and duration of congestion.

The primary travel time reliability measure employed by FDOT was the percent of on-time vehicle arrivals during the peak periods for the state's freeway system or various subcomponents of it. In this study, traffic conditions were declared congested when the roadway facility operated at LOS E or F. The mobility performance measures presented above were developed primarily for system level reporting and analysis.

3.1.2.4 *Indiana*

The operational performance of Indiana's state highway system was assessed using a variety of metrics based on traffic volume and speed data. As mentioned previously, the interstate highway performance measures consisted of 15-minute speed, congestion hours, distance-weighted congestion hours (weighted by the length of each segment), interstate speed profiles, 45 mph delay ($Delay_{45}$), total delay, and delta speed. In contrast, the performance of arterial roadways was evaluated using travel time-based metrics. The central tendency of travel times was expressed using average travel time and normalized average travel time (i.e., TTI); while the variability in travel times was quantified using the normalized travel time unreliability index (computed by taking the standard deviation of travel times over the analysis period and then dividing it by the travel time at speed limit). The most congested and most unreliable arterial segments within the study area were ranked based on the indices developed (Day et al., 2014).

3.1.2.5 *Kentucky*

Chen et al. (2015) evaluated the usage of probe vehicle speed data purchased from private vendors in generating travel time-based performance measures in assessing Kentucky's highway network. Highway performance metrics developed in this study included:

- Average a.m. peak speeds for (6-9 a.m.) and p.m. (3-6 p.m.) periods
- Travel time index for a.m. and p.m. periods by direction
- Planning time index for a.m. and p.m. periods by direction
- Buffer time index for a.m. and p.m. periods by direction
- Annual vehicle miles traveled (VMT) under congested conditions
- Annual vehicle hours traveled (VHT) under congested conditions
- Annual vehicle hours of delay

Restricted by the large amount of network links and the differences in the network geo-coding across multiple years, highway performances were compared at the area level by aggregating link-based measures into regional ones. The weighting factor utilized was vehicle-miles traveled (VMT). The final results indicated that the variability in travel time for the average users during peak periods decreased. However, considering the slight increase in congestion (measured by TTI), it was concluded that travel time in the analysis areas had become consistently longer.

3.1.2.6 *Minnesota*

The *Metropolitan Freeway System 2014 Congestion Report*, prepared by the Minnesota Metro District Office of Operations and Maintenance and Regional Transportation Management Center (RTMC), chose the percentage of congested freeway miles as the MOE to identify and document congestion along the Twin Cities urban freeway system (Minnesota RTMC, 2015). Congestion was identified and recorded when traffic speeds fell below 45 mph. Instead of using average speed, MnDOT chose median speed within each five-minute interval to determine the level of congestion. The analyses were performed for both morning (5 a.m. to 10 a.m.) and evening peak periods (2 p.m. to 7 p.m.).

3.1.2.7 *Oregon*

In Oregon DOT's *Operations Performance Measurement (Final Report)*, Eisele and Lomax (2004) identified a set of mobility performance measures to serve the needs of evaluating and monitoring roadway performances. Such performance measures included TTI, delay, BTI, V/C ratio, travel time, and travel speed. These measures were also applied to urban freeways, rural highways, and signalized arterial segments. All these measures can also be weighted by VMTs at the corridor, regional and/or state level.

3.1.2.8 *Texas*

Duthie et al. (2013) evaluated the impacts of geometric reconfigurations on the MoPac Expressway using several performance measures. Travel times, vehicular counts, and route choice behaviors were compared between the pre- and post-reconfiguration scenarios of the study area.

3.1.2.9 *Virginia*

Virginia DOT utilized an online dashboard platform to monitor, evaluate, and present performance measures to increase public awareness of the conditions of the transportation system and through that, increase VDOT's accountability to their stakeholders. VDOT's dashboard congestion measures included (Styles, 2013):

- Percentage of traffic flows traveling at various congestion levels (good, fair, and poor) were determined based on LOS. LOS A-C translated to good/green, LOS D&E to moderate/yellow, and LOS F to poor/red.
- Traffic speeds on HOV lanes. The percentage of vehicles traveling at 45 mph or below were calculated as well.
- Travel time on key interstate routes. Travel times for selected interstate routes were displayed during peak times.
- Incident duration - how long it took to clear an unplanned traffic event.
- Hours of delay - how many hours of extra travel time were experienced by travelers during peak periods within the year.

3.1.2.10 *Wyoming*

In order to assist travelers to more accurately assess real-time traffic conditions on Wyoming's rural interstate highways, Milliken and Young (2015) examined the potential benefits of reporting travel time-related metrics to the traveling public. A total of three indices were selected to gauge traffic conditions on rural interstates - travel time, average speed, and the travel time index number. In particular, a set of integers were set to represent different levels of travel time needed to traverse a roadway segment. For example, 0 corresponds to travel time ≤ 40 minutes and 1 represents travel time falling in between 40 and 55 minutes. The results suggested that reporting travel time indices (e.g., travel time or travel time index number) along with the current roadway condition (e.g., "slick in spots") could help travelers better assess traffic conditions.

3.2 Determining Performance Measures

3.2.1 Basic Principles

Based on the experience reviewed in Section 3.1, one can clearly see that the following principles should be considered in selecting performance metrics in the present study.

(1) The purpose of this dissertation is to discern freeway bottlenecks, rank the bottlenecks and compare various candidate mitigation strategies. The selected performance metrics should be able to achieve these goals.

(2) Multiple performance metrics are needed to quantify different dimensions of traffic congestion, which could/should include duration, extent, intensity and reliability.

(3) The proposed congestion mitigation strategy may directly affect travelers' route-choice behavior. Therefore, the selected MOEs should be able to capture traffic flow changes at various geographic scales: the segment level, the corridor/trip level, and area-wide.

(4) Travel time-based indices will be developed and applied as key performance metrics since they are gaining increasing interests from both researchers and practitioners. Aside from that, they are directly linked to travelers' route-choice behaviors and daily commuting experiences, and therefore, are readily acceptable to the traveling public and the elected decision-makers.

(5) HCM-based performance measures (V/C ratio and LOS) were considered as well, however, they should only serve as supplementary measures of performance. This is because:

- Either traffic volume or density remains invariant under extremely congested conditions. The V/C ratio and LOS are incapable of capturing congestion duration or intensity in this case.
- In identifying and ranking freeway bottlenecks, the present study mainly uses vehicle probe data obtained from INRIX. The dataset contains information regarding travel speeds and travel times at each TMC, while traffic volume and density related information is not included. Therefore, volume or density related metrics will not be applied during the stages of bottleneck identification and ranking. Instead, these HCM-based metrics can be obtained from the simulation software (i.e., DTALite) and will be used for the purpose of mitigation alternatives comparison.

(6) The selected MOEs should be acceptable to both the technical and non-technical audiences.

Table 3-4 shows the MOEs determined for the present study, as well as the definitions, units, and application scenarios (bottleneck identification, bottleneck ranking, and bottleneck mitigation alternatives evaluation). More detailed discussions about each performance metric are provided below.

3.2.2 Freeway Performance Measures

3.2.2.1 *Average Speed*

As mentioned in the FHWA report, travel speed is a building block performance measure used in most highway performance evaluations (Dowling, 2006). In this dissertation, the aggregated travel speed of each individual TMC i during interval t (denoted as V_{it}) is mainly used for bottleneck identification and ranking purposes. This value is obtained directly from INRIX.

3.2.2.2 *Travel Time*

Similar to travel speed, travel time is also a basic metric which can be used in determining all travel time-based performance measures, such as TTI or PTI. The link travel time data is also required from INRIX. Although travel time can be aggregated at the system level, in this study we mainly use travel time to assess traffic conditions on a segment, corridor or for a given O-D pair.

3.2.2.3 *V/C Ratio*

The V/C ratio is a conventional level-of-service measure for roadways, comparing roadway demand (vehicle volumes) with roadway supply (carrying capacity). The V/C ratio is still used in many agencies for planning and operations purposes, though it is not as widespread as it might have been ten years before (Margiotta et al., 2006). For consistency, it is employed as a secondary performance metric in an alternative comparison process. This measure can alert transportation providers to areas where traffic mitigation measures should be considered.

3.2.2.4 *Travel Time Index*

The travel time index (TTI) is a dimensionless quantity that compares travel conditions during the peak periods to the free-flow or posted speed limit conditions. It considers the peak-hour periods during the non-holiday weekdays and measures separately for (morning) inbound and (evening) outbound traffic. The TTI can be quickly and easily interpreted by most users in either an absolute sense (e.g., a TTI of 1.2 means that a free-flow 20-minute trip will take 24 minutes) or a relative sense (the trip will take 20 percent longer).

3.2.2.5 *Congested Hours*

This measure represents the total amount of time during the peak period when a TMC is operating under congested conditions in which the average speed on a TMC segment falls below a pre-determined reference speed.

3.2.2.6 *Frequency of Congestion*

This measures the percentage of time when the traffic operation on a roadway segment is considered as congested, i.e., when the travel speed is less than the reference speed. Since the FOC indicator counts the number of intervals when the travel speed is below a threshold speed value across multiple days, it is able to describe the reliability dimension of traffic conditions. Similar to the "congested hours" indicator, the FOC gauges the duration dimension of traffic congestion as well.

Table 3-4 Summary of Measures of Effectiveness (MOEs)

ID	Performance Metric	Definition	Units	Congestion Dimension	Geographic Scale	Problem Identification	Bottleneck Ranking	Alternatives Evaluating
1	Average Speed	The average speed consumed by vehicles traversing a given link, corridor, or between an O-D pair	mph	Intensity	Segment, Corridor	+	+	+
2	Travel Time	The average time to traverse a fixed distance of freeway	minutes	Intensity	Segment, Corridor	+	+	+
3	V/C Ratio	The ratio pf the roadway demand (vehicle volumes) to roadway supply (capacity)	none	Intensity	Segment, Corridor, Region	+		+
4	Travel Time Index	The ratio of the average travel time to the free-flow travel time along a freeway segment or corridor	none[2]	Intensity	Segment, Corridor	+	+	
5	Congested Hours	Hours a facility operates under the specified reference speed	hours	Duration	Segment, Corridor	+	+	
6	Frequency of Congestion	The percentage of time that travel speeds fall below the reference speed during the analysis period	%	Reliability, Duration	Segment, Corridor	+	+	
7	Route Volume Changes	The changes in the number of vehicles traveling from an origin to a destination using a specific route	%	Extent	Corridor			+
8	Planning Time Index	The ratio of the 95^{th} (or 80^{th}) percentile travel time to the free-flow travel time along a freeway segment or corridor	none[1]	Reliability	Segment, Corridor	+	+	
9	Buffer Time Index	The difference between the 95th (or 80th) percentile travel time and the average travel time, normalized by the average travel time.	none	Reliability	Segment, Corridor	+		
10	Coefficient of Variation	The standard deviation of travel time during the analysis period normalized by the average travel time	none	Reliability	Segment, Corridor	+		

Note: [1] The minimum value is 1.0.

3.2.2.7 *Route Volume Changes*

Usually, for a given O-D pair in the network, there are several routes available for travelers. The route volume changes index enables researchers and practitioners to determine the influence of congestion mitigation solutions on travelers' route choices during peak periods. Note that traffic volumes on a specific route of interest can be extracted from the simulation outputs.

3.2.2.8 *Planning Time Index*

The planning time index (PTI) is another travel time-based reliability metric. It represents how much total time a traveler should allow to ensure on-time arrivals. For example, a planning time index of 1.5 means that for a 30-minute trip in light traffic, one should plan for a 45-minute trip (30 minutes × 1.5 = 45 minutes). In this study, the PTI is used as a primary index of congestion reliability. An increased PTI implies a greater degree of variability in traffic, which generally translates to lower travel time reliability for the commuters. The degree of variation in travel time can be influenced by fluctuating demands and frequency and magnitude of recurring and non-recurring congestion.

3.2.2.9 *Buffer Time Index*

The buffer time index (BTI) is also a widely used reliability measure and is computed as the difference between the 95th (or 80th) percentile travel time and the average travel time, normalized by the average travel time.

3.2.2.10 *Coefficient of Variation*

The coefficient of variation (CV) is computed by taking the standard deviation of travel times during the analysis period and normalizing the standard deviation by the average travel time. A value of zero would indicate a travel time that is always perfectly constant, while a higher CV value implies a greater spread in travel times. In this study, both the BTI and CV can serve as a reliability measure of congestion and their effectiveness in locating and ranking freeway bottlenecks will be carefully examined in Chapter 4.

3.3 Summary

Detailed discussions about the significance of measures of effectiveness (MOEs) in highway performance evaluation, bottleneck identification, ranking and mitigation alternatives comparison, were presented. By reviewing previous experience in selecting measures at both federal and state levels, several basic principles in selection performance measures were synthesized and were used as guides of MOE selection in this study. Finally, a total of ten MOEs were chosen for possible applications in future tasks. The selected MOEs, which quantify traffic congestion/mobility at different geographic scopes (at the section, corridor/trip and network levels) and various dimensions (duration, extent, intensity, reliability) were presented in detail.

CHAPTER 4: DEVELOPING A SYSTEMATIC METHODOLOGY TO IDENTIFY BOTTLENECKS ON FREEWAYS

Freeway congestion continues to be a critical transportation concern in many metropolitan areas and small cities. According to the *2015 Urban Mobility Scorecard* (Schrank et al., 2015), on average, every auto commuter in Charlotte and Raleigh, North Carolina, spent an extra 43 and 34 hours traveling in 2014, respectively. Many congestion issues that impact NC drivers on a daily basis can be traced back to a bottleneck, be it stationary or moving. Developing an effective approach to identifying and ranking freeway bottlenecks is essential for locating congestion "hotspots" and allocating capital resources to address congestion-related issues.

In general, an integral bottleneck treatment plan should consist of four primary components: (1) locating recurrent freeway bottlenecks, (2) ranking each bottleneck, (3) developing effective bottleneck mitigation strategies, and (4) evaluating system performance before and after the implementation of the bottleneck improvement projects. Among them, developing an effective and systematic approach to locating and prioritizing freeway bottlenecks is of utmost importance which can lay a solid foundation for the next two steps. In this dissertation, the following factors are taken into account when developing a systematic bottleneck identification and ranking method:

- **Extended scope of application.** Previously, most of the bottleneck identification methods were designed and applied at the corridor level due to data collection restrictions. Unlike such methods, the current approach extends the application scope to the network level by using vehicle probe data collected on multiple interstate freeways in the study area. By doing so, it provides decision-makers a holistic view to make informed decisions through comparing traffic conditions within and across corridors.

- **Easy calculation and interpretation.** The proposed methodology employs travel time-based performance measures to locate and prioritize recurrent freeway bottlenecks, which are relatively easy to calculate compared to other performance measures. In the meantime, these travel time-based MOEs can be easily related to everyday commuting experience and thus are readily understandable to the traveling public.
- **Ability to account for multiple dimensions of traffic congestion.** As discussed in Chapter 3, it is impossible to describe all of the travelers' concerns about traffic congestion with a single MOE. Instead, combining multiple performance metrics that capture various dimensions of traffic congestion in the bottleneck identification and ranking process seems to be necessary. The effectiveness of using various MOEs to identify and rank recurrent freeway bottlenecks will be evaluated in this section.

After ranking each bottleneck, this dissertation would also like to reveal more detailed information related to traffic flow dynamics in the vicinity of the bottleneck location, including the start time, duration, location, length, and variations in all these features of a bottleneck across multiple days. Such information would be beneficial to determine the potential causes associated with each bottleneck and develop corresponding mitigation strategies in subsequent tasks.

The remainder of this chapter is structured as follows. Section 4.1 elaborates detailed features of traffic datasets aggregated at different levels. Section 4.2 presents and evaluates two methodological frameworks aiming at identifying and ranking recurrent freeway bottlenecks for planning applications. A comparative bottleneck identification framework based on vehicle probe data aggregated across multiple days is depicted in Section 4.3, followed by an innovative image processing approach that can extract daily variation in bottleneck features (e.g., start time and duration) through manipulating the disaggregated vehicle probe data in Section 4.4. Discussions on how to use the identification results in further engineering studies, such as determining the potential causes of a bottleneck, will be presented in the next chapter.

4.1 Aggregation Levels of Vehicle Probe Data

The primary purpose of this section is to discuss how traffic data aggregated at different levels of detail are applied to analyze traffic flow dynamics and to locate and prioritize recurrent freeway bottlenecks. Note that this section presents the general idea about how to apply MOEs aggregated at different levels to diagnose freeway bottlenecks. Detailed information about the definitions and calculations of relevant parameters will be elaborated later in Section 4.2.

4.1.1 Disaggregated Spatiotemporal Dataset

Generally, the spatiotemporal dataset contains traffic data (e.g., travel speeds) collected along multiple roadway segments and across multiple days. Regardless of whether the data are obtained from fixed loop detectors or through vehicle probe technology, such data can be organized into a three-dimensional matrix structure, as shown in Figure 4-1. The three-dimensions are the study section of the facility, the study period of the day, and the analysis day of interest for data reporting, respectively. Such data structure provides researchers a straightforward and intuitive manner to investigate when and how traffic congestion forms, propagates, and dissipates on a freeway facility. Since such dataset is constructed based on the original dataset granularity (i.e., 5-minute or 15-minute) as obtained from the data vendor and no further data aggregation operations have been applied, for convenience purpose, this kind of data structure is referred to as "disaggregated dataset" in this report even though each raw data point is actually computed by aggregating a certain amount of data points measured in the field within each 5-minute or 15-minute interval.

In Figure 4-1, each data panel is comprised of traffic data collected during a specific analysis day and each cell represents the travel speed observed during each analysis time period of an analysis roadway segment. A variety of detailed information with respect to each dimension of traffic congestion can be extracted from Figure 4-1: the beginning and ending time of traffic congestion (*duration dimension*), the roadway length under the influence of traffic congestion (*extent dimension*), the magnitude of travel speeds on each TMC (*intensity dimension*), and the variations in those indexes across multiple days (*reliability dimension, a.k.a., day-to-day dimension*). Although the disaggregated dataset provides the greatest level of detail about each bottleneck, identifying and ranking recurrent freeway bottleneck directly using such data structure also involves dealing with a large dataset and the analysis process may be computationally demanding. For example, if one assumes the study network consists of 324 TMCs (as shown later in the case study in Section 4.2.3) and the study period lasts one year, then the total number of data records would be 34,058,880 if the time granularity is 5-minute (324 TMCs × 12 intervals/hour × 24 hours/day × 365 days = 34,058,880). The total amount of data observations would still be greater than 10 million even if a 15-minute data aggregation interval is applied, let alone a larger network which may consist of thousands of TMC segments. Therefore, a certain level of data aggregation manipulations will be necessary in that it will greatly help reduce the computational complexity and accelerate the bottleneck identification and ranking process. Depending on the research purposes, the following two levels of data aggregation could be applied in this dissertation.

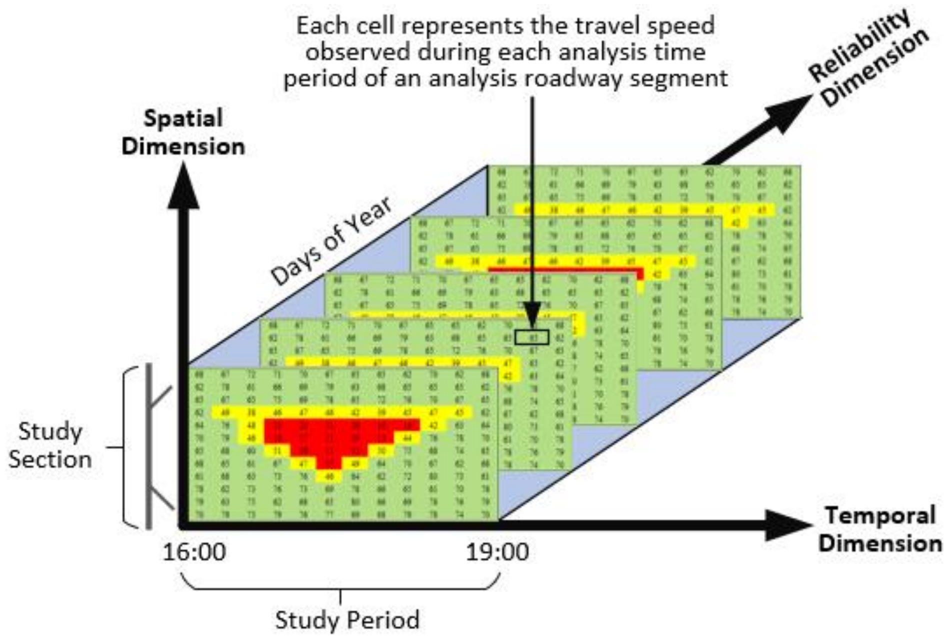


Figure 4-1 Three Dimensions of Traffic Data

4.1.2 Aggregating Traffic Data along the Reliability Dimension

Aggregating the data panels in Figure 4-1 along the depth axis (i.e., reliability dimension) provides a convenient way to inspect the average spatiotemporal influence of traffic congestion along a facility over a period of time (e.g., a month or a year). As an example, each cell in Figure 4-2 represents the arithmetic mean of the travel speeds observed in one analysis period (e.g., 16:00-16:15) of a study segment across multiple days. As one can see in Figure 4-2, on average, traffic flow breaks down at about 16:15 on segment 4 along the analysis freeway corridor. Traffic congestion generally propagates to five segments upstream of the bottleneck and can last for about two hours. Note that some original information in the three-dimensional matrix will get lost during the aggregation process. For instance, in Figure 4-2, information about how the congestion region varies in time and space from day to day is not shown during the aggregation process. Thus, striking a good balance between the computational complexity and data fidelity is an important consideration when developing a bottleneck identification and ranking algorithm. In this study, the two-dimensional aggregated data structure is used as a supplementary bottleneck identification approach which provides a comparative way to validate the effectiveness of the primary method (as presented later in Section 4.3). When aggregating speed observations collected on multiple days, other than the average speed, other MOEs (such as FOC and PTI) could also be developed.

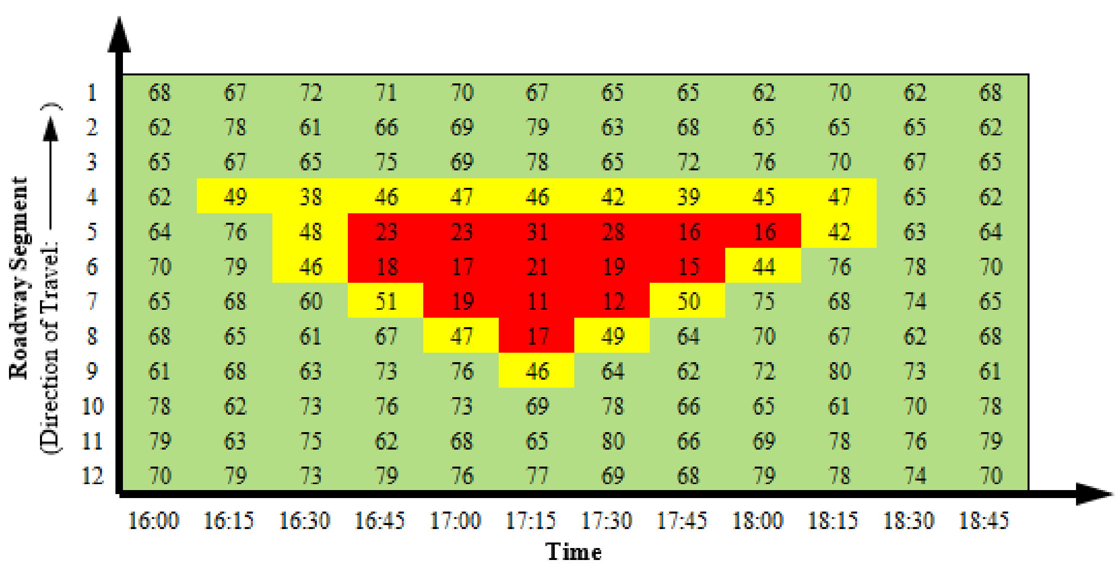


Figure 4-2 Two-Dimensional Aggregated Spatiotemporal Data Structure

4.1.3 Aggregating Traffic Data along Reliability and Temporal Dimensions

The original three-dimensional data structure can also be aggregated along both the reliability dimension (i.e., day-to-day dimension) and temporal dimension (i.e., within-day dimension). Specifically, a performance measure can be developed for each roadway segment by using and aggregating all data observations collected within the time intervals of interest (e.g., 4 p.m. to 7 p.m.) across the entire analysis time period (e.g., a month). Such aggregated indicators may include, but are not limited to, the average travel time, average speed, FOC, PTI, and TTI.

Figure 4-3 provides an example of the FOC indicator along the outer loop of interstate highway I-485 in Mecklenburg County, North Carolina. In Figure 4-3, each FOC value is calculated on each roadway segment by comparing all speed observations collected against the reference speed between 4 p.m. to 7 p.m. across all of the non-holiday weekdays in May 2015. Based on the information presented in Figure 4-3, one can easily determine those roadway segments which routinely experience traffic congestion during peak periods (i.e., recurrent freeway bottlenecks). For similar reasons, a fraction of raw information is left out during the aggregation process relative to original disaggregated three-dimensional data matrix. To address this issue, this dissertation employs multiple performance measures to quantify various dimensions of traffic congestion. Details about the solutions are presented in Section 4.2.2.

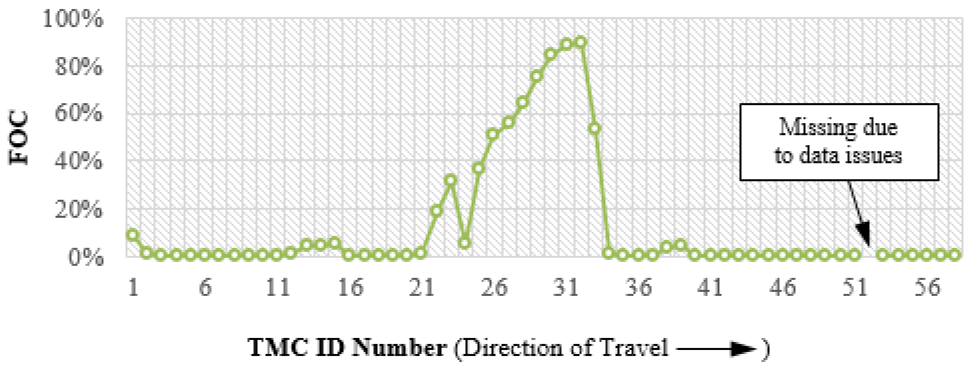


Figure 4-3 Frequency of Congestion on I-485 NB, Mecklenburg County, NC

In summary, each data aggregation level has its strengths and weaknesses and none of them provides a one-size-fits-all approach to studying recurrent freeway bottlenecks. Specifically, the original data matrix contains the richest information about traffic conditions existing along multiple road facilities across multiple days. However, it also involves the highest level of computational complexity. Thus, such data structure is suited for precisely describing bottleneck features at the operational level. In contrast, using traffic data aggregated across different time periods and across multiple days will greatly help reduce the computational burdens and enable both transportation practitioners and decision-makers to quickly locate congested freeway segments at the planning level, which is achieved at the expense of scarifying certain levels of data fidelity. The data format obtained by aggregating the raw data along the reliability dimension could only be viewed as an intermediate data aggregation level between the above two levels. In this dissertation, the author combines data structures at different levels of detail to develop a systematic toolkit to meet NCDOT engineers' needs of freeway bottleneck analyses at different levels. More specifically,

- A freeway bottleneck identification and ranking method is developed based on the data structure aggregated at the highest level. This provides an efficient and straightforward manner to quickly reveal congestion hotspots at the planning level. During the process, a number of travel-time-based MOEs are calculated, evaluated and compared in terms of their feasibility and effectiveness in locating and prioritizing recurrent freeway bottlenecks. Finally, a combination of the MOEs that yields the best performance is recommended as the primary bottleneck identification and ranking method developed and used in this dissertation.
- A complementary bottleneck identification approach is developed based on the two-dimensional aggregated spatiotemporal data structure. Comparisons of the bottleneck identification results obtained between the primary and complementary methods can help validate the effectiveness of the recommended approach.
- After the bottleneck identification and ranking process, detailed information concerning those top-ranked bottlenecks is also examined, including the bottleneck activation time, duration, bottleneck location, and length of its influential zone, etc. Thoroughly examining the daily patterns of the bottlenecks will greatly empower transportation researchers and practitioners to accurately determine the potential causes associated with each bottleneck and to better develop targeting bottleneck mitigation solutions at the operational level.

4.2 Bottleneck Identification and Ranking Methods at the Planning Level

The following sections examine two methodological frameworks that are developed and can be applied to identify and rank recurrent freeway bottlenecks. The major difference between these two approaches is that the first method adopts only travel time reliability (TTR) measures to fulfill the goal of this task, while the second approach utilizes a combination of both intensity and reliability measures. By comparing these two methods, the one that better achieves the goal of this task will be recommended.

4.2.1 Using Travel Time Reliability (TTR) Measures Only

4.2.1.1 *Selection of TTR measures for freeway bottleneck identification and ranking*

Although traffic congestion can be quantified from the following dimensions: duration, extent, intensity and reliability (Lomax et al., 1997), TTR measures have only recently been increasingly encouraged by FHWA for use to manage and operate transportation systems (Dowling et al., 2015). Previous research has led to the employment of various TTR measures to assist in highway performance evaluation and congestion management, such as the buffer time index (BTI), misery index (MI), coefficient of variation (CV), skew of travel time distribution, planning time index (PTI), and frequency of congestion (FOC). In this study, four reliability measures, FOC, PTI, BTI and CV, are selected during the first round as they have been widely used in previous studies (e.g., CDM Smith, 2014; Brennan et al., 2015; Wolniak and Mahapatra, 2014; Saberi and Bertini, 2010; Remias et al., 2014; Day et al., 2014). However, the calculation of BTI and CV relies on the average travel time (see Eq. 4-1 and Eq. 4-2 below), which may change over time due to variations in travel demand, road work activities and seasonal factors (Elefteriadou and Cui, 2005).

$$BTI_i = \frac{T_{i95} - \bar{T}_i}{\bar{T}_i} \left(or\ BTI = \frac{T_{i80} - \bar{T}_i}{\bar{T}_i} \right) \qquad \text{Eq. 4-1}$$

$$CV_i = \frac{1}{\bar{T}_i} \sqrt{\frac{1}{N} \sum_t (T_{it} - \bar{T}_i\ )^2} \qquad \text{Eq. 4-2}$$

where

T_{i95} (T_{i80}) = 95th (80th) percentile travel time on the TMC segment i during the study period (e.g., a.m. peak) across multiple days (e.g., a month),

$\bar{T}_i$ = average travel time on TMC i during the same observation period as mentioned above,

T_{it} = travel time observed on TMC i during time interval t, and

N = number of observations.

For instance, for the same TMC segment, the average travel time in January (winter season) may differ from that in July (summer season). Even in the same month, the average travel time on a roadway segment during morning rush hours usually differs from the one during evening rush hours, especially for commuting rural highways (HCM, 2010). Due to such dynamic and always-changing nature of the benchmark which is utilized to construct BTI and CV, both metrics do not allow the consistent tracking of reliability performances for a given facility over time. Hence, in this study, only FOC and PTI values are calculated for each TMC and each month. These values will be used in the following bottleneck identification and ranking process.

4.2.1.2 *Identifying and ranking freeway bottlenecks based on FOC*

(1) *Definition of FOC*

The FOC is a simple and straightforward measure of travel time reliability. It represents the percentage of travel times exceeding a threshold value; or equivalently, the percentage of travel speeds less than the reference speed. During each observation interval t, a binary variable δ_{itm} is created to label traffic status along a TMC segment i:

$$\delta_{itm} = \begin{cases} 1 & V_{itm} < V_{iR} \\ 0 & V_{itm} \geq V_{iR} \end{cases} \qquad \text{Eq. 4-3}$$

where

V_{itm} = travel speed collected on TMC segment i during time t in the m-th month, and

V_{iR} = reference speed on TMC i.

δ_{itm} = 1 means TMC segment i is congested during time t, and 0 otherwise. According to Brennan et al. (2015), the use of a fixed reference speed for all TMC segments does not account for discrepancies in the road geometry, posted speed limits, local driver behaviors, or other factors that can contribute to the variations in speed. Therefore, in this study, each TMC segment is assigned a congestion threshold based on the 85th percentile of the 5-minute speed observations collected during low volume hours (which is also known as the free-flow speed on a roadway segment, denoted as FFS_i). In previous studies, several percentage threshold values of the free-flow speed were proposed to identify congested conditions. For example, Florida DOT defined V_{iR} as 75 percent of FFS_i (FDOT, 2011); while in another study conducted by Washington State DOT, traffic status was evaluated using two speed thresholds (i.e., 60- and 75- percent of FFS_i) separately (Peterson, 2014). In order to investigate the impact of using different congestion threshold values on bottleneck identification and ranking outcomes, both threshold values (i.e., 60- and 75- percent of FFS_i) are examined in this study. For a roadway segment with a speed limit of 65 mph, these two thresholds define a speed range between 39 mph and 48.75 mph. Such range also covers the fixed speed threshold of 45 mph which was used in Day et al. (2014).

When travel speed are observed at 5-minute intervals, the FOC is calculated as:

$$FOC_{im} = \frac{1}{12T}\sum_{t \in T} \delta_{itm} \times 100\% \qquad \text{Eq. 4-4}$$

where

T = the time periods of interest in month m, in hours.

Considering the fact that traffic flow may exhibit directional characteristics during a.m. and p.m. peak periods, this study computes FOC values for three analysis periods separately: a.m. peak, p.m. peak, a.m. and p.m. peak. Specifically, for each peak period, the indicator is calculated for each segment by aggregating all travel speeds occurred during that time period across all non-holiday weekdays in each month. This is necessary especially in the bottleneck ranking procedure because roadway segments that are congested during both peak times negatively affect more travelers compared to those that are congested only during either a.m. or p.m. peak period. As such, these TMCs certainly deserve higher priority in the bottleneck ranking and mitigating process.

(2) *Bottleneck Identification*

Using the FOC values as calculated above, recurrent freeway bottlenecks during different peak periods will be identified. During each peak time period, all TMC segments will be ranked from highest to lowest based on the sum of their FOC values of each month within the entire study period (e.g., one year). Note that only a user-specified or pre-determined set of the most congested TMC segments (e.g., Top 30) are selected as recurrent freeway bottlenecks of interest for the study. The determination of such set is based on the literature review results and engineering judgment. In a previous study carried out by Arizona DOT (AZTechTM, 2012), a congested segment was declared when the average vehicle speed drops below a half of the free-flow speed for more than four hours in a week. In their study, the a.m. and p.m. peak periods were defined as 6 a.m. to 9 a.m. and 3 p.m. to 7 p.m., respectively, and the corresponding FOC values are 20% and 26.7%. In another bottleneck study conducted by FDOT, they used 75 percent of the free-flow speed as the threshold value to declare congested roadway conditions; and the portions of the roadway network with FOC greater than 40 percent were identified as congested roadways (FDOT, 2011). Based on the synthesis of all pertinent information, this study defines the top 30 congested TMC segments as recurrent freeway bottlenecks of interest. Under such definition, the FOC ranges calculated for the top 30 TMCs based on the 60% and 75% of FFS_i are 21.3%-76.7% and 31.1%-82.8% respectively, which are generally consistent with the research findings from previous studies. The detailed information about the identification results will be discussed later in Section 4.2.3.4.

(3) *Bottleneck Ranking*

As stated earlier, a complete bottleneck analysis procedure includes four aspects: identifying bottlenecks, ranking bottlenecks, developing mitigation strategies, and evaluating the effectiveness of bottleneck mitigation projects. When ranking the bottlenecks in this study, rather than focusing on a single TMC segment, adjacent TMC segments are combined as a group. This is necessary because traffic congestion on consecutive segments could be resulted from the same contributing factor (e.g., due to a single lane drop) and ranking the bottlenecks this way based on groups can greatly help develop and assess relevant bottleneck mitigation measures in a more objective and holistic manner in the future.

Let I_k denote the set of roadway segments incorporated in the combined bottleneck group k (BG_k for short). While using FOC as the reliability index, the group ranking index ($R_{BG_{k}\_FOC}$) for the morning or evening peak period is computed as:

$$R_{BG_{k}\_FOC} = \sum_{i \in I_k} \left(\sum_{m=1}^{M} FOC_{im} \right) \times VKT_i \qquad \text{Eq. 4-5}$$

where

FOC_{im} = FOC value of the i-th TMC segment in the bottleneck group during the m-th month of the study period, and

M = number of months within the study period. For example, if a one-year period of vehicle probe dataset is employed (as is in the case study in Section 4.2.3), then M = 12.

VKT_i is the vehicle kilometers traveled (VKT) on road segment i and is estimated as follows:

$$VKT_i = AADT_i \times L_i \times D_i \qquad \text{Eq. 4-6}$$

where

$AADT_i$ = average annual daily traffic volume on segment i in a given year (e.g., 2015),

L_i = length of segment i,

D_i = proportion of traffic moving in the peak direction of travel on a given roadway during the peak hours. During a.m. or p.m. peak period, D_i is assumed to be 0.6 for all peak directions of travel.

For the combined a.m. and p.m. peak periods, the group ranking index is calculated as the sum of the weighted FOC values during both a.m. and a.m. peak periods. A step-by-step bottleneck identification and ranking procedure based on FOC is exhibited in Figure 4-4.

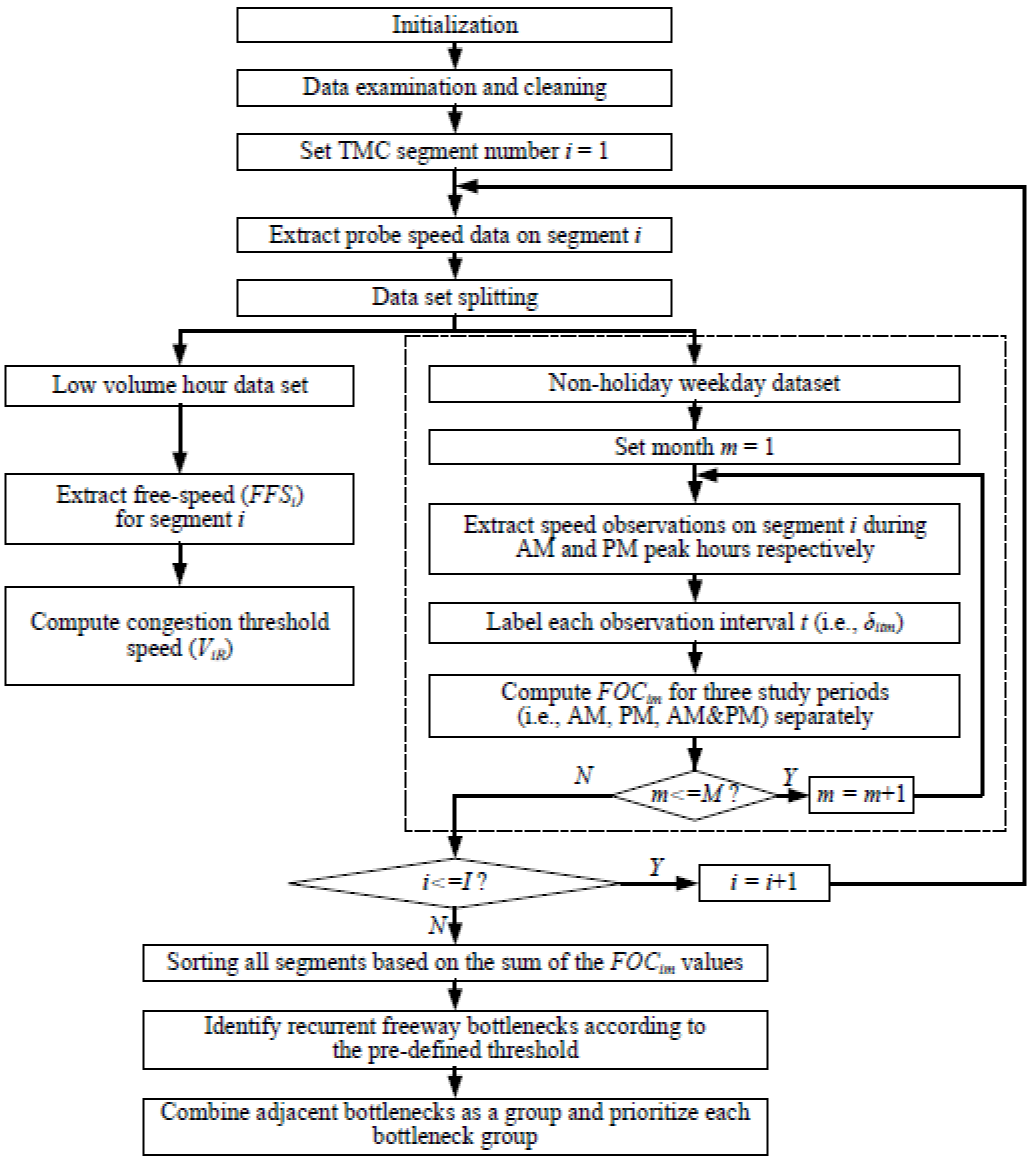


Figure 4-4 Bottleneck Identification and Ranking Framework Using FOC

4.2.1.3 *Identifying and ranking freeway bottlenecks based on PTI*

(1) *Definition of PTI*

The PTI is also a widely used reliability measure. It represents the extra time a traveler should budget in addition to the free-flow travel time to ensure 80 (or 95) percent on-time arrivals. Unlike BTI, the PTI is defined based on the free-flow travel time and uses a fixed benchmark for tracking roadway performances over time. Eq. 4-7 provides the calculation of PTI:

$$PTI_i = \frac{T_{i80}}{FFTT_i} \left(or\ PTI_i = \frac{T_{i95}}{FFTT_i} \right) \qquad \text{Eq. 4-7}$$

where $FFTT_i$ is the free-flow travel time associated with TMC i and is computed as the ratio of the link length to the free-flow speed:

$$FFTT_i = \frac{L_i}{FFS_i} \qquad \text{Eq. 4-8}$$

where

L_i = length of the TMC i (in miles), and

FFS_i = free-flow speed on TMC i.

Note that both threshold values (i.e., 80th and 95th percentile travel times) have been found in previous studies in defining PTI (e.g., FDOT, 2011; Wolniak and Mahapatra, 2014) and both are examined in this research. Similar to FOC, two PTI values during different peak times are computed for each TMC segment and each month.

(2) *Bottleneck Identification*

Previously, FDOT flagged congested conditions when the PTI (based on T_{80}) is greater than 3.0 for freeways (FDOT, 2011). Wolniak and Mahapatra (2014) considered a TMC segment extremely unreliable when its PTI (based on T_{95}) is greater than 2.5. To be consistent, the top 30 most congested TMC segments are defined as recurrent freeway bottlenecks of interest in this study. The PTI ranges calculated based on T_{80} and T_{95} are

2.4-7.1 and 3.1-9.4 respectively, which are generally in line with previous studies. While using the PTI to identify recurrent freeway bottlenecks, the following steps can be followed (using the a.m. peak as an example):

- **STEP 1:** Apply Eq. 4-7 and Eq. 4-8 to compute the monthly PTI values for all TMC segments by using vehicle probe data collected during a.m. peak hours within each month.
- **STEP 2:** Summarize the PTI values of a TMC segment across all months in the study period and then sorting the summarized PTI values in a descending order.
- **STEP 3:** Select a user-specified amount of TMCs as recurrent freeway bottlenecks of interest.

(3) *Bottleneck Ranking*

Likewise, the ranking procedure based on PTI is developed for each bottleneck group, rather than focusing on individual TMC segments. In ranking bottleneck groups, each congested roadway segment is weighed by its VKT:

$$R_{BG_k\_PTI} = \sum_{i \in I_k} \left(\sum_{m=1}^{M} PTI_{im} \right) \times VKT_i \qquad \text{Eq. 4-9}$$

where

PTI_{im} = PTI value of the i-th TMC during the m-th month of the study period.

All other terms are same or similar as previously defined.

4.2.1.4 *Limitations of using TTR Measures only to discern recurrent freeway bottlenecks*

The major limitation of employing reliability measures alone to discern and rank freeway bottlenecks is that neither FOC nor PTI accounts for the intensity dimension of congestion. For example, using FOC only reveals the percentage of travel times that exceed the threshold, however, information about the extent of travel times deviating from the threshold value is not conveyed. In terms of PTI, it only captures the 80th (or 95th) percentile of the travel time distribution on roadway segments, while other magnitude-related statistics of the travel time distribution (e.g., the mean or the median of the travel time distribution) is not reflected. It is very likely that the 80th (or 95th) percentile travel times of two TMC segments are nearly identical, but their average travel times could differ a lot, as illustrated later in Section 4.2.3.4. Therefore, using only TTR measures to discern and prioritize freeway bottlenecks may provide incomplete and sometime even misleading results. The following section provides a solution to this problem by integrating both reliability and intensity measures in the bottleneck identification and ranking framework.

4.2.2 Using Both Reliability and Intensity Measures

(1) *Definition of TTI*

This section employs the travel time index (TTI) to gauge the intensity dimension of traffic congestion. It is a dimensionless quantity that compares the average travel time during peak hours to the free-flow time, as formulated in Eq. 4-10. Note that, for each month, only non-holiday weekdays are considered and used in determining the TTI. For each TMC segment, the TTI is extracted for morning and evening traffic separately.

$$TTI_i = \frac{\bar{T}_i}{FFTT_i} \qquad \text{Eq. 4-10}$$

where

$\bar{T}_i$ = actual average travel time on TMC i during the observation period, and

$FFTT_i$ = free-flow travel time of TMC i.

(2) *Bottleneck Identification*

Since both PTI and TTI are dimensionless travel-time-based performance measures and are developed using the same benchmark for each roadway segment (i.e., free-flow travel time, see Eq. 4-7 and Eq. 4-10), it is reasonable to integrate both measures into the bottleneck identification and ranking framework. By doing so, both dimensions of traffic congestion on each TMC can be accounted for. The following procedure illustrates how to discern recurrent freeway bottlenecks in each peak period (i.e., a.m. peak, p.m. peak, a.m. and p.m. peak) separately:

- **STEP 1:** Compute the ranking index RI_{im} for each TMC i during month m:

$$RI_{im} = TTI_{im} + \gamma_i \cdot PTI_{im} \qquad \text{Eq. 4-11}$$

where

PTI_{im} = the planning time index of TMC i in the m-th month,

TTI_{im} = the travel time index of TMC i in the m-th month, and

γ_i = the weighting factor assigned to the reliability dimension.

- **STEP 2:** Sum up the RI_{im} values across the entire analysis period for each segment i (i.e., $\sum_m RI_{im}$) and then sort all segments under analysis in descending order on the basis of their summarized RI_{im} values.
- **STEP 3:** Single out a user-specified (or pre-defined) amount of most congested TMCs as recurrent freeway bottlenecks for the study. As discussed previously, the top 30 congested TMC segments are defined as recurrent freeway bottlenecks of interest in this study.

Of practical concern is how to determine the weighting factor γ. In practical applications, the magnitude of γ represents the extent to which the decision maker(s) might value the reliability dimension of traffic congestion with respect to the intensity dimension. The selection of γ is also often affected by local network characteristics. In this study, a concept akin to the variable 'reliability ratio (RR)', which is defined as the ratio of the value of travel time reliability (VTTR) to the value of travel time (VOTT), is adopted herein to determine the value of γ. The RR provides a relative measure of how travelers are likely to respond to changes in reliability relative to changes in average travel time (Noland and Polak, 2002). As travel time reliability-related performance measures are gaining more and more interests from transportation agencies, both VTTR and RR are playing important roles in project evaluation and decision-making processes. For example, the Maryland State Highway Administration (SHA) currently employs a VTTR in their life-cycle benefit-cost analysis (BCA) for existing congestion mitigation projects. In order to account for the potential reliability benefits of mobility improvement projects, the Maryland SHA adds 75% of the congestion-related savings as reliability savings to the overall project benefits (i.e., RR = 0.75). In this study, a varying weighting factor is defined for each TMC segment i:

$$\gamma_i = \frac{RR_i}{FFTT_i} \qquad \text{Eq. 4-12}$$

where

RR_i = the reliability ratio of TMC i, and

$FFTT_i$ = the free-flow travel time on segment i.

Note that defining the weighting factor in such a manner has several advantages:

- **(a)** Previous studies have noticed that RR cannot be replaced by a constant value; instead, the RR value can vary by a number of factors, such as trip purpose, income, and trip length (The University of Arizona et al., 2014). Similarly, for two TMC segments that have identical TTI and PTI values, their weighting factor γ may differ from each other due to the fact the travel time distributions on both TMCs are not necessarily the same. As a result, using a distinct value of γ for each TMC is recommended.

- **(b)** In the field of travel time reliability research, several methods have been developed to estimate the values of VTTR and RR, including the classic estimation method based on the discrete choice models (DCMs) and the newly proposed real options theory-based methods (Kittelson & Associates, 2013; Sadabadi et al., 2015). For instance, the SHRP 2 L35B project developed a data-driven approach to determining a range of local values for RR based on the real options theory. An entire year's worth of archived vehicle probe travel time data were used to estimate the local RR and VTTR values on five different corridors in Maryland. Such method only requires archived vehicle probe-based travel time data (as well as some model parameters) as the input data and thus significantly reduces the expenditures associated with the data collection process in the traditional DCM-based approaches. Note that the MATLAB code used to automate this process was also provided in Appendix of the SHRP 2 L35B project report. The data-driven approach will be used to estimate local RR values (and ultimately the weighting factor γ) in this study. A comprehensive review of the existing methods that can be used to determine RR values can be found in the technical reports of the SHRP 2 Projects L35A and L35B (The University of Arizona et al., 2014; Sadabadi et al., 2015).

- **(c)** Using the definition proposed in Eq. 4-12, it provides a more convenient and meaningful way to interpret the ranking index RI_{im} in Eq. 4-11, as explained below. Plugging Eq. 4-10 and Eq. 4-12 into Eq. 4-11 yields:

$$RI_{im} = TTI_{im} + \frac{RR_i}{FFTT_i} \cdot PTI_{im} = \frac{\bar{T}_{im}}{FFTT_i} + \frac{1}{FFTT_i} \cdot \frac{VTTR_i}{VOTT_i} \cdot PTI_{im}$$
$$= \frac{VOTT_i \cdot \bar{T}_{im} + VTTR_i \cdot PTI_{im}}{VOTT_i \cdot FFTT_i} \qquad \text{Eq. 4-13}$$

The numerator in Eq. 4-13 is a combination of travel time-related costs and reliability-related costs, while the denominator represents the travel cost under (absolutely reliable) free-flow traffic conditions (with a variance of 0). Therefore, from the economic perspective, the bottleneck ranking index RI_{im} can be interpreted as the ratio of the total travel cost under congested travel conditions to the travel cost during (absolutely reliable) free-flow traffic conditions.

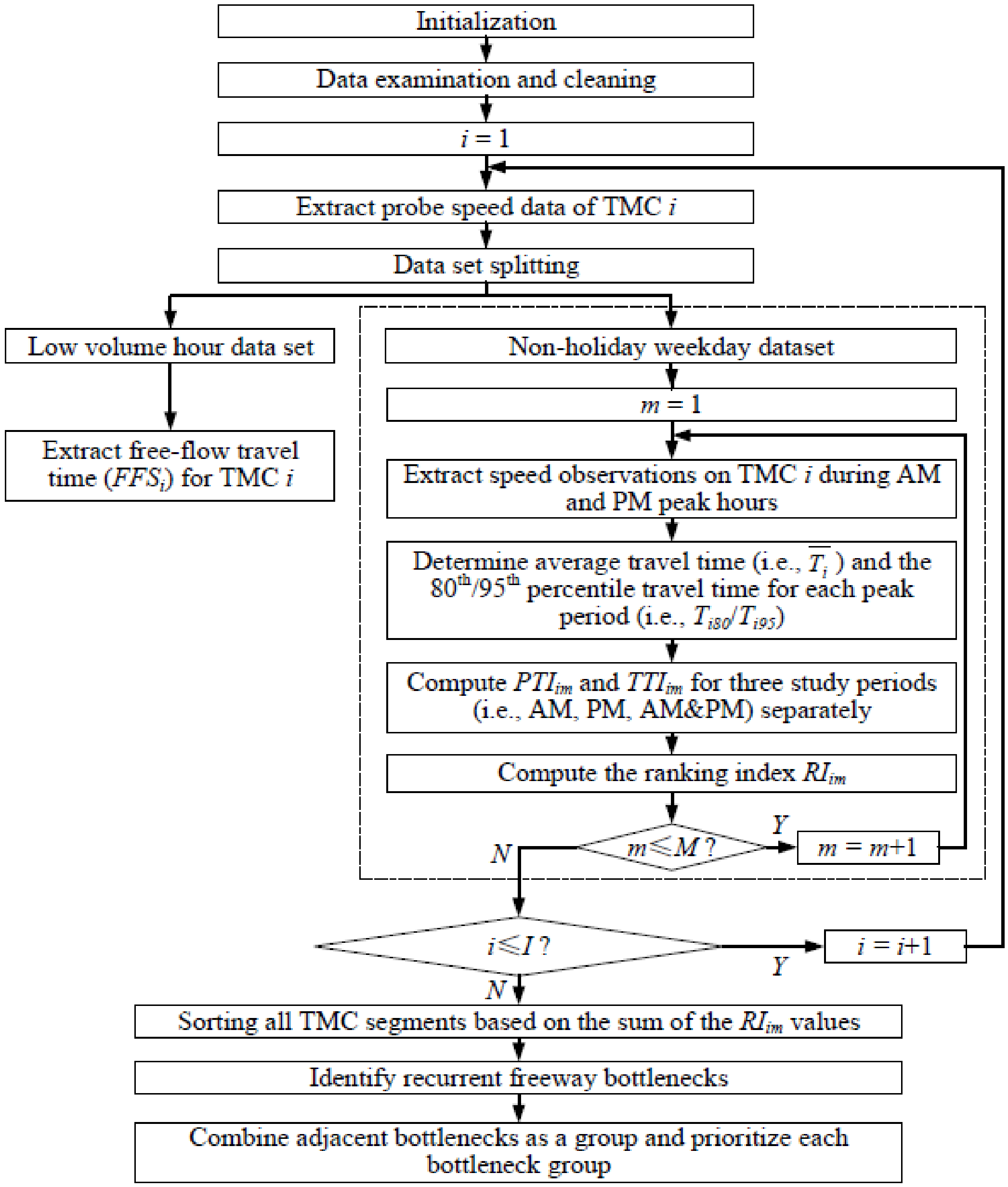


Figure 4-5 Bottleneck Identification and Ranking Framework Using PTI and TTI

(3) *Bottleneck Ranking*

Let I_k denote the set of roadway segments incorporated in the combined bottleneck group k (BG_k for short). The group ranking index (R_{BG_k}) is computed as:

$$R_{BG_k} = \sum_{i \in I_k} \left(\sum_{m=1}^{M} RI_{im} \right) \times VKT_i \qquad \text{Eq. 4-14}$$

where

R_{im} = ranking index of the i-th TMC segment during the m-th month, and

M = number of months within the study period, and

VKT_i = vehicle kilometers traveled on road segment i.

A similar bottleneck identification and ranking procedure based on PTI and TTI is presented in Figure 4-5.

4.2.3 Case Study

4.2.3.1 *Description of the case study dataset*

To evaluate the bottleneck identification and ranking frameworks as developed in Sections 4.2.1 and 4.2.2, vehicle probe data over a one-year period on four interstate highways (I-485, I-277, I-77, and I-85) in Mecklenburg County, North Carolina, is collected and used as a case study in this dissertation. The total length of the four interstate highways is 235.89 miles. Figure 4-6 presents the diagram of the interstate highway network in the study area. Specific characteristics of each freeway corridor are shown in Table 4-1.

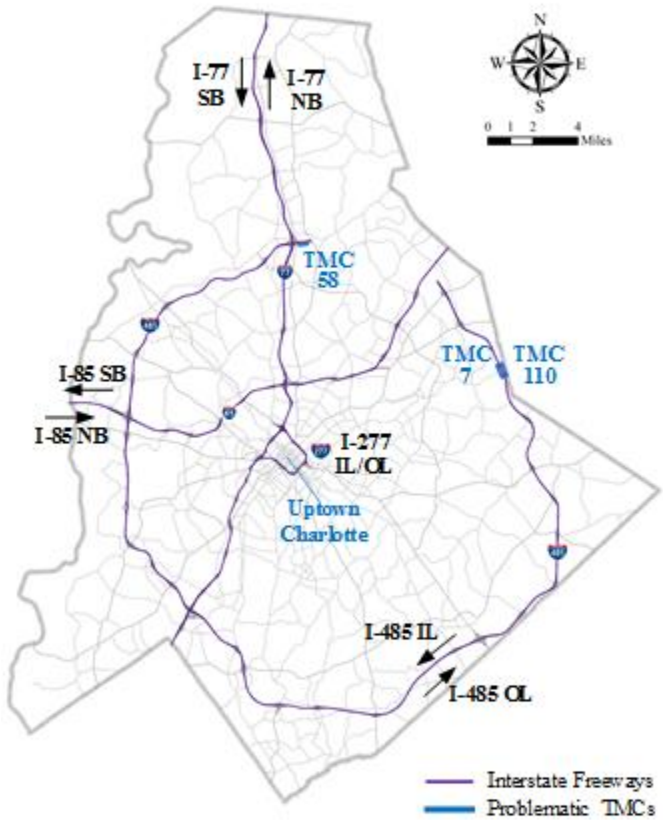


Figure 4-6 Interstate Freeway Network in Mecklenburg County, NC

Table 4-1 Specific Characteristics of Each Freeway Corridor

Road	**Direction**	**Length (miles)**	**TMC ID**	**AADT[1] (veh/day)**
I-485	Inner Loop (IL)	59.99	1-58	66,357
	Outer Loop (OL)	59.78	59-116	
I-277	Northbound (NB)	4.76	117-138	88,200
	Southbound (SB)	4.22	139-160	
I-77	Northbound (NB)	30.89	161-205	131,652
	Southbound (SB)	31.51	206-250	
I-85	Northbound (NB)	22.51	251-287	138,529
	Southbound (SB)	22.23	288-324	
Sum		235.89		

Note: [1] Average annual daily traffic volume (Data source: https://www.ncdot.gov/projects/trafficsurvey/)

Initially, the author requested a speed dataset from HERE through the Vehicle Probe Project (VPP) suite, which was suggested for use by NCDOT. A preliminary examination shows that: (1) from January 2015 to November 2015, no speed observations were collected on the interstate freeways within the scope of the study; and (2) in December 2015, about 33.7 percent of the speed data were missing for all TMC segments in the study area. Due to such high data missing rates in HERE dataset, another dataset obtained from INRIX is used to illustrate the proposed approaches in the following sections.

The INRIX dataset contains travel speeds measured on all 324 TMC segments throughout 2015. A table describing the spatial attributes of each TMC (e.g., TMC length, endpoint longitude and latitude information) is shown in Table 4-2. In this study, a total of approximately 34 million 5-minute speed records are used to develop the travel time reliability and intensity performance measures associated with each TMC segment during three analysis periods for each month of 2015. Note that applying vehicle probe data aggregated at either 5-minute or 15-minute levels are essentially identical for engineering applications; and both data aggregation levels have been found in previous studies (FDOT, 2011; CDM Smith, 2014; Cambridge Systematics, 2011; Day et al., 2014; and Peterson, 2014). The present study adopts vehicle probe data aggregated at 5-minute intervals so as to keep consistent with the reliability analysis procedure as recommended for freeways in HCM (2010). Table 4-3 exhibits an example of the raw 5-minute vehicle probe speed data requested from INRIX.

Table 4-2 An Example of TMC Network Spatial Attributes

TMC ID	TMC	Road	Dir.	Length (miles)	Latitude Start	Longitude Start	Latitude End	Longitude End
1	125-04958	I-485	IL	0.29	35.3411	-80.7278	35.3377	-80.7250
2	125N04958	I-485	IL	0.64	35.3377	-80.7250	35.3299	-80.7188
117	125P04839	I-277	OL	0.62	35.2231	-80.8713	35.2246	-80.8609
118	125+04840	I-277	OL	0.10	35.2246	-80.8609	35.2245	-80.8591

Table 4-3 An Example of 5-minute Raw Probe Speed Data from INRIX

TMC	Date-Time Stamp	Speed (mph)
125+04631	2015/5/8 20:00:00	64.73
125+04632	2015/5/8 20:00:00	64.41
125+04631	2015/5/8 20:05:00	69.58
125+04632	2015/5/8 20:05:00	70.27

4.2.3.2 *Data examination and cleaning*

Prior to calculating roadway performance measures, the data missing rates of each TMC segment are first examined. The results are briefed as follows:

- Nearly 57% of speed data were missing across the whole observation period on TMC segments 7 and 110. This could be caused by some technical issues.
- A preliminary examination also finds that TMC 58 abnormally experiences traffic congestion during night times in 2015. This is probably due to the construction activities conducted on I-485 during those times. As such, all three segments (i.e., TMCs 7, 58, and 110) have been labeled in Figure 4-6.
- It is also noticed that, on average, about 14% of speed data were missing on six other TMC segments (42, 43, 73, 74, 180, and 246). The missing observations mainly centered on the first two months of 2015. An analysis of the speed data collected from March to December 2015 shows that these six TMC segments experience little congestion during peak periods and that their FOC values range

from 0.5% to 9.4% when using 60 percent of the free-flow speed as congestion threshold speed. Thus, these 6 TMC segments will have little impact on the final outcomes of the bottleneck identification and ranking procedure in this study.

In summary, a total of 9 problematic TMC segments are identified in the case study and are precluded from further analysis. The data missing rates for all remaining TMC segments are about 0.4%.

4.2.3.3 *Extracting performances measures for each TMC segment*

After the data examination and cleaning process, the raw speed dataset is split into several subsets to facilitate extracting performance measures for all TMC segments during three analysis periods. The determination of these analysis periods is based on the literature review results (please refer to Table 2-3 for more detailed information) as well as the researcher's engineering judgment.

- **Low volume hour (LVH) datasets**. For each TMC segment, the speed measurements recorded between 10 p.m. and 5 a.m. throughout the full year of 2015 are singled out separately. These sub-datasets are used for determining the free-flow speed (FFS_i), free-flow travel time ($FFTT_i$), and reference speed (V_{iR}) for each TMC segment i.
- **AM peak hour datasets.** Vehicle probe data observed during morning rush hours (i.e., 6 a.m. to 9 a.m.) are extracted for each TMC segment and each month. Such sub-datasets are used for extracting roadway performance measures as developed in Sections 4.2.1 and 4.2.2, which include FOC_{im}, PTI_{im}, and TTI_{im}. Because traffic patterns during non-holiday weekdays are significantly different from those during holidays or weekends, only non-holiday weekday data are utilized to

analyze traffic conditions during peak time periods. Table 4-4 lists the holidays that are excluded from the analysis period.

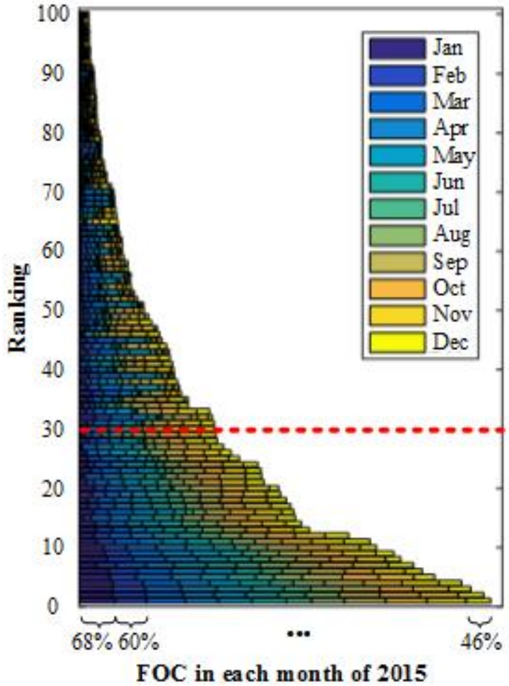
- **PM peak hour datasets.** Vehicle probe data observed during evening rush hours (i.e., 4 p.m. to 7 p.m.) are extracted for each TMC segment and each month. These sub-datasets are used to gauge traffic congestion during evening peak periods on each roadway segment and each month. For similar reasons, the analyses are restricted to non-holiday weekdays only.
- **AM and PM peak hour datasets.** A combination of the a.m. and p.m. peak hour datasets are extracted and used for quantifying traffic flow dynamics on each roadway segment during both peak time periods.

Table 4-4 Holidays Excluded in Extracting Performance Measures

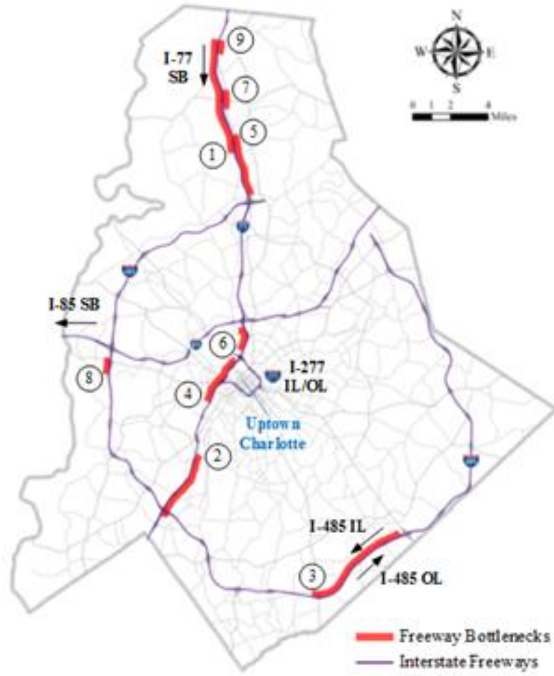
Holiday	**Date**	**Day of the Week**
New Year's Day	January 1, 2015	Thursday
Martin Luther King, Jr. Day	January 19, 2015	Monday
Washington's Birthday	February 16, 2015	Monday
Memorial Day	May 25, 2015	Monday
Independence Day	July 4, 2015	Saturday
Labor Day	September 7, 2015	Monday
Columbus Day	October 12, 2015	Monday
Veterans Day	November 11, 2015	Wednesday
Thanksgiving Day	November 25, 2015	Wednesday
Thanksgiving Friday	November 26, 2015	Thursday
Christmas Day	December 25, 2015	Friday

4.2.3.4 *Analytical results*

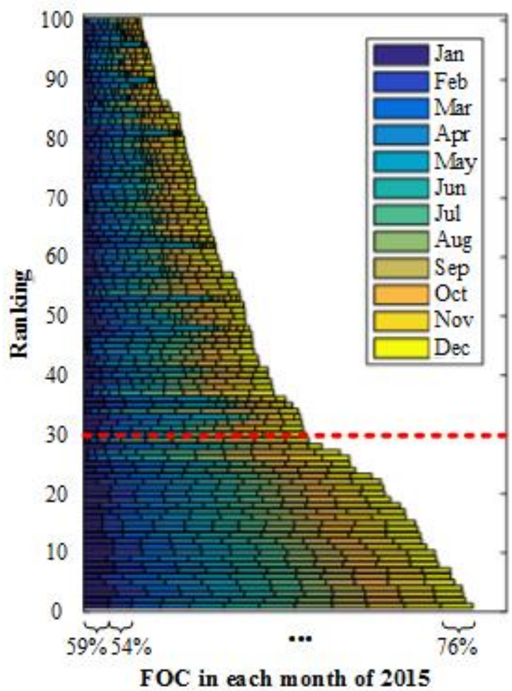
This section reports bottleneck identification and ranking results based on various performance measures separately.



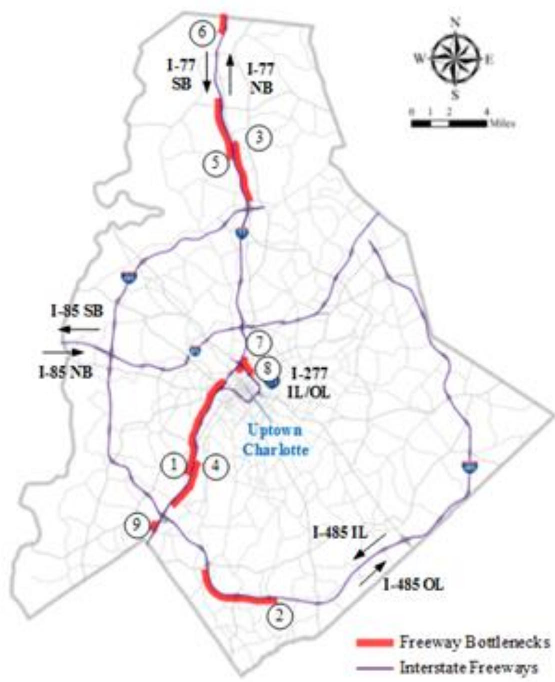
(a) Top 100 TMCs, AM Peak



(b) Bottleneck locations, AM Peak

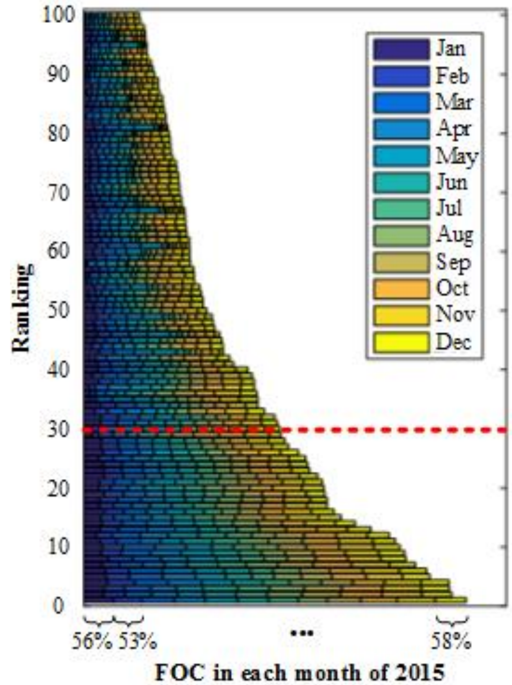


(c) Top 100 TMCs, PM Peak

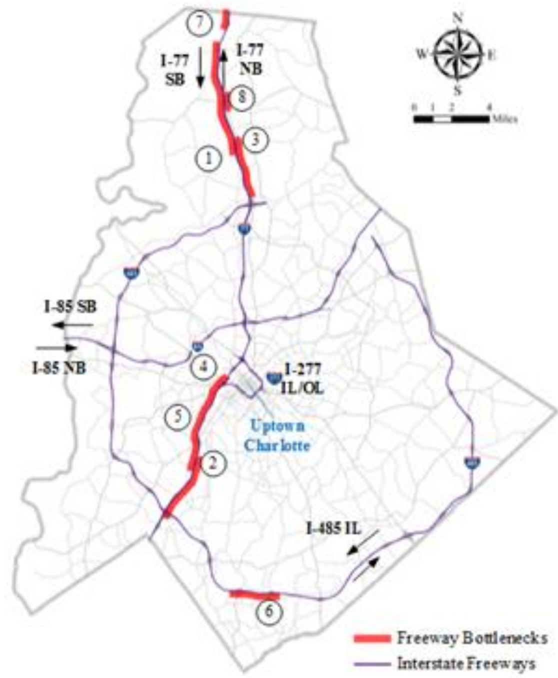


(d) Bottleneck locations, PM Peak

Figure 4-7 Bottleneck Identification Results Based on FOC_{60}



(e) Top 100 TMCs, AM&PM Peak



(f) Bottleneck locations, AM&PM Peak

Figure 4-7 (*continued*)

For convenience purpose, a subscript is added to the relevant performance metric to indicate the threshold value used in the definition. For example, FOC_{60} (as shown in Figure 4-7) indicates the frequency of congestion when travel speed drops below 60% of the free-flow speed.

(1) *Bottleneck identification and ranking results based on FOC*

Bottleneck identification results based on FOC

Figure 4-7 (a) and (c) show the monthly FOC_{60} values for the top 100 TMC segments on the list during a.m. and p.m. peak periods respectively. For each TMC segment, the FOC_{60} values in Figure 4-7 (e) are computed as the average of a.m. and p.m. FOC_{60} values. Note that TMCs ranked lower than 100 are not presented in this figure because their monthly FOC_{60} values are relatively small (less than 10%) and are not the focus of this study.

Based on Figure 4-7 (a) and (c), one can see that, compared to morning peak hours, commuters generally experience more frequent traffic congestion on interstate highways during evening peak hours. The monthly average FOC_{60} values for the top 100 TMC segments are 16.9% and 36.7% during a.m. and p.m. peak hours, respectively.

As discussed in Section 4.2.1, based on the FOC_{60} values, the top 30 congested TMC segments are selected as bottlenecks of interest in this study. Figure 4-7 (b), (d), and (f) illustrate the freeway bottlenecks identified during morning, evening, and both peak periods, respectively. As presented in Figure 4-7 (b), during morning peak period, 25 out of the 30 most congested roadway segments are located on I-77; the other 5 are located on I-485. For the most congested 30 TMC segments identified during a.m. peak periods, only 40 percent of them also emerge in the top 30 TMC segments during p.m. peak periods. The inconsistency in Figure 4-7 (b) and (d) clearly implies the fundamental difference between a.m. and p.m. traffic patterns on interstate highways in Mecklenburg County, NC. In Figure 4-7 (b), a bottleneck group (labeled as ③) is observed on I-485 inner loop with a total length of 5.65 miles during a.m. peak periods. Further engineering analysis indicates that it is most likely caused by high-demand commuting traffic toward uptown Charlotte during morning rush hours. In the meantime, Figure 4-7 (d) implies that travelers routinely experience congestion on I-485 outer loop during p.m. peak hours along some roadway segments (in bottleneck group ②). This root cause of such phenomena is higher inflow traffic during the a.m. peak and higher outflow traffic during the p.m. peak. Figure 4-7 (b) and (d) also suggest that some same TMC segments, such as those contained both in the bottleneck group ⑤ in Figure 4-7 (b) and in the bottleneck group ③ in Figure 4-7 (d), are heavily congested during both a.m. and p.m. peak periods. Therefore, in ranking and mitigating bottlenecks, such TMCs deserve higher priority because they negatively impact the travelers during both peak time periods. Figure 4-7 (f) depicts the freeway bottlenecks based on the FOC_{60} values measured during both a.m. and p.m. peak periods. It is apparent that treating those bottleneck groups with higher priority during both a.m. and p.m. peak periods will benefit a greater population of road users at different times.

Bottleneck ranking results based on FOC

As mentioned before, instead of ranking each individual TMC, all adjacent TMCs are combined into a group while ranking bottlenecks in this study. Table 4-7 presents the group ranking results of the bottlenecks identified during different peak time periods separately. Combining Figure 4-7 and Table 4-7, traffic engineers and decision makers can quickly extract and acquire detailed information about each bottleneck group. For example, Table 4-7 indicates that the most congested bottleneck group during morning rush hours is a 5.9-mi section between Gilead Road (Exit 23) and West Catawba Avenue (Exit 28) on southbound I-77. Its location can be found in Figure 4-7 (b), as denoted by ①. It is worth mentioning that ranking freeway bottlenecks for each peak time period separately is helpful in developing and evaluating corresponding candidate mitigation solutions.

Table 4-5 Bottleneck Group Ranking Results Based on FOC_{60}

Bottleneck group ID	Road name	Dir.[1]	Location	TMC ID	Length (mi)	Group ranking index ($R_{BG_k\_FOC}$)
AM peak (6 a.m. to 9 a.m.)						
1	I-77	SB	Gilead Rd (Exit 23) - W Catawba Ave. (Exit 28)	209-213	5.9	2967962
2	I-77	NB	Tyvola Rd (Exit 5) - Westinghouse Blvd (Exit 1B)	163-169	4.3	2254371
3	I-485	IL	Providence Rd (Exit 57) - US 74 (Exit 51B)	22-25	5.7	1443084
4	I-77	SB	Remount Rd - I 277	227-232	2.6	1345870
5	I-77	NB	Gilead Rd (Exit 23) - I 485 (Exit 19B)	196-197	3.0	774664
6	I-77	SB	I 277 (Exit 11) - I 85 (Exit 12)	222-224	1.1	687372
7	I-77	NB	US 73 (Exit 25)	199	0.7	170078
8	I-485	OL	US 74 (Exit 9)	72	0.6	117029
9	I-77	NB	Catawba Ave. (Exit 28)	201	0.5	93107
PM peak (4 p.m. to 7 p.m.)						
1	I-77	SB	Tyvola Rd (Exit 5) - W Morehead St (Exit 10A)	231-241	5.3	5260882
2	I-485	OL	Rea Rd (Exit 59) - NC 51 (Exit 64A)	87-90	4.3	2671667
3	I-77	NB	Gilead Rd (Exit 23) - I 485	196-197	2.8	2298979
4	I-77	NB	Tyvola Rd (Exit 5) - I 485 (Exit 3)	165-169	3.0	2270471
5	I-77	SB	Gilead Rd (Exit 23) - US 73 (Exit 25)	211-213	3.0	1348418
6	I-77	SB	Goodrum Rd (Exit 30)	206-207	0.7	455343
7	I-77	NB	I 277 (Exit 11A)	185	0.6	401792
8	I-277	OL	I 77 (Exit 5A)	137	0.4	251989
9	I-77	SB	Westinghouse Blvd	248	0.2	111332
AM&PM peak (6 a.m. to 9 a.m. and 4 p.m. to 7 p.m.)						
1	I-77	SB	Gilead Rd (Exit 23) - W Catawba Ave. (Exit 28)	209-213	5.9	2626582
2	I-77	NB	Tyvola Rd (Exit 5) - Westinghouse Blvd (Exit 1B)	163-169	4.3	2454572
3	I-77	NB	Gilead Rd (Exit 23) - I 485	196-197	2.4	1647382
4	I-77	SB	Clanton Rd (Exit 7) - W Morehead St (Exit 10 A)	231-234	3.0	1522568
5	I-77	SB	Tyvola Rd (Exit 5) - Clanton Rd (Exit 7)	236-241	2.6	1349484
6	I-485	OL	Rea Rd (Exit 59) -Johnston Rd (Exit 61)	88-90	2.4	768229
7	I-77	SB	Goodrum Rd (Exit 30)	206-207	0.7	275309
8	I-77	NB	US 73 (Exit 25)	199	0.7	183764

Note: [1] direction: NB - north bound, SB - south bound, IL – inner loop; OL- outer loop.

Impact of applying various threshold values in defining FOC

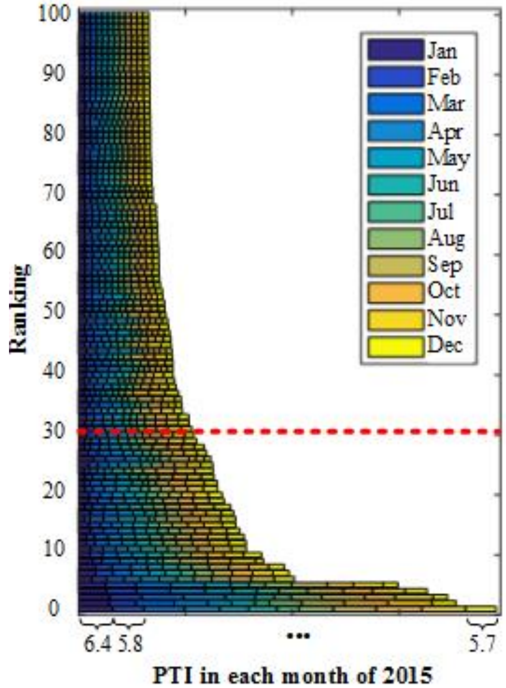
The impact of applying different threshold values in freeway bottleneck identification is also being analyzed. In this study, two threshold values for FOC are tested, which include 60% and 75% of the free-flow speed. The two threshold values represent different levels of traffic congestion: the former corresponds to more severe traffic congestion, while the latter translates to relatively light traffic conditions.

Research results show that about 83.3% - 86.6% of the bottlenecks identified by FOC_{60} also appear in the set of the top 30 TMC segments indicated by FOC_{75}. This indicates that the impact of using different congestion threshold values is not significant in this study. From the viewpoint of engineering applications, both threshold values can be applied to travel time reliability analysis and also bottleneck identification and ranking. On the other hand, such insignificance also implies an evident shortcoming of using the FOC index alone because it is incapable of quantifying the extent of travel speed deviating from the threshold speed and thus the intensity of the traffic congestion. In this regard, it is recommended that multiple congestion measures (e.g., both reliability and intensity measures) be used in freeway bottleneck analysis.

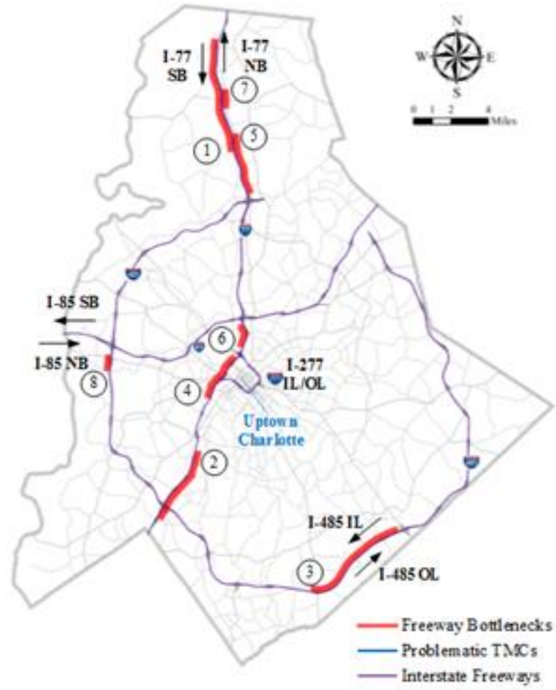
(2) *Bottleneck identification and ranking results based on PTI*

Bottleneck identification results based on PTI

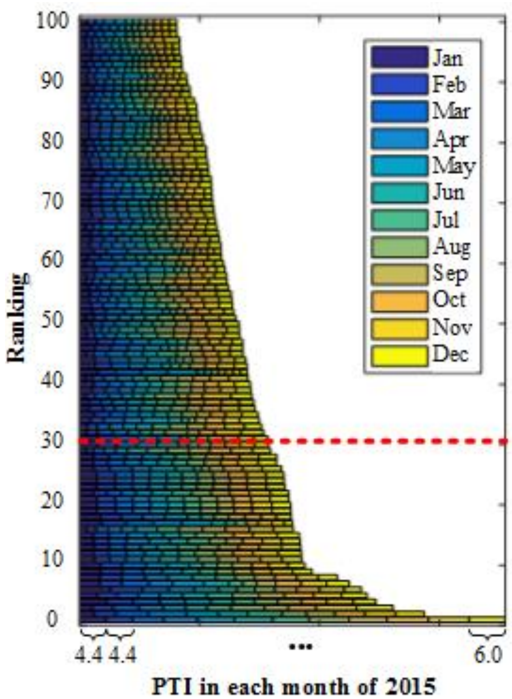
Figure 4-8 (a), (c), and (e) exhibit the monthly PTI_{80} values for the top 100 TMC segments during different peak periods. As one can see from Figure 4-8 (a) and (c), compared with morning peak hours, commuters experience more frequent unreliable traffic conditions on interstate freeways during evening peak hours. In fact, the average monthly PTI_{80} value for the top 100 TMC segments is 1.78 during a.m. peak hours and is smaller than 2.34 during p.m. peak hours. This finding is consistent with the result given by FOC_{60} as presented in the previous section.



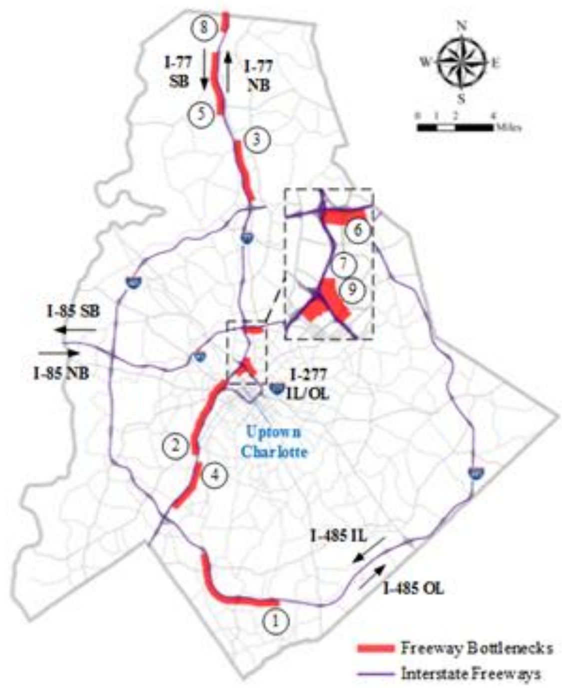
(a) Top 100 TMCs, AM Peak



(b) Bottleneck locations, AM Peak

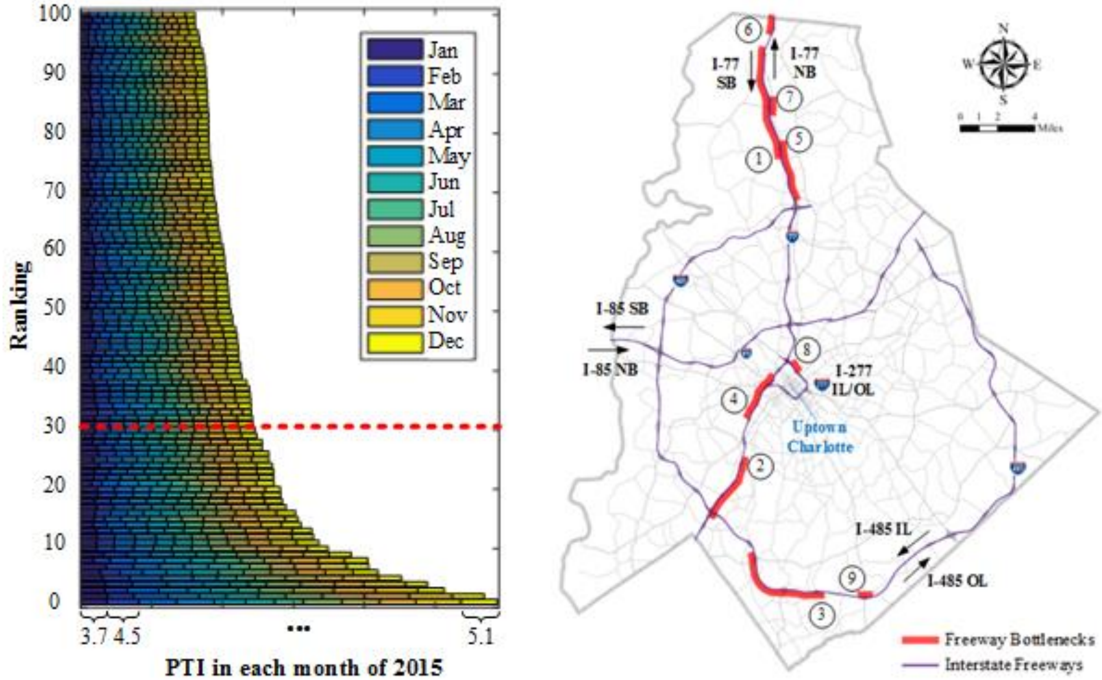


(c) Top 100 TMCs, PM Peak



(d) Bottleneck locations, PM Peak

Figure 4-8 Bottleneck Identification Results Based on PTI_{80}



(e) Top 100 TMCs, AM&PM Peak (f) Bottleneck locations, AM&PM Peak

Figure 4-8 (*continued*)

Based on the PTI_{80} values, the top 30 TMCs are identified as bottlenecks of interest in this study. Like FOC, such TMCs indicated by PTI_{80} values during a.m. and PM peak periods also yield directional characteristics. Combined bottleneck groups (which consist of several freeway segments) are separately identified on the I-485 inner loop during a.m. peak (marked as group ③ in Figure 4-8 (b)) and outer loop (marked as group ① in Fig. 4 (d)) during PM peak times. It is also found that, based on Figure 4-8 (b) and (d), only 36.7% of the top 30 TMCs identified during a.m. peak period also appear in those during PM peak period. For the same reason as discussed previously, such identical TMCs should be given higher priority on the list when ranking bottlenecks. Figure 4-8 (f) illustrates the ranking results of the bottleneck groups based on the average of the PTI_{80} values measured during a.m. and PM peak periods.

Bottleneck ranking results based on PTI

Based on Eq. 4-9, the group ranking index $R_{BG_k\_PTI}$ is calculated for each bottleneck group identified during each peak time periods and is shown in Table 4-6.

Table 4-6 Bottleneck Group Ranking Results Based on PTI_{80}

Bottleneck group ID	Road name	Dir.[1]	Location	TMC ID	Length (mi)	Group ranking index ($R_{BG_k\_PTI}$)
AM peak (6 a.m. to 9 a.m.)						
1	I-77	SB	Gilead Rd (Exit 23) - W Catawba Ave. (Exit 28)	209-213	5.9	23738248
2	I-77	NB	Tyvola Rd (Exit 5) - Westinghouse Blvd (Exit 1B)	162-169	4.5	17699951
3	I-485	IL	Providence Rd (Exit 57) - US 74 (Exit 51B)	22-25	5.7	9712883
4	I-77	SB	West Blvd (Exit 9A) - I 277 (Exit 10C)	227-232	2.6	8961198
5	I-77	NB	Gilead Rd (Exit 23) - I 485	196-197	3.0	6225408
6	I-77	SB	I 277 (Exit 11) - I 85 (Exit 12)	222-224	1.1	4615784
7	I-77	NB	US 73 (Exit 25)	199	0.7	1348331
8	I-485	OL	US 74 (Exit 9)	72	0.6	1137158
PM peak (4 p.m. to 7 p.m.)						
1	I-485	OL	Rea Rd (Exit 59) -N Polk St (Exit 65)	85-90	5.3	20507979
2	I-77	SB	Billy Graham Pkwy - W Morehead St (Exit 10A)	231-239	4.1	20232472
3	I-77	NB	Gilead Rd (Exit 23) - I 485	196-197	3.0	139445945
4	I-77	NB	Tyvola Rd (Exit 5) - I 485 (Exit 3)	165-169	2.8	12438102
5	I-77	SB	US 73 (Exit 25) - W Catawba Ave. (Exit 28)	210-211	3.0	6984159
6	I-85	NB	Statesville (Exit 39)	272	0.7	3221505
7	I-77	NB	W 5th St - Oaklawn Ave.	184-185	0.7	3172022
8	I-77	SB	Goodrum Rd (Exit 30)	206-207	0.7	2096492
9	I-277	OL	I 77 (Exit 5A)	137	0.4	1503868
AM&PM peak (6 a.m. to 9 a.m. and 4 p.m. to 7 p.m.)						
1	I-77	SB	Gilead Rd (Exit 23) - W Catawba Ave. (Exit 28)	209-213	5.9	18348395
2	I-77	NB	Tyvola Rd (Exit 5) - Westinghouse Blvd (Exit 1B)	163-169	4.3	16388832
3	I-485	OL	Rea Rd (Exit 59) - NC 51	86-90	5.0	12327403
4	I-77	SB	Clanton Rd (Exit 7) - W Morehead St (Exit 10 A)	229-234	2.6	10785914
5	I-77	NB	Gilead Rd (Exit 23) - I 485	196-197	3.0	10085001
6	I-77	SB	Goodrum Rd (Exit 30)	206-207	0.7	1543124
7	I-77	NB	US 73 (Exit 25)	199	0.7	1348234
8	I-485	OL	I 77 (Exit 5A)	137	0.4	1024417
9	I-277	IL	US 16 (Exit 57)	25	0.5	880029

Note: [1] direction: NB - north bound, SB - south bound, IL – inner loop; OL- outer loop.

Note that the information presented in Table 4-6 is helpful for decision makers and engineers to better develop effective congestion mitigation plans while facing constrained budgets in which bottleneck groups with higher ranks will need to be considered first.

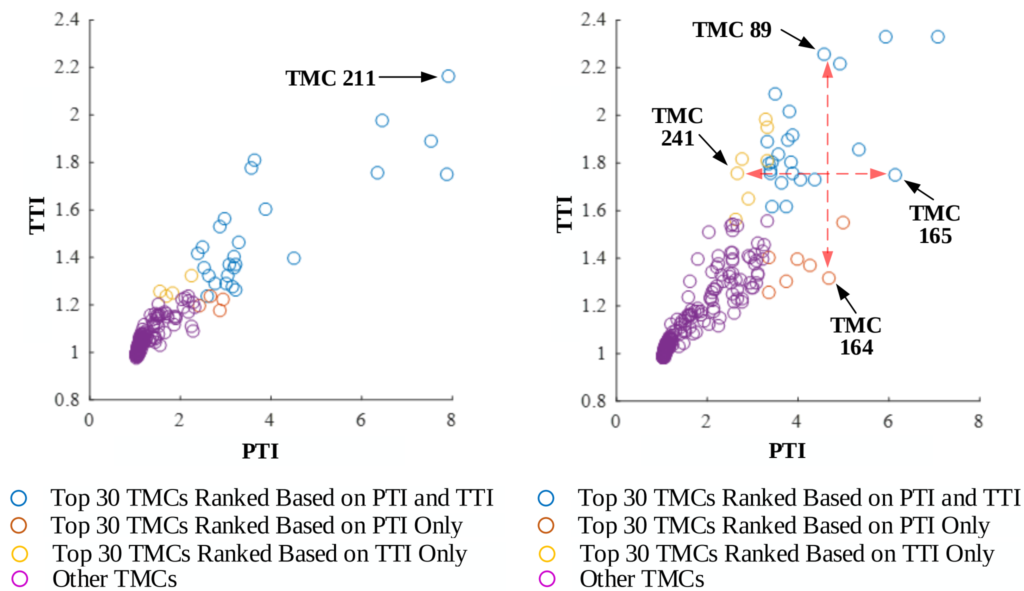
Impact of applying various threshold values in defining PTI

In this study, it is also found that the difference of applying various threshold values (between 80% and 95%) in determining PTI values is small. Nearly 70% - 90% of the top 30 TMCs identified by PTI_{80} are identical to those indicated by PTI_{95}. However, it has been widely recognized that the 95^{th} percentile travel time is more susceptible to non-recurring traffic incidents (e.g., extreme weather or major incidents that require closing the road) for practical applications (Cambridge Systematics, 2014). In addition, the SHRP 2 reliability research suggested that the 95^{th} percentile travel time may be too extreme a value to be influenced significantly by operations strategies (Cambridge Systematics, 2013). In that regard, although both threshold travel times are practically feasible and theoretically almost identical for defining PTI, it is recommended that the 80^{th} percentile travel time be used to calculate the PTI in freeway bottleneck analysis.

(3) *Bottleneck identification and ranking results based on a combination of PTI and TTI*

Comparison between Congestion Reliability and Intensity Measures

The differences in quantifying various dimensions of traffic congestion are examined first. Figure 4-9 provides a quantitative demonstration of the results of both congestion measures of all TMC segments. The horizontal axis in each sub-figure denotes the monthly average PTI values of each TMC while the vertical axis is the monthly average TTI values of the same TMC.



(a) PTI vs TTI (AM Peak) (b) PTI vs TTI (PM Peak)

Figure 4-9 Comparison of Congestion Reliability and Intensity Measures

The circles scattered in the upper right-hand corner in each sub-figure correspond to the situations under which travelers on such TMCs routinely experience unreliable traffic conditions with low speeds during peak periods (such as TMC 211 in Figure 4-9 (a)). The disparity between the magnitudes of congestion intensity of two TMC segments has also been observed although they have nearly identical reliability performance values (such as the TMCs 89 and 164 in Figure 4-9 (b)). Meanwhile, it is noteworthy that there exist two TMCs that have similar TTI values (intensity dimension) but their reliability values could be significantly different from each other. For example, the horizontal distance between TMCs 241 and 165 implies the difference between the reliability levels on two TMCs although they have almost identical intensity performances. Such findings confirm that when identifying and ranking recurrent freeway bottlenecks, it is necessary to account for both dimensions of traffic congestion.

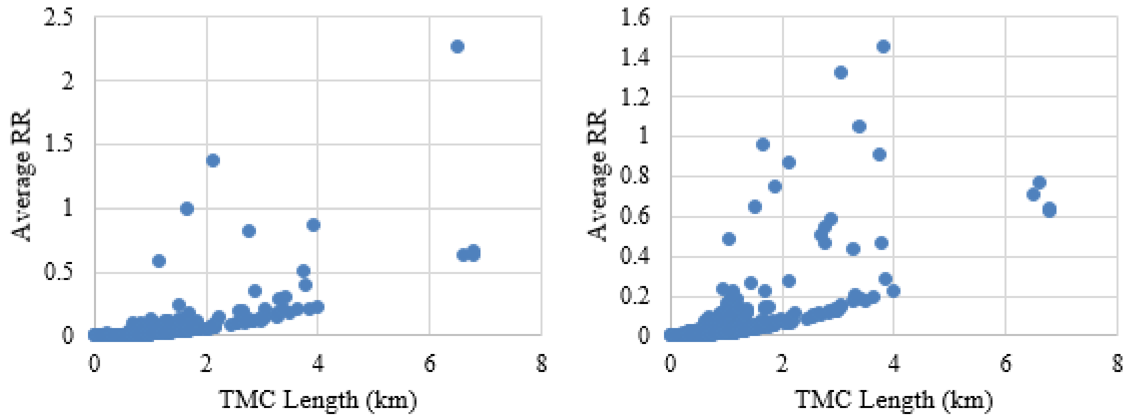
Bottleneck identification results

Figure 4-10 presents the RR values computed for each TMC segment using the MATLAB code as attached in Sadabadi et al. (2015). Each dot in Figure 4-10 is the average of 36 (3 hours, every 5-minute) RR values obtained by applying the *BinT* function provided in Appendix B to the SHRP 2 Project L35B report for each 5-minute of the corresponding peak period over a TMC segment.

As shown in Figure 4-10, the RR value generally increases with the length of the roadway segment. This finding is consistent with the results observed in Sadabadi et al. (2015). The author also compares the RR values obtained in this study with those obtained in Sadabadi et al. (2015). For instance, the average RR values across all TMC segments during morning rush hours is 0.07 and the average travel time ($\bar{T}$) on all TMCs is 0.75 minutes. Previously, based on the experimental results, Sadabadi et al. (2015) estimated the following relationship between the average travel ($\bar{T}$) time and the RR:

$$RR = 1 - e^{17.355\left(e^{-0.004\bar{T}}-1\right)} \quad \text{Eq. 4-15}$$

Replacing the $\bar{T}$ value in Eq. 4-15 with 0.75 yields an RR value of 0.05. Therefore, the RR value obtained in this study (0.07) is a little larger than that in Sadabadi et al. (2015). This is also true for p.m. peak periods. Such difference could be reasoned by the fact that driver behaviors, roadway facilities, traffic compositions, and weather conditions may differ from one place to another. Finally, the weighting factor for each TMC segment i (γ_i) can be determined once the value of RR_i is figured out.



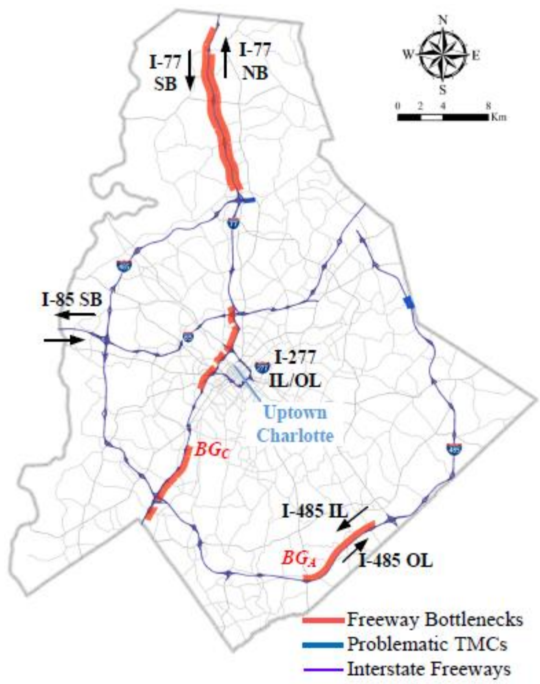
(a) AM Peak Period (b) PM Peak Period

Note: [a] Input data: vehicle probe travel time data obtained from INRIX.
[b] Key parameters adopted in the *BinT* function:
guarnateed travel time (tau_guaranty): the average travel time on each TMC segment;
option length (optlength): the 95th percentile travel time on each TMC segment;
tolerance level (tol): 5%;
number of steps (n): 2000;
portion of VOTT traveler will be penalized for arriving late (late_penalty): 1;
portion of VOTT traveler will be penalized for arriving early (early_penalty): 0.05.

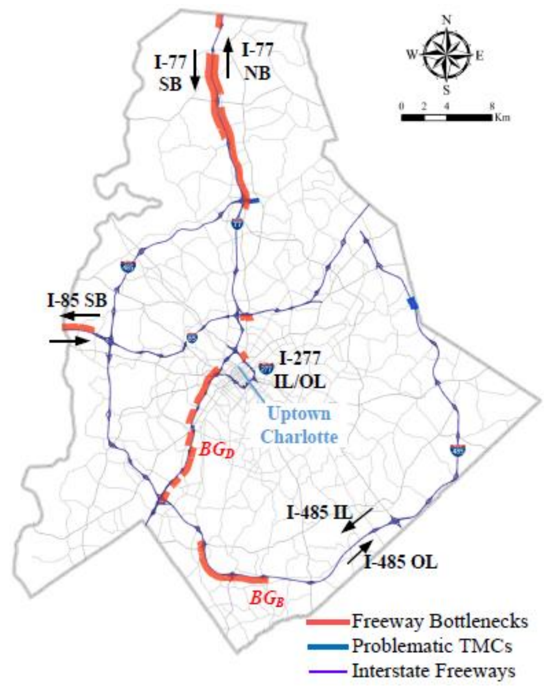
Figure 4-10 Reliability Ratio (RR) on the TMC Segments in the Study Area

Following the procedures presented in steps 1 – 3 in Section 4.2.2, Figure 4-11 (a) - (c) illustrate the top 30 bottleneck segments identified during different peak times. Note that, for each roadway segment, the ranking index used in Figure 4-11 (c) is an average of the ranking index values obtained during a.m. and p.m. peak periods.

On the basis of Figure 4-11, one can see that traffic congestion on the Interstate freeway network in Mecklenburg County exhibits different patterns during morning and evening rush hours. For instance, a bottleneck group (labeled as BG_A in Figure 4-11 (a)) is located on the I-485 inner loop with a total length of 5.2 mi during a.m. peak times. In the meantime, Figure 4-11 (b) implies that commuters routinely have to drive at low speeds on the I-485 outer loop during p.m. peak hours along some roadway segments in bottleneck group BG_B in Figure 4-11 (b). As previously discussed, the root cause of such phenomena is high inflow traffic during the a.m. peak period and high outflow traffic during the p.m. peak period. Figure 4-11 (a) and (b) also suggest that some TMC segments (such as those contained both in the bottleneck group BG_C in Figure 4-11 (a) and in the bottleneck group BG_D in Figure 4-11 (b)) are heavily congested during both a.m. and p.m. peak periods. Therefore, in ranking and mitigating these bottlenecks, such TMCs deserve higher priority because they adversely affect more travelers during both peak times. Figure 4-11 (c) illustrates the locations of the freeway bottlenecks when accounting for travel conditions during both and a.m. and p.m. peak periods.

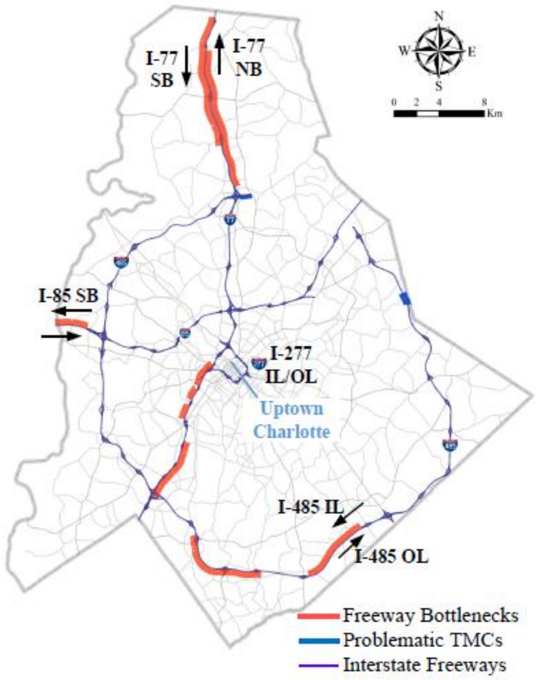


(a) Bottleneck Identification Results (AM Peak)



(b) Bottleneck Identification Results (PM Peak)

Figure 4-11 Freeway Bottleneck Identification Results Using PTI and TTI



(c) Bottleneck Identification Results (AM&PM Peak)

Figure 4-11 (*continued*)

Bottleneck ranking results

Table 4-7 presents the group ranking results of the bottlenecks identified during different peak time periods. Using a combination of Figure 4-11 and Table 4-7, it provides a convenient way for traffic engineers and decision makers to easily locate and extract detailed information about each bottleneck group. Along with further engineering analysis and judgment, the bottleneck identification and ranking results are essential for determining the possible causes of the bottlenecks and developing appropriate congestion mitigation plans.

Table 4-7 Bottleneck Group Ranking Results Using Both PTI and TTI

Bottleneck group ID	Road name	Dir.[1]	Location	TMC ID	Length (mi)	Group ranking index (R_{BG_k})
AM peak (6 a.m. - 9 a.m.)						
1	I-77	NB	Tyvola Rd (Exit 5) - Westinghouse Blvd (Exit 1B)	163-169	4.3	12070888
2	I-77	SB	I 485 (Exit 19A) - Goodrum Rd (Exit 30)	208-214	9.3	11944469
3	I-77	NB	Catawba Ave. (Exit 28) - I 485 (Exit 19A)	196-200	7.8	4999697
4	I-77	SB	W 5th St (Exit 10C) - La Salle St (Exit 12)	223-225	2.0	4977686
5	I-77	SB	Remount Rd - W Morehead St (Exit 10A)	231-232	1.5	3278683
6	I-485	IL	Providence Rd - E John St (Exit 52)	23-25	5.2	2924060
7	I-77	SB	TRADE ST/5TH ST (Exit 10)	227	0.8	1411912
8	I-77	SB	I-85/Statesville Ave (Exit 13)	221	1.0	1290475
9	I-77	NB	Westinghouse Blvd (Exit 1)	161	0.8	1126041
PM peak (4 p.m. – 7 p.m.)						
1	I-77	SB	Clanton Rd (Exit 7) - W Morehead St (Exit 10A)	231-234	2.4	10285110
2	I-485	OL	Rea Rd (Exit 59) - NC 51 (Exit 64B)	86-90	5.0	9578668
3	I-77	NB	NC-73 (Exit 25) - I 485	195-198	5.7	8041208
4	I-77	NB	Tyvola Rd (Exit 5) - Nations Ford Rd (Exit 4)	167-169	1.6	6248469
5	I-77	SB	Gilead Rd (Exit 23) - NC-73 (Exit 25)	210-212	4.8	4000191
6	I-77	SB	Tyvola Rd (Exit 5) - Woodlawn Rd (Exit 6)	239-240	0.9	3956845
7	I-77	NB	Arrowood Rd/Exit 3	165	1.1	2970682
8	I-77	SB	Griffith St (Exit 30)	206-207	0.7	2498131
9	I-85	NB	Statesville Ave (Exit 39)	272	0.7	2288588
10	I-77	SB	NC-49/Tryon St (Exit 6)	236	0.7	2159720
11	I-85	SB	NC-273 (Exit 27)	324	2.1	2157757
12	I-77	NB	I-485 (Exit 2)	163	1.3	1689921
13	I-277	OL	I-77/US-21/W 5th St (Exit 5)	137	0.4	1575874
14	I-77	NB	US-21 (Exit 28)	200	2.3	1138126
AM&PM peak (6 a.m. – 9 a.m. and 4 p.m. – 7 p.m.)						
1	I-77	NB	Tyvola Rd (Exit 5) - Westinghouse Blvd (Exit 1B)	163-169	4.3	12777995
2	I-77	SB	Gilead Rd (Exit 23) - Griffith St (Exit 30)	207-213	7.3	10116593
3	I-77	NB	US-21 (Exit 28) - Gilead Rd (Exit 23)	196-200	7.8	6943193
4	I-485	OL	Rea Rd (Exit 59) - NC 51 (Exit 64B)	86-90	5.0	6457074
5	I-77	SB	Remount Rd - W Morehead St (Exit 10A)	231-232	1.5	4675399
6	I-77	SB	Clanton Rd (Exit 7)	234	0.6	1691587
7	I-77	SB	NC-49/Tryon St (Exit 6)	236	0.7	1606465
8	I-85	SB	NC-273 (Exit 27)	324	2.1	1559055
9	I-485	IL	John St (Exit 52)	24	4.0	884280

Note: [1] direction: NB - north bound, SB - south bound, IL – inner loop; OL- outer loop.

4.3 Identifying Freeway Bottlenecks Using 2-D Data Structure

This section describes how to identify recurrent freeway bottlenecks using a two-dimensional data structure, each cell of which represents an analysis interval along an analysis segment. The indicator is calculated by aggregating the speed (or travel time) observations collected during that time interval across multiple days. Again, a number of performance measures can be applied to achieve this goal, including FOC, PTI, TTI, and so on. For illustration purpose, we only present how to extract the FOC values for each TMC during each time interval and how to utilize the FOC indicator to discern recurrent freeway bottlenecks in a freeway network. Other performance measures (such as PTI and TTI) can also be applied to realize the same function by following the proposed procedure herein. It should be pointed out that, since this method does not account for the variations in traffic dynamics across different days, such method is utilized as a supplementary tool to validate the effectiveness of the primary bottleneck identification approach developed in Section 4.2.

For any roadway segment i, the corresponding FOC value within a 5-minute interval can be developed by following the procedure below:

- **STEP 1:** Flag traffic conditions within each time interval and each day:

$$\delta_{itd} = \begin{cases} 1 & V_{itd} < V_{iR} \\ 0 & V_{itd} \geq V_{iR} \end{cases} \quad \text{Eq. 4-16}$$

where

V_{itd} = travel speed collected on TMC segment i during time t in day d, and

V_{iR} = reference speed on TMC i.

- **STEP 2:** Compute the FOC for TMC segment i and time interval t:

$$FOC_{it} = \frac{1}{D}\sum_{d} \delta_{itd} \times 100\% \qquad \text{Eq. 4-17}$$

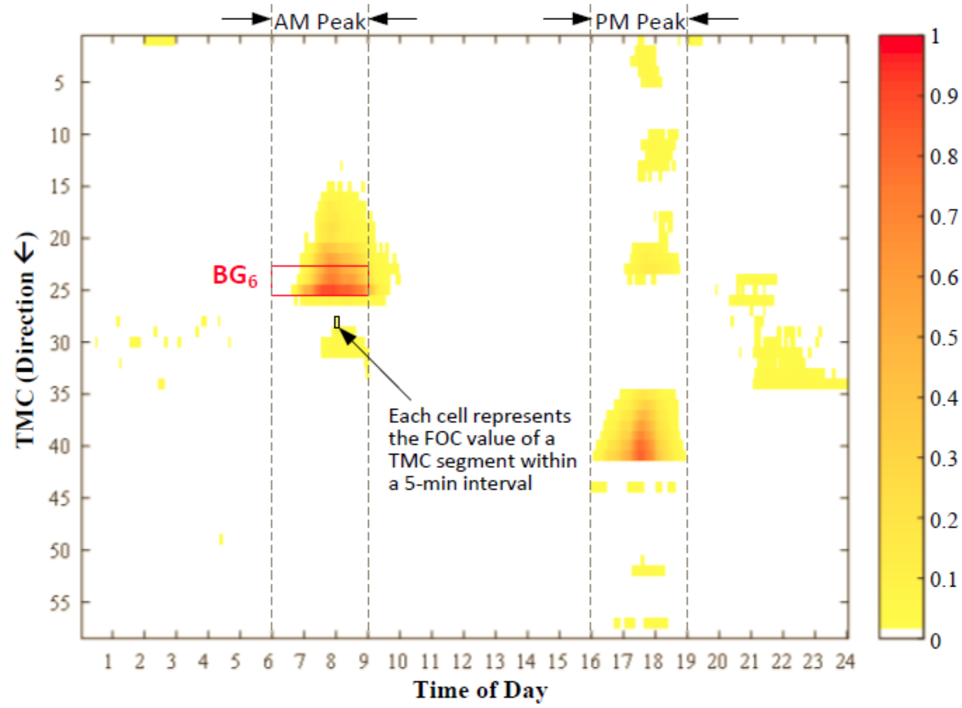
where

D = the total number of non-holiday weekdays in the study period.

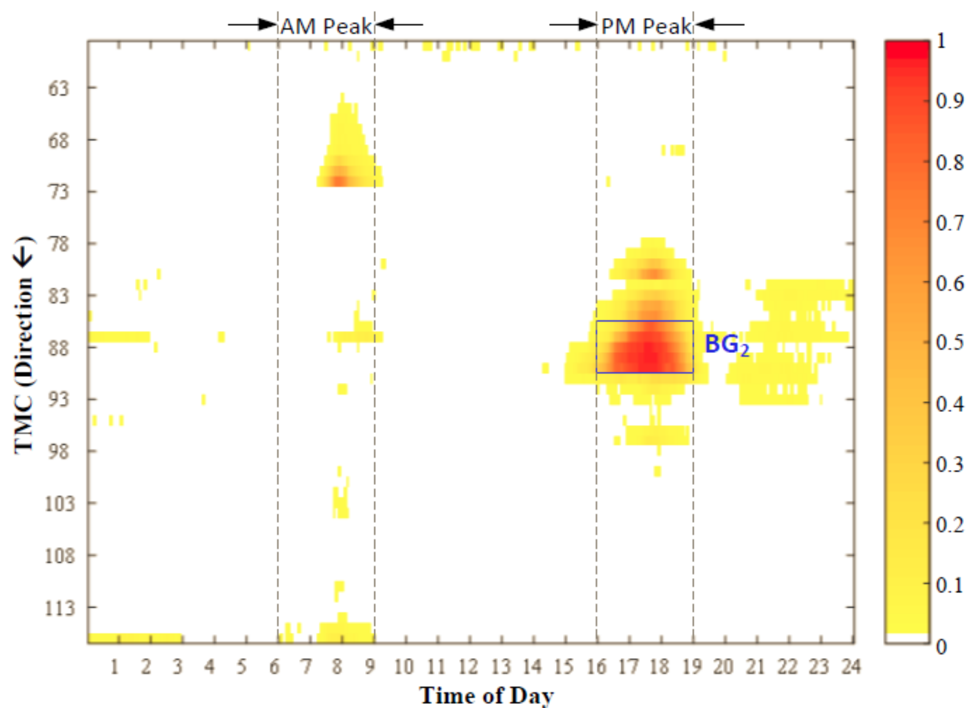
Let I denote the number of TMCs being analyzed and also let the data collection interval be 5-minute (as we did in the case study). Performing the above steps for each TMC would result in an I by 288 ($12 * 24$) data points.

- **STEP 3:** Plot the two-dimensional FOC matrix for each road direction in the network. This would provide a straightforward and visualized tool for decision-makers to grasp the average traffic conditions along a corridor.

Using the same dataset as in Section 4.2.3, Figure 4-12 - Figure 4-15 present the two-dimensional FOC contour maps for each interstate highway and in each direction. Note that in these figures, the horizontal axis denotes the time of day and the vertical axis represents TMC segments along one direction of an interstate highway. Each cell represents the frequency of travel speeds dropped below 60 percent of the free-flow speed using all speed data collected during that time interval across a total of 251 non-holiday weekdays in 2015. The darker the color, the higher the FOC. For comparison purpose, the top 30 most congested TMC segments identified using a combination of TTI and PTI are mapped into the FOC contour maps as well. Each bottleneck group identified during morning peak time periods is represented by a red rectangle in Figure 4-12 - Figure 4-15, while the bottleneck groups discerned during p.m. rush hours are marked using blue rectangles.



(a) Inner Loop

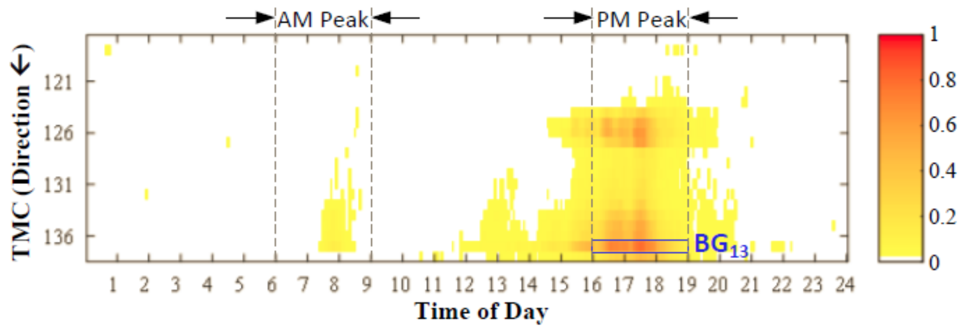


(b) Outer Loop

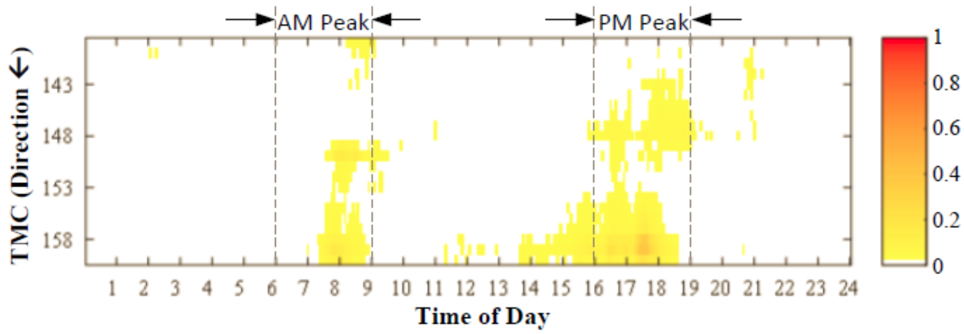
Figure 4-12 Two-Dimensional FOC Contour Map for I-485

The following conclusions about the findings can be drawn based on Figure 4-12:

- Traffic congestion on I-485 yields apparent directional characteristics. Congested TMC segments during morning rush hours are generally different from those during evening peak hours. As discussed previously, this is because I-485 serves as a main commuting road for people entering and exiting the uptown Charlotte area during different peak hours.
- The FOC contour maps show that, during morning peak periods, traffic congestion generally occurs in the vicinity of TMC 22-25, and TMC 72; during evening peak periods, drivers routinely experience frequent congestion at around TMC 86-90. These congested areas have also been singled out in the primary method, as indicated by those rectangles.
- A portion of the inner loop I-485 (TMC 35-41) are also observed to experience congestion during p.m. peak hours. From Figure 4-12 (a), we can see that low-speed traffic conditions in this area mainly exhibit at 17:00 - 18:00. Since we only select the top 30 TMCs as bottlenecks of interest in this study, this area does not make to the list and show up in the primary method’s identification results. In practical application, this problem could be solved by enlarging the user-specified amount of congested TMCs for analysis if necessary.



(a) Outer Loop

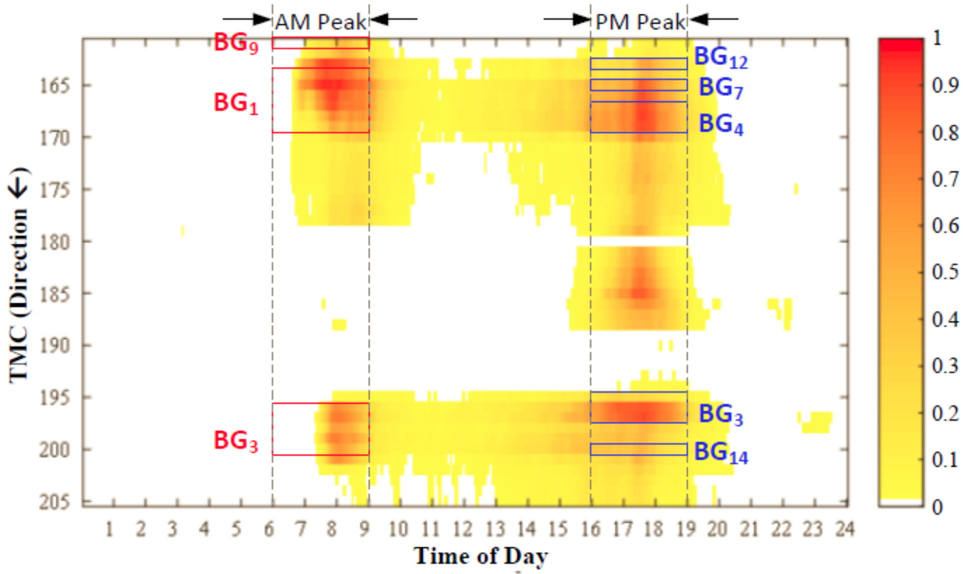


(b) Outer Loop

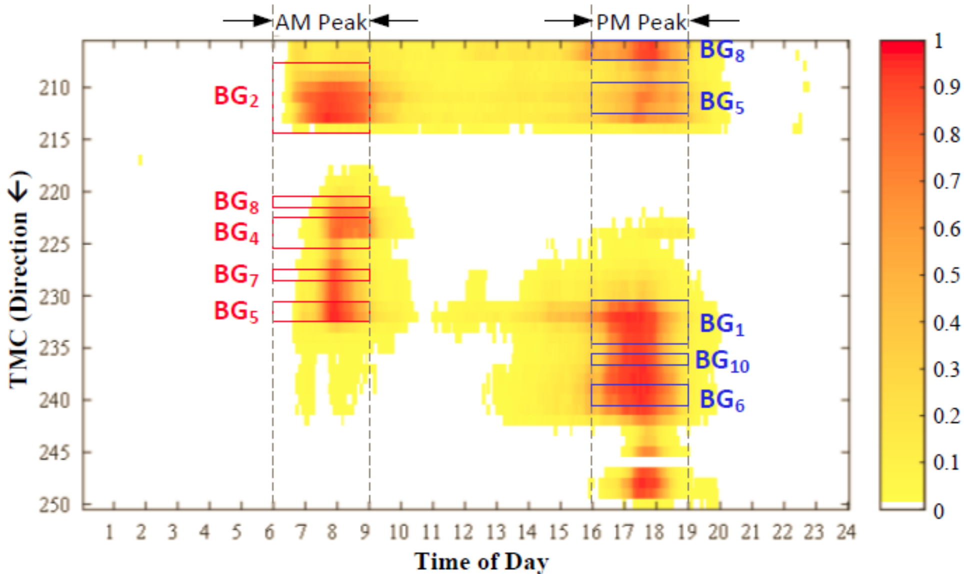
Figure 4-13 Two-Dimensional FOC Contour Map for I-277

Based on Figure 4-13, the following findings are observed for I-277:

- Traffic flow is relatively smooth in the morning in both directions on I-277.
- Travelers may suffer some moderate level of traffic congestion ($FOC < 0.6$) during evening rush hours in both directions on I-277.
- TMC 137 is declared as a bottleneck (included on the Top 30 list) during p.m. peak periods by using the main approach, and Figure 4-13 (a) confirms that this segment frequently experiences traffic congestion during p.m. rush hours.



(a) Northbound



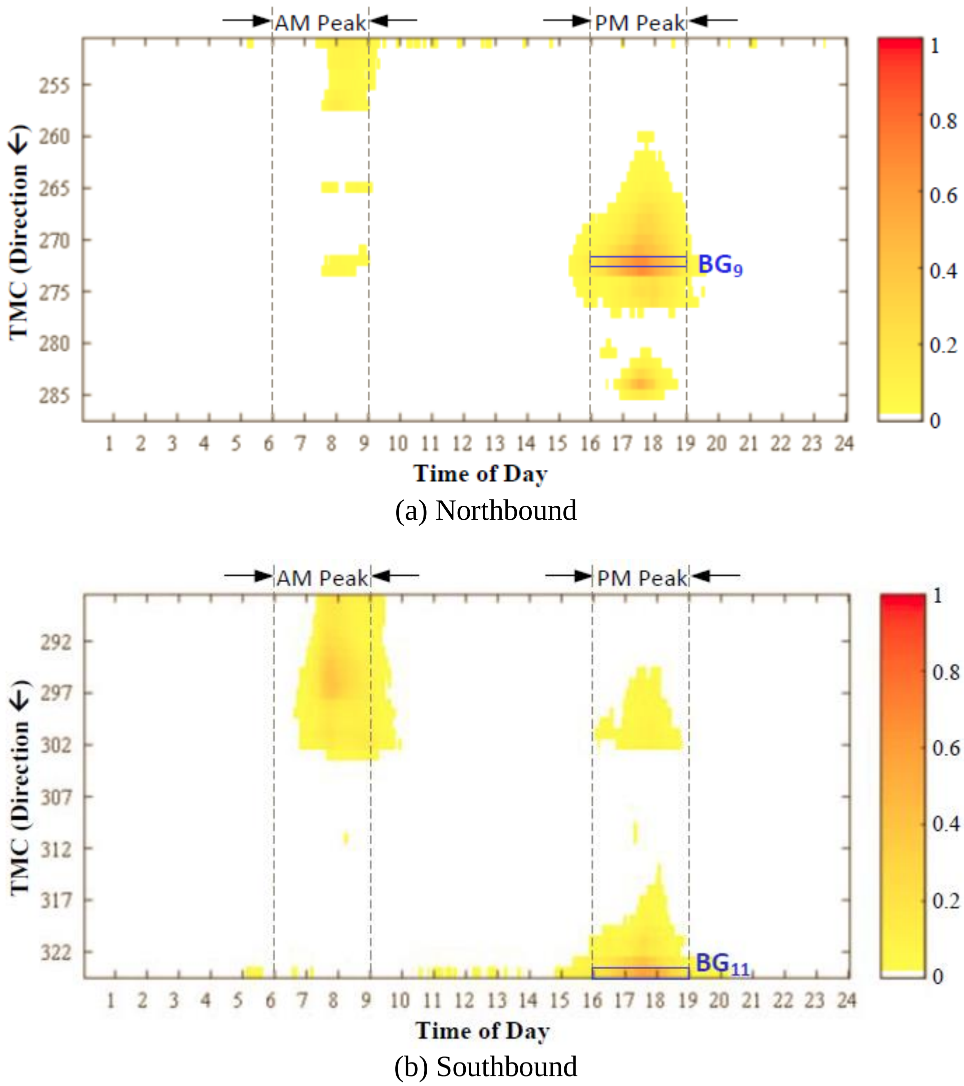
(b) Southbound

Figure 4-14 Two-Dimensional FOC Contour Map for I-77

Figure 4-14 reveals several features of traffic congestion on I-77:

- I-77 is the busiest interstate highway in Mecklenburg County, especially during peak travel times.

- Figure 4-14 (a) and (b) clearly validate that freeway bottlenecks determined based on the primary approach are consistent with the FOC contour map.
- Some TMC segments are heavily congested during both a.m. and p.m. peak hours, such as TMCs 164-169, TMCs 209-211, and TMCs 231-232. Therefore, these TMCs deserve higher priority in the process of ranking and mitigating bottlenecks.



(a) Northbound

(b) Southbound

Figure 4-15 Two-Dimensional FOC Contour Map for I-85

Figure 4-15 presents characteristics of traffic flow dynamics on I-85:

- Compared to other interstate highways in Mecklenburg County, for both directions on I-85, drivers may suffer minor to moderate level of congestion during peak times. Traffic conditions on I-85 during non-peak times are light.
- The seventh bottleneck group identified by using the main approach overlaps with the TMC segment that has the highest FOC values in Figure 4-15 (a).

In summary, the two-dimensional FOC contour map provides a visualized tool to assist in validating the effectiveness of the primary bottleneck identification and ranking method as developed and presented in Section 4.2. The findings suggest that, in the primary method, using 6 a.m. to 9 a.m. and 4 p.m. to 7 p.m. as the a.m. and p.m. peak periods is appropriate. Most congested traffic conditions occur within these two time intervals. In addition, those recurrent freeway bottlenecks as identified based on a combination of PTI and TTI are generally consistent with the results based on the FOC contour maps for each interstate highway corridor, which thus confirms the validity of the primary approach developed in this study.

4.4 Characterizing Recurrent Freeway Bottlenecks at the Operation Level

The intent of this section is to exhibit bottleneck features at a different level. Aside from bottleneck locations, other characteristics (such as bottleneck start time, duration, length and their daily variations) will also be presented. It is expected that such detailed information would help transportation professionals better understand the potential causes of each bottleneck and therefore propose targeting countermeasures in subsequent tasks. The original three-dimensional data matrix, which contains traffic flow information at the highest level of detail, has been applied to achieve this goal. As an example, the I-485 outer loop is used to illustrate the methodology.

4.4.1 Traffic Flow Patterns around the Bottlenecks (I-485, Outer Loop)

Speed contour plots (SCPs) provide an intuitive visualization of traffic flow patterns along a corridor by time of day, day of the month, and month of the year. Figure 4-16 presents an illustrative example of the SCPs of the I-485 outer loop using the 5-minute probe vehicle speed data. Due to space restrictions, only a portion of the original three-dimensional data matrix, i.e., those collected in May 2015, are presented here. Considering the fact that vehicle speeds are susceptible to different traffic demand patterns on weekends and holidays, only non-holiday weekday data are presented herein. In Figure 4-16, lower speeds are represented by red color. The white line segments are caused by missing data on TMC 110.

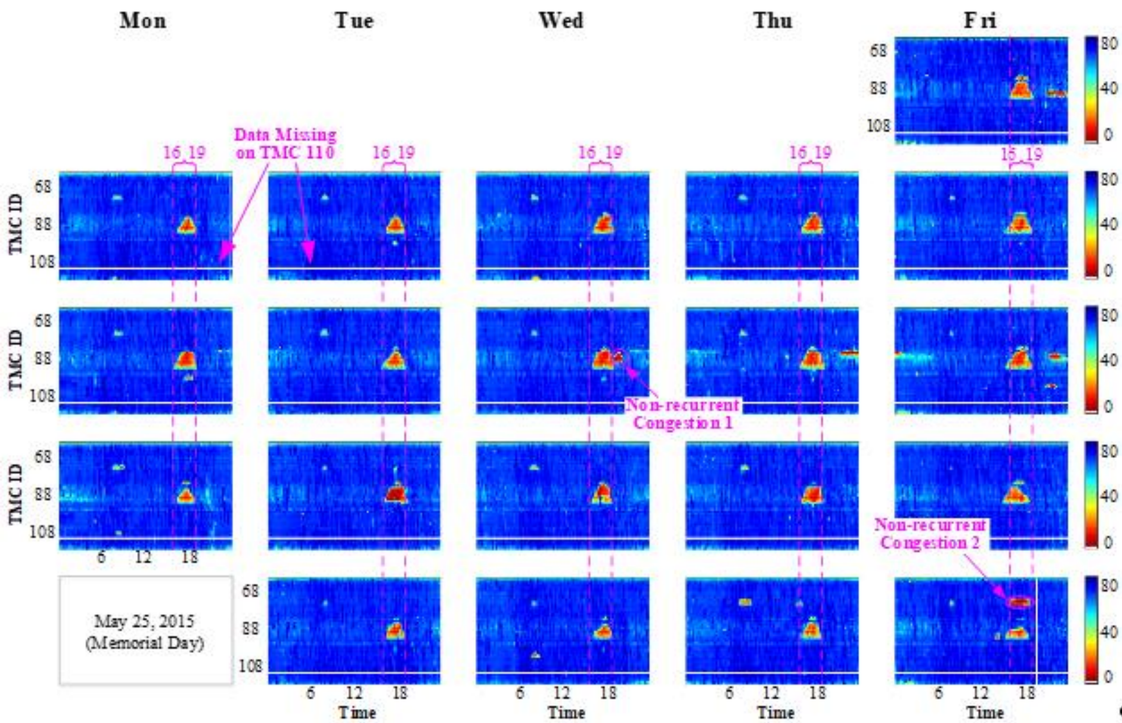


Figure 4-16 Daily Speed Contour Maps of TMCs of the I-485 Outer Loop in May 2015 during Non-Holiday Weekdays

Note: Traffic flows in the same direction as the increasing order of TMC ID numbers.

Based on Figure 4-16, a series of congested segments are frequently observed during evening peak times. Traffic jams generally begin to form on TMC 91 at about 4 p.m. and then propagate upstream to other TMC segments. Typically, the congestion lasts for about 3 hours and disappears around 7 p.m. It is apparent that, during evening peak times, commuters traversing these roadway segments have to spend more time in contrast to that spent under free-flow conditions. Figure 4-16 also exhibits information on non-recurrent congestion. For instance, two irregular traffic jams are observed on May 13 and May 29, respectively. The first one occurred on TMC segments 83-87 from 7:00 p.m. to 8:30 p.m., while the second one took place on TMCs 70-73 between 3:30 p.m. and 6:30

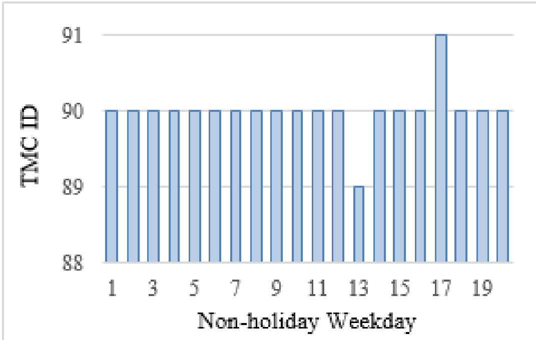
p.m. Compared to recurrent congestion, non-recurrent congestion has a lower frequency of occurrence and is randomly distributed in time and space.

4.4.2 Bottleneck Features and Their Daily Variations

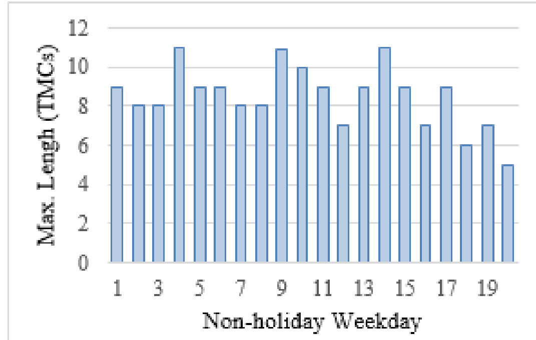
An innovative image processing program based on MATLAB has been developed to extract information about each congested region in every SCM in Figure 4-16. Figure 4-17 presents daily variations in several characteristics of the bottleneck group on the outer loop of I-485:

- **Bottleneck location.** For most of the time, traffic jams begin at TMC 90; however, some minor perturbations have been noticed as well, such as the 13^{th} and 17^{th} non-holiday weekday in May 2015. This is quite normal since traffic congestion is stochastic in nature.
- **Bottleneck length.** Traffic congestion may propagate to 5 to 11 TMC segments upstream of the bottleneck. On average, about 8 TMC segments upstream could be affected by the bottleneck, as shown in Figure 4-17 (b).
- **Bottleneck start time.** Traffic breakdown usually begins at 15:30 to 16:30 for non-holiday weekdays.
- **Bottleneck duration.** For each occurrence of the bottleneck, it may last 2.5 to 3.5 hours per day. This is consistent with the previous discussions in Section 4.4.1.

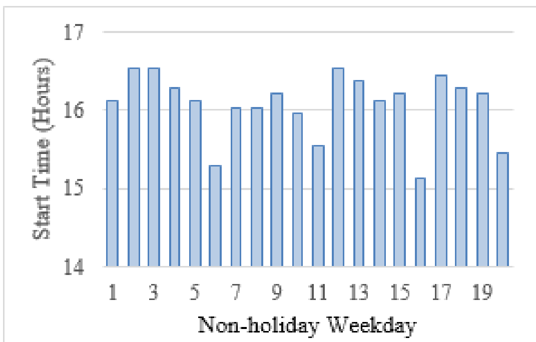
All the information can be gathered for each bottleneck group as identified in Section 4.2.3 and provided to researchers to help them determine the potential causes of each bottleneck and developing effective mitigation solutions.



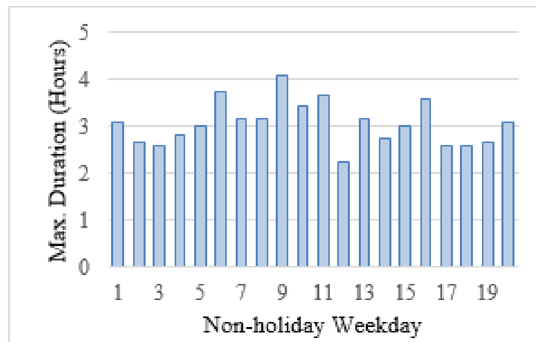
(a) Variations in Bottleneck Location



(b) Variations in Bottleneck Start Time



(c) Variations in Bottleneck Length



(d) Variations in Bottleneck Duration

Figure 4-17 Detailed Information about Bottlenecks on Outer Loop of I-485 in May 2015 during Non-Holiday Weekdays (PM Peak)

4.5 Summary

In this chapter, a systematic approach to identifying and ranking recurrent freeway bottlenecks at the network level is developed. First of all, a variety of congestion performance measures were tested and analyzed in terms of their feasibility and effectiveness in identifying recurrent freeway bottlenecks. The research results show that using TTR measures alone does not account for the intensity dimension of traffic congestion on each TMC segment, and therefore, simultaneously using both reliability and intensity measures in locating and ranking bottlenecks are highly recommended. A case study is performed to illustrate the proposed methodology which can help NCDOT engineers apply the recommended approach to other freeways in North Carolina when necessary. After that, the two-dimensional FOC matrix is developed to validate the effectiveness of the primary bottleneck identification method. The findings suggest that those recurrent freeway bottlenecks as identified based on a combination of PTI and TTI are generally consistent with the results based on the FOC contour maps for each interstate highway corridor, which thus confirms the validity of the primary approach. Finally, detailed information about the location, length, activation time, and duration of each bottleneck is extracted using the original three-dimensional data structure. All these information, combined with traffic volume counts collected from other sources and information collected from field trips, will be used to determine the test bed bottleneck sites in subsequent tasks.

CHAPTER 5: EXAMINING TEST BED BOTTLENECK SITES

Once the bottlenecks are located, the next step is to determine the potential causes of each bottleneck. By doing so, the bottlenecks identified in Chapter 4 can further be analyzed and examined in detail, and targeting countermeasures can be developed and evaluated as well. To achieve this goal, this study examined potential contributing factors from both supply and demand sides about each bottleneck. From the supply side, roadway geometric configurations (e.g., number of lanes, vertical and horizontal curves, on- and off-ramps, and weaving sections) and operational strategies (e.g., ramp metering, variable speed limit control, and high occupancy vehicle (HOV) lanes) determine the effective capacity of a roadway facility. From the demand side, various demographic characteristics (e.g., population) and land development patterns (e.g., residential, commercial, and mixed land use) affect growth in travel demand and changes in travel patterns.

After the causes of top-ranked bottlenecks are examined and identified, various candidate improvement projects will then be developed to mitigate the congestion for each of these bottlenecks on the test bed network, and their effectiveness will be evaluated as well. The most appropriate modeling tools will be determined and required modeling data will be synthesized based on the set of performance measures developed in Chapter 3. The selected DTA model must and will reflect the specific requirements of this research, and should possess both the regional-scale transportation modeling capability and representation of local traffic dynamics.

5.1 Methodology

Since the root cause of bottleneck occurrence is the imbalance between travel demand and capacity supply, two separate analyses are performed for each bottleneck group. First, the geometric configurations and land use patterns in the vicinity of each bottleneck group are examined. After that, an operational analysis is conducted for the roadway segments near the most downstream endpoint of each bottleneck group. In this research, the downstream endpoints of all bottleneck groups identified in Chapter 4 are located at either on-ramp freeway junctions or off-ramp freeway junctions. It is postulated that the complex interactions between mainline traffic flows and merging (or diverging) traffic flows on ramp segments are the leading causes of traffic jams of each bottleneck group. Therefore, an operational analysis following the analytical procedures in the *Highway Capacity Manual* 2010 (TRB, 2010) is performed to verify such hypotheses. The HCS 2010 software, Version 6.8, developed by the University of Florida in 2010, is employed to calculate MOEs in the ramp influence zone. Figure 5-1 and Figure 5-2 provide a schematic illustration of a typical on-ramp and off-ramp freeway junction, respectively.

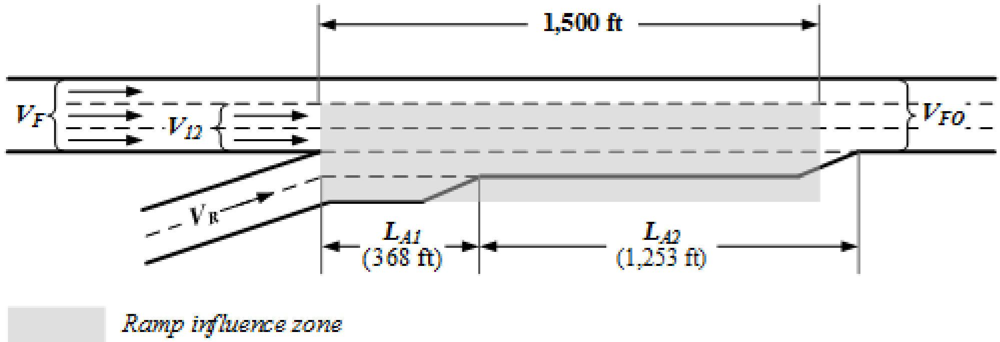


Figure 5-1 Schematic Illustration of a Typical On-Ramp Freeway Junction

Note: Adopted from *Highway Capacity Manual 2010*, TRB 2010

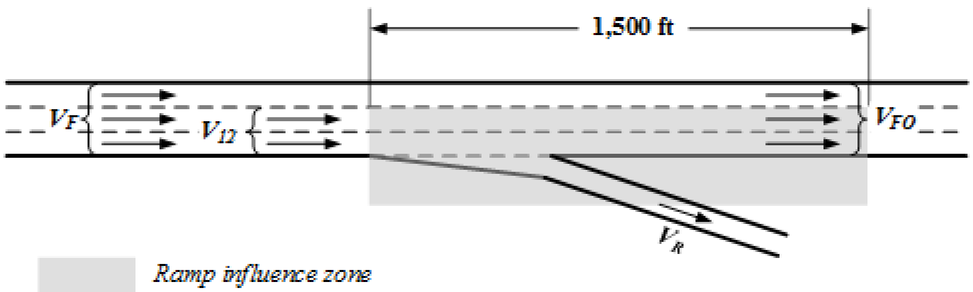


Figure 5-2 Schematic Illustration of a Typical Off-Ramp Freeway Junction

Note: Adopted from *Highway Capacity Manual 2010*, TRB 2010

Although the HCS 2010 software provides a variety of MOEs for analysis, in this study, only the following performance measures are used for determining the potential contributing factors of each bottleneck.

- **For on-ramp freeway junctions:**

  V_{FO}: exiting freeway volume;

  C_{FO}: capacity of exiting freeway lanes;

  V_{R12}: the sum of the ramp flow and the freeway flow in lanes 1 and 2;

  C_{R12}: the sum of the capacity of the ramp flow and the freeway flow in lanes 1 and 2;

D_R: density of the ramp influence area; and

LOS: level of service of the ramp influence area.

- **For off-ramp freeway junctions:**

V_F: entering freeway volume;

C_F: capacity of entering freeway lanes;

V_{12}: freeway volume in lanes 1 and 2;

C_{12}: capacity of freeway lanes 1 and 2;

V_{FO}: exiting freeway volume;

C_{FO}: capacity of exiting freeway lanes;

V_R: ramp volume;

C_R: ramp capacity;

D_R: density of the ramp influence area; and

LOS: level of service of the ramp influence area.

This HCM analytical procedure can help determine the potential causes of each bottleneck. However, the major limitation is that it only measures traffic conditions within the influence area of the ramp junction (as presented below), while quantitative evaluation of traffic flows on adjacent roadway segments (or at the corridor level) is not provided.

5.2 Data

The following information about the ramp-freeway junction is needed to conduct an operational analysis using the HCM procedure (TRB, 2010):

- Type of ramp: on-ramp, off-ramp, major merge, major diverge;
- Side of junction: right-hand, left-hand;

- Number of lanes on freeway and ramp roadways;
- Number of ramp lanes at ramp-freeway junction: 1 lane, 2 lanes;
- Length of acceleration/deceleration lane(s);
- Free-flow speed (FFS) of the mainline freeway segment (55-70 mph) and the ramp roadway (20-50 mph);
- Terrain: level, rolling, or mountainous;
- Demand flow rates on both freeway and ramp segments during peak hour;
- Heavy vehicle presence: percent trucks and buses, percent RVs;
- Peak hour factor (PHF): up to 1.00;
- Driver population factor: 0.85-1.00; and
- Information concerning adjacent upstream or downstream ramps:

  a) Upstream or downstream distance to the merge/diverge under study,

  b) Demand flow rate on the upstream or downstream ramp, and

  c) Peak hour factor and heavy vehicle percentages for the upstream or downstream ramp.

Note that the geometric features of freeway and ramp facilities are observed and measured from Google Earth, including the type of ramp, side of junction, number of lanes, length of acceleration or deceleration lane(s), lane width and lateral clearance of mainline freeway segment, and terrain. For all ramp roadways, the FFS are assumed to be 45 mph as recommended in the *NCDOT Congestion Management Capacity Analysis Guidelines* (NCDOT, 2015). For basic freeway segments, the FFS is estimated by using the HCM methodology (presented in HCM 2010, Chapter 11, Basic Freeway Segments), as illustrated below:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22 \cdot TRD^{0.84} \qquad \text{Eq. 5-1}$$

where

FFS = FFS of basic freeway segment (mph),

f_{LW} = adjustment for lane width (mph),

f_{LC} = adjustment for right-side lateral clearance (mph), and

TRD = total ramp density (ramps/mi).

Adjustments made to reflect the effects of narrower average lane width and lateral clearance are shown in Table 5-1 and Table 5-2 below. The TRD is defined as the number of ramps (on and off, one direction) located between 3 mi upstream and 3 mi downstream of the midpoint of the basic freeway segment under study, divided by 6 mi. Like other geometric features, the TRD is also derived from Google Earth. As pointed out in the HCM 2010, FFS should be rounded to the nearest 5 mph and is bounded between 55 and 70 mph for mainline freeway segments.

Table 5-1 Adjustment to FFS for Average Lane Width, f_{LW} (mph)

Average Lane Width (ft)	**Reduction in FFS, f_{LW} (mph)**
≥ 12	0.0
$\geq 11 - 12$	1.9
$\geq 10 - 11$	6.6

Note: Excerpted from *Highway Capacity Manual 2010*, page. 11-11.

Table 5-2 Adjustment to FFS for Right-Side Lateral Clearance, f_{LC} (mph)

Right-Side Lateral Clearance (ft)	**Lanes in One Direction**			
	2	**3**	**4**	**5**
≥ 6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

Note: Excerpted from *Highway Capacity Manual 2010*, page. 11-12.

The GIS database, which contains the annual average daily traffic (AADT) counts of North Carolina highways, is obtained from NCDOT (NCDOT, 2015). To conduct operational analyses, directional traffic flow rates on both freeway and ramp segments during peak periods are needed. Specifically, the directional hourly volume (DHV), which describes the peak-hour volume in the peak direction of flow, is derived using the AADT, K factor, and D factor:

$$DHV = AADT \times K \times D \qquad \text{Eq. 5-2}$$

where

DHV = directional hourly volume,

K = proportion of daily traffic occurring during the peak hour, and

D = percentage of traffic in the peak direction during the peak hour.

Table 5-3 provides the general ranges for K and D factors. Using lower values of K and D factors in Table 5-3 will result in a conservative estimate of travel demand on the roadway segment and higher K and D values will yield a liberal estimate of the demand flow rate. In this study, two separate DHV values (DHV_{Low} and DHV_{High}) are estimated for each roadway segment. Traffic performances of the ramp-freeway junction under both scenarios are evaluated accordingly.

The truck percentages are also extracted from the NCDOT GIS database. Recommended values for the PHF (0.9) and driver population factor (1.00) in the *NCDOT Congestion Management Capacity Analysis Guidelines* are utilized for analysis (NCDOT, 2015). As suggested in HCM 2010, the study period is the peak 15-minute interval within the peak hour.

Table 5-3 General Ranges for *K* and *D* Factors

Facility Type	**Normal Ranges of Values**	
	***K*-Factor**	***D*-Factor**
Rural	0.15-0.25	0.65-0.80
Suburban	0.12-0.15	0.55-0.65
Urban:		
Radial Route	0.07-0.12	0.55-0.60
Circumferential Route	0.07-0.12	0.50-0.55

Note: Excerpted from *Traffic Engineering (Fourth Edition)*, 2011, page. 98.

5.3 Determining Bottleneck Causes and Developing Mitigation Solutions

This section employs the most severe bottleneck group ranked in Table 4-7 in a.m. and p.m. peak periods as an example to illustrate how to analyze and determine potential causes of each bottleneck group. Targeting countermeasures will also be developed accordingly.

5.3.1 Determining Bottleneck Causes

5.3.1.1 *Geometric Analysis*

The most congested bottleneck group on interstate freeways in Mecklenburg County, North Carolina, is a 4.3-mi stretch of northbound I-77 located between Exit 1 (I-

485) and Exit 5 (Tyvola Road), as shown in Figure 5-3. This section is a three-lane freeway segment which intersects with several interstate and local highways passing this area (including I-485, West Arrowood Road, Nations Ford Road, and Tyvola Road). The southern endpoint of the bottleneck group is only 1.3 miles away from the North Carolina-South Carolina state border. There are two closely connected interchanges located at about 0.6 miles downstream of the bottleneck area (to uptown Charlotte). Figure 5-3 also presents the AADTs along mainline I-77 in the study area.

Further engineering judgment indicates that the complex geometric configurations in the vicinity of the bottleneck location are the main contributing factors which result in frequent traffic congestion in this area, especially during peak travel times.

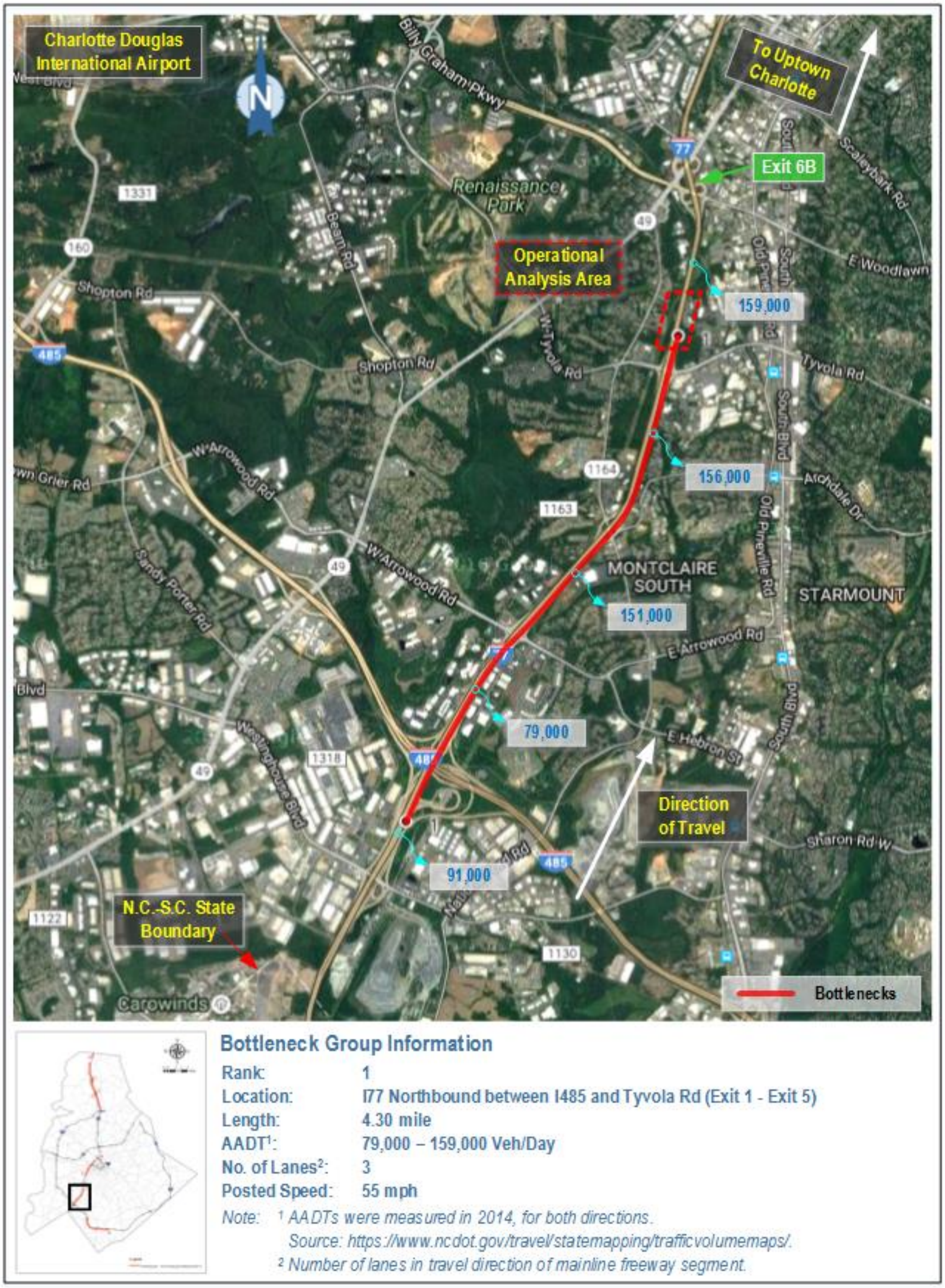


Figure 5-3 Bottleneck Group on I-77 Northbound (Ranked No. 1)

5.3.1.2 *Operational Analysis*

As discussed previously, for the first bottleneck group, the AADTs are measured at several locations along the congested bottleneck segments. However, the main focus of this study is on the traffic conditions at the ramp-freeway junction connecting Tyvola Road and I-77 Northbound. This is in line with the bottleneck identification results obtained in Chapter 4 which indicate that traffic jams are more likely to originate from this junction and then propagate upstream. Table 5-4 lists the input data used and also the output data which provide MOEs of the ramp analysis module in the HCS 2010 software for the study site.

The output data in Table 5-4 indicates that: (1) in the low-demand scenario, demand volume on both freeway and ramp segments (i.e., V_{FO} and V_{R12}) are close to their capacity (i.e., C_{FO} and C_{R12}). Traffic density in the ramp influence zone is 25.4 pc/mi/ln and travelers experience LOS C in this area. At LOS C, speed within the ramp influence area begins to decline as turbulence levels become much more noticeable. Vehicles on both the ramp and freeway segments begin to adjust their speeds to accomplish smooth transitions; (2) in the high-demand scenario, the demand volume significantly surpasses the facility capacity in this area and traffic breakdown occurs in this case. Based on the operational analysis results, it is concluded that the high travel demand level during peak hours is another determining factor which contributes to the recurrent congestion in this area. Field observations also validate such conclusion, as depicted in Figure 5-4.

Table 5-4 Operational Analysis of Tyvola Rd./I-77 On-Ramp Junction

Input Data		
Freeway Data		
	• Number of lanes on mainline freeway: 3 lanes; • FFS of the freeway segment: Average lane width = 12 ft, f_{LW} = 0 mph; Right-side lateral clearance = 9 ft, f_{LC} = 0 mph; TRD = 1.83 ramps/mi $FFS = 75.4 - 3.22 * 1.83^{0.84} = 70.05 \text{ mph} \approx 70\text{mph}$ • Demand flow rate on mainline freeway: AADT 2014 = 159,000 vpd $DHV_{Low} = 159{,}000 \times 0.07 \times 0.50 = 5{,}565\ vph$ $DHV_{High} = 159{,}000 \times 0.12 \times 0.55 = 10{,}494\ vph$ • Truck percentage = 7%, RV percentage = 0%	
Ramp Data		
	• Type of ramp: on-ramp • Side of junction: right-hand • Number of lanes on ramp roadway: 2 lanes; • Number of ramp lanes at ramp-freeway junction: 2 lanes; • FFS of the ramp roadway: 45 mph; • Length of acceleration/deceleration lane(s): Length of the first acceleration lane (L_{A1}): 368 ft, and Length of the second acceleration lane (L_{A2}): 1,253 ft; • Demand flow rate; AADT 2014 = 11,000 vpd $DHV_{Low} = 12{,}000 \times 0.07 \times 0.50 = 420\ vph$ $DHV_{High} = 12{,}000 \times 0.12 \times 0.55 = 792\ vph$ • Truck percentage = 0%, RV percentage = 0%	
Other Parameters:		
	• Peak hour factor: 0.9; • Terrain: Level; • Driver population factor: 1.00; and • Adjacent upstream or downstream ramps: None (A two-lane ramp is always considered to be isolated in HCM 2010).	

Output Data	Low-Demand Scenario	High-Demand Scenario
V_{FO}	6,867 vph	12,948 vph
C_{FO}	7,200 vph	7,200 vph
V_{R12}	4,167 vph	10,248 vph
C_{R12}	4,600 vph	4,600 vph
D_R	25.4 pc/mi/ln	72.7 pc/mi/ln
LOS	C	F

Note: (1) V_{FO}: exiting freeway volume, (2) C_{FO}: capacity of exiting freeway lanes; (3) V_{R12}: the sum of the ramp flow and the freeway flow in lanes 1 and 2, i.e., $V_{R12} = V_{12} + V_R$; (4) C_{R12}: the sum of the capacity of the ramp flow and the freeway flow in lanes 1 and 2; (5) D_R: density of the ramp influence area; and (6) LOS: level of service.

Figure 5-4 Traffic Congestion at the On-Ramp Junction near the Northern Endpoint of Bottleneck Group 1 (8:50 AM, September 1, 2016)

5.3.2 Developing Bottleneck Mitigation Solutions

To alleviate traffic congestion in this area, the following bottleneck mitigation measures can be considered:

- **Capacity expansion.** Adding two auxiliary lanes on northbound I-77 between the on-ramp junction (which connects Tyvola Road and I-77 NB) and Exit 6B. It is expected that adding auxiliary lanes to the existing configuration will minimize the interactions between mainline traffic stream and merging and diverging traffic stream from adjacent ramps.
- **Congestion pricing.** Congestion pricing is a travel demand management tool. As certain roadways are priced, drivers will be more likely to combine multiple destinations into one trip, share vehicles, change their destination, and/or shift routes to untolled or less tolled roads.

- **Expanding existing roadway capacity and implementing congestion pricing.** Such bottleneck mitigation strategy represents the idea that improving roadway performance through increasing network capacity supply while simultaneously managing travel demand.

It is important to note that the author have also performed similar analyses for all other bottlenecks identified in a.m. and p.m. peak periods to identify leading factors contributing to the congested traffic near the bottleneck. Base on this, corresponding bottleneck mitigation measures have been developed accordingly.

5.4 Summary

In this chapter, geometric information of each bottleneck group identified in Chapter 4 was collected and analyzed in order to determine contributing factors to each bottleneck group. An operational analysis, which is based on the HCM 2010 procedure, is conducted to help identify bottleneck causes. The results indicate that, in this study, the most common causes of the bottlenecks include excessively high travel demand, dense ramp junctions along interstates, and lane drops, etc. After that, corresponding countermeasures are developed in order to alleviate traffic congestion for each bottleneck group.

Additionally, it is also noticed that although the static analytical procedures presented in the Hihgway Cpacity Manual (which computes density and LOS of a freeway facility) is appropriate for analyzing the performance of localized road sections (such as the ramp influence zone), such procedures are limited in their ability to analyze corridor or network-wide effects. To address this issue, a mesoscopic dynamic traffic modeling tool, DTALite, will be employed to quantitatively evaluate traffic conditions before and after the implementations of proposed bottleneck mitigation strategies at both the local and regional level, as elucidated in Chapters 6 and 7. A detailed comparison of various traffic assessment tools was provided in Table 2-4.

CHAPTER 6: CALIBRATING AND VALIDATING A BASE DTA MODEL

To evaluate and prioritize the effectiveness of proposed bottleneck mitigation strategies in Chapter 5, a holistic transportation modeling approach is needed to improve freeway bottleneck analysis at the network level. As discussed previously, the static analytical procedures are only suited for analyzing localized road sections and they are incapable of capturing traffic flow dynamics at the network level. In addition to that, because the causes of bottlenecks can be highly complex and if one is ameliorated, one or more unexpected bottlenecks can quickly emerge elsewhere. In this dissertation, a mesoscopic dynamic traffic assignment (DTA) modeling tool, DTALite, is employed for evaluating various freeway bottleneck mitigation strategies. DTALite is a fully functional, open-sourced mesoscopic DTA simulation package that can be downloaded from http://code.google.com/p/nexta/. In conjunction with the *Network eXplorer for Traffic Analysis* (NeXTA) graphic user interface, it provides transportation planners, engineers, and researchers with a theoretically rigorous and computationally efficient traffic network modeling tool (Zhou and Taylor, 2014). The major benefit of using DTA is the capability of describing traffic congestion at a finer spatial and temporal resolution than traditional static traffic assignment models (Sloboden et al., 2012).

The primary goal of this chapter is to describe how to develop and calibrate a DTA model to accurately represent the base year traffic conditions for the test bed bottleneck sites as identified in Chapter 4. The robustness of the calibrated parameters is then tested in the validation step using a different subset of network data and/or performance measures. Once the model is well calibrated and validated for the base year, it will be used in the next chapter to evaluate the impact of various future scenarios on system bottleneck mitigation and travel conditions by incorporating future planning-level decisions and projected demand data into the base model.

6.1 Data Preparation

Typical inputs to DTA models can be classified as supply-side and demand-side. The supply-side inputs to a simulation-based DTA model include parameters such as roadway capacities, the number of lanes and speed limits. Demand-side inputs comprise information related to the composition of vehicle types and time-dependent origin-destination (O-D) matrices. During the model calibration and validation processes, field observed traffic data (e.g., traffic volumes and/or route travel times) need to be collected and used as well. The following subsections elaborate the datasets used for developing the base DTA model for the test bed sites and the datasets used for model calibration and validation procedures.

6.1.1 Network Description

The study network used for scenario testing is located in the Mecklenburg County (i.e., Charlotte metropolitan area), North Carolina. An initial version of the regional travel demand model, which is the model used by the Charlotte Regional Transportation Planning Organization (CRTPO) and Charlotte Department of Transportation (CDOT) staff for their current travel demand forecasting activities, was requested and provided to the research team in the TransCAD format. In 2012, a household travel survey was conducted to update the trip generation and trip distribution information in the CRTPO model. Other updated data was also collected and used from the 2010 Census (CRTPO, 2014). In this dissertation, the network data and the projected O-D travel demand for the year of 2015 are used for constructing the base DTA model. Note that in the previous tasks undertaken in this study, the primary freeway bottleneck identification method was developed based on the vehicle probe data collected in the year of 2015 (see Section 4.2.3 for a brief description of the dataset used for bottleneck identification). Thus, for consistency purposes, the year of 2015 is also set as the base year and the model calibration and validation work presented in subsequent sections are based on the traffic conditions in 2015.

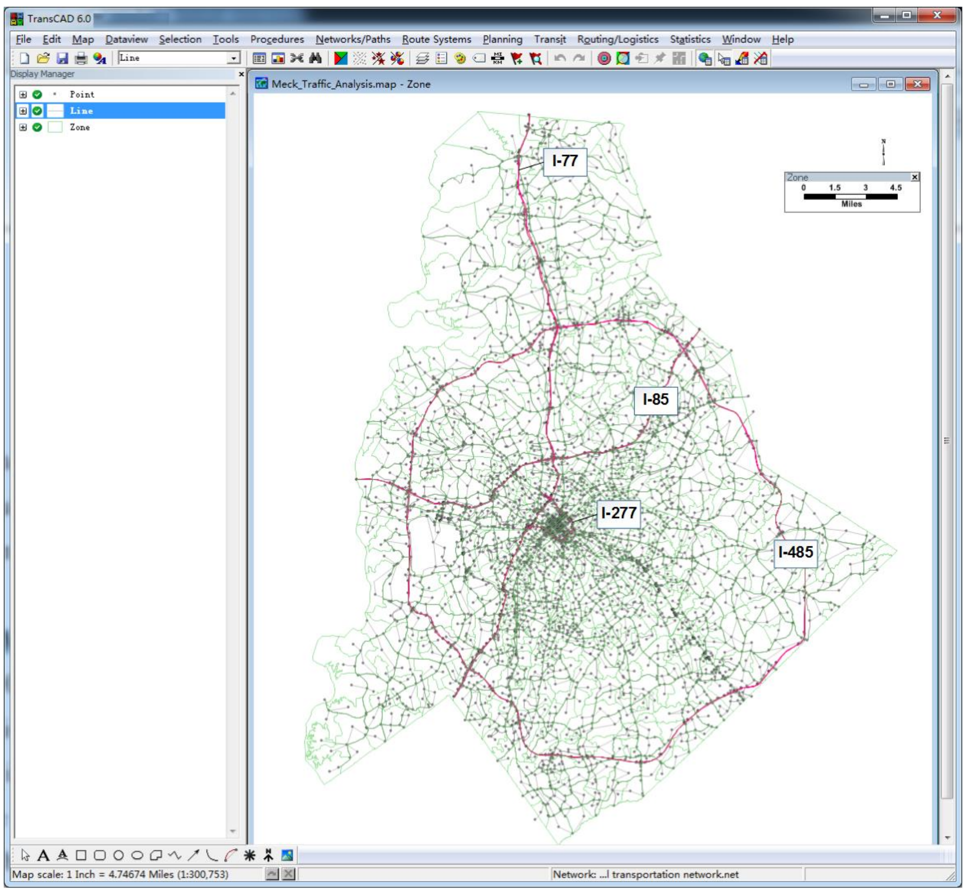


Figure 6-1 Charlotte Metropolitan Area Network Loaded in TransCAD

The Mecklenburg County regional planning network used by the CRTPO consists of 1170 traffic analysis zones (TAZs), 4499 nodes and 9522 links. The maximum service flow rate (in pc/h/lane), number of lanes, and the speed limit (in mph) provided by CRTPO are directly used as inputs in developing the dynamic traffic assignment model in DTALite. Figure 6-1 shows the Mecklenburg County regional planning network in the TransCAD environment. The four major interstate freeways in the Charlotte metropolitan area, I-77, I-85, I-485, and I-277, are highlighted in the figure. The current road network structure coded in TransCAD is converted to the data structure used in the NeXTA/DTALite package using NeXTA's network import tool. Figure 6-2 presents the converted regional network in the NeXTA/DTALite environment. A step-by-step tutorial regarding how to convert the network file from TransCAD into NeXTA/DTALite can be found in Lin and Tian (2015) and Zhou et al., (2015).

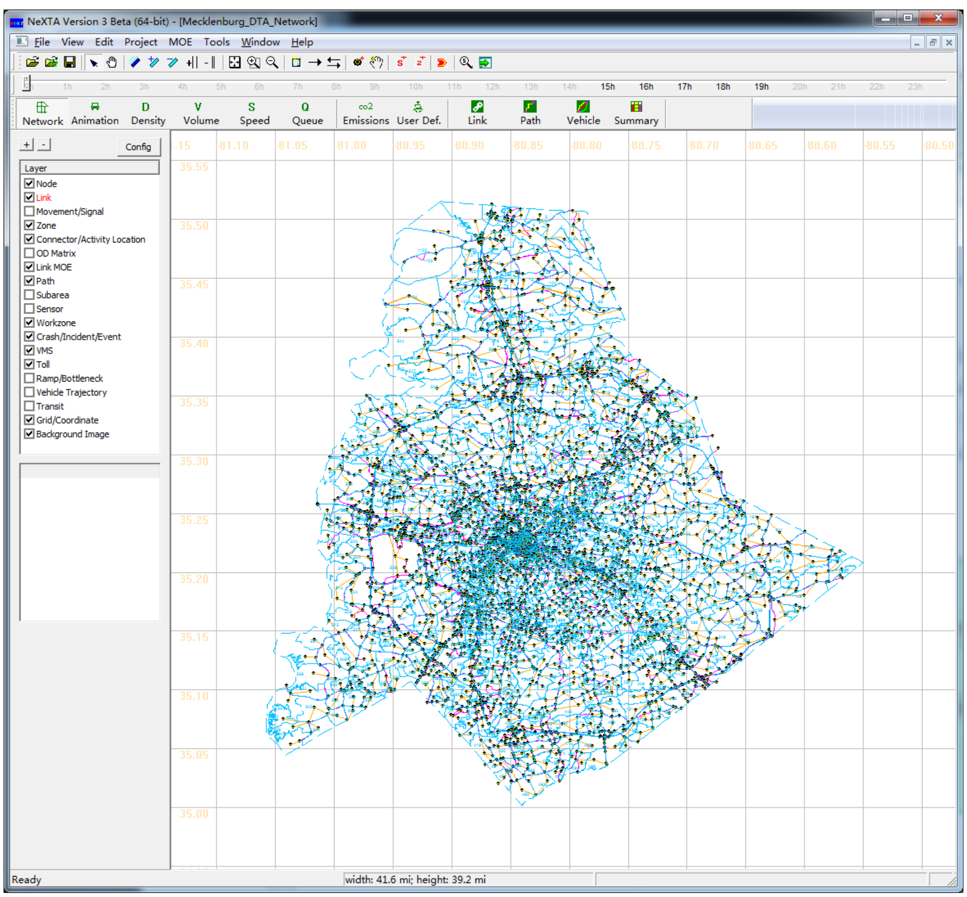


Figure 6-2 Charlotte Metropolitan Area Network Loaded in NeXTA/DTALite

6.1.2 Travel Demand Attributes

6.1.2.1 *Time-Dependent Demand Profile*

The original travel demand data obtained from CRTPO contains trip information during four different time periods: morning peak period (6:30 to 9:30 a.m.), midday time period (9:30 a.m. to 3:30 p.m.), evening peak period (3:30 to 6:30 p.m.), and nighttime period (6:30 p.m. to 6:30 a.m.). Research results achieved in previous sections have already clearly shown that, both the intensity and reliability of traffic congestion on interstate freeways during evening peak periods are worse than that in morning peak periods in the study area. As such, the following model calibration and validation procedures focus on representing traffic conditions during p.m. peak periods.

The original peak time analysis period is defined as from 3:30 to 6:30 p.m.. However, in order to measure network statistics accurately over the entire analysis period, a 30-minute “warm-up” period is added before the p.m. peak analysis period (3:00 to 3:30 p.m.). Additionally, a 30-minute duration is set as the “cool-down” period after the completion of the analysis period (6:30 to 7:00 p.m.). Over the entire simulation period, travel demand is loaded into the network in 15-minute intervals. Note that the original O-D tables provided by CRTPO span the entire p.m. peak period. As such, a disaggregated temporal demand profile at a finer time resolution (i.e., 15-minute) needs to be derived. In this case, the 24-hour demand profile used in the FHWA report *Traffic Analysis Toolbox Volume XII: Work Zone Traffic Analysis - Applications and Decision Framework* is used to develop the demand loading profile in 15-minute intervals, as illustrated in Figure 6-3 below (Zhang et al., 2012).

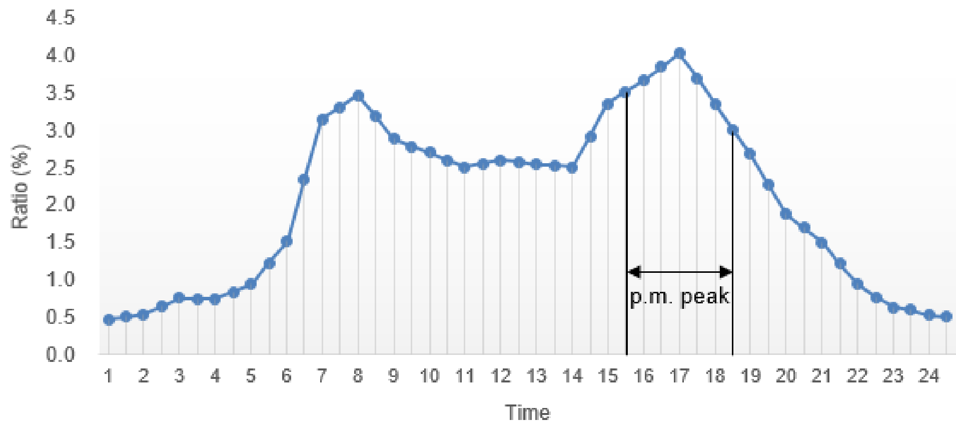


Figure 6-3 24-Hour Demand Profile

(Cited from *Traffic Analysis Toolbox Volume XII: Work Zone Traffic Analysis – Applications and Decision Framework*; Original Source: Transportation Research Board, 2010)

On the basis of Figure 6-3, the percentage of the 15-minute demand to the overall p.m. peak period demand is determined through linear interpolation. Figure 6-4 presents the four time periods incorporated throughout the entire simulation period. Note that the p.m. peak analysis period (3:30 to 6:30 p.m.) is the primary time period of interest. As shown in Figure 6-4, the height of each bar represents the ratio of the demand in the respective 15-minute interval to the overall travel demand during evening peak period. The sum of the twelve bars within the peak analysis period is restricted to be 100%. In this study, two relatively low demand loading ratios (2.5% and 5%) are set up for the "warm-up" period before the start of the peak analysis period. The third period (6:30 to 7:00 p.m.) is intended to simulate post-peak traffic and is referred to as the "cool-down" period. Like the "warm-up" period, the demand loading percentages are set to be 5% and 2.5% to allow the travel demand to gradually reduce to zero. Finally, the fourth period (i.e., the network clear-up time period which runs from 7:00 p.m. to the time the network is clear up) is designed to clear up the network. Zero travel demand is loaded into the network during this time period. By doing so, it allows sufficient time to collect statistics for all vehicles generated during the analysis period (Kittelson & Associates, 2014). It is also worth mentioning that, deriving the 15-minute demand profile using empirical values based on the travel patterns in the past studies may generate a series of dynamic O-D demand matrices which are different from reality on the ground. Later, a subarea of the Charlotte regional network will be created and used for scenario testing purpose. The initial O-D table and the temporal demand profile are used to create the network path flows through running the DTALite assignment engine. Based on the assignment results, the built-in origin-destination matrix estimation (ODME) tool in NeXTA/DTALite will be employed to adjust the demand patterns in the sub-network. More detailed information about the DTALite's ODME feature is introduced in Section 6.2.

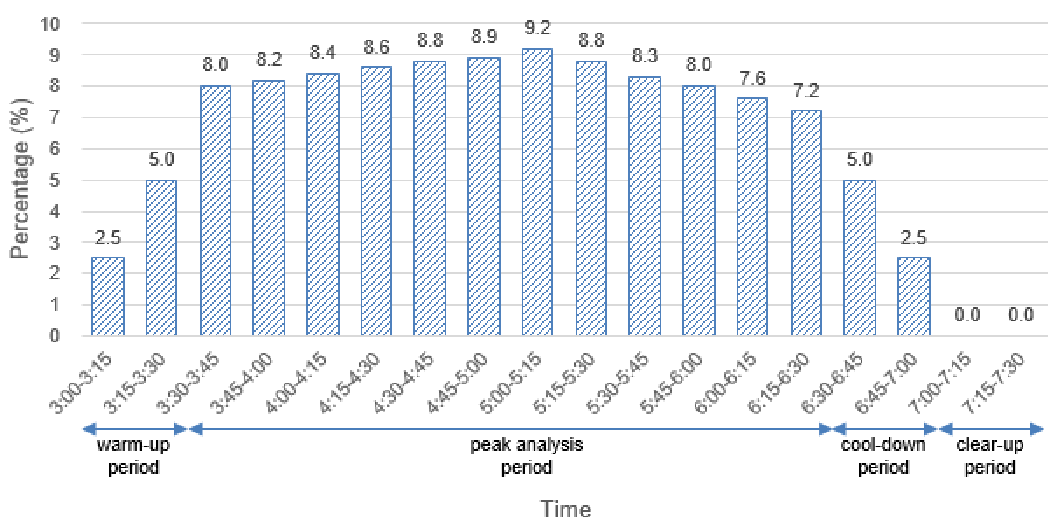


Figure 6-4 Demand Profile for the Base Network

6.1.2.2 *Demand Matrices by Vehicle Class*

The original travel demand files obtained from CRTPO comprise multiple matrices representing travel demand generated by different vehicle types: single occupancy vehicles (SOV), two-person carpool vehicle trips (POOL2), three or more person carpool vehicle trips (POOL3), commercial vehicles (COM), medium trucks (MTK), and heavy trucks (HTK). For convenience purposes, all vehicle types are converted into passenger car units using the following equation:

$$PCU = SOV + POOL2 + POOL3 + COM + 1.5*MTK + 1.5*HTK \quad \text{Eq. 6-1}$$

where PCU is the total passenger car units. The passenger car equivalent (PCE), 1.5, is used for converting medium trucks and heavy trucks into equivalent passenger car units (TRB, 2010).

6.1.3 Description of the Subarea Network

The original Charlotte regional network is relatively large. As such, directly calibrating such a DTA model requires extra care and can be difficult and time-consuming. Instead, focusing on a subarea of the original network produces great efficiencies in testing and debugging the enhanced DTA model. In this dissertation, a sub-network is created from the original network, as shown in Figure 6-5.

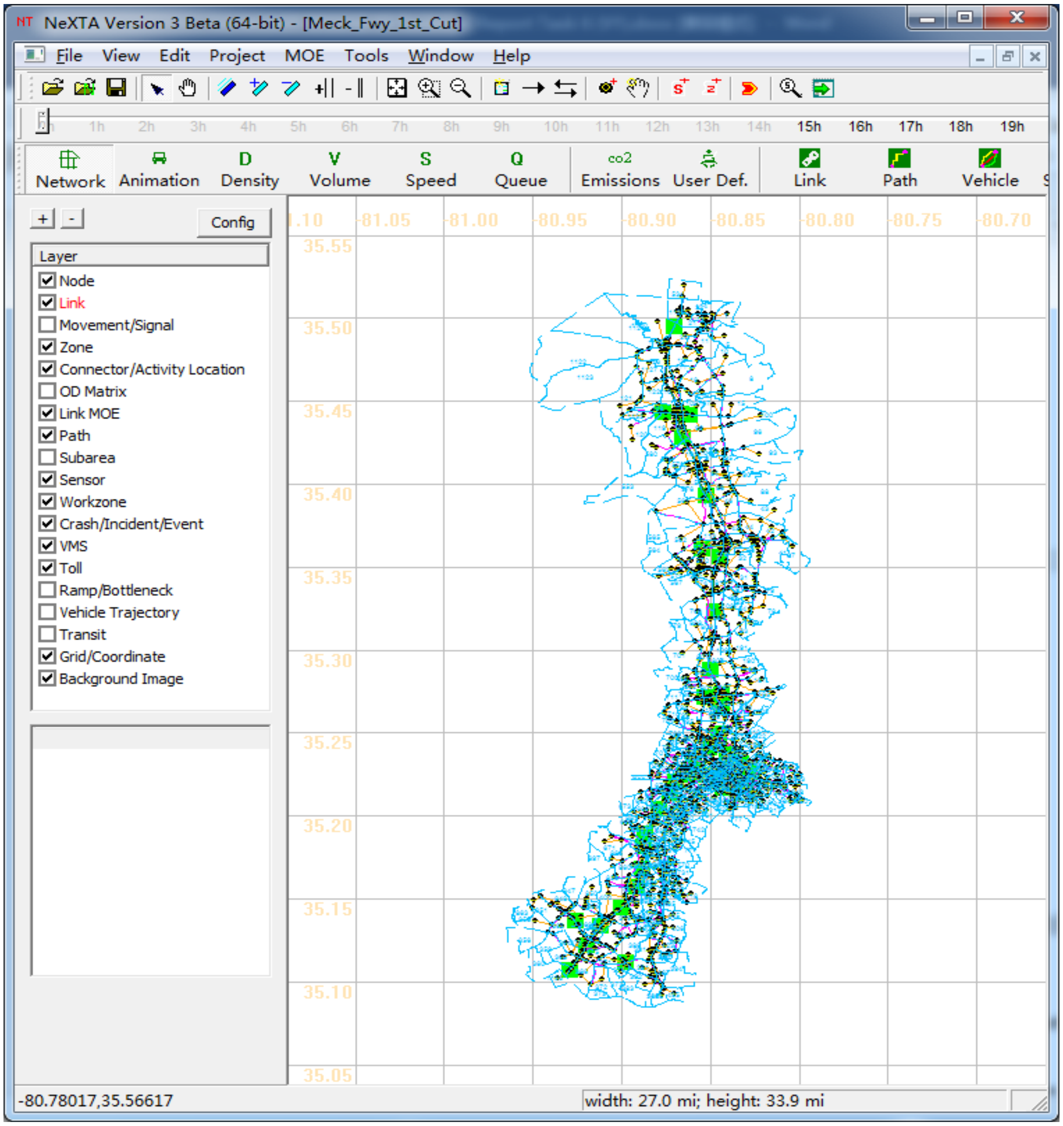


Figure 6-5 A Sub-Network for the DTA Model

The subarea network is characterized by significant congestion on both interstate freeways, I-77 and I-277, in the Charlotte metropolitan area. I-77 is an important interstate highway across the Mecklenburg County and serves as a major north-south corridor for through traffic. I-277 is a four to eight-lane downtown beltway that surrounds Charlotte center city. It carries a high portion of the into- and out-of-town traffic during peak periods. According to the research results achieved in Section 4.2.3, during p.m.

peak periods, 11 out of 14 bottleneck groups identified on interstate freeways in the Charlotte area are located on either I-77 or I-277. In that regard, the selected sub-network covers the majority of the freeway bottleneck groups as discerned in Section 4.2.3. The Uptown Charlotte area is also incorporated in the sub-network as it is a major trip generation and attraction hub in the study area.

NeXTA/DTALite's *Subarea Cut* tool is used to simplify the subarea creation process (Lin and Tian, 2015). Based on the subarea boundary designated by the user, the *Subarea Cut* tool in NeXTA deletes all of the network objects (nodes and links) outside of the subarea boundary and automatically creates external zones at the subarea boundary. When the subarea is created, the path flows are aggregated at the links which cross the subarea boundaries, assigning the aggregated trips to the external zone created at the end of those links (Taylor et al., 2012). Later, in the calibration step, NeXTA's ODME feature will be used to update the demand table in the sub-network. Table 6-1 lists the summary statistics of the sub-network created from the original CRTPO regional planning network. This subarea is well suited to the scenario testing purpose due to its size and the prevalence of congested conditions during typical weekday evening peak hours.

Table 6-1 Summary Statistics about the Charlotte Subarea Network

Network Characteristic	**Entire Network**	**Subarea Network**
Number of nodes	4,499	618
Number of links	9,522	1,098
Number of TAZs	1,170	119
Number of originating vehicle trips	643,501	243,817

6.1.4 Traffic Volume Counts

The model calibration process involves the identification of a set of DTA model inputs and parameters that can result in model outputs that are reasonably close to those field observations. Typical data used for model calibration consists of traffic volumes, travel times and speeds. In this dissertation, the *average annual daily traffic (AADT) Stations Shapefile* which contains AADT values for the freeway and major thoroughfares are obtained from NCDOT's website (NCDOT, 2016). The original shapefile provides AADT values for each count station for several years (from 2002 to 2015). It is noticed that only a portion of the count stations have updated AADT values for the year of 2015. As such, only those count stations providing AADT values for the year of 2015 are selected for calibration purposes. Certainly, all select sensor stations are located within the sub-network. As a result, a total of 40 traffic count stations are selected and their locations are represented as green squares in Figure 6-5.

In order to be consistent with the simulated traffic counts, the AADT values collected in 2015 are rescaled for the evening peak period (3:30 - 6:30 p.m.) using a combination of the *K*-factor and *D*-factor as recommended in the *Highway Capacity Manual* 2010 as well as the 24-hour demand profile as presented in Figure 6-3. Table 6-2 presents an example of the traffic volume counts derived at various sensor stations; such data will be used in the subsequent model calibration procedure.

Table 6-2 Example of Traffic Volume Counts Used for Model Calibration

Sensor ID	X Coord.	Y Coord.	From Node ID	To Node ID	Sensor Type	AADT 2015	Start Time (in min)	End_ Time_ (in min)	Count
2	-80.84919739	35.38249969	188	407	link_count	107,000	930	990	3852
							990	1050	4226.5
							1050	1110	3798.5
3	-80.86399841	35.42559814	478	479	link_count	96,000	930	990	3456
							990	1050	3792
							1050	1110	3408
5	-80.83010101	35.22890091	9	11	link_count	76,000	930	990	2736
							990	1050	3002
							1050	1110	2698

6.1.5 Critical Route Travel Times

Upon the completion of the calibration process, the robustness of the calibrated parameters is then tested in the validation step using a different subset of network data. Unlike the traffic volume data used in model calibration step (see discussions in the previous section), this section introduces how to apply the path travel times (instead of using traffic volume data) on several critical routes to validate the performance of the calibrated model. In this regard, both directions of the interstate freeway I-77 in the sub-network are defined as the critical routes. The simulated and field travel times along both directions of I-77 are collected and will be used in the validation step.

The field travel times are calculated using vehicle probe speed data collected on both directions of I-77 in the year of 2015. The data set requested from INRIX contains 5-minute speed observations on all TMCs along the critical routes defined above. Eq. 6-2 illustrates the calculation of the route travel time using vehicle probe speed data:

$$RTT_k = \sum_{i \in I} \frac{L_i}{v_{ik}} \times 60 \qquad \text{Eq. 6-2}$$

where

RTT_k = the route travel time during observation period k (min),

L_i = the length of the i-th segment (mi),

v_{ik} = the vehicle probe speed observed during the k-th time period on TMC segment i (mph), and

I = the set of roadway segments incorporated on the northbound/southbound direction of I-77 in the sub-network.

The constant of 60 converts the travel time in hours into minutes. In order to represent the typical p.m. peak travel conditions in the study area, only non-holiday weekday data are used to extract the route travel times along the critical routes. It is noteworthy that the route travel time obtained from Eq. 6-2 is a rough approximation to the actual travel time. This is because it only accounts for the instantaneous traffic conditions at time period k, while the dynamic characteristics of such traffic conditions (over time and space) are not considered. In particular, for a relatively long route, the actual travel time it takes may significantly change over the time for a vehicle to traverse the entire path. More accurate travel time estimation method is needed in the future.

6.2 Model Calibration

The baseline model is calibrated in DTALite with its built-in ODME tool and manual adjustments. Prior to running the ODME feature in DTALite, several test runs are executed through the assignment engine in NeXTA/DTALite. The main purpose of this step is to check the basic network attributes and geometric representation such as the length and number of lanes, directions, link connectivity, free-flow speeds, and capacities. A thorough network check is helpful for subsequent modeling steps. During the test runs, the baseline network is simulated for 100 days. It is observed that the sub-network typically reaches a relatively stable condition after 20 simulation iterations, as illustrated in Figure 6-6. Hence, in this study, a 30-iteration simulation run is used to create a relatively stable network status in the following procedures.

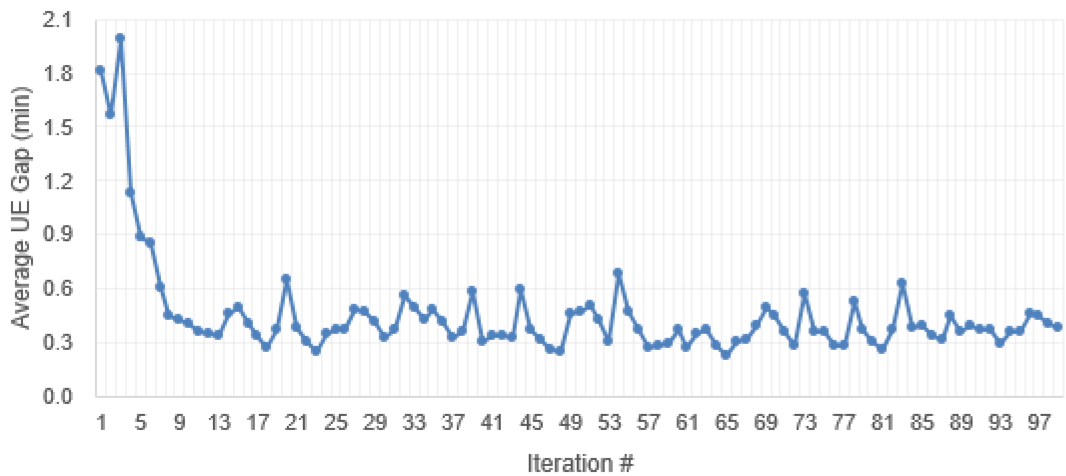
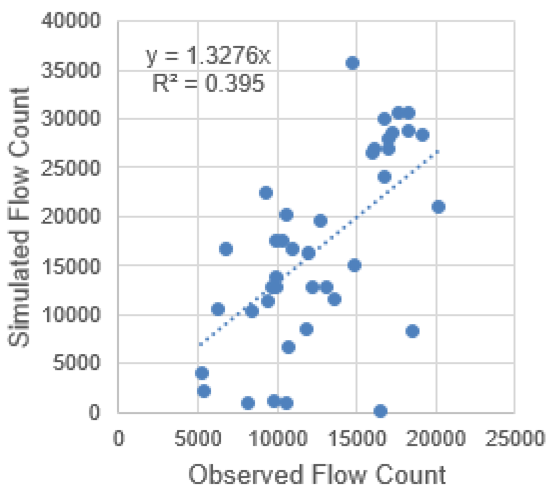
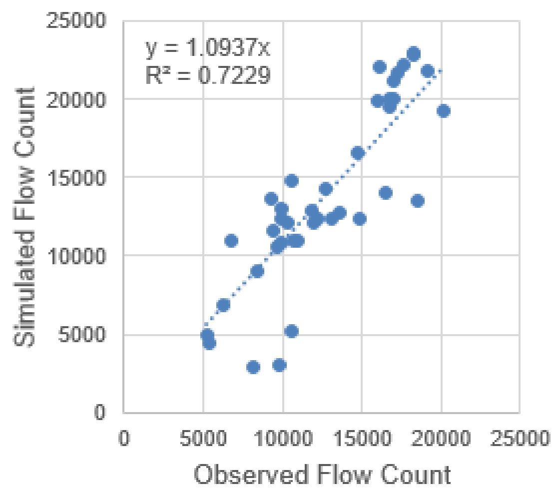


Figure 6-6 Relationship between the Average UE Gap and the Number of Simulation Iterations

NeXTA's ODME tool is a technique used to adjust demand patterns to closely align the simulated O-D link flows with these observed traffic conditions. This is normally accomplished in an iterative process by assigning trips to paths in a network, comparing observed and simulated link counts, adjusting the input demand data, and then moving to the next iteration where the trips are re-assigned (Taylor et al., 2012; Lu et al., 2013). To calibrate the sub-network in the Charlotte metropolitan area, the ODME module in DTALite is set to adjust 5% of the O-D demand at each iteration, allowing the model to run to completion faster without sacrificing solution quality. A detailed description regarding how to use the ODME module in NeXTA/DTALite can be found in NeXTA/DTALite User's Guide (Taylor et al., 2012). Figure 6-7 compares the observed and simulated link counts at the selected count locations. On average, the initial equilibrium assignment (before ODME) produces link volumes that are relatively higher than those observed link volumes with a slope of 1.33 (R^2=0.395). Both under- and over-estimation are observed at multiple locations. After running ODME, the under- and over-estimation are reduced, and the R^2 value improves to 0.73 over all observations.



(a) Before ODME



(b) After ODME

Figure 6-7 Calibration Results for the Charlotte Sub-Network using ODME

6.3 Model Validation

The robustness of the calibrated model is validated through comparing the simulated model outputs with the observed traffic conditions. Figure 6-8 (a) and (b) exhibit a number of statistics about the route travel time during each 5-minute interval in the evening peak period, including the 15th percentile travel time, the average, and the 85th percentile travel time. The route travel times collected from the mesoscopic simulation-based DTA model are presented in Figure 6-8 as well. It is found that, for the sub-network DTA model developed for the current study, the simulated route travel times are generally consistent with field observations. The root-mean-squared-error (RMSE) statistics is further computed to quantitatively measure the differences between the simulated values and the values actually observed:

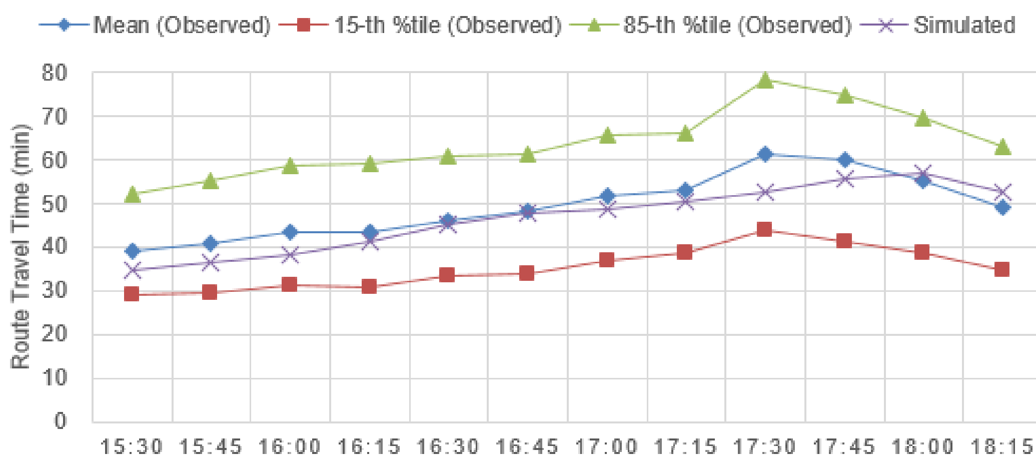
$$RMSE = \sqrt{\frac{\sum_{k=1}^{12}\left(\widehat{RTT}_k - RTT_k\right)^2}{12}} \qquad \text{Eq. 6-3}$$

where

$\widehat{RTT}_k$ = the simulated route travel time during the k-th observation interval (min), and

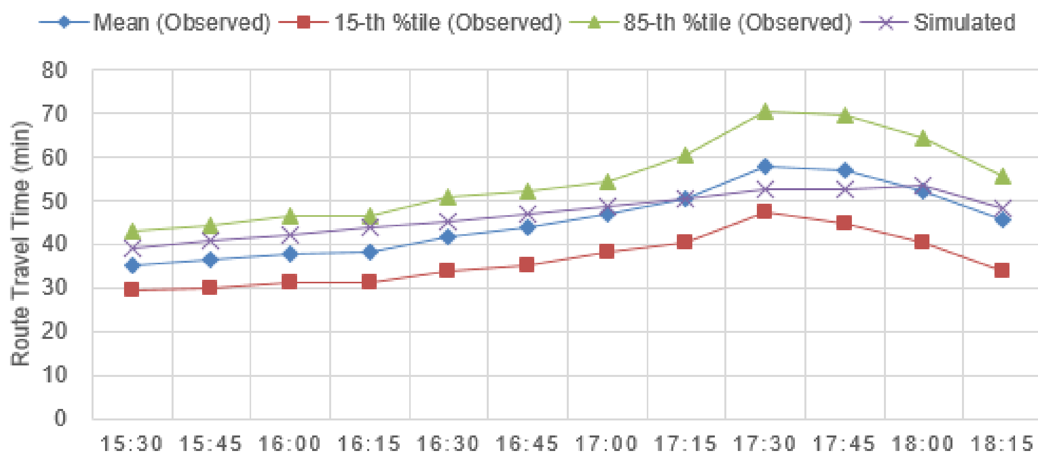
RTT_k = the observed route travel time during the k-th observation interval (min).

The calculated RMSEs for both critical routes along I-77 are 4.06 (Northbound) and 3.71 (Southbound), respectively, indicating a relatively good quality of the calibrated DTA model.



(a) I-77 Northbound

Figure 6-8 Validation Results for Charlotte Sub-Network



(b) I-77 Southbound

Figure 6-8 (*Continued*)

6.4 Summary

This chapter presents detailed information about the development of the mesoscopic DTA model in the study area. Field traffic counts and route travel times are collected to calibrate and validate the baseline DTA model. The validations results indicate a good quality of the calibrated DTA model and it is ready for use in the subsequent task to evaluate the impact of various future scenarios on system bottleneck mitigation strategies.

CHAPTER 7: COMPARING THE IMPACT OF VARIOUS CANDIDATE IMPROVEMENT PROJECTS ON SYSTEM-WIDE AND LOCAL TRAVEL CONDITIONS USING DTA

Although a number of operational improvement strategies can be considered for use to alleviate traffic congestion caused by freeway bottlenecks (as described in Section 2.4), there is no single "silver bullet" answer as to which strategy is the best. This is because the effectiveness of any particular bottleneck mitigation strategy is highly dependent upon the geometric configurations, traffic compositions, driver behaviors, and operating conditions of the network in which it is applied. Since improved traffic conditions and new infrastructure can directly affect route-choice behavior of travelers and will lead to a new regional traffic flow pattern, which may either mitigate or exacerbate existing system bottlenecks, a comprehensive system-wide evaluation of each candidate project is needed before making informed decisions. This is by no means a trivial exercise because the addition of a high-performance link or an extra lane, or even some simple low-cost improvements can lead to a deteriorated system-level performance. Such counterintuitive results have been widely reported in the literature, and such phenomenon is known as the Braess's paradox (Braess, 1968).

The section illustrates how to apply the mesoscopic dynamic traffic assignment (DTA) modeling tool, DTALite, to evaluate and quantify the impact of various candidate bottleneck mitigation projects on system-wide performance. As described before, the sub-network that is used for this purpose encompasses a large area along two significant interstate freeways in the Charlotte metropolitan area, I-77 and I-277, as shown in Figure 6-5. Note that, based on the previous findings, there are 11 out of 14 freeway bottleneck groups during p.m. peak periods located on these two interstate freeways. Table 7-1 presents detailed information about each bottleneck group identified in the study area.

Table 7-1 Bottleneck Groups Identified on I-77 and I-277 (PM Peak Period)

Bottleneck group No.[1]	**Road name**	**Dir.**	**Location**	**TMC ID**	**Length (km)**	**Group ranking index (R_{BG_k})**
1	I-77	SB	Clanton Rd (Exit 7) - W Morehead St (Exit 10A)	231-234	2.4	10285110
3	I-77	NB	NC-73 (Exit 25) - I 485	195-198	5.7	8041208
4	I-77	NB	Tyvola Rd (Exit 5) - Nations Ford Rd (Exit 4)	167-169	1.6	6248469
5	I-77	SB	Gilead Rd (Exit 23) - NC-73 (Exit 25)	210-212	4.8	4000191
6	I-77	SB	Tyvola Rd (Exit 5) - Woodlawn Rd (Exit 6)	239-240	0.9	3956845
7	I-77	NB	Arrowood Rd/Exit 3	165	1.1	2970682
8	I-77	SB	Griffith St (Exit 30)	206-207	0.7	2498131
10	I-77	SB	NC-49/Tryon St (Exit 6)	236	0.7	2159720
12	I-77	NB	I-485 (Exit 2)	163	1.3	1689921
13	I-277	OL	I-77/US-21/W 5th St (Exit 5)	137	0.4	1575874
14	I-77	NB	US-21 (Exit 28)	200	2.3	1138126

Note: [1] Bottleneck groups located on I-485 and I-85 are not included herein.

While implementing bottleneck alleviation strategies on interstate freeways, it is expected that traffic will likely switch to alternate routes as a response to the changes in roadway capacities and/or travel costs due to potential toll charges. To capture the potential route switching behaviors, all nearby arterials and local streets parallel to I-77 are incorporated in the sub-network. The sub-network which represents the base year traffic conditions of the test bed bottleneck sites is developed and calibrated using both automatic (the OD demand matrix estimation (ODME) features in DTALite) and manual modifications to correct some data errors when importing to DTALite. The robustness of the calibrated parameters is then tested in the validation step using route travel time data obtained from INRIX. For more information about the model calibration and validation step, readers are encouraged to refer to Sections 6.2 and 6.3.

Starting from the baseline model, a series of scenarios will be evaluated and compared using the mesoscopic simulation tool – DTALite. Such process can provide answers to the following questions: (1) will a particular bottleneck mitigation strategy mitigate or exacerbate traffic conditions in the study area? (2) what type of bottleneck mitigation strategies should we implement? For instance, capacity expansion or traffic demand management? (3) In some cases, the congested area may cover multiple roadway segments, so how to select roadway segments to implement the proposed mitigation solution? (4) what are the network performance if multiple solutions are combined and implemented simultaneously? It is anticipated that the systematic procedures developed here will enable engineers and decision-makers to directly evaluate, quantity and compare the effectiveness of various bottleneck mitigation solutions.

7.1 Scenario Design

Based on the validated DTA model for the base year, various operational improvement strategies can be considered, which may include but are not limited to the following: shoulder conversions, re-striping merge or diverge areas, lane additions, providing real-time route information, and road pricing, etc. In this chapter, two widely used bottleneck mitigation strategies are considered and evaluated: lane additions and road pricing. Lane addition is a typical engineering solution which aims at alleviating traffic congestion from the capacity side, while road pricing is a common demand management strategy. Both have been widely used in practical applications.

Of practice concern is how to determine the specific location to implement those bottleneck alleviation measures. One can take the first bottleneck group in Table 7-1 as an example, which is located at I-77 southbound with a total length of 2.4 miles and encompasses four TMC segments, as shown in Figure 7-1. While implementing capacity expansion strategies, engineers need to determine which roadway segment the additional lane will be added on. In this research, a three-step procedure is developed to assist in quantifying and assessing the impact of adding an extra lane and/or road pricing in the study area:

- **STEP 1:** evaluate the effectiveness of adding an extra lane;
- **STEP 2:** evaluate the effectiveness of road pricing; and
- **STEP 3:** evaluate the effectiveness of combined strategies.

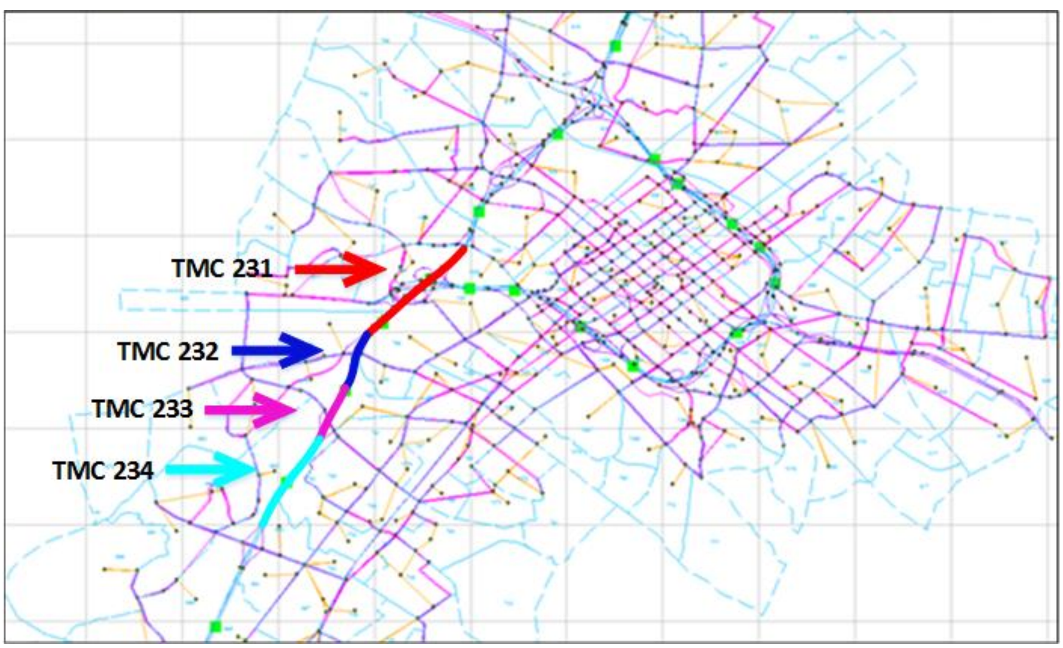


Figure 7-1 Bottleneck Group No. 1 in DTALite

In the first step, the impact of adding an extra lane is evaluated from two perspectives: at the single TMC segment level and at the bottleneck group level. Using the previous example, this dissertation developed several scenarios in an attempt to reduce traffic congestion within the first bottleneck group listed in Table 1:

- **Scenario 1:** adding an extra lane on TMC 231;
- **Scenario 2:** adding an extra lane on TMCs 232 and 233;
- **Scenario 3:** adding an extra lane on TMC 234; and
- **Scenario 4:** adding an extra lane on TMCs 231 to 234;

It is worth mentioning that in some cases multiple TMC segments are located within two neighboring interchanges (such as TMCs 232 and 233 in Figure 7-1) and in practical applications considering adding an extra lane on all of those TMCs simultaneously makes more sense as compared to expanding roadway capacity on only one single TMC. As a result, a total of 26 scenarios were designed for implementing the lane addition strategy, as presented in Table 7-2. Each scenario will be designed and simulated using DTALite. The effectiveness of each solution will be determined by comparing the simulation results of each scenario listed in Table 7-2 with the baseline condition.

Table 7-2 Scenarios Designed for Implementing the Lane Addition Strategy

Scenario No.	Bottleneck Group No.	TMC No.	Scenario Description
1	1	231	Add 1 more lane on TMC 231
2	1	232-233	Add 1 more lane on TMCs 232 and 233
3	1	234	Add 1 more lane on TMC 234
4	1	231-234	Add 1 more lane on TMCs 231 - 234
5	3	195	Add 1 more lane on TMC 195
6	3	196	Add 1 more lane on TMC 196
7	3	197	Add 1 more lane on TMC 197
8	3	198	Add 1 more lane on TMC 198
9	3	195-198	Add 1 more lane on TMCs 195 - 198
10	4	167	Add 1 more lane on TMC 167
11	4	168	Add 1 more lane on TMC 168
12	4	169	Add 1 more lane on TMC 169
13	4	167-169	Add 1 more lane on TMCs 167 - 169
14	5	210	Add 1 more lane on TMC 210
15	5	211	Add 1 more lane on TMC 211
16	5	212	Add 1 more lane on TMC 212
17	5	210-212	Add 1 more lane on TMCs 210 - 212
18	6	239-240	Add 1 more lane on TMCs 239 - 240
19	7	165	Add 1 more lane on TMC 165
20	8	206	Add 1 more lane on TMC 206
21	8	207	Add 1 more lane on TMC 207
22	8	206-207	Add 1 more lane on TMCs 206 - 207
23	10	236	Add 1 more lane on TMC 236
24	12	163	Add 1 more lane on TMC 163
25	13	137	Add 1 more lane on TMC 137
26	14	200	Add 1 more lane on TMC 200

In the second step, the road pricing strategy is implemented at the bottleneck group level. In the meantime, this dissertation considered three different toll rates to implement the road pricing strategy: $0.3 per link, $0.5 per link, and $0.7 per link. For example, for the first bottleneck group in Table 7-1, the following scenarios will be designed and simulated:

- **Scenario 1:** setting link based tolls on TMCs 231-234 with a rate of $0.3/link;

- **Scenario 2:** setting link based tolls on TMCs 231-234 with a rate of $0.5/link; and
- **Scenario 3:** setting link based tolls on TMCs 231-234 with a rate of $0.7/link.

Table 7-3 shows the 15 scenarios which were created for implementing the road pricing strategy. Note that only the top 5 bottleneck groups are evaluated in this study.

In the last step, several scenarios that combine both lane additions and road pricing strategies will be designed and evaluated, as described later in Section 7.2.3.

Table 7-3 Scenarios Designed for Implementing the Road Pricing Strategy

Scenario No.	Bottleneck Group No.	TMC No.	Scenario Description
1	1	231-234	Setting link based tolls on TMCs 231-234 (rate: $0.3/link)
2	1	231-234	Setting link based tolls on TMCs 231-234 (rate: $0.5/link)
3	1	231-234	Setting link based tolls on TMCs 231-234 (rate: $0.7/link)
4	3	195-198	Setting link based tolls on TMCs 195-198 (rate: $0.3/link)
5	3	195-198	Setting link based tolls on TMCs 195-198 (rate: $0.5/link)
6	3	195-198	Setting link based tolls on TMCs 195-198 (rate: $0.7/link)
7	4	167-169	Setting link based tolls on TMCs 167-169 (rate: $0.3/link)
8	4	167-169	Setting link based tolls on TMCs 167-169 (rate: $0.5/link)
9	4	167-169	Setting link based tolls on TMCs 167-169 (rate: $0.7/link)
10	5	210-212	Setting link based tolls on TMCs 210-212 (rate: $0.3/link)
11	5	210-212	Setting link based tolls on TMCs 210-212 (rate: $0.5/link)
12	5	210-212	Setting link based tolls on TMCs 210-212 (rate: $0.7/link)
13	6	239-240	Setting link based tolls on TMCs 239-240 (rate: $0.3/link)
14	6	239-240	Setting link based tolls on TMCs 239-240 (rate: $0.5/link)
15	6	239-240	Setting link based tolls on TMCs 239-240 (rate: $0.7/link)

7.2 Comparison Results

7.2.1 Lane Additions

The impact of adding an extra lane in the close vicinity of the bottleneck is evaluated using several performance metrics, including average trip time (min), average trip distance (mile), average travel speed (mph), and the average volume-to-capacity (V/C) ratio. All these performance measures are collected and compared between the pre- and post-reconfiguration models ("before" and "after" cases, respectively) of the study area using the DTALite mesoscopic simulation tool. Results for various lane addition scenarios are presented in Figure 7-2 to Figure 7-6. The dash red line represents the value of the corresponding performance metric in the baseline condition.

Figure 7-2 indicates that, for all 26 capacity expansion scenarios, adding an extra lane in the bottleneck area has little impact on the network average travel speed (which is the average of the travel speeds on all road segments in the network). The network average travel speed of all 26 scenarios is 40.74 mph (which is only 0.07 mph higher than the average travel speed under the baseline condition) with a standard deviation of 0.08 mph. In contrast, its impact on the average travel speeds of interstate freeways is a little more significant. As exhibited in Figure 7-3, of all 26 scenarios, the average travel speed on interstate freeways is 49.64 mph (0.27 mph higher than the baseline condition) with a standard deviation of 0.42 mph.

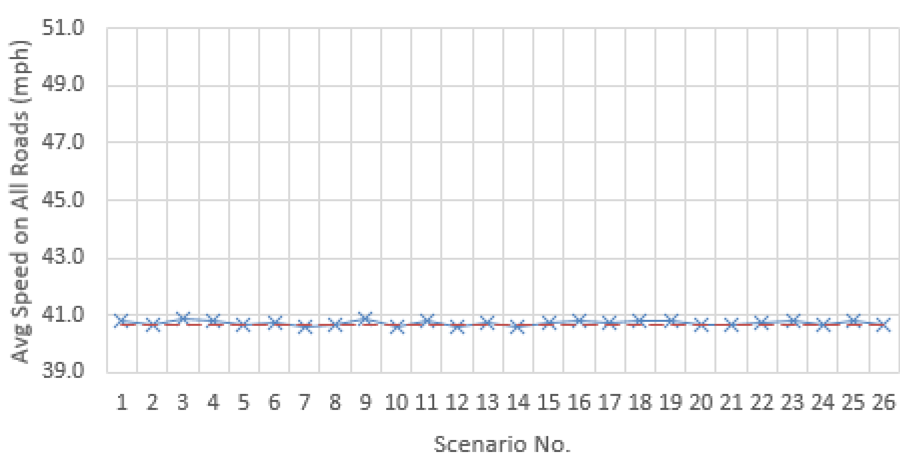


Figure 7-2 Average Travel Speeds on All Roadway Segments

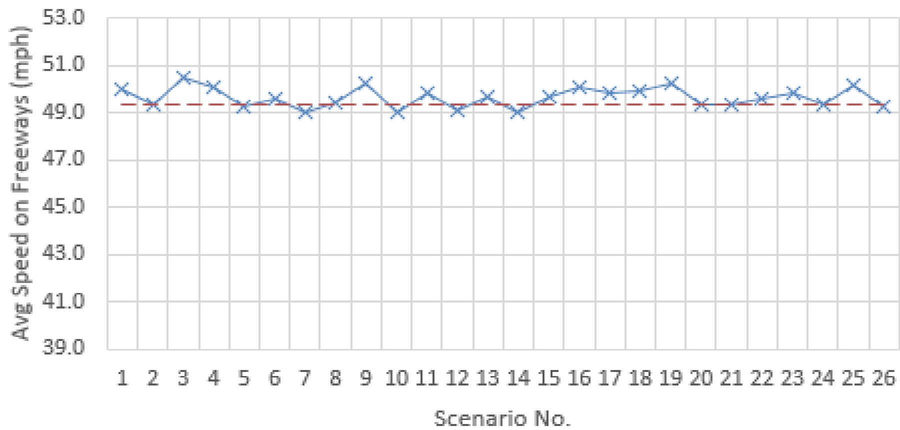


Figure 7-3 Average Travel Speeds on Interstate Freeways

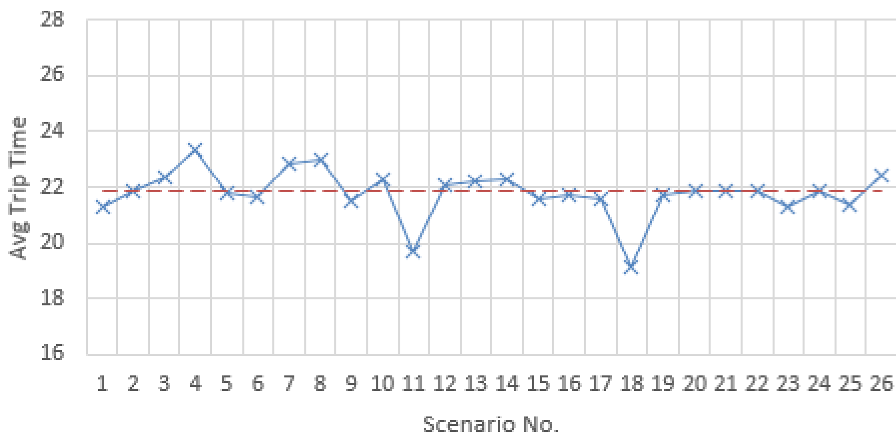


Figure 7-4 Average Trip Time in the Sub-network (min)

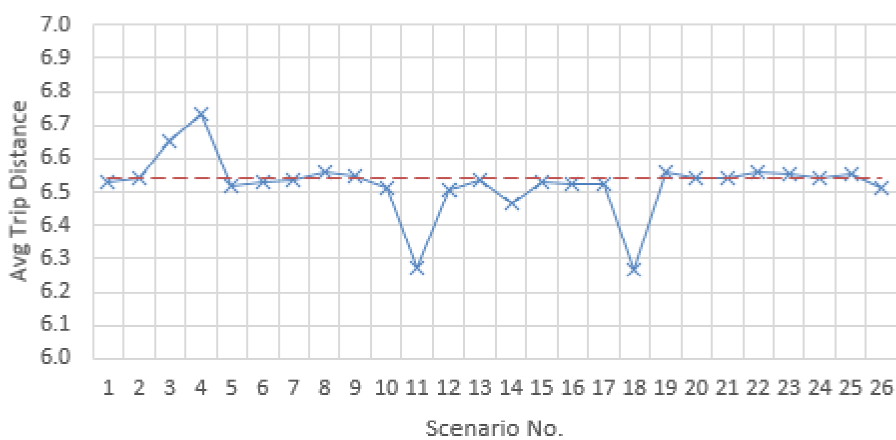


Figure 7-5 Average Trip Distance in the Sub-network (mile)

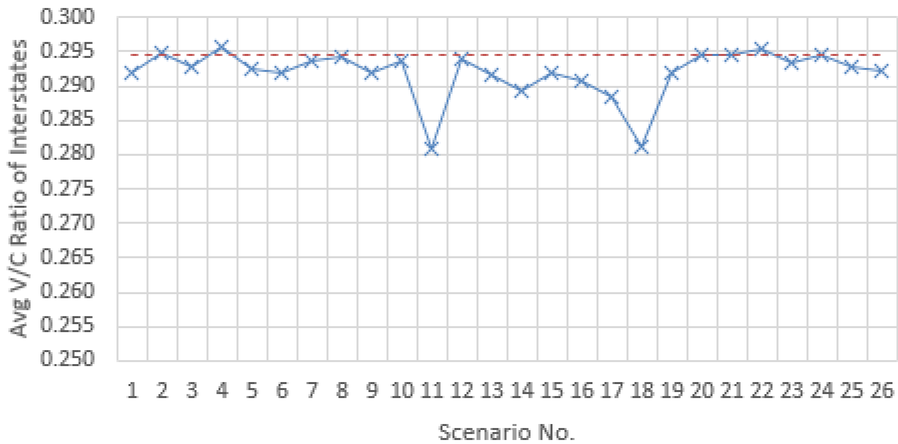


Figure 7-6 Average V/C Ratio of Interstate Freeways in the Sub-network

Figure 7-4 to Figure 7-6 imply that, in some cases, adding an extra lane within the bottleneck area may improve network performances, such as in scenarios 11 and 18 – in which the average travel speeds on interstate freeways are higher than the baseline situation, and the average trip time, the average trip distance, and the average V/C ratio on interstate freeways are lower than that under the baseline conditions. In other words, all metrics indicate an improvement in the network performance under both scenarios. However, it is also observed that adding an extra lane in the bottleneck area may lead to a deteriorated network performance, such as scenario 4. It is observed that after adding one more lane on TMCs 231 – 234, the average trip travel time, the average trip distance, and the average V/C ratio of interstate freeways all slightly increase. As previously mentioned, such counterintuitive results have been widely reported in the literature, and such phenomenon is known as the Braess's paradox. As such, the decision makers must be very careful to ensure that informed decisions are made as to where to add more lanes.

The author also noticed the existence of hidden bottlenecks while evaluating candidate bottleneck mitigation projects. For example, while adding an extra lane on northbound I-77 between I-485 and NC state route 73 (i.e., Scenario 9 in Table 7-2), it is observed that the V/C ratio downstream of the bottleneck slightly increases, although the bottleneck mitigation project does decrease traffic congestion at the bottleneck, as shown in Figure 7-7.

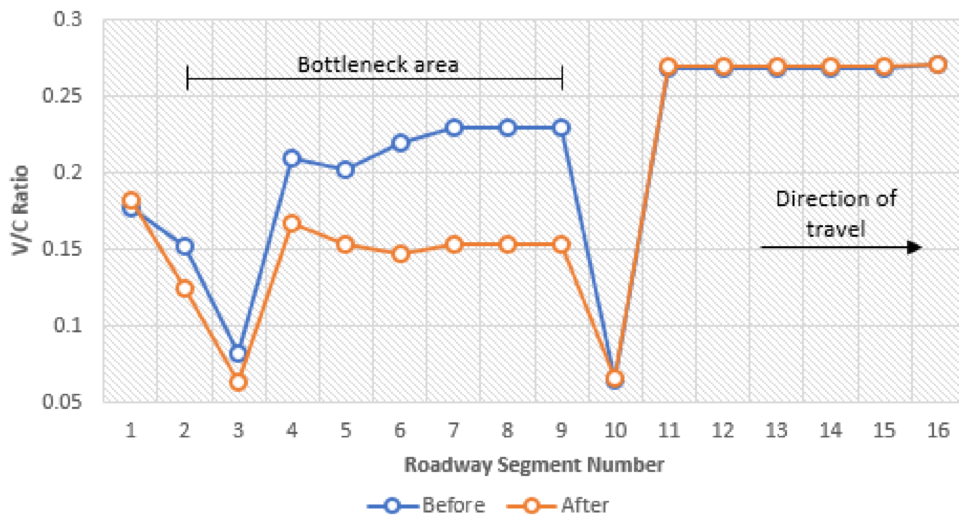


Figure 7-7 Hidden Bottleneck

Because scenarios 11 and 18 both yield a relatively better network performance as compared to other scenarios, their potential effectiveness in combination with road pricing strategy will be further examined in the Section 7.2.3.

7.2.2 Road Pricing

The same MOEs employed to evaluate the impact of adding more lanes are also used to assess the effect of several road pricing scenarios when setting various link-based tolls. Figure 7-8 to Figure 7-12 present the corresponding results with respect to each MOE for all tolling scenarios.

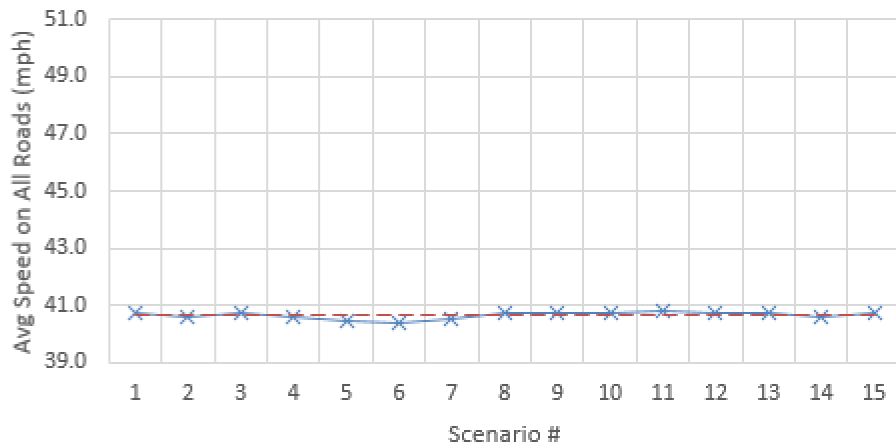


Figure 7-8 Average Travel Speeds on All Roadway Segments

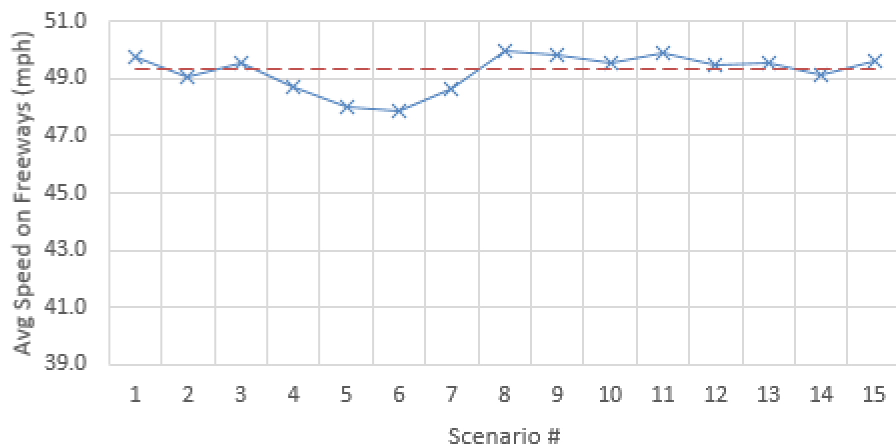


Figure 7-9 Average Travel Speeds on Interstate Freeways

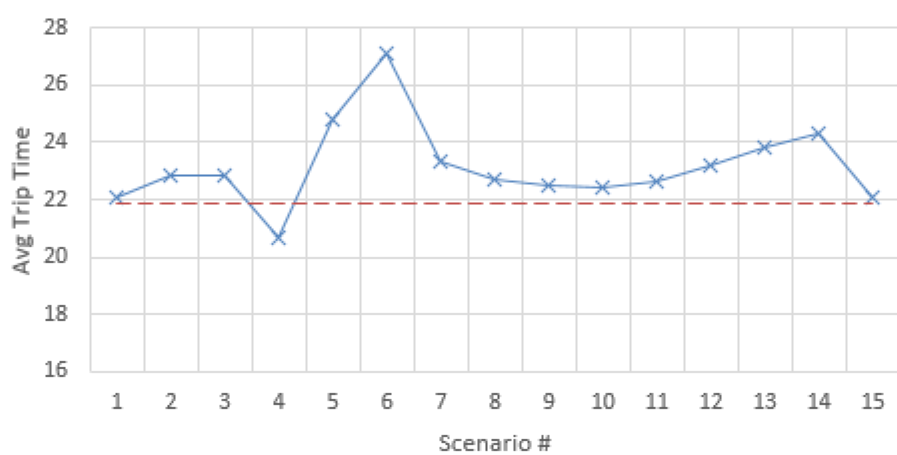


Figure 7-10 Average Trip Time in the Sub-network (min)

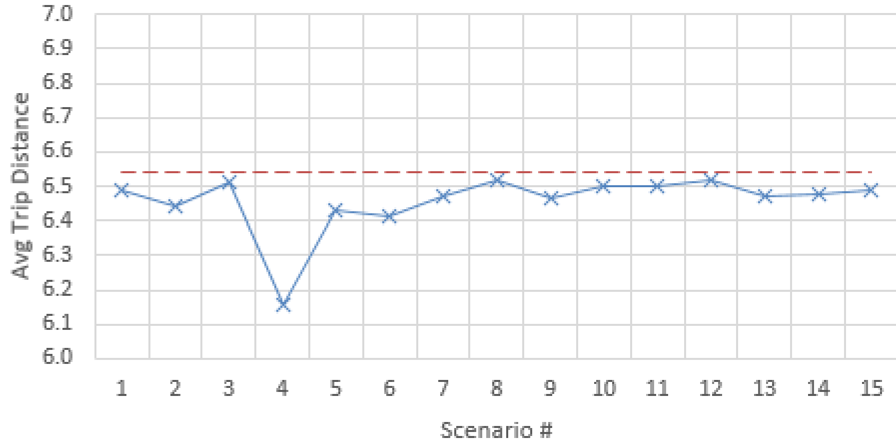


Figure 7-11 Average Trip Distance in the Sub-network (mile)

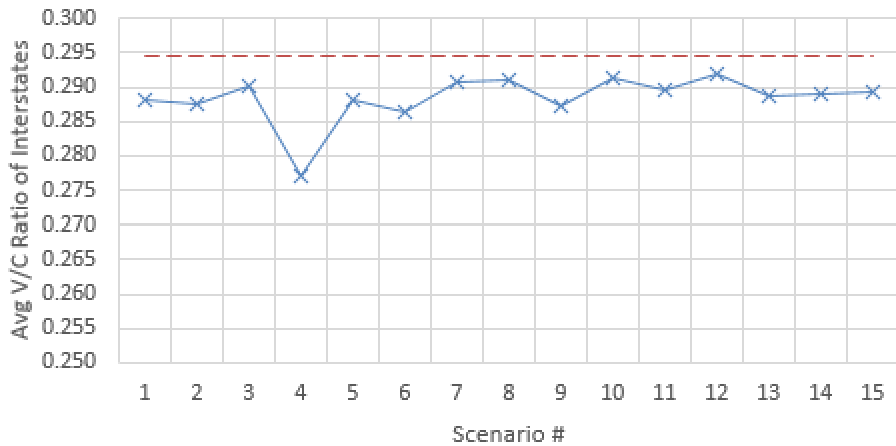


Figure 7-12 Average V/C Ratio of Interstate Freeways in the Sub-network

Similar to those lane expansion scenarios, the impact of applying link-based toll strategy on the network average travel speed is minor, as shown in Figure 7-8. In contrast, they also have a little more significant influence on the average travel speeds on freeway segments (Figure 7-9). Interestingly, charging vehicles in the close vicinity of the bottleneck results in decreased trip distances (Figure 7-11) and V/C ratios on interstate freeways (Figure 7-12), and increased trip travel times (Figure 7-10, except for scenario 4). The finding is reasonable considering the fact that increasing travelers' cost on interstate freeways (by levying tolls) will induce a portion of users to switch to local roads, in which the speeds are relatively lower and frequent stops are typically encountered due to different controls (signalized- or STOP/YIELD sign- controlled) at the intersections although they may be more direct in connecting origins to destinations and therefore shorter in travel distance. As a result, the average trip length and average V/C ratio on interstate freeways will be reduced, and the average trip travel time will be increased accordingly.

In particular, this study carefully examined the impact of adding toll lanes under scenario 4. Figure 7-13 illustrates the locations of the toll lanes in the study area. Thanks to the Link MOE tool provided in DTALite, it is possible to compare the traffic volumes before and after introducing the toll lanes. As is shown in Figure 7-14, during most p.m. peak time period, the inflow rate on TMC 199 in the base scenario (the pink curve) is higher than that under the tolling condition (the red curve). Such phenomenon clearly indicates the impact of adding toll lanes will affect drivers' route choice behavior and thus will influence the traffic volume on the mainline interstate freeway in the sub-network.

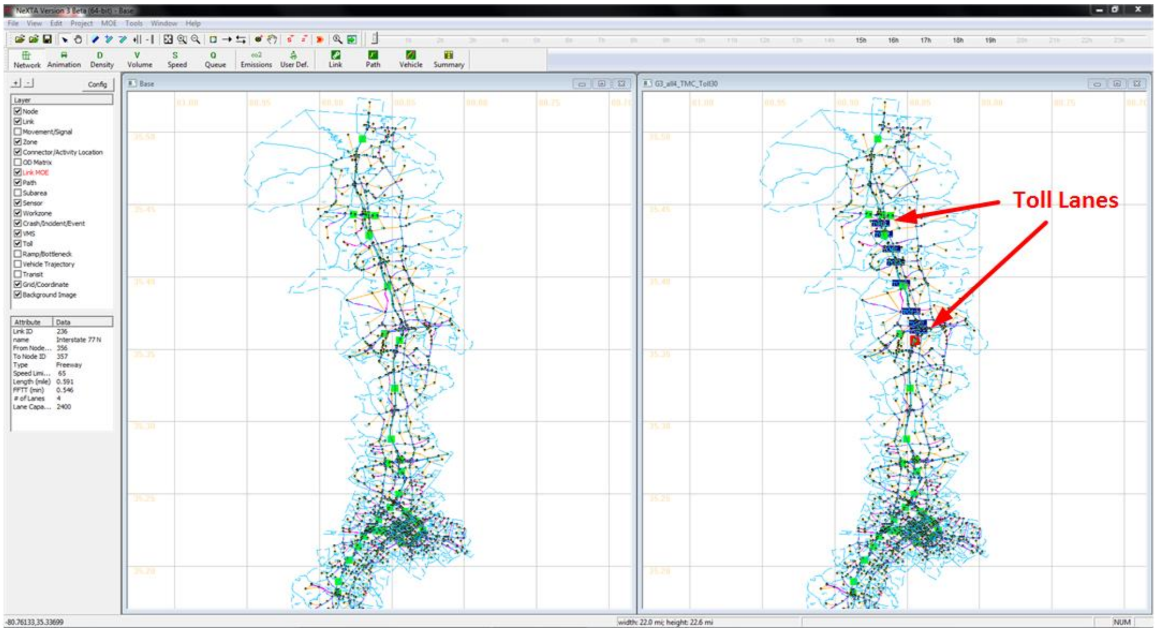


Figure 7-13 Setting Toll Lanes on I-77 NB (Scenario 4)

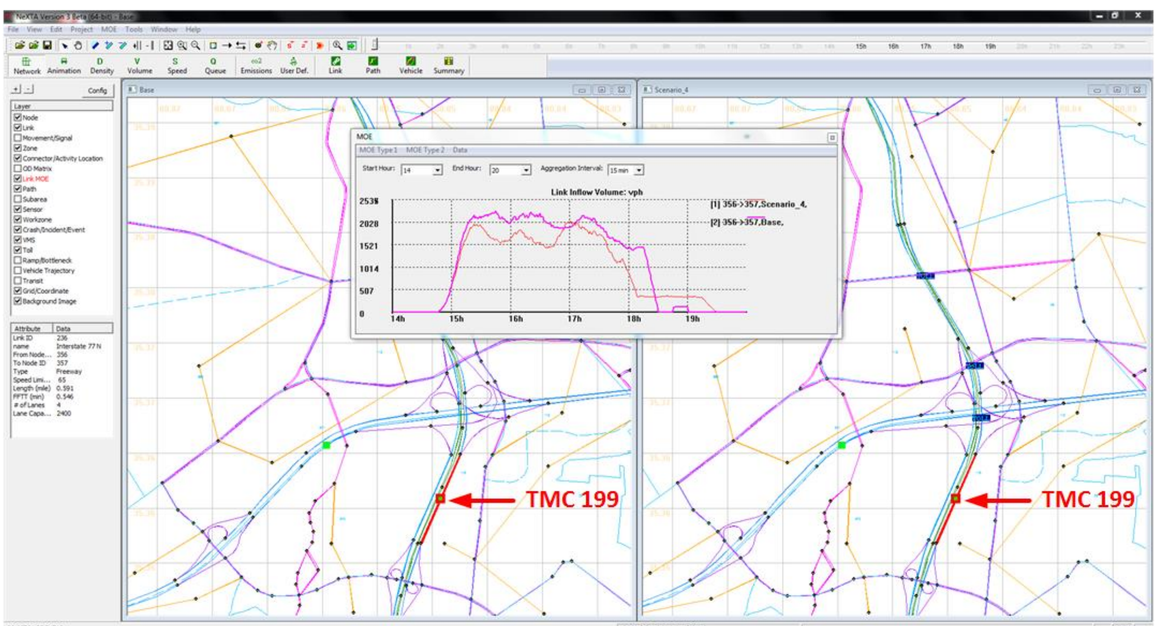


Figure 7-14 Traffic Volume Changes Caused by Levying Tolls on Toll Lanes

7.2.3 Combined Strategies

The primary goal of this section is to assess the feasibility and effect of concurrent operational improvement strategies on network performance. In the first two steps, there are 26 lane expansion scenarios and 15 road pricing scenarios, respectively. It is certainly impossible to enumerate all strategy combinations (i.e., a total of $2^{26} \cdot 2^{15} = 2^{31}$ combinations minus some overlapping scenarios) and run all these simulations within a reasonable amount of time. As such, only a limited number of strategy combinations are evaluated herein. This dissertation selects scenarios 11 and 18 from the lane addition strategy group because both scenarios yield a relatively better network performance, and scenarios 1 to 6 in the road pricing strategy group for evaluation (scenarios 1 to 3 are related to the most severe bottleneck group, scenario 4 corresponds with an increased network performance). Table 7-4 describes the 18 strategy combinations considered in this section.

Table 7-4 Combinations of Bottleneck Mitigation Strategies Evaluated

ID	**Lane Addition Scenario ID**		**Road Pricing Scenario ID**						**Solution Description**
	11	**18**	**1**	**2**	**3**	**4**	**5**	**6**	
1	1	0	1	0	0	0	0	0	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 231-234 (rate: 0.3$/link)
2	0	1	1	0	0	0	0	0	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.3$/link)
3	1	1	1	0	0	0	0	0	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.3$/link)
4	1	0	0	1	0	0	0	0	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 231-234 (rate: 0.5$/link)
5	0	1	0	1	0	0	0	0	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.5$/link)

Table 7-4 (*continued*)

ID	Lane Addition Scenario ID		Road Pricing Scenario ID						Solution Description
	11	**18**	**1**	**2**	**3**	**4**	**5**	**6**	
6	1	1	0	1	0	0	0	0	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.5$/link)
7	1	0	0	0	1	0	0	0	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 231-234 (rate: 0.7$/link)
8	0	1	0	0	1	0	0	0	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.7$/link)
9	1	1	0	0	1	0	0	0	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.7$/link)
10	1	0	0	0	0	1	0	0	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 195-198 (rate: 0.3$/link)
11	0	1	0	0	0	1	0	0	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.3$/link)
12	1	1	0	0	0	1	0	0	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.3$/link)
13	1	0	0	0	0	0	1	0	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 195-198 (rate: 0.5$/link)
14	0	1	0	0	0	0	1	0	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.5$/link)
15	1	1	0	0	0	0	1	0	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.5$/link)
16	1	0	0	0	0	0	0	1	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 195-198 (rate: 0.7$/link)
17	0	1	0	0	0	0	0	1	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.7$/link)
18	1	1	0	0	0	0	0	1	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.7$/link)

Note: [1] indicates the corresponding scenario is designed and included as part of the solution, 0 otherwise.

Various performance metrics under each scenario are obtained through executing the DTA-based models, and the results are presented in Figure 7-15 to Figure 7-19. Not surprisingly, the V/C ratios on interstate freeways are lower than that under the baseline condition for all scenarios, as exhibited in Figure 7-19. This may be reasoned as follows: although adding more lanes in the bottleneck area can increase the roadway capacity which may encourage the travelers to take a route traversing the bottleneck due to the infrastructure improvements, introducing toll lanes encourages some more travelers to use alternate routes such as local roads so as to reduce their total travel cost. Therefore, the V/C ratios on interstate freeways are reduced.

In addition, it is also found that, implementing scenario 10 (i.e., adding 1 more lane on TMC 168 and apply road pricing on TMCs 195-198 with a rate of 0.3$/link) can yield the shortest average travel time in the sub-network as compared to other combined strategies.

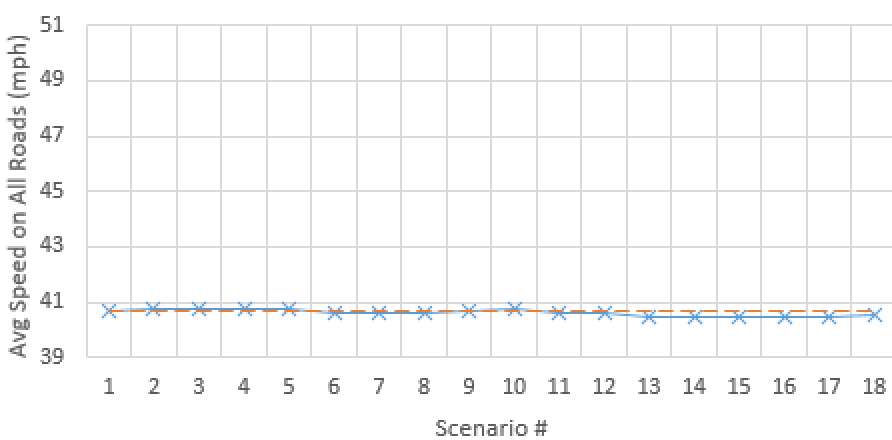


Figure 7-15 Average Travel Speeds on All Roadway Segments

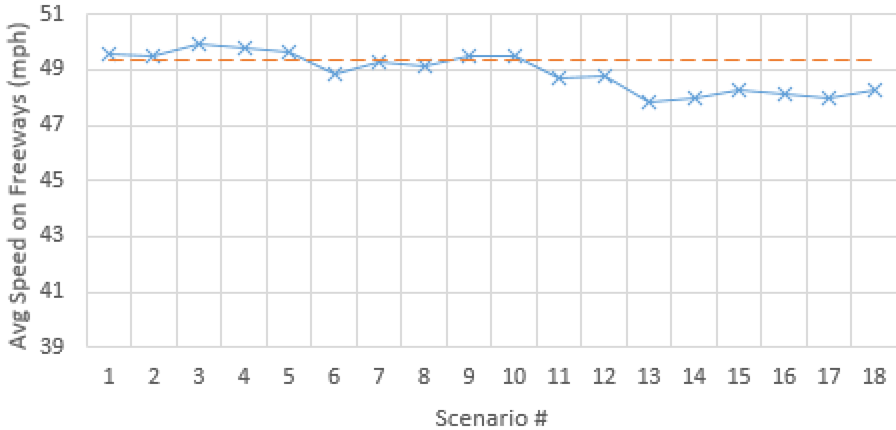


Figure 7-16 Average Travel Speeds on Interstate Freeways

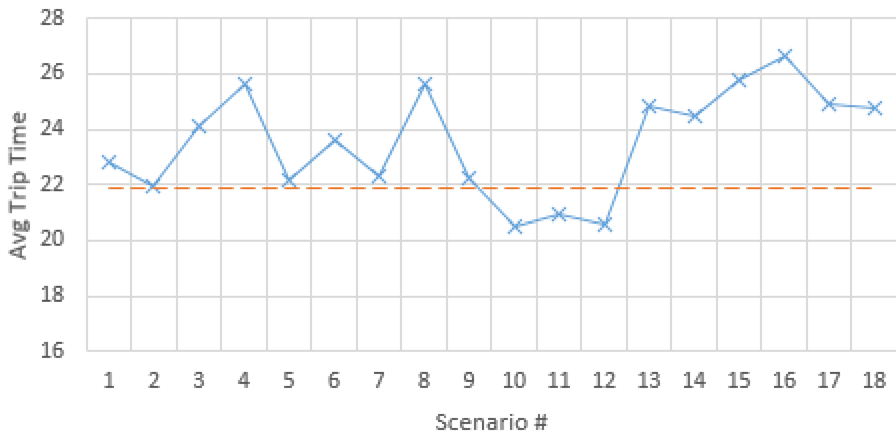


Figure 7-17 Average Trip Time in the Sub-network (min)

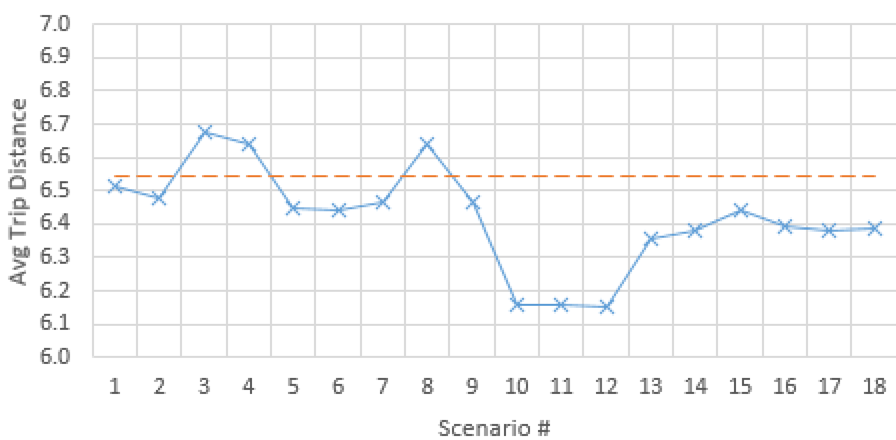


Figure 7-18 Average Trip Distance in the Sub-network (mile)

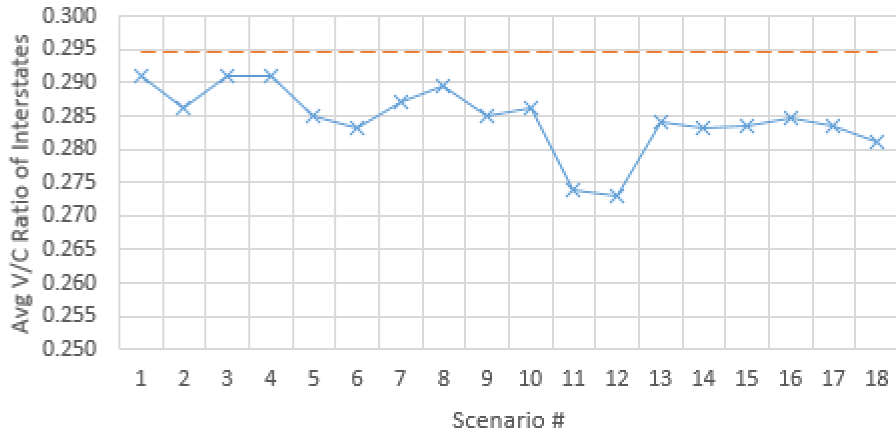


Figure 7-19 Average V/C Ratio of Interstate Freeways in the Sub-network

7.3 Summary

The main purpose of this chapter is to illustrate how to evaluate and quantify the effectiveness of various bottleneck improvement solutions using DTALite. A variety of scenarios are considered and examined herein. Based on the analysis results, a project ranking framework will be developed in the next chapter.

CHAPTER 8: DEVELOPING A FRAMEWORK TO RANK POTENTIAL IMPROVEMENT PROJECTS

In Chapter 7, a series of scenarios to mitigate freeway bottlenecks were developed and evaluated. Based on the congestion mitigation strategy adopted, these scenarios can be classified into three groups: (1) adding an extra lane on the bottleneck segments (26 scenarios), (2) setting link-based tolls at the bottleneck area (15 scenarios), and (3) applying combined strategies (i.e., lane addition and road pricing) at the bottleneck area (18 scenarios). Each scenario was simulated using the mesoscopic dynamic traffic assignment tool DTALite. Their effectiveness was assessed and determined through comparing the simulation outputs of each corresponding scenario with respect to the baseline conditions. It is well understood that, in reality, lack of funds may constraint the number of projects that can be selected for implementation in the transportation network. As such, the development and use of a framework to carefully prioritize transportation projects is critical. The primary purpose of this chapter is to develop a performance-based framework to evaluate and rank candidate bottleneck mitigation alternatives. It is expected that the research results of this task can provide insightful and objective information for traffic engineers and decision-makers in choosing effective mobility improvement strategies.

8.1 The General Project Ranking Framework

The general project ranking framework contains five major components:

- **STEP 1:** Developing candidate bottleneck mitigation projects. In this dissertation, a total of 59 scenarios aiming at alleviating traffic congestion caused by freeway bottlenecks.

- **STEP 2:** Evaluating each project. Since new infrastructures and/or road pricing strategies can directly affect travelers' route-choice behavior and will lead to a new regional traffic flow pattern, which may either mitigate or exacerbate existing system bottlenecks, a comprehensive system-wide evaluation of each candidate project is needed to quantify the potential influence of each scenario. This is accomplished using the mesoscopic dynamic traffic assignment tool DTALite. It is important to note that steps 1 and 2 were executed and documented in Chapter 7.
- **STEP 3:** Screening of projects. Based on the simulation outputs, only projects that result in positive outcomes (i.e., reduced network average travel time) are selected for use in the subsequent project ranking process.
- **STEP 4:** Benefit-cost analysis (BCA). The BCA is a widely used technique for transportation project evaluation and prioritization based on the principles of economic analysis (Kitchen, 2012). In this step, the benefits and costs of each project will be determined first. After that, the corresponding cost-benefit ratio will be computed. The projects selected in step 3 will be ranked accordingly.
- **STEP 5:** Sensitivity analysis. A series of sensitivity analyses will be conducted to examine how the outcome of benefit-cost analysis changes with changes made to inputs, assumptions, or the manner in which the analysis is set up. Figure 8-1 below shows the general framework developed for project ranking in this project.

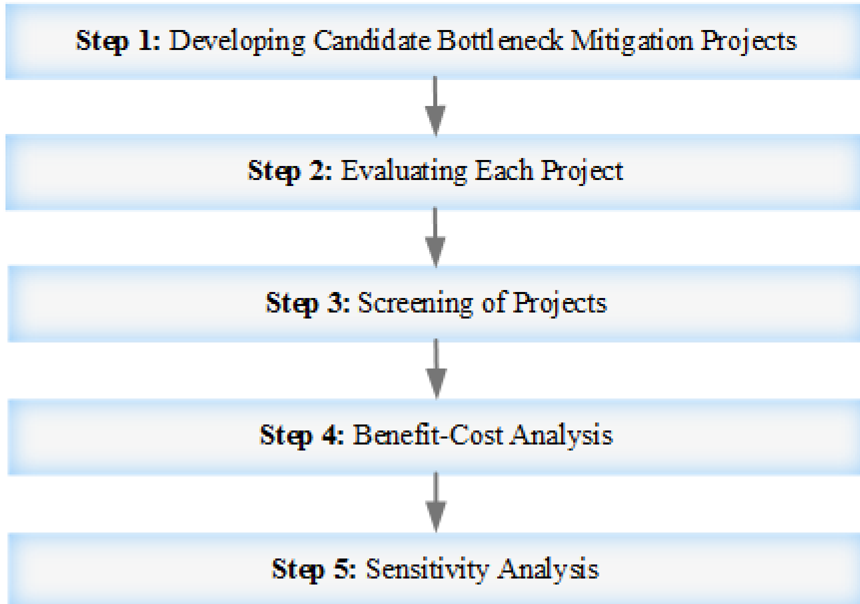


Figure 8-1 Project Ranking Framework

8.2 Demonstration of the Developed Framework

8.2.1 Screening of projects

As mentioned previously, steps 1 and 2 have been executed in Chapter 7. Based on the simulation outputs, Table 8-1 lists various candidate bottleneck mitigation solutions considered in this study. Note that information regarding whether each project generates positive or negative effects on the transportation network performance is also presented. As one can see in Table 8-1, only 18 out of the 59 candidate projects result in decreased network average travel time, while the other 48 projects (which accounts for 81 percent) yield deteriorated network performances. In this regard, cautious should be taken when determining which improvement projects will be implemented. It is worth mentioning that the performance index, network average travel time, reflects the interests of all users of the road network, rather than a localized area. The 18 projects are selected before proceeding to the next ranking procedure.

Table 8-1 Evaluation of Candidate Bottleneck Mitigation Strategies

Scenario No.	Bottleneck Group No.	TMC No.	Scenario Description	Increased Network Performance?
Lane additions				
1	1	231	Add 1 more lane on TMC 231	Yes
2	1	232-233	Add 1 more lane on TMCs 232 and 233	
3	1	234	Add 1 more lane on TMC 234	
4	1	231-234	Add 1 more lane on TMCs 231 - 234	
5	3	195	Add 1 more lane on TMC 195	Yes
6	3	196	Add 1 more lane on TMC 196	Yes
7	3	197	Add 1 more lane on TMC 197	
8	3	198	Add 1 more lane on TMC 198	
9	3	195-198	Add 1 more lane on TMCs 195 - 198	Yes
10	4	167	Add 1 more lane on TMC 167	
11	4	168	Add 1 more lane on TMC 168	Yes
12	4	169	Add 1 more lane on TMC 169	
13	4	167-169	Add 1 more lane on TMCs 167 - 169	
14	5	210	Add 1 more lane on TMC 210	
15	5	211	Add 1 more lane on TMC 211	Yes
16	5	212	Add 1 more lane on TMC 212	Yes
17	5	210-212	Add 1 more lane on TMCs 210 - 212	Yes
18	6	239-240	Add 1 more lane on TMCs 239 - 240	Yes
19	7	165	Add 1 more lane on TMC 165	Yes
20	8	206	Add 1 more lane on TMC 206	
21	8	207	Add 1 more lane on TMC 207	Yes
22	8	206-207	Add 1 more lane on TMCs 206 - 207	Yes
23	10	236	Add 1 more lane on TMC 236	Yes
24	12	163	Add 1 more lane on TMC 163	
25	13	137	Add 1 more lane on TMC 137	Yes
26	14	200	Add 1 more lane on TMC 200	
Road pricing				
27	1	231-234	Set link based tolls on TMCs 231-234 (rate: $0.3/link)	
28	1	231-234	Set link based tolls on TMCs 231-234 (rate: $0.5/link)	
29	1	231-234	Set link based tolls on TMCs 231-234 (rate: $0.7/link)	
30	3	195-198	Set link based tolls on TMCs 195-198 (rate: $0.3/link)	Yes
31	3	195-198	Set link based tolls on TMCs 195-198 (rate: $0.5/link)	
32	3	195-198	Set link based tolls on TMCs 195-198 (rate: $0.7/link)	
33	4	167-169	Set link based tolls on TMCs 167-169 (rate: $0.3/link)	
34	4	167-169	Set link based tolls on TMCs 167-169 (rate: $0.5/link)	
35	4	167-169	Set link based tolls on TMCs 167-169 (rate: $0.7/link)	
36	5	210-212	Set link based tolls on TMCs 210-212 (rate: $0.3/link)	
37	5	210-212	Set link based tolls on TMCs 210-212 (rate: $0.5/link)	
38	5	210-212	Set link based tolls on TMCs 210-212 (rate: $0.7/link)	
39	6	239-240	Set link based tolls on TMCs 239-240 (rate: $0.3/link)	
40	6	239-240	Set link based tolls on TMCs 239-240 (rate: $0.5/link)	
41	6	239-240	Set link based tolls on TMCs 239-240 (rate: $0.7/link)	

Table 8-1 (*continued*)

Scenario No.	Bottleneck Group No.	TMC No.	Scenario Description	Increased Network Performance?
Combined strategies (lane additions & road pricing)				
42	1,4	231-234, 168	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 231-234 (rate: 0.3$/link)	
43	1,6	231-234, 239-240	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.3$/link)	
44	1,4,6	231-234, 168, 239-240	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.3$/link)	
45	1,4	231-234, 168	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 231-234 (rate: 0.5$/link)	
46	1,6	231-234, 239-240	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.5$/link)	
47	1,4,6	231-234, 168, 239-240	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.5$/link)	
48	1,4	231-234, 168	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 231-234 (rate: 0.7$/link)	
49	1,6	231-234, 239-240	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.7$/link)	
50	1,4,6	231-234, 168, 239-240	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 231-234 (rate: 0.7$/link)	
51	3,4	195-198, 168	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 195-198 (rate: 0.3$/link)	Yes
52	3,6	195-198, 239-240	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.3$/link)	Yes
53	3,4,6	195-198, 168, 239-240	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.3$/link)	Yes
54	3,4	195-198, 168	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 195-198 (rate: 0.5$/link)	
55	3,6	195-198, 239-240	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.5$/link)	
56	3,4,6	195-198, 168, 239-240	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.5$/link)	
57	3,4	195-198, 168	Add 1 more lane on links TMC 168, and Add toll lanes on TMCs 195-198 (rate: 0.7$/link)	
58	3,6	195-198, 239-240	Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.7$/link)	
59	3,4,6	195-198, 168, 239-240	Add 1 more lane on links 168, and Add 1 more lane on TMCs 239-240, and Add toll lanes on TMCs 195-198 (rate: 0.7$/link)	

8.2.2 Benefit and Cost Estimation

8.2.2.1 *Project benefit*

It is important to note that the following estimations are developed for planning-level applications only. Detailed evaluation of the benefits and costs should be conducted prior to implementing each project at the project level.

According to the *Prioritization 3.0 Highway Scoring Criteria* (*Summary Report*) created by the NCDOT, the benefit of a bottleneck mitigation project on travel time savings is expected to provide over 30 years. Also, the average value of travel time (VOTT) for NC travelers is assumed to be $22/hour while converting the travel time savings resulted from the project into monetary values (NCDOT, 2014).

For each candidate project, the total travel time savings are determined by subtracting the average travel time in each scenario (the “after case”) from the average travel time under the base condition (the “before case”). Once this is calculated, the total travel time savings are then converted into monetary forms using the current VOTT of $22 per hour provided by NCDOT, as shown in Table 8-2.

Results from previous studies have shown that the reliability benefits brought by road improvement projects are approximately one-third of the benefits of travel time savings (Eliasson 2008; Santos and Fraser 2006). For simplicity, such relationship is also assumed to be true for the study areas in this research.

Although the safety benefits resulted from road improvement projects may also need to be considered (e.g., Duthie et al., 2013), they are not accounted for herein in this study. This is because either adding an extra lane or implementing road pricing strategy along the bottleneck segments may shift traffic flow to alternate routes and thus lead to a new regional traffic flow pattern, and it is not a trivial task to accurately predict the impact of road improvement projects on the number of crashes and crash outcomes at the network level. In addition to that, the toll revenues generated in scenarios 30, 51, 52, and 53 are not considered in the project benefits either. These revenue changes are simply cash transfer between the governments and residents; the present study assumes that there will be no change in social welfare as in most benefit-cost analyses (e.g., Zerbe and Dively 1994; Bunker and Kajewski, 2016). In summary, Table 8-2 presents the total benefits of each project.

Table 8-2 Project Benefits

Scenario No.	**Avg Trip Time (min)**	**Travel Time Savings (min)[1]**	**Total Travel Time Savings During P.M. Peak (mins)[2]**	**Total Travel Time Savings During P.M. Peak**	**30 Year Travel Time Savings**	**30 Year Travel Time Reliability Savings**	**Total Benefits**
Lane additions							
1	21.30	0.59	118795.84	$43,558	$476,965,314	$158,988,438	$635,953,752
5	21.80	0.09	18496.01	$6,782	$74,261,482	$24,753,827	$99,015,310
6	21.68	0.21	43130.35	$15,814	$173,168,341	$57,722,780	$230,891,122
9	21.48	0.41	82411.58	$30,218	$330,882,486	$110,294,162	$441,176,648
11	19.67	2.21	448421.90	$164,421	$1,800,413,918	$600,137,973	$2,400,551,891
15	21.56	0.33	66630.21	$24,431	$267,520,279	$89,173,426	$356,693,705
16	21.74	0.15	30590.34	$11,216	$122,820,195	$40,940,065	$163,760,260
17	21.58	0.31	63368.59	$23,235	$254,424,881	$84,808,294	$339,233,174
18	19.11	2.78	562558.29	$206,271	$2,258,671,520	$752,890,507	$3,011,562,027
19	21.76	0.13	25930.88	$9,508	$104,112,483	$34,704,161	$138,816,644
21	21.89	0.00	81.03	$30	$325,352	$108,451	$433,802
22	21.85	0.04	7759.01	$2,845	$31,152,407	$10,384,136	$41,536,543
23	21.33	0.56	112454.93	$41,233	$451,506,558	$150,502,186	$602,008,744
25	21.39	0.50	101211.47	$37,111	$406,364,036	$135,454,679	$541,818,715
Road pricing							
30	20.71	1.18	238766.68	$87,548	$958,648,224	$319,549,408	$1,278,197,632
Combined strategies (lane additions and road pricing)							
51	20.53	1.36	275637.15	$101,067	$1,106,683,161	$368,894,387	$1,475,577,548
52	20.96	0.93	188606.63	$69,156	$757,255,640	$252,418,547	$1,009,674,186
53	20.59	1.30	262388.09	$96,209	$1,053,488,189	$351,162,730	$1,404,650,919

Note: [1] The average travel time under the base conditions is 21.8879 min.
[2] A total of 202,585 vehicles are simulated during p.m. peak period.

8.2.2.2 *Project cost*

The project costs incorporated in this study include both construction costs and operations and maintenance (O&M) costs. In terms of construction cost, according to a previous study conducted by NCDOT, adding a 13-mi general purpose lane in both directions of I-77 will cost approximately $80 to $130 million (Skinner and Peeler, 2010). Linearly interpolating this value yields a cost of $3.08 to $ 5 million per mile. As such, the construction cost of adding a new lane is assumed to be $4 million per mile. For road tolling facilities, it is quite challenging to estimate the construction costs since the costs could vary from place to place and data from comparable projects are scarce. For the ongoing 26-mi I-77 Express Lane project, NCDOT estimated that the total cost would be $647 million (NCDOT, 2017), which corresponds to an average cost of $24.88 million per mile. In this study, the construction cost of a toll road is assumed to be $25 million per mile. A sensitivity analysis will be conducted in the following section to investigate the impact of various construction costs on project ranking results.

The O&M cost is another important aspect in cost-benefit analysis and can vary among distinct projects. In some studies, the O&M costs were estimated individually; while for others, it was simply computed as a fixed percentage of the construction cost for the whole planning horizon. For example, in a previous benefit-cost analysis of road pricing in downtown Seattle, Danna et al. (2012) presumed the construction cost to be $362 million, while the O&M cost was estimated to be $38.9 million per year. In this case, the annual O&M accounts for about 10% of capital cost. While in another study conducted by Bunker and Kajewski (2016), they suggested that simply one percent of the construction cost be entered as the O&M cost for the whole planning horizon. Since previous studies showed considerable variations in estimating the O&M cost, this study assumes that, for all candidate projects, the annual O&M cost accounts for 5% of the construction cost. The impact of using various percentage values will be evaluated in subsequent sections as well.

Table 8-3 presents the estimation results of the project costs for all scenarios, the corresponding benefit/cost ratios (B/C ratios), and the ranking results. Several useful implications can be drawn based on Table 8-3:

- Among the 18 projects which yield a positive influence on the network performance, there are 17 projects generate higher benefits as compared to the project costs (i.e., the B/C ratio is greater than 1). The only exception is project 21. The B/C ratio of project 21 is less than 1 indicating that this project is not economically efficient.
- Scenarios 11 and 18 produce the highest B/C ratios in this study, as highlighted in Table 8-3. Several other lane-addition projects also result in a relatively high B/C ratio, such as scenarios 25, 23, 1, and 15. This finding implies that low-cost capacity improvement projects can yield greater benefits in some cases.
- Either toll pricing (i.e., scenario 30) or combined strategies (i.e., scenarios 51-53) can yield relatively high benefits. However, the capital investments associated with these projects are also massive. Considering the fact that installing toll lanes and electronic toll devices could take longer time than a simple lane-addition project, their disruptions on traffic conditions may also be longer. In this regard, those low-cost capacity expansion projects are highly recommended.

Table 8-3 Cost Evaluation of Candidate Projects.

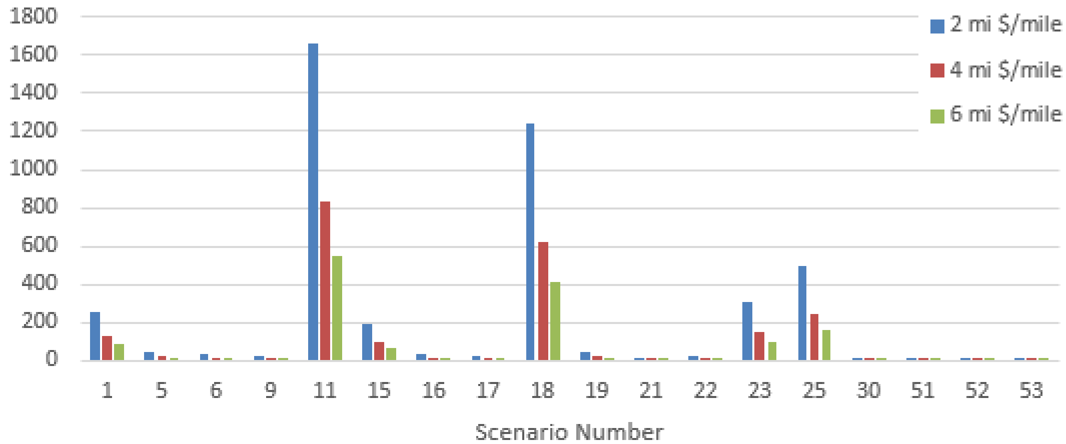
Scenario No.	Construction mileage	Toll lane mileage	Construction cost (million $)[1]	O&M cost (million $)[2]	Total cost (million $)	Total Benefits (million $)	B/C Ratio	Rank
Lane additions								
1	0.94		3.75	5.62	9.36	635.95	67.91	5
5	0.89		3.57	5.36	8.93	99.02	11.09	8
6	2.44		9.76	14.63	24.39	230.89	9.47	10
9	5.74		22.96	34.44	57.40	441.18	7.69	11
11	0.56		2.23	3.35	5.58	2400.55	430.55	1
15	0.71		2.84	4.26	7.10	356.69	50.21	6
16	1.73		6.90	10.35	17.26	163.76	9.49	9
17	4.80		19.20	28.80	48.00	339.23	7.07	12
18	0.93		3.72	5.58	9.30	3011.56	323.82	2
19	1.04		4.16	6.24	10.40	138.82	13.35	7
21	0.38		1.54	2.30	3.84	0.43	0.11	18
22	0.76		3.04	4.56	7.60	41.54	5.47	13
23	0.74		2.96	4.44	7.40	602.01	81.35	4
25	0.42		1.69	2.53	4.22	541.82	128.47	3
Road pricing								
30		5.74	143.50	215.25	358.75	1278.20	3.56	16
Combined strategies (lane additions and road pricing)								
51	0.56	5.74	145.74	218.61	364.35	1475.58	4.05	14
52	0.93	5.74	147.22	220.83	368.05	1009.67	2.74	17
53	1.49	5.74	149.46	224.19	373.65	1404.65	3.76	15

Note: [1] The construction cost of adding a new general purpose lane is assumed to be $4 million per mile; while the construction cost of a toll road is assumed to be $25 million per mile.
[2] The annual O&M cost is presumed to be 5% of the construction cost.

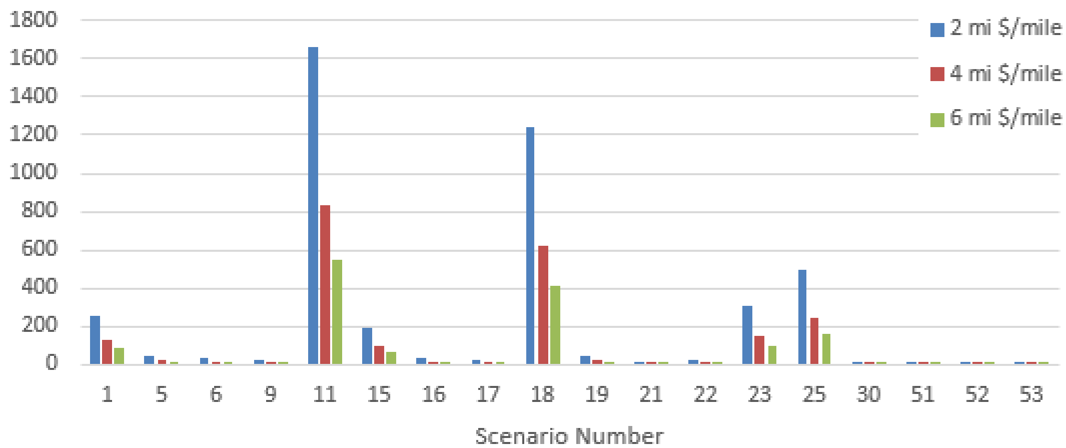
8.2.2.3 *Sensitivity analysis*

To investigate the robustness of the outcome of benefit-cost analysis, the research further analyzed how various input data affects the bottleneck ranking results. Three input variables during the benefit-cost analysis procedure are selected for sensitivity analysis:

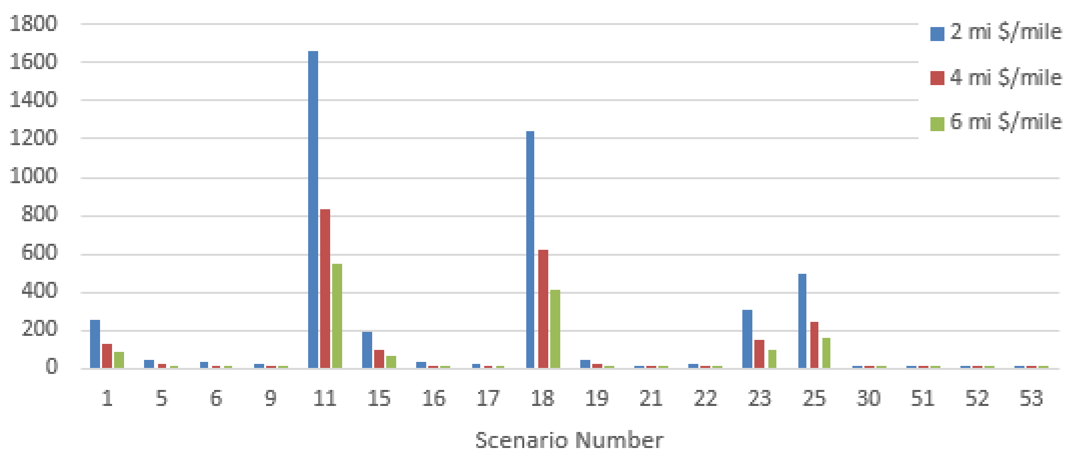
- (1) Percentage of the O&M cost: 1%, 5%, and 10%;
- (2) The construction cost of toll road: $15, $25, and $35 million per mile;
- (3) The construction cost of adding a general purpose lane: $2, $4, and $6 million per mile.



(a) Construction cost for toll road = 1.5*107 $/mile

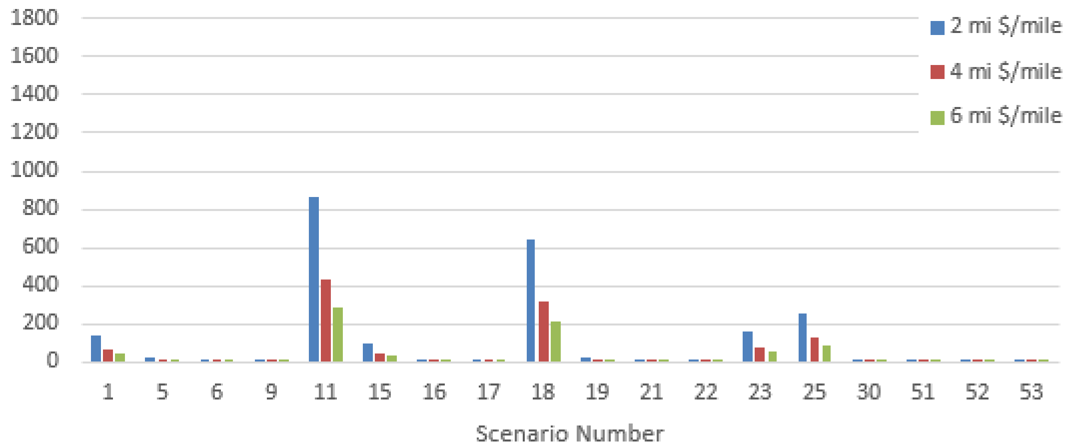


(b) Construction cost for toll road = 2.5*107 $/mile

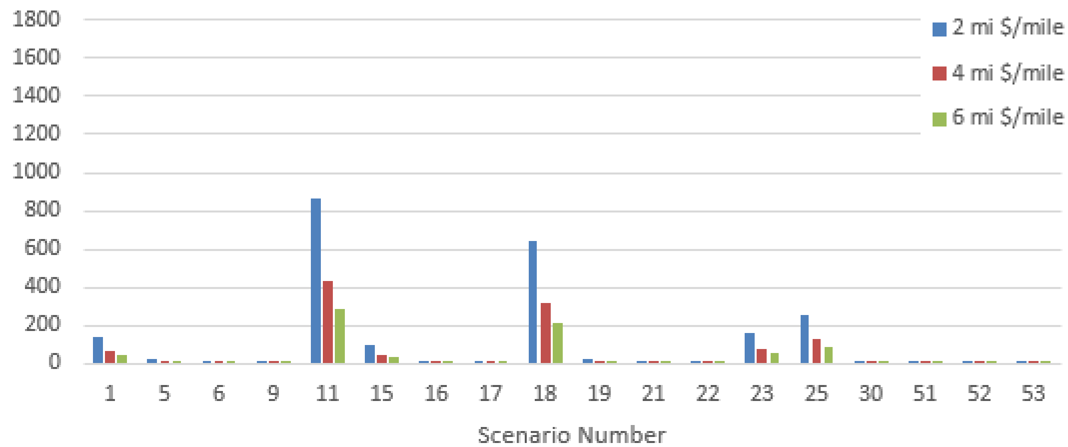


(c) Construction cost for toll road = 3.5*107 $/mile

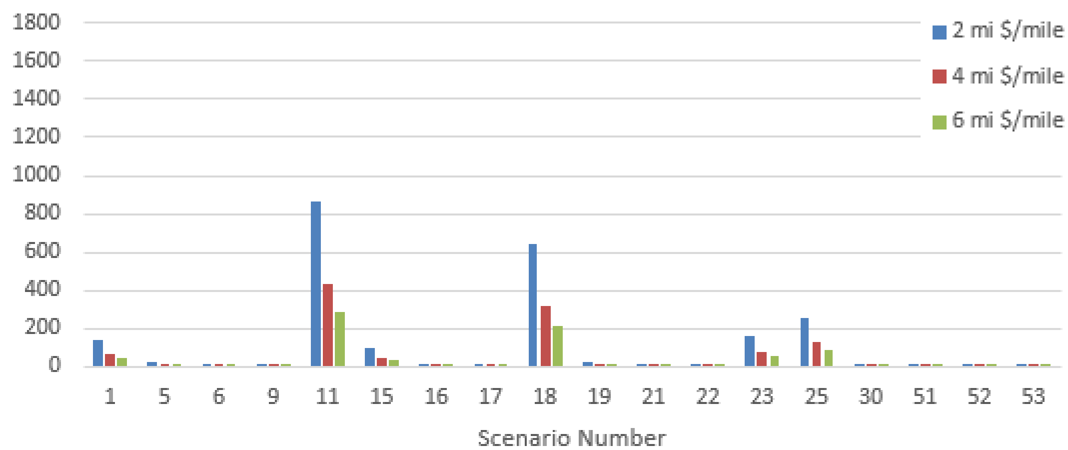
Figure 8-2 Results of Sensitivity Analysis (Percentage of O&M cost = 1%)



(a) Construction cost for toll road = 1.5*107 $/mile

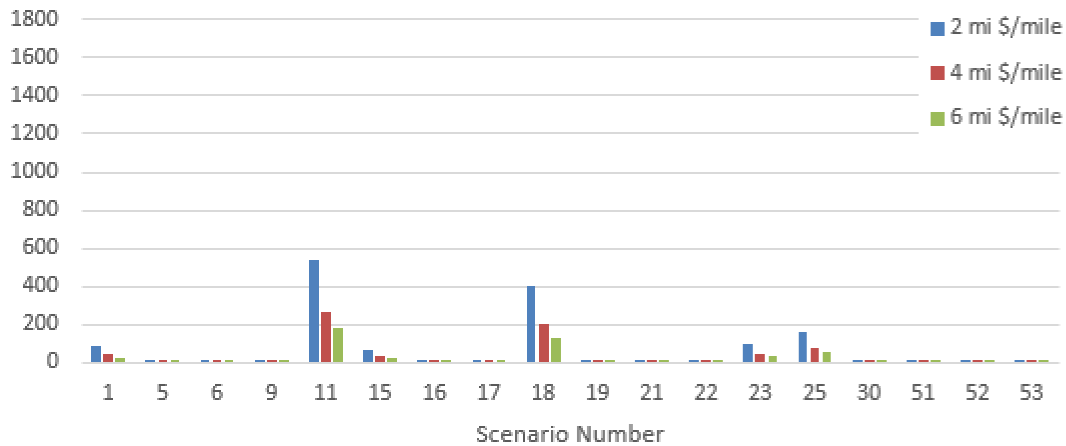


(b) Construction cost for toll road = 2.5*107 $/mile

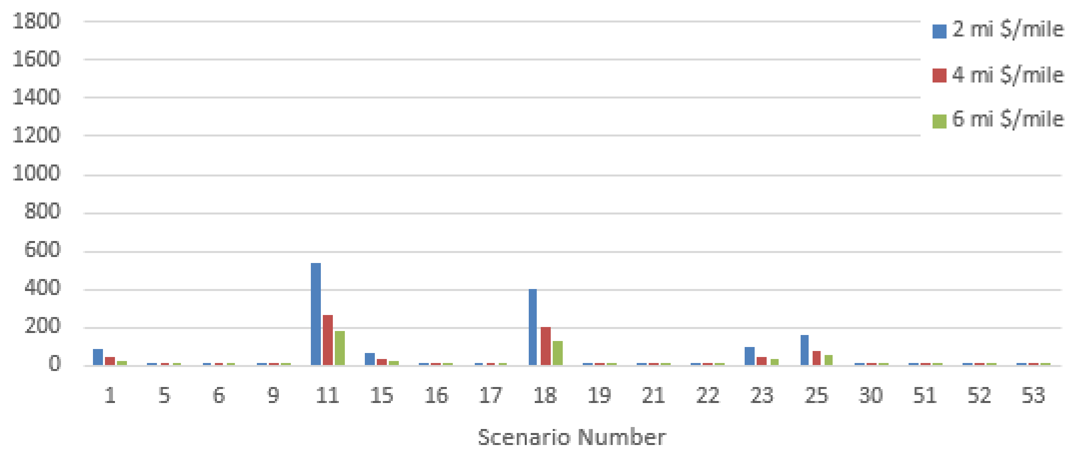


(c) Construction cost for toll road = 3.5*107 $/mile

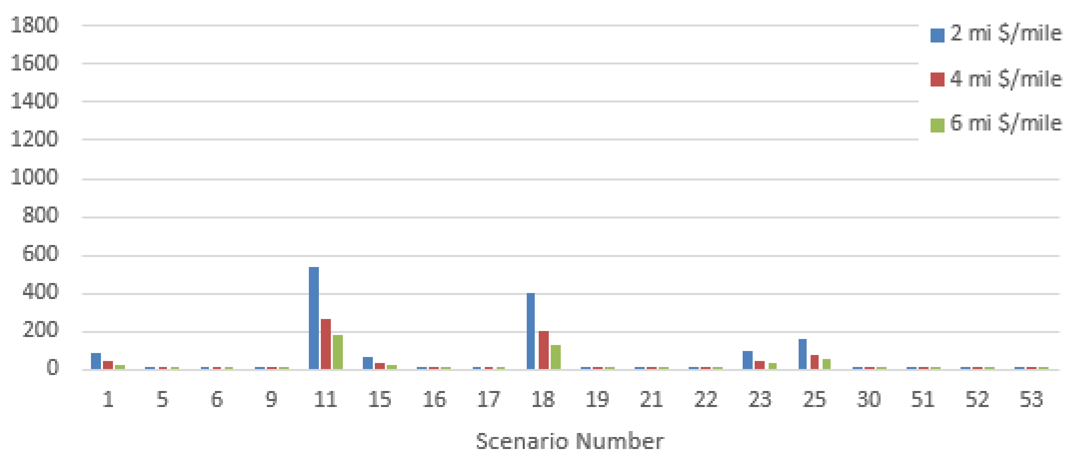
Figure 8-3 Results of Sensitivity Analysis (Percentage of O&M cost = 5%)



(a) Construction cost for toll road = 1.5*107 $/mile



(b) Construction cost for toll road = 2.5*107 $/mile



(c) Construction cost for toll road = 3.5*107 $/mile

Figure 8-4 Results of Sensitivity Analysis (Percentage of O&M cost = 10%)

Figure 8-2 to Figure 8-4 illustrates the sensitivity analysis results under different conditions. Note that in each figure, the blue, red, green bars represent the construction costs of adding a general purpose lane are $2, $4, and $6 million per mile, respectively.

Generally, as the share of the O&M cost increases, the B/C ratios for all scenarios decrease, as one can see in Figure 8-2 (a), Figure 8-3 (a), and Figure 8-4 (a). Such finding is consistent with our expectation since the O&M cost is entered as a fixed percentage of the construction cost in this study. Increasing the share of O&M cost will directly reduce the B/C ratios for all scenarios.

On the other hand, as the construction cost of a toll road increases from $15 million to $35 million, the B/C ratio decreases for scenarios 30, 51, 52, and 53. However, since the B/C ratios for toll-related scenarios are relatively lower in this study, changes in the construction cost of a toll road exhibit low impact of the ranking results, as shown in Figure 8-2 (a) – (c).

Last, increasing the construction cost of adding a general purpose lane reduces the B/C ratios for lane addition projects, as indicated by the blue, red, and green bars in each figure.

Overall, the most significant finding of the sensitivity analysis is the project ranking results are very stable in this study. The superiority of low-cost capacity expansion projects, such as scenarios 11 and 18, is obvious. As such, scenarios 11 and 18 are highly recommended for mitigating freeway bottlenecks in this study.

8.3 Summary

A framework to evaluate and prioritize candidate bottleneck mitigation projects is presented herein. Based on the simulation outputs obtained from Chapter 7, a case study is conducted to illustrate the proposed framework. The research results of this chapter can provide insightful information for decision-makers in selecting effective mobility improvement strategies.

CHAPTER 9: SUMMARY AND CONCLUSIONS

Developing a systematic and efficient freeway bottleneck analysis framework is essential for improving mobility and reliability of the transportation system. During the past years, a number of freeway bottleneck identification methods have been developed to assist transportation professionals in locating congested roadway segments. However, most of these methods were developed based on loop detector data; and their applications are restricted by the number of detectors installed on the roads. In recent years, the improvements in the fidelity and quality of the vehicle probe data provide a great opportunity for transportation professionals to apply such data and overcome the geographic coverage and spacing restrictions of traditional loop detector data. This dissertation presents a systematic approach to discerning and prioritizing freeway bottlenecks at the network level using such data.

As a number of measures can be derived from the vehicle probe data, this dissertation first analyzed and tested the feasibility of applying only travel time reliability measures in identifying and ranking recurrent freeway bottlenecks. During the process, two commonly used reliability measures, frequency of congestion (FOC) and planning time index (PTI), are selected and used to gauge traffic conditions along four interstate freeways (I-485, I-277, I-77 and I-85) in Mecklenburg County, North Carolina. The impacts of applying different threshold values in defining FOC or PTI indices are also evaluated. The results indicate that using either FOC or PTI alone reveals only a specific facet of the travel time distribution, yet could not be able to quantify the intensity of the traffic congestion caused by the bottlenecks. As a result, using parameters of multiple dimensions (e.g., both travel time reliability and intensity measures) to quantify traffic congestion is highly recommended. In this dissertation, the PTI and the travel time index (TTI) are chosen to describe the reliability and intensity dimension of traffic congestion on each roadway segment because both indicators are dimensionless travel time-based performance measures and are developed using the same benchmark (i.e., free-flow travel time).

To properly determine the weighting factor assigned between two dimensions of traffic congestion, concepts in the engineering economics area (e.g., the value of travel time reliability (VTTR) and the value of travel time (VOTT)) are borrowed herein to help interpret the comprehensive bottleneck ranking index, which accounts for both reliability and intensity measures. A data-driven, real options theory-based approach developed in the previous SHRP 2 Project L35B is employed to determine a local range of the weighting factors. Using such techniques, the bottleneck ranking index for each roadway segment can be interpreted as the ratio of the total travel cost under congested travel conditions to the travel cost under free-flow traffic conditions.

To illustrate the proposed freeway bottleneck analysis framework, a case study is performed to evaluate traffic conditions and identify freeway bottlenecks on Mecklenburg interstate freeways in North Carolina, using probe vehicle speed data collected in 2015. It is worth mentioning that even though the bottleneck identification method is developed based on vehicle probe data, such method can also be applied to loop detector data as long as the detector counts in the study area are abundant. In addition to the travel time-based approach, the author also evaluated the identified bottlenecks based on the two-dimensional FOC matrix and daily speed contour maps.

After freeway bottlenecks are identified, this study collects and analyzes geometric characteristics of each bottleneck group to determine their potential contributing factors. An operational analysis, which is based on the HCM 2010 procedure, is conducted to help identify potential bottleneck causes. The results indicate that, in this research, the most common causes of the bottlenecks include excessively high travel demand, dense ramp junctions along interstates, and lane drops, etc. Based on that, corresponding countermeasures are developed to alleviate traffic congestion for each bottleneck group. Realizing the fact that new construction activities or operational improvements can directly affect travelers' route-choice behavior and may lead to a new regional traffic flow pattern, a dynamic traffic assignment model based on DTALite is developed and calibrated to assess the effectiveness of the bottleneck mitigation projects at the network level. The simulation outputs clearly indicate that in certain scenarios, simply adding one more lane in the bottleneck area may deteriorate traffic performances. For instance, it is observed that after adding one more lane on TMCs 231 – 234, the average trip travel time, the average trip distance, and the average V/C ratio of interstate freeways all slightly increase. Such counterintuitive results have been widely reported in the literature, and such phenomenon is known as the Braess's paradox. In that regard, the decision makers must be very careful to ensure that informed decisions are made as to where to add more lanes.

In the last step, a performance-based framework is developed to facilitate the project ranking process. Various bottleneck mitigation alternatives are analyzed and compared using the benefit-cost analysis and sensitivity analysis techniques.

In summary, the research results can provide insightful and objective information for decision-makers and transportation professionals to (1) objectively evaluate and identify freeway bottlenecks, (2) competently develop various congestion mitigation strategies and evaluate their impacts at the network level, and (3) efficiently allocate limited transportation budget in a more effective manner.

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