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Mobility and Reliability Performance Measurement

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by

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16. Abstract

This project grew out of the fact that mobility was identified early on as one of the key performance focus areas of NCDOT's strategic transformation effort. The Transformation Management Team (TMT) established a TMT Mobility Workstream Team in 2007. This team began working on a mobility implementation plan in early 2008, completed the report in May 2008, and presented final recommendations to the Strategic Management Committee (SMC) in November 2008. The team recommended that NCDOT measure mobility of highway and other modes, naming the enabling tasks as 1) defining the performance measures, 2) assessing baseline performance, and 3) setting performance targets. The research presented in this final report included tasks designed to contribute to each of these enabling tasks.

Key findings and conclusions are presented regarding data accuracy, signal system data availability and quality, route travel time estimation and performance metric calculation, estimation of volume and volume-based metrics in the absence of direct volume observation, temporal specification of the mobility performance metric analysis period, and mobility metric uses beyond operational monitoring and management.

Primary deliverables were a robust and validated algorithm for estimating route travel times from segment travel times, a decision framework and accompany models for estimating volume, VMT, and system delay in the absence of direct volume observation, and a preliminary framework for project lifecycle mobility value estimation.

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EXECUTIVE SUMMARY

This project grew out of the fact that mobility was identified early on as one of the key performance focus areas of NCDOT's strategic transformation effort. The Transformation Management Team (TMT) established a TMT Mobility Workstream Team in 2007. This team began working on a mobility implementation plan in early 2008, completed the report in May 2008, and presented final recommendations to the Strategic Management Committee (SMC) in November 2008. The team recommended that NCDOT measure mobility of highway and other modes, naming the enabling tasks as 1) defining the performance measures, 2) assessing baseline performance, and 3) setting performance targets. The research presented in this final report included tasks designed to contribute to each of these enabling tasks. The key findings, recommendations, and project deliverables are briefly summarized below.

Phase I

The first two project tasks involved qualitative assessment of data available for mobility performance measurement. In the first task (see Chapter 2), detailed comparison and crosschecking was performed for five locations where the probe-based INRIX data and the fixed sensor Traffic.com data could be compared directly. The comparison yielded several important findings including the identification of systematic time lags in the INRIX data in response to speed drops at the onset of congestion and speed recovery when congestion dissipates. The cross-checking also revealed that the Traffic.com sensors at a specific location, I-40 and Davis Drive, are reporting systematically erroneous (low) speeds and need to be recalibrated. Although the INRIX and Traffic.com data were in closer agreement at the other study locations, it was also found through careful analysis that inherent differences, such an the INRIX speed lags mentioned above, render it infeasible at this time to fuse INRIX speeds with contemporaneous Traffic.com volume observations. The second task (see Chapter 3) involved primarily assessment of the presence and cause of missing values in the INRIX data. Although the missing data rate was low, namely 3.83% for the year 2010 data used in the analysis, the project team recommends that imputation of missing values be strongly considered for defined analysis periods that yield relatively small samples.

The next two tasks dealt directly with mobility performance measurement with Task 3 investigating methods to estimate route travel times from segment speeds/travel times and the resulting mobility metrics and Task 4 evaluating alternative methods for temporally defining the time period for performance assessment. The key deliverable for the third task (see Chapter 4) is a validated, robust algorithm for generating route travel time estimates from segment travel times. This algorithm creates stitched pseudo-trajectories that mimic the experience of travelers moving along the route as traffic conditions evolve over time. This method was found to be superior in all cases to a simpler method that estimates route travel times by summing across multiple segments at a simultaneous reporting interval. In addition to yielding less accurate route travel time estimates, the simultaneous method lagged behind the stitched method in identifying the emergence of congested travel times and this lag increased for longer routes and for routes that experience congestion near the downstream end of the route. The stitched route travel time estimation algorithm is fully described in Chapter 4 and will be provided as a macro-enabled Excel workbook.

The fourth task (see Chapter 5) confirmed that metric calculation should be strictly segregated at points in time where the capacity and traffic flow characteristics change for a studied route or sub-network. For example, if a route is subject to a construction period than involves a work zone that closes travel lanes after which the route reopens with additional travel lanes, travel time reliability metrics should be calculated independently for each of these capacity condition periods. In terms of temporal specification, it was determined that a one year analysis period is appropriate to control for seasonal variation and provide sufficient data samples. The detail specification of the analysis period must be based on the specific performance assessment goal. For example, analysis period sampling could be designed to assess overall 24/7 system performance or to assess weekday PM peak period performance.

The next two tasks involved investigation of signal system data quality and availability for mobility performance assessment on signalized arterials. The Task 5 research (see Chapter 6) revealed that useful data are available within the OASIS signal control software. However, the data suffer from accuracy issues related to hard-coded rounding methods and methods of spanning across time period boundaries. The data are also not easily accessible for performance measurement purposes, and the current OASIS software version allows reporting of detector data only down to a minimum time interval of one-minute. Therefore, the project team recommends that the NCDOT coordinate closely with current and future software vendors to ensure that improvements in accuracy, accessibility, and data resolution find their way in to future versions. Additional research findings regarding the use of OASIS system data for arterial performance assessment will be forthcoming in the final report for NCDOT research project RP 2012-12 *Development of Near Real Time Performance Measurements for Closed-Loop Signal Systems (CLS) Using Historical Traffic Data from Existing Loop Detectors and Signal Timing Data*.

The sixth task (see Chapter 7) involved the evaluation of previous NCDOT field studies conducted to assess the accuracy of OASIS detector speed estimates relative to the average effective vehicle length parameter. While the studies did confirm that setting the average effective vehicle length to a more appropriate value would marginally improve the speed estimates, the results were not entirely consistent. The project team recommends that similar speed studies be performed for any location where the NCDOT deems that validated accuracy of OASIS speeds is important. The results also indicated that, even though local adjustment of the OASIS average effective vehicle length could improve local speed estimation, the current 20 foot default average effective vehicle length should be yielding reasonable numbers in most situations. A much larger study with many more sites would be needed if the NCDOT decided that a general assessment of the default average effective vehicle length parameter is needed.

Phase II

The seventh project task (see Chapter 8) involved a detailed investigation and validation of the Task 3 stitched route travel time estimation method and a rigorous evaluation of the various reliability metrics. The evaluated metrics included those that are relatively well established, such as the *Planning Time Index* (PTI), and metrics that are less well known, such as the *Skew* statistic. An extensive data set was assembled for this effort. The data were from five locations that included six states plus the District of Columbia. The data were acquired for the two year timeframe encompassing all of 2010 and 2011.

The route travel time estimation procedure performed well and the resulting estimates provided the basis for calculating the candidate performance metrics. The research team postulated that in order to provide significant additional information, key performance metrics should not be strongly linearly correlated with the basic measure of average travel rate (the inverse of speed, typically expressed in minutes per mile, or the related *Travel Time Index* (TTI)). The analysis across the five locations revealed that all of the relatively well established reliability metrics, such as PTI, are well correlated to the average travel rate. This is not to say that these measures are not useful. Rather, these measures essentially tell the same story as the average travel rate or the TTI but only from a different angle. Said another way, the high correlation indicates that in many instances, these metrics could be estimated from the average travel rate rather than measured directly. The research found that two measures in particular, namely the *Skew* statistic and the *Semi-Standard Deviation*, were not strongly correlated with average travel rate. Furthermore, both of these metrics are able to identify locations where non-recurring congestion is the primary source of congestion rather than recurring congestion and are also able to provide a sense of the relative magnitude of the non-recurring congestion events. Therefore, the project team recommends that the NCDOT include one or both of these measures in its internal performance analysis. This recommendation is consistent with the SHRP 2 L02 recommendation of the *Semi-Standard Deviation* but inconsistent with FHWA's recommendation that complex statistical measures not be used. However, the FHWA recommendation is related to understanding and interpretation of reliability measures by non-technical interested parties. That is why the project team recommends that the NCDOT consider these metrics for internal analysis. The project team also recommends that the NCDOT strive to become comfortable with analyzing and interpreting entire travel time distributions in addition to the calculated metrics. This recommendation stems from the fact that no individual metric or set of metrics can reveal all the potentially important nuances in observed travel time distribution and is consistent with the recommendations of SHRP 2 L02 and L08, both of which were carried out by NC State researchers.

The next task (see Chapter 9) involved the investigation of methods to estimate traffic volume for situations where only speed data are available, as well as methods to use these estimates to calculate VMT and volume-based system delay. The research team found that this was the first serious and systematic effort to develop methodologies to do this kind of volume estimation. Therefore, the findings and recommendations for this task should be considered preliminary.

In essence, the volume estimation method that emerged from the research uses a critical speed threshold (CST) to identify congested INRIX observations, uses either the default or a specially-fitted *HCM* model to estimate the volume for congested observations, and uses an AADT profile to estimate volume for uncongested observations and for low speed observations that occur at times where there is no historically-based expectation of congested conditions. This method is incorporated into a general VMT estimation framework that includes other data availability conditions. Finally, the volume estimation method is applied to the calculation of system delay metrics. However, if system delay metrics are not also desired, then VMT estimates based solely on AADT will be sufficiently accurate. The project team also recommends that local AADT profiles (as opposed to generic national or state profiles) are needed for accurate estimation because the generic profiles cannot take characteristics such as peak directionality into account. Increased accuracy can also be gained by using a site-specific-fitted *HCM*-based model rather than the default *HCM* model for congested conditions. However, this model fitting will require at least a one-half year's data, and preliminary results indicate that the increase in metric accuracy may not be sufficient to justify the effort.

Task 9 (see Chapter 10) involved the development of a framework for estimating the lifecycle mobility value for major improvement projects that may cause a temporary decrease in mobility during construction. A preliminary framework was provided that outlines the steps necessary in scoping and defining the analysis and in conducting the necessary modeling and drawing appropriate comparisons and conclusions. The framework is ready for test application. Although tools and accompanying valuation methods are not yet available to fully model and value travel time variability, tools do exist, such as the open source, freely available dynamic traffic assignment network modeling program DTALite, for assessing the expected traffic conditions under no-build and build scenarios over the project lifecycle. Test application to actual upcoming projects will provide important lessons learned and help identify and define research and development needs.

Ongoing research is beginning to provide tools for modeling travel time variability. For example, a tool is being developed by NCSU researchers under the project SHRP 2 L08 *Incorporation of Travel Time Reliability into the Highway Capacity Manual* that will create synthetic freeway route travel time distributions. After the L08 project wraps up in the summer 2013, this tool could be used in conjunction with reasonable route diversion estimates to assess route-level lifecycle mobility impact.

The final research task (see Chapter 11) involved consideration of other uses of mobility and reliability performance metrics beyond ongoing monitoring of system operations. Initially traveler information was considered a promising candidate. However, the nature of the analysis periods sampled for system and route performance assessment do not align well with the information needs of individual travelers, and emerging social traveler information services that exploit crowd sourced data and individual traveler experience are likely to be the best sources of dynamic traveler information. Upon further consideration and review of emerging practice of other transportation agencies such as the New Zealand Transport Agency, the project team recommends that the NCDOT consider strategic planning and programming as the next high priority user of the emerging mobility and reliability performance measures.

Two important changes occurred over the course of the project that, although not touched on in the body of the report, bear mentioning in this executive summary. These changes both involve the Regional Integrated Transportation Information System (RITIS) housed at the University of Maryland’s Center for Advanced Transportation Technologies (CATT) Lab. The first of these changes relates to data availability. At the beginning of the project, the NCDOT had acquired a year's worth of 15-minute INRIX data for a set of key routes and used this data to create an initial proto-type mobility monitoring system. One of the initial discussions involved whether or not the NCDOT would ever consider archiving data at a shorter time interval. Now through its I-95 Corridor Coalition partnership, the NCDOT has full access the RITIS one-minute archived INRIX data. Equally if not more importantly, this access extends to the RITIS Vehicle Probe Project Suite, which includes powerful analysis tools such as the Congestion Scan and Bottleneck Ranking tools. The NCDOT is already making effective use of these tools. The availability of data and analysis capabilities through RITIS has changed the background context for implementation of the recommendations and deliverables of this project. However, the research results remain valuable and important. The research team appreciates the opportunity to have conducted this research and looks forward to working with the NCDOT, specifically with the Transportation Systems Operations Unit, in research implementation.

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CHAPTER 1. INTRODUCTION

Mobility is one of the key performance focus areas for the North Carolina Department of Transportation (NCDOT) with this focus gaining both traction and momentum during the NCDOT's strategic transformation effort undertaken in 2007 and 2008. The Transformation Management Team (TMT) charged with leading the strategic transformation established a TMT Mobility Workstream Team in 2007. This team began working on a mobility implementation plan in early 2008, completed the report in May 2008, and presented final recommendations to the Strategic Management Committee (SMC) in November 2008. The team recommended that NCDOT measure the mobility of highway and other modes, naming the enabling tasks as 1) defining the performance measures, 2) assessing baseline performance, and 3) setting performance targets.

Transportation mobility assessment, including the key mobility component of system reliability, is timely and critically important. However, mobility performance measurement is still a relatively new concept and over the past four years the National Academy of Sciences has led a significant multipronged and directly relevant research effort under the Strategic Highway Research Program (SHRP) 2 Capacity and Reliability programs. In order to achieve the TMT Mobility Workstream team goals, NCDOT must implement monitoring and measurement techniques for mobility and reliability that continue to be under research and development and still in the early stages of implementation. The use and understanding of traffic statistics generated from various monitoring systems in the state such as Traffi.com, Inrix and SpeedInfo is a critical activity in defining and assessing mobility targets.

As the research team began the effort documented in this project report, the Mobility Workstream team had already implemented a beta suite of link-based performance measures. The research project tasks, as introduced and described in the next section, were designed to address a series of research questions that must be answered to enable delivery of performance measures that are rigorous, responsive, and comprehensive. The questions fall in categories such as data checking, fusion, and cleansing; temporal and spatial averaging and aggregation; and data extraction, imputation, and performance measure calculation for signalized arterials.

1.1 Research Approach and Task Descriptions

The project tasks are organized in two phases. The first phase generated research findings and develop methods to refine and extend the beta performance measurement system, focusing primarily on freeway data. Phase I also included data analysis and assessment and methodology development based on a signalized arterial case study conducted by NCDOT. The second phase involved implementation and testing of the enhancements developed in Phase I along with the development of a framework for assessing the lifecycle mobility benefit of transportation system improvement project. The individual tasks are described below. The task detail below includes the original task descriptions from the project contract authorization document for documentation purposes along with a discussion of any changes in task detail that were necessary during the course of the project.

1.1.1 Phase I

1.1.1.1 Task 1 – Data Source Cross-Checking

Contract Authorization Document Description

The primary freeway data source for the NCDOT is the INRIX coverage for about 15,000 miles of the highest volume roads across the entire state. This data consists of travel times and speeds derived primarily from probe vehicles. In the Triangle region, there are two other freeway data sources. SpeedInfo delivered the earliest Triangle system which provides point speeds from roadside radar sensors. The SpeedInfo sensors were rendered unnecessary by the advent of statewide INRIX data provision and have been decommissioned. However, SpeedInfo data were still available to the research team for the cross-checking task. Additionally, extensive Triangle freeway coverage is provided by Traffic.com. The Traffic.com coverage includes I-40 from 15-501 to the Clayton Bypass, I-440, Wade Avenue Extension, and I-540 from I-40 to US 1. The Traffic.com data comes from fixed side-fire radar stations and include speed, volume, and lane occupancy.

The collocation of these three data systems provide a valuable opportunity for cross-checking to assess their relative accuracy, investigate potential measurement bias, and compare and contrast the types of performance measures that can be obtained from these distinct detection technologies. Although, validations studies have been conducted for INRIX data (these studies will of course be consulted), preliminary comparisons of INRIX and Traffic.com data indicate that there may be some measurement bias issues. Wherever the three traffic data sensor systems are consistently reporting significantly different conditions, the location will be analyzed in detail to isolate and explain the source of the difference.

The final results of this task will be a detailed comparative assessment of data system accuracy issues relative to specific sensor location characteristics and recommendations for how to account for or correct measurement errors to minimize their impact on performance metric calculation.

Revisions during the Project

No change in task details was needed.

1.1.1.2 Task 2 – Data Cleansing and Filtering

Contract Authorization Document Description

The preliminary analyses of the INRIX and Traffic.com data referred to above [a brief discussion of preliminary analysis and accompanying exhibits was included in the proposal and contract authorization document] have also illustrated the need for carefully designed procedures to identify outlying observations and filter out these outliers prior to calculating performance metrics. The project team will consult best practices in traffic data cleansing techniques and develop tailored outlier detection and filtering methods for each traffic data collection system.

Revisions during the Project

No change in task details was needed.

1.1.1.3 Task 3 – Route Travel Time Estimation and Performance Assessment

Contract Authorization Document Description

Although link based performance metrics are useful, real information value from a system user and system manager perspective comes from mobility and reliability measures calculated for important routes through the transportation network. The first step in creating a layer of route-based mobility performance metrics is establishing the key routes. Therefore, the first output of this task will be a logical and consistent methodology for identifying key routes within regional networks and at a statewide strategic corridor level. Even though a reasonably good set of key routes could be identified using a combination of local knowledge, engineering judgment, and common sense, it will be important to encapsulate this knowledge and judgment in a repeatable methodology to enhance the validity of comparisons over time and between regions within the state.

After key system routes are identified, estimating route travel times whether from point sensor data or from probe-based link observations, is not a straightforward process. Route travel times must be "stitched together" from link travel times. For all but the shortest of routes, this process will involve “walking” through the time dimension of the link travel time data. In other words, creating the route travel times is not simply a matter of adding up the constituent link travel time observations at a given point in time. Furthermore, because route travel times increase as traffic demand along the route increases, this “walking the travel time” process must be designed to account for and adapt to changes in traffic conditions along the routes. Therefore, the second output of this task will be well-defined, broadly applicable methods for deriving route-based travel times from both link-based and point sensor-based measurements.

Revisions during the Project

No change in task details was needed.

1.1.1.4 Task 4 –Temporal Specification for Performance Metric Calculation

Contract Authorization Document Description

Mobility performance metrics are by definition calculated based on archived traffic data. This leads to a fundamental question of how far to look back into the data archive when calculating the metrics. When considering an essentially static transportation network component (route or link), there are two basic approaches that can be taken. The first approach is to establish a look back window that defines the temporal sample used to calculate the mobility performance metrics. This method results in a moving sample window of constant size. The second approach uses the concept of exponentially weighted smoothing to recursively calculated averages and variances in a manner that weights near term observations more heavily with an exponential decaying weight for observations further in the past. The project team’s initial hypothesis is that the recursive, exponentially weighted method will be the best choice. Two key reasons for this hunch are 1) the exponential weighting parameter is likely to be more strongly indicated by the data and therefore less arbitrary than a fixed, level-average look back window and 2) the recursive updating procedure requires fewer observations to be read into memory for the calculations and therefore is less computationally intensive. Nonetheless, the project team will test this hypothesis and recommend the method that is most consistent with the data and provides the most reasonable results.

A second issue in temporal specification for performance metric calculation involves dealing with changes to the network. For example, in the case of a major roadway improvement, such as widening to provide additional travel lanes, there are three distinct time periods related to the improvement. These time periods are 1) the time prior to the beginning of construction, 2) the construction period during which work zone activities are likely to reduce throughput, and 3) the post-construction period in which the envisioned increase in capacity and mobility have been provided. This issue has been discussed in preliminary consultations with NCDOT, and there is general agreement that performance metric calculation should be done separately for each of these periods. Although this is a relatively straightforward and fully reasonable approach, the research team will identify locations to assess this concept and will determine if additional specifications are needed to ensure that the process is applied consistently. Also, databases describing and scheduling widening or construction activities along with the network performance database may need to be merged.

Revisions during the Project

No change in task details was needed.

1.1.1.5 Task 5 – Signal System Data Asset Assessment

Contract Authorization Document Description

Along with the freeway tier of the statewide network and regional networks, enhanced mobility on signalized arterials is essential to regional transportation safety and efficiency. For decades, the federal, state, and local governments have invested significant resources in advanced traffic control. The resulting traffic signal systems collect vast amounts of traffic condition data through system and approach detectors. By design, this data is essentially used only internally for the control functions of the systems. However, this data represents an immensely valuable, untapped resource for monitoring and measuring mobility within these critical transportation systems.

The project team will work with NCDOT and municipal signal systems professionals to provide a comprehensive assessment of the data potentially available in the predominant systems across the state. Although NCDOT's effort to transition all state maintained systems to the Oasis™ system should streamline access to data from state-maintained signals and systems, there are a variety of systems used by municipalities across the state. Therefore, there is a need to develop a comprehensive assessment of the data available. The project team will also investigate and develop recommendations for tapping into the data available from the various control systems.

Revisions during the Project

No change in task details was needed.

1.1.1.6 Task 6 – NCDOT Signalized Arterial Case Study – Analysis and Methodology Development

Contract Authorization Document Description

The NCDOT is planning to conduct a field study on using OASIS™ data to develop mobility measures. One of the key components of this process is deriving speed information from system detectors. Speed estimation from single loop detectors requires the determination of average effective vehicle length. The determination of average vehicle length is complicated not only by the length variation in the traffic stream but also by the effect of new, non-metallic vehicle materials on effective length and by the fact that the mix of vehicle types is not constant by time of day. Therefore, the first output of this task will be a methodology for determining average vehicle length including recommendations for varying the length by time of day and day of week. The project team will also assess and make recommendations on the performance metric computational procedures for signalized arterials based on the case study findings.

Revisions during the Project

No change in task details was needed.

1.1.2 Phase II

1.1.2.1 Task 7 – Testing and Implementation of Performance Measure Refinements and Enhancements

Contract Authorization Document Description

As needed, the project team will test the refinements and enhancements developed in Phase I. The project team will assist the NCDOT in implementing the refinements and enhancements that are determined to be ready for implementation.

Revisions during the Project

No change in task details was needed.

1.1.2.2 Task 8 – Framework for Extending Vehicle Miles Traveled Estimates

Contract Authorization Document Description

Although the speed and travel time information provided by INRIX and the speed only information provided by SpeedInfo can be used to assess travel time related mobility metrics, these systems do not directly support the calculation of system productivity and efficiency measures such as vehicle miles traveled (VMT), vehicle hours of travel (VHT), and vehicle hours of delay (VHD). The Traffic.com system in the Triangle region provides an opportunity to develop methods to derive vehicle-based measures from speed/travel time only systems. The idea is that traffic characteristic relationships developed from observations that include volume data can be used to estimate flow rates from speed data. The project team will also conduct experiments to artificially “remove” Traffic.com sensors to assess the level of count detection that would be needed to provide sufficiently accurate traffic volume estimates. Finally, the project team will also conduct experiments that treat select Traffic.com sensors as “temporary” stations and will assess the relative accuracy of a strategy that uses temporary counts to provide the necessary traffic flow relationships.

Revisions during the Project

No change in task details was needed.

1.1.2.3 Task 9 – Framework for Estimating Lifecycle Mobility Value

Contract Authorization Document Description

The issue discussed above concerning the segregation in time of performance metrics in the presence of major networks improvements points to another potential evaluation that would have significant value to the NCDOT. In general, when major improvements are needed to provide enhanced mobility, there is actually a decrease in mobility during the construction phase. If this temporary decrease in mobility is viewed as an “investment” for the future, it should be possible to develop a framework that sets the temporary loss in mobility against the increase in mobility provided by the major improvement over its useful life. The mobility performance metrics are the keys to enabling this assessment. The project team will develop a recommended framework that uses the mobility performance metrics to derive this project lifecycle mobility value.

Revisions during the Project

No change in task details was needed.

1.1.2.4 Task 10 – Recommendations for Uses beyond Mobility Performance Measurement

Contract Authorization Document Description

Although the primary focus of this research project will be supporting NCDOT's need to establish a mobility performance measurement system, the project team will also provide recommendations on other mission elements that can be enhanced and supported by the data and measurement systems. For example, the systems that evaluate historic travel times will also enable significantly improved dynamic travel time information. The key additional system function that would be needed to support dynamic travel time information will be the prediction of the near-term evolution of traffic conditions within the network. Other uses might include incident detection on remote rural freeways. The results of this task will be a list of recommendations for additional uses along with the additional features that would be needed to enable these uses.

Revisions during the Project

No change in task details was needed.

1.1.2.5 Task 11 – Project Final Report

Contract Authorization Document Description

The findings and results of the Phase I and II tasks will be documented in the project final report.

Revisions during the Project

No change in task details was needed.

1.2 Organization of the Report

Chapters 2 through 11 provide detailed discussions of the findings of the project tasks. The relationship of the chapters to the project tasks is as follows:

- Chapter 2 covers Task 1 – Data Source Cross-Checking
- Chapter 3 covers Task 2 – Data Cleansing and Filtering

- Chapter 4 covers Task 3 – Route Travel Time Estimation and Performance Assessment
- Chapter 5 covers Task 4 – Temporal Specification for Performance Metric Calculation
- Chapter 6 covers Task 5 – Signal System Data Asset Assessment
- Chapter 7 covers Task 6 – NCDOT Signalized Arterial Case Study – Analysis and Methodology Development
- Chapter 8 covers Task 7 – Testing and Implementation of Performance Measure Refinements and Enhancements
- Chapter 9 covers Task 8 – Framework for Extending Vehicle Miles Traveled Estimates
- Chapter 10 covers Task 9 – Framework for Estimating Lifecycle Mobility Value
- Chapter 11 covers Task 10 – Recommendations for Uses beyond Mobility Performance Measurement

Task 11 is a report preparation tasks and therefore is not represented in the chapter sections that discuss the research findings.

The overall project findings and conclusions are presented in Chapter 11, the summary of recommendations is presented in Chapter 12, and the implementation and technology transfer plan is presented in Chapter 13. An appendix follows the report chapters and provides technical detail on the *HCM*-based speed flow model fitting discussed in Chapter 9.

CHAPTER 2. TASK 1 – DATA SOURCE CROSS-CHECKING

In the Triangle area, there are 3 sources of mobility and reliability data that NCDOT can use: INRIX, Traffic.com, and SpeedInfo. While SpeedInfo is only able to report speed at a point, the other two data sources provide useful but also comprehensive data and are the focus of our comparisons. INRIX provides link based data while Traffic.com provides point based data. INRIX and Traffic.com provide co-located data at many areas where the Traffic.com sensor is near the midpoint of the INRIX segment. Cross-checking was performed to determine how closely the different data sources match, where they do not match, possible reasons why they do not match, and ways to improve the data provided.

2.1 Data Description: INRIX

Sources:

- one-minute data – www.ritis.org
- Five-minute data – i95.inrix.com
- 15-minute data – NCDOT

INRIX uses GPS probes and, in some locations, other data sources to collect speed information on over 1 million miles of roads across North America (*1*). Two sources were utilized to collect INRIX speeds, using 2010 data and later 2011 data. One minute aggregation speed data were collected from the Regional Integrated Transportation Information System (RITIS) (*2*) and five minute aggregation speed data were collected from the I-95 Corridor Coalition INRIX webpage (*3*). All five minute aggregation data were collected for the twenty study weekdays, and one minute aggregation data were collected when non-systematic speed differences were identified. Speeds are reported for TMC (Traffic Message Channel) codes defined by TeleAtlas and NAVTEQ in real time and archived. Each freeway TMC code represents a directional roadway segment with a geo-located beginning and ending point. The INRIX system assigns vehicle-based measurements to TMC segments and averages these readings across one-minute base reporting intervals. Speed data aggregated at a 15-minute interval were collected from RITIS and NCDOT.

In addition to speed, INRIX reports Travel Time, Average Speed, Reference Speed, Score and C-Values. Average speed is a time of day and day of week average that is updated, while Reference speed is the 85th percentile measured speed capped at 65 mph. Score indicates if the speed is historical (reference speed), real time or a blend of real time and historical data, while the C-Value is a measure of confidence for real time data. The reported one-minute speeds are missing 3.9% of the time periods in 2010, while there were no missing values in the 2010 five-minute data.

There are approximately 3,500 TMC segments in North Carolina that define the freeway network. The road network is segmented by interchange ramps so that the segments are either internal (within the interchange between the off and on ramp) or external (between interchanges from the on ramp to the next off ramp). With the addition of important arterials, the INRIX system available to the NCDOT includes a total of approximately 20,000 TMC segments for the combined freeway and arterial network.

Table 2.1 Detailed Data Attributes - INRIX

Field	Data type	Description
TmcCode	9 digit text	Unique spatial identifier for each segment and direction
TimeUTC	Date and Time	Date and Time in UTC format (UTC-5h=EST, -4hr-EDT) ONLY IN FIVE-MINUTE DATA RESOLUTION
measurement_tstamp	Date and Time	Local Date and Time ONLY FOR ONE-MINUTE DATA RESOLUTION
DTK	7 digit number	Date/Time code
Speed	Integer	Reported speed for the time period (MPH)
AverageSpeed	Integer	Average speed --unique for each segment, time period, and day of the year (MPH)
ReferenceSpeed	Integer	Reference speed --unique for each segment, identical at all times and days of the year (MPH)
Score	Integer	10, 20, or 30
TravelTimeMinutes	Number	Calculated from reported “Speed”; 2 decimal places for 5 min data, 3 decimal places for 1 min data
C_Value	Integer	0-100, “Confidence Value”, only reported if Score=30
Delta	Integer	=“Speed” – “AverageSpeed”; =0 if there is no AverageSpeed reported, ONLY IN ONE-MINUTE DATA

Important details regarding the INRIX data are –

- "Score" data are classified into 3 groups:
    - Score = 10 – Speed is taken from ReferenceSpeed. Reported when there is no probe data or AverageSpeed.
    - Score = 20 – Speed is taken from AverageSpeed. Only reported when there are no probes (and not ~10pm to ~4am).
    - Score = 30 – Speed is calculated from some probe data, quality and quantity of probes is unknown. Presumably C_Value is a measure of confidence.
- 15-minute data only contain speed to nearest MPH.
- Five-minute data are available through a web interface for download by day (each day's file contains all TMCs in NC). One-minute data are available and were obtained from the Regional Integrated Transportation Information System (RITIS) hosted by the University of Maryland's Center for Advanced Transportation Technology (CATT) Lab.
- Five-minute aggregation appears to be done on the five-minute period following the time (i.e. the five-minute interval data designated at time interval 12:00 were aggregated from one-minute periods starting at 12:00, 12:01, 12:02, 12:03, and 12:04).
- One-minute data has approximately 3.9% missing time periods for 2010. There are no gaps in the 15-minute data provided by NCDOT (initially provided by INRIX), and it is not clear how missing values were handled in the 15-minute aggregation.

2.2 Data Description: Traffic.com

The source for this data was stakeholder.traffic.com, and the data were at a five-minute aggregation. Traffic.com collects speed and flow data using a mixture of side-fire microwave radars and acoustic sensors installed at fixed permanent locations along interstates in the Triangle Region of North Carolina. There are 59 stations in the Triangle along I-40, I-440, and part of I-540. They are spaced approximately 1.5 miles apart throughout the network. Five minute aggregation speed data were collected from the stakeholder webpage of Traffic.com (*4*) at ten locations for the twenty study weekdays. Observations of speed and flow aggregated at a 15-

minute interval were also collected from Traffic.com. Traffic.com also reports number of valid readings in the reporting period as well as information on volume categorized by vehicle class. The passenger car (pc) equivalent volume is converted from volume by vehicle classification. Class 1 vehicles (non-commercial) are thought to be equivalent to pc; class 2, 3 and 4 vehicles (single-unit, single trailer and multi-trailer commercial) are thought to have average pc equivalence of two. The PCE volume is then converted to a per lane hourly flow rate by the number of lanes and time interval. Density is calculated, in the 15-minute interval, by this one-lane based PCE flow rate divided by speed.

Traffic.com reports speed, volume, occupancy and the number of valid readings in the reporting period. There are infrequent gaps in the reported data; however there are gaps longer than 24 hours in which no data were reported. The time periods immediately before and following the gap tend to have questionable speed/volume data.

Table 2.2 Detailed Data Attributes – Traffic.com

Field	Data type	Description
StationId	Number	Unique identifier for each station
StationDescription	Text	Text description of station location
Day	Text	3 letter designation for day of the week
Date	Date	Local Date
Time	Time	Local Time
Duration	Integer	Number of minutes sampled
Direction	Text	E/W designation
NumberOfLanes	Integer	Number of lanes travelling in the direction
Speed	Number	Speed in mph, 2 decimal places
Volume	Integer	Vehicle count in the reporting period
Occupancy	Number	% Occupancy, 2 decimal places
Class1	Integer	Count of non-commercial vehicles
Class2	Integer	Count of single-unit commercial vehicles
Class3	Integer	Count of single trailer commercial vehicles
Class4	Integer	Count of multi-trailer commercial vehicles
ReadingsTaken	Integer	Number of readings in reporting period
ValidReadings	Integer	Number of readings that the sensor does not detect an error in reporting period

2.3 Data Description: SpeedInfo

SpeedInfo collects speed data using bi-directional radar sensors located in the Triangle Region. There are a total of 63 sensors in the region, with variable spacing between sensors. One-minute speed data were collected from the NCDOT Traffic Traveler Information Management System webpage (*5*) at the three study locations with sensors nearby on I-40 for the twenty study weekdays. SpeedInfo only reports speed, and one minute speeds were aggregated to five minute average speeds for comparison purposes.

2.4 Study Locations

Five minute aggregation period data were collected at 5 locations in the Triangle Region in both directions where the Traffic.com sensors were located near the midpoint of the segments. The ten sites are: I-40 & Davis Drive, I-40 & Harrison Avenue, I-40 & Hammond Road, I-440 & Lake Boone Trail, and I-440 & Capital Boulevard in each direction. Data was collected for the aforementioned segments during the weekdays from 8/9/10 to 9/3/10 and later compared to data for the weekdays from 8/8/11 to 9/2/11. Each location is on an urban interstate or interstate loop. The locations of the INRIX segments, Traffic.com sensors, and SpeedInfo sensors (where available) are shown in Figure 2.1, Table 2.3, and Table 2.4. Information on the Traffic.com point sensor type, manufacturer, model, and installation date are included in Table 2.5.

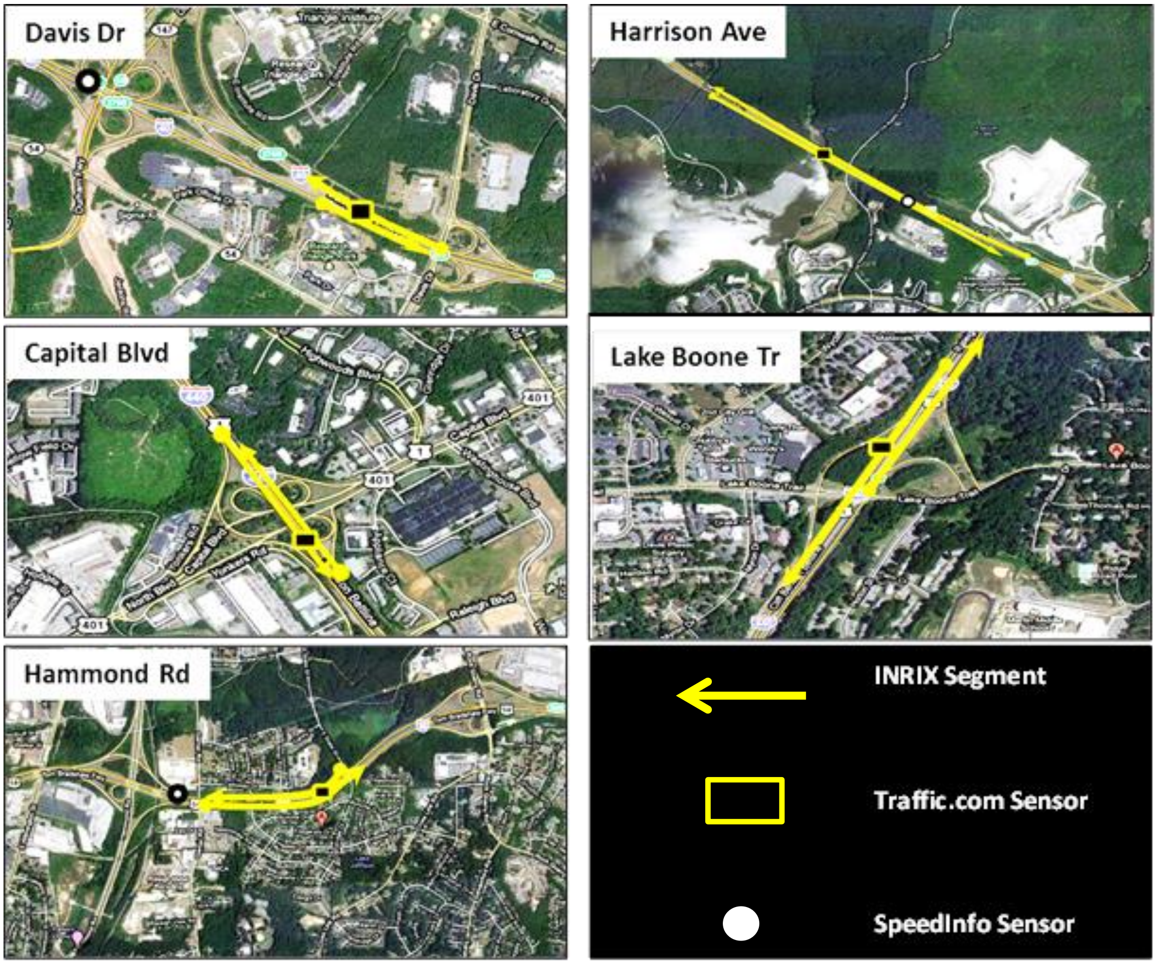


Figure 2.1 Study Locations

Table 2.3 Study Segment Descriptions for 2010

Location		TMC Code	Length of INRIX Segment (mi)	Traffic.com Sensor Code	# of Lanes	Segment Type
I-40	Davis Dr. EB	125-04866	0.42	040340	4	Off Ramp
	Davis Dr. WB	125+04867	0.51	040340	4	On Ramp
I-440	Capital Blvd. EB	125-04988	0.53	440135	4	On Ramp
	Capital Blvd. WB	125+04988	0.49	440135	3+1 Weave	Weave
I-40	Hammond Rd. EB	125-04961	0.82	040190	4	Basic
	Hammond Rd. WB	125+04962	0.75	040190	4	Basic
	Harrison Ave. EB	125-04860	1.69	040300	4	Basic
	Harrison Ave. WB	125+04861	1.63	040300	4	Basic
I-440	Lake Boone Tr. EB	125-04979	0.32	440180	3	On Ramp
	Lake Boone Tr. WB	125+04979	0.47	440180	3	Off Ramp

Table 2.4 Study Segment Descriptions for 2011

Location		TMC Code	Length of INRIX Segment (mi)	Traffic.com Sensor Code	# of Lanes	Segment Type
I-40	Davis Dr. EB	125-04866	0.40	040340	4	Off Ramp
	Davis Dr. WB	125+04867	0.48	040340	4	On Ramp
I-440	Capital Blvd. EB	125-04988	0.53	440135	4	On Ramp
	Capital Blvd. WB	125+04988	0.49	440135	3+1 Weave	Weave
I-40	Hammond Rd. EB	125-04961	0.74	040190	4	Basic
	Hammond Rd. WB	125+04962	0.72	040190	4	Basic
	Harrison Ave. EB	125-04860	1.69	040300	4	Basic
	Harrison Ave. WB	125+04861	1.64	040300	4	Basic
I-440	Lake Boone Tr. EB	125-04979	0.35	440180	3	On Ramp
	Lake Boone Tr. WB	125+04979	0.53	440180	3	Off Ramp

Table 2.5 Point Sensor Types, Models, and Installation Dates.

Location		Sensor Type	Sensor Manufacturer	Sensor Model	Installation Date
I-40	Davis Dr. EB	Microwave Radar	EIS	X3	8/12/2008
	Davis Dr. WB	Acoustic	Smartek	SAS 1	8/12/2008
I-440	Capital Blvd. EB	Microwave Radar	EIS	X3	8/28/2008
	Capital Blvd. WB	Microwave Radar	EIS	X3	8/28/2008
I-40	Hammond Rd. EB	Microwave Radar	EIS	X3	8/21/2008
	Hammond Rd. WB	Acoustic	Smartek	SAS 1	8/21/2008
	Harrison Ave. EB	Microwave Radar	EIS	X3	8/15/2008
	Harrison Ave. WB				
I-440	Lake Boone Tr. EB	Microwave Radar	EIS	X3	9/11/2008
	Lake Boone Tr. WB				

2.5 Evaluating Differences in Reported Speeds

It is becoming increasingly important to determine if data of different types are similar, as valid data fusion can be utilized to supplement probe networks (*6*). Point sensors that collect traffic data continuously can improve the quality of the probe network when coverage is sparse or non-existent. Additionally, point sensors typically detect traffic measures that probe networks cannot, such as volume, density and estimated vehicle length. A fused network would provide immensely useful information to planners, operators, managers and drivers.

Because INRIX samples across the entire length of TMC segments, the resulting speed data is fundamentally different from Traffic.com speed data sampled at a fixed point along each segment. Therefore, along segments with both Traffic.com and INRIX coverage, a significant speed difference between reported speed from the two systems might occur due to placement of the Traffic.com station relative to nominal queue formation and dissipation or relative to points along the segment where operational characteristics change, say for example due to pronounced changes in horizontal and/or vertical alignment. Site selection for this study was conducted with the goal of selecting sites that would minimize this bias and the resulting impact on comparison of the delay metrics.

This task seeks to determine if the link speeds reported by INRIX are similar to the point speeds reported by Traffic.com and identify patterns in and possible explanations for the differences. The following sections summarize the results of the speed comparison, identify systematic differences and provide guidance for evaluating speed differences.

The speed differences at all sites were normally distributed, with three locations indicating a mean speed difference greater than 5 mph. In addition to the systematic speed differences, non-systematic speed differences were identified where the difference was more than 1.5 standard deviations lower than the mean difference. This may indicate inherent inaccuracies in reported GPS speeds under heavy congestion, including instances of time lag in recovering from congested speeds.

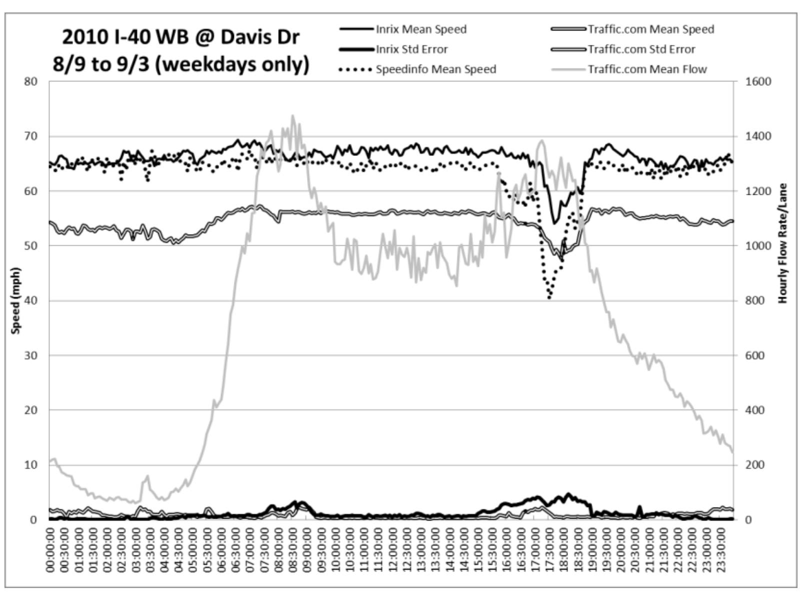
2.6 Mobility Data Comparisons

2.6.1 INRIX vs. Traffic.com using Speed Profiles

Once the speed data were collected from the two or three sources for each direction of the ten study locations in 2010, time of day weekday average speed profiles were created for all 10 pairs of segments and sensors and graphed to determine visually if the speeds were similar and if the shape of speed drops in the peak periods were similar. SpeedInfo speeds were included in the analysis if available. A location (I-40 EB & WB @ Davis Dr.) was found where Traffic.com sensors reported speeds 10 mph slower than INRIX (Figure 2.2). The INRIX segment on I-40 & Davis Drive westbound is a weaving segment while the eastbound direction is a basic segment, and the Traffic.com sensor is near the midpoint of each. Westbound showed a large speed difference between INRIX and Traffic.com throughout the day, while SpeedInfo reported different speeds during the PM peak period. This is likely due to the placement of the SpeedInfo sensor, which is located downstream of the INRIX segment within a shorter weave. Eastbound showed similar speed variations. I-440 EB & WB @ Capital Boulevard also shows a systematic speed difference. Both INRIX segments on I-440 & Capital Boulevard are basic segments, and the Traffic.com sensor is near the midpoint of the segment. Capital Boulevard showed a large speed difference throughout the day in the westbound direction, but does not show a large speed difference in the eastbound direction.

Otherwise, most sites had 20 weekday average speeds within 5 mph or less of each other at the same time period (Figure 2.3). The INRIX segments on I-440 & Lake Boone Trail are both basic segments and the Traffic.com sensor is located at the midpoint of the westbound segment and within the eastbound segment. This site showed a small speed difference throughout the day in the westbound direction, which is just upstream of a bottleneck, while there was very little speed difference in the eastbound direction. The INRIX segments on I-40 & Harrison Avenue are the two longest study segments and are both basic segments with a fairly steep upgrade from the midpoints to the east. The Traffic.com sensor is located at the midpoint of the segments, 300 feet west of the grade change. Both directions showed very little speed differences.

Data for 2011 was then compiled to examine whether the data remained the same or there was a significant change from the 2010 data. The 2011 data once again showed most sites had speeds that were within 5 mph or less of each other with the exception of the aforementioned sites at Davis and Capital. The speed profiles for 2010 provided below have been matched up with the respective graph for 2011. These graphs reiterate that the data remained very similar from 2010 to 2011.



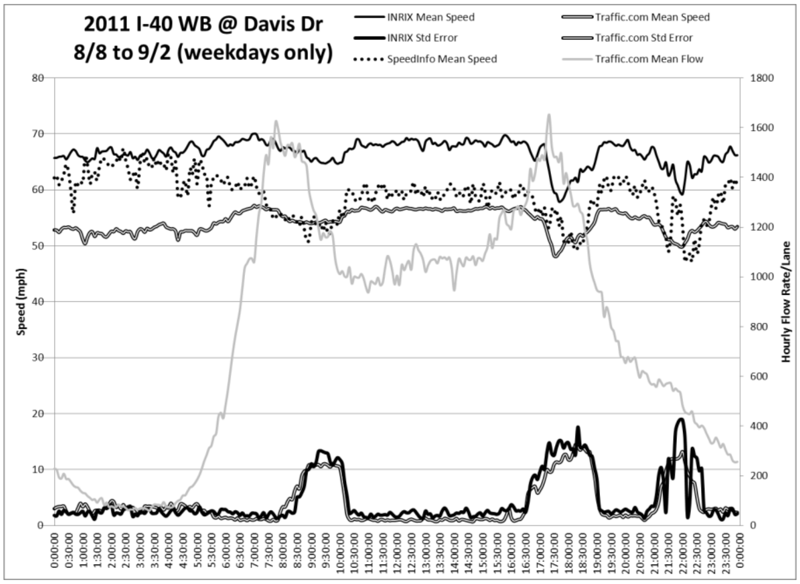


Figure 2.2 Speed and Volume Comparison at Davis Drive for 20 Weekdays

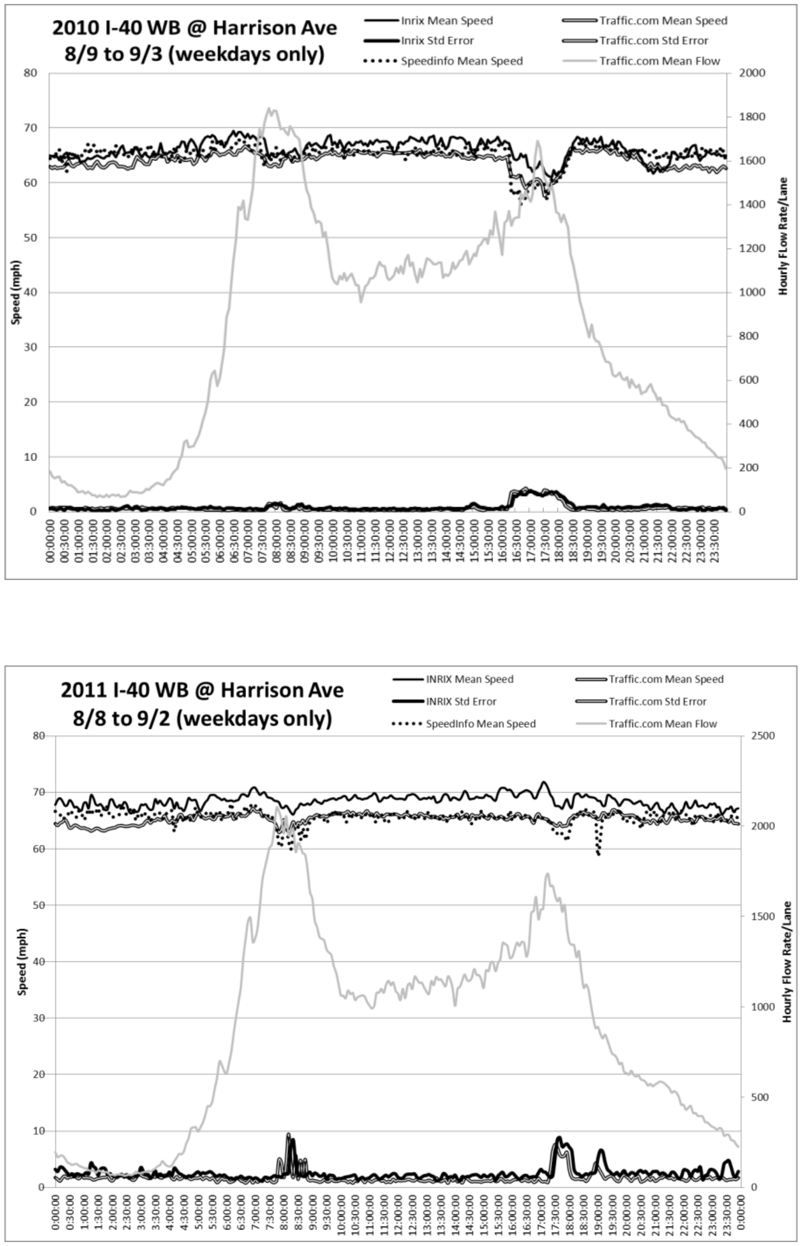


Figure 2.3 Speed and Volume Comparison at Harrison Avenue for 20 Weekdays

2.6.2 INRIX and Traffic.com vs. GPS Floating Car Runs

Due to the 10 mph speed difference found at the Davis Drive location, floating car GPS runs were performed in 2010 to determine which source was providing valid data. A total of 17 GPS floating car runs were performed. Three drivers drove from 11 AM to 3 PM on I-40 from Harrison

Avenue to US 15-501 and back in order to provide data at both the Davis Drive and Harrison Avenue locations. Floating car runs took place on Tuesday, Wednesday, and Thursday October 5-7, 2010 and the GPS data was compared to the two locations mentioned as well as to all other Traffic.com sensors along the route. GPS space mean speeds were calculated and compared to each INRIX segment in the run and speeds recorded by the GPS unit closest to Traffic.com sensors in the run were compared to the sensor speeds.

Figure 2.4 shows the results of the GPS floating car runs at the I-40 & Davis Drive location in the westbound direction. For the most part, the INRIX and GPS speeds were very similar; while the Traffic.com speeds were much lower (approximately 10 mph slower). This was also true in the eastbound direction, indicating that the reported INRIX speeds are reasonable while there may be a systematic error with the Traffic.com sensor at this location. Nearby segments and sensors showed similar speeds to the GPS runs. Figure 2.5 shows that INRIX and Traffic.com both reported similar speeds to the collected GPS floating car speed at the I-40 & Harrison Avenue location in the westbound direction. Similar speeds from the three sources were also seen at I-40 & Miami Boulevard in the eastbound direction, where the Traffic.com sensor is located at the western end of the INRIX segment. However, during the GPS runs, two sites (at Aviation Boulevard and at Alexander Drive) were found where INRIX speeds dropped throughout a 30 minute to 2 hour period while Traffic.com reported steady speeds (Figure 2.6 and Figure 2.7). This could be due to bad probe data, as Traffic.com and GPS runs showed steady speeds at the same time period. The remaining locations had similar speeds from all sources, with the INRIX speeds tending to match the GPS floating car speeds better than the Traffic.com speeds when INRIX and Traffic.com reported different speeds. Floating car runs were not performed for comparison with the 2011 data.

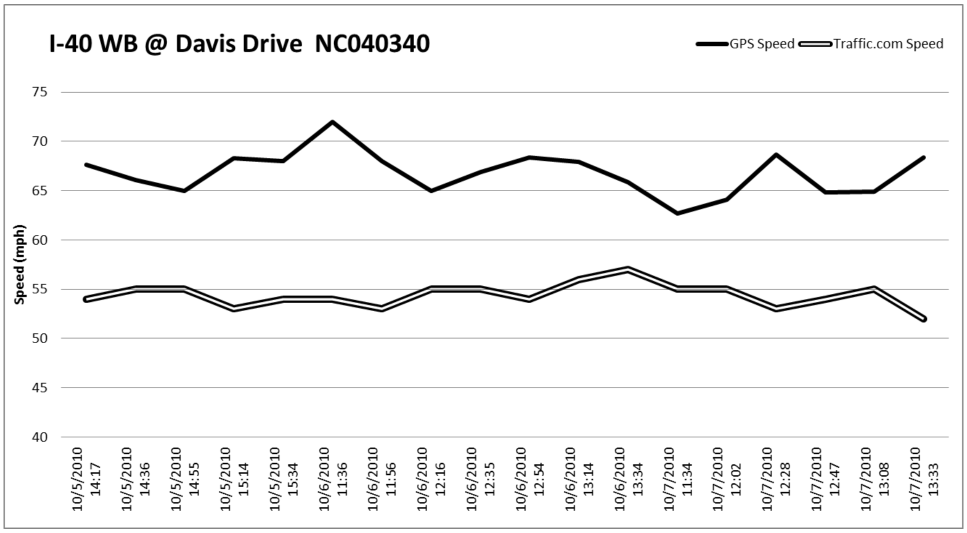


Figure 2.4 Comparison of GPS and Traffic.com Speeds at Davis Drive

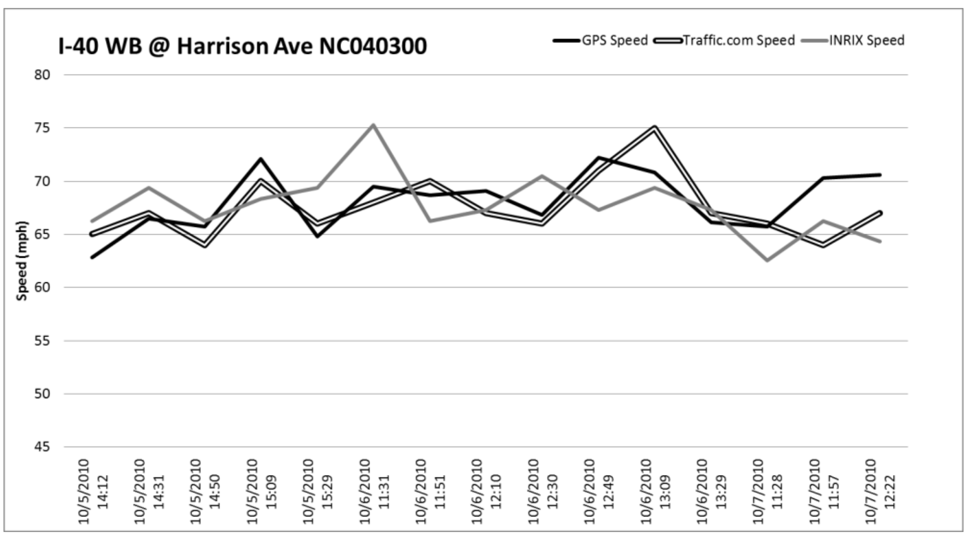


Figure 2.5 Comparison of GPS, INRIX, and Traffic.com Speeds at Harrison Avenue

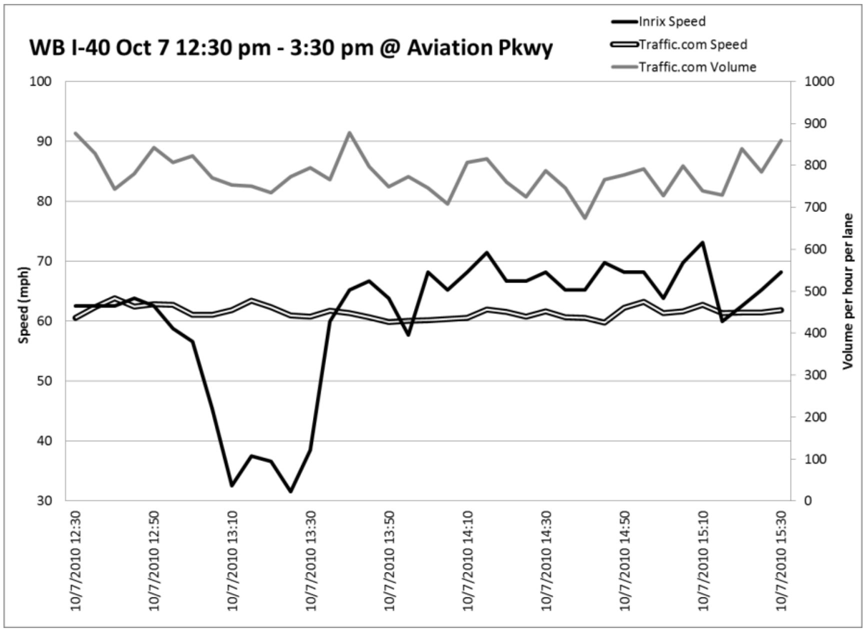


Figure 2.6 Comparison of INRIX and Traffic.com Speeds at Aviation Parkway

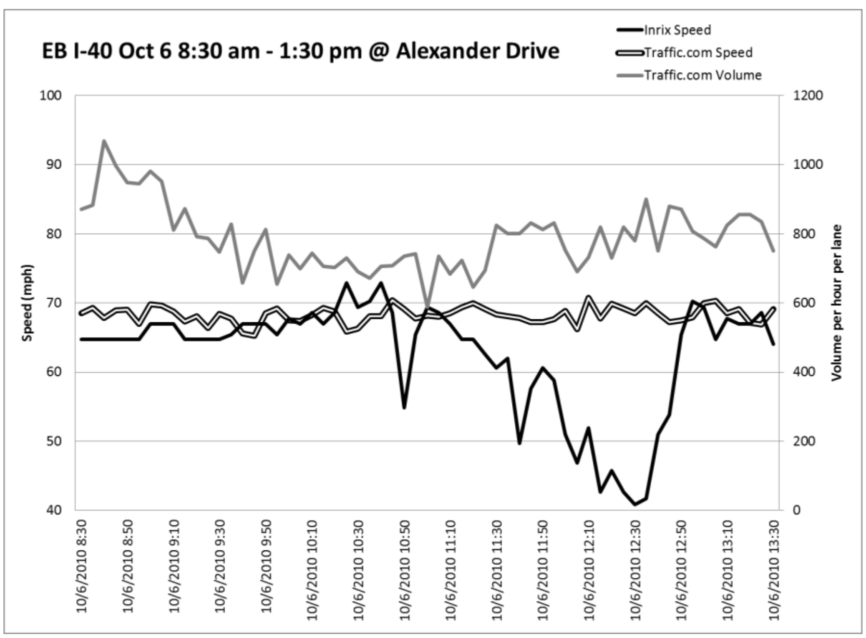


Figure 2.7 Comparison of INRIX and Traffic.com Speeds at Alexander Drive

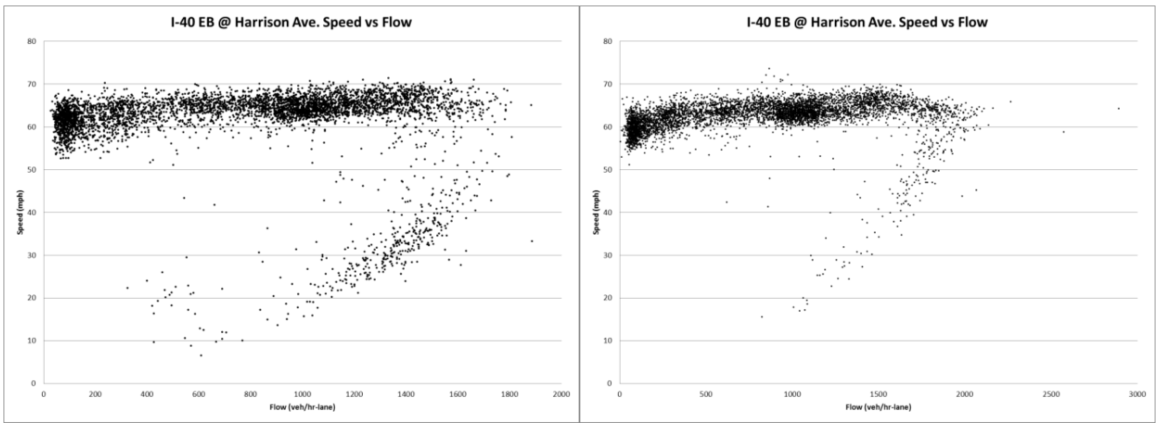
2.6.3 Speed-Flow Relationships

Traffic.com data at the two locations was further examined to see whether speed flow density relationship matched expectations from traffic flow theory. Speed-flow relationships were created using the Traffic.com volumes and either Traffic.com speeds or INRIX speeds. Differences in the relationships shown were visually analyzed, and each graph was compared to typical speed-flow relationships from the *Highway Capacity Manual* 2010 (*HCM* 2010) (*7*). Any departures from typical relationships were further examined to find the cause.

Figure 2.8 shows the speed-flow relationships derived from the weekday study periods across all times of day using speeds from both sources (20 days x 24 hours x 12 five minute periods = 5760 possible) for Harrison Avenue in 2010 (a) and 2011 (b). The relationship at I-440 & Lake Boone Trail in the westbound direction using Traffic.com volumes and Traffic.com speeds is similar to the expected relationship shown in the *HCM* 2010. When the INRIX speeds are used with the Traffic.com volumes, the relationship changes dramatically and the semi-parabolic shape is lost. A cluster of low speeds during very low flow conditions appears in the graph for westbound I-440 at Lake Boone Trail, where low speeds were reported by INRIX from approximately 3 AM to 5 AM on multiple days. At these times, Traffic.com reports speeds 50-60 mph. It is unknown why INRIX is reporting low speeds, but it is reasonable to assume that the speeds are in error.

The relationship at I-40 & Harrison Avenue in the eastbound direction is similar to the *HCM* 2010 relationship when using Traffic.com volumes and speeds, while a different relationship is shown when using INRIX speeds and Traffic.com volumes. These sites are two of the most congested in the study that did not display a very large speed difference in the initial evaluation. The sites with little congestion maintained a linear shape clustered around free flow speeds, with a little more spread in speeds introduced when using INRIX speeds and Traffic.com volumes. The

Davis Drive segment still showed unexpected free flow speeds (10 mph slower than expected). Further discussion on cause of the scatter created by occasional time lag in INRIX is continued in the non-systematic differences section. INRIX reports speeds accurate to the whole mile per hour, while Traffic.com reports speeds to the hundredths place. Occasional outliers existed, but the rest of the study sites displayed normal free flow to congested behavior.



(a) 2010 Speed vs. Flow (b) 2011 Speed vs. Flow

Figure 2.8 Harrison Avenue 20 Weekdays of 5-minute Traffic.com Data

2.6.4 Analysis of Systematic Differences

Speed difference histograms were plotted for each location and in each direction to determine if the differences between INRIX and Traffic.com were normally distributed to test for bias. To quantify systematic differences in speed, the mean speed difference for the entire 20 days was calculated for each pair of segments and sensors. Additionally, the standard deviation of speed differences was calculated for each pair. Only INRIX and Traffic.com speeds were compared as they were available at all 10 pairs of segments and sensors. These measures were repeated with absolute speed differences.

2.6.4.1 Mean Speed Difference

The mean speed difference is defined as the sum of the speed differences (i.e. the difference between the reported INRIX speed and the reported Traffic.com speed) divided by the number of data N collected during the study period. The equation for mean speed difference is

$$\bar{d} = \frac{1}{N}\sum_{t=1}^{N} d_t \tag{1}$$

where:

x_t = INRIX Speed at time t

y_t = Traffic.com Speed at time t

$d_t = x_t - y_t$

N = Total number of data collected

2.6.4.2 Standard Deviation of Speed Differences

The standard deviation of speed differences is

$$\sigma = \sqrt{\frac{\sum_{t=1}^{N}\left(d_t - \bar{d}\right)^2}{N-1}} \tag{2}$$

2.6.4.3 Absolute Speed Differences

The above measures were also calculated from absolute speed differences, replacing d_t with $|d_t|$ where $|d_t| = |x_t - y_t|$.

The speed differences were shown to be normal, so the mean of actual and absolute speed differences as well as the standard deviation of actual and absolute speed differences were calculated at each location and direction to summarize the systematic speed differences. Table 2.6 and Table 2.7 below show a summary of the systematic and non-systematic speed differences found at each location in 2010 and 2011. As discovered in the visual analysis, the largest speed differences were found at I-40 & Davis Drive in both directions and I-440 & Capital Boulevard in the westbound direction. All other locations had speed differences within the proposed 5 mph range. Absolute speed differences also identified I-40 & Lake Boone Trail in the westbound direction as a location with mean speed differences greater than 5 mph. The population of probe vehicles can have a large effect on the speeds reported; probe fleets made up of commercial vehicles would report biased speeds by sampling more often from the slower right lanes, which would exhibit a negative mean speed difference. This occurred in some segments, however the magnitude was not consistent and as a whole the study locations do not indicate similar systematic differences between the technologies.

Table 2.6 Analysis of Speed Differences between INRIX and Traffic.com 2010

	Mean Diff. (mph)	Std. Dev. (mph)	Mean Absolute Diff. (mph)	Std. Dev. (mph)	Positive Deviations	Negative Deviations	30+ min Deviations	Longest Deviation (min)
I-40 @ Davis Dr EB	13.31	6.85	13.51	6.92	310	101	14	130
I-40 @ Davis Dr WB	11.51	4.24	11.61	3.95	155	126	8	85
I-440 @ Capital Blvd EB	-3.13	4.54	4.06	3.72	136	211	2	35
I-440 @ Capital Blvd WB	-8.84	5.18	8.95	4.99	100	155	4	35
I-40 @ Hammond Rd EB	2.27	5.05	4.07	3.75	153	140	7	55
I-40 @ Hammond Rd WB	-3.99	4.49	4.95	3.39	144	132	7	145
I-40 @ Harrison Ave EB	0.72	6.61	4.30	5.07	74	110	10	90
I-40 @ Harrison Ave WB	1.95	3.74	3.21	2.74	164	126	5	40
I-440 @ Lake Boone Tr NB	-0.69	5.54	3.95	3.95	135	142	10	90
I-440 @ Lake Boone Tr SB	4.53	6.03	6.06	4.49	90	137	4	40
Total	N/A	N/A	N/A	N/A	1461	1380	71	145

Table 2.7 Analysis of Speed Differences between INRIX and Traffic.com 2011

	Mean Diff. (mph)	Std. Dev. (mph)	Mean Absolute Diff. (mph)	Std. Dev. (mph)	Positive Deviations	Negative Deviations	30+ min Deviations	Longest Deviation (min)
I-40 @ Davis Dr EB	11.3	4.26	11.43	5.97	155	138	5	55
I-40 @ Davis Dr WB	12.22	3.89	12.32	6.86	166	63	7	80
I-440 @ Capital Blvd EB	-1.53	3.68	3.12	4.42	201	199	8	40
I-440 @ Capital Blvd WB	1.53	3.54	2.87	4.12	137	154	4	40
I-40 @ Hammond Rd EB	2.75	4.33	3.91	7.38	153	146	10	40
I-40 @ Hammond Rd WB	-0.13	3.94	3.06	5.47	166	152	14	85
I-40 @ Harrison Ave EB	3.87	3.88	4.43	5.87	198	149	6	120
I-40 @ Harrison Ave WB	2.90	2.98	3.29	3.67	215	152	1	30
I-440 @ Lake Boone Tr NB	1.38	4.71	3.30	7.36	136	66	9	75
I-440 @ Lake Boone Tr SB	6.27	5.15	6.97	8.95	67	79	3	30
Total	N/A	N/A	N/A	N/A	1594	1298	67	120

2.6.5 Analysis of Non-Systematic Differences

Assuming normally distributed speed differences, differences that deviate from the mean would be expected to occur randomly. For this study, differences that deviated from the mean more than 1.5 standard deviations were scrutinized. A "Positive Deviation" indicates that INRIX is reporting a speed that is higher than the Traffic.com speed plus the mean speed difference plus 1.5 standard deviations, while a "Negative Deviation" indicates that INRIX is reporting a speed that is lower than the Traffic.com speed plus the mean speed difference minus 1.5 standard deviations. These positive or negative deviations could be due to random errors in either system.

While randomly distributed deviations are expected, continuous positive or negative deviations indicate more serious errors in either system or a possible time lag between systems. If there is enough evidence of long, continuous deviations that cannot be attributed to systematic lag, fusing the two data sources would not be recommended.

The length of continuous Positive or Negative Deviations were tracked for each segment in each direction (Figure 2.9 and Figure 2.10). The maximum deviation for each segment in each direction along with the number of deviations greater than 30 minutes for each was recorded. Deviations longer than 30 minutes are highly unlikely assuming a random time distribution of deviations. Using a geometric distribution with a probability of 0.93319 to randomly draw a sample greater than 1.5 standard deviations below the mean in a normal distribution, the probability that it will take 6 or more periods to get the first sample greater than 1.5 standard deviations below the mean is 8.89×10^{-8}. The probability of it taking 18 periods, as in the 90 minute deviation, is 4.70×10^{-23}, approximately 100,000,000,000,000 (One hundred trillion) times less likely than the probability of winning the current Powerball Grand Prize (*8*). These extreme odds indicate that there is a non-systematic error occurring in one or both of the data sources in addition to the systematic error.

	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145
Positive Deviations	956	289	129	45	13	9	3	5	0	0	2	1	1	1	1	0	1	1	1	0	0	0	1	0	0	1	0	0	1
Negative Deviations	807	314	138	54	25	14	10	8	3	2	3	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Figure 2.9 Length (min) of Deviations from Mean Speed Differences in 2010

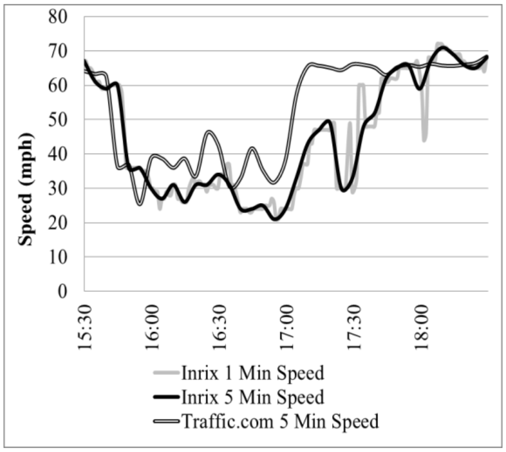
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
Positive Deviations	842	457	159	67	29	17	8	5	2	1	1	0	3	0	1	1	1	0	0	0	0	0	0	0
Negative Deviations	806	251	123	66	25	17	6	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 2.10 Length (min) of Deviations from Mean Speed Difference in 2011

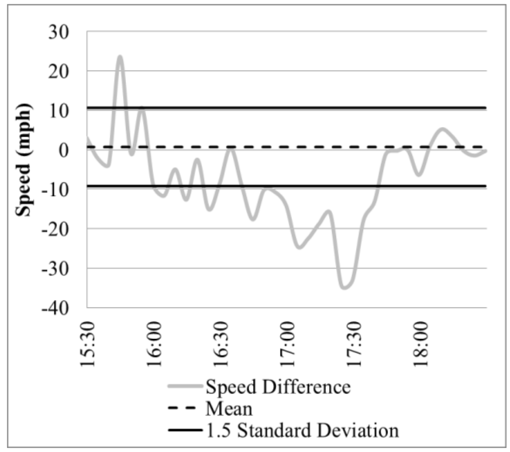
Further analysis was performed on the long deviations for both 2010 and 2011, and three sources of non-systematic differences were identified. Deviations that persisted for one hour or longer were selected for this process. Between 2010 and 2011, 16 long positive deviations and 3 long negative deviations occurred. Figure 2.11 shows the 60 minute deviation found at I-40 & Harrison Avenue in the eastbound direction. In this case, the INRIX speeds tracked the beginning of the congestion with only slight time lag of one time period, but the speeds took much longer to recover to normal after the congestion compared to Traffic.com. The short latency in reported INRIX speeds was also found in a New Jersey study (*9*). The time lag in recovery from slow speeds has a large effect on the speed flow relationships for INRIX speed and Traffic.com volume. As Traffic.com measures volumes and speeds that return to normal, INRIX still reports slow speeds, and therefore fusing the Traffic.com volumes to INRIX speeds scatters the speed-flow relationship during and for a period after congestion.

Figure 2.12 represents a time with no noticeable congestion reported by either Traffic.com or the one-minute INRIX speeds. However the five-minute INRIX speeds drop and stay much lower than either of the other two data streams for the 90-minute deviation displayed in Figure 2.12. This indicates a possible error in the aggregation from one-minute to five-minute speeds, especially given that the one-minute INRIX speeds track very closely to the Traffic.com speeds. This discrepancy is not consistent however, as is shown in the 120-minute negative deviation illustrated in Figure 2.13. In this case, the INRIX one-minute and five-minute speeds track very closely.

Long duration positive deviations are displayed in Figure 2.14 and Figure 2.15 for I-40 at Hammond Road. These long positive deviations occurred during off peak time periods when congestion was not present. Because the INRIX data quality is dependent on the number of INRIX probe vehicles, it is likely that these long positive deviations were a result of INRIX reporting historical data as opposed to actual observed data during time periods where there were insufficient probe vehicle observations.

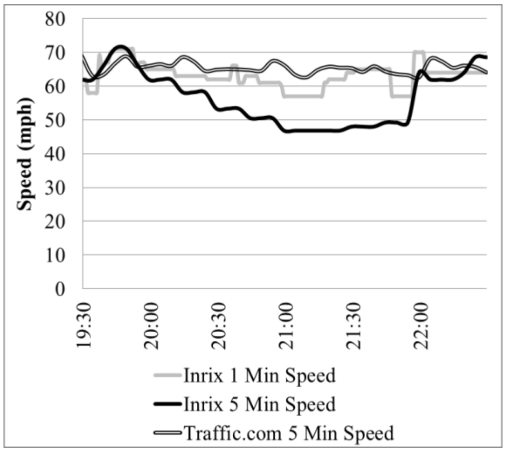


(a) Speed Comparison

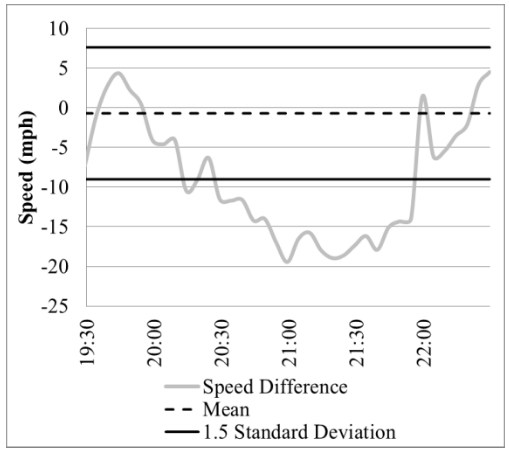


(b) Speed Difference

Figure 2.11 60 Minute Negative Deviation: I-40 EB & Harrison Ave. for 2010

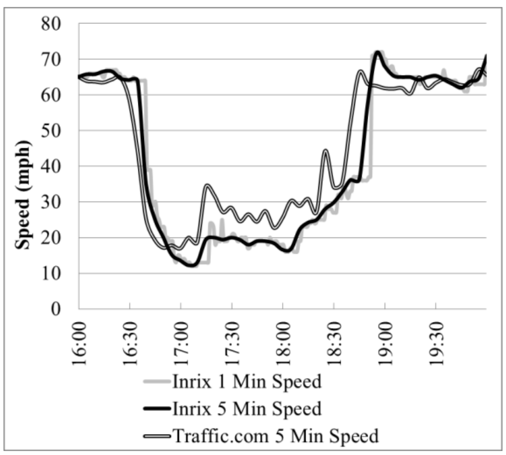


(a) Speed Comparison

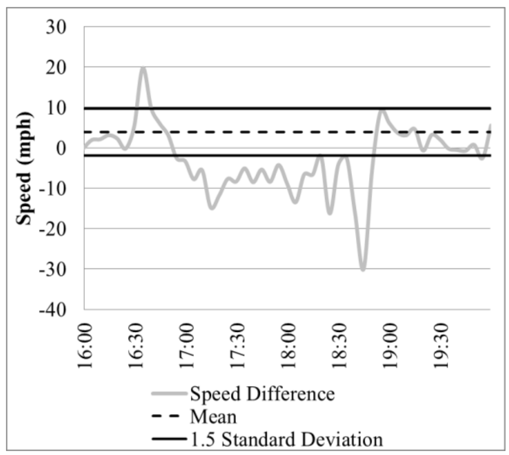


(b) Speed Difference

Figure 2.12 90 Minute Negative Deviation: I-440 EB & Lake Boone Tr. for 2010

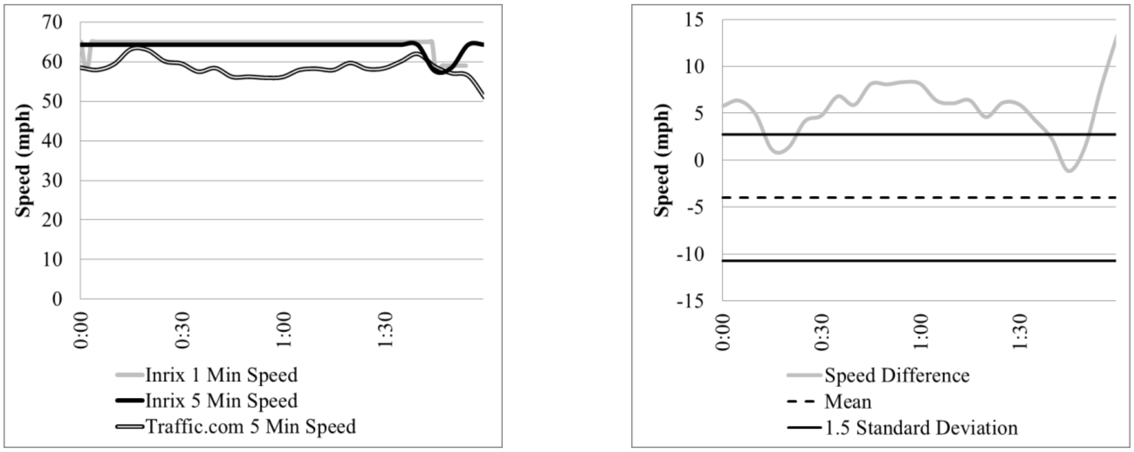


(a) Speed Comparison



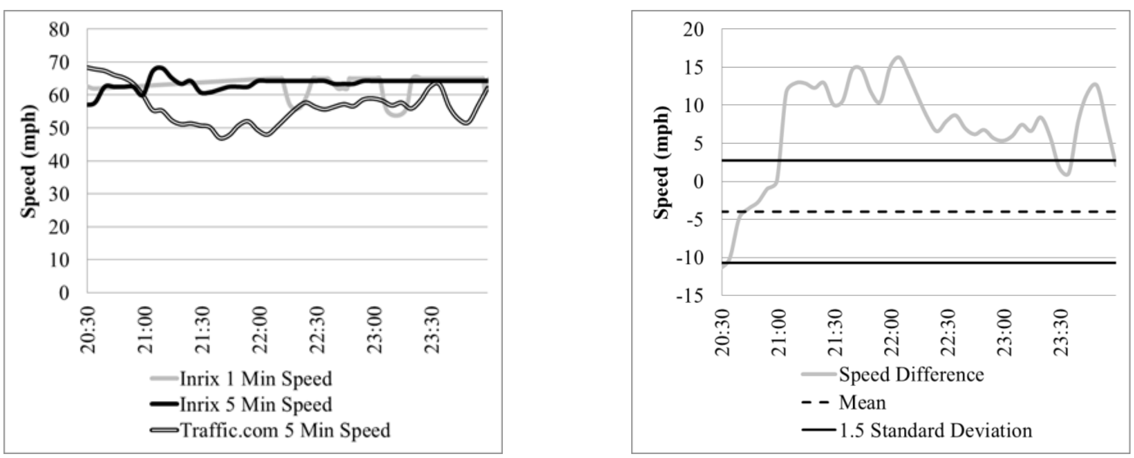
(b) Speed Difference

Figure 2.13 120 Minute Negative Deviation: I-40 EB & Harrison Ave. for 2011



(a) Speed Comparison (b) Speed Difference

Figure 2.14 75 Minute Positive Deviation: I-40 WB & Hammond Rd. for 2010



(a) Speed Comparison (b) Speed Difference

Figure 2.15 145 Minute Positive Deviation: I-40 WB & Hammond Rd. for 2010

2.7 Summary and Recommendations

This chapter presented a comparative evaluation of reported speeds from collocated point and link based speed detection at five bi-directional freeway locations in the years 2010 and 2011. Systematic speed differences occurred at nearly all study locations, but the mean speed difference value was unique to each site. Speeds from GPS floating car runs closely matched INRIX speeds at locations with large speed differences between INRIX and Traffic.com. This indicates a systematic error in the Traffic.com speeds at these locations, and it is recommended that the Traffic.com sensors for each direction at I-40 and Davis Drive be checked and recalibrated as necessary.

Speed-flow relationships using fused data did not maintain the traditional shape observed in past freeway studies and reflected in the *HCM* 2010. The expected speed-flow relationship form was however present in plots using data only from the Traffic.com side-fire microwave radar and acoustic sensors. Speed-flow relationships with fused data displayed more scatter in the congested region compared to relationships created with only point sensor data. Non-systematic differences were observed that indicated two sources of possible error in the INRIX speed data that could explain this scatter. An inconsistent time lag was found in congested speeds, with significant slowdowns consistently reported one period later than in the Traffic.com data, while recovery in speeds were reported by INRIX up to 60 minutes later than could be observed in the Traffic.com data. These lags in onset of and recovery from congestion could plausibly be the source of much of the scatter shown in the speed-flow relationships in the fused data congested region. The aggregation procedure that INRIX uses to create five minute speeds was also inconsistent, with a 90-minute period observed where five minute speeds were much lower than one minute speeds. While systematic differences in speed can be easily taken into consideration by applying the mean speed difference, non-systematic discrepancies require further study and consideration. Based on the findings, data fusion is not recommended until further study can identify, filter, or adjust reported speeds that are subject to non-systematic error.

CHAPTER 3. TASK 2 – DATA CLEANSING AND FILTERING

This task utilized INRIX data at a one-minute resolution for the full year 2010. In order to build travel time indices for the eight preliminary routes provided by NCDOT, 140 INRIX TMC segments code were used.

- The total number of data points available were 70,768,460
- A complete data set for one full year should have 73,584,000 data points (60 min/hr × 24 hr/day × 365 day/yr × 140 segments)
- Thus, about 3.83% of the data is missing / zero speed

Route travel times cannot be computed when one or more segments do not report travel times. For Route 3, which consists of 22 INRIX segments, 8.5% of the possible route travel times could not be constructed due to missing data. Route 7 and Route 8 have 65 INRIX segments and 14% of possible route travel times cannot be calculated due to missing data. Therefore, imputing missing data was considered to improve the quality of the final result. Upon further examination, it was decided that this approach would be unnecessary. INRIX data at a 15-minute resolution was also analyzed, as well as 2011 data for one-minute and 15-minute resolutions. The 15-minute resolution for 2010 was missing 1.31% of the data and also showed a speed of zero for 0.109% of the data. The INRIX data for 2011 at a one-minute resolution was similar to 2010, with 3.78% of the data missing and a speed of zero for 0.020% of the data. The 15-minute resolution for 2011 showed different results from 2010, with 2.96% of the data missing and a speed of zero for 0.009% of the data.

Table 3.1 shows the percentage of Traffic.com missing data at the sensors comprising Route 3 and Route 4 for the entire years of 2010 and 2011. Three of the sensors had significant amounts of data missing such that the data was discarded.

Table 3.1 Missing Data for Traffic.com

	2010				2011			
	Valid Readings	Possible Readings (stated)	Possible Readings (actual)	% Missing Readings	Valid Readings	Possible Readings (stated)	Possible Readings (actual)	% Missing Readings
040240	3133717	3145590	3153600	0.63%	3131049	3153600	3153600	0.72%
040250	3117360	3138570	3153600	1.15%	3126288	3153600	3153600	0.87%
040260	DISCARD DATA				DISCARD DATA			
040270	DISCARD DATA				DISCARD DATA			
040280	4089068	4141680	4204800	2.75%	4074986	4204800	4204800	3.09%
040290	3978255	4074000	4204800	5.39%	4180537	4204800	4204800	0.58%
040300	4177632	4194600	4204800	0.65%	4174984	4204800	4204800	0.71%
040310	5129349	5157450	5256000	2.41%	5183168	5241600	5256000	1.39%
040320	4026003	4072440	4204800	4.25%	4184076	4204800	4204800	0.49%
040330	5057294	5143500	5256000	3.78%	5202514	5256000	5256000	1.02%
040335	DISCARD DATA				DISCARD DATA			
040340	4024112	4091640	4204800	4.30%	3951388	4204800	4204800	6.03%
040350	3578483	3615045	3679200	2.74%	3496971	3568320	3679200	4.95%

3.1 Distribution of Consecutive Time Intervals with Missing Data

It was observed that the missing data was not randomly distributed by segment. Rather, during most periods with some missing data, all 140 INRIX segments had data missing in the same time period. In other words, if data was missing at 8:45 am, it was missing for all the segments at that time. Overall, missing data statistics for 2010 show that:

- 69.42% of the missing time gaps are only one minute long.
- 95.83% of the time gaps are less than or equal to 10 minutes in length.

- Only 1.06% of all the time gaps are greater than 3 hours long.
- 0.102% of data have (-1) value as its reported travel time (results from speed of zero).

Table 3.2 shows the number of missing data distribution with count (applied to all 140 segments) and Figure 3.1 is a graphical representation.

Table 3.2 Missing data distribution (INRIX one-minute resolution for 2010)

Time Gap Length	# Missing	Percent of Total	Cumulative Percent
1 min	2,025,240	69.42	69.42
2 min	349,580	11.98	81.41
3 min	163,660	5.61	87.02
4 min	92,960	3.19	90.20
5 min	59,080	2.03	92.23
6 min	41,860	1.43	93.67
7 min	26,040	0.89	94.56
8 min	15,120	0.52	95.08
9 min	11,620	0.40	95.47
10 min	10,360	0.36	95.83

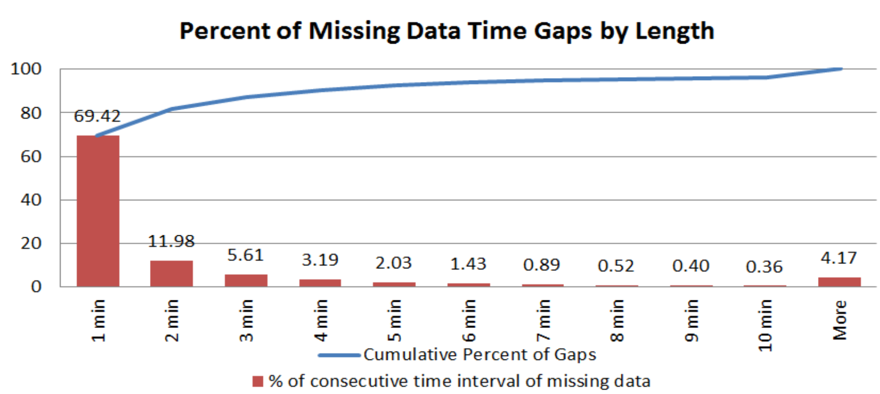


Figure 3.1 Distribution of missing data time gaps by length (one-minute INRIX data)

3.2 Source of and Recommendations for Handling Missing Data

RITIS technical personnel were contacted regarding the missing data, and they stated that the majority of the missing data were due to server communication issues between INRIX and RITIS. RITIS is planning to backfill larger gaps in data due to server downtime, but some missing data will remain regardless. Traffic.com data, from side-fire radar, may be missing due to sensor recalibration, loss of power, or communication failure. It is recommended that missing data imputation be considered in all calculations of aggregate reliability or mobility measures and sample sizes reported, especially when measures are calculated for a small sample based on the definition of the analysis period (i.e. 95th percentile of 52 observations of travel times on Mondays at 10:00 AM in 2010).

CHAPTER 4. TASK 3 – ROUTE TRAVEL TIME ESTIMATION AND PERFORMANCE ASSESSMENT

4.1 Purpose for Route Metrics vs. Link Metrics

Network reliability performance reported as traveler information must be portrayed from the traveler's perspective. While link travel times may be directly useful to transportation agencies, drivers experience the road network on a route basis, rather than as links or points where traffic data are normally collected. Agencies may desire to monitor path travel times for planning, operations assessment, or traveler information purposes. Drivers also do not experience an entire path simultaneously. In order to create route metrics from individual links, route travel times are stitched through space and time. Path travel times may be created dynamically for drivers who provide their origin and destination information or may be created from archived link data for evaluating the operations of important corridors. The Travel Time Data Collection Handbook recommends applying travel times from their corresponding time period if the simultaneous route travel time is longer than the study time or aggregation period (*10*). Route travel times were stitched through space and time rather than simultaneously summing segment travel times (also known as instantaneous travel times). This was done by selecting from the database the appropriate time-dependent average travel time on a segment that matches the time when that segment is entered based on route departure time. Route travel time prediction has been shown to be more accurate when route travel times from vehicle trajectories are used rather than the corresponding link travel times (*11*)(*12*). In travel time studies using different technologies it is also useful to stitch travel times when links from one source contain multiple links from another source (*13*). An algorithm was developed to calculate temporally-stitched route travel times at different aggregation periods and compares the resulting route travel times to simultaneous route travel times for each departure time period. The resulting estimates involve walking link travel times through time and are compared to travel time estimates derived by simultaneously summing link travel times for common departure times.

Also included in the algorithm is a calculation of the length of links in congestion, as well as the maximum contiguous length of congested links. Congested route travel times can be identified by a cutoff maximum contiguous length of congested links. Identification of congested travel times is important because the statistical distribution of travel times is markedly different under congested conditions than under free flow conditions. Travel time distributions were created from the identified congested or uncongested route travel times. Multiple definitions of congested route travel times were considered and distributions created from each definition were compared.

When comparing the estimation methods to observations it is important to remember that the Bluetooth sample and the sample that INRIX uses to estimate link space mean speeds and travel times are different. Bias can be introduced by either source, but with increased usage of network probe data it is important to quantify improvement in path travel time estimation and understand the factors that contribute to larger differences in path travel time estimates between the two methods examined.

Also of concern to agencies is selection of the ideal aggregation intervals for ITS data. Optimal aggregation periods vary based on uses for the data as well as the time of day it is collected (*14*). Using very fine aggregation provides very exact travel times for traveler information purposes, but at high expense due to storage and processing needed for a full data set. Longer aggregation periods can still be useful for planning and operations purposes with much lower storage and processing costs.

In the application of the algorithm, if the route being evaluated included a segment-time period combination with no travel time data, the route for that time period was not constructed. Additional filtering was performed during the second round of stitching where routes travel times were not constructed for periods where any individual segment travel time was longer than 30 minutes. Such unreasonably long link travel times likely represent system measurement error and would in turn yield extremely long and erroneous route travel times. For the route evaluated, this 30 minute maximum travel time translates to a minimum speed of 3 mph on the longest segment and much lower speeds on the shorter segments.

Temporary Bluetooth readers were placed at two locations (one on each end) on Route B in Figure 4.1. At each location, two different readers were placed by the freeway, one pole-mounted and one placed on the ground. The readings from both types of readers were combined into a single record for each location in order to maximize the possible matches between locations. The Bluetooth devices collected data from October 31, 2011 to January 6, 2012 except for short periods during battery charging. Link travel times were downloaded for the same time period to compare estimation error for path travel times in both directions.

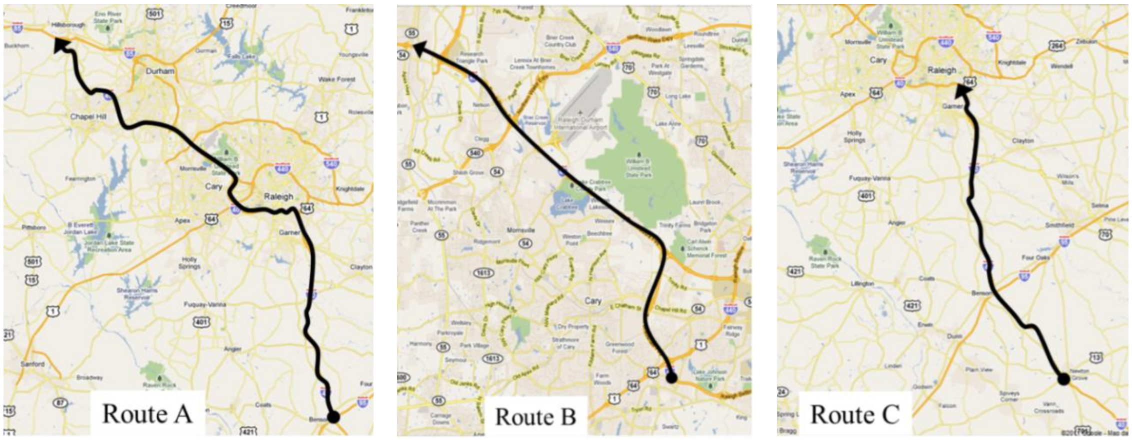


Figure 4.1 Study Paths

Link travel times were collected for an 82.88 mile corridor of I-40 WB from NC-50/55 in Sampson County to I-85 in Orange County. Travel times were available in one-minute aggregation periods throughout 2010 with approximately 3.8% of missing records. One-minute travel times were also aggregated to five and fifteen-minute travel times using an average of available one-minute travel times. No vehicle sample size weighting could be done, because the probe sample size in each minute is not provided by INRIX. All travel times were considered to be representative of the average travel time on the link for a vehicle entering the link in the time period (i.e. 12:00:00-12:00:59 for one-minute aggregation or 12:00:00-12:14:59 for fifteen-minute aggregation). The analysis used both one-minute travel time data for all of 2010 and 15-minute travel time data where it was available, i.e. January through July of 2010. Only a small amount of data was missing from the 15-minute segment data, so all possible routes were constructed at that resolution.

Travel times were calculated for three routes on I-40 WB in North Carolina for 2010. Figure 4.1 contains maps of the three paths. Route A (one of the key routes identified in NCDOT's prototype mobility monitoring system) is a mixture of urban and rural interstate, is 69.32 miles long on I-40 WB from I-95 to I-85, and contains 65 INRIX links. The path serves commuter traffic on interior sections, but typically only intercity traffic travels the entire path. The path encompasses all of Route B and a majority of Route C. The speed limit is 70 mph from the origin until approximately 17 miles into the path, where the speed limit drops to 65 mph for the remainder of the route. The speed limit travel time for the entire route is 62.64 minutes. Around 3.9% of the one-minute segment data for 2010 was missing, and as a consequence, approximately 14% of the 2010 route travel times were not constructed.

Route B (NCDOT's Route 3), an urban interstate route, is 14.72 miles long along I-40 WB from US-1 to NC-147, and contains 23 INRIX links. The path is primarily a commuter route that connects Raleigh, NC to Durham, NC, and it serves and passes through the Research Triangle Park, a major employment center in the area. The speed limit is 65 mph along the entire path, and the speed limit travel time is 13.59 minutes. Around 4% of the one-minute segment data are missing for 2010; and with the filters described earlier, approximately 8.5% of possible 2010 route travel times were not constructed.

Route C, a rural interstate, is 39.84 miles long on I-40 WB from NC-50/55 to I-440, and contains 17 INRIX links. The path crosses I-95 on the way to Raleigh, NC from southeastern North Carolina. The speed limit is 70 mph from the origin until approximately 30 miles into the path, where the speed limit is 65 mph for the remainder of the path, and the speed limit travel time is 34.53 minutes.

Planning time index (PTI), Travel time index (TTI), and the count of constructed route travel times were calculated as follows:

- PTI (t) = (95^{th} percentile travel time at time period t) / (free flow travel time).
- TTI (t) = (mean travel time at time period t) / (free flow travel time).
- Count (t) = count of all routes constructed after filtering at time period t.

Figure 4.2 and Figure 4.3 show graphs of these values for Tuesdays and Thursdays, respectively, for all one-minute periods in 2010. These graphs were constructed from one-minute INRIX data.

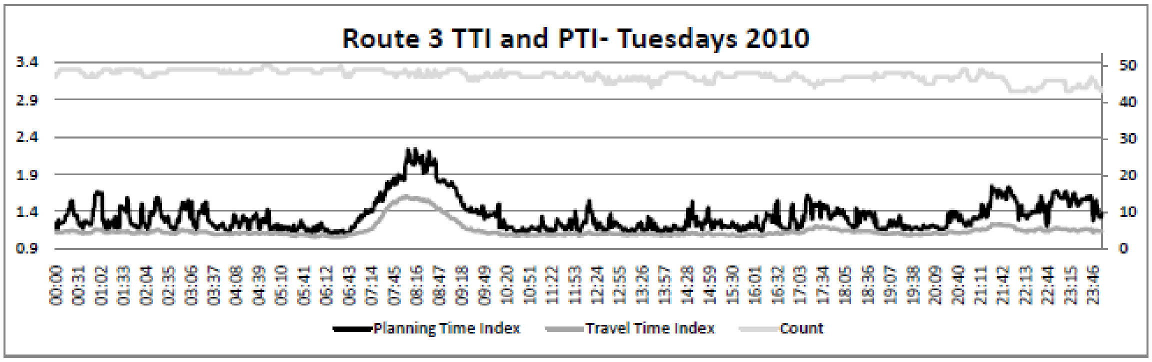


Figure 4.2 TTI and PTI for one-minute Departure Time Routes for all Tuesdays in 2010

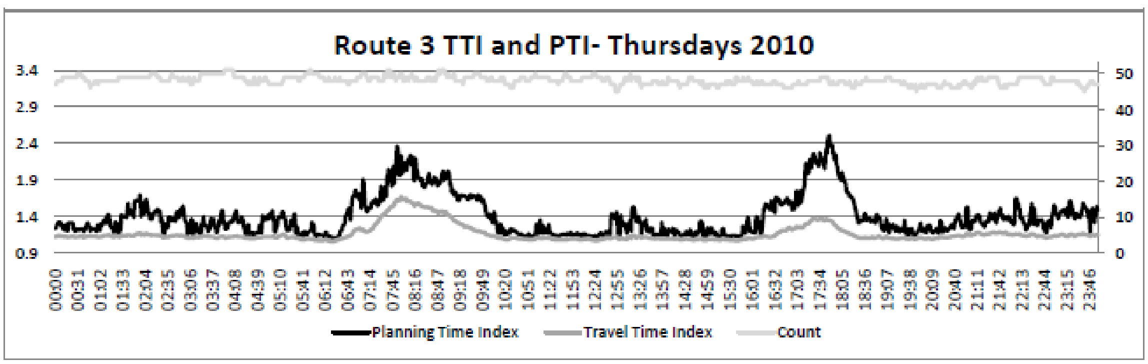


Figure 4.3 TTI and PTI for one-minute Departure Time Routes for all Thursdays in 2010

4.2 Effect of Aggregation Periods

While one-minute data represents the finest aggregation period available from INRIX, 15-minute data is currently collected, processed, and used by NCDOT. In order to compare the metrics created based on the aggregation period used, routes were stitched using one and 15-minute data (using the same stitching and filtering methods) during the time period where both data resolutions overlapped – January 2010 to July 2010. Route travel times calculated using one-minute link travel time data were compared to the route travel times calculated using five and fifteen-minute average link travel times for routes of varying length. The study found a mean absolute travel time difference less than 6% of the route free flow travel time using one-minute link travel times. As aggregation intervals increased, the mean differences decreased. Lag between peaks of average travel time from each method decreased as length decreased, as aggregation periods increased, and as congestion occurred earlier in the route.

The algorithm also tracks bottlenecks experienced in each calculated route travel time. It does so by tracking the maximum length of contiguous congested links and separates route travel times by the maximum length of contiguous congested links creating two distinct travel time distributions. Findings indicate that the congested route travel time distribution may also contain a third distribution of route travel times under extreme congestion due to incidents.

- TTI from the constructed routes matched well during off peak hours, with some peak hours showing similar TTIs while other times had 15-minute TTIs lower or higher than the one-minute TTI. Figure 4.4 through Figure 4.6 show Monday, Thursday, and all weekday graphs of PTI, TTI, and count of routes constructed for both aggregation periods.
- In the aforementioned graphs, 15-minute PTIs are very rarely higher than any one-minute TTIs in the same period (except in some cases where 15 min PTI lags behind 1 min PTI) which would indicate that 15-minute data may indicate better performance and reliability than what is measured in the one-minute data.
- Also in Figure 4.4 through Figure 4.6, the hours of darkness show high variability in PTI and this was considered to be due to construction along the route. It is possible that the 15-minute aggregation does not pick up the PTI peaks due to construction that the one-minute aggregation does.
- Figure 4.7 shows the percentile route travel time index at each minute of the day. 95^{th} percentile is the PTI and the mean is the TTI reported in the previous figure.

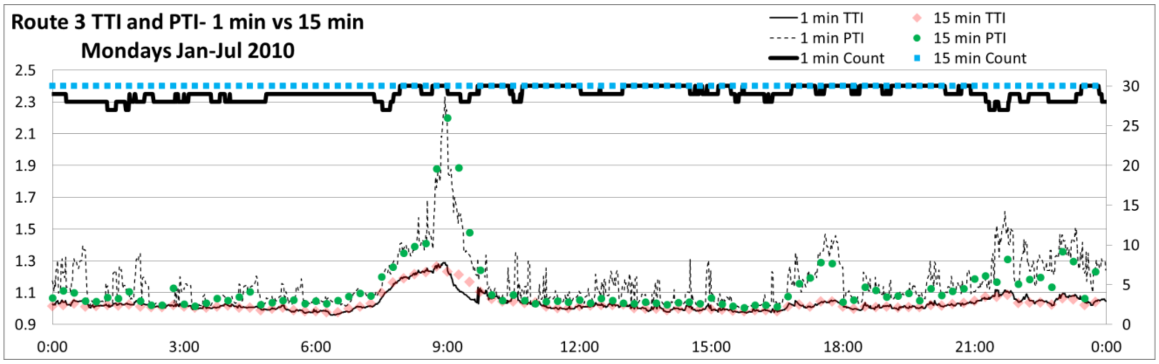


Figure 4.4 Comparing Route TTI and PTI based on Route Departure Time on Mondays

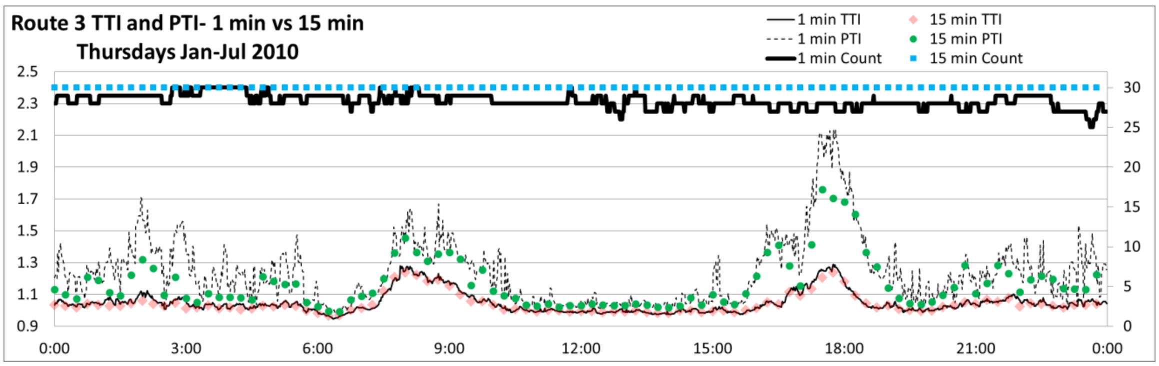


Figure 4.5 Comparing Route TTI and PTI based on Route Departure Time on Thursdays

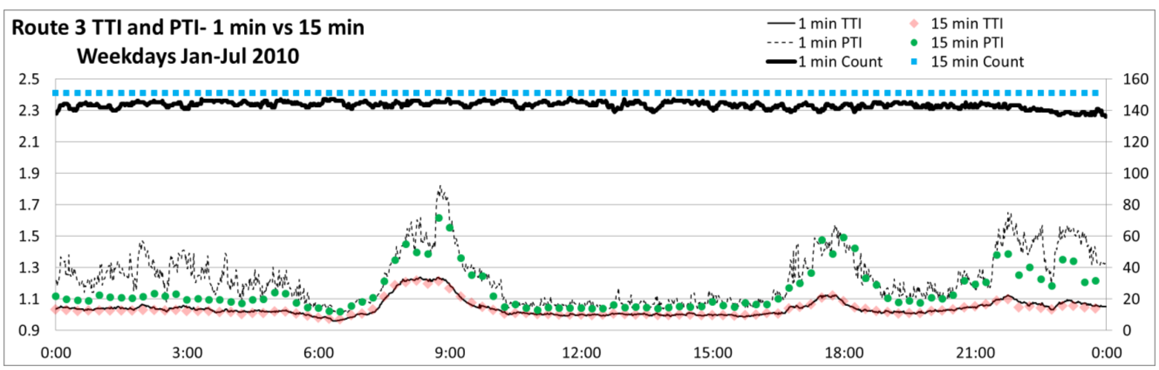


Figure 4.6 Comparing Route TTI and PTI based on Route Departure Time on all Weekdays

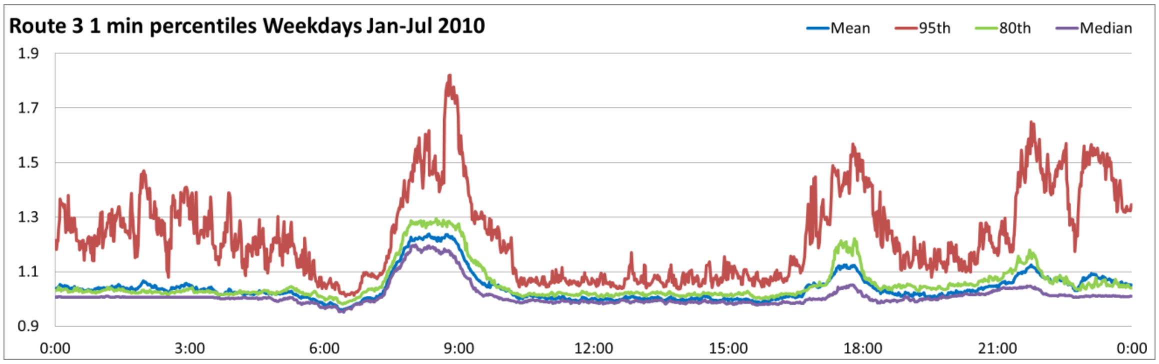


Figure 4.7 Comparing Percentile Travel Times based on Route Departure Time on all Weekdays

4.3 Algorithm Description

An algorithm was developed to stitch, or walk, route travel times by creating a pseudo-trajectory based on link space mean speed data. The algorithm is equivalent to a phantom vehicle that travels at the space mean speed of the link it is driving on at each reporting interval. Stitched travel times were reported based on the route departure time because this is a variable drivers control without having to know changing traffic characteristics. Stitching can be performed at any aggregation interval and with links of any length. While routes of any length can be calculated, the primary focus should be on important routes with a sufficient number of vehicles traversing the entire route. The algorithm was essentially designed to create phantom vehicle trajectories from the link travel time data in order to report travel times consistent with what drivers actually experience rather than looking only at the moment in time snapshots that the traditional simultaneous route travel time estimation methods create.

Figure 4.8 illustrates the two different to estimating route travel times from link travel times. All stitched trajectories for a two hour period are shown. For a single departure time indicated with an arrow, the simultaneous phantom trajectory (based on link speeds at the departure time) is shown as a solid bold line and the stitched trajectory is shown as a dashed bold line. The reference time for the link travel times used in the simultaneous trajectory is equal to the departure time in all links, shown as a solid vertical grey line, while the reference time for the link travel times in the stitched trajectory is equal to the departure time plus the travel time to the current position therefore tracking an increase or decrease in subsequent link travel time in changing conditions.

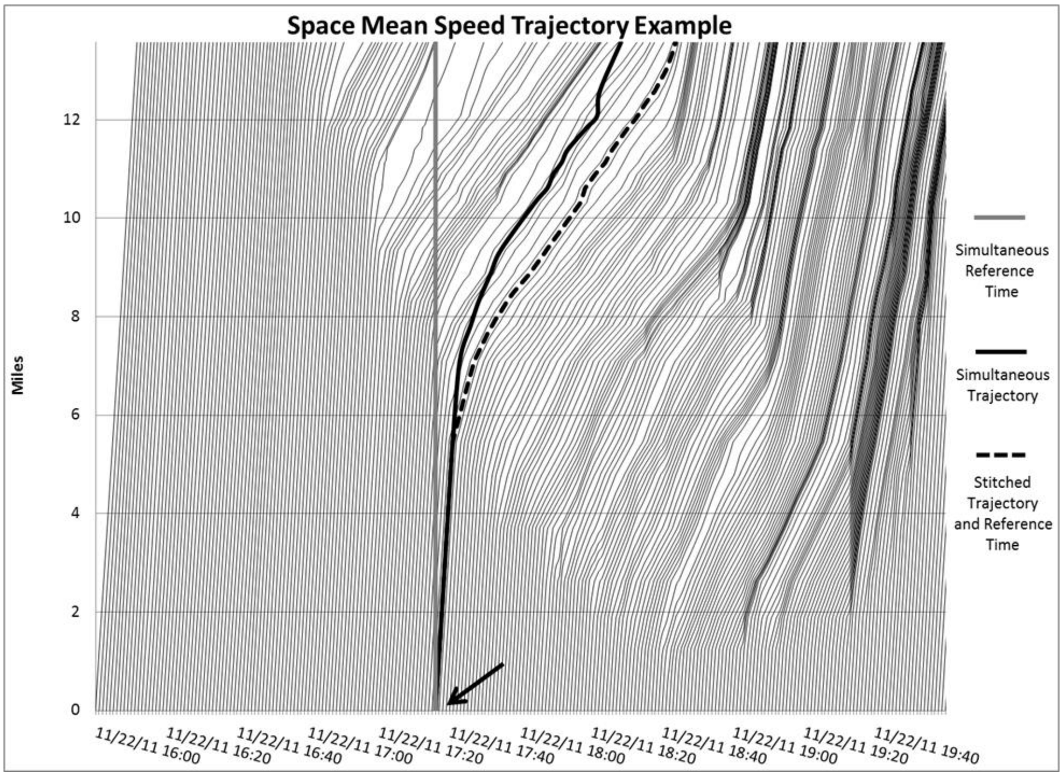


Figure 4.8 Example of Two Estimation Methods at the Same Departure Time

Included in the algorithm were checks for missing or irrational link travel times. Travel times were recorded with the error code of -1 minutes approximately 0.009% of the time due to 0 mph reported speeds. Link travel time was missing (no travel time recorded) for 3.8% of all time periods in the 2010 dataset. When any missing or irrational travel times were encountered while calculating an individual route travel time, the algorithm does not report a route travel time for that departure time and moves to the first link at the next interval departure time. Additionally, when link travel times are encountered that are greater than or equal to 20 times longer than free flow travel, the algorithm does not report a route travel time estimate. The explanation for extreme link travel time errors is related to the fact that INRIX technology creates travel times from GPS speeds, and even small GPS speed errors (typically acceleration error) can greatly affect speed-derived travel times at low speeds (*15*).

Figure 4.9 provides a VBA script for MS Excel macro subroutine implementation of the algorithm. There are two required input spreadsheets, the first with link space mean speeds ordered from the first link starting in the second column to the last link column wise and from the first reporting interval start time starting in the second row to the final reporting interval start time row wise. The first column therefore should contain the start time of each reporting interval for each row or link travel times. Although, the first row can contain link IDs, this row is not read in by the VBA code. The second input spreadsheet contains link characteristics and has a column containing Link IDs, a second column containing link length, and the third containing link free flow speed. The code will look for the first link characteristics in the second row, i.e. the first row may contain headings. Speeds and lengths can be in mph and miles or kph and kilometers.

The key step of the algorithm is the 3rd inner loop that calculates link travel time for the constructed trajectory. The speed for the link at the phantom vehicles current time (departure time + cumulative travel time) is checked for missing or 0 speed. Then there is a check if the phantom vehicle can complete travel on the link before the next reporting interval. If travel on the link cannot be completed before the next reporting interval, then the amount of time remaining in the reporting interval is added to the running total of link travel time and the distance the phantom vehicle travels during that time at the reported space mean speed is added to the previous position on the link. If the phantom vehicle can complete travel on the link before the next reporting interval, the travel time to complete travel on the link is added to the running total of link travel time from previous reporting intervals on the same link and the current position on the link is set to the end of the link, and the total link travel time is added to the cumulative path travel time.

```
For departtime from 1 to end
    stitchtime = departtime
    For segment from 1 to last
        If traveltime(stitchtime,segment) = blank Or <= 0 Or > (freeflow(segment) * 20) Then
            routetraveltime(departtime) = null // Do not report in case of error
            GoTo Label1
        Else
            routetraveltime(departtime) += traveltime(stitchtime,segment)
            If traveltime(stitchtime,segment) > freeflow(segment) / 0.6 Then // Check for congestion
                length += segmentlength(segment) // Increase length
                count += 1 // Increase run count
                runlength += segmentlength(segment) // Increase running length
                delay += (traveltime(stitchtime,segment) - freeflow(segment)) // Increase delay
                If run > max Then // Check for most contiguous segments
                    max = run
                End If
                If runlength > maxlength Then // Check for longest contiguous segments
                    maxlength = runlength
                End If
            Else
                run = 0 // Reset running count
                runlength = 0 // Reset running length
            End If
            stitchtime += traveltime(stitchtime,segment) // Move to correct time
        End If
    Next segment
    Label1:
Next departtime
```

Figure 4.9 Visual Basic Script for Excel Implementation of Travel Time Stitching Algorithm

4.4 Evaluation Methodology

4.4.1 Estimated Travel Times vs. Observed Travel Times

Route travel times are calculated for all departure times included in the Bluetooth dataset. The defined Route B contains the entire Bluetooth path, but an indexed travel time (Actual Travel

Time/Free Flow Travel Time) is compared between each direction of travel. Mean Absolute Percentage Error (MAPE) and a 95% Confidence Interval (CI) are calculated for each estimation method, direction of travel, and during all times or only congested times where the observed path travel time is at least 1.5 times higher than the free flow travel time.

MAPE is calculated with the following equation:

$$MAPE = \frac{1}{N}\sum_{t=1}^{N}\left|\frac{(ObsTTI_t - EstTTI_t)}{ObsTTI_t}\right| * 100 \qquad (3)$$

where: TTI = $\frac{Actual\ Travel\ Time}{Free\ Flow\ Travel\ Time}$

N = Number of Observations

$ObsTTI_t$ = Observed TTI at time t

$EstTTI_t$ = Estimated TTI at time t

A 95% CI around the MAPE is calculated with the following equation:

$$95\%\ CI = MAPE \pm t^* * \left(\frac{s_{APE}}{\sqrt{n}}\right) \qquad (4)$$

where: t^* = Critical Value for t Distribution with n-1 Degrees of Freedom with p = 0.025

s_{APE} = Sample Standard Deviation of Absolute Percentage Error

In addition to the MAPE and CI for each combination of factors, the Travel Time Index for the two estimation methods and observations were plotted for large congestion events. Visual analysis was performed to identify temporal differences in the estimation methods that aggregate statistics do not distinguish.

4.4.2 Travel Time Index Distributions

Travel Time Index (TTI) distributions were created using one-minute aggregation period stitched route travel times at different time periods. TTI distributions were created for a time period typically congested on weekdays and a time period that is typically in free flow on weekdays. In addition to distributions using all TTIs, Route TTIs were also categorized as congested or uncongested using a unique definition depending on the travel characteristics.

4.4.3 Sensitivity Analysis of Estimation Methods to Route Characteristics

As route travel times were calculated using identical link travel times, the stitched and simultaneous travel time methods were not expected to have large systematic differences in route travel time across the entire study period of 2010 at all times. To quantify systematic differences, the average absolute travel time difference, the standard deviation of absolute travel time differences and the percentage difference compared to Free Flow Travel Time were calculated for each route at each aggregation interval for all time periods, AM peak period and PM peak period. The hours considered were 6:00 AM – 10:00 AM for the AM peak period and 4:00 PM – 8:00 PM for the PM peak period. The maximum and minimum travel time were also calculated for each method.

Average route travel time profiles were created using all weekday data for each route, route travel time estimation method and aggregation period combination. Visual analysis was performed to find trends across route characteristics and aggregation intervals that aggregate statistics do not distinguish.

4.5 Time of Day TTI Distributions

The TTI was calculated for each route travel time constructed from the stitched method in 2010. As can be seen in the TTI and PTI graphs, there are distinct differences in the mean and 95th percentile TTIs between peak and non-peak periods. Route TTIs were collected at certain peak and non-peak times (8:15 AM, 8:30 AM, 8:45 AM, 12:00 PM, and 5:55 PM) for all weekdays to examine the difference in the distribution of TTIs.

The PDF (probability density function) and CDF (cumulative distribution function) were also examined for specific time periods (Figure 4.10 shows the graph for 8:45 AM). There is evidence of a bimodal distribution (i.e. two peaks) during this time period, which is typically congested in the AM peak period as evidenced in Figure 4.6.

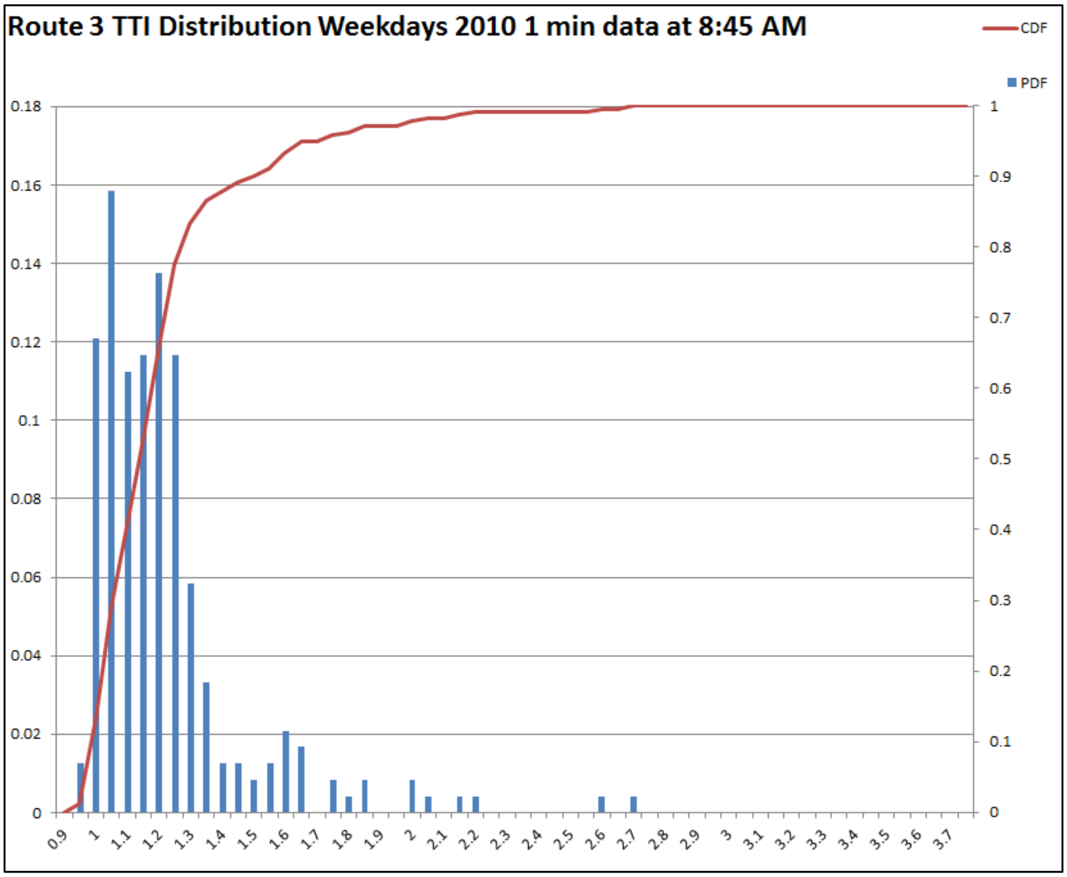


Figure 4.10 TTI distribution for all one-minute weekday routes departing at 8:45 AM

Distributions during uncongested periods (e.g., noon) seem to have a single peak near a TTI of 1.0 as shown in Figure 4.11. It is possible that there are different distributions of travel time or TTI when the route is entirely in free-flow versus when the route experiences some congestion.

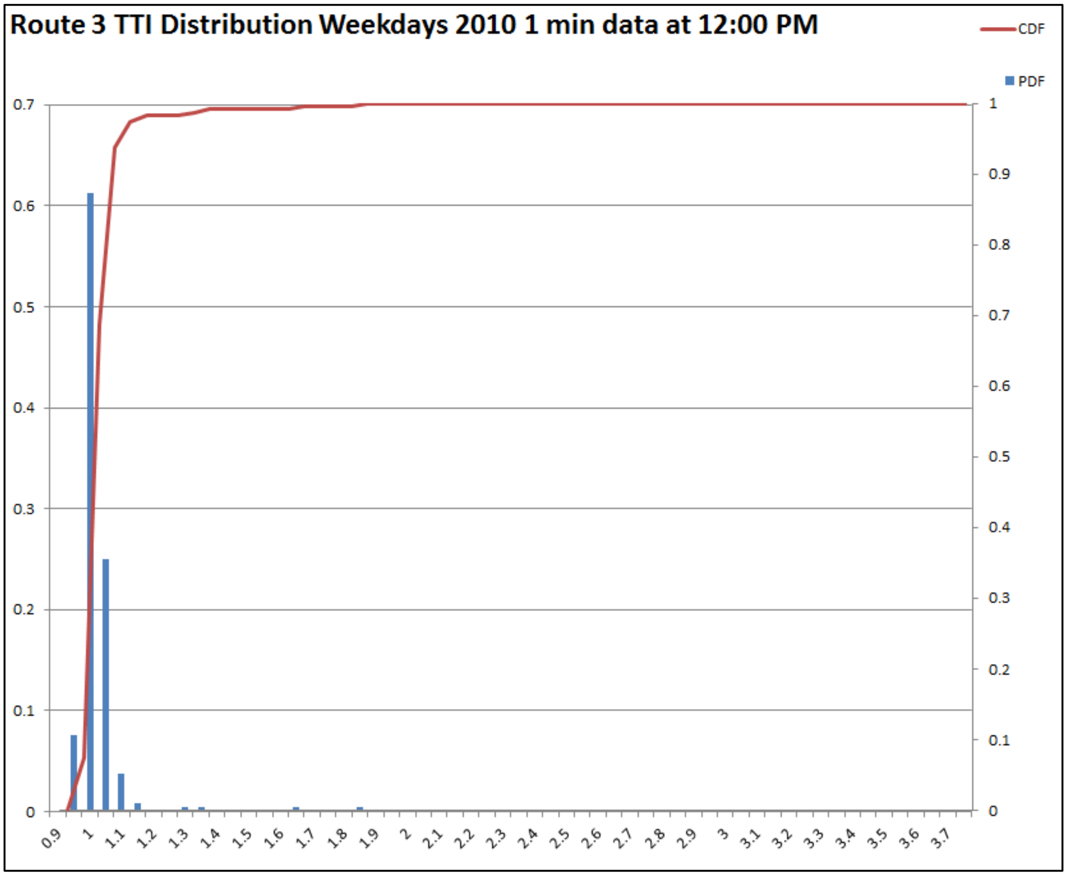


Figure 4.11 TTI distribution for all one-minute weekday routes departing at 12:00 PM

Route TTIs were considered congested if the maximum length of contiguous congested links was longer than one mile. Congested links were identified as links with average travel speeds 40 mph or less (compared to the 65 mph speed limit). In addition to this value, the algorithm calculates the total length of congested links, the number of congested links and the maximum number of contiguous congested links. Further definitions of route congestion were tested using the metrics calculated by the algorithm. A second definition for route congestion considered uses the same definition of congestion used for links, applied to route TTIs (average travel speed of 40 mph). Using this definition, TTIs larger than 1.625 are identified as congested when the entire route speed limit is 65 mph. The TTI cutoff for routes with different speed limits is 40 mph divided by the effective speed limit on the route (length weighted average speed limit). This definition lowers the percentage of time periods that are considered in congestion across all time periods, and essentially chops the tail of the overall distribution. The increase shown in the first bin indicating congestion is misleading, as this is an artifact of the cutoff value (1.625) lying in the middle of the bin. Under a third definition of congested links, routes that have a total delay due to congestion that is larger than 20% of the Route Free Flow Travel Time are considered congested. If a link is identified as congested (40 mph or less), then the delay due to congestion for that link is equal to the reported travel time minus the link free flow travel time. This definition produces congested distributions that peak at slightly higher TTIs than the first route congestion definition, but does not directly use a cutoff TTI as delay due to link speeds lower than the free flow but higher than 40 mph is not a factor. A fourth and final definition of route congestion was also considered that classifies routes congested when the total length of congested links (40 mph or less) is larger than 10% of the route length. This definition does not have the same issues with multiple bottlenecks as the first definition, but maintains a congested distribution shape similar to the first definition.

Between the four definitions of congested routes, there is no clear and easy definition that can be applied to all routes. The first definition only takes into account the bottleneck that creates the worst queue in the route, while the second definition ends up merely using a cutoff TTI to classify routes. The third definition does not use a direct cutoff by considering only delay due to congestion, but while this preserves a tail in the uncongested distribution, no TTIs below 1.2 are a part of the congested distribution. The fourth definition of congested routes both preserves the tail in the uncongested distribution and does not identify as many low TTIs as congested when compared to the first definition. The congested distribution from this definition fits a continuous

Burr distribution; however the 10% factor used must be adjusted depending on the type of route. Commuter routes may have a higher percentage tolerance of total congested link length compared to intercity routes where drivers do not expect routine or major delays. In addition, the distribution differences between aggregation periods were examined. Figure 4.12 shows the distribution for one-minute data from 8:45 AM to 8:59 AM while Figure 4.13 shows the distribution of 15-minute data in the same time period. While the CDF is similar in overall shape, the granulation of 15-minute data is very evident compared to the smoothness shown in the one-minute distribution.

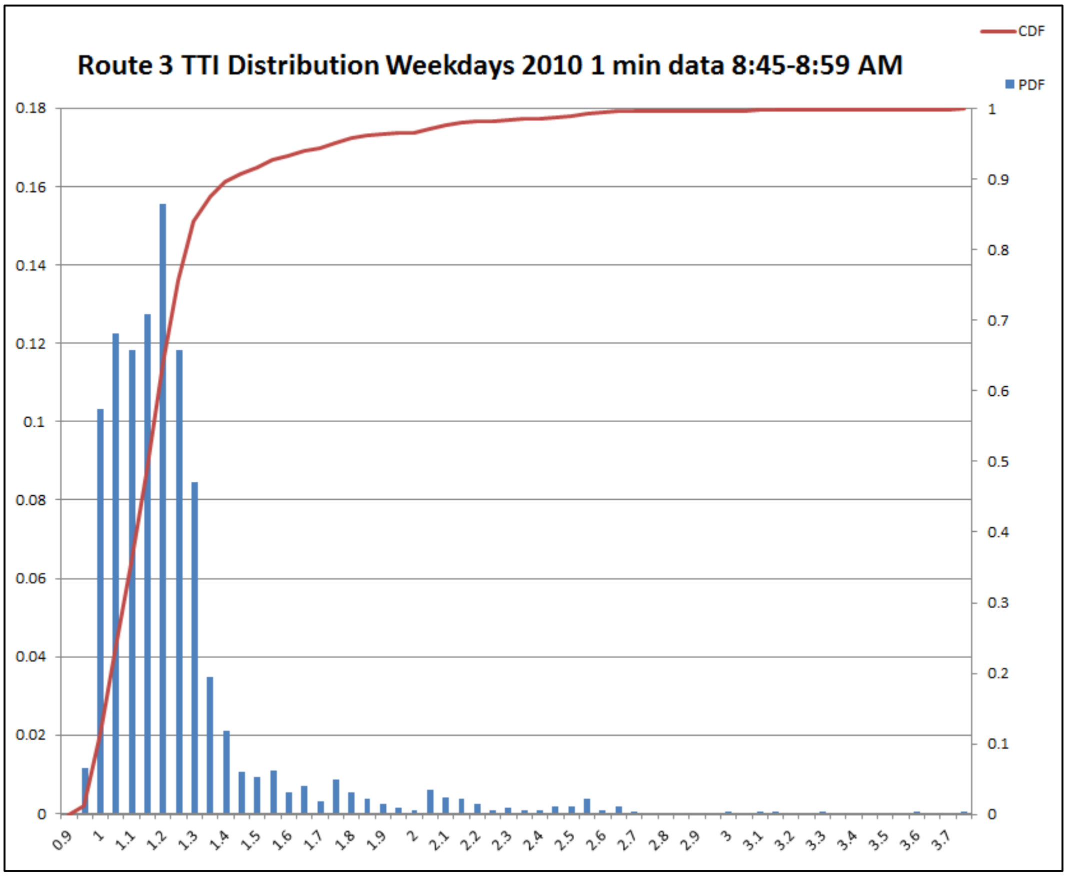


Figure 4.12 TTI distribution for all one-minute weekday routes departing from 8:45 AM to 8:59 AM

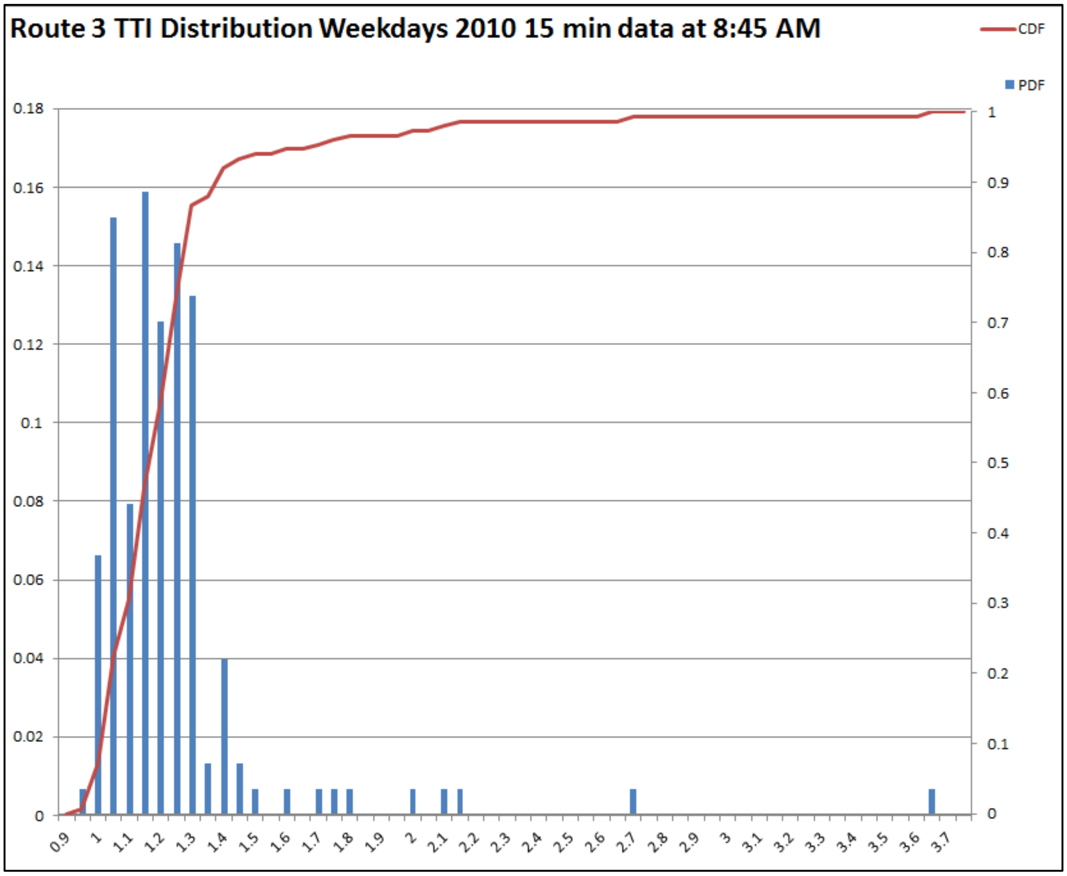


Figure 4.13 TTI distribution for all 15-minute weekday routes departing at 8:45 AM

4.6 Results for Estimated Travel Times vs. Observed Travel Times

Route travel time error for estimation from both methods compared to Bluetooth travel times was calculated for each observed travel time. Error was calculated based on indexed travel times to account for minor path length differences between the estimation path and path between Bluetooth devices. The two Bluetooth devices for each origin and destination were placed at equal offsets from the freeway. The westernmost Bluetooth devices were placed on the outside shoulder of the eastbound lanes and the easternmost Bluetooth devices were placed in the median of the freeway. This resulted in more eastbound observations than westbound observations, as shown in Table 4.1.

Table 4.1 Estimation Method Error by Direction and Time Period

Estimation Method	Direction	All Time Periods		Congested Time Periods Only	
		MAPE and CI	Observations	MAPE and CI	Observations
Stitched	EB	6.40% ± 0.071%	30563	20.66% ± 1.130%	953
Simultaneous	EB	6.77% ± 0.085%	30563	25.30% ± 1.229%	953
Stitched	WB	6.30% ± 0.110%	13573	21.19% ± 1.946%	445
Simultaneous	WB	7.34% ± 0.165%	13573	37.04% ± 2.446%	445

For both sample periods and in both directions, the stitched method has a lower MAPE and a tighter 95% confidence interval. When all observations are included, a vast majority of the points are in uncongested conditions. The pseudo-trajectory created from the stitched method still pulls link space mean speeds at later times farther in the path, but since there is very little transition between the departure and arrival time the two methods will estimate more accurate and similar travel times during free flow conditions. The results for the congested time periods, where the observed travel times are at least 1.5 times longer than the path free flow travel time, show wide margins of improvement for the stitched method compared to a typical simultaneous estimation method especially in the more congested westbound direction.

For each direction, three congested time periods were identified for visual analysis to display results from the two estimation methods against observed travel times. All travel times were indexed to the free flow travel time (approximately 12 minutes in both directions) to account for minor route length differences. As mentioned earlier, bias may be present in either source of travel time data. For the Bluetooth observations, outliers were first identified using the non-parametric IQ4 method. Some additional outliers were identified by visual analysis, and these visually identified outliers are indicted by filled circles. Bluetooth observations considered to be valid are indicated by hollow circles.

Both travel time estimation methods are based on the same database of INRIX link space mean speeds. The Bluetooth and stitched travel times would not be expected to align precisely because, as discussed in Chapter 2, latency or time lag issues are present in the INRIX data. Another source of difference between the INRIX and Bluetooth observations is the potential for significant differences in the composition and characteristics of the respective vehicle samples.

Figure 4.14 identifies a time period that experiences two congestion events. The first is a long non-recurring congestion event that lasts approximately 2.5 hours. In this event, both the stitched and simultaneous estimates lag behind the observed increase in travel times but the stitched method estimates increase earlier than the simultaneous method. This holds true for the second recurring evening congestion on the path, as the stitched estimate increases at a time closer to the observations. During the clearance of congestion, the stitched method is nearly in the middle of the cluster of observations while the simultaneous method lags in reporting the departure time for the peak path travel time and the transition back to uncongested travel.

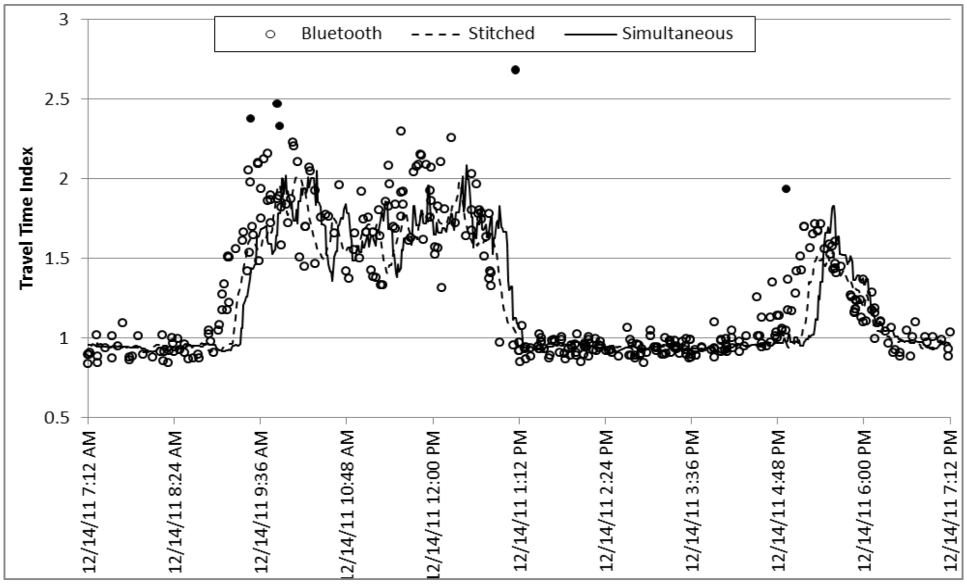


Figure 4.14 Eastbound Route Travel Time Estimates and Observed Route Travel Times – Two Congestion Events

Similarly, Figure 4.15 shows that the stitched estimation fits the transition from the peak travel time to an uncongested regime very well. However, in this case, the link space-mean speeds fluctuate greatly during the peak period, which throws off both estimation methods from the shape of the observed travel time profile. While both methods do not track perfectly, the stitched method also acts to smooth some of the wild link speed fluctuations that cause huge jumps in the simultaneous path travel times.

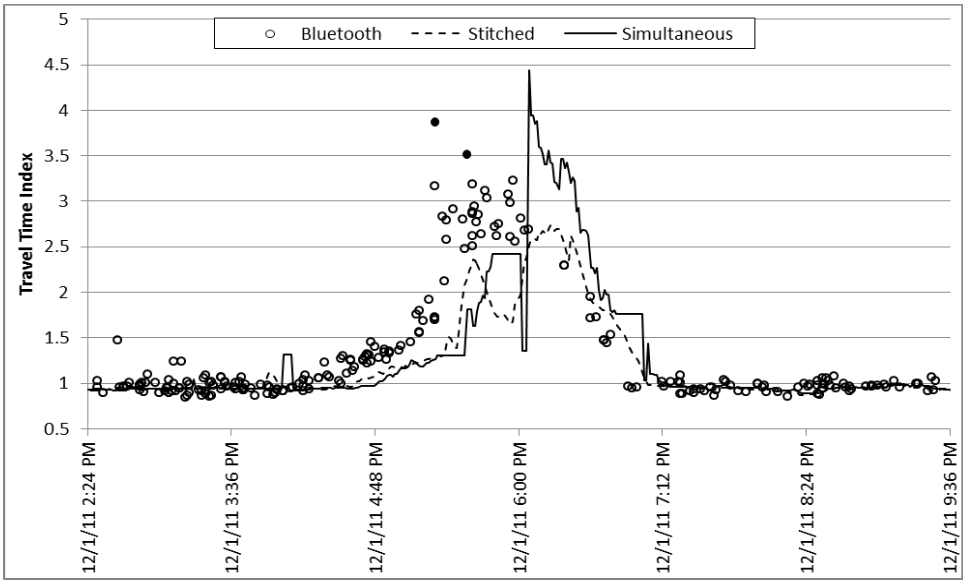


Figure 4.15 Eastbound Route Travel Time Estimates and Observed Route Travel Times – Transition to Uncongested Flow

Figure 4.16 shows other limitations inherent in the link speed dataset. When either method encounters a time period with a null link speed, no path travel time can be calculated for a stitched or simultaneous trajectory that passes through the link in that time period. For the error calculation, only Bluetooth observations with a departure time for which both methods could estimate path travel times were included. Although there are several missing stitched and simultaneous estimations in Figure 4.16, the trends identified in the previous two figures are also evident in this recurring congested period. The stitched estimates increase and peak earlier than the simultaneous estimates and match the observed peak Bluetooth travel times more closely.

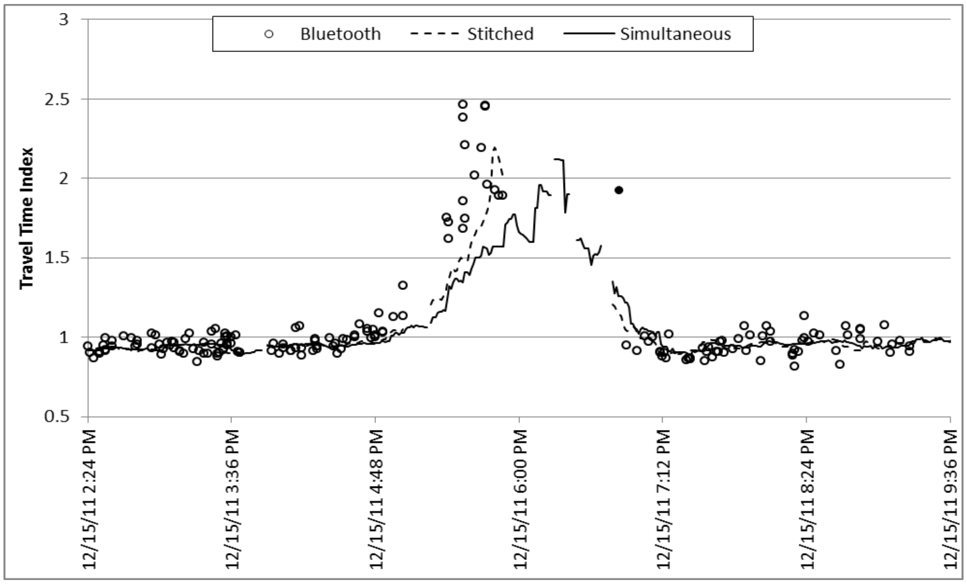


Figure 4.16 Eastbound Route Travel Time Estimates and Observed Route Travel Times – Time Period with Missing Link Travel Times

The westbound route experiences more severe recurring congestion than the eastbound route. Figure 4.17 shows a congestion event that includes two collisions that occur just as traffic demand is increasing for the PM peak period. Both collisions occur near the downstream end of the path, causing maximum impact on path travel times. Peak observed travel times with an index of approximately six correlate to a travel time of 70+ minutes to traverse a 13.3 mile path. The extreme congestion exaggerates the differences between the two estimation methods and highlights the major improvements that the stitching methods provide. Other than a small lag that could be due to lag in link speed reporting, the stitched estimates fall extremely close to the observations while the peak of the simultaneous estimates is overestimated and lags significantly behind the observed peak.

Figure 4.18 shows a recurring congestion period that contains high travel times without weather or incidents contributing to congestion. The lag between the stitched estimate and observed travel time increases is approximately 15-minutes, the same as shown in the previous figure. Meanwhile, the lag is twice as long for the transition from uncongested travel for the simultaneous estimate and the peak occurs an hour after the observed peak.

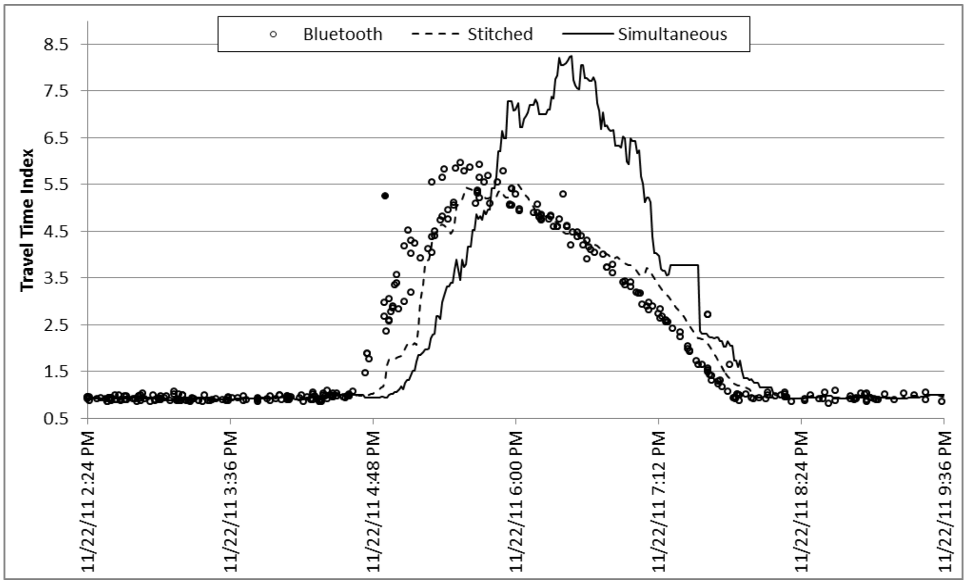


Figure 4.17. Westbound Route Travel Time Estimates and Observed Route Travel Times – PM Peak with Two Collisions

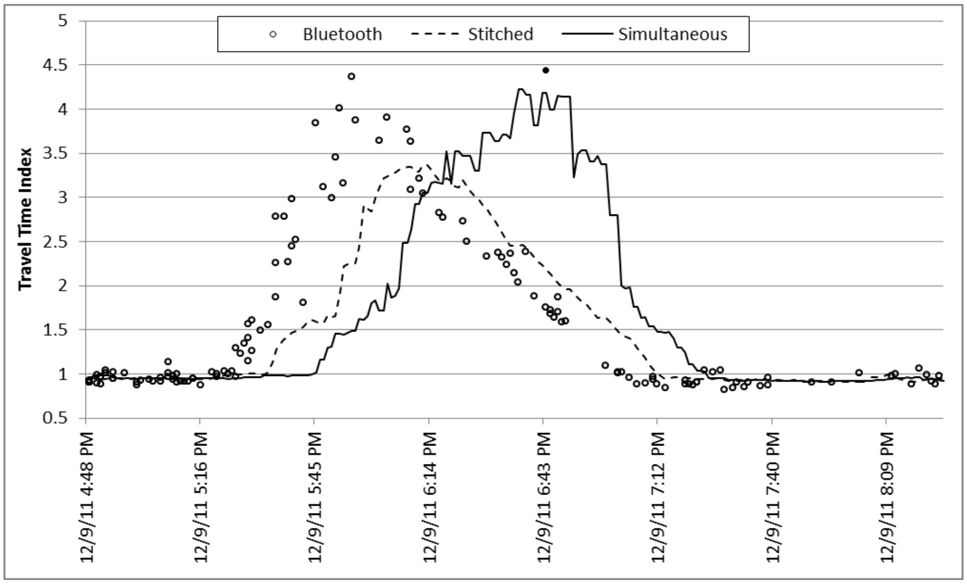


Figure 4.18. Westbound Route Travel Time Estimates and Observed Route Travel Times – Recurring Congestion with No Severe Weather or Incidents

Figure 4.19 shows a second issue that very low link speeds can create. When the speed is 0, the stitched method adds the amount of time in the reporting interval (in this case, one minute) to the running total of link travel time and then reads the speed for the next reporting interval on the same link. However, the simultaneous method would report infinite travel time for the entire path for all the departure times in a reporting interval where any link reports 0 speed. This is displayed in Figure 4.19 where the stitched travel time jumps up by as many minutes as the link reports 0 speed in a row and then steadily drops, while the simultaneous estimate is infinitely high when any link reports 0 speed.

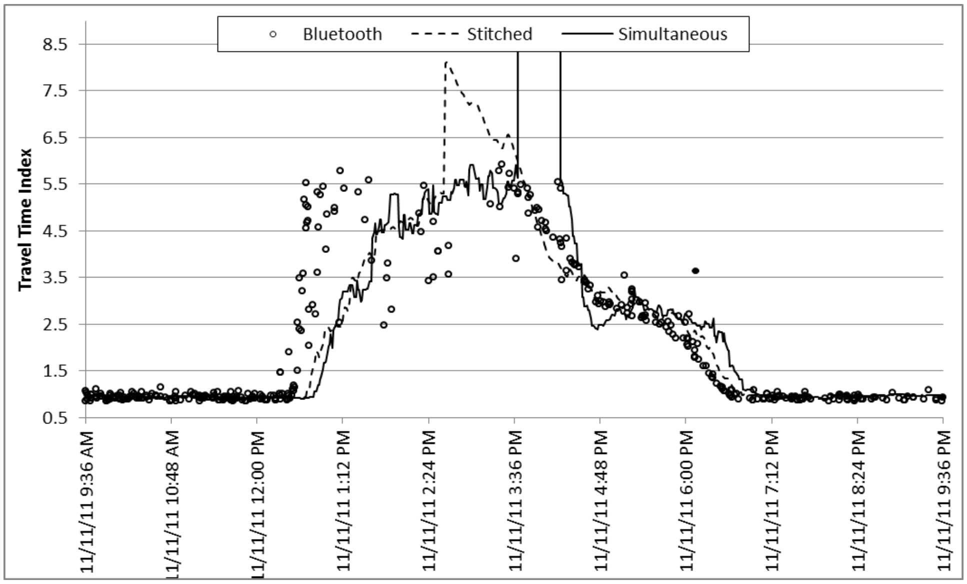


Figure 4.19. Westbound Route Travel Time Estimates and Observed Route Travel Times – Very Low Link Speed Condition

4.7 Results for Sensitivity Analysis of Estimation Methods to Route Characteristics

Table 4.2 shows the statistics of the stitched and simultaneous path travel times as well as the absolute differences for all weekday times in 2010. The free flow travel time is shown in parentheses next to each route name. Any time periods where one or both methods did not report a travel time were not considered. Calculations were also performed on the AM peak periods and PM peak periods for weekdays in 2010. Mean, standard deviation and maximum travel times are reported for each method of all time periods in 2010. The mean, standard deviation and maximum absolute differences were calculated for each of the three time periods.

Table 4.2 reveals that the mean travel time for all time periods does not change significantly when link travel times are aggregated. This is expected, as the overall means are also close to the free flow travel time since the paths are in free flow conditions a majority of the time. The mean absolute travel time difference for each path increases when examining the AM and PM peak periods. Route B and C both have diminishing mean absolute differences in all time periods, while the mean increases from one-minute to five-minute aggregation period in Route A. As the aggregation period increases, the amount of time periods that the stitching method goes through decreases, and short paths with travel times shorter than the aggregation period (as in Route B at fifteen-minutes aggregation) have stitched travel times identical to simultaneous travel times. The absolute difference is close to 0 minutes in Route B with a fifteen-minute aggregation period, however travel times in the congested period are larger than fifteen-minutes, so some stitching is performed that creates different travel times from simultaneous travel times.

Table 4.2. 2010 Absolute Travel Time Differences (Minutes)

		Route A (62.64)			Route B (13.59)			Route C (34.53)		
		1 Min	5 Min	15 Min	1 Min	5 Min	15 Min	1 Min	5 Min	15 Min
Stitched	Mean	63.93	64.48	64.50	14.24	14.24	14.24	35.97	36.09	36.11
	Std. Dev.	3.29	4.55	4.43	2.40	2.34	2.28	1.90	2.29	2.21
	Max.	123.95	120.40	117.85	60.62	59.89	55.79	86.40	82.72	79.91
Simultaneous	Mean	63.71	64.57	64.58	14.27	14.25	14.25	35.96	36.11	36.13
	Std. Dev.	2.54	4.83	4.75	2.58	2.51	2.41	1.80	2.38	2.36
	Max.	122.83	121.94	119.66	94.05	78.21	59.06	116.59	114.56	95.52
All- Absolute	Mean	1.71	1.95	1.58	0.44	0.28	0.04	0.93	0.91	0.55
	Std. Dev.	2.48	2.94	2.52	1.03	0.77	0.42	1.43	1.54	1.15
	Max.	60.62	57.12	46.16	53.16	38.16	21.96	69.88	66.66	48.52
AM- Absolute	Mean	3.18	3.73	3.05	0.62	0.45	0.13	1.60	1.68	1.13
	Std. Dev.	4.19	4.55	3.89	1.49	1.33	0.82	2.66	2.79	2.16
	Max.	50.06	44.77	37.82	53.16	38.16	21.96	70.78	66.66	38.39
PM- Absolute	Mean	2.40	2.83	2.27	0.62	0.44	0.09	0.99	0.98	0.56
	Std. Dev.	3.33	4.01	3.45	1.24	1.00	0.65	1.27	1.53	1.13
	Max.	60.62	57.12	41.97	36.25	22.37	15.99	41.07	38.31	25.39

Average weekday route travel time profiles are shown in Figure 4.20 for each aggregation interval and method. All three routes experience some level of recurring congestion at one or two peak periods. Figure 4.20a compares methods and routes at one-minute aggregation for all weekdays in 2010. Routes A and C show a lag in the simultaneous method in reporting a peak in travel time. Route A has a large peak in the AM period and a smaller peak in the PM period, and both are reported approximately 30 minutes apart depending on the method. The magnitudes of the average travel time in the AM peak for Route A appear to be different between methods, but Figure 4.20b and Figure 4.20c show that the difference appears to be due to an artifact in the one minute data that does not occur in aggregated route travel times. In the case of Route C, a smaller AM peak is reported with no PM peak in travel times. The different methods indicate a peak in route travel time approximately 20 min apart. Average weekday route travel times calculated for Route B at one-minute aggregation do not show any clear differences, even at or near the AM peak in travel times.

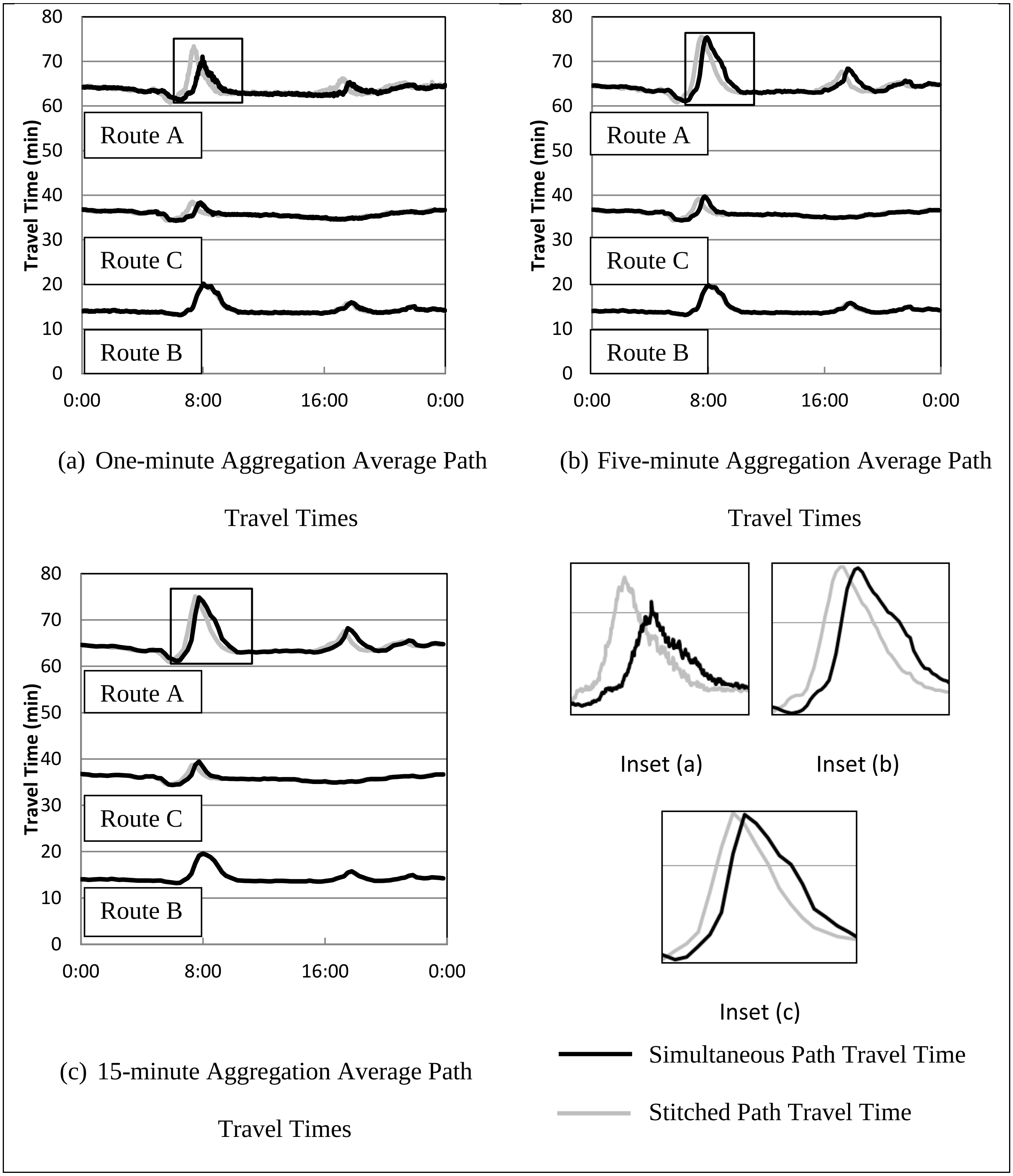


Figure 4.20. 2010 Weekday Path Travel Time Profiles

All else being equal, route travel times calculated using the stitching method will indicate congestion earlier than the simultaneous method as the downstream link travel times are taken from time periods later than the route departure time. Therefore, the lag in the simultaneous route travel times seen in Route A and Route C are expected, while the absence of lag in Route B merits in depth analysis. The absence of lag for Route B can be partially attributed to the creation of weekday averages, as the peak may not be consistently at the same time of day for each day of the week or throughout the year. However, this should not reduce lag as drastically as was found, so the links that make up Route B were examined. It turns out the most highly congested links occur near the beginning of the link, so the stitched route travel times experience the congestion at nearly the same time period as simultaneous route travel times with the same departure time. Further analysis into the links of Route A and C found that the most highly congested links were located approximately two-thirds of the way through Route A and at the downstream end of Route C.

Figure 4.20b shows average path travel times at five minute aggregation for all weekdays in 2010. Route A and Route C again display a difference between the time the peak average travel times occur similar to one-minute aggregation travel times, but the time between the peak of the stitched and simultaneous travel times decreased to approximately 20 and fifteen-minutes respectively. Route B maintains no noticeable difference in the time of the peak average travel time between the two methods. Similarly, Figure 4.20c shows that Route A and Route C both have a one time period (fifteen-minute) difference in the time of the peak average travel time at fifteen-minute aggregation for all weekdays in 2010. Again, Route B does not display a difference in the time of the peak average travel time between the methods.

Further examination of the patterns displayed in Figure 4.20 indicates that the difference in time between the peak average travel time for the stitched and simultaneous method appears to be a function of the aggregation period, the route length, and the location along the route at which congestion occurs. Aggregating from one-minute link travel times to fifteen-minute link travel times decreases the time difference between the peaks, but both routes that had a large time difference between peaks maintained at least one time period between the peaks of the stitched and simultaneous average route travel times. The length of the route also affects the time between peak average times, with a larger difference appearing in longer routes compared to shorter routes in the same aggregation period except in the case of fifteen-minute periods, where the aggregation and granularity of the averages leaves one time period between peaks. As seen in all aggregation periods, Route B does not have a large time difference between peaks due in most part to the fact that the most congested links in the route are located near the beginning of the route. Route B and Route C have a single cluster of congested links where a bottleneck often creates queues backing up into multiple links. Route A encompasses the bottlenecks from both Route B and Route C.

4.8 Summary

Estimation error for the proposed stitching method was lower for all measures across all factors when compared to the typical simultaneous method of estimating path travel times from link travel times. Detailed analysis of six congested periods identified that the stitched method more closely followed observed travel times during congestion times, especially when considering an inherent lag in the link travel time data informing the two estimation methods.

This study found that when comparing stitched route travel times to simultaneous route travel times, the annual mean absolute route travel time difference was less than 2.5% of the free flow route travel time for routes of varying characteristics and aggregation periods when examining all times of day together. The annual mean difference increased to a maximum of 6% when comparing AM and PM peak periods separately, but typically the difference decreased as the aggregation period increased.

The study also found that the time of day average travel time from the simultaneous method lagged behind the stitched method in reporting a peak in travel times for the two longest routes. In-depth examination found that the amount of lag between peaks was a function of the aggregation period, length of the route, and the location of the most highly congested links in the route. Increasing the aggregation period decreased the lag, while longer routes and routes with highly congested links closer to the end of the route increased the lag. Application of longer aggregation periods with simultaneous route travel times may be acceptable for planning or operations purposes, but it is important to determine that the small differences do not increase dramatically if looking at individual days of the week compared to all weekdays together. For traveler information, the level of aggregation may be determined based on desired travel time accuracy, but in order to report route travel times that accurately reflect what drivers will experience, stitching link travel times into route travel times rather than summing simultaneous link travel times is recommended.

The proposed algorithm also included reliability metrics calculated for each departure time. TTI distributions were created for different times of day, with highly peaked distributions during free flow conditions and skewed distributions with more spread during congested times of day. Four definitions of congested routes were examined, with limitations in use and both desired and unwanted effects.

In order to monitor critical paths in a transportation network, network probe data reported for links such as travel time or space mean speed must be converted to route values. All time of day dependent reliability measures will experience lag compared to what a driver would experience when calculated using simultaneous path travel times rather than stitched path travel times when reporting measures based on path departure time. While operating agencies may be comfortable with a simultaneous snapshot of path performance, reporting path performance from a historical reliability perspective or utilizing short term prediction on links must be reported in a driver's perspective for ATIS.

CHAPTER 5. TASK 4 – TEMPORAL SPECIFICATION FOR PERFORMANCE METRIC CALCULATION

Mobility performance metrics are by definition calculated based on archived traffic data. This leads to a fundamental question of how far to look back into the data archive when calculating the metrics. When considering an essentially static transportation network component (route or link), there are two basic approaches that can be taken. The first approach is to establish a look back window that defines the temporal sample used to calculate the mobility performance metrics. This method results in a moving sample window of constant size. The second approach uses the concept of exponentially weighted smoothing to recursively calculated averages and variances in a manner that weights near term observations more heavily with an exponential decaying weight for observations further in the past.

The project team's initial hypothesis as stated in the project proposal and the project authorization document was that the recursive, exponentially weighted method will be the best choice. The two primary thoughts behind this hypothesis were 1) an appropriate value for the exponential weighting parameter is likely to be identifiable from the data through time series analysis and therefore less arbitrary than a fixed, level-average look back window and 2) the recursive updating procedure requires fewer observations to be read into memory for the calculations and therefore is less computationally intensive. As promised, the project team tested this hypothesis and also took advantage of ongoing, related research in developing the recommendations presented later in this chapter.

A second issue in temporal specification for performance metric calculation involves dealing with changes to the network. For example, in the case of a major roadway improvement, such as widening to provide additional travel lanes, there are three distinct time periods related to the improvement. These time periods are 1) the time prior to the beginning of construction, 2) the construction period during which work zone activities are likely to reduce throughput, and 3) the post-construction period in which the envisioned increase in capacity and mobility have been provided. The project team had preliminary discussions on this issue with NCDOT, and there was general agreement that performance metric calculation should be done separately for each of these periods. Although this is a relatively straightforward and fully reasonable approach, the research team investigated level shifts in mobility metrics for the I-40 route improvements under project I-4744. As expected, there was a clear step wise change in the mobility metrics for the preconstruction, work zone, and post-construction phases. Therefore, the intuitive recommendation to restart all metrics whenever significant geometric changes occur was confirmed.

Figure 5.1 below was provided to the NCDOT project steering and implementation committee as part of the project Phase 1 presentation. This chart highlights the difference between a level average computed over a fixed time window and an exponential average that is recursively updated as new observations are available. In the course of the project and considering findings and recommendations from other ongoing research that members of the project team were involved in (namely, SHRP 2 Project L-02 *Establishing Monitoring Programs for Mobility and Travel Time Reliability* and Project L-08 *Incorporation of Travel Time Reliability into the Highway Capacity Manual*) it became apparent that the key features of exponentially weighted averaging, i.e. recursive updating and higher weighting for recent observations, are not applicable to mobility metrics. Of more importance is clear definition of the analysis period. For example, routes and regions could be compared to one another over a concurrent time frame and/or compared to themselves over time. It is likely to be important to make such comparisons based on multiple analysis periods. For example, mobility metrics could be computed and compared for –

- 24/7 operations over an entire year
- Weekday operations over an entire year
- Weekday, peak period operations an entire year

For these kinds of comparison, it will be important to control for seasonal variations, and therefore, a full year sample with equal weighting will be most appropriate. Even for seasonal variation, samples based on a specification such as month or quarter will be most appropriate.

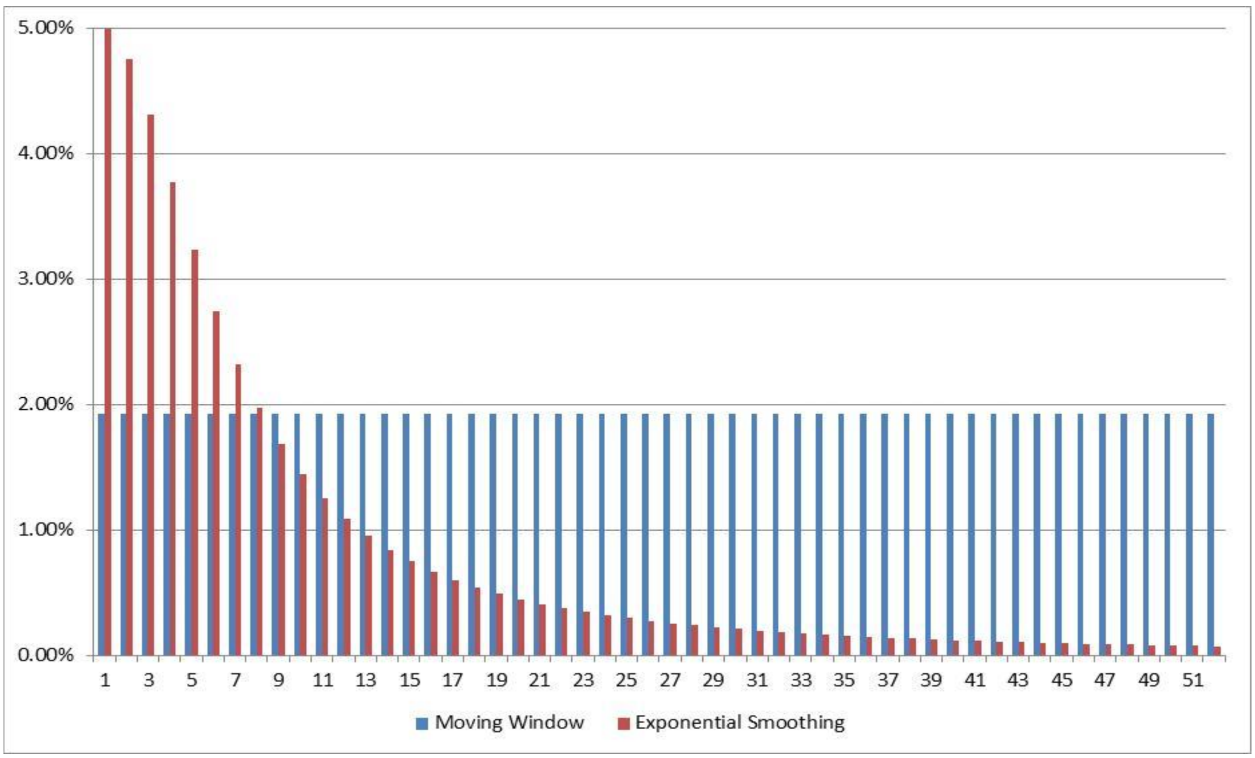


Figure 5.1. Comparison of Level Moving Average and Exponential Smoothing

The most compelling reason that the project team moved away from the idea of exponentially weighted metrics is that the ongoing, related research and specific findings for this project as discussed in Chapter 9 indicate that while calculated mobility metrics have definite value it will be important for transportation network managers to become comfortable understanding, analyzing, and comparing the actual travel time distribution that lie behind the metrics that are calculated based on these distributions. The exponentially weighted metrics originally envisioned by the project team would be appropriate if the metrics were best viewed as sufficient system measures that can be modeled as time series. However, as explained above, cutting edge research now views these metrics as helpful descriptive statistics for a sample of travel times over a properly and carefully defined analysis period. Therefore, the project team's recommendation for temporal specification is that –

- The desired comparative analyses period must be clearly defined
- The appropriate analysis period should then be specified based on the desired comparative analyses
- The assembled travel time data for the specified analysis period be considered a straightforward statistical sample for calculating metrics and for characterizing and analyzing the travel time distribution

CHAPTER 6. TASK 5 – SIGNAL SYSTEM DATA ASSET ASSESSMENT

Generally, urban travelers' daily travel paths include combinations of freeway routes and local signalized arterials. Therefore, monitoring and, if possible and necessary, improving signalized arterial performance is essential for a holistic approach to improving network level mobility and reliability. Although federal, state, and local governments have invested significant resources in advanced traffic control for decades, signalized arterials as designed and deployed are information and data poor with respect to performance monitoring and management. This is true because signal system data, such as detector data and signal data, are essentially used only for the signal operation, not for monitoring and evaluating arterial performance. Therefore, investigation and assessment of the data available within signal control systems that could be exploited for system monitoring and performance evaluation is well-motivated. The project team examined the data assets of two systems, OASIS used by NCDOT and ACTRA used by the City of Raleigh.

6.1 OASIS

OASIS is a traffic control software product developed by Econolite for implementation in an Advanced Transportation Controller (ATC) Type 2070 controller published by AASHTO, ITE, NEMA, and CALTRANS. NCDOT's effort to transition all state maintained systems to the OASIS system will help streamline access to detection and signal operation data from state maintained signals and systems.

6.1.1 OASIS Log Data:

OASIS provides seven system event log file histories (shown in Table 6.1): system alarms, special events, front panel data entry, coordination plans, implemented functions, split monitoring, and detector count station data. These logs are stored in the non-volatile RAM memory and can be cleared upon upload from a central computer. Of these seven logs, the most important log files for arterial performance monitoring are the split monitor log and the detector data log. Detailed analysis of the detector data log are discussed in the following section.

Table 6.1 OASIS Log Files

Logs	Data Type	
System Alarms Log	• Detector Failures • Hardware Failures	• Phase Conflict • Logs Full
Special Events Log	• Stop Time • Police Switch	• Preemptions
Front Panel Entries Log	• Data Element modified • Old data value • New data value	• Current user • Timestamp
Coordination Plans Log	• Source of plan implementation • Plan implemented	• Offset • Timestamp
Implemented functions Log	• Source of function implementation • Function implemented	• Timestamp
Split Monitor Log	• Active Vehicle Phases • Active Vehicle Phases State • Active Pedestrian Phases • Active Pedestrian Phases State • Active Overlaps • Active Pedestrian Overlaps • Coordination Plan	• Local Clock • Offset • Preemptions • Vehicle Calls • Pedestrian Calls • Status Response Packet
Detector Data Log	• Detector Reference • Detector Status • Average Wait • Volume	• Occupancy • Average Speed • Average Gap

The minimum time interval for detector data storage is one-minute and signal event data are stored based on coordination cycle length.

6.1.2 OASIS Detector Data Log

OASIS provides detector count station data through three attributes for each fixed time reporting interval. The first attribute is the detected vehicle volume, and the second attribute is the calculated occupancy percentage. The final attribute is the calculated space mean speed. The project team extensively analyzed each attributes in order to assess the quality of the OASIS log data.

For volume logs, the base time interval for vehicle detection is 0.1 seconds. Any vehicles which occupy the detector for less than 0.1 seconds will go undetected. In experiments with a bench test controller, it was confirmed that at occupancy times less than 0.1 seconds the system reports 0 volume, 0 occupancy, and 0 speed. Therefore, for accurate OASIS vehicle volume count, all vehicles should occupy the detector for at least 0.1 seconds.

In the OASIS log file, the log entry reports occupancy values as integers. Therefore, the project team found it necessary to determine whether the OASIS software rounds up or down when reporting occupancy values. From test results, it was confirmed that the software consistently rounds down when reporting occupancy.

For detectors like those used in the OASIS system, there are two possible ways to correctly calculate space mean speed. The first method involves using total occupied time, detector length (e.g. 6 ft), and default vehicle length (e.g. 20 ft). For speed calculation, the system must save total occupied time and the number of detected vehicles. These values are utilized in the formula below –

$$\bar{u} = \frac{Total\ travel\ length}{Total\ travel\ time} = \frac{\#\ of\ vehicles * (detector\ length + vehicle\ length)}{Total\ occupied\ time} \quad (5)$$

The second method involves using occupancy, loop detector length and default vehicle length.

$$\bar{u} = \frac{100 * (detector\ length + vehicle\ length)}{Occupancy * Total\ length\ of\ time\ interval} \quad (6)$$

If based on the same data with no rounding, the two methods are identical. However, for the second method to yield accurate results, the system would have to archive the exact occupancy results instead of rounded integer values. In addition, the confirmed OASIS procedure of strictly rounding down the reported occupancy values introduces additional errors. Fortunately, operational testing confirms that OASIS uses the first method (equation (5)). However, software operation testing confirmed that the OASIS software also strictly rounds down for reporting speeds, which introduces a systematic bias in recorded speeds.

Another important issue that required investigation was the determination of how OASIS handles the situation when a vehicle occupies the detector during a time period that spans two data collecting intervals. For the test, the bench controller was set to record the detector log at the smallest allowable reporting interval of one minute. A single vehicle actuation was simulated on the boundary between two reporting intervals as shown in Table 6.2. According to test results, if a vehicle occupies a detector during a time than spans the boundary between two data collection time periods, OASIS reports the corresponding vehicle count in the second time period. However, the software calculates and reports a rounded down occupancy percentage independently for both time periods. This method of handling vehicles that span reporting interval boundaries result in an overestimation of travel speed for the interval-spanning vehicles, as can be seen in the Table 6.2 (For the software operational test, no other vehicle calls were present in either reporting interval).

Table 6.2. Boundary Condition Test Results for a Single Vehicle Spanning Two Reporting Intervals

Start of Time Interval (HH:MM)	Detector Occupancy (sec)		Volume	Occupancy (%)		Speed (mph)	
				Actual	Reported	Actual	Reported
18:22	2	0.5	0	0.83	0	8.9	0
18:23		1.5	1	2.50	2		11
18:27	4	1.5	0	2.50	2	4.4	0
18:28		2.5	1	4.17	4		7
19:15	10	4.7	0	7.83	7	1.8	0
19:16		5.3	1	8.83	8		3

The fact that OASIS rounds down both the calculated vehicle occupancy and calculated vehicle speed creates a range of possible displayed speeds for given actual occupancies.

Table 6.3 shows the speed ranges for each occupancy range for a log of one-minute data collection with an interval volume of one vehicle. It should be noted that the results below do not reflect the potential error for vehicles spanning the reporting interval discussed above. The imprecision highlighted in

Table 6.3 result solely from the issue of rounding down reported occupancies.

Table 6.3. Possible Occupancy Range with Speed by Reported Occupancy

One-minute Data Log with Vehicle Volume = 1			
Occupancy		Possible Maximum speed (mph)	Possible Minimum speed (mph)
Reported (%)	Actual Occupied Time (sec)		
0	0.1 to 0.5	177	35
1	0.6 to 1.1	29	16
2	1.2 to 1.7	14	10
3	1.8 to 2.3	9	7
4	2.4 to 2.9	7	6
5	3.0 to 3.5	5	5
6	3.6 to 4.1	4	4
7	4.2 to 4.7	4	3
8	4.8 to 5.3	3	3
9	5.4 to 5.9	3	3
10	6.0 to 6.5	2	2
11	6.6 to 7.1	2	2
12	7.2 to 7.7	2	2
13	7.8 to 8.3	2	2
14	8.4 to 8.9	2	1
15	9.0 to 9.5	1	1
⋮	⋮	⋮	⋮
29	17.4 to 17.9	1	0

6.2 ACTRA

ACTRA is a transportation management software system that monitors and controls traffic from a central control center developed by Siemens ITS for implementations using EPAC™, 170, 2070ATC, or EPIC™ controllers. ACTRA allows integration of convenient traffic analysis optimization tools including AAP™ (Passer™ and Transyt-7F™) and Synchro™. Also, ACTRA provides GIS based area maps. The ACTRA system is currently used by the city of Raleigh. The section below describes the type of data available from the ACTRA system that could be exploited for mobility and reliability performance monitoring. Because the NCDOT does not use the ACTRA software system, the project team did not perform a detailed analysis of the measurement calculation and reporting procedures for ACTRA as was performed for OASIS.

6.2.1 ACTRA Reports:

The ACTRA system provides *system* reports and *intersection* reports. System reports are system wide reports that can be generated by time of day. Intersection reports include ten different report types that are listed below:

- Intersection Communications Faults Report
- Intersection Cycle Measures of Effectiveness Report
- Intersection Detector Faults Report
- Intersection Detector Volume Report
    - Date and Time - current system date and time (when report was generated)
    - Local Name - the name of the selected Intersection
    - Report Start/Report End - the time range this report covers
    - Date/Time - start time for that line of data
    - Detector Number - identification of the detector
    - Volume - counts
- Intersection EDI Monitor Fault Report
- Intersection Local Alarm Report
- Intersection Measures of Effectiveness Report
    - Local Name - the name of the selected Intersection

    - Date and Time - current system date and time (when report was generated)
    - Report Start/Report End - the time range this report covers
    - Start Time
    - Dial/Split/Offset
    - Phase/Volume/Stops
    - Delay x 10
    - Utilization - in seconds
- Intersection MMU Monitor Fault Report
- Intersection Speed Data Report
    - Date and Time - current system date and time (when report was generated)
    - Local Name - the name of the selected Intersection
    - Report Start/Report End - the time range this report covers
    - Date/Time - beginning time for the pattern monitored
    - Dial/Split/Offset of the pattern monitored
    - Percent Lower, Percent Within, and Percent Higher - the percentage of the vehicles that were lower, within, or higher than the set speed range for the specified pattern
- Intersection System Detector Report
    - Date and Time - current system date and time (when report was generated)
    - Local Name - the name of the selected Intersection
    - Report Start and Report End dates and times - the interval covered by this report
    - Sample Time - date and starting time
    - Interval - the sample interval in minutes
    - Detector number
    - Raw Volume - counts
    - Raw Occupancy - counts (number of seconds)
    - Average Volume
    - Average Occupancy

EPAC controllers can store up to 72 of the most recent volume log records for the current report interval with up to 24 detectors to collect volume data for the selected intersection. For example, if you use a report interval of 10 minutes, the 72 logged records would cover a 12 hour period. As the number of records exceeds 72, the oldest record is deleted to make room for the new record. The minimum time interval for volume log data storage is one-minute.

6.3 Summary

Data are available within signal system control software (such as OASIS and ACTRA) that have potential value in conducting mobility and reliability monitoring and performance evaluation on signalized arterials. This data can be used as currently generated within these systems. However, the fact that the software systems were designed with a view of the data existing for the sole purpose of tactical operation of user-established signal timing plans and with the resulting system logs and reports being primarily envisioned for operational monitoring, there are issues that need to be addressed in future software enhancements if signal control system data are to become more accessible and useful for performance monitoring purposes.

The first key issue is data accessibility. In both the OASIS and ACTRA systems, detailed detector data is stored locally in intersection and field master controllers in relatively low capacity memory buffers. Therefore, separate manual or semi-automated protocols must be established to download the data for archiving and analysis at frequent intervals or the data will be overwritten. For the NCDOT's OASIS-based closed loop systems, this process involves establishing a dial-up connection at regular intervals to field master controllers using Econolite's TransLink software. Eventually, if signal system and approach detector data is to be readily accessible for performance monitoring, more streamlined data retrieval and archiving must become basic and essential features of the functional requirements for future software versions.

The second key issue is computational precision and accuracy. Using OASIS as an example, the current hard-coded process of rounding occupancy to an integer percentage and speed to integer miles per hour is not precise enough to provide useful information. Furthermore, the fact that the current OASIS software rounds down (i.e. truncates values by removing the decimal fractions) introduces inherent bias in the results. More complex computational issues such as the way OASIS handles vehicles that span reporting interval boundaries must also be addressed if the system is to provide sufficiently precise and unbiased traffic flow characteristics data.

The project team is currently working on a follow on NCDOT research project titled "Development of Real Time Performance Measurements for Closed-Loop Signal Systems Using Existing Loop Detectors" (RP 2012-12) in which detail exploitation of the split monitor log for performance evaluation is also being investigated. Detailed data on the cycle by cycle, phase by phase signal operations also holds great potential for enhancing arterial performance evaluation. Therefore, future signal control software should also evolve to include ready access to signal operational data as well.

CHAPTER 7. TASK 6 – NCDOT SIGNALIZED ARTERIAL CASE STUDY – ANALYSIS AND METHODOLOGY DEVELOPMENT

Arterial travel time (or travel speed) is an essential operational characteristic that must be measured or estimated for arterial mobility and reliability performance assessment. Therefore, it would be very beneficial if sufficiently accurate speed estimates could be derived from system detectors. Chapter 6 introduced and discussed the OASIS detector log files and explained how OASIS calculates the space mean speed value recorded in the detector data log. Speed estimation from single loop detectors requires as an input the average effective vehicle length. OASIS uses a default value of 20 feet for the average effective vehicle length. This task involved a review of a previously conducted NCDOT field study to determine the most appropriate value for average effective vehicle length.

7.1 Average Vehicle Length Field Study

7.1.1 Intersection of US 70 and South Robertson Street

The NCDOT conducted average vehicle length field studies on November 16th, 2009 and January 19th, 2010 at the intersection of US 70 and South Robertson Street in Johnston County (see Figure 7.1).

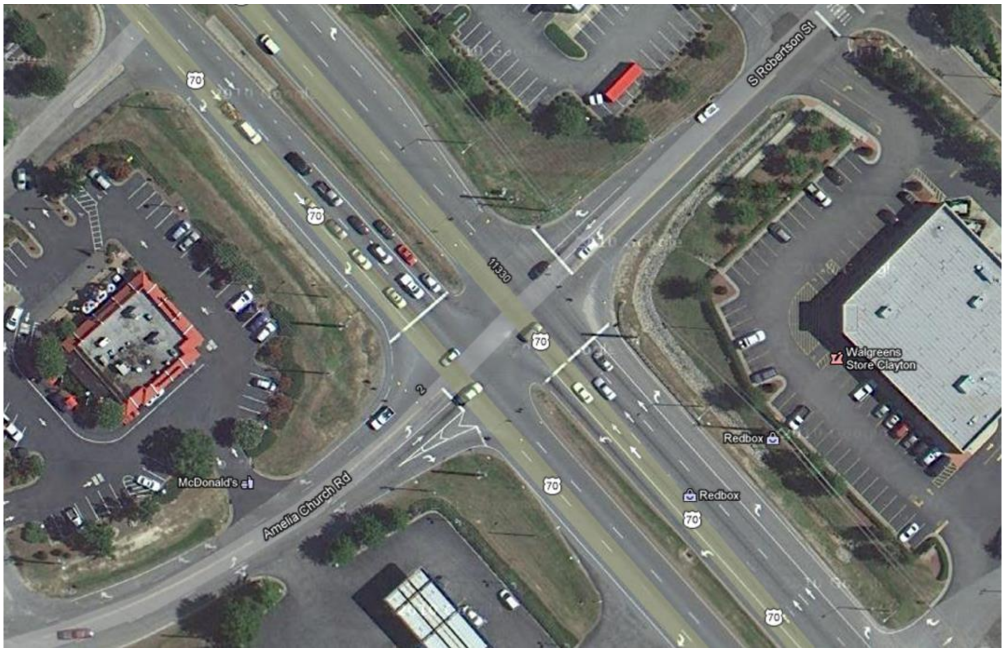


Figure 7.1 Intersection of US 70 and South Robertson Street

The South Robertson Street intersection has two eastbound through lanes and three westbound through lanes. The NCDOT collected travel speeds in the vicinity of the inductive loop detectors using a speed gun and compared the collected speed results with the OASIS reported speeds. The up-stream loop detector size is 6’× 6’ and the installation location is 300 feet from the intersection stop bar. After initial field observations, the NCDOT research team decided to conduct the first test by setting the average vehicle length to 16 feet in OASIS and comparing the field measured and OASIS estimated speeds. With an average vehicle length value of 16 feet, the OASIS reported speeds were consistently lower than the field measured speeds.

Therefore, the NCDOT research team changed the average vehicle length to 18 feet and conducted field measurements again. Results for the two tests are shown in Table 7.1 and Table 7.2 below.

Table 7.1. US 70 at Robertson Street Speed Comparison 8am to 12 noon on Nov. 16, 2009 (16 feet average vehicle length).

Loop Detector	OASIS Speed (A)	Field Speed (B)	Difference (A-B)
WB Right Lane	27	34.04	-7
WB Middle Lane	30	37.38	-7
WB Left Lane	30	36.49	-7
EB Right Lane	23	31.59	-8
EB Left Lane	32	33.83	-2

Table 7.2. US 70 at Robertson Street Speed Comparison 8am to 12 noon on Jan. 19, 2010 (18 feet average vehicle length).

Loop Detector	OASIS Speed (A)	Field Speed (B)	Difference (A-B)
WB Right Lane	24	33.21	-9
WB Middle Lane	31	38.35	-7
WB Left Lane	35	37.13	-2
EB Right Lane	22	28.29	-6
EB Left Lane	33	29.90	+3

Based on the tests at the South Robertson Street intersection, the NCDOT research team concluded that there did not appear to be a significant observable difference in OASIS speed accuracy when using either 16 feet or 18 feet as an average of vehicle length.

7.1.2 Intersection of US70 and John Street

The NCDOT conducted additional average vehicle length field studies on November 18th, 2009 and January 20th, 2010 at the intersection of US 70 and John Street (see Figure 7.2).

Figure 7.2. Intersection of US70 and John Street.

The John Street intersection has three through lanes in both the eastbound and westbound directions. However, the eastbound center lane loop detector had a malfunction so that only the other five lanes had reported speeds from OASIS. These reported speeds were compared to field collected speed results that are shown in Table 7.3 and Table 7.4. The upstream loop detector size is 6’ × 6’ and the installed location is 300 feet from the intersection stop bar.

Table 7.3. US 70 at John Street Speed Comparison 8am to 12 noon on Nov. 18, 2009 (16 feet average vehicle length).

Loop Detector	OASIS Speed (A)	Field Speed (B)	Difference (A-B)
EB Right Lane	34	40.25	-6
EB Left Lane	40	43.68	-4
WB Right Lane	36	40.83	-5
WB Middle Lane	39	42.97	-4
WB Left Lane	43	44.25	-1

Table 7.4. US 70 at John Street Speed Comparison 8am to 12 noon on Jan. 20, 2010 (18 feet average vehicle length).

Loop Detector	OASIS Speed (A)	Field Speed (B)	Difference (A-B)
EB Right Lane	40	42.02	-2
EB Left Lane	48	44.86	+3
WB Right Lane	41	41.45	0
WB Middle Lane	43	45.17	-2
WB Left Lane	44	44.90	-1

For the US 70 and John Street intersection, the NCDOT test results indicated that using 18 feet as an average vehicle length setting for OASIS provided better speed estimation than did a 16 feet average vehicle length.

7.2 Summary

The previously conducted field studies demonstrate that setting an appropriate average effective vehicle length can improve the speed estimates that the OASIS system derives from single loop detectors. However, the results were not entirely consistent. This could have been due to a non-representative vehicle sample for the field measured speeds. Also, the detailed analysis of the OASIS computational procedures discussed in Chapter 6 reveals that there are other sources of potential error, such as the OASIS procedure of rounding all speeds down, that will be difficult to control for in a simple field experiment. Nonetheless, the NCDOT field study results indicate that an average effective vehicle length in the range of 18 feet should provide reasonable results. The similarity between the 16 foot and 18 foot average effective vehicle length results also implies that the 20 foot default value used by OASIS should also provide reasonable results in many situations. Even so, given that the effective length signature of vehicles passing over a magnetic inductance loop detector depends on many local factors, the NCDOT studies also support a conclusion that an independent field study would be needed for any location where verifiably accurate speed estimates from the OASIS system are required.

CHAPTER 8. TASK 7 – TESTING AND IMPLEMENTATION OF PERFORMANCE MEASURE REFINEMENTS AND ENHANCEMENTS

8.1 Introduction

The route travel time estimation procedure developed in Task 4 and the corresponding candidate travel time mobility and reliability performance metrics were tested and evaluated across multiple locations in several states. The multi-state assessment was designed to test the robustness and transferability of the methodology and to look for generalizable findings with regard to performance metrics.

8.2 Additional Study Locations for Travel Time Reliability Measures

Segment-based analysis was performed at 5 locations: 1) I-40 in NC, 2) I-64 in VA, 3) I-95 in FL, 4) I-95 in DE, PA and NJ, and 5) I-395 in VA and DC. 15-minute INRIX data was collected over the time spans indicated in Table 8.1. In the case of I-64 in Virginia, only 5 segments report travel time for the entire year so reliability measures for the remaining segments have a much lower sample size.

Figure 8.1 shows all five locations. Both rural and urban freeway segments were included as the methods can measure both types.

Table 8.1. INRIX Segment Sample Size (15-minute).

					Data Points		
Study Location	Freeway Miles	# Segments	Start Date	End Date	Possible	Actual	%
1	141.44	131	1/1/2010	12/31/2011	9167904	8984517	98.0%
2	221.33	212	1/1/2011	12/31/2011	7408128	2206518	29.8%
3	280.88	297	7/1/2011	12/31/2011	5217696	5183541	99.3%
4	171.90	234	1/1/2011	12/31/2011	8176896	8145306	99.6%
5	23.61	115	1/1/2011	12/31/2011	4018560	4003035	99.6%

Figure 8.1. All INRIX Segment Study Areas.

8.3 Travel Time Reliability Performance Measure Definitions

Figure 8.2 shows a theoretical probability density function of travel rates for a section of freeway. Included are a majority of the performance measures described in the next subsections.

While the figure shows actual travel times, these values can be normalized to travel rates in units of minutes per mile to compare segments and facilities of different lengths directly. All measures are calculated for the average traffic stream travel rates for a given time domain, as INRIX reports a single measure for each time period and not individual vehicle measures.

Travel Rate is one of two typical measures that normalize travel times. The second is the Travel Time Index (*17*), which is the observed travel time divided by the free flow travel time. The following equation calculates the Travel Time Index for a given Travel Rate:

$$Travel\ Time\ Index = Travel\ Rate\ (\frac{min}{mi}) * \frac{Free\ Flow\ Speed\ (mph)}{60\ min/hr} \tag{7}$$

8.3.1 Average Travel Rate

The average travel rate is calculated as a straight average of travel rates over the time domain. The average travel rate is not a true reliability measure, as it reports a nominal level of congestion as opposed to providing any information on the variation of travel rates. Travel time reliability measures that can be well predicted by the average do not provide new information to decision makers, so correlation tests will use the average travel rate as a baseline comparison to determine which reliability measures are providing unique information. The equation below was used to calculate average travel rates:

$$\bar{\tau} = \frac{1}{N}\sum_{t=1}^{N} \tau_t \tag{8}$$

where:

$\bar{\tau}$ = Average Travel Rate

τ_t = Travel Rate at time t

N = Total Observations in the time domain

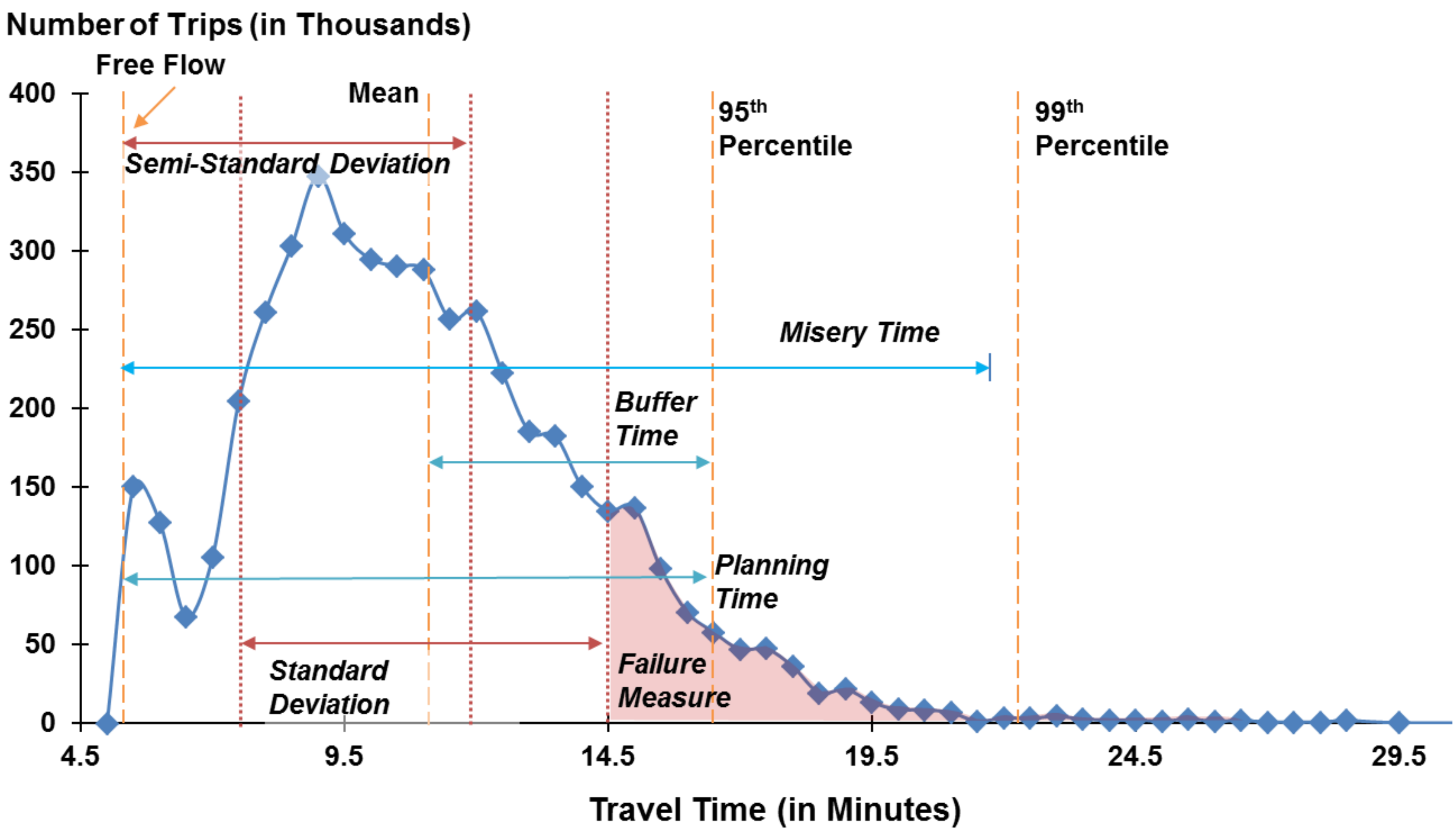


Figure 8.2. Travel Time Reliability Performance Measures Overlaid on Travel Time Distribution. (*16*)

8.3.2 Standard Deviation

The standard deviation is a typical statistical measure used to quantify the variation in a distribution or dataset around the average. The FHWA advises against using the standard deviation as a reliability measure because it is more difficult for non-technical decision makers to understand (*18*), but it is included to compare reliability-focused measures to a traditional measure.

$$s = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(\tau_t - \bar{\tau})^2} \tag{9}$$

where:

s = Standard Deviation of Travel Rate

8.3.3 Coefficient of Variation

The coefficient of variation is another typical statistical measure that can be used to compare distributions or datasets with different means. The coefficient of variation is discouraged for use as a reliability measure for the same reasons as the standard deviation (*18*). The equation below shows how the coefficient of variation was calculated:

$$Coefficient\ of\ Variation = \frac{s}{\bar{\tau}} * 100 \tag{10}$$

8.3.4 80th, 85th, 90th, 95th Percentile Travel Rate

Upper percentiles of travel time distributions, mostly the 95^{th} percentile, are used for many reliability measures and typically indexed to median or average travel times. All travel rate percentiles were calculated in SAS. The following formulas describe how SAS calculates a given percentile from an ordered dataset:

$$n * p = j + g \tag{11}$$

where:

n = Total observations in the dataset

p = Percentile to calculate / 100

j = Integer value of $n * p$

g = Decimal value of $n * p$

$$\tau_p = (1 - g) * \tau_j + g * \tau_{j+1} \tag{12}$$

where:

τ_p = p*100 Percentile Travel Rate

τ_j = jth ordered observation

8.3.5 Average- and Median-based Buffer Index

Buffer Index measures were created to describe how much worse the 95th percentile travel rate is compared to typical travel rates. Early research focused on an average-based buffer index, but it has been shown that under highly skewed distributions, the buffer index based on the average can actually decrease as variability increases (*19*). A buffer index based on the median has been used more recently that continues to increase as variation increases. Equation 13 shows the formula to calculate an average-based buffer index and Equation 14 shows the formula to calculate a median-based buffer index.

$$Average - based\ Buffer\ Index = \frac{(95th\ Percentile\ Travel\ Rate - Average\ Travel\ Rate)}{Average\ Travel\ Rate} \tag{13}$$

$$Median - based\ Buffer\ Index = \frac{(95th\ Percentile\ Travel\ Rate - Median\ Travel\ Rate)}{Median\ Travel\ Rate} \tag{14}$$

8.3.6 Misery Rate

The misery rate is a performance measure that quantifies how much delay the worst trips experience. Past research has identified the worst 5% of trips to the worst 20% of trips to include in the calculation, but the average travel rate of the worst 5% of trips was calculated for this project. The following equation shows how the misery rate was calculated for an ordered dataset.

$$Misery\ Rate = \frac{1}{0.05N} \sum_{t=0.95\text{N}}^{N} \tau_t \tag{15}$$

8.3.7 Semi-Standard Deviation

The semi-standard deviation is a one-sided statistic that measures deviations from a reference value. In the case of travel rate or travel time distributions, the reference value is typically the free flow travel rate or travel time and the deviations are only calculated for observations where the travel rate or travel time is higher than free flow. Observations with faster space mean speeds than the free flow speed contribute 0 to the statistic. Equation 16 shows how the semi-standard deviation was calculated:

$$Semi\text{-}Standard\ Deviation = \sqrt{\frac{1}{N} \sum_{t=1}^{N} [max(\tau_t - \tau_{FF}, 0)]^2} \tag{16}$$

8.3.8 Skew

The skew statistic is a statistical measure that measures the tendency of the deviations to be larger in one direction than in the other. Travel time and travel rate distributions are typically positively skewed and have tails to the right compared to space mean speed distributions which are typically negatively skewed and have tails to the left. Equation 17 shows how skew was calculated:

$$Skew = \frac{n}{(n-1)(n-2)} \sum_{t=1}^{n} \left(\frac{\tau_t - \bar{\tau}}{s}\right)^3 \tag{27}$$

8.3.9 Failure Rate

The failure rate is the proportion of trips or time where travel occurs at a travel time or travel rate above a threshold or below an equivalent space mean speed. In this thesis, only speed data is available, so the rates are calculated as a proportion of time. The failure rate is analogous to typical engineering approaches to reliability, however the threshold for failure is not clear-cut as it is for a structural analysis. Two failure rates were calculated; one identifying the proportion of time the segment or facility had a space mean speed lower than 50 mph and one for the proportion of time the segment or facility had a space mean speed lower than 40 mph. The equation below shows how the failure rates were calculated:

$$Failure\ Rate = \frac{f}{n} \tag{38}$$

where:

f = Number of observations with space mean speed below threshold

8.4 Correlation between Segment Reliability Measures and the Average Travel Rate

A correlation test was performed on reliability performance measures calculated for each segment across all times and days sampled. Reliability performance measures should provide new information to decision makers compared to standard mobility measures like the mean. Table 8.2 and

Table 8.3 show the mean and standard deviation of each reliability measure across all segments. Table 8.4 shows the correlation coefficients for each combination of reliability measures and highlights four measures that are lowest correlated to the average travel rate: standard deviation, coefficient of variation, semi-standard deviation and skew.

Table 8.2. Segment Reliability Measure Values: Mean and Standard Deviation.

	Average Rate	Standard Deviation	Coefficient of Variation	80th PCTL	85th PCTL	90th PCTL	95th PCTL
Mean Value	0.991	0.298	28.5	0.991	1.01	1.056	1.213
Standard Deviation	0.126	0.271	22.917	0.108	0.149	0.266	0.555

Table 8.3. Segment Reliability Measure Values: Mean and Standard Deviation (cont.).

	Median BI	Average BI	Misery Rate	Semi Standard Deviation	Skew	Failure rate <50 mph	Failure rate <40 mph
Mean Value	0.257	0.19	1.719	0.311	28.59	0.05	0.023
Standard Deviation	0.465	0.323	0.951	0.291	34.93	0.124	0.04

All four reliability measures identified by the correlation test are standard measures of variation, and literature advised against using these as they are not easily explained to a non-technical decision maker. A closer look into the relationships between each reliability measure and the average travel rate can be found in the next section. For the PM Peak hour, the four measures that show the lowest correlation to the average travel rate are coefficient of variation, median buffer index, mean buffer index and skew.

Table 8.4. Segment Reliability Measures Correlation Coefficients.

Variable	Average	Standard Deviation	Coefficient of Variation	80th PCTL	85th PCTL	90th PCTL	95th PCTL	Median BI	Average BI	Misery Rate	Semi stdev	Skew	Percent below 50mph	Percent below 40mph
Average	1	0.682	0.525	0.938	0.922	0.894	0.906	0.816	0.809	0.875	0.761	-0.229	0.86	0.914
Standard Deviation	0.682	1	0.973	0.476	0.505	0.567	0.705	0.718	0.691	0.862	0.992	0.14	0.449	0.67
Coefficient of Variation	0.525	0.973	1	0.314	0.334	0.394	0.544	0.578	0.554	0.752	0.946	0.227	0.301	0.527
80th PCTL	0.938	0.476	0.314	1	0.961	0.852	0.768	0.632	0.631	0.674	0.575	-0.211	0.893	0.838
85th PCTL	0.922	0.505	0.334	0.961	1	0.932	0.812	0.694	0.679	0.691	0.596	-0.195	0.848	0.859
90th PCTL	0.894	0.567	0.394	0.852	0.932	1	0.903	0.833	0.811	0.745	0.641	-0.178	0.766	0.866
95th PCTL	0.906	0.705	0.544	0.768	0.812	0.903	1	0.978	0.972	0.892	0.76	-0.177	0.724	0.887
Median BI	0.816	0.718	0.578	0.632	0.694	0.833	0.978	1	0.994	0.885	0.754	-0.161	0.59	0.822
Average BI	0.809	0.691	0.554	0.631	0.679	0.811	0.972	0.994	1	0.865	0.729	-0.161	0.6	0.822
Misery Rate	0.875	0.862	0.752	0.674	0.691	0.745	0.892	0.885	0.865	1	0.892	-0.211	0.636	0.849
Semi stdev	0.761	0.992	0.946	0.575	0.596	0.641	0.76	0.754	0.729	0.892	1	0.104	0.546	0.737
Skew	-0.229	0.14	0.227	-0.211	-0.195	-0.178	-0.177	-0.161	-0.161	-0.211	0.104	1	-0.177	-0.211
Percent below 50mph	0.86	0.449	0.301	0.893	0.848	0.766	0.724	0.59	0.6	0.636	0.546	-0.177	1	0.859
Percent below 40mph	0.914	0.67	0.527	0.838	0.859	0.866	0.887	0.822	0.822	0.849	0.737	-0.211	0.859	1

8.5 Visual Analysis of Relationships between Segment Reliability Measures and the Average Travel Rate

Further information on the relationships between each reliability measure and the average travel rate can be gleaned from a visual analysis of the scatter plots of each measure against the average for all segments.

8.5.1 Standard Deviation

Figure 8.3 shows the relationship between the standard deviation and the average travel rate. The two are loosely correlated (0.682 correlation coefficient) and have a linear relationship with scatter increasing as the average travel rate increases.

8.5.2 Coefficient of Variation

Figure 8.4 shows the relationship between the standard deviation and the average travel rate. The two are loosely correlated (0.525 correlation coefficient) and the coefficient of variation tends to increase linearly and displays increasing scatter as the average travel rate increases similarly to the standard deviation.

8.5.3 Travel Rates – 80th, 85th, 90th and 95th Percentile

Figure 8.5, Figure 8.6, Figure 8.7 and Figure 8.8 show the relationships between the 80th, 85th, 90th and 95th percentile travel rate, respectively, and the average travel rate. The correlation coefficients for each percentile are 0.938, 0.922, 0.894 and 0.906 respectively, indicating that all four are very well correlated to the average travel rate. All four relationships appear to have an exponential relationship with the average travel rate, while the values are more scattered in the upper average travel rates for the 90th and 95th percentile travel rates.

Average and Median-based Buffer IndexFigure 8.9 and Figure 8.10 show the relationships between the average-based buffer index and median based buffer index, respectively, and the average travel rate. Both measures are loosely correlated to the average travel rate with correlation coefficients of 0.816 and 0.809 respectively. The average buffer index is flat for very low average travel rates, but increases exponentially after an average travel rate of approximately 1 min/mi. The median buffer index displays a similar pattern to the average buffer index.

Misery RateFigure 8.11 shows the relationship between the misery rate and the average travel rate. The two are well correlated (0.875 correlation coefficient) and the relationship is linear with increasing scatter as the average travel rate increases.

8.5.4 Semi-Standard Deviation

Figure 8.12 shows the relationship between the semi-standard deviation and the average travel rate. The two are fairly correlated (0.761 correlation coefficient) and the relationship is linear, following a similar pattern to the standard deviation with increasing scatter for higher average travel rates.

SkewFigure 8.13 shows the relationship between skew and the average travel rate. The correlation coefficient between these measures is the lowest for any reliability measure (-0.229) and has an inversely proportional relationship. The highest skew values identify segments with very low average travel rates as the least reliable. This makes sense in that high values for skew will tend to be associated with segments that experience heavy delay primarily due to non-recurring congestion because non-recurring events will be present in long tails while recurring congestion as a normal occurrence will heavily influence the mean travel time. In other words, high skew and low average travel rate segments would have the skew value greatly affected by the outlying travel times from non-recurring congestion. On the other hand, travel times during non-recurring congestion on segments with higher average travel rates (nominal recurring congestion) do not deviate as far from the mean travel time.

8.5.5 Failure Rate

Figure 8.14 and Figure 8.15 show the relationship between the failure rate and the average travel rate with a threshold of 50 mph and 40 mph, respectively. Both failure rates are well correlated with the average travel rate (0.860 and 0.914 correlation coefficients, respectively) and the 50 mph failure rate has an exponential relationship with the average travel rate, while the 40 mph failure rate relationship is more linear.

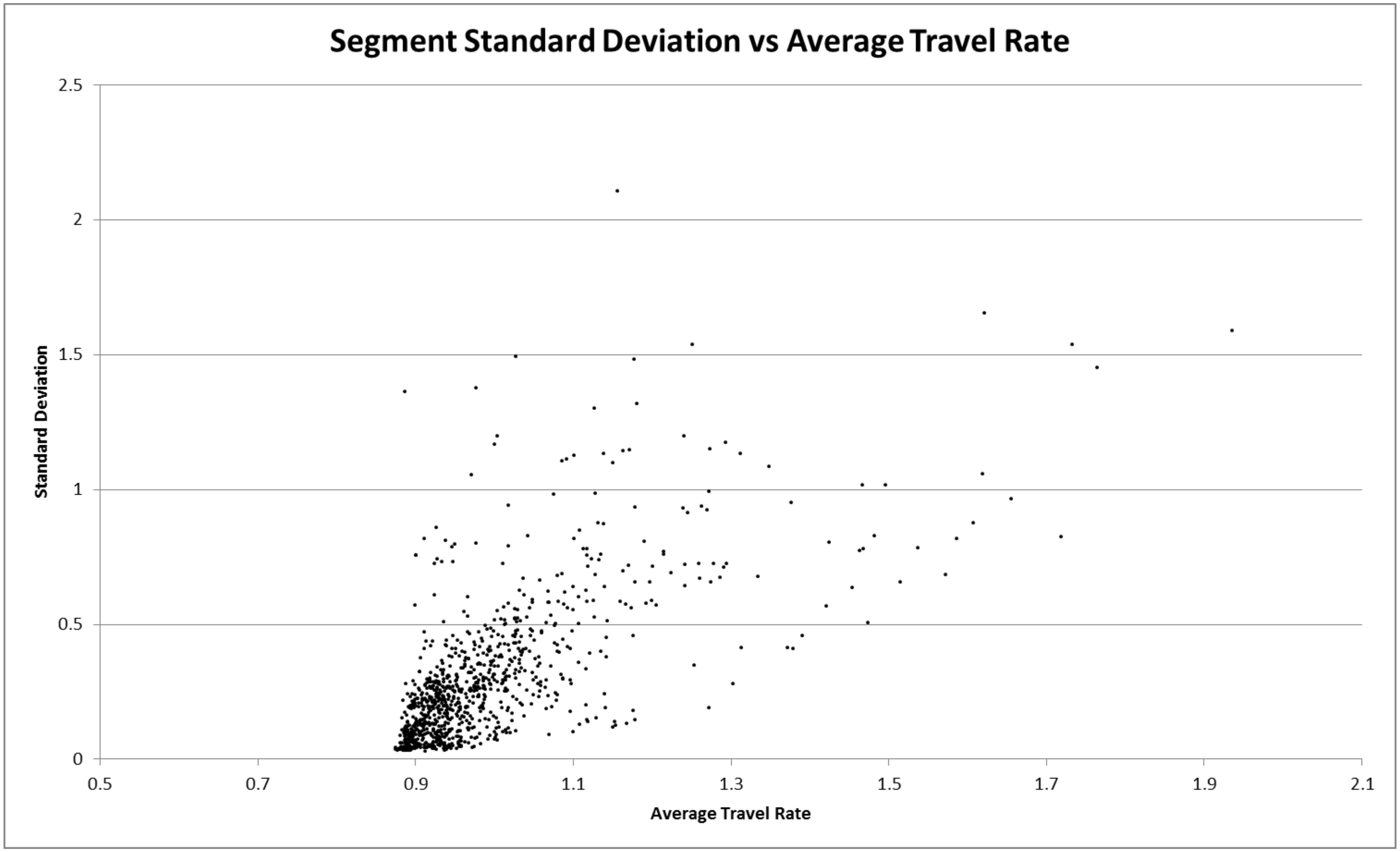


Figure 8.3. Segment Standard Deviation vs. Average Travel Rate.

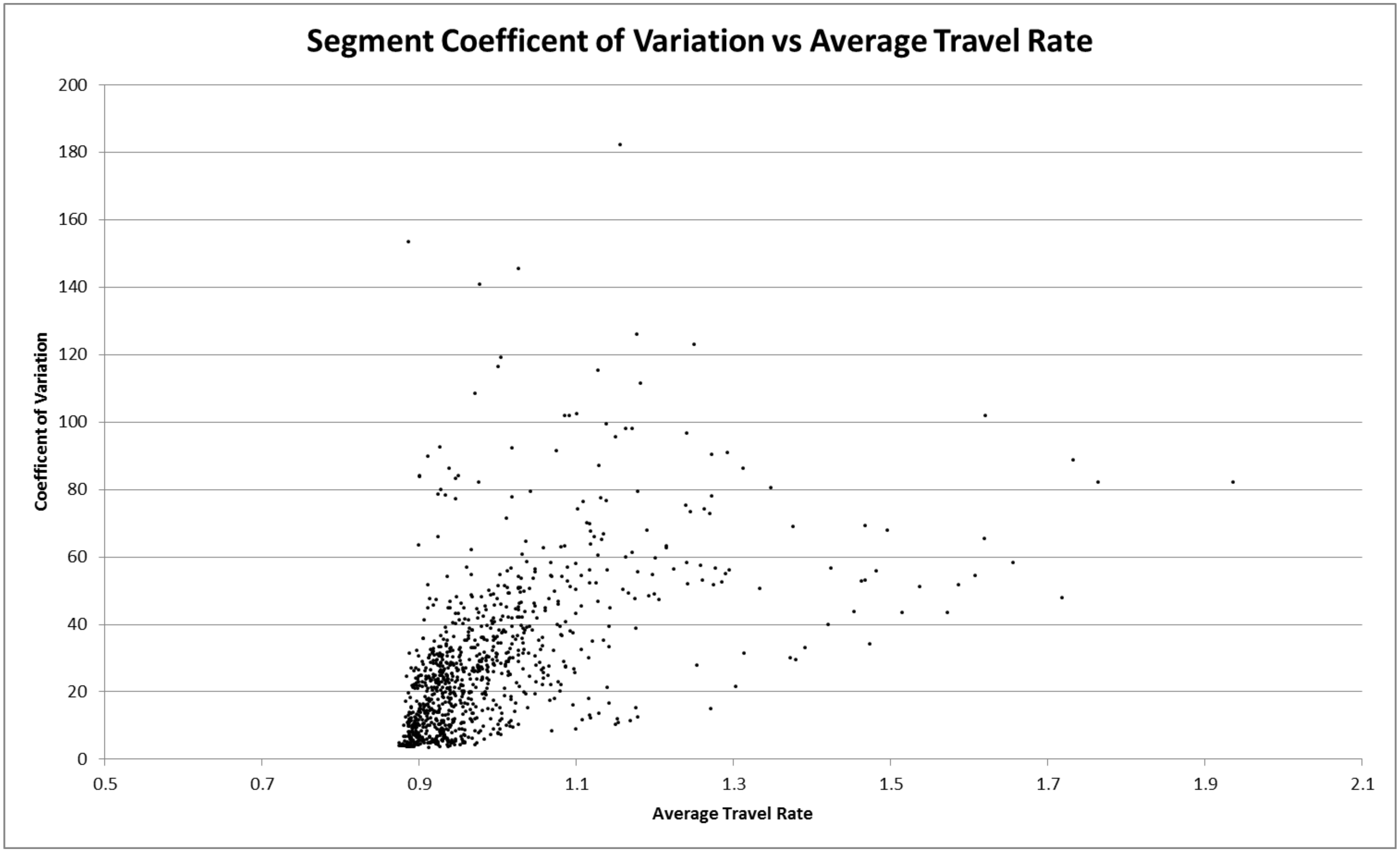


Figure 8.4. Segment Coefficient of Variation vs. Average Travel Rate.

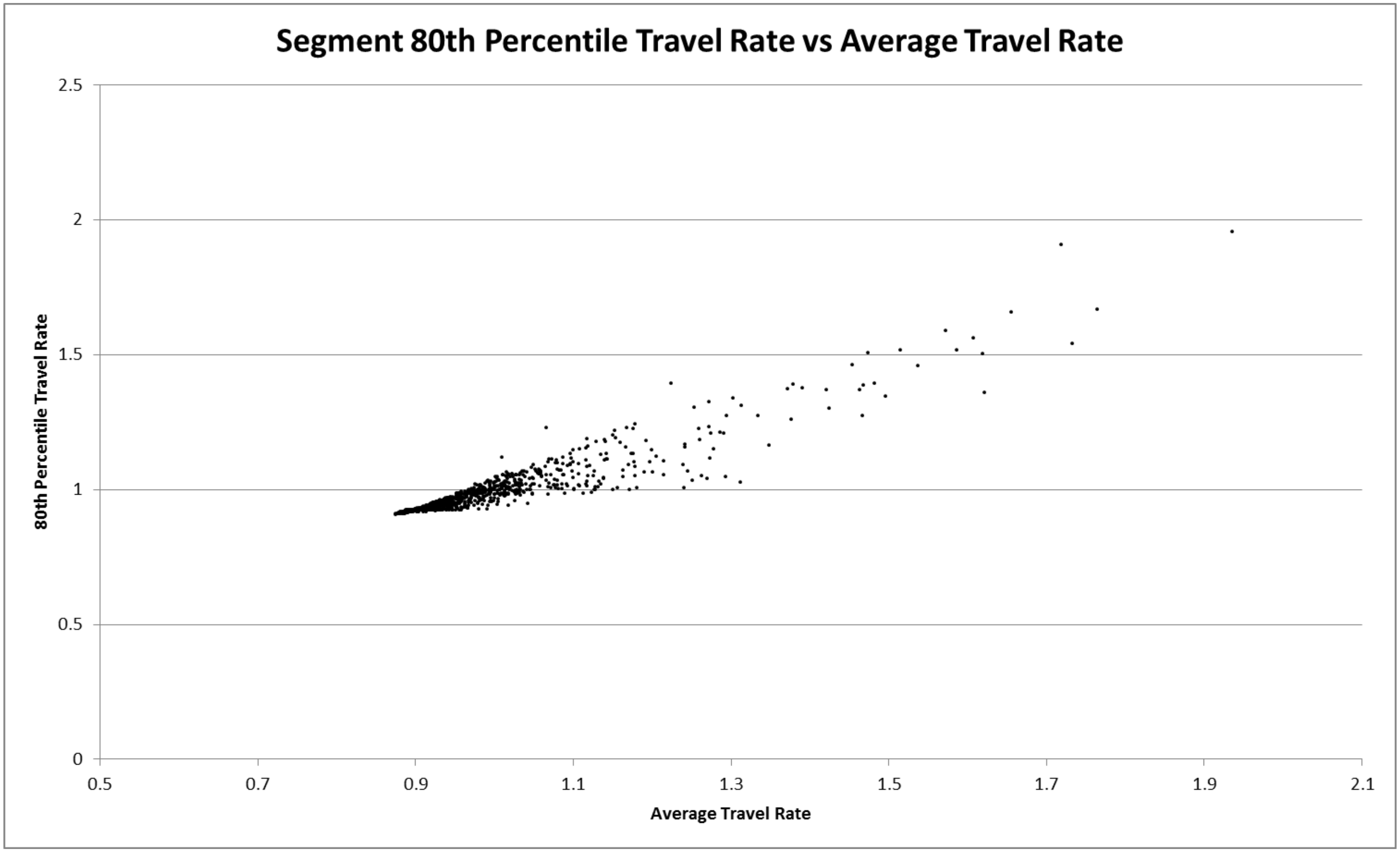


Figure 8.5. Segment 80th Percentile Travel Rate vs. Average Travel Rate.

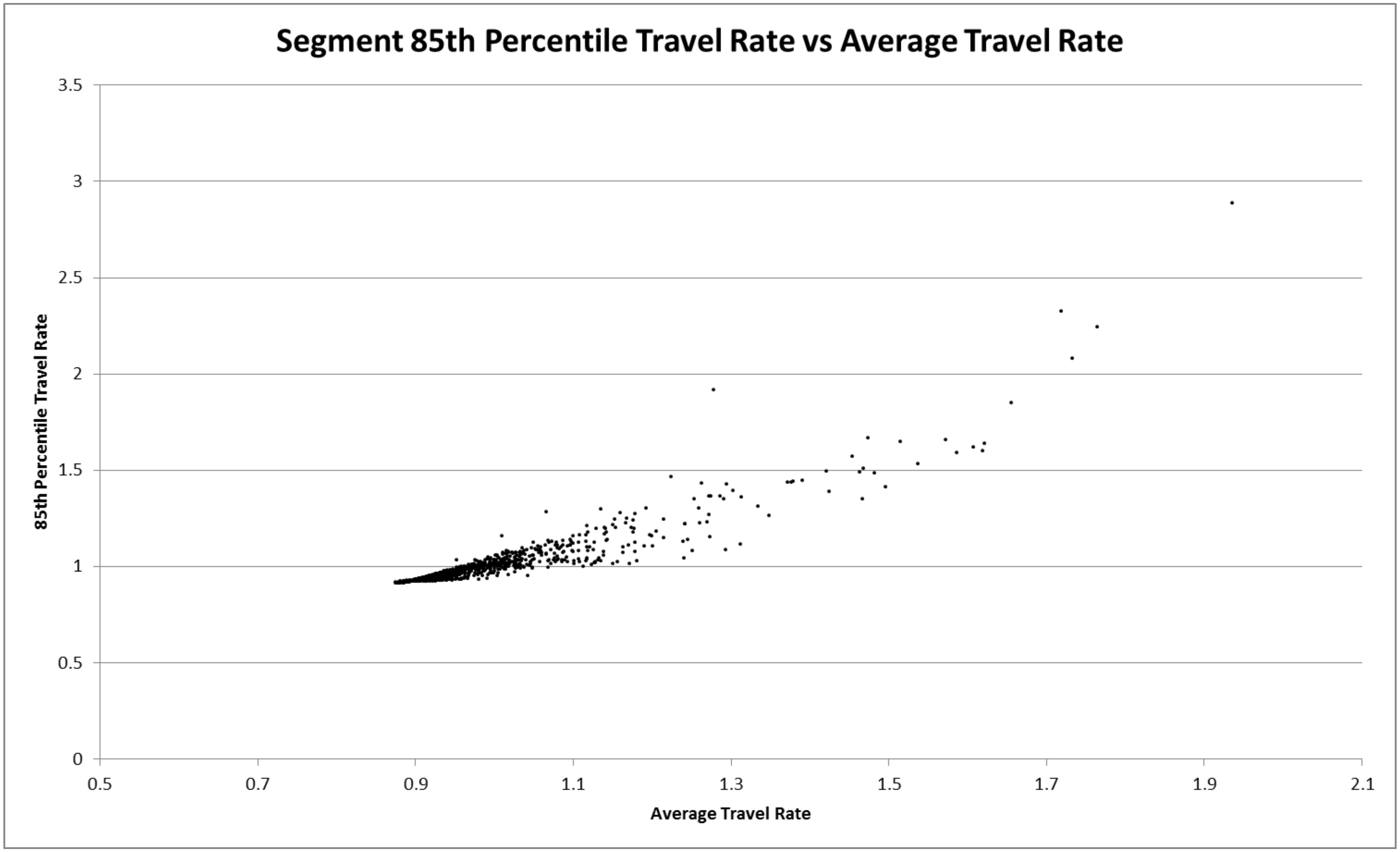


Figure 8.6. Segment 85th Percentile Travel Rate vs. Average Travel Rate.

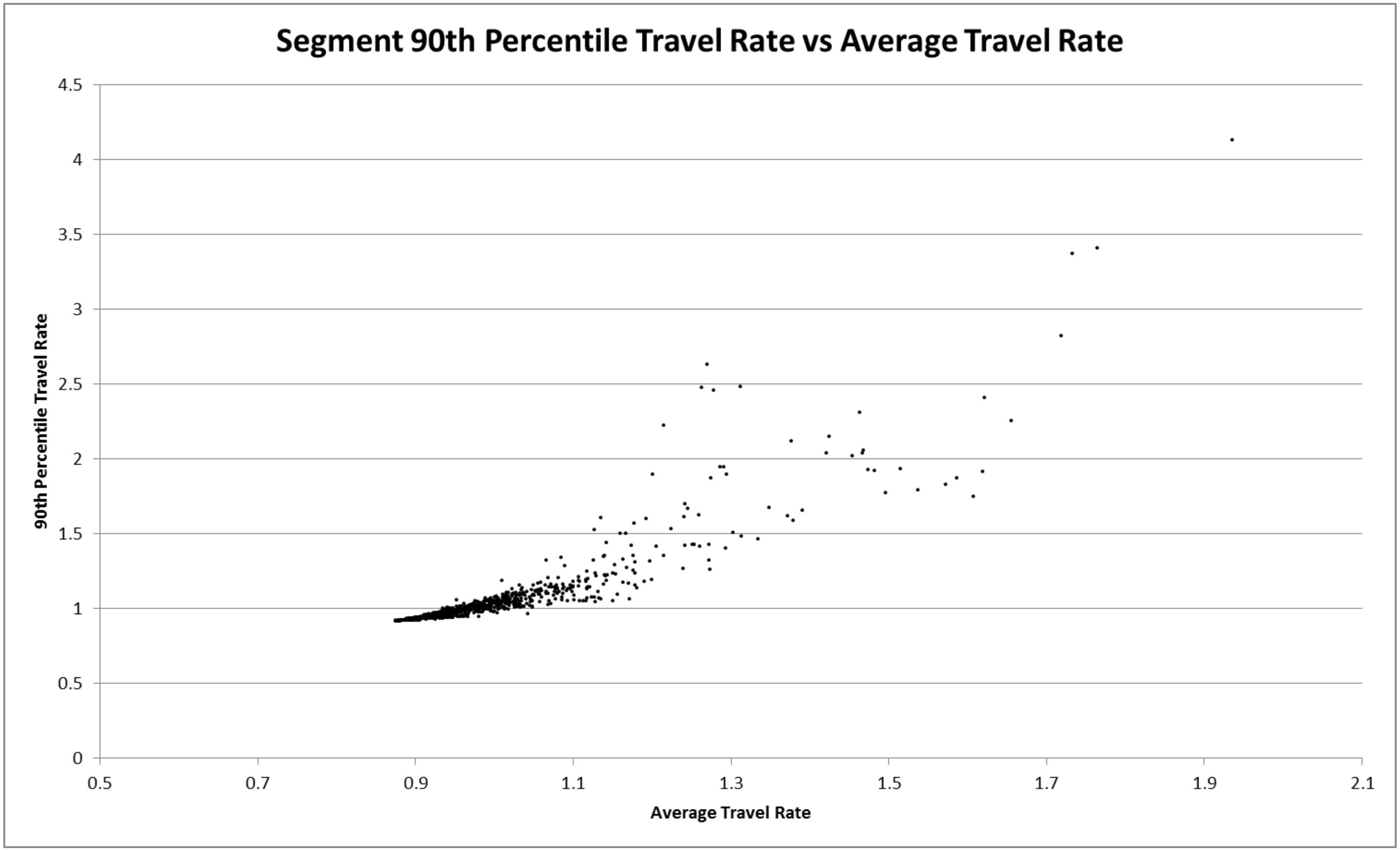


Figure 8.7. Segment 90th Percentile Travel Rate vs. Average Travel Rate.

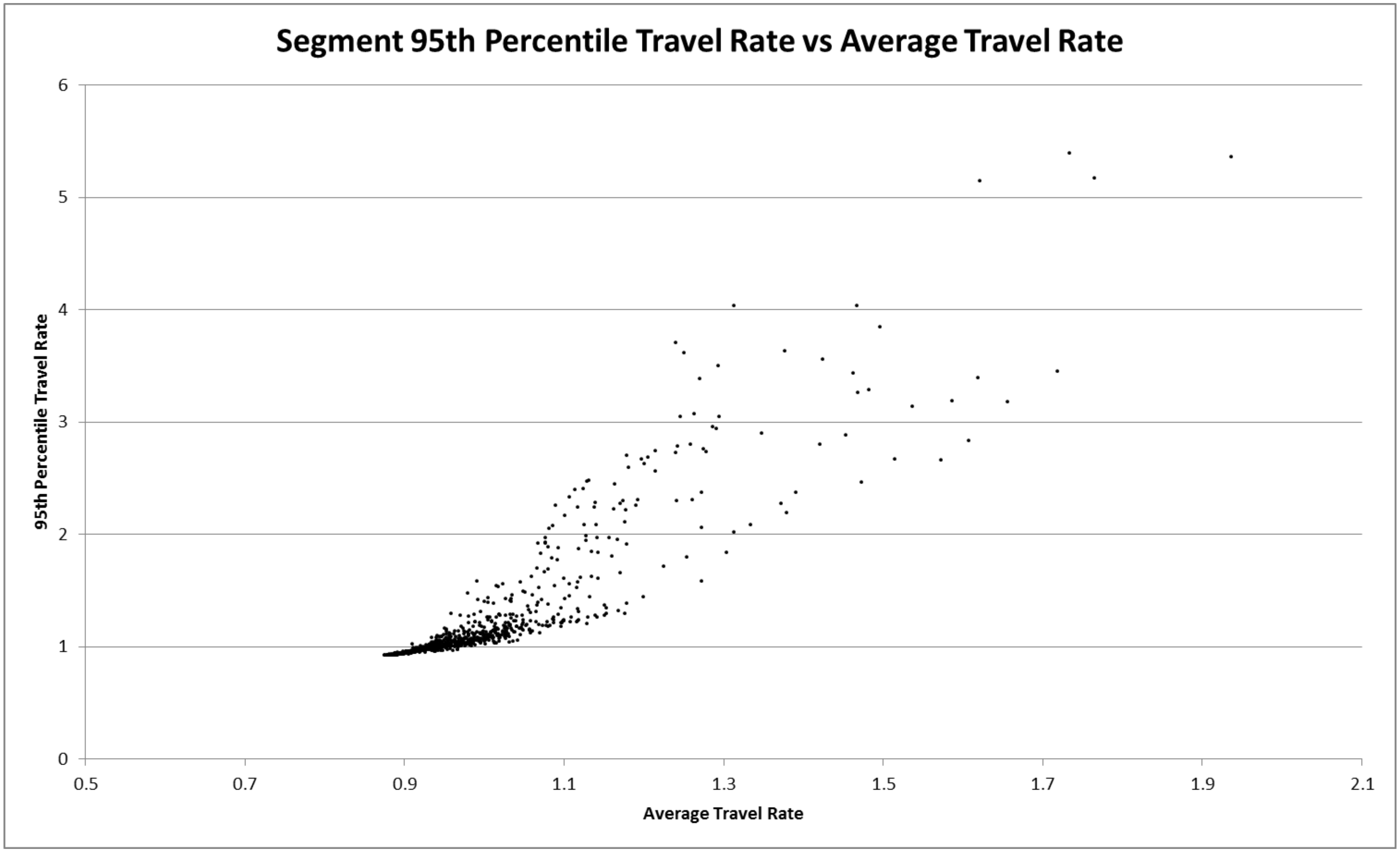


Figure 8.8. Segment 95th Percentile Travel Rate vs. Average Travel Rate.

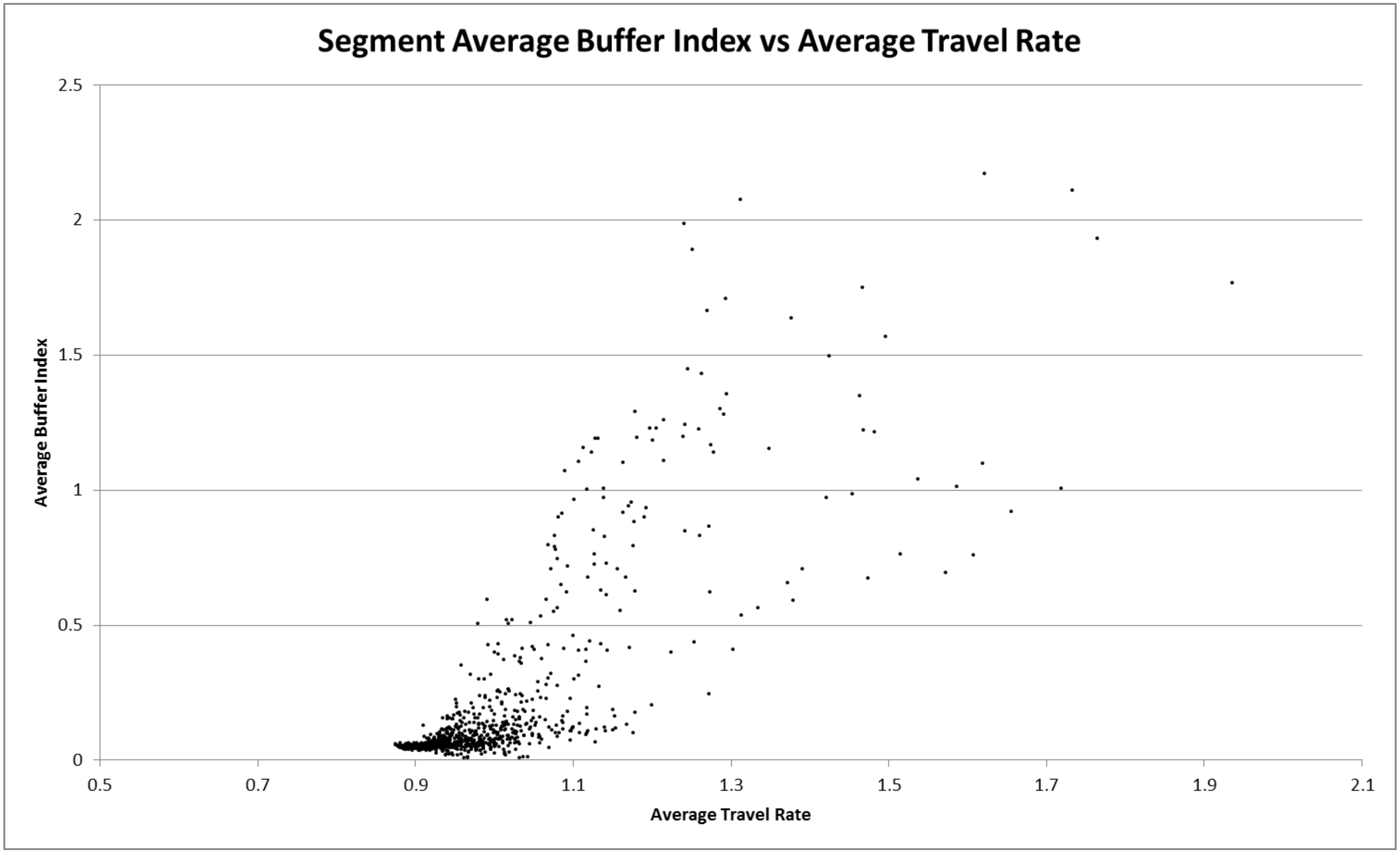


Figure 8.9. Segment Average Buffer Index vs. Average Travel Rate.

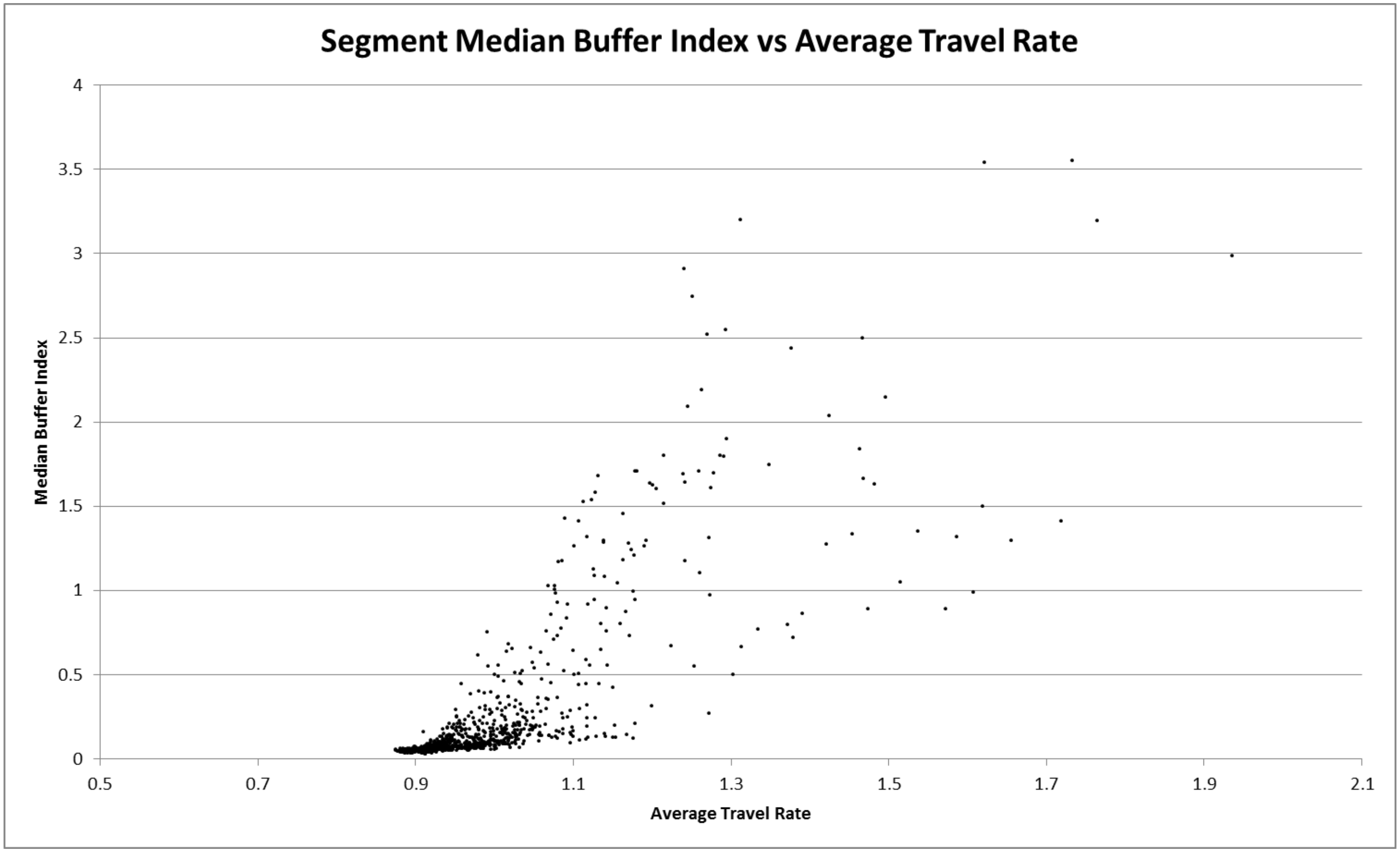


Figure 8.10. Segment Median Buffer Index vs. Average Travel Rate.

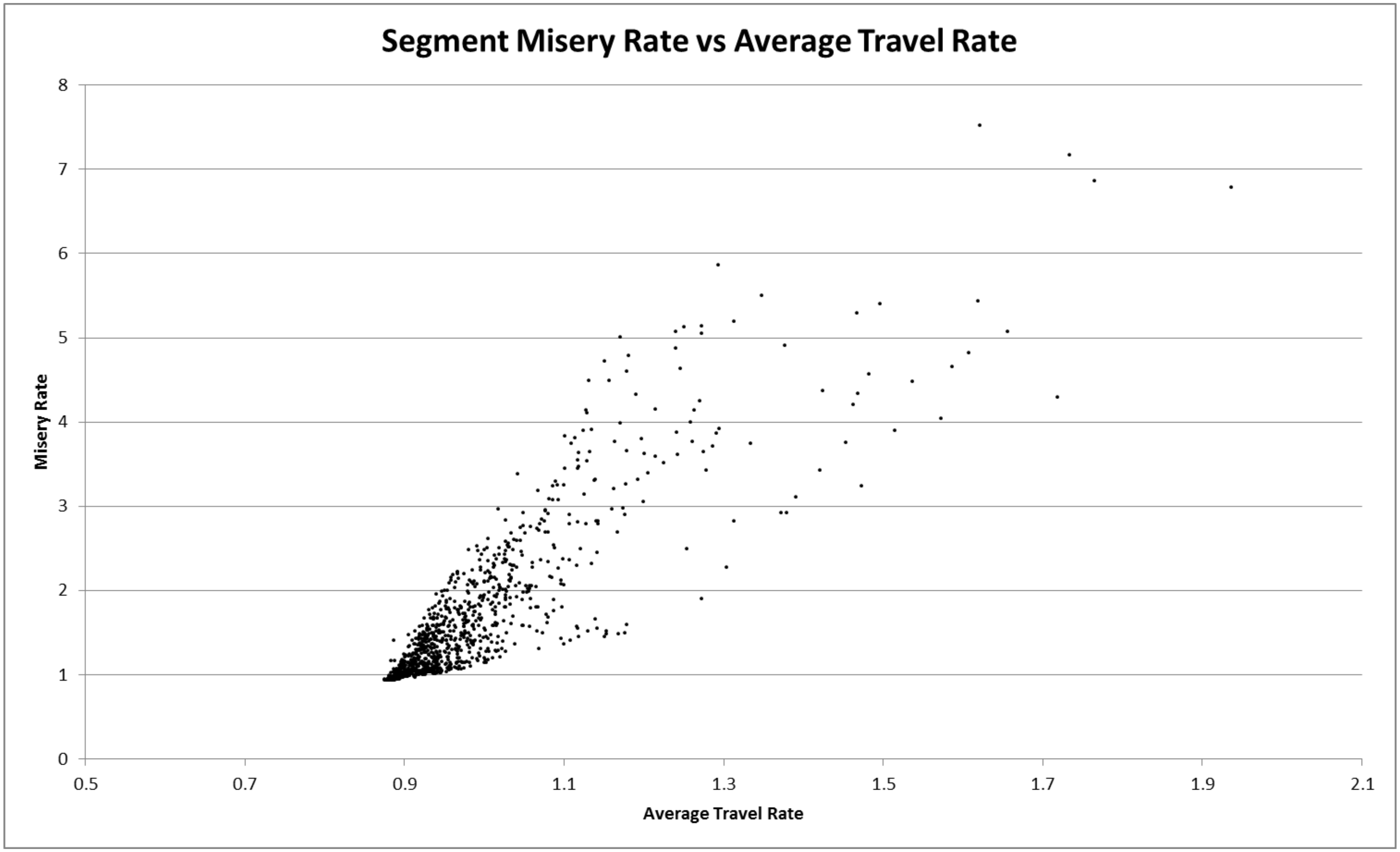


Figure 8.11. Segment Misery Rate vs. Average Travel Rate.

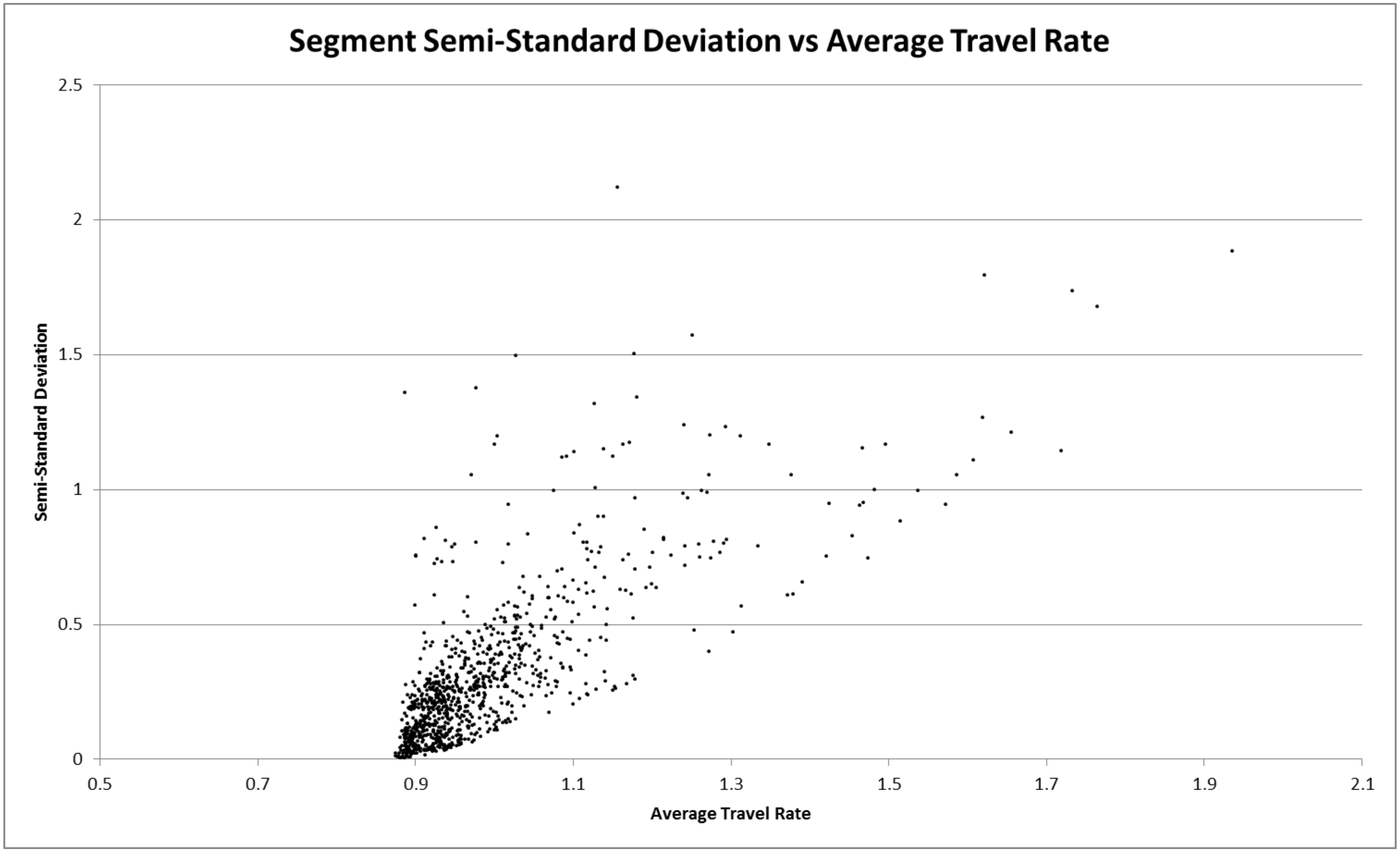


Figure 8.12. Segment Semi-Standard Deviation vs. Average Travel Rate.

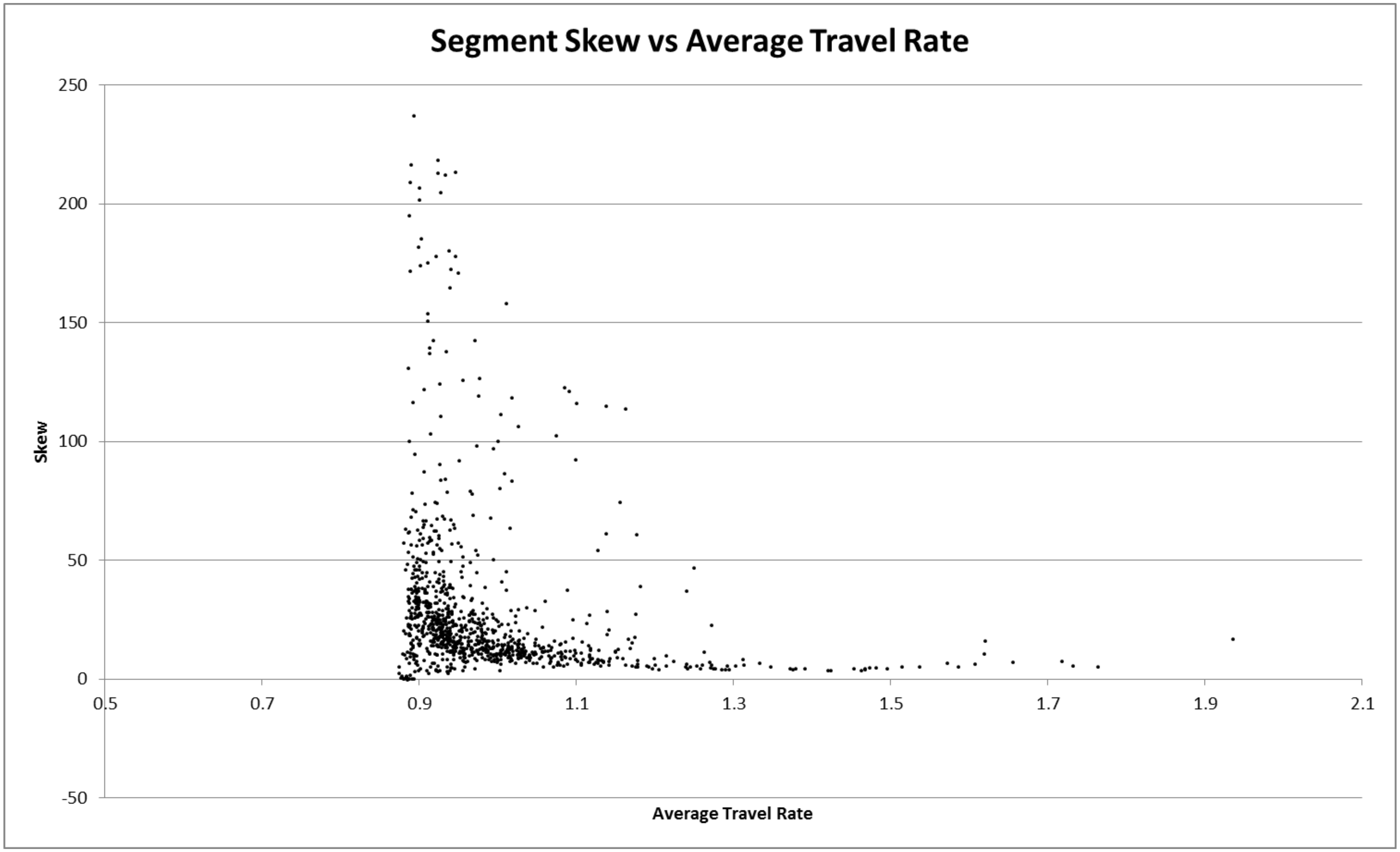


Figure 8.13. Segment Skew vs. Average Travel Rate.

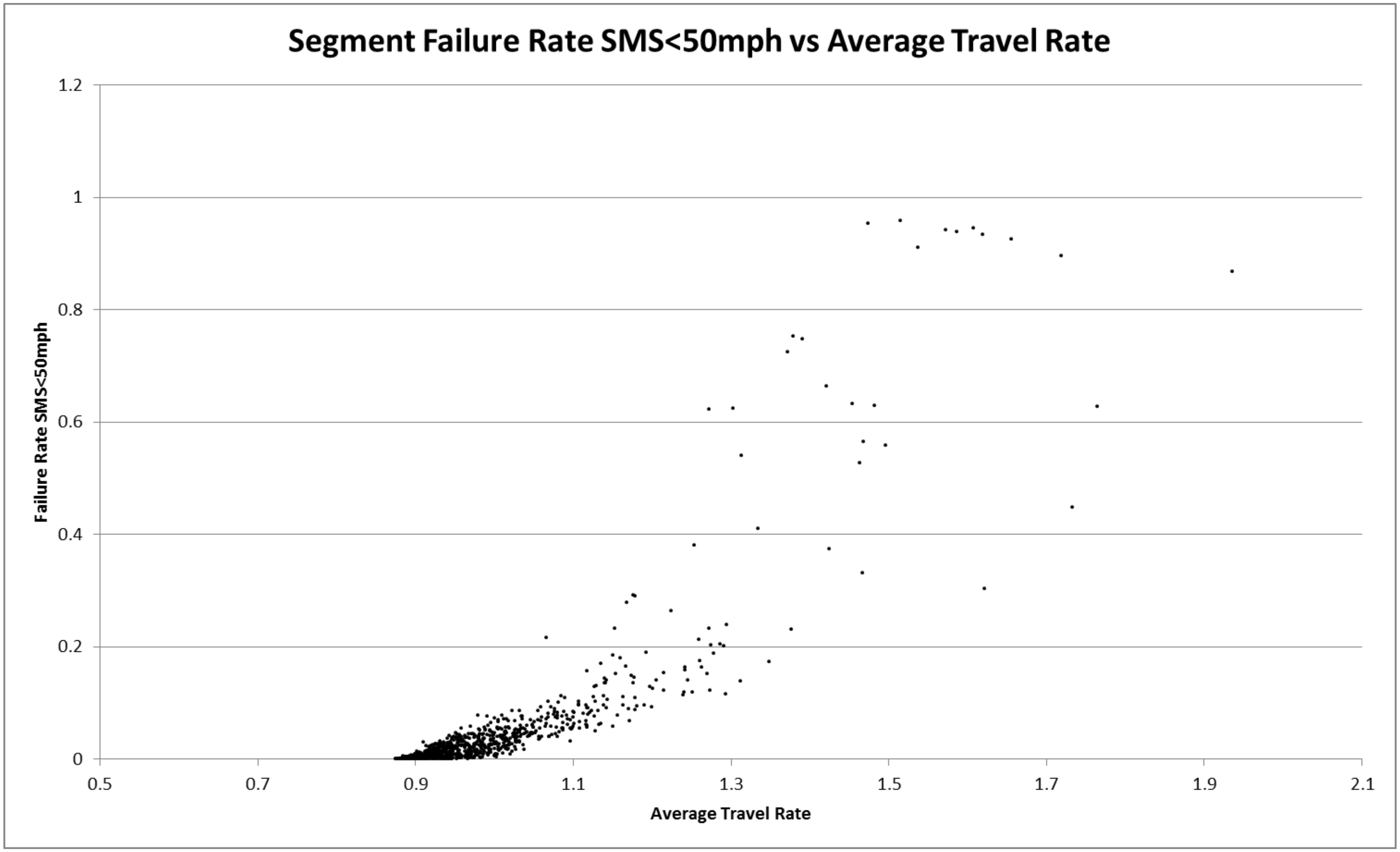


Figure 8.14. Segment Failure Rate where Space Mean Speed less than 50 mph vs. Average Travel Rate.

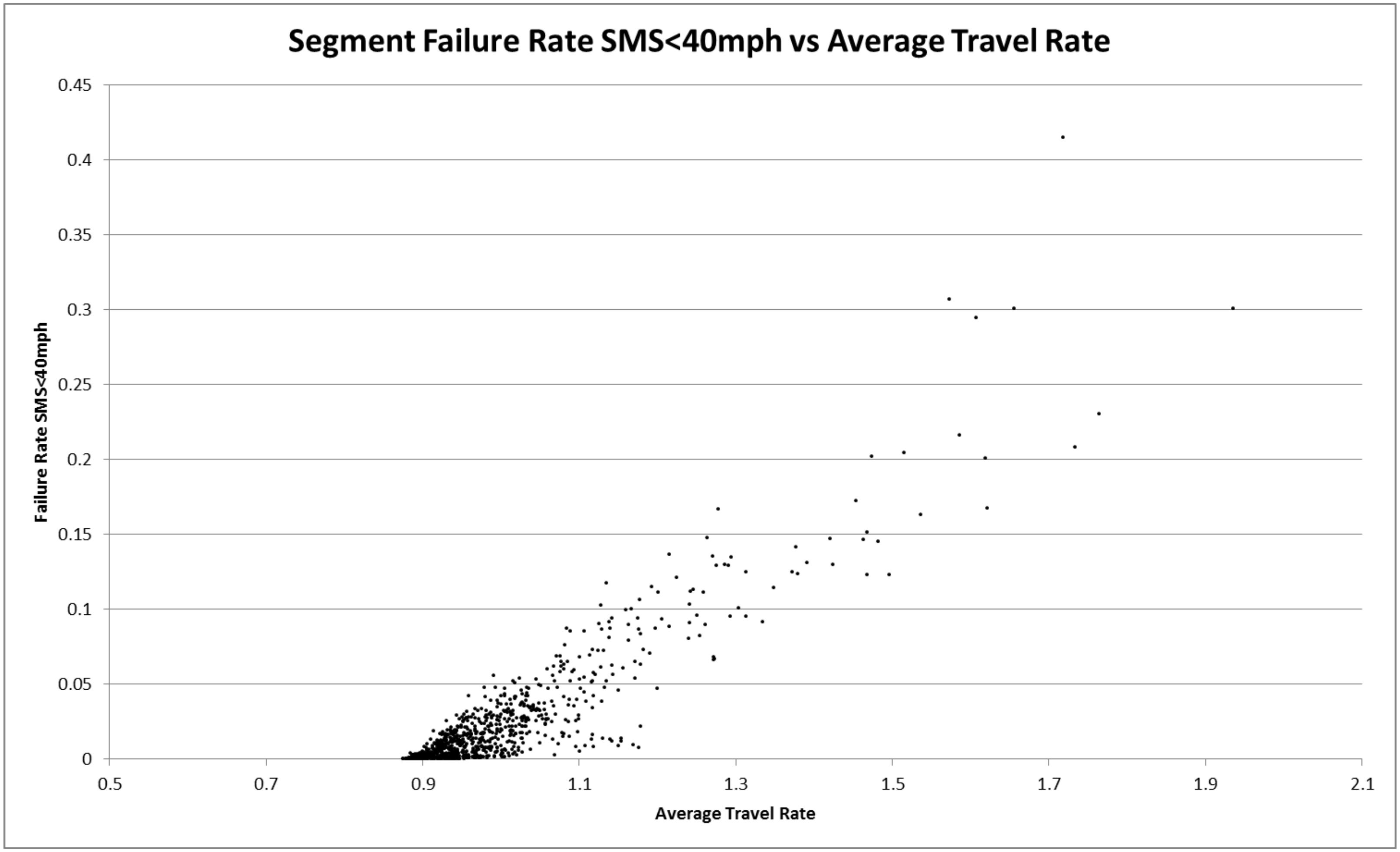


Figure 8.15. Segment Failure Rate where Space Mean Speed less than 40 mph vs. Average Travel Rate.

8.6 Conclusions and Recommendations from Performance Measure Testing

Travel time reliability measures should provide additional information to decision makers, rather than restating typical performance measures. Most common reliability measures are well correlated to the average travel rate. However, the Federal Highway Administration advises against using the four measures with the lowest correlation to the average travel rate because they are statistical measures that non-technical decision makers may not understand. Detailed analysis of the relationships between each measure and the average travel rate concluded that *Skew* may indicate segments or facilities with non-recurring congestion that is disproportionally larger than recurring congestion. The *Semi-Standard Deviation* also appears to indicate both the frequency and severity of non-recurring congestion, and is recommended in SHRP2 L02 as a useful performance measure. While other measures that have been more thoroughly researched, such as the 95th percentile travel time (or PTI when indexed), show high correlation to the average performance, their use can still inform a preliminary analysis.

No single measure appears to be ideal, and each measure is calculated from a part of or the entire travel time distribution. Though single measures can simplify decision making, it is recommended that full distributions be compared where appropriate. Performance measures indicating unreliable travel times would enable operators to identify locations in need of detailed study, including possible sources of non-recurring congestions. With increasing exposure to these distributions and careful explanations as to what they represent, decision makers can effectively prioritize traffic management and geometric improvements.

CHAPTER 9. TASK 8 – FRAMEWORK FOR EXTENDING VEHICLE MILES TRAVELED ESTIMATES

9.1 Introduction

As pointed out in the project proposal and subsequent project authorization document, although the INRIX traffic coverage provides rich information on traffic conditions across the state, the INRIX data provides no direct information regarding traffic volumes served by the transportation network. Therefore, implementation of user or vehicle-based metrics such as vehicle miles traveled or vehicle hours of delay in areas of the state covered only by INRIX data will require some method to estimate vehicle throughput.

9.2 Methodological Background

The current version of the *HCM 2010* presents the basic freeway speed flow relationship as a model with three regimes that are 1) free flow speed, 2) undersaturated flow with declining speed, and oversaturated flow (*7*). The oversaturated flow regime is modeled as a linear relationship between flow and density from which a flow versus speed relationship can be derived (*20*). Therefore, for freeway segments whose operations closely follow the *HCM* model, the derived flow versus speed model could be used for congested regime volume estimation if speed-only data is available for such segments. Also, for low speed observations that occur during time periods where high volumes are historically unlikely, volume estimates based on AADT along with a time-of-day profile could be used to avoid unrealistically high volume estimates.

However, the default *HCM* basic freeway segment models depend only on the Free Flow Speed (FFS). This represents a drawback to widespread direct application of the *HCM* model because FFS it is not the only factor that affects the speed flow relationship within the congested regime. The default *HCM* model will also have difficulty correctly representing the actual speed flow relationship within congestion consistently given real world uncertainty in weather, road conditions, driver behavior, etc. Therefore, a method to adjust the *HCM*-based oversaturated speed flow relationship to better-fit local freeway operations is proposed in this study.

For the identified congested observations, volume is estimated using a combination of a local time-of-day volume profiles along with AADT data for historically low flow periods and the default or adjusted *HCM* speed-flow model for time periods that could be reasonably subject to congested flow. The resulting volume estimates are then used in conjunction with the speed data to compute volume-based metrics, specifically a *volume-weighted travel time index* (VTTI), *vehicle hours of delay* (VHD), and *annual delayed hours* (ADH).

Testing of these methods was accomplished by focusing on locations in the Triangle Area that are covered by both INRIX data and Traffic.com fixed point detectors that provide volume and speed data. Specifically, the metrics calculated as described above from the INRIX speed data were compared to corresponding values calculated using Traffic.com volume and speed data.

9.3 Data Collection

This study collected 15-minute aggregated data from Traffic.com and INRIX for 5AM to 10PM weekdays. AADT statistics were also obtained from the North Carolina Department of Transportation (NCDOT) Traffic Survey Unit. The 15-minute time interval is a common interval used by many state DOTs for archiving freeway data (*21*) and 15-minutes also corresponds to the interval for *HCM* freeway analysis.

9.3.1 Data Description

Traffic.com volume and speed data and INRIX speed data were used as data sources for model development and metrics calculations. The passenger car equivalent (PCE) volume is converted from volume by vehicle classification. The PCE volume is then converted to one-lane based flow rate by the number of lanes and time interval, which is ready for the model fitting. Density is calculated, in the 15-minutes interval, by this one-lane based PCE flow rate divided by speed.

AADT data on all North Carolina freeways from 2002 to 2010 was downloaded from the NCDOT Traffic Survey Unit web page. Monthly and daily demand factors (i.e. Monthly Average Daily Traffic/AADT) were calculated from the data from thirteen Traffic.com sensors along I-40 for the year 2010. These factors are also used to adjust the six-month Traffic.com volume to an estimated total AADT for 2012. National urban, rural monthly and daily default demand factors are also be available from a 1997 study by Hallenbeck (*22*). However, these demand factors may not be applicable to freeway facilities in NC, and they specifically do not take into account the directional nature of commuting routes that are characteristically inbound or outbound for home-based work trips. Local 15-minute time-of-day volume profiles were developed from two-week (normal weekdays in May and October) Traffic.com volume samples of each site and year. The NCDOT has also established a statewide 15-minute demand profile for urban and rural facilities that can be used to estimate volume accurately when demand does not significantly exceed volume during peak hours. Using the 15-minute time-of-day volume profile and Monthly Daily factors, all 15-minute volumes are estimated from AADT at each location and year.

9.3.2 Site Selection

Setting aside the issue of measurement error, an ideal site would be one where the placement of the Traffic.com station is located at a point along the corresponding TMC segment that would yield fixed point traffic condition data that are strongly correlated with corresponding traffic conditions along the entire segment. Traffic.com sensor data is used as the benchmark for metric development and evaluation, and therefore the Traffic.com data should be unbiased relative to the segment traffic conditions. Therefore, basic freeway segments were identified with Traffic.com sensors located near the middle of the corresponding INRIX TMC segment. Central placement provides an initial indication, although not a guarantee, of an acceptable site. Application of this procedure identified Traffic.com station 40390 (covers both directions) along I-40 near Durham, NC with a speed limit of 65 mph as an the most appropriate site volume estimation and metric development. This location corresponds to INRIX westbound segment 125+04871 and eastbound segment 125-04870 (see

Figure 9.1). Traffic.com and INRIX data from this site were assembled for four years from 2009 to June 2012.

Less than ideal sites, namely 40300WB (includes a steep grade), 440200EB (located near a lane drop) and 440210EB (a short segment internal to an interchange with only one year of data), were also analyzed in this study. Traffic.com and INRIX data were collected at these three imperfect sites for one year, namely 2010. The study location 040300WB is on I-40 westbound near Harrison Rd, Cary, NC with a speed limit of 65 mph. The locations 440210EB and 440200EB are located close together on I-440 eastbound near Western Boulevard, Raleigh, NC with a speed limit of 55 mph.

Figure 9.2 shows a map of the three less than ideal locations. The nearest ramp type to the sensor and their distances are shown in Table 9.1.

Figure 9.1. Ideal Study Location near Durham, NC.

Figure 9.2. Other Study Locations near Raleigh, NC.

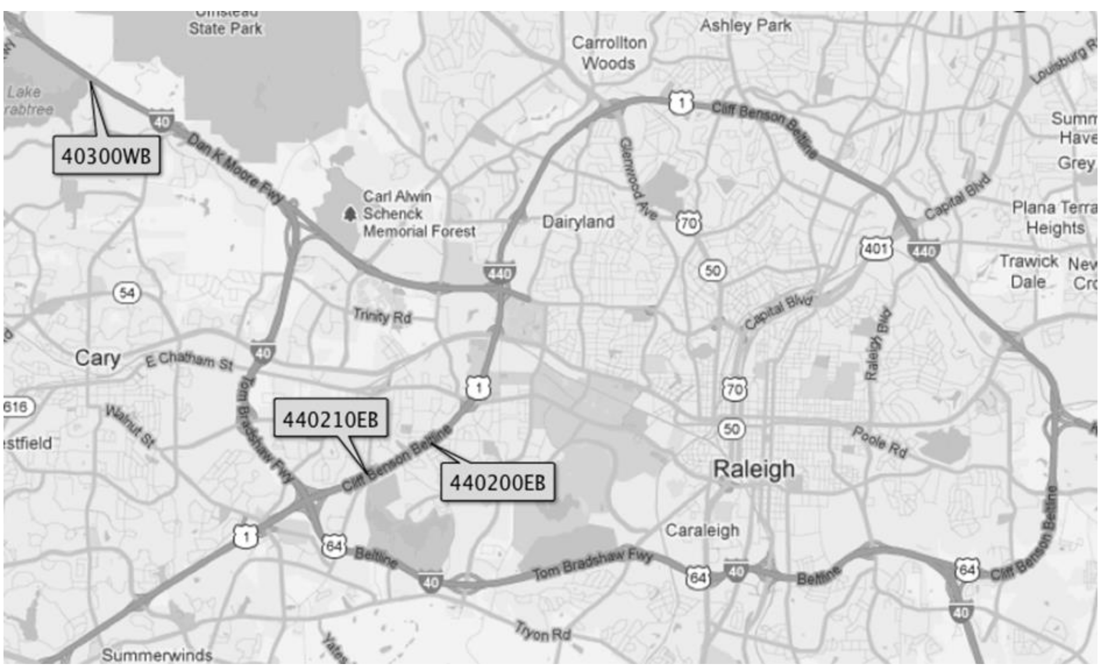


Table 9.1. Nearest Upstream and Downstream Ramps Information to Sensors

Sensors	Upstream		Downstream	
	Ramp Type	Dist. from Sensor (ft)	Ramp Type	Dist. from Sensor (ft)
040390WB	On	3100	Off	2265
040390EB	On	2265	Off	3100
040300WB	On	4770	Off	4455
440210EB	Off	1075	On	1375
440200EB	On	1180	Off	795

* All distances refer to the distance between the sensor and the gore of ramp, measured to closest 5 ft.

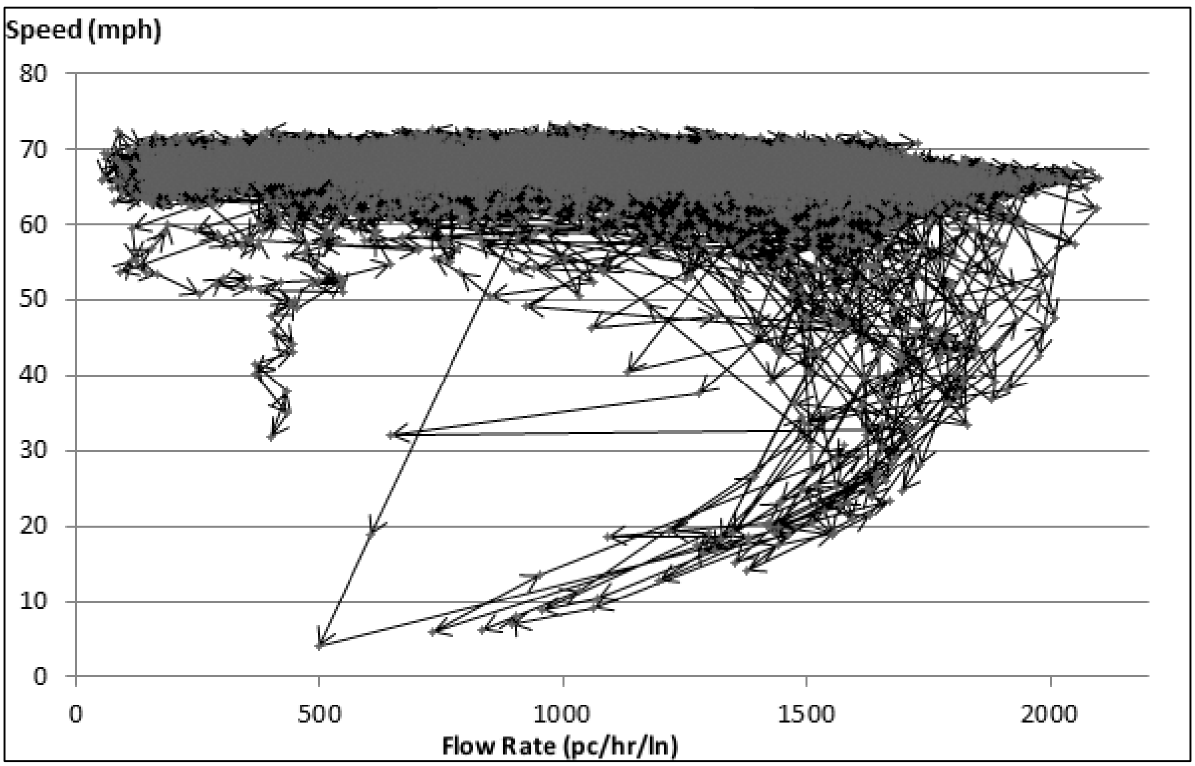
The sites 040300WB and 440210EB meet the *HCM* definition of basic segment, while site 440200EB is an *HCM* overlap segment (i.e. the 1,500 ft on and off ramp segment influence areas overlap). Even though the *HCM* freeway model is designed only for basic segments, the project team decided that it would be worthwhile to test the compatibility of *HCM* or fitted models to a non-basic segment.

9.3.3 Data Cleaning

The proposed methodology in this chapter is only applicable to time periods where normal operations prevail. For example, significant capacity and vehicle operations impacts due to situations such as extreme weather conditions, major incidents, or work zones would preclude accurate volume estimation using either the default HCM oversaturated model or normal volume levels based on AADT and local 15-minute volume profiles. Therefore, anomalous observations arising from conditions such as those just described needed to be identified and removed prior to development of the volume estimation method and the resulting metrics. The importance of data cleaning is clearly illustrated in the speed flow data from Traffic.com sensor 40390 during the year

2009 shown in Figure 9.3. This Traffic.com sensor is located approximately one half mile east of the Highway-54/Chapel Hill Road interchange. The data in Figure 9.3 are 15-minute time interval westbound data from the year 2009. Also, as mentioned above, the data are for weekdays only between 5AM to 10PM. This time period was selected because it covers time of recurring congestion and, based on preliminary analysis, it was determined that this period corresponds to the time frame during which INRIX is most likely to provide trustworthy probe-based speed data. All volume-based measures have been converted to per-lane passenger car equivalent measures.

Figure 9.3. Speed Flow Observations for 40390 WB during 2009 from Traffic.com.



The lines and arrows in speed flow chart connect the 15-minute interval data points in time series order. Therefore, the plot illustrates congestion formation and recovery patterns. The chain of low speed observations occurring at a flow rate of around 400 pc/hr/ln was found to correspond to a heavy snow event that occurred on 1/20/2009. These observations correspond to the type of extreme operational situations discussed above and need to be filtered out prior to development of the volume estimation methodology. Other data points with low speed and low flow are likely to be either mixed state data (congested and uncongested conditions occurring within the 15-minute reporting interval) or capacity-reducing incidents. Archived incident data were not available at the detail necessary to identify observations corresponding to historical incidents.

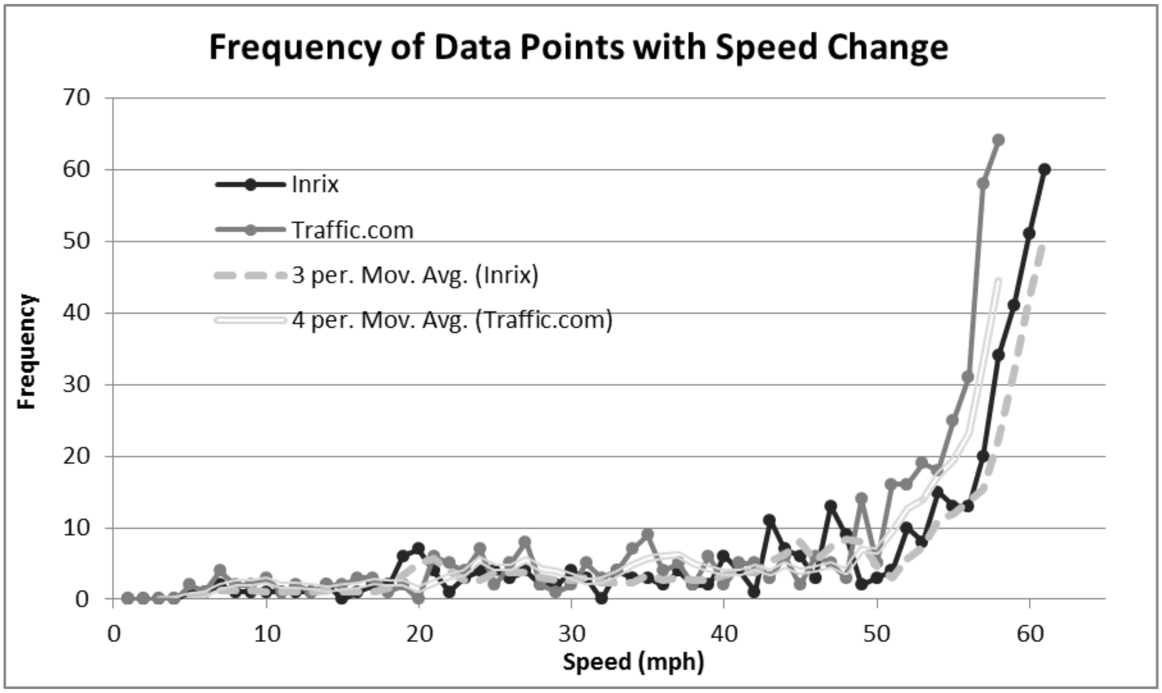
Previous research has found that rain reduces average vehicular speeds by 8 to 12% and capacity by 7 to 8%, wet surface conditions reduce average speeds by 6 to 7%, and light snow impacts demand, leading to a significant reduction in observed traffic volume (*23*). If metrics are calculated based on one full year of data and compared across years, the data with slight speed reduction caused by rain or a wet pavement surface need not be filtered since regular rain should be relatively consistent between years. However, severe adverse weather, such as heavy snow and extremely low visibility, must be taken into account because such events will cause severe reductions in speed and capacity (*24*) (*25*). It is important to note that the INRIX system has some built-in capability to adjust unusual speeds according to historical records. For example, for the heavy snow event identified in the data shown in Figure 9.3, the corresponding INRIX data indicates an average speed of about 55 mph. This average speed is about 7 mph higher than that from Traffic.com over the same period. Furthermore, about 18% of the recorded INRIX speeds during that period are historically based speeds while the percentage of historically based speeds is only 8% throughout the year. Therefore, the INRIX system appears to have recognized the abnormal speeds captured from the probe vehicles and made some adjustments before recording the speed values.

9.4 Volume Estimation Models

9.4.1 Critical Speed Threshold

The Critical Speed Threshold (CST) is developed to separate the oversaturated (congested) flow observations from the other flow regimes. All metrics calculated in this study describe system delay only for congested time intervals as identified by the CST. Delay for these observations is calculated relative to the posted speed limit. Thus, the methodology developed in this study does not include delay for time intervals with speed between speed limit and the CST and, conversely, calculates system delay metrics that only measure the congested intervals. This approach is reasonable because 1) the delay due to congestion constitutes the majority of total freeway delay and is therefore of primary interest to travelers, system managers, and policy makers; 2) most observations with speeds between the posted speed limit and the CST will be from the free flow regime. Therefore, the use of a CST design to clearly identify congested observations will provide a stable and consistent system delay estimation methodology.

Figure 9.4. 15-minute Data Frequency Change with Speed from Traffic.com Sensor 40390 WB 2009.



The speed histogram in Figure 9.4, with bin size of 1 mph, is used to identify the speed threshold at which speed bin frequencies increase sharply. This value is taken to be the CST that separates the uncongested and congested regimes. For both Traffic.com and INRIX data, the frequency of data points rises sharply when speed is around 50 mph. Given the fluctuation in the finely divided bin frequencies, a moving average (average points on the left) was used to help identify the CST. The appropriate number of observations in the moving window was investigated at different sites. Based on the moving average curve, the CST was defined to be the speed at which there are no further frequency drops along the moving average curve in the direction of increasing speed. CST selection results using two to five bins for the moving average curves were compared at all sites as shown in Table 9.2.

Table 9.2. Two to Five Bins Moving Average Curves Comparison

Sites	Traffic.com				INRIX				Systematic Speed Difference (INRIX vs. Traffic.com)
	Two Bins	Three Bins	Four Bins	Five Bins	Two Bins	Three Bins	Four Bins	Five Bins	
40390 EB2009	52	52	52	51	48	49	50	51	0.49
40390 EB2010	55	56	52	52	49	49	49	50	3.34
40390 EB2011	51	51	51	51	54	54	54	56	6.15
40390 EB2012	53	54	54	53	62	62	54	61	6.78
40390 WB2009	52	52	52	53	48	49	49	50	-1.35
40390 WB2010	54	54	53	53	53	53	53	53	-0.62
40390 WB2011	52	49	49	51	57	58	56	56	3.67
40390 WB2012	52	53	52	53	60	60	59	54	4.71
40300 WB2010	55	55	54	54	52	54	54	55	1.60
440200 EB2010	47	42	42	41	38	39	39	32	4.44
440210 EB2010	41	42	42	41	46	46	48	43	6.81

* Outliers are marked underline; selections are marked bold

The moving averages smooth the bin-to-bin fluctuations in the data that are likely to be a random feature of each particular data set. However, using too large of a moving window will result in loss of information. Thus, the number of bins that are averaged should be as small as possible while providing adequate smoothing of the random bin frequency fluctuations. Furthermore, the CST would not be expected to change across years if there have been no significant change in road conditions and driver behaviors. This expectation was applied to the east and westbound data from station 40390 and used to help identify the appropriate moving average window size. Based on collective analysis of the data presented in Table 9.2, a moving average window of four bins is recommended for Traffic.com data while three bins are recommended for INRIX data. However, these are specific recommendations for the sites included in this study, and the general recommendation is to conduct a similar analysis of multiple moving average window sizes to determine the appropriate number of bins for determination of the CST.

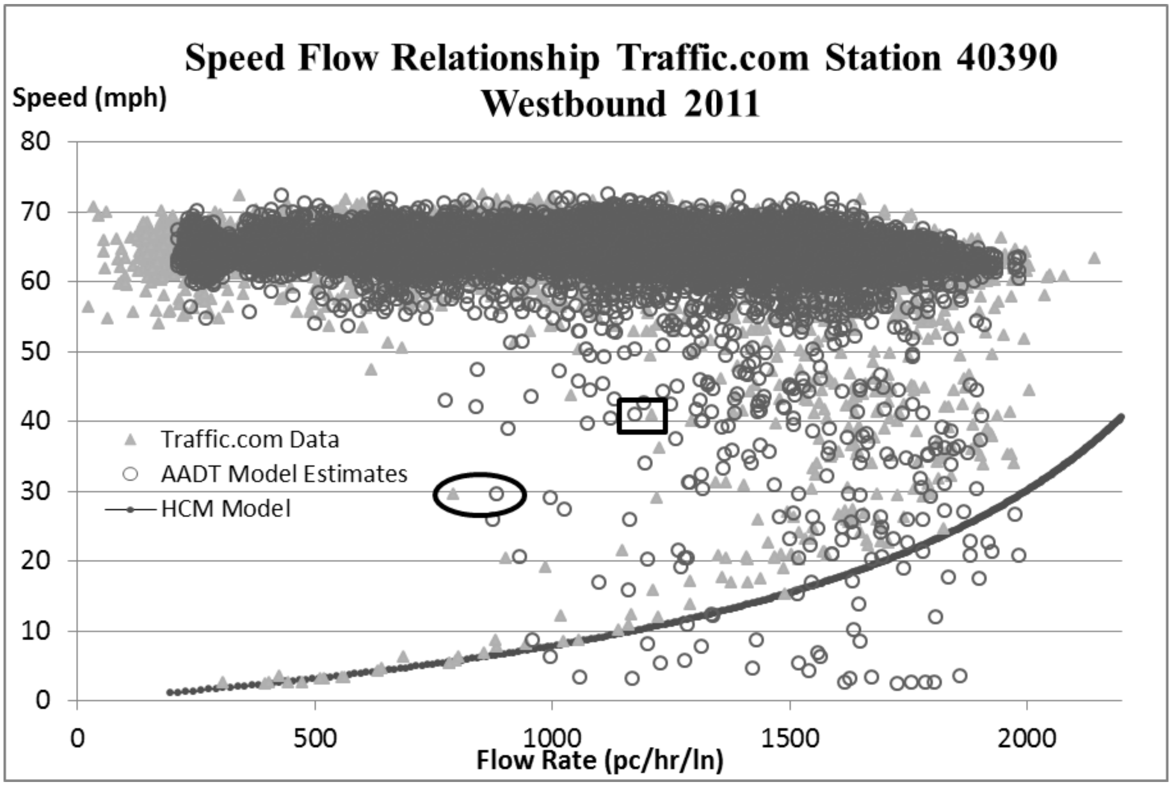
Another method to determine the CST is to apply a simple line referring to 10 mph below posted speed limit. Analysis of Traffic.com speed and flow observations reveals that typical variation of speeds under free flow conditions is approximately ±5 to ±10 mph from the mean speed during low flow conditions (free flow speed). Since freeway free flow speed (FFS) is generally higher than the posted speed limit, 10 mph below speed limit provides a reasonable and robust threshold for distinguishing between uncongested and congested observations. However, inspection of actual speed flow data is nonetheless necessary to ensure the CST is sufficient but not too conservative if a large cluster of data lie below CST, then the CST may need to be lowered. Conversely, if there is a clear gap between the free flow data and the threshold, then the threshold may be overly conservative and raising the threshold should be considered. It is recommended that the CST be set rather conservatively to ensure no undersaturated data are included for model fitting purposes.

9.4.2 Hybrid AADT-HCM Volume Estimation Model

A hybrid approach based on two models is used for the congested state volume estimation based on speed data. The two component models are 1) the default *HCM* speed flow curves and 2) an AADT based model. Traffic.com speed versus flow observations are shown in

Figure 9.5 along with points representing each observed speed plotted versus flow rate estimated from the two models for westbound data collected at station 40390 for the year 2011.

Figure 9.5. Traffic.com Actual Speed Flow Data along with *HCM* and AADT Model Volume Estimation.



The *HCM* model fits most of the congested observations (those with speed below about 15 mph) well at this site. However, the fit is noticeably worse for observations with speeds between 15 mph and the CST. For these observations the *HCM* model overestimates volume in nearly all cases. Freeway data in general tend to evidence more variation and conversely less stability in traffic states lying between severe congestion and free flow, which leads to an expectation that the default *HCM* model would not provide a close fit to these data. For the severe congestion regime with speeds less than 15 mph, a small difference of speed leads to significant difference in estimated volume according to the *HCM* model (*26*). This fact could in turn lead to volume estimation error. However, the results indicate that error in the *HCM* model volume estimation is less severe than for volume predicted by AADT model in the heavily congested regime.

The AADT model provides common volume information by time interval across the year. The AADT model speed flow relationship, shown as circles in

Figure 9.5, is built by matching time stamps of AADT model output and INRIX or Traffic.com data. The AADT model is able to fit the mixed state very well since it is looking at the 'average' volume over the year, while it would significantly overestimate volume during the severe congested regime. For instance, the triangle and circle highlighted by an oval (with flow rate around 800 pc/hr/ln) indicate that the default 15-minute volume at 6/30/2010 20:00 to 6/30/2010 20:15 from AADT model would be 11.6% higher than the volume collected from Traffic.com during the same 15-minute period. Similarly, points highlighted by a rectangle (with flow rate around 1200 pc/hr/ln) indicate that AADT model estimated volume is 3.0% lower than Traffic.com volume. Most of this error would be canceled out during averaging metrics over the whole year if no significant difference of AADT and Traffic.com total is caught. Thus, for data with slight congestion (still under the CST), AADT model would provide a decent volume estimate according to daytime factors.

In order to model delay due to congestion (defined as speed being under CST with extremely bad weather, lane closure, incidence, etc. data filtered out), the *minor volume* estimated from the *HCM* and AADT model is selected as the final volume estimation.

9.4.2.1 Basic HCM Model

The data points within the upper 1% traffic volume range for the full year weekday and daytime observations are viewed as representative of the freeway capacity at each site. The average volume of this sample was found to be generally equivalent to the traditional capacity defined in the *HCM* (*27*). Therefore, the average flow of these observations was defined as the capacity at each site, and the average speed of these observations was defined as the speed at capacity. The observations at each site with speed higher than speed at capacity and volume lower that 500 pc/hr/ln were selected as the basis for free flow speed (FFS). Previous research suggests that the expected or mean value of pre-breakdown flow and queue discharge rates appear to be approximately 400 pc/hr/ln less than the HCM capacity values (*28*). The threshold of 500 pc/hr/ln ensures that no pre-breakdown flow or queue discharge data are included in FFS determination. Even though this approach is more conservative than the 1000 pc/hr/ln recommended by a previous study (*27*), it contains sufficient data for FFS determination. The speed at capacity line is used to filter out low speed, low volume data points that do not fall on the theoretical HCM speed flow curve, and the volume of 500 further helps to confine observations to the free flow regime. The resulting FFS, calculated as the mean of the identified free flow observations, is used to select the representative HCM speed-flow curve. However, if the volume information is not sufficient or available, the mean of the upper 5% of all speeds is recommended as the FFS criteria for HCM model selection.

The *HCM* basic freeway segment speed flow model provides a single set of capacity values as a function of Free Flow Speed (FFS), which does not take the local conditions into account (*29*). Also, in this study, Traffic.com volume is converted to a per lane based flow rate by averaging the total section volume by the number of lanes. This caused bias in the speed volume relationship and the capacity because in general volume is distributed unevenly across lanes and the lane distribution varies when traffic is approaching capacity (*30*) or at other times of day (*31*). Another source of error is the fact that speeds are unevenly distributed across the lanes (*32*). Furthermore, it is to be expected that even precisely and accurately measured traffic condition data for conditions lying between the free flow regime and the severely congested regime would be very noisy due to the unstable traffic conditions during this transition regime. Therefore, the selected *HCM* curve would fit well with the FFS but not the near capacity regime.

However, the selection of *HCM* curve should not significantly affect the error of volume prediction. This is true because, generally speaking, only the low speed (speed under around 15 mph) section of the curve is used if the minimum of *HCM* predicted volume and AADT model predicted volume are used as final value for volume estimation. The part of the speed-flow curve corresponding to this regime is not sensitive to FFS and could predict volume very well as illustrated in

Figure 9.5 above.

9.4.2.2 AADT Model

NC freeway AADT data could be acquired from the Traffic Survey Unit at the NCDOT website. It is assumed that daily traffic demand equals daily traffic volume, so that AADT, along with monthly daily factors and daily 15-minute volume profiles calculated from local and recent data, could be used to generate 15-minute default volume. Local daily 15-minute profiles are developed from two-week Traffic.com speed flow data collection from each site and year. Heavy vehicles and directional difference could both be handled by this profile, since Traffic.com offers vehicle composition information and speed flow data in both directions. The NC urban default daily 15-minute demand profile could be used only when the demand does not usually significantly exceed the volume. Thus a local data collection to develop the daily 15-minute profile is always recommended when conditions permit.

In this study, the AADT values have been compared to Traffic.com average daily volume with adjustment of missing readings. For Traffic.com station 40390 in years 2009 and 2010, there is only approximately a +3% difference for AADT and Traffic.com, as shown in

Table 9.3. This percentage is kept for AADT estimation for 2011 and 2012 when they are not available at this time, assuming the difference is systematic and consistent over the years.

Table 9.3. Comparison between default AADT and Average Daily Traffic Count from Traffic.com Sensor 40390.

	Vehicle/day	2009	2010	2011	2012
EB	Traffic.com	55,289	55,246	56,128	56,491
	AADT	57,454	56,807	57,874	58,430
WB	Traffic.com	53,452	53,676	54,433	54,693
	AADT	55,546	55,193	56,126	56,570
Both Directions	AADT Total	113000	112000	114000	115000
	Error Rate	3.92%	2.83%	3.11%	3.43%

* Please note the AADTs for each direction are assigned according to directional traffic count ratio from Traffic.com. AADT from 2011 and 2012 are assigned according to the error rate around 3%.

9.4.3 HCM-based Speed Flow Fitted Model

An *HCM*-based freeway model fitted to Traffic.com speed and flow data would have more capability, than the default *HCM* model, to represent local speed flow relationship on the specific site. Detailed model fitting procedures and examples are available in Appendix A.

9.4.4 Volume Estimation Summary

The basic methodology followed in this volume estimation research thread involves determining a critical speed threshold for identifying congested time intervals and then applying a congested regime model for volume estimation. During uncongested periods, speed provides little or no information useful for estimating corresponding volume. Therefore, for overall VMT estimation, the best estimates would come from directly applying the Traffic Survey Unit AADT statistics.

For the steps in congestion regime volume estimation, the research developed both a histogram-based method and a simple speed drop threshold method for determining the CST. Either CST method should produce acceptable results if applied properly. The histogram-based method however is less susceptible to the risk of being overly conservative in the congestion regime identification. In terms of model selection, a hybrid AADT- *HCM* model is proposed for volume estimation from speed data when time, expertise, and data are not available for local model fitting. However, whenever possible, developing an *HCM*-based model fitted to local data will provide a more accurate speed flow relationship for volume estimation.

Other recommendations include:

- Data collected under inclement weather, construction, incidents, etc. should be filtered out. Speed flow relationship plot / data cleaning process is necessary before volume estimation;
- Use histogram method for CST since it is based on real data; the CST should not be different significantly across years or sites if the road condition and driver behaviors are similar;
- HCM curve selection from speed only data is acceptable; selection from speed flow data require at least half year of dataset that ensure rich data around capacity;
- Local volume profile for AADT model is necessary for an accurate flow rate estimation; this profile require at least two week typical traffic speed and flow data collection; it is recommended that data collection be conducted in May and August.
- Default *HCM* curve for the hybrid AADT-*HCM* is acceptable since only the low speed part of *HCM* curve is actually used.
- The fitted *HCM* speed flow relationship are significantly better than the default one, but the fitted model requires at least half a year of speed flow data that ensures enough information for model fitting. It is recommended that 100 steady state congested data points reasonably spanning a broad range of density levels should be the minimum sampling requirement.

Detailed application and testing of the recommended methods is presented in the following sections.

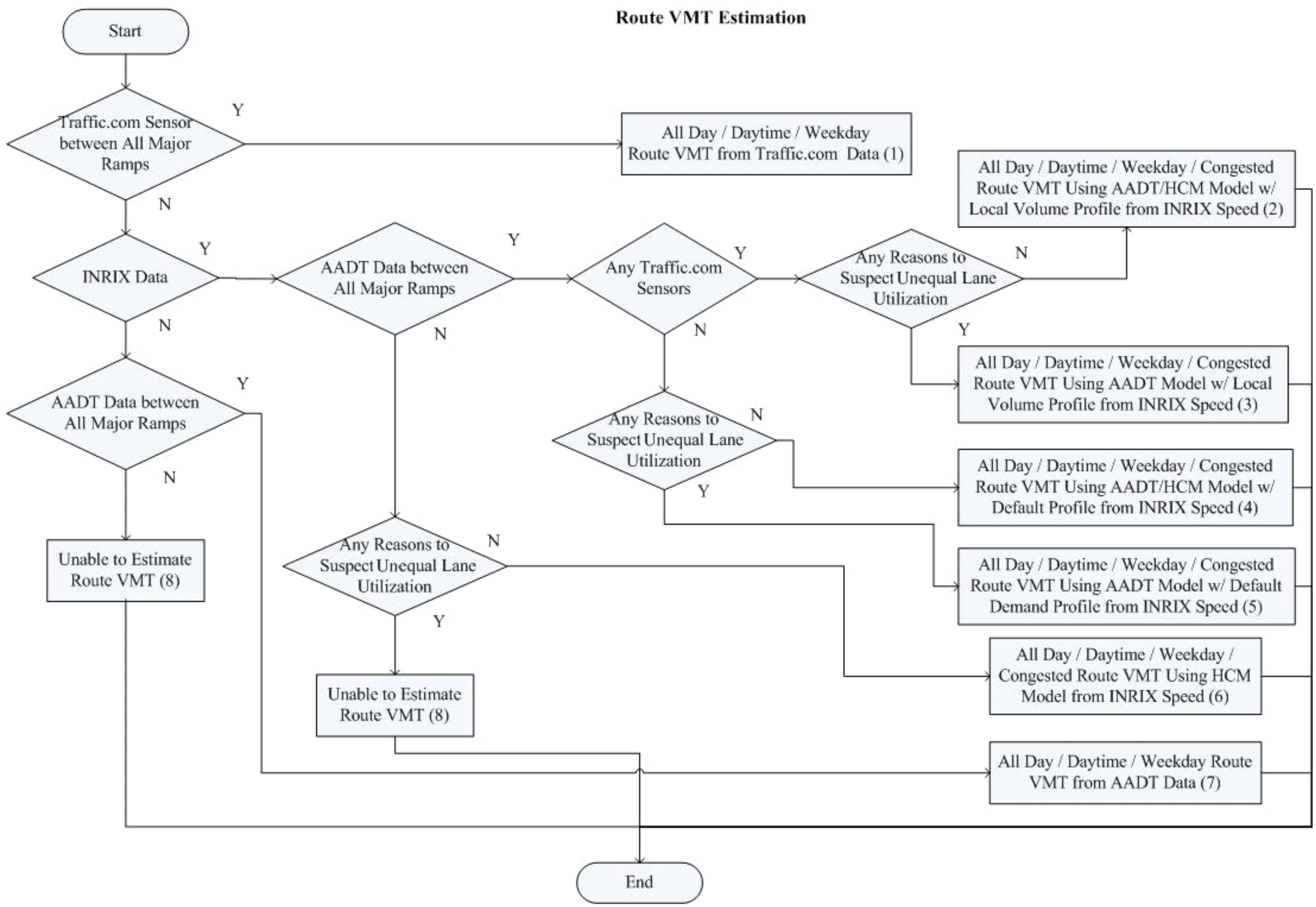
9.5 Route VMT Estimation Strategy

The volume estimation model would also benefit system delay metrics on route basis. A flow chart showing the strategy for route VMT estimation, based on the available data sources, is developed and proposed in this chapter.

9.5.1 Route VMT Estimation Flow Chart

With the volume estimation methods, route VMT could be estimated using the following logic in Figure 9.6. The numbers in parentheses represent the rank of route VMT estimation quality.

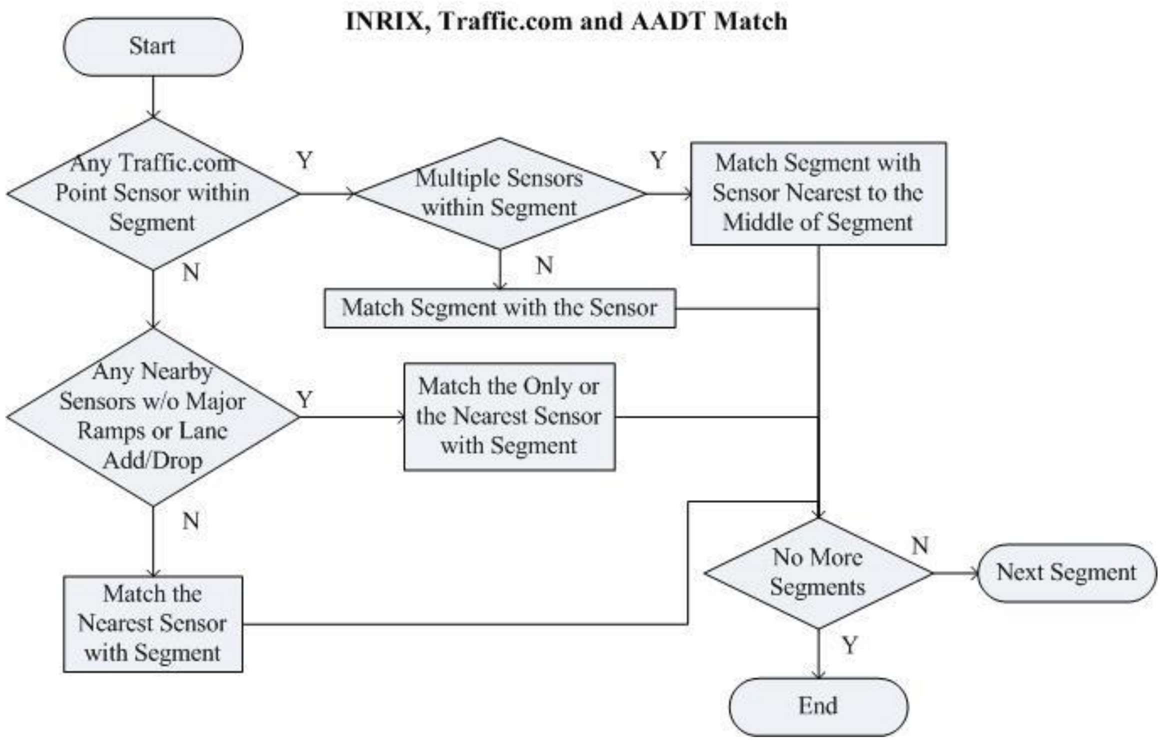
Figure 9.6. Route VMT Estimation Strategy.



9.5.2 VMT Site Study and Recommendations

Traffic.com, INRIX and AADT data were collected for Route 4 on I-40 to develop and test route VMT estimation strategy. Figure 9.7 shows the logic to match Traffic.com point sensors to INRIX and AADT segments for comparison of route VMT estimation from different data sources. Please note both INRIX and AADT segments are defined between ramps, and thus the same logic would be used to match them to Traffic.com sensors.

Figure 9.7. INRIX, Traffic.com and AADT Detector/Segment Match Strategy.



For this route, the segment length weighted Traffic.com data missing rate would be around 2.4%. Route VMT estimated from Traffic.com volume data (ranked 1st in the route VMT estimation flow chart) is used as a reference value in this comparison. Please note heavy vehicles (using a factor of 1.117 from Traffic.com data) and directional factors (different at each segment) are considered in this comparison.

For this route, if INRIX data is available, all day/daytime and weekday/congested route VMT could be estimated using the volume estimation model proposed in this chapter, with different available data sources (ranked 2nd to 6th in the flow chart). Details are shown in Table 9.4 and Table 9.5 below.

Table 9.4. Route VMT Comparison with Limited Traffic.com Sensors.

Rank	1	2	2	3
Data Source	Traffic.com	Inrix/AADT		
Filter	Daytime, weekday, and CST			
Model	None	Hybrid Model	Hybrid Model	AADT Model
Profile	None	One profile	Four profiles	
Route VMT	35,427,898	31,073,576	31,073,209	33,259,552
Error Rate	0.0%	-12.3%	-12.3%	-6.1%

Table 9.5. Route VMT Comparison without Traffic.com Sensors.

Rank	1	4	5	6
Data Source	Traffic.com	Inrix/AADT	Inrix/AADT	Inrix
Filter	Daytime, weekday, and CST			
Model	None	Hybrid Model	AADT	HCM
Profile	None	NC Default		N/A
Route VMT	35,427,898	28,864,244	30,134,568	44,141,909
Error Rate	0.0%	-18.5%	-14.9%	24.6%

It is recommended that one volume profile for the AADT model is enough if the traffic pattern along the route does not change significantly. Route 4 does not meet the equal lane utilization criterion since there are many weaving and ramp segments and lane adds/drops along the route, which is the reason for a lower error rate of the AADT model estimates than that from the hybrid model. Also, the high error rate of *HCM* model in Table 9.5 is for the reasons of non-equal lane utilization and the overestimation of the *HCM* model itself. A fitted *HCM* based speed flow model is an alternative for the default *HCM* model, when sufficient speed flow data is available.

For this route, if only AADT data is available (ranked 7th in the flow chart), annual total route VMT or route VMT during daytime and weekday periods could be estimated with error rate around 12%. Even though the error rate is not the worst performer, no congestion information could be obtained from this VMT value. Therefore, this data condition was ranked the lowest in the flow chart of the situations that produce VMT estimates. In other words, AADT statistics alone can provide a reasonably accurate estimate of route VMT if other data sources are not available but AADT statistics alone cannot provide an estimate of volume under congested conditions.

9.6 System Delay Metrics Comparison

Freeway system delay metrics measure vehicle delay in the systematic point of view within a certain time and space. The time has been defined as one-year 5AM to 10PM normal weekdays, and the space is limited to one basic segment in this study. These metrics would take either travel time or combination of travel time and flow rate into account, and measure prevalence or severity of congestion, or both of them. Please note that all volumes used in these metrics are converted to passenger cars.

9.6.1 System Delay Metrics

9.6.1.1 Annual Delayed Hours

Annual Delayed Hours (ADH) is a straightforward metric that reveals the prevalence of real congestion. The delayed hours are defined as time with speed under the CST, as shown in the equation below:

$$ADH = \frac{Number\ of\ 15\ min\ data\ under\ CSF}{4} \tag{19}$$

It is expected that the ADH estimated from Traffic.com and INRIX data would be different because of the systematic speed difference between these two data sources. However, this metrics would provide direct information of prevalence of congestion.

9.6.1.2 Vehicle Hours of Delay

The total Vehicle Hours of Delay (VHD) is calculated based on only the data with speed under CST, as shown below:

$$VHD = \sum 15\ min\ Volume\ \times (15\ min\ Travel\ Time - 15\ min\ Speed\ Limit\ Travel\ Time) \quad (20)$$

Average VHD of all vehicles and of all delayed vehicles (VHD/Hr and VHD/Delayed Hr) are both important. The former looks at both prevalence and severity of system congestion in combination, while the latter only looks at the severity of congestion. They are calculated using the formulas below:

$$\frac{VHD}{Hr} = \frac{VHD}{Total\ Number\ of\ Hours\ of\ the\ Whole\ Year\ Data} \quad (21)$$

$$\frac{VHD}{Delayed} Hr = \frac{VHD}{ADH} \quad (22)$$

9.6.1.3 Volume-weighted Travel Time Index

The *Volume-weighted Travel Time Index* (VTTI) is calculated based on only the data with speed under CST, as shown below:

$$VTTI = \frac{\sum(15\ \mathrm{min}\ Volume\ under\ CSF \times 15\ min\ Travel\ Time\ Index\ under\ CSF)}{Total\ Volume\ under\ CSF} \quad (23)$$

where the Travel Time Index (TTI) is defined as:

$$TTI = \frac{Travel\ Time}{Speed\ Limit\ Travel\ TIme} \quad (24)$$

This metric only focuses on the severity of congestion, like the VHD/delayed hr does, but weights volume much less than speed or travel time. The VTTI would have richer information about system delay than Travel Time Index (TTI) does, since the former weighted travel time by volume.

9.6.2 Metrics Comparison Results

9.6.2.1 Metrics Comparison from the Ideal Site

System delay measurement metrics along with the volume estimation method are tested at two sites across four years from 2009 to 2012 (only January to May 2012). According to the method recommended above, Critical Speed Threshold (CST) and FFS selection results from these sites are listed in Table 9.6.

Table 9.6. Free Flow Speed (FFS) and Critical Speed Threshold (CST) Selection.

	Westbound				Eastbound			
	2009	2010	2011	2012	2009	2010	2011	2012
FFS	70	70	65	65	65	65	65	65
Traffic.com CST	52	53	49	52	52	52	51	54
INRIX CST	49	53	58	60	49	49	54	62
CST Selected	52				52			

The minimum of CST from Traffic.com and INRIX speed data are recommended for CST to compare the metrics results. Also, CST should not change significantly across year when road conditions and driver behaviors are believed to be consistent. Please note some significant differences of CST from Traffic.com speed and INRIX speed has been noticed. This difference may be because of systematic errors, unexpected queue spill back, etc. that cause speed data to be different. Therefore, a uniform CST of 52 mph for both directions, the lower value of average

CST from Traffic.com and INRIX across years, is recommended for metrics calculation and comparison, which ensures a fair comparison of the real congestion regime.

Metrics comparison results are listed in Table 9.7 and

Table 9.8 below. The error rate compares metrics calculated from estimated volume versus those from Traffic.com actual volume and speed. Error rates within or barely within 10% are marked bold.

Table 9.7. Metrics Comparison Results from the Ideal Site Westbound.

		System Delay Metrics Comparison Results - 040390WB				
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	NC Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
2009	VTTI	2.317	2.198	2.761	2.370	2.353
	Err Rate	0.00%	-5.15%	19.16%	2.26%	1.54%
	TTI	0.970		0.989		
	Err Rate	0.00%		2.03%		
	VHD/Hr	0.711	0.779	0.843	0.978	0.930
	Err Rate	0.00%	9.60%	18.61%	37.63%	30.83%
	VHD/Delayed Hr	82.10	76.48	92.87	82.50	78.43
	Err Rate	0.00%	-6.84%	13.12%	0.49%	-4.48%
	ADH	45.00		52.25		
		System Delay Metrics Comparison Results - 040390WB				
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	NC Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
2010	VTTI	2.201	2.172	2.522	2.466	2.432
	Err Rate	0.00%	-1.34%	14.57%	12.05%	10.48%

	TTI	0.965		0.974		
	Err Rate	0.00%		0.93%		
	VHD/Hr	0.623	0.644	0.704	0.767	0.719
	Err Rate	0.00%	3.31%	12.94%	23.20%	15.42%
	VHD/Delayed Hr	75.19	77.68	80.90	88.24	82.67
	Err Rate	0.00%	3.31%	7.59%	17.36%	9.95%
	ADH	35.75		38.25		
2011	VTTI	2.578	2.352	2.374	2.540	2.541
	Err Rate	0.00%	-8.79%	-7.92%	-1.48%	-1.44%
	TTI	1.015		0.960		
	Err Rate	0.00%		-5.42%		
	VHD/Hr	1.261	1.274	0.803	0.842	0.803
	Err Rate	0.00%	0.98%	-36.31%	-33.21%	-36.37%
	VHD/Delayed Hr	99.30	100.27	75.57	94.99	90.50
	Err Rate	0.00%	0.98%	-23.89%	-4.33%	-8.86%
	ADH	54.75		39.00		
		System Delay Metrics Comparison Results - 040390WB				
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	NC Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
2012 Six Month	VTTI	2.068	2.032	2.365	2.277	2.244
	Err Rate	0.00%	-1.73%	14.36%	10.13%	8.51%
	TTI	1.013		0.943		
	Err Rate	0.00%		-6.95%		
	VHD/Hr	0.685	0.657	0.628	0.687	0.639

	Err Rate	0.00%	-4.13%	-8.31%	0.25%	-6.74%
	VHD/Delayed Hr	69.33	66.47	77.58	83.16	77.36
	Err Rate	0.00%	-4.13%	11.90%	19.95%	11.58%
	ADH	21.50		18.25		

Table 9.8. Metrics Comparison Results from the Ideal Site Eastbound.

		System Delay Metrics Comparison Results - 040390EB				
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	NC Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
2009	VTTI	2.887	3.134	3.006	2.896	2.824
	Err Rate	0.00%	8.56%	4.11%	0.30%	-2.20%
	TTI	0.994		0.987		
	Err Rate	0.00%		-0.75%		
	VHD/Hr	0.624	0.663	0.797	0.903	0.814
	Err Rate	0.00%	6.20%	27.74%	44.72%	30.52%
	VHD/Delayed Hr	96.74	102.73	98.27	111.33	100.41
	Err Rate	0.00%	6.20%	1.58%	15.09%	3.79%
	ADH	28.50		35.75		
2010	VTTI	2.922	2.655	2.898	2.812	2.801
	Err Rate	0.00%	-9.16%	-0.83%	-3.76%	-4.16%
	TTI	1.022		0.971		
	Err Rate	0.00%		-4.99%		
	VHD/Hr	0.725	0.782	0.674	0.797	0.759
	Err Rate	0.00%	7.83%	-7.03%	9.97%	4.66%
	VHD/Delayed Hr	109.45	118.02	94.58	111.88	106.48
	Err Rate	0.00%	7.83%	-13.58%	2.22%	-2.71%
	ADH	28.50		31.25		

		System Delay Metrics Comparison Results - 040390EB				
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	NC Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
2011	VTTI	2.780	2.418	3.081	2.985	2.963
	Err Rate	0.00%	-13.05%	10.83%	7.36%	6.58%
	TTI	1.055		0.959		
	Err Rate	0.00%		-9.07%		
	VHD/Hr	1.030	1.062	0.974	1.086	1.015
	Err Rate	0.00%	3.15%	-5.46%	5.46%	-1.49%
	VHD/Delayed Hr	106.31	109.66	110.60	123.37	115.25
	Err Rate	0.00%	3.15%	4.04%	16.04%	8.41%
	ADH	41.75		38.75		
2012 Six Month	VTTI	2.787	2.817	3.178	3.092	3.063
	Err Rate	0.00%	1.07%	14.02%	10.96%	9.92%
	TTI	1.377		0.946		
	Err Rate	0.00%		-9.86%		
	VHD/Hr	1.377	1.352	1.090	1.518	1.403
	Err Rate	0.00%	-1.85%	-20.88%	10.21%	1.83%
	VHD/Delayed Hr	114.12	112.01	118.72	135.48	125.18
	Err Rate	0.00%	-1.85%	4.03%	18.71%	9.69%
	ADH	26.25		24.75		

The error rates of ALL metrics results with speed from Traffic.com and volume estimated from Traffic.com speed are within 10% (except 2011EB, being -13.05%), which indicates that ALL metrics, when looking at the whole year average, are compatible with the volume estimation method proposed in this chapter. The average of whole year helps to cancel out internal errors during volume estimation. However, with speed from INRIX and volume estimated from INRIX speed, only Volume-weighted TTI (VTTI) could always generate error rate within 10% (except 2010WB, being 12.05%).

Traffic.com gathers speed data from fixed location sensors while INRIX gathers from probe vehicles within the segment. The speed difference from these two data sources directly leads to the difference in calculation results of Annual Delayed Hours (ADH) that is defined as annual number of hours below the Critical Speed Threshold (CST). The difference of ADH would then be reflected in metric VHD/Hr since the VHD are calculated only with speed below CST while the total hours for both data sources should be very close. The VHD/Delayed Hr, however, would not be affected by the difference of ADH. The speed difference would also affect the volume estimation. This impact would be magnified for both VHD metrics, since both volume and delay comes from speed.

Both VTTI and VHD/Delayed Hr measure the severity of congestion, but the former weights volume less than does the latter. This is the reason that VTTI is the most robust metric even when comparing from different data sources. Nevertheless, ADH could directly reflect prevalence of congestion, and VHD/Hr could offer information on both severity and prevalence of congestion, across years from the same data source with no change in data collection scope, quality, technique, etc.

Metrics calculated from AADT model with NC urban default time-of-day profile would generally generate error rate around 15% and always higher than those from AADT model with local profile. For the AADT model, it is always recommending that the temporary volume data be collected to fit the local volume profile if condition permits. The reason is that the demand profile may overestimate volume during peak hours and this becomes even worse when the congestion is severe.

A fitted model would not always generate lower error rate when compared to the default *HCM* model for metrics calculation. The fitted model would fit the actual Traffic.com data better than the default *HCM* model does, but when it comes to comparison between Traffic.com and INRIX in terms of delay metrics, the promotion becomes insignificant. Generally, the hybrid *HCM*-AADT volume estimation model would use around 20% estimations from the default *HCM* model (or around 80% from AADT model since the minor estimates of these two models are used as final volume estimates) if the default *HCM* model were applied, but around 50% estimations from the fitted model if an *HCM*-based model were fitted.

9.6.2.2 Metrics Comparison from Other Sites

The volume estimation method and system delay metrics may be compatible to the situation that speed difference from both data sources becomes larger and conditions within segment become unstable and complicated. Sites, not as ideal as 40390, such as 40300WB with grade, 440200EB near a lane drop and 440210EB being a short internal segment, are tested for the volume estimation method and all metrics.

Traffic.com station 40300WB is a long basic segment on I40 near the Harrison bridge, Cary, NC so that a significant grade may affect traffic characteristics; 440200EB is on I440, near Western Boulevard, Raleigh, NC and near a lane drop and thus driver behaviors may be different from that on the ideal basic segment; 440210EB is on I440 near Jones Franklin Rd, Raleigh, NC that is an internal segment within interchange so that INRIX may not have enough probe data to form a decent speed dataset. The metrics results are listed in Table 9.9.

Table 9.9. Metrics Comparison Results from Other Sites.

		System Delay Metrics Comparison Results			
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
040300WB 2010	VTTI	2.237	2.324	2.242	2.177
	Err Rate	0.00%	3.89%	0.20%	-2.67%
	TTI	1.000		0.971	
	Err Rate	0.00%		-2.93%	
	VHD/Hr	1.526	1.559	2.226	2.023
	Err Rate	0.00%	2.17%	45.85%	32.60%
	VHD/Delayed Hr	171.22	174.94	162.46	147.70
	Err Rate	0.00%	2.17%	-5.11%	-13.74%
	ADH	39.50		60.25	
440200EB 2010	VTTI	2.105	2.146	2.076	2.077
	Err Rate	0.00%	1.95%	-1.40%	-1.34%
	TTI	0.976		0.910	
	Err Rate	0.00%		-6.77%	
	VHD/Hr	0.217	0.220	0.186	0.182
	Err Rate	0.00%	1.18%	-14.13%	-16.11%
	VHD/Delayed Hr	21.19	21.44	18.84	18.41
	Err Rate	0.00%	1.17%	-11.08%	-13.13%
	ADH	45.25		43.50	

		System Delay Metrics Comparison Results			
	Speed data Source	Traffic.com	Traffic.com	INRIX	INRIX
	Flow data Source	Traffic.com	Local Profile AADT & HCM	Local Profile AADT & HCM	Local Profile AADT & Fitted
440210EB 2010	VTTI	2.092	2.105	1.881	1.876
	Err Rate	0.00%	0.65%	-10.08%	-10.30%
	TTI	1.016		0.910	
	Err Rate	0.00%		-10.39%	
	VHD/Hr	1.269	1.271	0.966	0.919
	Err Rate	0.00%	0.17%	-23.83%	-27.54%
	VHD/Delayed Hr	34.14	34.20	28.96	27.54
	Err Rate	0.00%	0.17%	-15.20%	-19.33%
	ADH	160.75		144.50	

Results reveal that error rates of ALL metrics results with speed from Traffic.com and volume estimated from Traffic.com speed are within even 5%. This means the volume estimation method and system delay metrics are not just adaptable to ideal basic segments. It is still true that only VTTI could generate error rate within 10% when comparing metrics with speed from INRIX and volume estimated from INRIX speed to metrics from actual Traffic.com data. Grades may cause speed difference from Traffic.com sensor and INRIX probe vehicles and thus the ADH, known from 40300WB. Lane drop may not be a problem if only a few drivers actually use the lane being dropped within the segment, like the situation in 440200EB. Internal short segments may decrease the quality of INRIX speed data but not as severe as to cause lots of missing reports, known from 440210EB.

9.6.3 Delay Estimation Summary and Recommendations

Key findings of the investigation and development of methods to estimate delay from detection that provides speed/travel time observations but no volume measurements include:

- The system delay metrics, VTTI, VHD and ADH, can be estimated based on the volume estimation model.
- Estimated delay metrics are more robust if they are aggregated to one year and calculated from a single data source.
- Even at locations where significant speed difference were observed between Traffic.com and INRIX, the error rate for the delay metric VTTI could still be within 10%. This is because the VTTI is not as sensitive to volume and thus not as sensitive to the speed difference between data sources. However, the other metrics may be significantly affected by speed errors.

Recommendations for implementing delay estimation for areas with no volume detection include:

- A local profile (temporal variation across weekdays and weekends) is necessary for the AADT model because a general default demand profile will be biased for volume estimation, especially for heavily directional commuting routes. These profiles could be obtained either from the Traffic Survey Unit's ongoing count program or a special data collection effort.
- The investigations undertaken on this project indicate that there would likely be insufficient marginal benefit from fitting local *HCM*-based speed flow models for the delay metrics. The hybrid *HCM*-AADT model performs well in general while the fitted models did not consistently generate a lower error rate.
- In cases where is it desirable to fit an *HCM*-based model, a minimum data series of one-year speed and volume data collection is recommended. A full year's data set will avoid seasonal bias, and the fitting data set must be long enough to provide an adequate number of steady-state observations after mixed state and anomalous observations have been filtered out.
- The volume estimation method and delay metrics can be applied to non-ideal segments, such as segments with significant grade, segments near lane adds/drops, short segments

within interchanges, etc. However, higher error rates should be expected in such locations.

- In light of the foregoing findings and recommendations, the delay metrics estimated for routes, regional or area networks, and entire system networks will be most valuable for comparison over time to assess improvements in delay for the specific route or network. Given the inherent error in volume and delay estimation in the absence of volume observations, the resulting metrics should not be considered to be highly accurate absolute measures of traveler delay.

CHAPTER 10. TASK 9 – FRAMEWORK FOR ESTIMATING LIFECYCLE MOBILITY VALUE

The idea for this task sprung from a desire for NCDOT to have a way to analyze the lifecycle impact of major system improvements that result in temporary degradation of mobility during the construction phase but provide significant improvement in mobility over the useful life of the improved facility. At a conceptual level, the project team recommends the following framework:

Step 0 – Inputs to the process include a fully defined improvement project or set of alternative projects. This full project definition must include details on how the project(s) will be staged and how the construction work zone will be configured for each stage. The study area must also be defined. The study area must be sufficient to include all routes that will be impacted to a measurable degree but not so large as to smooth out the impacts across unaffected links and routes.

Step 1 – For the project or for each alternative project the following milestone dates must be set:

- Beginning of construction
- Transition to each project stage
- Completion of project
- End of project improvement useful life

Step 2 – Traffic demand levels must be estimated for each time frame between the Step 1 milestones. If necessary, multiple demand periods must be estimated for long time frames. Multiple demand period are likely to be needed at least for the time between the completion of the project and the end of the useful life of the project improvements.

Step 3 – Model the operations within the study area for the no build case and for all defined project alternatives. If travel time reliability is to be included in the comparative analysis, then a modeling tool that can produce a reasonable, unbiased set of travel times over each demand period must be used.

Step 4 – Construct travel time distributions for the no build and project alternatives and calculate the appropriate mobility and reliability metrics.

Step 5 – Compare and summarize the mobility impacts of each alternative.

Step 6 – If acceptable factors exist, the operational mobility impacts can be converted to monetary value for the no build and each alternative. Factors are readily available for delay. However, the research is ongoing and there is no consensus to this point on how to value travel time variability in relation to average travel time. As results come available for projects such as SHRP 2 L05 *Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes* it will hopefully be possible in the future to convert reliability impacts into monetary value in addition to expected overall delay.

This general framework is not be fully enabled without the modeling tools necessary to conduct Step 3. There are two ongoing research and modeling tool development threads that hold promise. First is the mesoscopic, dynamic traffic assignment thread. This class of modeling tool would allow network level analysis of the entire study area as defined in Step 0. Research on methods to model capacity-side variability in this class of models was conducted in SHRP 2 C05 *Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs*.

A second thread involves the FREEVAL family of modeling tools originating with the *Highway Capacity Manual*. A version that explicitly models travel time variability of a defined *reliability reporting period* (FREEVAL-RL) is being developed under SHRP 2 L08 *Incorporation of Travel Time Reliability into the Highway Capacity Manual*. A version that explicitly models work zone operations was developed for NCDOT under Research Project 2010-08 *Corridor-Based Forecasts of Work-Zone Impacts for Freeways and Multi-lane Highways* and development of an arterial work zone version is underway under NCDOT Research Project 2013-09 *Delay and User Cost Estimation for Work Zones on Urban Arterials*. In the future, the features of these versions will hopefully be merged. Although route-based, FREEVAL could provide effective modeling if coupled with a methodology to create reasonable diversions.

Although implementation of the lifecycle mobility value framework is not possible yet in terms of validated tools for estimating travel time reliability, the framework can be implemented in an abridged manner to produce expected delay estimates and corresponding travel time delay value using currently available tools. The results from this type of analysis would have definite comparative value even though the results would not include the impacts of non-recurring severe weather and incident events. Based on results from NCDOT Research Project 2012-36 *Work Zone Traffic Analysis & Impact Assessment* the project team's current recommendation would be to use the DTALite software tool for this analysis. If a scenario-based reliability analysis framework like the one developed for FREEVAL-RL is incorporated in future versions, then DTALite could become a network level modeling tool for full implementation of the lifecycle modeling value framework.

CHAPTER 11. TASK 10 – RECOMMENDATIONS FOR USES BEYOND MOBILITY PERFORMANCE MEASUREMENT

The main area of use envisioned for the findings, recommendations, and products of this research beyond the primary purpose of mobility performance assessment was traveler information. However, one of the key understandings that has come into ever sharper focus over the past two years of reliability monitoring and performance assessment research is that system-level performance and travelers experience of the transportation network, although related, are very distinct and must be kept clearly separate to avoid confusion.

This important distinction is made clear by considering the official definition of the New Zealand Transport Agency (NZTA), namely that "Trip time reliability is measured by the unpredictable variations in journey times, which are experienced for a journey undertaken at broadly the same time every day. The impact is related to the day-to-day variations in traffic congestion, typically as a result of day-to-day variations in flow. This is distinct from the variations in individual journey times, which occur within a particular period." (*33*) Trip time reliability assess by sampling across many days at the same time period (consistent with the NZTA definition) would be useful information to travelers. Even in this case however, it would be important to communicate that this information would not precisely apply to individual travelers if derived from time period sampled data. This is because time period samples would yield trip time reliability for a hypothetical driver who traveled at the space mean speed for each routine time of day, day of week trip. Therefore, individualized trip time reliability information, which is the type information that would be most useful to travelers, is likely to be provided in the future through private companies based on crowed sourced data. An example of one such company that experienced significant growth during the course of this research project is the free social GPS application Waze created by Waze Mobile.

The metrics investigated and evaluated in this project will therefore have value almost exclusively as route and system level performance measures. It is possible that longitudinal analysis of these metrics would be useful to large commercial interests for location decisions with significant transportation logistics considerations. The project metrics do not however align with the NZTA definition of evaluating travel times for specific time periods over many days. Even so, the data will be available for this kind of analysis. Such finely specified time of day, day of week reliability measures are likely to be more complex than is appropriate for the kind of system-level performance measurement envisioned by this research project. Also, as mentioned above, time of day, day of week travel time reliability statistics based on time sample averages are also not likely to be the best source of reliability information for individual traveler trip decisions. The NZTA is beginning to use sample-based time period travel time reliability in economic evaluation of improvements and travel demand modeling. Project SHRP 2 L05 *Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes* is also working to provide methodologies to allow DOTs and MPOs to "fully integrate mobility and reliability performance measures and strategies into the transportation planning and programming processes." Therefore, transportation system strategic planning and programming is likely to be the key application area for mobility and reliability performance measurement beyond the operational and system management uses initially served by the NCDOT's mobility and reliability monitoring program.

CHAPTER 12. SUMMARY OF FINDINGS AND CONCLUSIONS

The chapter provides the project's key findings and conclusions summarized by task. The project team's recommendations based on these findings and conclusions are summarized in the following chapter.

12.1 Task 1 – Data Source Cross-Checking

Findings and conclusions for the comparative analysis between five bi-directional locations with INRIX and Traffic.com data coverage were –

- Systematic speed differences occurred at nearly all study locations
- Observed mean speed difference values were unique to each site
- Speeds from GPS floating car runs more closely matched INRIX speeds at the I-40 and Davis Drive locations where there were significant speed differences between INRIX and Traffic.com
- Systematic error in the Traffic.com speeds is present at the I-40 and Davis Drive Traffic.com sensors in both directions

Findings and conclusions for the investigation of speed-flow relationships using fused INRIX and Traffic.com data were –

- Speed-flow relationships using fused data did not maintain the traditional expected shape
- Expected speed-flow relationship form was in plots using only Traffic.com data
- Speed-flow relationships with fused data displayed more scatter in the congested region
- Non-systematic speed differences were observed that indicated two possible sources of error in the INRIX speed data, namely:
    - INRIX lags behind Traffic.com by one reporting period for slowdowns and by up to 60 minutes for speed recovery
    - A 90-minute period was observed where five minute INRIX speeds were much lower than one minute speeds

- Systematic differences in speed between the two data sources can be easily taken into consideration if the mean speed difference is known
- Non-systematic discrepancies require further detailed study

12.2 Task 2 – Data Cleansing and Filtering

One-minute resolution data for the full year 2010 and for 140 INRIX segments were used to investigate data quality issues. These INRIX segments correspond directly to the segments needed to construct the eight high priority routes provided by the NCDOT. The data were obtained from the data repository maintained by RITIS. Key findings were –

- 2,815,540 one-minute observations were missing out of a total of 73,584,000 (3.83% missing)
- 69.42% of the missing time gaps are only one minute (one interval) long
- 95.83% of the time gaps are less than or equal to 10 minutes long
- Only 1.06% of all the time gaps are greater than 3 hours long
- According to RITIS the majority of the missing one-minute data are due to communication errors or disruptions with INRIX

12.3 Task 3 – Route Travel Time Estimation and Performance Assessment

A robust algorithmic method for creating stitched synthetic trajectories from INRIX data was developed. Key findings and conclusions from the development and testing of this travel time stitching algorithm were –

- Estimation error for the proposed stitching method was lower for all travel time metrics across all factors when compared to the typical simultaneous method
- Detailed analysis of six congested periods identified that the stitched method more closely followed observed travel times during congestion times
- The stitched travel time estimation method is important for mitigating the impact of the inherent lag in the INRIX link travel time data identified in Task 2

- The time of day average travel time from the simultaneous method lagged behind the stitched method in reporting a peak in travel times for the two longest routes
- In-depth examination found that the amount of lag between peaks was a function of the aggregation period, length of the route, and the location of the most highly congested links in the route. Specifically,
  - Increasing the aggregation period decreased the lag
  - Longer routes increased the lag
  - The presence of highly congested links close to the end of the route increased the lag
- Application of longer aggregation periods with simultaneous route travel times may be acceptable for planning or operations purposes provided the small differences do not increase dramatically when looking at individual days of the week compared to all weekdays together

12.4 Task 4 –Temporal Specification for Performance Metric Calculation

The project team considered and evaluated alternate methods for specifying the temporal basis for mobility and reliability performance metric calculation. Key findings and conclusions were –

- Performance metrics will evidence a significant and abrupt shift when there is a major change in operational characteristic of a key route or subnetwork
- A level one year period sample will yield metrics that are not affected by seasonal variation
- Detailed evaluation requirements will inform the selection of most appropriate data sample
- Performance metrics are best viewed as special descriptive statistics calculated from well-designed samples
- The time series nature of exponentially-weighted averaging does not support the focus of analysis period sampling

12.5 Task 5 – Signal System Data Asset Assessment

The data resident in the OASIS signal system software deployed by the NCDOT was studied in detail. The ACTRA central control system software used by the City of Raleigh was also investigated for data availability thought to a lower level of detail. Key findings and conclusions were –

- Useful data are currently available within signal system control software but with limitations
- Signal control software systems were designed with the following viewpoints –
  - data were for sole purpose of tactical operation of user-established signal timing plans
  - system logs and reports were for operational monitoring
- The viewpoints above create issues of accessibility and accuracy
- In both the OASIS and ACTRA systems, detailed detector data is stored locally in intersection and field master controllers in relatively low capacity memory buffers
- Therefore, separate manual or semi-automated protocols must be established to download the data for archiving and analysis at frequent intervals
- For the NCDOT's OASIS-based closed loop systems, this process involves establishing a dial-up connection at regular intervals to field master controllers using Econolite's TransLink software
- OASIS uses a hard-coded process of rounding down occupancy to an integer percentage and speed to integer miles per hour
- Rounding down is neither precise nor accurate enough to provide sufficiently useful information
- Additional accuracy problems result from more complex computational issues such as the way OASIS handles vehicles that span reporting interval boundaries

12.6 Task 6 – NCDOT Signalized Arterial Case Study – Analysis and Methodology

The project team analyzed a prior field study conducted by the NCDOT to assess the relationship between the OASIS average effective vehicle length parameter and the accuracy of corresponding vehicle speed estimates. Key findings and conclusions were –

- Setting a more appropriate average effective vehicle length can improve the speed estimates that the OASIS system derives from single loop detectors
- Speed improvement results were not entirely consistent
- Inconsistency in the speed accuracy testing could be partially explained by a non-representative vehicle sample and/or the OASIS procedure of rounding all speeds down

- Nonetheless, the NCDOT field study results indicate that an average effective vehicle length in the range of 18 feet should provide reasonable results
- The similarity between the 16 foot and 18 foot average effective vehicle length results also implies that the 20 foot default value used by OASIS should also provide reasonable results in many situations

12.7 Task 7 – Testing and Implementation of Performance Measure Refinements and Enhancements

A detailed evaluation of the performance measures was conducted on data from five locations. The five study locations provide data from six states plus the District of Columbia. Key findings and conclusions were –

- Travel time reliability measures should provide additional information to managers and decision makers, rather than restating typical performance measures
- Most common reliability measures are well correlated to the average travel rate
- Detailed analysis of the relationships between each measure and the average travel rate revealed that the *Skew* statistic is effective in identifying segments or routes with non-recurring congestion that is disproportionally larger than recurring congestion
- The *Semi-Standard Deviation* statistic also appears to indicate both the frequency and severity of non-recurring congestion and is recommended in SHRP2 L02 as a useful performance measure
- Although other measures that have been more thoroughly researched, such as the 95^{th} percentile travel time (or PTI when indexed), show high correlation to the average performance, their use can still inform a preliminary analysis
- No single measure appears to be ideal, and each measure is calculated from a part of or the entire travel time distribution

12.8 Task 8 – Framework for Extending Vehicle Miles Traveled Estimates

This task involved three elements: 1) development and assessment of a method to estimate volume with only INRIX speed and/or AADT as an input, 2) development and assessment of a method to estimate VMT, and 3) development and assessment of a method to estimate volume based delay metrics. All of these methods were designed to be applied in locations where no permanent volume detection is available. Specifically, they are envisioned for NC locations with only INRIX data available.

Key findings and conclusions for volume estimation are –

- The foundation is determining a critical speed threshold for identifying congested time intervals and then applying a congested regime model for volume estimation
- During uncongested periods, speed provides little or no information useful for estimating corresponding volume
- For overall VMT estimation, AADT estimates from the NCDOT Traffic Survey Unit are sufficient
- Both methods for determining a critical speed threshold (CST) for identifying congestion were effective
- Investigated methods were 1) a histogram-based method and 2) a simple speed drop threshold method
- The histogram-based method is less susceptible to the risk of being overly conservative in congestion regime identification
- Both tested models -- the hybrid AADT- *HCM* model and the *HCM*-based model fitted to local data – provided reasonable results
- If representative local data is available the *HCM*-fitted model will provide a more accurate speed flow relationship for volume estimation.

Key findings and conclusions for the VMT estimation were –

- A flow chart was developed to guide the selection of VMT estimation method based on data availability
- If AADT estimates are available between all ramps, VMT can be effectively estimated from AADT alone

Key findings and conclusions for the delay metrics investigation were –

- The system delay metrics, VTTI, VHD and ADH, can be estimated based on the volume estimation model.
- Estimated delay metrics are more robust if they are aggregated to one year and calculated from a single data source.
- The VTTI is not as sensitive to volume and thus not as sensitive to the speed difference between data sources
- VHD and ADH are likely to be significantly affected by speed errors

12.9 Task 9 – Framework for Estimating Lifecycle Mobility Value

A conceptual framework was developed for estimating the lifecycle mobility value of major transportation improvement projects. Key findings and conclusions of this effort are –

- Lifecycle timeframe must be accurately segregated into pre and post-construction periods
- Demand estimates will be needed throughout the timeframe
- Comparative mobility value will require modeling both the no-build and project scenarios across the lifecycle period
- Tools exist currently to model and estimate expected travel times
- Tools are still in development for modeling and estimating variability in travel times resulting from non-recurring congestion events and demand fluctuation
- Research is also ongoing regarding appropriate methods for valuing travel time variability

12.10 Task 10 – Recommendations for Uses beyond Mobility Performance Measurement

The project team considered uses beyond mobility performance measurement for the methods and metrics developed for the project. Key findings and conclusions are –

- Mobility and reliability performance metrics evaluated, developed, and tested under this project are not the best sources of traveler information
- Detailed reporting and analysis of these performance measures over time may have value for private sector users such as industrial or distribution center siting

- The performance measures presented in this research may provide useful information for travel demand modeling if applied to time period sampling that closing mimics the NZTA definition of trip time reliability from a traveler perspective
- Strategic planning and programming are likely to be the institutional processes to make use of the mobility and reliability performance metrics beyond the primary application of operational monitoring and management

CHAPTER 13. SUMMARY OF RECOMMENDATIONS

This chapter provides the project's key recommendations summarized by task. These recommendations are based on the findings and conclusions summarized in the previous chapter.

13.1 Task 1 – Data Source Cross-Checking

Task 1 project team recommendations are –

- The Traffic.com sensors for both the eastbound and westbound directions at I-40 and Davis Drive should be checked and recalibrated
- As needed, future comparative studies could be conducted either in a routine or ad hoc manor to check accuracy for Triangle locations covered by both INRIX and Traffic.com
- Data fusion linking INRIX and Traffic.com data is not recommended until further study can identify, filter, or adjust reported speeds that are subject to non-systematic error

13.2 Task 2 – Data Cleansing and Filtering

Task 2 yielded only one recommendation, namely that the presence of missing values be fully considered when calculating performance metrics. In some cases, imputation of missing values will not be necessary. However, in cases where the defined analysis period yields a small sample, say for example it is desired to determine the 95th percentile speeds for Mondays at 8:00 am for a one-year period. If all observations were available, the sample size would be 52. In this case it would not take many missing observations to have a severe impact on the sample 95th percentile estimate. Therefore, for such small sample analysis periods, full consideration of the impact of missing values may lead to a determination that it is necessary to impute values for the missing observations prior to generating the performance measure or sample statistic.

13.3 Task 3 – Route Travel Time Estimation and Performance Assessment

Task 3 also yielded a single recommendation. Based on the performance of the developed stitched trajectory route travel time estimation method, the project team recommends that NCDOT use this algorithm for all internally generated route travel time analyses and that NCDOT require that any third party provider of route travel time analyses use the algorithm or an equivalent method to estimate route travel times from segment travel times. The stitched travel time method will in all cases provide estimates that are much closer to the experience of transportation system users than will simplistic methods that do not use a rigorous method to simulate the trajectories of vehicles traveling along the route.

13.4 Task 4 –Temporal Specification for Performance Metric Calculation

The project team recommends that performance metrics be calculated on a properly designed sample that provides a sufficiently unbiased representation of the desired analysis period. Specifically, the project team's recommendations for temporal specification are –

- The desired comparative analyses period must be clearly defined
- The appropriate analysis period should then be specified based on the desired comparative analyses
- The assembled travel time data for the specified analysis period be considered a straightforward statistical sample for calculating metrics and for characterizing and analyzing the travel time distribution

In terms of changes to roadway segments that result in significant capacity changes, such as establishment of work zones and completion of major geometric improvements, the project team recommends that defined analysis periods should not span across such major changes in operational conditions

13.5 Task 5 – Signal System Data Asset Assessment

The project team recommends that NCDOT's ongoing interaction with its signal system software vendor (Econolite for OASIS or whatever future vendor may be selected) include the requesting and working toward improving –

- Ease of system data archival and access
- Data availability at a finer resolution than the current one-minute aggregation minimum
- Computational rigor in terms of accuracy and precision of derived system measures including detector speed, volume, and occupancy

13.6 Task 6 – NCDOT Signalized Arterial Case Study – Analysis and Methodology

The project team recommends that the NCDOT conduct additional field studies in locations where accuracy in the OASIS reported speed is important. The prior field studies, although conducted properly, were not sufficient to provide generalizable detailed conclusions. As noted in the findings above, the studies do support the general notion that speed estimates can be improved when a more appropriate value is set for average effective vehicle length. However, longer duration studies would be useful for setting accurate local values, and a sufficiently representative set of studies would be needed to support a change in the default average effective vehicle length parameter.

13.7 Task 7 – Testing and Implementation of Performance Measure Refinements and Enhancements

The project team makes the following recommendations regarding mobility and reliability performance metrics –

- Use of the relatively well-established reliability metrics, such as PTI, does have value and should continue. However, these traditional reliability metrics were shown to be highly correlated to the average travel rate and consequently to the TTI and therefore provide minimal additional information

- Even though FHWA has counseled against using statistical measures such as standard deviation because they may be difficult for non-statisticians to understand and interpret, the NCDOT should consider adopting, for internal use, either the *Skew* statistic or the *Semi-Standard Deviation* statistic. Although these are even more complex than the standard deviation, the project research showed that these metrics are effective in identifying locations where congestion is dominated by non-recurring rather than recurring congestion and in providing an indication of the relative magnitude of the non-recurring congestion events.
- Appropriate NCDOT personnel should also work to become comfortable evaluating and interpreting full representations of observed travel time distributions. No single metric or set of metrics can effectively capture all the important nuances present in real world travel time distributions.

13.8 Task 8 – Framework for Extending Vehicle Miles Traveled Estimates

The recommendations for Task 8 should be considered preliminary because volume estimation from speed-only data is an area of new research, and the efforts by the research team represents one of the first serious attempts at developing and validating these methods against contemporaneous, collocated volume detection. Continued research along these lines aimed at producing a robust and unbiased method for estimating volume when speed-only data is available is well-motivated and will hopefully continue. Three related subtasks were pursued under Task 8: 1) volume estimation, 2) VMT estimation, and 3) vehicle-based delay estimation.

Recommendation for volume estimation are –

- Data collected under inclement weather, construction, incidents, etc. should be filtered out. Visual analysis of speed-flow plots and data cleaning is necessary before volume estimation
- The histogram method for setting the critical speed threshold (CST) is preferred because it is based on observed data and is more robust than a simple speed threshold
- The appropriate *HCM* curve be selected for use with speed only data. Selection from speed data requires at least a half year of data to ensure sufficient observations near capacity.
- A local volume profile for AADT model is necessary for an accurate flow rate estimation. This profile should be based on at least two weeks of speed and flow data collection under

typical conditions. Data collection should be conducted in a month that provides average conditions, such as May or October.

- The default *HCM* curve for the hybrid AADT-*HCM* is acceptable because only the low speed, congested regime of the *HCM* curve is used.
- The fitted *HCM* speed flow relationships are significantly better than the default model. However, the fitted model requires at least half a year of speed-flow data to ensure sufficient information for model fitting. It is recommended that 100 steady state congested data points reasonably spanning a broad range of density levels be the minimum sampling requirement.

Recommendations for VMT estimation in the absence of volume detection are –

- If volume under congested conditions is also desired, then the VMT estimation flow chart given as Figure 9.6 should be used to determine the method likely to yield the most accurate results.
- If VMT estimation alone is desired (i.e. delay will not be estimated), the findings of the VMT estimation investigation confirm that using AADT data alone will provide sufficiently accurate VMT estimates and there is little value in applying more complex methods.

Recommendations for delay estimation in the absence of volume detection are –

- A local profile (temporal variation across weekdays and weekends) is necessary for the AADT model because a general default demand profile will be biased for volume estimation, especially for heavily directional commuting routes. These profiles could be obtained either from the Traffic Survey Unit's ongoing count program or a special data collection effort.
- The investigations undertaken on this project indicate that there would likely be insufficient marginal benefit from fitting local *HCM*-based speed flow models for the delay metrics. The hybrid *HCM*-AADT model performs well in general while the fitted models did not consistently generate a lower error rate.
- In cases where is it desirable to fit an *HCM*-based model, a minimum data series of one-year speed and volume data collection is recommended. A full year's data set will avoid seasonal bias, and the fitting data set must be long enough to provide an adequate number of steady-state observations after mixed state and anomalous observations have been filtered out.
- The volume estimation method and delay metrics can be applied to non-ideal segments, such as segments with significant longitudinal grade, segments near lane adds/drops, short

segments within interchanges, etc. However, higher error rates should be expected in such locations.

13.9 Task 9 – Framework for Estimating Lifecycle Mobility Value

The project team recommends that NCDOT look for an upcoming project to test and modify as necessary the framework described in Chapter 10. It will be valuable and instructive to go through the project of identifying the calendar break points between the major lifecycle time periods and to construct the necessary demand levels and timeframes. The framework can then be further tested by using a tool such as DTALite to estimate expected values for metrics such as overall vehicle delay and travel time indices. As validated methodologies emerge for assigning value to travel time variability and tools emerge that provide analysis period estimates of travel time variability, the NCDOT will then be prepared to fully implement the framework and thereby take impacts to travel time reliability into account in lifecycle mobility assessment.

13.10 Task 10 – Recommendations for Uses beyond Mobility Performance Measurement

The project team recommends that as mobility and reliability performance measurement become more established and accepted the NCDOT begin to consider and take steps to exploit strategic planning and programming uses of mobility and reliability performance metrics.

CHAPTER 14. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

14.1 Introduction and Deliverables

The project research among the implementable recommendations under each project task has produced the following key deliverables –

- A validated algorithm for creating stitched route travel times from segment-based speed data (Task 3)
- A preliminary formalized strategy for selecting the best method for estimating VMT when only speed data is available (Task 8)
- A preliminary framework for estimating the lifecycle mobility value for major system improvements (Task 9)

14.2 Travel Time Estimation Algorithm

This stitched route travel time algorithm is described in Chapter 4 to allow coding in any suitable programming or scripting language and provided as an Excel ready VBA script in Figure 4.9. If desired, the project team will also provide a ready to use Excel template file with the Figure 4.9 VBA script already embedded. This algorithm would be useful to the Traffic Systems Operations Unit in their ongoing efforts to bring mobility and reliability performance measurement to the forefront. The algorithm could ultimately be used in an internal enterprise mobility and reliability performance measurement system. It could also be used internally for special studies of important routes and/or to provide quality checks for route performance metrics provided by others. While the algorithm is simple to use, and Chapter 4 includes details on how to use the algorithm in its Excel implementation, the project team is eager to provide addition information and assistance as needed for interested NCDOT personnel.

14.3 VMT Estimation Strategy

The formalized route VMT estimation procedure selection flow chart provided in Figure 9.6 is part of the preliminary recommendations given within the general investigation of how to generate volume-based metrics for routes and subnetworks where only speed data is available. This is a very important line of research for the NCDOT because much of the state's network is now served only by INRIX. The INRIX data providing in these areas does not provide any volume data. Therefore, volumes must be imputed in some way if volume-based mobility and reliability metrics are to be generated. System delay estimates based on volumes imputed for speed-only locations hold much more potential value than do VMT estimates given that reasonable VMT estimates can be derived directly from the AADT data provided by the Traffic Survey Unit.

Given that the VMT and system delay estimation procedures described in Chapter 9 are both relatively complex and preliminary, the project team is eager for the Traffic Systems Operations Unit to experiment with these procedures and begin a discussion that will help to clearly define desired outputs from such procedures and the additional research and development efforts that are needed to enable such procedures to provide the desired outputs.

14.4 Lifecycle Mobility Value Framework

A preliminary framework for estimating the lifecycle mobility value for major system improvements is detailed in Chapter 10. As stated in the related recommendations in the previous chapter, the project team encourages the Traffic Systems Operations Unit to identify one or more projects to begin to test and modify the framework. The framework itself is not complex. However, it is likely that the process of defining the various demand and capacity condition timeframes within the overall project lifecycle will not be simple. Lessons learned during these trial applications of the framework will be important for molding the process into process that will provide useful and valid estimates of lifecycle value. As with the volume estimation related procedures, the trial applications will also help identify and define research and development needs.

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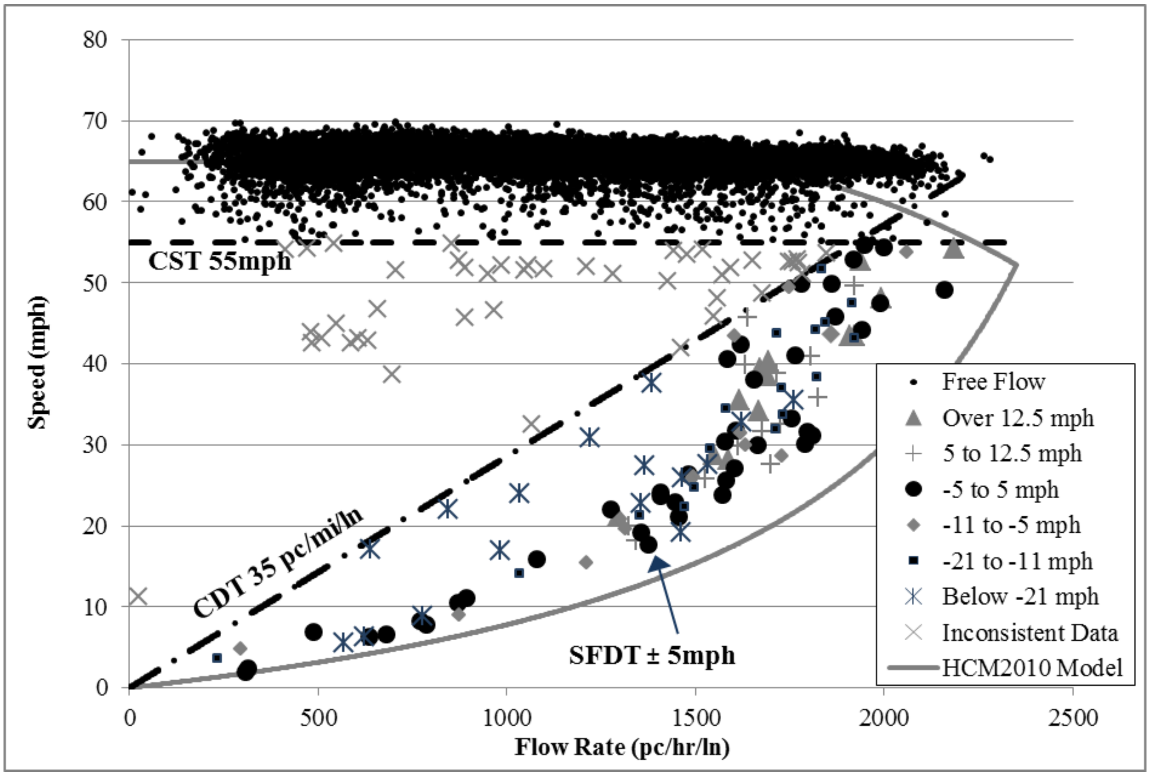
APPENDIX A. HCM-BASED SPEED FLOW FITTED MODEL

A.1 Data Selection Thresholds

Three fixed thresholds were defined to identify steady state congested observations, namely the Critical Speed Threshold (CST), Critical Density Threshold (CDT) and Speed First Difference Threshold (SFDT) for use in model fitting. CST has been defined above. This method avoids possible bias caused by capacity and jam density difference between the default *HCM* model and the specific site, and thus the fitted model represents the actual speed flow relationship much better than the default *HCM* models does, which is shown by the Traffic.com sensor data from the three sites.

Analysis of the study data revealed that a density threshold (CDT) is required to filter out inconsistent data with low speed and low volume that indicate either significant capacity reduction and degraded operations resulting from inclement weather, work zones, incidents or mixed state observations resulting from 15-minute periods that include both congested and uncongested traffic conditions. A threshold is also applied to the difference in speed from the previous observation (SFDT) to further distinguish stable congestion observations from observations that correspond to a mix of congested and uncongested conditions that may have passed the CST and CDT. The three thresholds are shown in Exhibit A.1 with Traffic.com speed flow data from station 040300 at westbound I 40 near Harrison Avenue.

Exhibit A.1 Typical Speed Flow Relationship with Thresholds at 040300WB



A.1.1. Critical Density Threshold

The Critical Density Threshold (CDT) is applied to filter out anomalous observations that pass the CST. These data are inconsistent with the *HCM* speed flow curve for reasons such as inclement weather, work zones, incidents, or mixed states of congested and uncongested flow within the observation interval. A density of 35 pc/mi/ln, the threshold that separates LOS of D and E in the *HCM* (*7*), is defined as the CDT. All observations with density less than the CDT are filtered out prior to model fitting. Previous research applied a CDT corresponding to the threshold between LOS of C and D to filter out low speed, low flow outliers (*27*). However, this paper recommends, based on analysis of the observational data, a higher CDT to strictly confine the model fitting observations to the oversaturated regime.

A.1.2. Speed First Difference Threshold

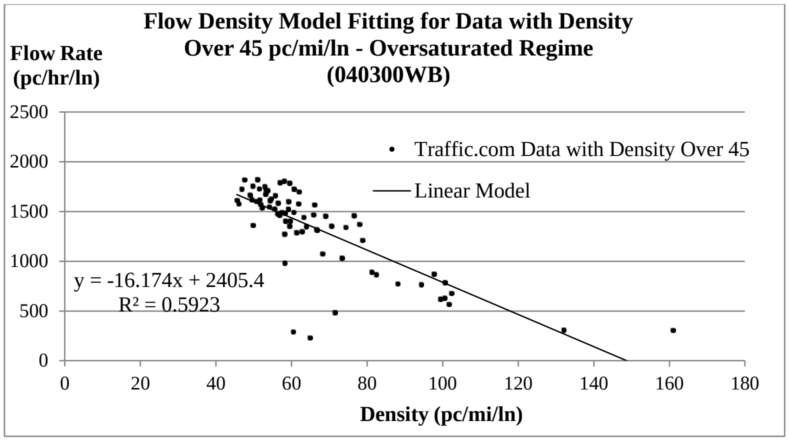
The Speed First Difference Threshold (SFDT) is used to distinguish the data points passing the CST and CDT that represent a single state within the congestion regime. The 15-minute observation interval ensures sufficient readings and corresponds to the HCM traffic equilibrium definition. However, a 15-minute interval can frequently include mixed state information during queue formation and discharge. Therefore the SFDT is used to identify stable congestion observations appropriate for fitting the HCM-based speed flow model. In the field data study, this threshold eliminated almost half of the observations that passed the speed and density thresholds. Therefore, a relatively large dataset, such as one year of data, is required for model fitting. The SFDT was set to retain observations whose speeds differ from the previous 15-minute observation by 5 mph or less. In this way, the SFDT filters out mixed state or unstable data that would lead to bias in the resulting fitted model.

A.2 Fitted Model Development Method

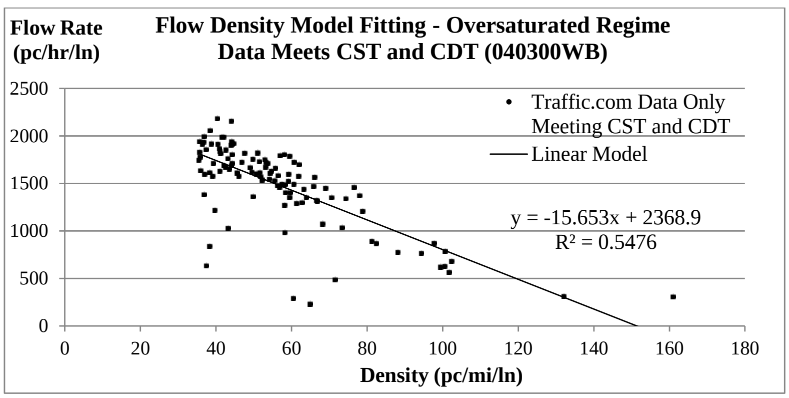
For a visualization of the three-threshold methodology, the observations passing the CST and CDT were grouped into five bins. The central bin represents the steady state observations according to the SFDT (absolute value of speed difference ≤5 mph). The remaining four bins were created as two bins on either side of the steady state bin with equal numbers of observations in each bin. A plot of the observations categorized in this manner is shown in Exhibit A.1. Preliminary analysis and trial model fitting at each site confirmed that only data within steady state bins provide a reasonable set of single state congested observations that is well-modeled by a linear oversaturated regime flow density model. Exhibit A.2 shows the comparison between model fitting results using (a) data with the HCM density threshold of 45 pc/mi/ln, (b) data that only pass the CST and CDT, and (c) steady state data that pass all three thresholds from Traffic.com station

040300 WB. The data that meet the *HCM* threshold appear to fit the linear flow density relationship reasonably well. But this threshold leaves some mixed state data points that could affect the model fitting. Also, the *HCM* threshold cut out some data with density slightly less than 45 pc/mi/ln that could actually better fit the linear model. The steady state data model has a significantly better goodness of fit in terms of R^2 and visually displays better fidelity in flow and density linearity than does the model fit to all data that only pass CST and CDT. The linear relationship is more clearly visible in the steady state data, making it easier to visually identify outliers, as shown in Exhibit A.2. Please note two data points, identified as outliers because of the apparent violation of the linearity in the flow density relationship, are removed from the steady state data set prior to model fitting as shown in Exhibit A.2c.

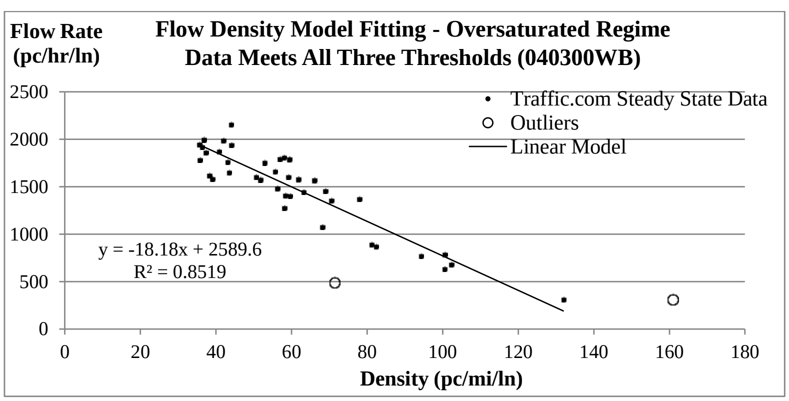
Exhibit A.2 Effects of Three Thresholds on Model Fitting.



a) Model Fitting for Only Data with Density Over 45



b) Model Fitting for Data Meeting CST and CDT

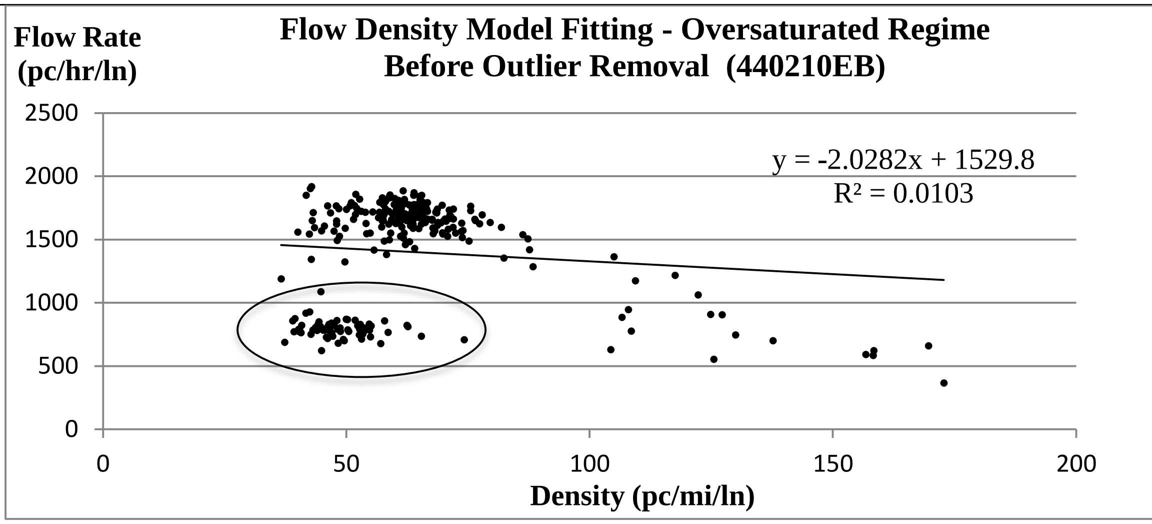


c) Model Fitting of Steady State Data Meeting All 3 Thresholds

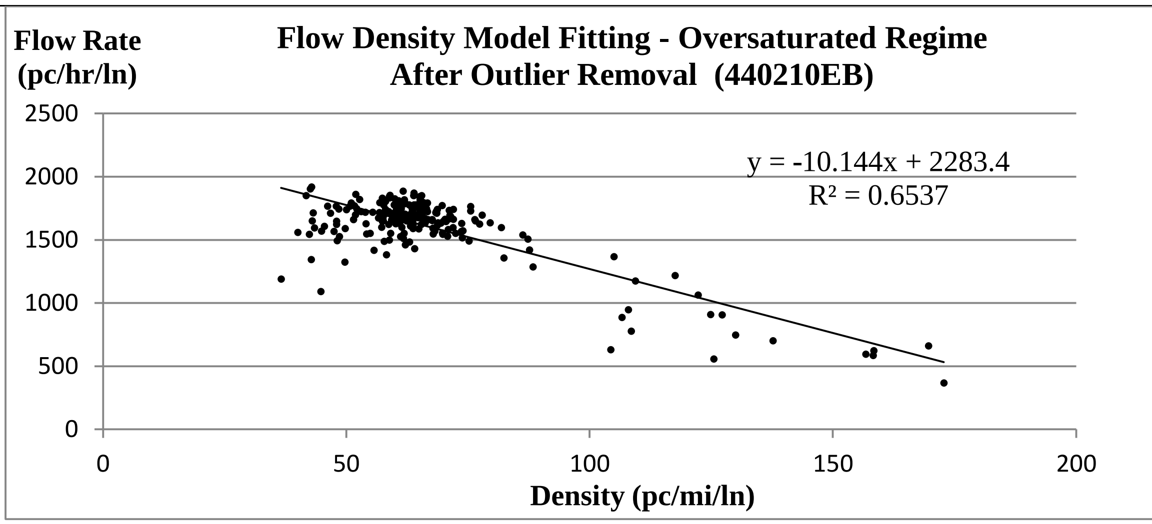
Exhibit A.3 shows the difference in model fitting before and after outlier filtering for site 440210EB. Exhibit A.3a shows a cluster of observations in the low flow, low-density region clearly separated from the primary data cluster. These data are near the density of 45 pc/mi/ln that is the density at capacity by definition of *HCM.* Thus, these data should show a flow rate near capacity. In this way, it is believed that the cluster is most likely because of capacity drop possibly caused by construction, inclement weather, or the like. This outlying cluster strongly influences the model fitting results and is the reason for a very low R^2. Detailed investigation reveals that these data points were continuously collected during 1/26/2010 to 1/29/2010 and are consistent with the effect that would be expected from the loss of a travel lane during this period. The available construction, incident or adverse weather documents were not sufficient to identify the cause. When this cluster of outlying observations is removed, a reasonable linear flow density model could be fitted with R^2 of 0.65.

The model fitting results from 040300WB and 440210EB indicates jam densities of around 140 and 225 pc/mi/ln, respectively. These fitted model values are very different from the *HCM* default of 190 pc/mi/ln. Therefore the fitted flow density relationships would be expected to generate better flow estimates from speeds than the default *HCM* model for these sites, especially under very heavy congestion.

Exhibit A.3 Flow Density Model Fitting Before and After Outlier Removed for Observations Passing all Three Thresholds.



a) Model Fitting before Outlier Filtering



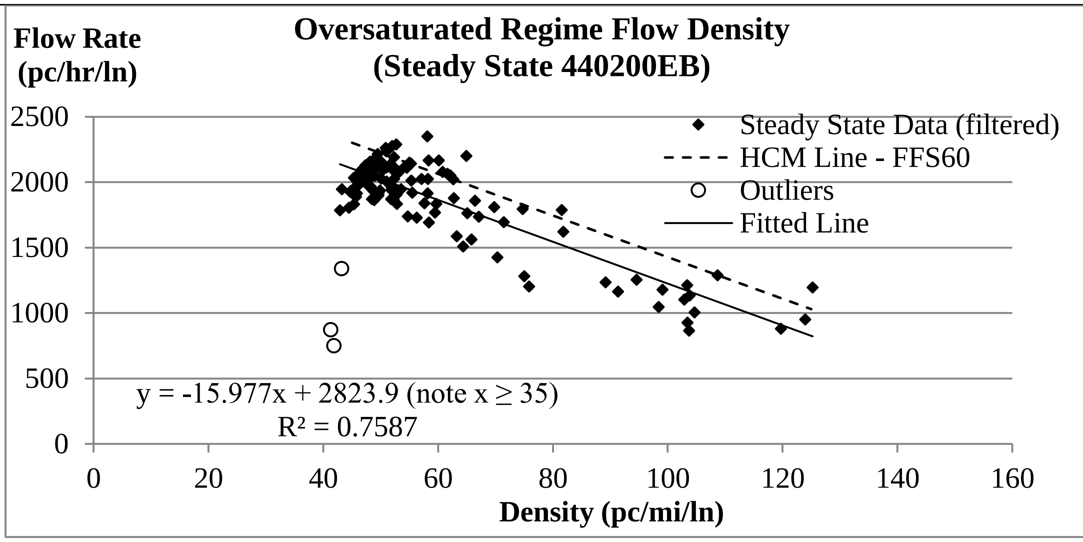
b) Model Fitting after Outlier Filtering

A.3 Fitted Model Comparison

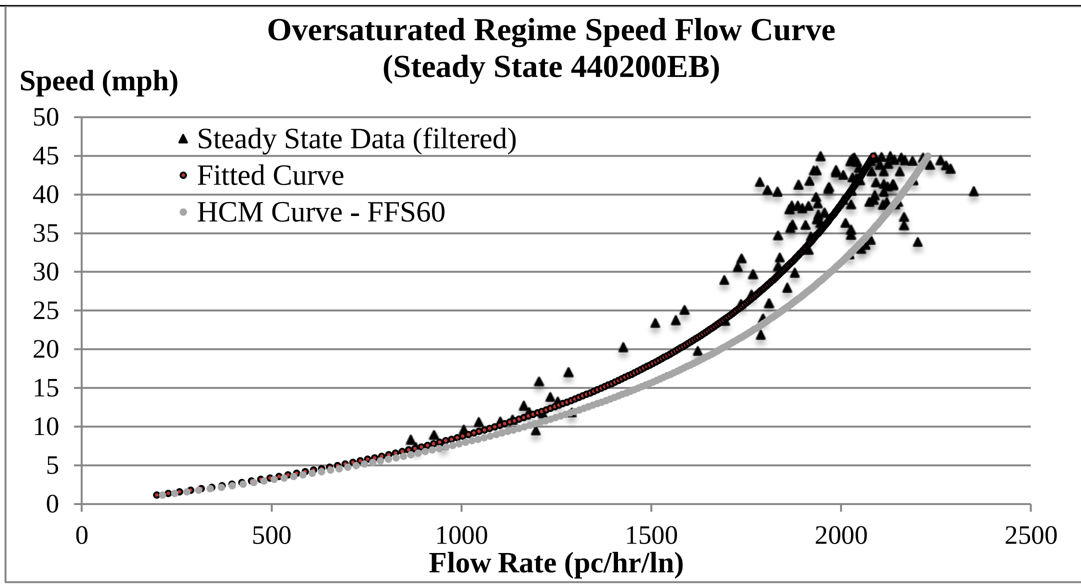
A.3.1. Improved Capacity Estimation

The capacity of a basic freeway segment in reality could be lower than the theoretical value of the *HCM* model for a variety of reasons. This capacity overestimation or underestimation by the *HCM* model would cause bias in speed flow relationship during congested regime, as illustrated by the station 440200EB shown in Exhibit A.4. Note that three outliers, apparently violating the flow density linearity, are filtered out during model fitting. The proposed *HCM*-based model is fitted to the steady state congested data, and thus should predict capacity that is slightly lower than the capacity at the maximum flow defined in the *HCM*. Exhibit A.4 shows that the fitted speed flow curve derived from the fitted flow density linear model has a clearly improved capability of representing the steady state congestion data and the freeway segment capacity than the default *HCM* model does. This improvement usually comes with the improvement in jam density that would be discussed later.

Exhibit A.4. Oversaturated Regime Speed, Flow and Density Relationship Comparison at 440200EB.



a) Oversaturated Regime Flow Density Relationships



b) Oversaturated Regime Speed Flow Relationships

The results of comparison of capacity from the HCM model and the fitted model to the average flow rate of the top 1% flow sample are shown in Table A.1. The fitted model represents steady state congestion, and thus generates the maximum queue discharge flow rate as its capacity. This value is expected to be lower than the maximum flow by *HCM* definition as capacity. This is proven by the results from the three study sites, shown in Table A.1. *HCM* models tend to overestimate capacity.

Table A.1. Capacity Comparison between the Top 1% and the HCM and Fitted Model Capacities.

	Avg. Speed at top 1% flows	Avg. Flow Rate at top 1% flows	Avg. Density at top 1% flows	FFS	HCM Capacity	Fitted Model Max Flow
040300WB	64.2	2070	32.3	65	2300	1965 (-15%)
440210EB	45.0	1895	42.1	55	2250	1865 (-17%)
440200EB	50.3	2280	45.3	60	2300	2145 (-7%)

* Avg. stands for average; Capacity from fitted model is calculated based on Avg. speed for the top 1% flow sample; the percentage difference in last column is calculated with respect to HCM capacity.

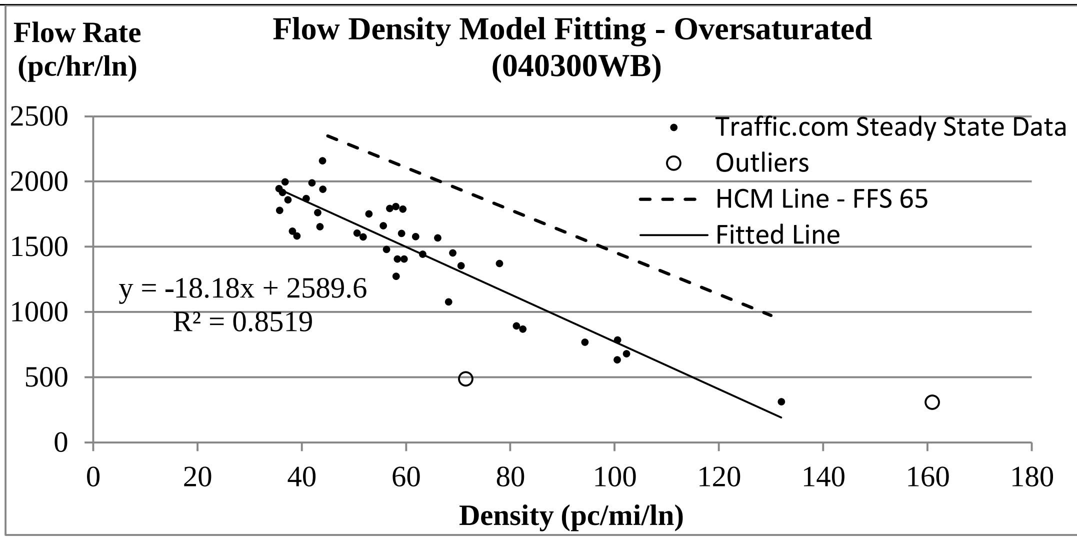
Site 440200EB is an overlap HCM segment. The reason to include an overlap segment in this study is to check the compatibility of the fitted model to data from different freeway segments. The model fitting result reveals that the fitted speed flow curve could correctly represent traffic characteristics during steady congested state in this overlap segment as well. It would be no surprise that the fitted model is better than the *HCM* model that is designed only for basic segment, but it offers possibilities to apply the traditional *HCM* freeway basic model to a wide range of segment types.

A.3.2. Improved Jam Density Estimation

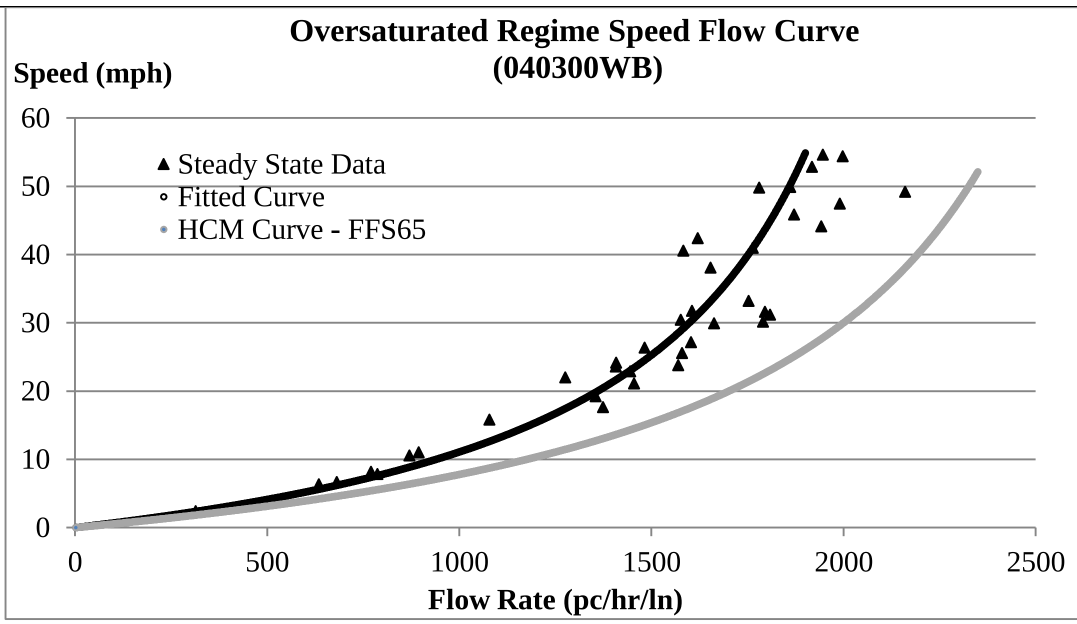
Anchoring the opposite end of the linear model beginning at capacity, jam density is the other key parameter defining the quality of the freeway speed flow model. Site specific characteristics, such as local vehicle composition, driver behavior, and extreme geometric features, such as steeper than normal longitudinal grade, can significantly affect jam density on freeway segments and in turn the shape of the oversaturated regime speed flow curve. Exhibit A.5 shows the difference between fitted curve and *HCM* curve where fitted capacity and jam density differ significantly from the *HCM* default values.

Specifically, the fitted curve indicates a jam density of 140 pc/mi/ln, which is much lower than the *HCM* model default of 190 pc/mi/ln. The lower jam density leads to a steeper curve and thus a better fit to the steady state data.

Exhibit A.5. Oversaturated Regime Speed Flow Curves Comparison at 040300WB



a) Oversaturated Regime Flow Density Relationships



b) Oversaturated Regime Speed Flow Relationships