2-2011

Assessment and Refinement of Real-Time Travel Time Algorithms for Use in Practice, Phase II

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FINAL REPORT

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OTREC-RR-11-13
February 2011

A National University Transportation Center sponsored by the U.S. Department of Transportation's Research and Innovative Technology Administration

ASSESSMENT AND REFINEMENT OF REAL-TIME TRAVEL TIME ALGORITHMS FOR USE IN PRACTICE, PHASE II

Final Report

OTREC-RR-11-13

by

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OTREC
OREGON TRANSPORTATION RESEARCH
AND EDUCATION CONSORTIUM

February 2011

Technical Report Documentation Page

1. Report No. OTREC-RR-11-13	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Assessment and Refinement of Real-Time Travel Time Algorithms for Use in Practice, Phase II		5. Report Date February 2011 6. Performing Organization Code
7. Author(s) Kristin Tufte[1], Soyoung Ahn[2], Sirisha Kothuri[1]		8. Performing Organization Report No.
9. Performing Organization Name and Address [1]Portland State University, P.O. Box 751, Portland, OR 97207 [2]Arizona State University, PO Box 875306, Tempe, AZ 85287-5306		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 2008-145
12. Sponsoring Agency Name and Address Oregon Transportation Research and Education Consortium (OTREC) P.O. Box 751 Portland, Oregon 97207		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The Federal Highway Administration (FHWA) has put a high priority on the use of existing dynamic message signs (DMS) to provide travel time estimates to the public. The Oregon Department of Transportation (ODOT) has three DMS in the Portland metropolitan area configured to display travel time information. In the near future, ODOT would like to make travel time estimates available on additional DMS, over the Internet on tripcheck.com and via 511. Travel time estimates are valuable to the traveling public; however, the estimates must be accurate to be useful. The purpose of this study is to extend prior travel time research conducted by Portland State University with additional analysis to provide statistical confidence in travel time estimates and to determine the best travel time estimation approach for ODOT. The initial ODOT-funded phase of this project gathered a large amount of ground truth data and analyzed the performance of the current algorithms and current infrastructure using that data. However, additional work remains to be done. OTREC Phase I of this project will focus on using the existing data to understand the conditions under which travel time estimation algorithms are not accurate. This extension will build on that work to investigate improvements to travel time estimation algorithms and to identify a set of metrics for travel time accuracy and guidelines for when travel time estimates should be provided. At the conclusion of the project, it is desired that a methodology can be recommended that will provide accurate measures of travel time for use with DMS, the Internet and 511 applications.

17. Key Words Travel time estimates, traffic congestion, travel algorithms		18. Distribution Statement No restrictions. Copies available from OTREC: www.otrec.us	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 50	22. Price

ACKNOWLEDGEMENTS

The authors would like to acknowledge their collaborators at Portland State University and at the Oregon Department of Transportation. In particular, the authors would like to acknowledge the Technical Advisory Committee members for this project: Galen McGill, Dennis Mitchell, Jack Marchant and Amy Mastraccio. The authors also acknowledge the Oregon Transportation Research and Education Consortium (OTREC) for funding the project.

DISCLAIMER

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EXECUTIVE SUMMARY

Travel time estimation is an important feature of Advanced Traveler Information Systems (ATIS). Research has suggested that changing traffic conditions can negatively impact the accuracy of travel time estimation. If traffic conditions change after a travel time estimate is provided, but before the traveler encounters congestion, the travel time estimate may be incorrect. Technically speaking, the upstream or downstream movement of a congestion wave during increasing or decreasing congestion, respectively, negatively impacts the accuracy of travel time estimation.

This project examines the impact of congestion shock waves on the accuracy of travel time estimation on Portland, OR, metropolitan freeways. Bottlenecks on the freeways are identified and shock wave speeds at many bottleneck locations have been analyzed. In addition, practical and theoretical development of the impact of congestion shock waves is presented, and a brief discussion of metrics for evaluating the accuracy of travel time estimates is included.

This project builds upon two previous projects funded by the Oregon Department of Transportation (ODOT) and the Oregon Transportation Research and Education Consortium (OTREC). In the initial ODOT-funded project, data for over 500 ground truth travel time runs were collected on Portland freeways (*Tufte, 2007*). The initial projects analyzed the accuracy of travel time estimates for these runs using the collected ground truth data in addition to data from PORTAL, the regional transportation data archive (*Bertini, 2005*). The results indicated that average absolute percent error for travel time estimates was 12.5% (*Tufte, 2007*).

The follow-up OTREC project investigated factors correlated with estimation errors (travel time estimation window), and assessed the impact of additional detection and the accuracy of ODOT Dynamic Message Sign (DMS) messages (*Tufte, 2008*). This project extends that work by analyzing the impact of congestion waves on estimation accuracy and studying additional accuracy metrics.

The research team has reached the following conclusions and presents the following results:

- Identification of ground truth runs impacted by changing travel conditions.
- Identification of bottlenecks in the Portland region.
- Analysis of shock wave propagation speeds at several bottleneck locations.
- Theoretical sensitivity analysis of the impact of errors in disregarding the propagation of congestion wave, wave speed estimation and estimated speed in congestion.
- Discussion of metrics that take into consideration congestion variability.

1.0 INTRODUCTION

The Oregon Department of Transportation (ODOT) currently provides travel times on three dynamic message signs (DMS) in the Portland, OR, metropolitan area. The Federal Highway Administration (FHWA) has strongly encouraged states to utilize their existing DMS infrastructure to provide travel time information to the public (*Paniati, 2004*).

In addition to the three DMS that currently provide travel times, there are 15 other DMS along the various highways in the Portland area. In the near future, ODOT wants to expand the provision of travel time estimates to these additional DMS signs, 511 and TripCheck.com. At the conclusion of this project, it is desired that ODOT will have enough confidence in their estimation methodology to expand their provision of travel time estimates.

Currently, ODOT uses the standard midpoint algorithm to generate travel time estimates from loop detector data. There are about 600 double-loop detectors embedded under Portland's freeways. These loop detectors report count, occupancy and speed every 20 seconds. This data is received in real time by the ODOT Traffic Management Operations Center (TMOC) and is also sent in real time to Portland State University (PSU). PSU has been archiving this data since July 2004 as part of the PORTAL transportation data archive (*Bertini, 2005*).

In the initial phase of this project, over 500 ground truth travel time runs were collected and the accuracy of various travel time estimation algorithms was assessed (*Tufte, 2007*). The initial analysis included statistical and graphical analysis of accuracy on freeway segments in Portland as well as a comparison of several in-practice and published travel time estimation algorithms. The ground truth travel times were compared with travel times calculated with archived loop detector data from PORTAL. That analysis provided insight into the sources of travel time estimation error, including issues such as lack of adequate detector infrastructure and detector failures.

Changing conditions has always been proposed as a source of error in travel time estimation. Traffic theory states that travel time estimates should be able to be accurate during free-flow conditions and also during stable congestion; however, travel time estimates should be inaccurate during transition conditions – when a congestion shock wave is actively propagating. This project investigates and quantifies the impact of shock wave propagation on travel time estimates, and shows the sensitivity of travel time estimates to shock wave speed, length of a travel time estimation segment, and location of a bottleneck within a segment.

The analysis of the ground truth runs in the initial phase of this project showed an average 12.5% error in travel time estimation. A major goal of the initial phase was to understand the sources of error in travel time estimation and to attempt to improve estimation accuracy through the use of improved algorithms, such as travel time estimation algorithms based on traffic theory (*Coifman, 2002*). In the course of the initial study, however, some anomalies were noticed. While the team found runs in which the clearing of congestion caused a significant overestimation of travel time, the team struggled to find runs in which the onset of congestion caused an underestimation of travel time. The team found many runs where vehicles encountered congestion and many runs with significant (>20%) errors in travel time estimation, but not runs where the error was high (> 20%) *and* there was evidence that the error was caused by congestion increasing during the ground truth run. This led the team to test the sensitivity of travel time estimates to shock wave propagation.

This report presents new analysis, building on previous work, with a goal of increasing the understanding of the impact of congestion shock waves on travel time estimation accuracy. This report includes the identification of several bottlenecks and estimations of shock wave speeds for those bottlenecks. Theoretical and practical analysis of the error introduced by changing conditions and shock wave propagation has been completed. This report begins with a brief summary of the study area and results from the prior project. Analysis and results from this project follow.

2.0 BACKGROUND

The OTREC project described in this report is a continuation of a previous travel time validation study performed by PSU for ODOT (*Tufte, 2007*) and OTREC (*Tufte, 2008*). In the original study for ODOT, a large amount of ground truth data for Portland freeways was collected and analyzed. This section briefly summarizes the study area and results of the prior project. The study area for the current OTREC project is the same as the study area for the prior projects.

2.1 STUDY AREA

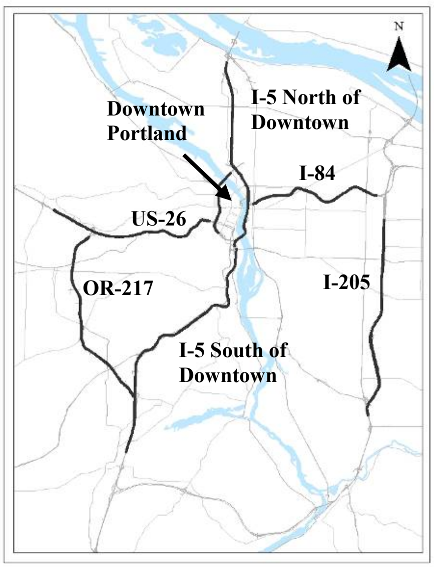


Figure 2.1 Map of Study Area

Figure 2.1 shows a diagram of the study area, with the segments studied marked in black. Data collection and analysis was done for all Portland freeways; however, due to interest and detector infrastructure, special emphasis was placed on I-5 and OR 217. Note that I-5 was divided into two segments for the purpose of the study; one extending from the southern suburbs into downtown (labeled South of Downtown) and the other extending from downtown to the Washington/Oregon border (North of Downtown).

Portland freeways are instrumented with dual-loop detectors. These detectors are placed just upstream of all onramps and report speed, volume and occupancy every 20 seconds. The 20-second data is archived in the PORTAL transportation data archive (*Bertini, 2005*) at PSU.

2.2 GROUND TRUTH DATA COLLECTION

The ground truth data used for this study was collected from probe vehicles with GPS-enabled Garmin iQue® units. Software running on the iQue®s reported vehicle position and speed every three seconds, so a complete vehicle trajectory was obtained for each ground truth run. A total of 544 runs representing over 160 hours of driving were collected. The data collection and analysis was focused primarily on I-5 NB and SB and OR 217 due to interest and detector infrastructure.

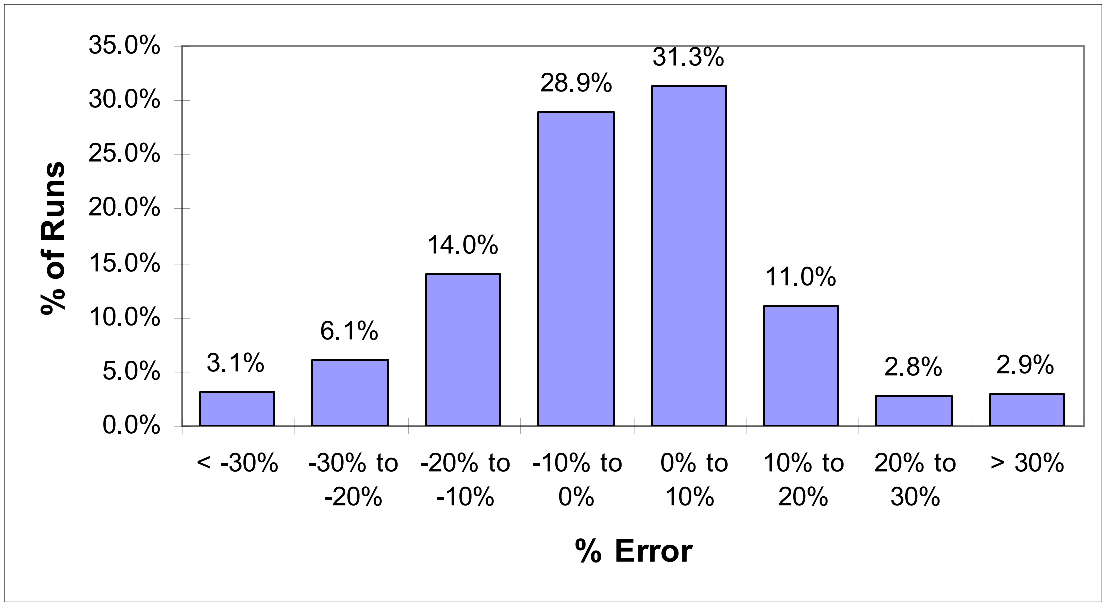


Figure 2.2 Histogram of Average Percent Error - All Runs

2.3 ANALYSIS

The initial portion of this study found an overall mean absolute percent error of 12.5% and standard deviation percent error of 20.8. Figure 2.2 shows a histogram of the mean error percentages for all runs. The mean errors plotted in this histogram are the error between ground truth travel times and the associated estimated travel time derived using data from PORTAL and the ODOT ATMS travel time estimation algorithm. The study showed that accuracy varied significantly from segment to segment.

This variance was due to many reasons, including variations in detector placement, freeway geometry, detector failures during ground truth runs, and presence or absence of congestion. The mean absolute percent error (MAPE) varied from 4.3% on I-405 NB to 17.1% on I-84 WB. I-405 NB is a short freeway segment with very limited congestion; I-84 WB is a highly congested segment with poor detector infrastructure. The previous projects selected an error threshold of 20% based on FHWA direction (*Meehan, 2005*); it is believed that errors above 20% are unacceptable and are potentially detrimental to drivers. In the study, three primary causes of errors were found: detector failure, inadequate detector infrastructure and changing conditions.

The majority of the analysis in this and prior projects uses the standard midpoint algorithm, which is the algorithm used by ODOT to estimate travel times. Four additional algorithms were also analyzed: a traffic theory-based algorithm developed by Coifman (*Coifman, 2002*), and in-practice algorithms from the Washington DOT (*Washington DOT*), Minnesota DOT (*Kwon, 2004*) and San Antonio DOT (*San Antonio*). The accuracy differences between these algorithms were limited. Finally, influence area modifications were tested and were shown to help improve travel time estimates. Additional details on the data collection, analysis, related work and an evaluation of other states' methodologies can be found in the project report (*Tufte, 2007*).

The standard midpoint algorithm is a common algorithm for travel time estimation. In the standard midpoint algorithm, a freeway segment is broken into a series of contiguous "influence areas." There is one influence area per detector station; for a detector station, B, the influence area extends from the midpoint between B and the next upstream detector to the midpoint between B and the next downstream detector, as shown in Figure 2.3. The standard midpoint algorithm calculates travel time for each influence area as (influence area length)/speed, where speed is an average of recent speeds at the detector station associated with that influence area. The travel time for a freeway segment is the sum of the travel times for the influence areas in that segment.

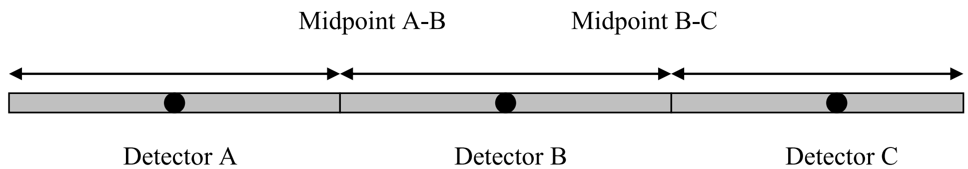


Figure 2.3 Midpoint Influence Areas

3.0 METHODOLOGY

In this project, several methods were used to attempt to understand the effect of increasing congestion on travel time estimation. Calculations of observed wave speeds during certain travel time runs were completed and an attempt was made to identify travel time runs affected by changes in congestion. This section begins with a discussion of how changing conditions can affect travel time, followed by the identification of ground truth runs impacted by changing conditions and a comparison of instantaneous and real-time travel time estimates.

3.1 IMPACT OF CHANGING CONDITIONS ON TRAVEL TIME ESTIMATION

Traffic theory and travel time research papers have indicated that accuracy of travel time estimation can be negatively affected by changing traffic conditions. A traveler driving through a given road segment is given a travel time estimate at or before the time they enter that segment. If traffic conditions on the segment change significantly after the estimate is provided, but before the traveler exits the segment (for example, if conditions change as the traveler is driving through the segment), the travel time estimate may be incorrect as it was based on conditions just prior to the time the estimate was provided.

Figure 3.1 shows a diagram of a freeway segment on which one might estimate travel time. In this figure, traffic flows from left to right and **we** assume that there is a DMS at the start of the segment which displays travel time estimates for the segment. Thus, the travel time estimates will be provided using data received just prior to the time when the vehicle enters the segment.

From another point of view, travel time estimates will be based on conditions just prior to the time the vehicle entered the segment. In Figure 3.1, the bottom green and red line shows the conditions at the time the vehicle arrived at the DMS/entered the segment, with red indicating congestion and green indicating free flow. **We** see in Figure 3.1 that a small portion at the end of the segment is congested. **We** assume that **we** are in a time period where congestion is increasing, so as the vehicle drives through the segment the congestion wave moves upstream towards the vehicle as indicated in the figure. The upper red and green line shows the conditions as encountered by the vehicle. The area in the middle of the figure, where the upper line is red and the lower line is green, is the area of the segment for which conditions are different for the travel time estimation than those experienced by the vehicle. It is in this area of the segment that the travel time estimate will be affected by the changing conditions.

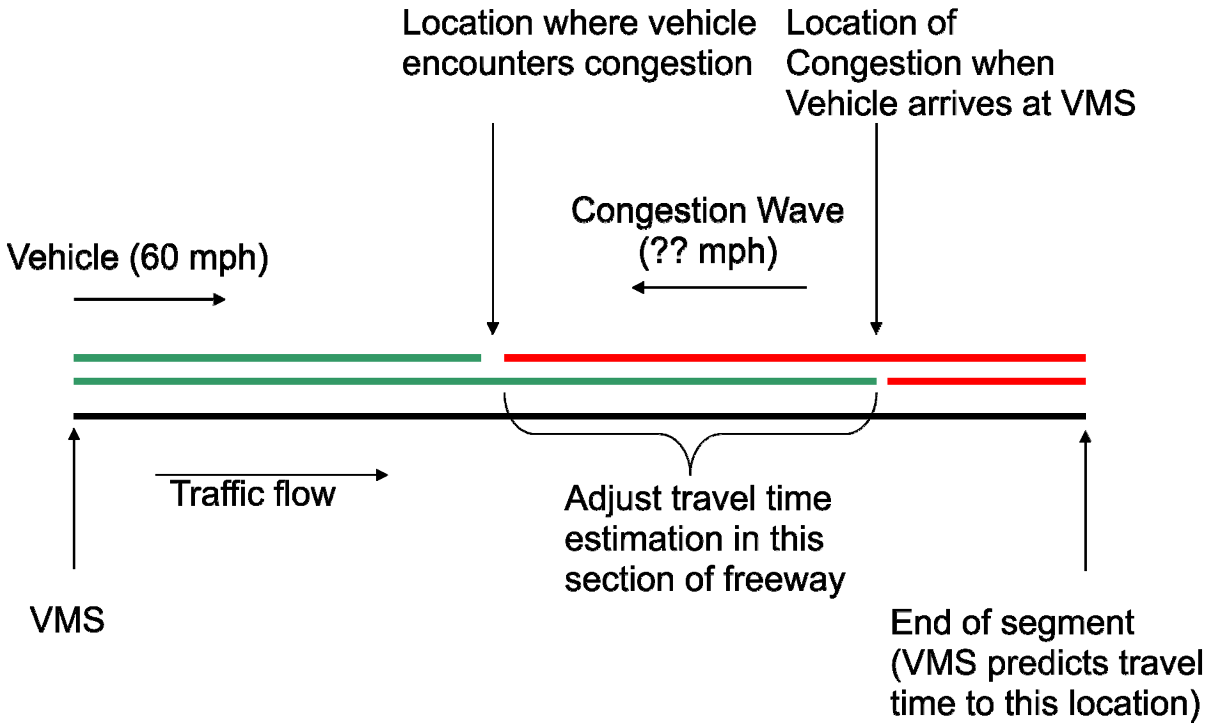


Figure 3.1 Diagram of Impact of Shock Wave on Vehicle Travel

Algorithms have been proposed to adjust for such changing conditions. One such algorithm (*Coifman, 2002*) was tested in an earlier phase of this project (*Tufte, 2007*). A key need for adjusting for changing conditions is the speed of the congestion wave. Thus in this project, congestion wave speeds were analyzed and estimated for several bottlenecks in the Portland metropolitan area.

3.2 RUNS AFFECTED BY CHANGING CONDITIONS

The travel time data collection that occurred in the first phase of this project collected over 500 ground truth travel time runs on Portland freeways. As part of this project phase, an attempt was made to identify runs that had a travel time estimation error due to conditions changing during the run. Figure 3.2 shows a plot of speeds versus location for one such run, run 338. Run 338 started at **4:58** p.m. on April 25, 2007, and occurred on the segment of I-5 NB from downtown Portland to the Columbia River. The estimated travel time for this run was 17 minutes and 21 seconds while the actual travel time was 42 minutes and 59 seconds, an underestimation error of 60%.

In the figure, the small light-red dots indicate the speeds experienced by the probe vehicle and the larger blue dots indicate the speeds observed at the detectors just prior to the start of the run and, as such, are the speeds used for travel time estimation. **We** term these "instantaneous speeds." The larger red dots indicate the "real-time speeds," the speeds that were recorded by the detectors at the approximate time the probe passed over the detector.

One can see that the real-time speeds match the probe speeds relatively well, indicating that the detectors were reporting accurate speeds. The larger blue dots, marking instantaneous speeds, indicate significantly higher speeds. In this run, **we** believe the botteleneck activated after the instantaneous speeds were recorded, but before the vehicle reached the bottleneck area. Run 338 is an example of a run whose travel time estimate was affected by the changing conditions of bottleneck activation.

Figure 3.3 shows the same type of plot for run 307. Run 307 occurred on April 24, 2007, on the same segment of I-5 NB. This run started at **17:47**; the ground truth travel time was 7 minutes and 15 seconds and the estimated travel time was 9 minutes and 23 seconds, an overestimation error of 29%. In this run, **we** can see that the instantaneous speeds were lower than the real-time speeds and speeds experienced by the probe vehicle. In this case, congestion was active when the vehicle entered the segment and when the instantaneous speeds were recorded, but cleared by the time the vehicle reached the (previously) congested section.

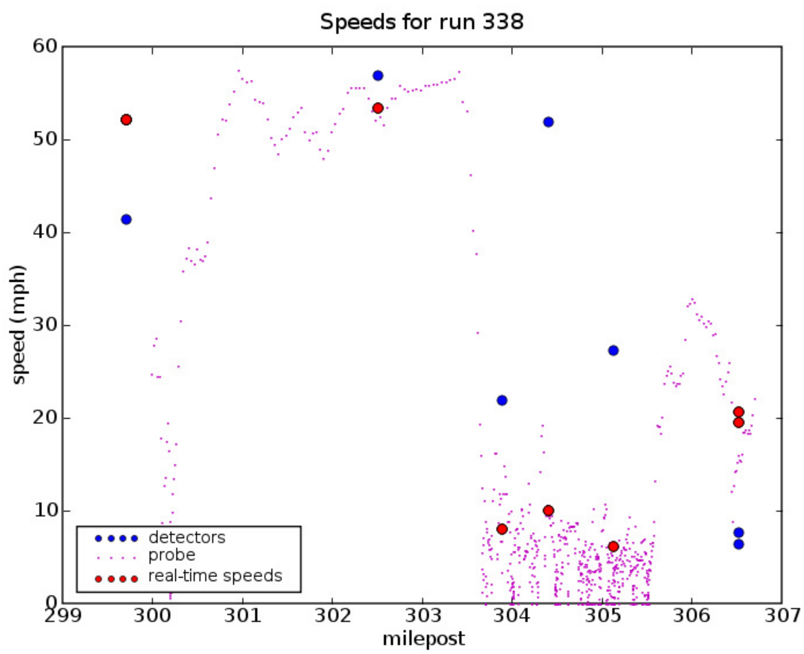


Figure 3.2 Probe and Detector Speeds for Ground Truth Run 338

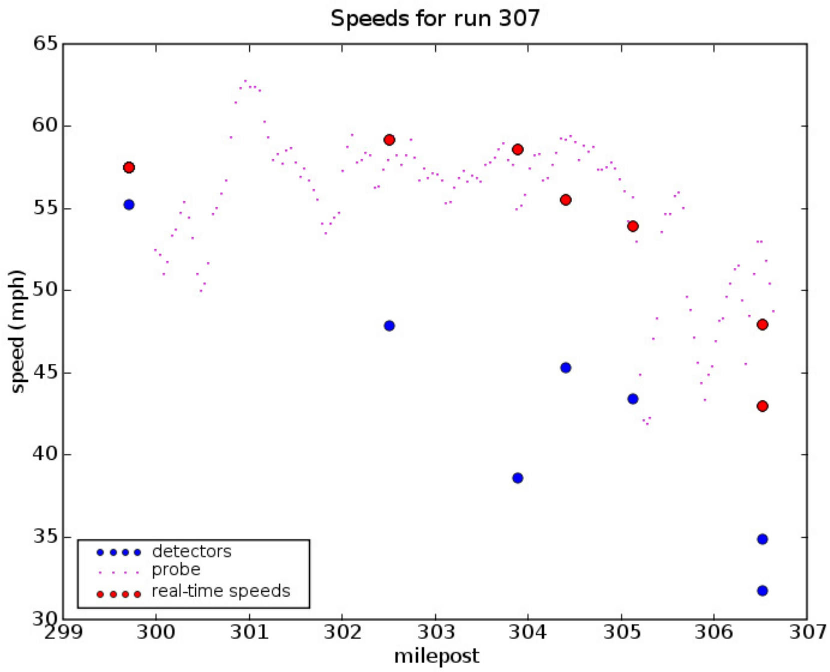


Figure 3.3 Probe and Detector Speeds for Ground Truth Run 307

3.3 COMPARISON OF REAL-TIME AND INSTANTANEOUS TRAVEL TIME ESTIMATES

In order to provide a driver with a travel time estimate, that estimate must be made with data that is available at or before the time the vehicle enters the segment. **We** use the term "instantaneous speeds" to refer to speeds measured at the time the vehicle enters the segment, noting that these speeds can be used for real-time travel time estimations. **We** use the term "real-time speeds" to refer to speeds measured by detectors at the time the vehicle passes a detector. These real-time speeds are not usable for real-time travel time estimation as they are not available at the time the travel time estimate needs to be provided to a driver. However, they are useful for analysis purposes. Travel time estimates using real-time speeds and instantaneous speeds were calculated and compared. Table 3 shows a comparison of errors between estimates made using instantaneous speeds and estimates made using real-time speeds. Surprisingly, the estimates showed no significant differences. (*Kothuri, 2007*). The lack of differences between the instantaneous and real-time estimates indicates that changing conditions may not be a significant factor in travel time estimation error.

TABLE 3 Effects of Additional Detectors on Errors

Segment Description	Instantaneous Error (%)			Real Time Error (%)		
	MAPE	**SDPE**	**SE**	**MAPE**	**SDPE**	**SE**
OR 217 NB	13.12	11.98	1.65	9.66	10.52	1.35
OR 217 SB	11.39	12.99	1.56	12.19	15.01	1.80

I-5 NB SoD	8.14	11.37	1.13	6.72	9.46	0.97
I-5 SB SoD	10.75	14.09	1.20	11.47	15.11	1.29
I-5 NB NoD	17.05	32.03	3.27	15.40	26.93	2.56
I-5 SB NoD	13.37	16.43	1.09	14.38	17.49	1.17

4.0 CONGESTION WAVE SPEED ANALYSIS

Congestion wave speeds have been calculated for a number of the bottlenecks in Portland. **We** describe the methodology for calculating the wave speeds followed by a summary of the calculated wave speeds.

4.1 WAVE SPEED CALCULATION METHODOLOGY

Congestion wave speeds were estimated using historical data. The average wave speed (in each segment) and its variability from day to day were measured. The technique used was visual inspection of the movement of the congestion waves across a set of consecutive detectors. The goal was to understand the wave speed and its variations under different conditions.

We use April 25, 2007, on I-5 NB as an example to explain the wave speed calculation methodology. Figure 4.1 shows a schematic of the I-5 NB freeway from downtown to the Columbia River. The bridge over the Columbia River is a known bottleneck for this freeway segment. The congestion wave originates north of the Jantzen Beach detector (the northernmost detector on I-5 in Oregon) and moves upstream. **We** wish to calculate the speed of the congestion wave as it moves from its origination north of Jantzen Beach upstream past Jantzen Beach, Marine Drive and further upstream interchanges. Figures 4.2 through 4.5 show plots of speed over time for the afternoon of April 25, 2007, for the four detector locations upstream of the Columbia River Crossing bottleneck along I-5 NB. Inspecting these figures, one can see the initial onset of congestion at the most downstream location – Jantzen Beach - at just before 3:45 p.m. The congestion wave continues upstream, arriving at Marine Drive at approximately 4 p.m., Denver Avenue at approximately 4:15 p.m. and, finally, Portland Boulevard at around 4:55 p.m.

Visual inspection of the plots and data was done to determine congestion wave arrival time at each detector (and associated milepost), and allowed the research team to calculate the speed of the congestion wave over a segment for a particular day. On April 25, 2007, for the I-5 NB Columbia River bottleneck, wave speed was determined to be 7.2 mph. Figure 4.6 shows a time versus distance plot of the speed of this wave.

Quality filtering was used in wave speed calculations. At least three detector pairs were required to be available and a subjective quality filter was applied. Days were assigned one of five subjective qualities: Excellent, Good, Marginal, Poor and Bad. Runs with qualities of Poor or Bad were excluded from the analysis.

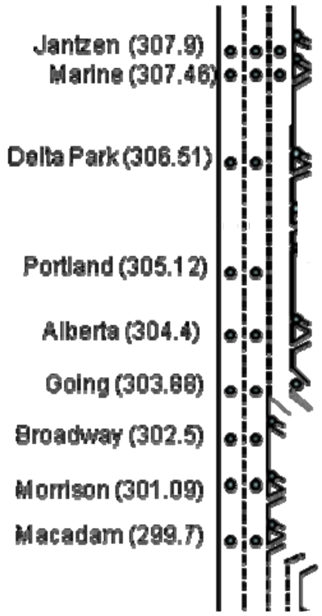


Figure 4.1 Schematic of I-5 NB North of Downtown Portland

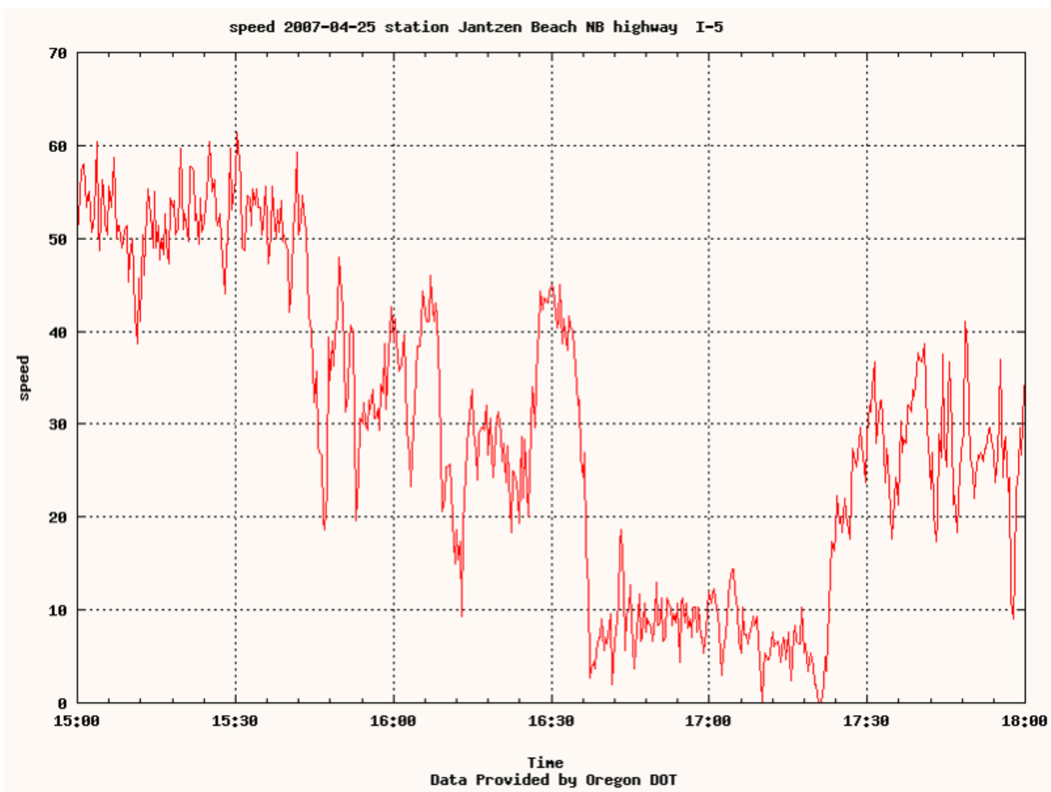


Figure 4.2 Speed on I-5 NB at Jantzen Beach (mp 307.9) April 25, 2007

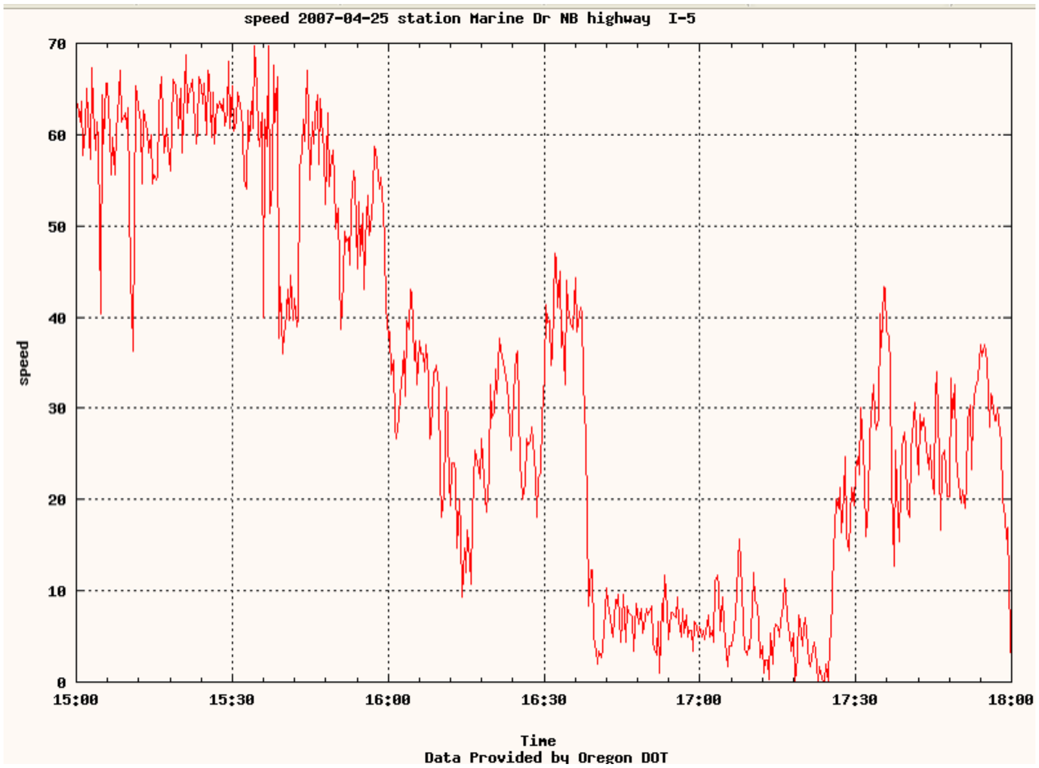


Figure 4.3 Speed on I-5 NB at Marine Dr (mp 307.46) April 25, 2007

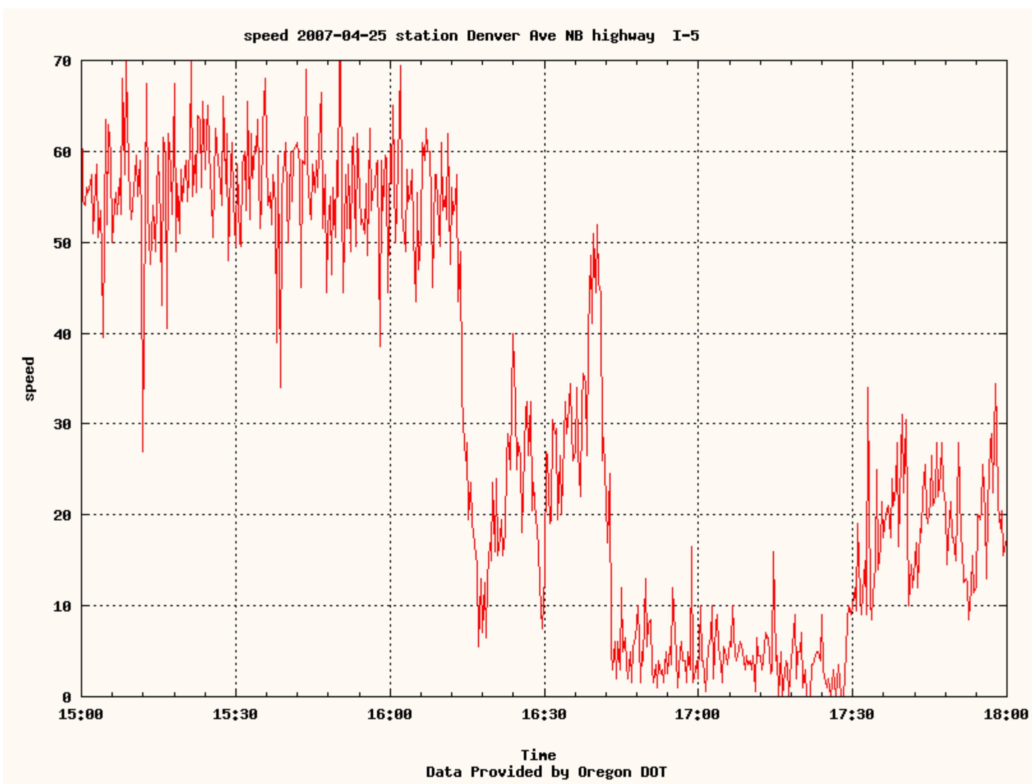


Figure 4.4 Speed on I-5 NB at Delta Park/Denver Ave (mp 306.51) April 25, 2007

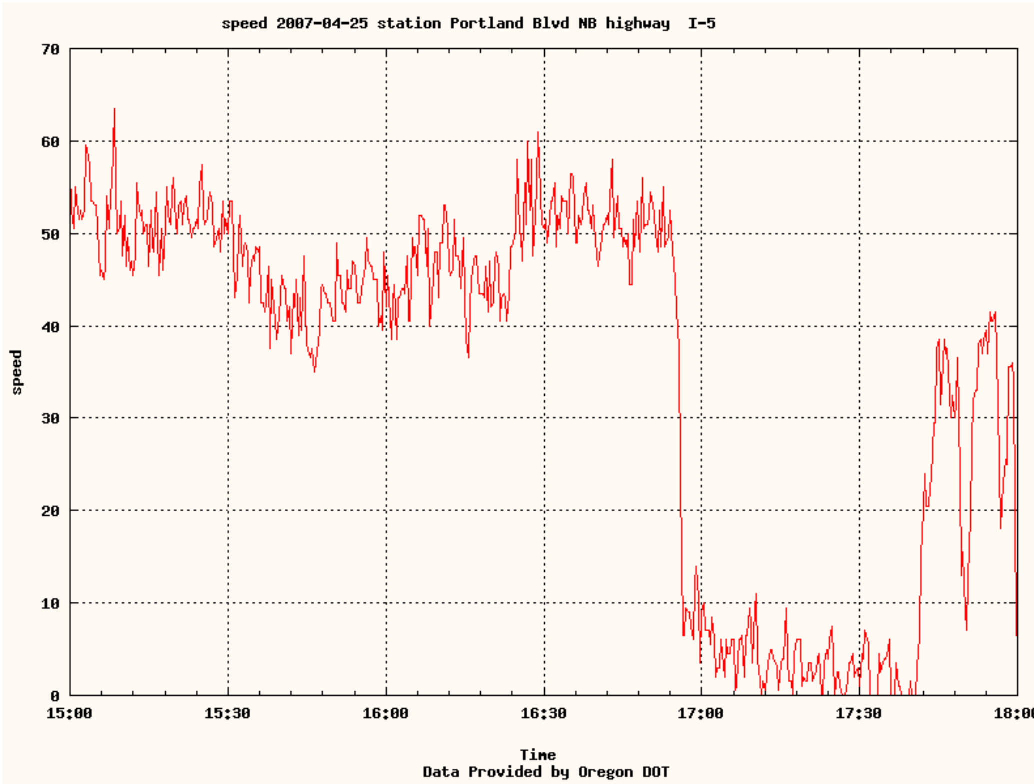


Figure 4.5 Speed on I-5 NB at Portland Blvd (mp 305.12) April 25, 2007

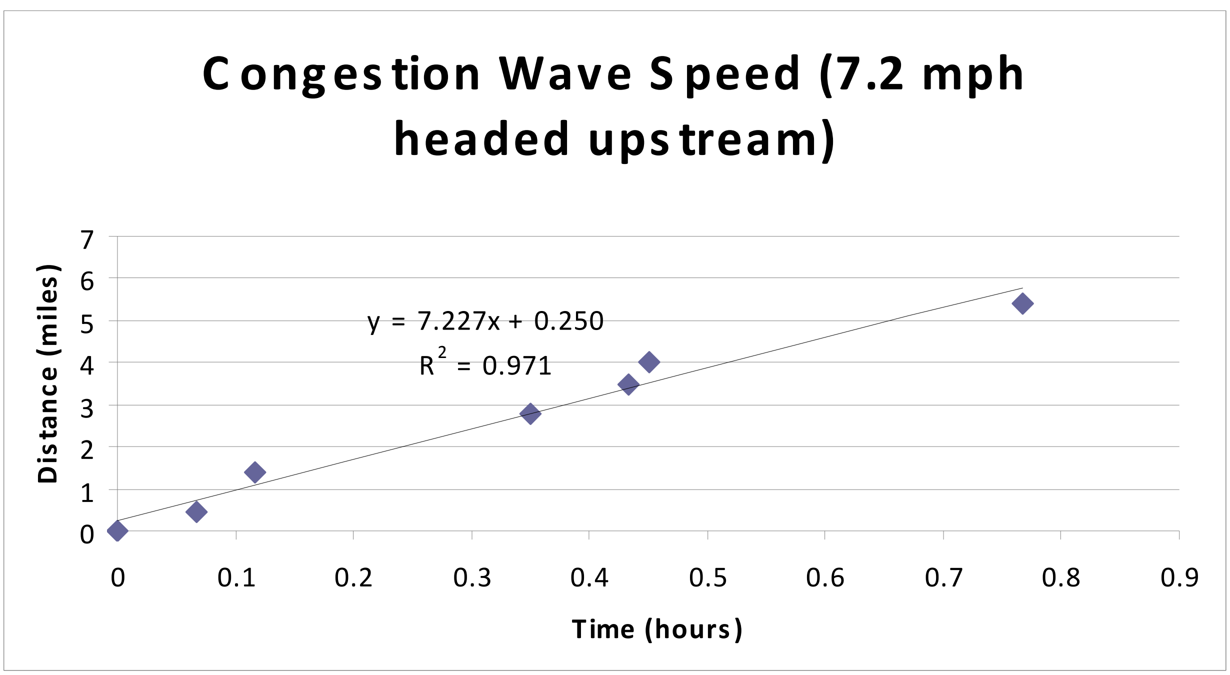


Figure 4.6 Congestion Wave Speed for Run 338 - I-5 NB North of Downtown - April 25, 2007

4.2 BOTTLENECK LOCATIONS

This project identified bottleneck locations on Portland freeways. The identification was done using visual inspection of Timeseries plots from the PORTAL transportation data archive (*Bertini, 2005*) and visual inspection of plots from the collected ground truth runs. Additional bottleneck identification efforts have been undertaken by researchers at PSU (*Wieczorek, 2010*) and the FHWA. Table 4.1 Bottlenecks on Portland Metropolitan Freeways shows bottlenecks that have been identified in the Portland area.

Table 4.1 Bottlenecks on Portland Metropolitan Freeways

Freeway & Direction	**Milepost**	**Length (miles) (Approx)**	**Activation Time (Approx)**	**Length of Activation (hours) (Approx)**	**Comments**
I-205 NB	19.79	4	7:00 AM	2	At onramp from SE Division
I-205 NB	19.79	6	4:00 PM	3	
I-205 NB	9	5	4:00 PM	2	Starts on the bridge between the offramp from Hwy 43 and the exit to Hwy 99
I-205 SB	18.92	6	4:00 PM	2	From the offramp for SE Division/ SE Powell
217 NB	2.2	4	4:00 PM	2	At the exits/onramps for SW Canyon Rd and SW Beaverton-Hillsdale Hwy
217 SB	4.5	3	7:00 AM	2	Between exit for Hall Boulevard and onramp for Scholls Ferry Rd
I-84 E	0.54	0.5	3:00 PM	1	Due to initial merge from I-5 N/S to form I-84E and first onramp from NE Irving St (at mp 0.54)
I-84 W					Not enough data in timeseries or probe runs.
I-5 N	297.5	3	7:00 AM	2	Terwilliger Curves

I-5 N	307.9	5	3:00 PM	4	CRC backup
I-5 S	306	1	7:30 AM	2	Lane drop
I-5 S	290	2	5:30 PM	1	I-5, OR 217 merge
US 26 E	73.55	4 4	7:00 AM 4:00 PM	2.5 3	Vista Ridge Tunnel
US 26 W	65.65	2	4:00 PM	2	Lane drop

4.3 CONGESTION WAVE SPEEDS

In this section, **we** include the wave speed calculations for several Portland-area bottlenecks. A summary table (Table 4.2) showing average wave speed for each bottleneck is provided first, followed by detailed wave speed calculation tables showing estimated wave speeds for particular runs for two of the bottlenecks.

Table 4.2 Congestion Wave Speeds for Selected Bottlenecks on Portland Metropolitan Freeways

Bottleneck Description	**Milepost**	**Avg (mph)**	**Min (mph)**	**Max (mph)**	**Std Dev**	**Num Days (N)**
217 NB – SW Canyon Rd/ SW B/H Hwy	2.2	9.0	4.9	13.2	2.9	19
217 SB – Hall/Scholls Ferry	4.5	9.8	3.1	12.9	2.4	16
I-5 N – Terwilliger	297.5	8.3	4.8	29	7.3	10
I-5 N – Jantzen Beach/ CRC	307.9	6.2	4.0	8.9	1.2	12

4.3.1 I-5 NB – CRC /Jantzen Beach

Table 4.3 Detailed Wave Speed Calculations for I-5 NB – CRC/Jantzen Beach

Date/Time	Wave Speed	Detector Pairs	Subjective Quality	Day of Week
July 11, 2007	4.0	3	Good	Wednesday
Aug 22, 2007	7.0	4	Good	Wednesday
Sept 19, 2007	5.7	3	Marginal	Wednesday
Oct 3, 2007	6.2	5	Good	Wednesday
Oct 10, 2007	8.9	5	Marginal	Wednesday
Oct 31, 2007	7.0	5	Marginal	Wednesday
Nov 7, 2007	6.4	5	Marginal	Wednesday
Nov 14, 2007	5.8	5	Marginal	Wednesday
Dec 5, 2007	5.5	4	Marginal	Wednesday
Dec 12, 2007	5.7	4	Marginal	Wednesday
July 13, 2007	6.5	5	Marginal	Friday
Nov 9, 2006	5.2	5	Marginal	Friday

4.3.2 I-5 NB – Terwilliger

Table 4.4 Detailed Wave Speed Calculations for I-5 NB - Terwilliger

Date/Time	Wave Speed	Detector Pairs	Subjective Quality	Day of Week
July 11, 2007	5.5	5	Good	Wednesday
July 18, 2007	5.6	5	Marginal	Wednesday
Aug 8, 2007	2.0	4	Bad	Wednesday
Aug 15, 2007	4.8	5	Marginal	Wednesday
Aug 22, 2007	10.8	2	Poor	Wednesday
Sept 5, 2007	5.3	3	Marginal	Wednesday
Sept 12, 2007	5.4	2	Marginal	Wednesday
Sept 19, 2007	5.4	4	Good	Wednesday
Sept 26, 2007	10.9	2	Poor	Wednesday
Oct 3, 2007	7.2	4	Marginal	Wednesday
Oct 10, 2007	8.8	4	Poor	Wednesday
Oct 24, 2007	8.7	4	Marginal	Wednesday
Nov 7, 2007	3.5	4	Poor	Wednesday
Nov 14, 2007	6.8	4	Marginal	Wednesday
Nov 28, 2007	5.1	4	Marginal	Wednesday
Dec 5, 2007	3.9	5	Poor	Wednesday

5.0 SENSITIVITY ANALYSIS FOR TRAVEL TIME ESTIMATION

In this report, the results of sensitivity analysis for travel time estimation are presented. Three types of errors in estimation are considered:

1) Error by disregarding the propagation of congestion wave;

2) Error in wave speed estimation; and

3) Error in estimated speed in queue.

5.1 ERROR BY DISREGARDING THE PROPAGATION OF CONGESTION WAVE

Error of this type occurs when the midpoint algorithm is used and wave propagation is not considered in predicting travel time. In the midpoint algorithm, travel time is estimated based on instantaneous speeds measured at different loop detector stations, and the measured speeds are unchanged while the vehicle traverses the link. Thus, the propagation of speed disturbance in time and space is not considered in the estimation process. This is illustrated in Figure 5.1.

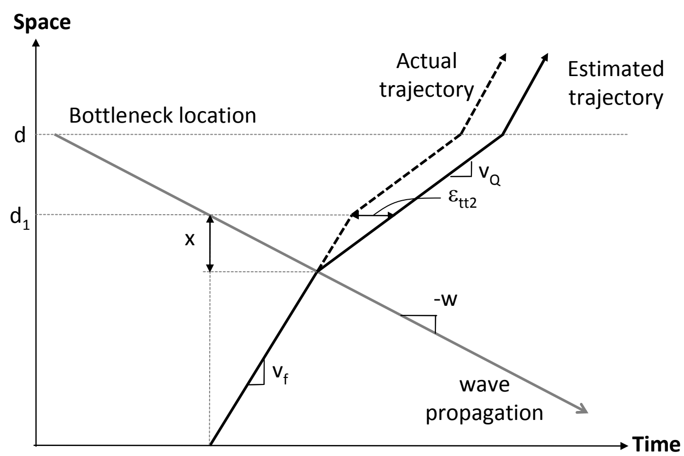


Figure 5.1 Illustration of the Error in Travel Time Due to Disregarding the Propagation of the Congestion Wave

The variables in the figure are defined as follows:

v_f: free-flow speed (assumed 60mph)

v_Q: the speed in queue

w: the speed of a backward-moving shock wave, signaling the onset of a queue

d: the distance to an active bottleneck from the upstream end of a freeway link

d_1: the distance to the back of the queue from the upstream end of a freeway link

x: the distance that the wave travels from the time a vehicle enters the link to the time it crosses the wave

ε_{tt2}: the error in travel time resulting from disregarding the wave propagation (type 2 error)

The dashed trajectory represents the estimated trajectory assuming that the vehicle travels according to the instantaneous speeds sampled from loops at the time of its entry. Thus, the error in travel time is generated because the vehicle is assumed to travel at free-flow speed for x additional miles. From the figure, x, ε_{tt2} and the actual link travel time, tt_a can be quantified as follows.

$$x = \frac{w}{v_f + w} d_1 \qquad \text{(Eq. 5.1)}$$

$$\varepsilon_{tt2} = x \cdot \left(\frac{1}{v_Q} - \frac{1}{v_f} \right) \qquad \text{(Eq. 5.2)}$$

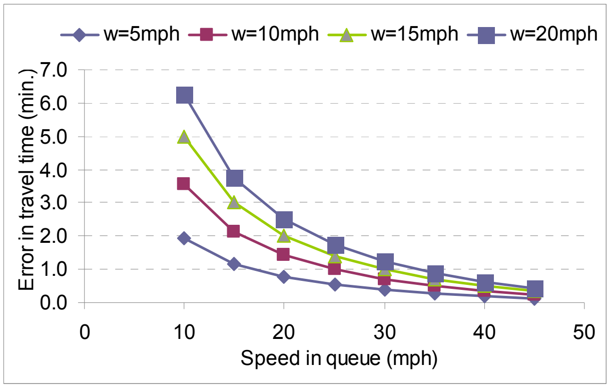
$$tt_a = \frac{d_1 - x}{v_f} + \frac{d - d_1 + x}{v_Q} \qquad \text{(Eq. 5.3)}$$

The error in travel time is quantified in both magnitude and percent, and its sensitivity to the parameters v_Q, w and d_1 is analyzed through numerical analysis. The results are presented in Figure 5.2. Figure 5.2 (a), (c) and (e) show the magnitude of errors in travel time with respect to the speed in congestion, while Figure 5.2 (b), (d) and (f) show their respective percent errors. In each figure, the horizontal axis represents the speed in congestion, and the errors associated with different wave speeds (5, 10, 15 and 20 mph) are shown as a separate series as labeled in the legend. Several observations are notable from the figure:

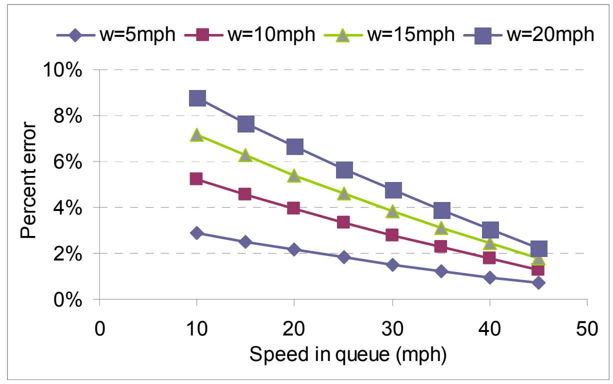
Magnitude of error

- The magnitude of error decreases at a decreasing rate with respect to the speed in queue, v_Q.
- For a given d_1 and v_Q, the error increases at a decreasing rate with respect to wave speed, w.
- The rate of decrease is larger for larger d_1.
- For a given speed in queue and wave speed, the error increases linearly with d_1.

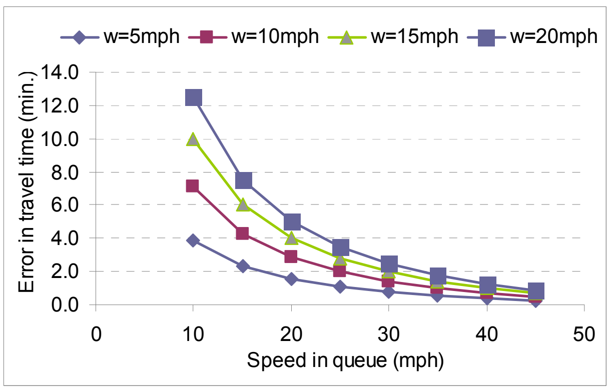
Findings are similar for percent errors. Of note, the magnitudes of errors are the same for the same d_1 values even if d is different. This is intuitive given that x (thus ε_{tt}) depends on d_1 but not d. However, the percent error changes with respect to d for the same d_1. This is also intuitive given that the percent error is calculated based on the actual travel time, which also depends on d.



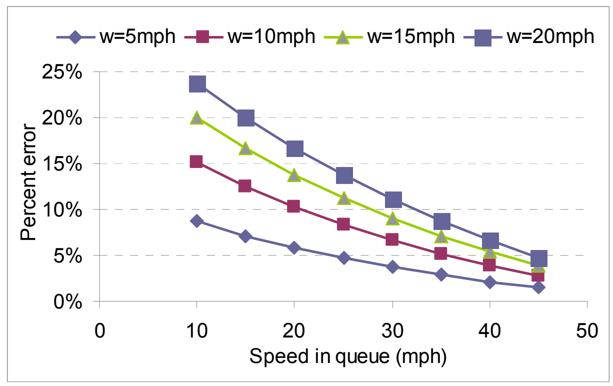
(a) Error in travel time (d_1=5 miles)



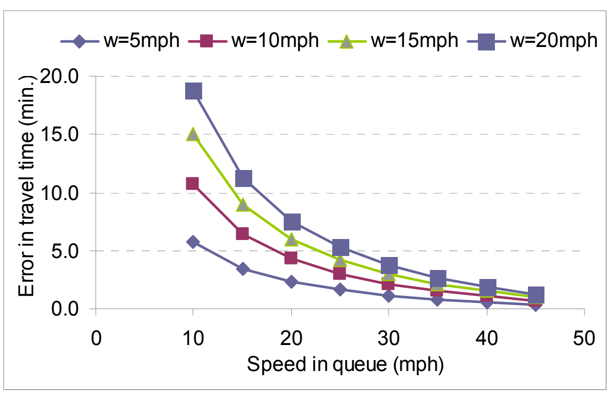
(b) Percent error (d_1=5 miles)



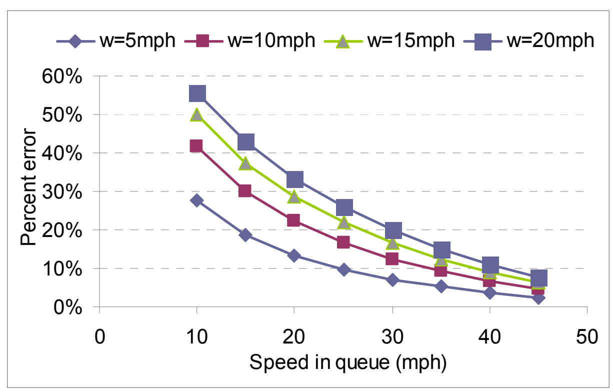
(c) Error in travel time (d_1=10 miles)



(d) Percent error (d_1=10 miles)



(e) Error in travel time (d_1=15 miles)



(f) Percent error (d_1=15 miles)

Figure 5.2 Errors in Travel Time Due to Disregarding Wave Propagation. (d=15 miles)

5.2 ERROR IN WAVE SPEED ESTIMATION

The error of this type occurs when the wave speed is not accurately estimated. If the wave speed is overestimated, then a vehicle is predicted to join the queue earlier, resulting in an overestimated travel time. Analogously, if the wave speed is underestimated, then the travel time would also be underestimated. This is illustrated in Figure 5.3 with an example of overestimated wave speed.

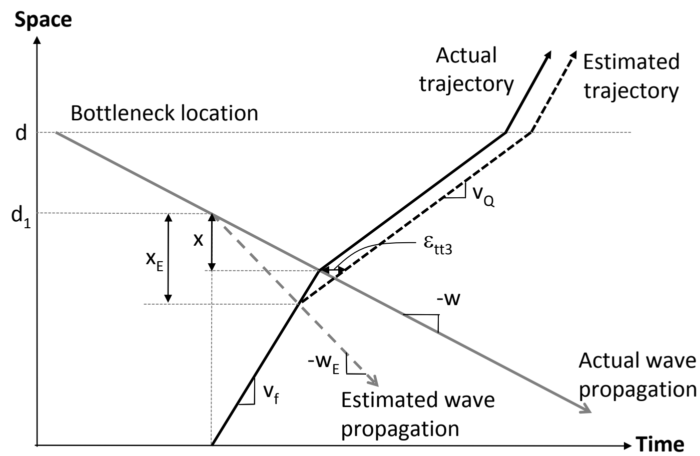


Figure 5.3 Illustration of the Error in Travel Time Due to the Error in Estimated Wave Speed.

The additional variables that have not been defined are as follows:

w_E: the *estimated* speed of the shock wave

x_E: the *estimated* distance that the wave travels from the time a vehicle enters the link to the time it crosses the wave

ε_{tt3}: the error in travel time due to the error in estimated wave speed (type 3 error)

The dashed trajectory represents the estimated trajectory assuming that the vehicle joins the queue based on the wave propagation speed of w_E. The error in travel time is generated because the vehicle is assumed to join the queue x_E - x upstream of the actual location of the tail end of the queue. Thus, the error in travel time corresponds to the additional travel time by assuming the speed of v_Q between x_E and x. From the figure, x_E and ε_{tt3} can be quantified as follows:

$$x_E = \frac{w_E}{v_f + w_E} d_1 \qquad \text{(Eq. 4)}$$

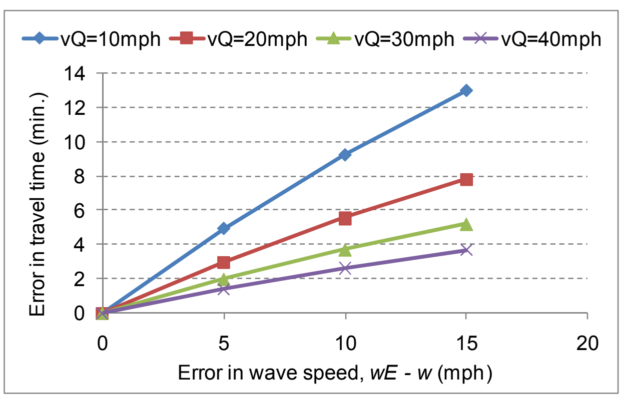
$$\varepsilon_{tt3} = (x_E - x) \cdot \left(\frac{1}{v_Q} - \frac{1}{v_f} \right) \qquad \text{(Eq. 5)}$$

The error in travel time is quantified in both magnitude and percent and its sensitivity to the error in estimated wave speed, and parameters v_Q and w are analyzed. The results are presented in Figure 5.4 (a), (c) and (e), which show the magnitude of errors in travel time with respect to the error in estimated wave speed, w. Figure 5.4 (b), (d) and (f) show their respective percent errors. In each figure, the horizontal axis represents the error in w, and the errors associated with different speed in queue (10, 20, 30 and 40 mph) are shown as a separate series as labeled in the legend. Figure 5.5 illustrates the effect of the distance to the tail end of the queue for w_E =15 mph and w =10 mph as an example. Notable observations are:

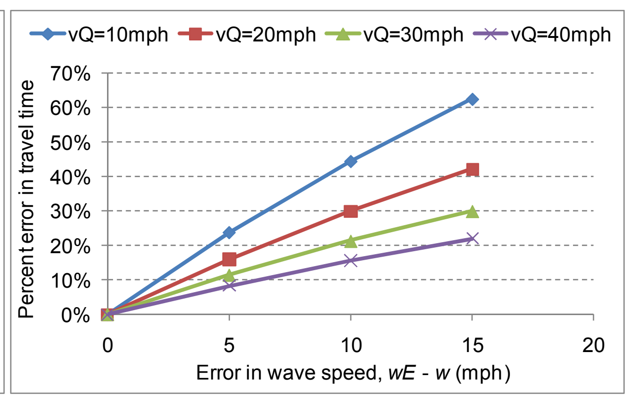
Magnitude of error

- The magnitude of error in travel time increases at a decreasing rate with respect to the error in w.
- For a given error in w, the error in travel time increases at an increasing rate with respect to speed in queue, v_Q.
- For given errors in w and v_Q, the error in travel time decreases with respect to the actual wave speed.
- The error in travel time increases linearly with respect to the distance to the tail end of the queue.

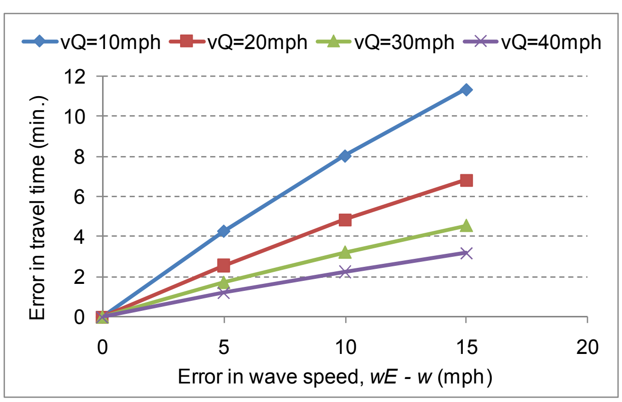
Findings are similar for percent errors.



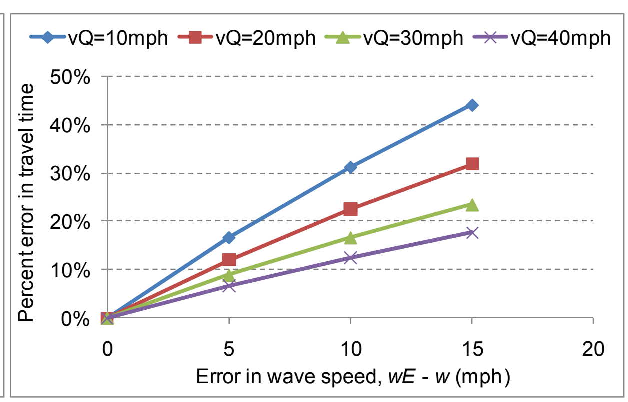
(a) Error in travel time (w=5 mph)



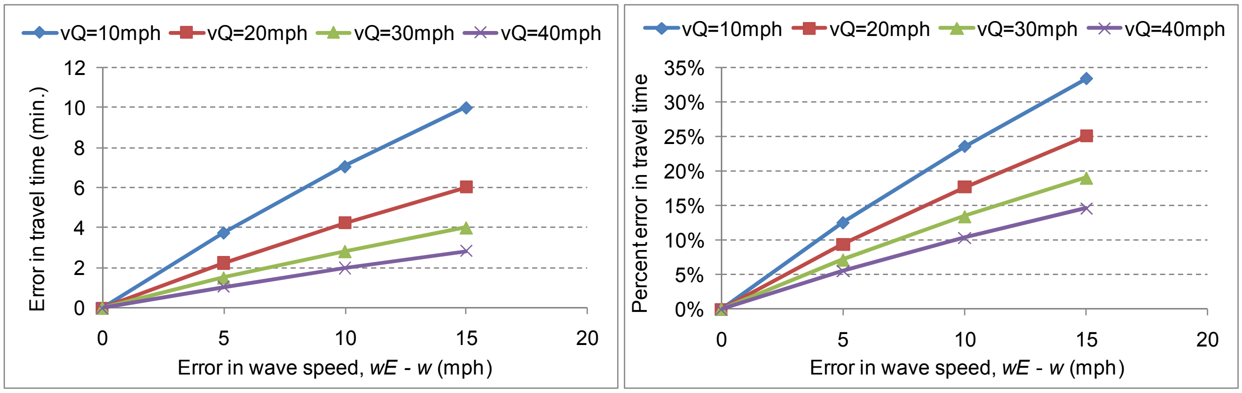
(b) Percent error (w=5 mph)



(c) Error in travel time (w=10 mph)



(d) Percent error (w=10 mph)



(e) Error in travel time (w=15 mph) (f) Percent error (w=15 mph)

Figure 5.4 Errors in Travel Time Due to the Error in Estimated Wave Speed ($d=d_i=15$miles)

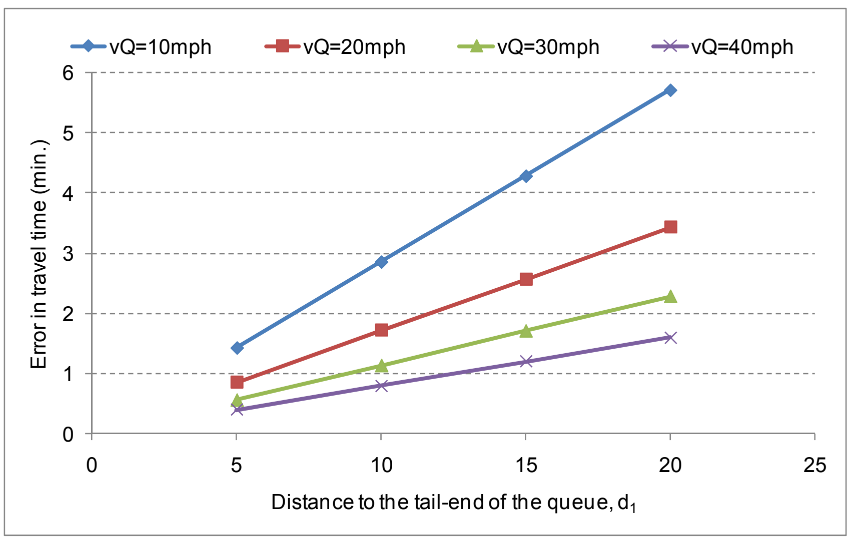


Figure 5.5 Error in Travel Time vs. the Distance to the Tail End of the Queue (w_E=15mph, w=10mph)

5.3 ERROR IN ESTIMATED SPEED IN CONGESTION

This section presents the results regarding the sensitivity of error in travel time with respect to error in estimated speed in queue. This type of error occurs when the (average) speed in queue is not estimated accurately, impacting the travel time in queue. This is illustrated in Figure 5.6 with an example of underestimated speed in queue.

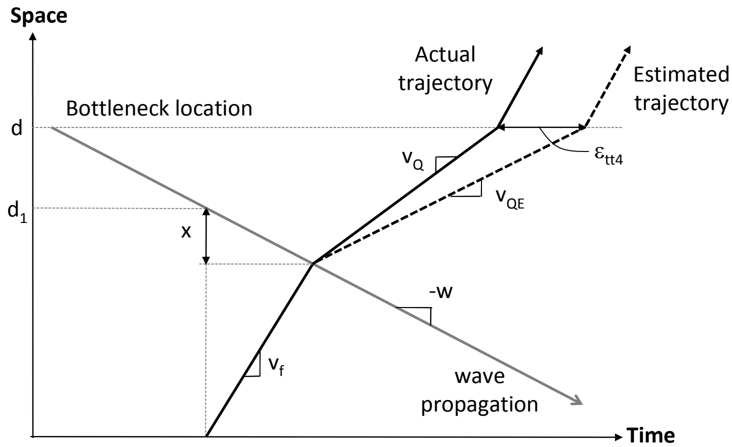


Figure 5.6 Illustration of the Error in Travel Time Due to the Error in Estimated Speed in Queue.

The additional variables that have not been defined are as follows:

v_{QE}: the *estimated* speed in queue

ε_{tt4}: the error in travel time due to the error in estimated speed in queue (type 4 error)

It is notable that the error in travel time increases as the vehicle travels in queue. The total error in travel time, ε_{tt4} is expressed as

$$\varepsilon_{tt4} = (d - d_1 + x) \cdot \left(\frac{1}{v_{QE}} - \frac{1}{v_Q} \right) \qquad \text{(Eq. 6.6)}$$

Note that the error increases linearly with the distance to the bottleneck and decreases linearly with the distance to the back of the queue. The latter is intuitive in that with a smaller d_1, a vehicle travels longer in queue, resulting in a larger error in travel time. The result of a more in-depth sensitivity analysis is presented in Figure 5.7. In each figure, the horizontal axis represents the error in speed in queue (= $v_{QE} - v_Q$), and the errors associated with different wave speeds (5, 10, 15 and 20 mph) are shown as a separate series as labeled in the legend. Figure 5.7 (a), (c) and (e) display the magnitude of error in travel time with respect to the estimated speed in queue. Their respective percent errors are also presented in Figure 5.7 (b), (d) and (f). Several observations are summarized below.

Magnitude of error

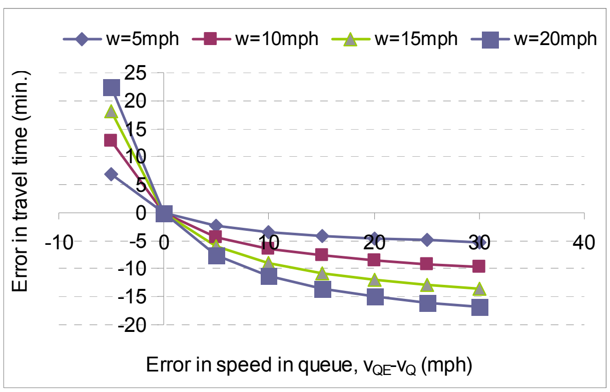
- Underestimation of v_Q results in a higher penalty than overestimation by the same (absolute) magnitude. For instance, Figure 5.7 (a) shows that for w = 20mph, the error in travel time due to underestimation by 5 mph is about 23 minutes, while the error due to overestimation by 5 mph is about -8 minutes.

- As the error in speed in queue increases, error in travel time increases at a decreasing rate. For example, for w = 5 mph, the error in travel time converges to about -5 minutes as the error in speed in queue increases.

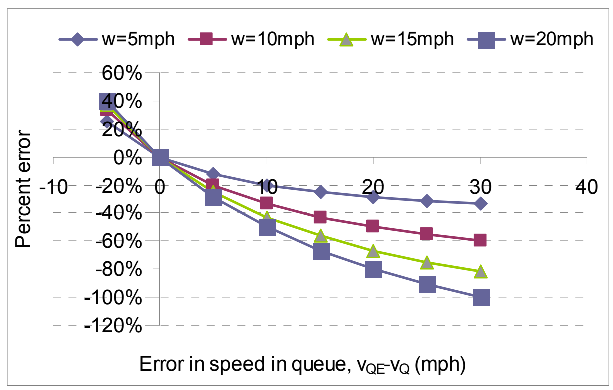
- Error in travel time increases with wave speeds. This is intuitive since a larger wave speed indicates that a vehicle would join the queue earlier.

- For the same value of error in speed in queue, the error in travel time decreases with respect to the actual speed in queue. This can be observed by comparing Figure 5.7 (a), (c) and (e). For instance, the error in speed in queue of 10 mph corresponds to the error in travel time of around -12 minutes when w = 20 mph and v_Q = 10 mph. However, for the same level of error in speed in queue and w, the errors in travel time are around -4 and -2 minutes when v_Q = 20 mph and v_Q = 30 mph, respectively.

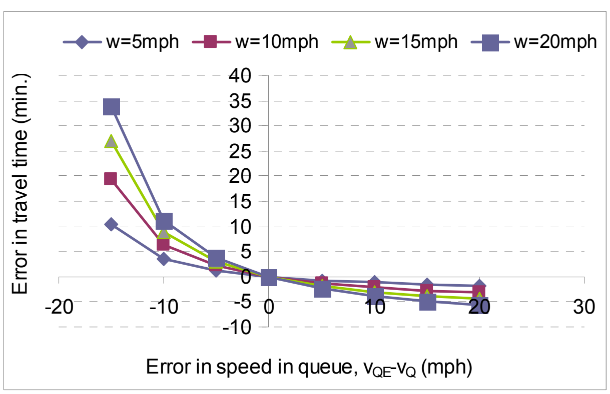
Findings are similar for the percent errors in travel time.



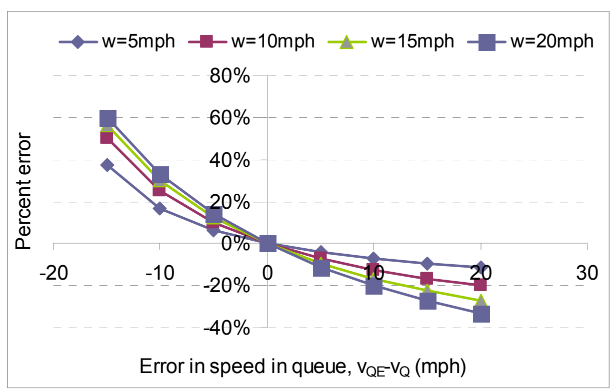
(a) Error in travel time (v_Q=10 mph)



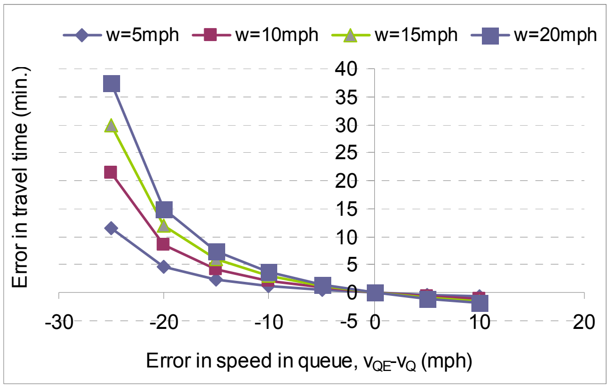
(b) Percent error (v_Q=10 mph)



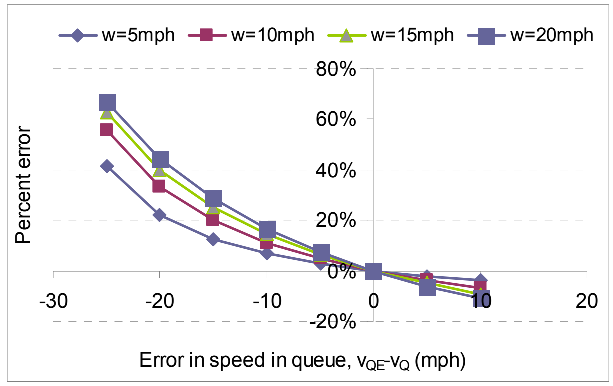
(c) Error in travel time (v_Q=20 mph)



(d) Percent error (v_Q=20 mph)



(e) Error in travel time (v_Q=30 mph)



(f) Percent error (v_Q=30 mph)

Figure 5.7 Errors in Travel Time Estimation Due to the Error in Estimated Speed in Congestion. ($d=d_1$=15 miles)

6.0 METRICS

Accurate travel times have the potential to benefit the travelling public and inaccurate travel times can be detrimental. Ideally, the errors should be lower than 10%; however, travel time estimations with errors up to 20% can still provide benefits to users (*Toppen, 2003*). Accuracy improvements are needed in cases of travel times with errors greater than 20%. According to Toppen and Wunderlich, the day-to-day variability of travel times in the region will dictate how accurate the travel times need to be to obtain benefit. In a region with a large variability in travel times, less accurate travel times can also provide benefits whereas in a region with relatively stable travel times knowledge of historical travel times can provide more benefit than inaccurate estimation (*Toppen, 2003*).

Reliability can be considered as a measure of the variability in the region's travel times. Reliability is defined as the consistency in travel times measured from day to day and/or across different times in a day. Therefore, if the travel times in a network are highly variable, the reliability of the travel times will be low and vice versa. Travel time reliability is significant to many users of the transportation system such as shippers, freight carriers and even individual drivers. A few metrics are available to quantify reliability; these are outlined below.

90^{th} or 95^{th} Percentile Travel Time: This metric conveys to the user how much the travel time would be on days with heaviest travel. While this metric has the advantage of being easily understood by the users, the disadvantage is that it cannot be compared across trips because of varying trip lengths.

Buffer Index: This metric represents the extra travel time that users add to their average travel times in order to ensure on-time arrival. The extra time is called buffer time.

Planning Time Index: This metric represents the total time that a traveler should allot to the trip to ensure an on-time arrival. While the buffer time represents the extra time that travelers need to add to their trip, the planning time represents the total travel time.

Estimating the above listed indices for each highway corridor and the network as a whole will indicate the variability of travel times. Calculation of these indices for each highway, along with a brief discussion, are presented in the following section.

I-5 Corridor

The I-5 corridor is a heavily traveled interstate freeway that runs north-south through Portland. For the purposes of the earlier study, this corridor was split into four segments – two directional segments north of downtown and two directional segments south of downtown. However, in order to study the reliability of this corridor, the two north segments were pooled together and the two south segments were pooled together.

I-5 North

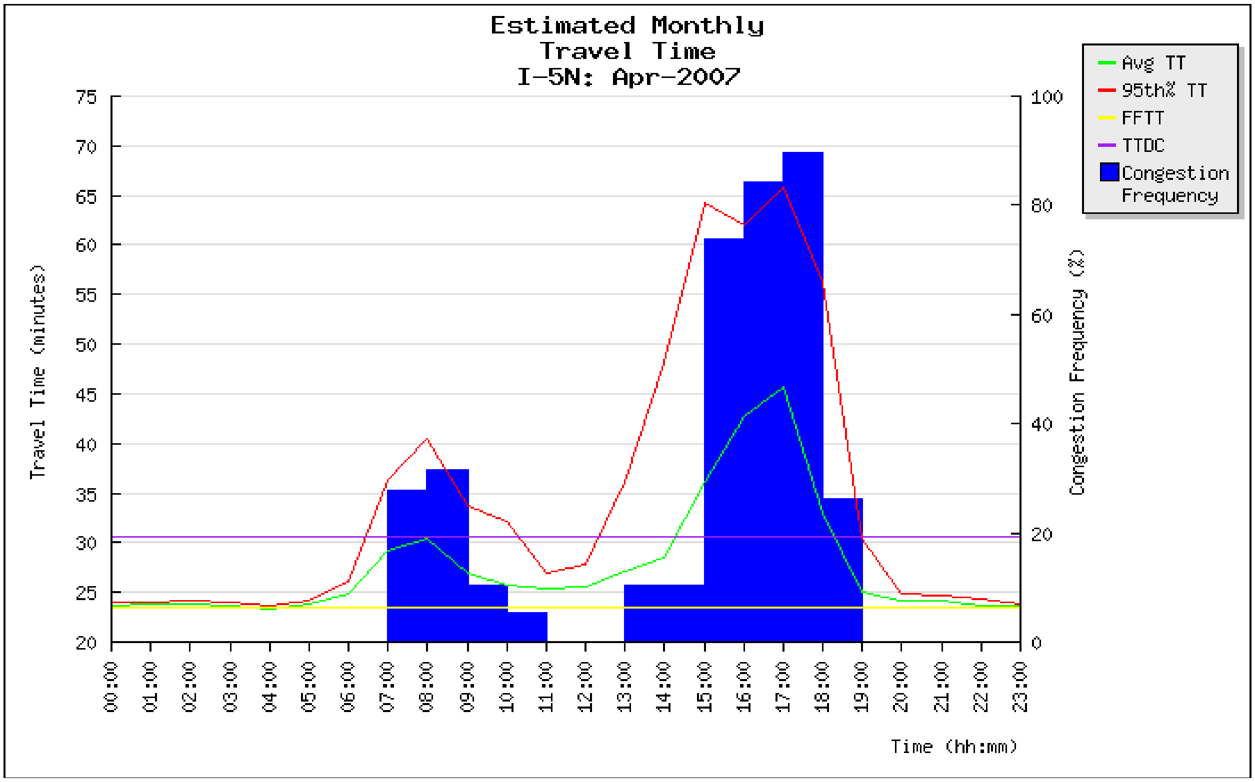


Figure 6.1 Plot of Estimated Monthly Travel Time for I-5 NB with Reliability Measures

Figure 6.1 shows the plot of estimated monthly travel time for the I-5 NB corridor, with the average and 95% travel times. Table 6.1 shows the values for the average and 95% travel times. The average travel time in April 2007 was 26.8 minutes and the 95% travel time was considerably larger at 41.2 minutes. The buffer time was 14.3 minutes. These figures indicate that the travel time is highly variable along this corridor and travelers have to allot at least 15 extra minutes to ensure an on-time arrival. Table 6.2 provides similar measures for weekdays only. For weekdays only, the buffer time increases to 18.2 minutes, indicating increased variability.

The implication from the above plots and tables is that travel times along the I-5 corridor are subject to a high degree of variability. Therefore, using the Toppen and Wunderlich principle, travel times need not be accurate to be beneficial.

Table 6.1 Monthly Reliability Measures for I-5 NB

Avg TT	Avg TS	Avg VS	FFTT	FFTS	95th% TT	95th% TS
26.85 Mins	51.44 MPH	54.33 MPH	23.48 Mins	58.82 MPH	41.17 Mins	33.55 MPH

Table 6.2 Reliability Measures for Weekdays for I-5 NB

Avg TT	Avg TS	95th% TT	95th% TS
27.67 Mins	49.92 MPH	45.88 Mins	30.10 MPH

I-5 South

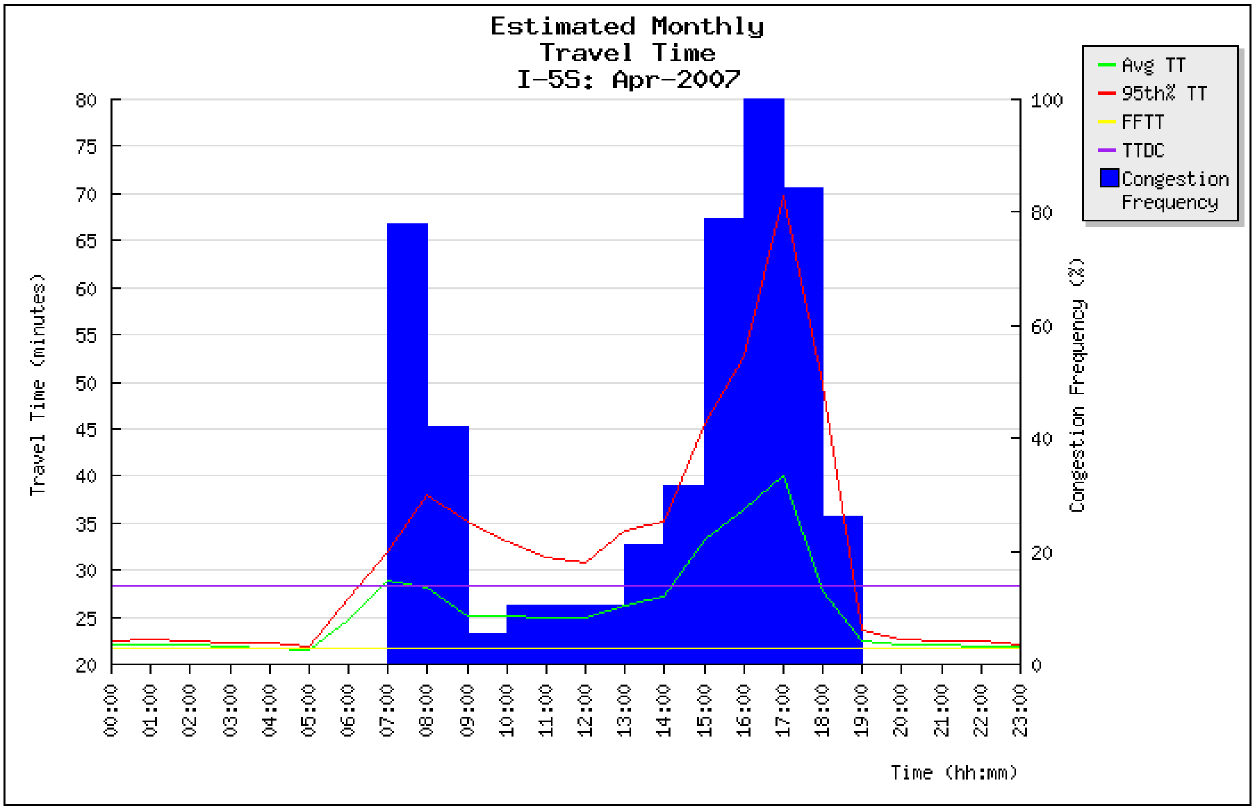


Figure 6.2 Plot of Estimated Monthly Travel Times for I-5 SB with Reliability Measures

Table 6.3 Monthly Reliability Measures for I-5 SB

Avg TT	Avg TS	Avg VS	FFTT	FFTS	95th% TT	95th% TS
24.81 Mins	50.11 MPH	55.16 MPH	21.75 Mins	57.16 MPH	35.19 Mins	35.33 MPH

Table 6.4 Reliability Measures for Weekdays for I-5 SB

Avg TT	Avg TS	95th% TT	95th% TS
25.61 Mins	48.54 MPH	37.90 Mins	32.80 MPH

Figure 6.2 shows the plot of estimated monthly travel time for I-5 SB, with the average and 95% travel times. Table 6.3 shows the values for the average and 95% travel times. The average travel time in April 2007 was 24.8 minutes and the 95% travel time was 35.2 minutes for a buffer time of 10.4 minutes, somewhat smaller than the buffer time for I-5 NB. The travel time along I-5 SB is somewhat less variable that that of I-5 NB - unsurprising since the Columbia River Crossing on I-5 NB is more significant than any bottleneck on I-5 SB. Travel times on I-5 SB may need to be slightly more accurate to benefit travelers.

7.0 CONCLUSION

Travel time estimation is an important feature of Advanced Traveler Information Systems (ATIS). This project evaluated the impact of congestion shock waves on the accuracy of travel time estimation using both theoretical and quantitative methods. Research has suggested that changing traffic conditions can negatively impact the accuracy of travel time estimation. This report provides theoretical and quantitative results to support that theory. In addition, bottlenecks on Portland freeways have been identified and shock wave speeds at several bottleneck locations have been analyzed. Finally, a discussion of accuracy metrics has been presented.

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