Toward Understanding and Reducing Errors in Real-Time Estimation of Travel Times

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Abstract: In recent years the increased deployment of intelligent transportation systems infrastructure has enabled the provision of real-time traveler information to the public. Many states as well as private contractors are providing real-time travel time estimates to commuters to help improve the quality and efficiency of their trips. Accuracy of travel time estimates is important, as inaccurate estimates can be detrimental. Improving the accuracy of real-time estimates involves identifying and understanding the sources of error. This paper reports on the errors found during the evaluation of real-time travel time estimates in Portland, Oregon and provides solutions for reducing estimation error. The midpoint algorithm used by the Oregon Department of Transportation was used to estimate travel times from speeds obtained from loop detectors. The estimates were assessed for accuracy by comparisons with ground truth probe vehicle runs. The findings from the study indicate that 85% of the travel time runs had errors below 20% and, further, that accuracy varied widely between segments. The evaluation of high-error runs revealed the main causes of errors as transition traffic conditions, failure of detectors and detector spacing. Potential solutions were identified for each source of error. In addition, a method was tested for evaluating the benefits of additional detectors by simulation of virtual detectors. The results indicate that additional detection helps in reducing the mean average percent error in most cases but the location of detectors is critical to error reduction.

INTRODUCTION

As congestion continues to worsen in major metropolitan areas in the United States, many jurisdictions are choosing to provide travel information to the public. This information allows drivers to intelligently choose times and routes for their trips, improving the efficiency of those trips and thereby reducing congestion and delay. The travel information provided includes road conditions, road closures, accident information and travel time estimates. Of these items, travel times are perhaps the most challenging to provide due to the complexities involved in generating accurate estimates. Travel times must be accurate to be useful; inaccurate travel information can be worse than no information at all.

The Oregon Department of Transportation (ODOT) currently provides travel times on three dynamic message signs (DMS) in the Portland region, but would like to expand that coverage in the near future to provide travel times on additional DMS and via 511 and the Internet. As part of a recently-concluded travel time study performed for ODOT (*1*), over 500 ground truth travel time probe runs were collected. These ground truth travel times were compared with estimated travel times calculated based on speeds and counts obtained from inductive loop detectors installed on Portland-area freeways. Of the runs analyzed, 15% exhibited errors over the FHWA-suggested error threshold of 20% (*2*).

The objective of this paper is to improve the understanding of the various causes of errors in real-time travel time estimation and to identify cost-effective solutions for improving estimation accuracy. To understand how to improve accuracy, it is essential to identify the reasons underlying the estimation errors. To this end, the travel time estimates exhibiting larger errors were analyzed in detail using statistical and graphical analysis. Several sources of error were identified including traffic conditions changing during probe vehicle runs, detector failure and the inability of detectors to capture traffic conditions due to reasons that included large detector spacing and unsuitable detector placement. The loop detectors on Portland-area freeways were installed for the purpose of enabling the original ramp metering system; as a result the detector spacing and placement is often inappropriate for travel time estimation. Several potential methods for reducing error were assessed. The impact of additional detection was investigated by means of simulated virtual detectors based on probe vehicle speeds; the results provide a methodology for analyzing the effectiveness of additional detection. In addition, the performance of various alternative estimation algorithms was analyzed. The study described in this paper extends a previous travel time study performed at Portland State University (*3*) with the addition of a much larger data set, a detailed analysis of high-error runs, an assessment of the impact of adding additional detection and an evaluation of several estimation algorithms currently in use by other departments of transportation.

The remainder of this paper is organized into several sections. A description of the study area and the data collection methodology is presented in the next section, followed by analysis, identification and description of the estimation errors. The final section discusses the benefits of additional detection to reduce a particular type of error followed by conclusions and ideas for future research.

STUDY AREA AND DATA COLLECTION

The Portland metropolitan region advanced traffic management system (ATMS) consists of a traffic management operations center (TMOC) and a freeway surveillance system with 671 inductive loop detectors (including Vancouver, Washington), 195 stations, 185 ramp meters and 18 dynamic message signs (DMS) as of July 2007. The inductive double loop detectors record speed, occupancy and count every 20 seconds and transmit this data in real time to ODOT's Region 1 TMOC. As part of their advanced traveler information system (ATIS), ODOT displays current travel time estimates on three DMS located along the I-5 corridor.

The study area consisted of directional segments on all major freeways in the Portland area as shown in Figure 1. For all highways except I-5 there are two segments for each freeway, one for each direction. I-5, I-84 and OR-217 segments extend the length of the freeway; US 26 and I-205 are limited sections of the freeway due to location of detection and construction. I-5 has been divided into four segments, two south of downtown and two north of downtown as show in Figure 1. Ground truth travel times were collected using probe vehicles equipped with GPS-enabled Garmin iQue™ 3600 devices. Software developed by the ITS Lab at Portland State University for the iQues (*4*) was used to record the position and speed of the probe vehicle every three seconds. Data was collected in morning and afternoon weekday peaks on selected days during the period January – May 2007. Data was collected on all freeways in the Portland metropolitan area. Segments on two freeways (I-5 and OR-217) were selected for extended data collection and detailed analysis based on infrastructure, perceived level of interest, and congestion. Less data was collected on segments with known detector infrastructure issues and construction during the collection periods (I-205, I-405, US-26, I-84).

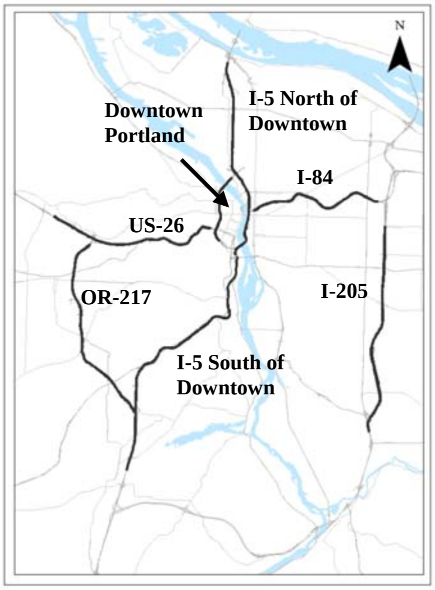

FIGURE 1 Map of the study area.

Once the travel time collection was complete, the data from the iQues was downloaded and processed. The probe vehicle runs were cut to match the predefined segments shown in Figure 1 using ArcGIS. For each probe run, the travel time was calculated as the difference in the time recorded at the end of the segment and the time recorded at the start of the segment. Travel time estimates from the loop detector data were obtained from PORTAL, the official transportation data archive for the Portland region (*5*).

DATA ANALYSIS

To understand the accuracy of current ODOT travel time estimation, a variety of analyses were performed. The analysis of all segments combined is presented first, followed by detailed segment-by-segment analysis. Subsequent sections describe investigations into methods for improving estimation accuracy.

A total of 544 runs were collected and analyzed for this study. Figure 2 presents a histogram of estimation errors over all runs on all segments. The metric in this figure is percent error which is calculated as the difference between estimated travel time and ground truth travel time as a percentage of ground truth travel time. The travel time estimation algorithm is a standard midpoint algorithm using the most recent three minutes of 20-second speed readings. Recent research and FHWA analysis indicates that travel time estimation errors should ideally be less than 20% (*2*,*6*). Based these results, an error threshold of 20% was adopted for this study; this threshold applies to absolute error.

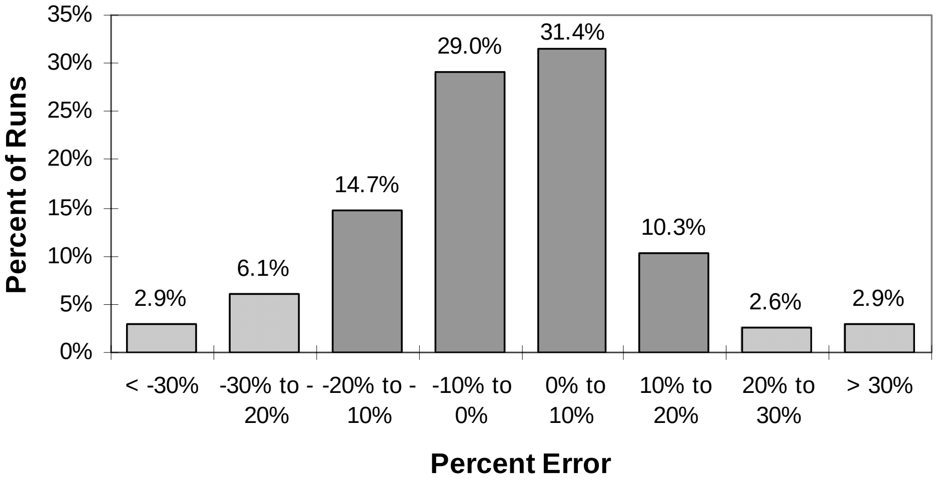

FIGURE 2 Histogram of average percent errors.

Figure 2 indicates that the accuracy of estimation is good with 60% of the travel time runs having errors less than 10%, and an additional 25% of runs having errors less than the threshold of 20%. Therefore, 85% of runs have errors less than the 20% threshold, leaving 15% of the runs (marked with lighter shading) where improvement is needed. Table 1 shows a breakdown of error rates by highway segment. For each segment, a number of descriptive statistics are provided as follows:

MAPE (Mean Absolute Percent Error): Percent error is calculated as described above. Using absolute percent error prevents positive and negative values from canceling each other out (*6*).
SDPE (Standard Deviation of Percent Error): Recommended metric for evaluation of travel time accuracy (*6*).
MPE (Mean Percent Error) and SE (Standard Error): Standard error is the standard deviation of the absolute percent errors divided by the square root of the number of runs and represents the error in the mean. MPE and SE together provide a measure of estimation bias. A negative MPE indicates underestimation; conversely a positive value indicates overestimation. If the MPE is more than one SE away from zero, it is likely that the bias is significant.
Num Runs: This field indicates the number of ground truth runs collected on a segment. As described previously, the number of runs collected on each segment varied depending on level of congestion, detector infrastructure and perceived interest.
Percent Errors < 20%, 30%*:* Theses two fields indicate the percent of runs for a particular segment that show absolute errors less than 20% and 30%, respectively.

For all segments as shown in Table 1, the mean absolute percent error values are below 20%. The SDPEs are less than or equal to 20% with the exception of the I-5 NB segment North of Downtown, which has a SDPE of 31.5. This large SDPE is a result of large positive (over-estimation) and negative (under-estimation) errors on this segment. The mean percent errors reveal over or under estimation bias. For example, the segment I-5 NB South of Downtown has an overestimation bias, while estimates on OR 217 NB are biased towards underestimation. The level of accuracy varies widely from segment to segment. Some segments such as I-5 SB north of downtown show only 76% of runs that have errors less than 20% whereas other segments such as I-5 NB south of downtown show 91% of the runs that have errors less than 20%.

TABLE 1 Errors by Highway Segment

Segment Description	Length (mi.)	Avg Detector Spacing (mi.)	MAPE	SDPE	MPE	SE	Num Runs	Percent Estimates with Error < 20%	Percent Estimates with Error < 30%
I-5 NB South of Downtown	8.8	0.88	7.7	10.8	1.9	1.3	67	91.0	97.0
I-5 SB South of Downtown	8.0	1.14	11.0	14.4	-2.4	1.9	60	86.7	95.0
I-5 NB North of Downtown	6.71	0.96	16.9	31.5	7.9	3.6	77	82.0	87.0
I-5 SB North of Downtown	7.31	0.73	13.5	16.5	-2.0	1.9	76	76.3	94.7
OR 217 NB	6.99	0.78	11.8	11.9	-8.2	1.8	45	82.2	96.0
OR 217 SB	6.99	0.78	11.4	13.0	-8.5	1.9	45	86.7	91.1
I-84 EB	5.07	1.27	11.5	20.0	3.7	5.4	14	85.7	85.7
I-84 WB	4.8	1.20	17.1	19.6	-6.2	5.0	15	46.7	80.0
I-205 NB	7.51	1.07	7.8	10.0	2.1	1.8	32	96.9	100.0
I-205 SB	7.22	0.90	9.0	15.2	0.1	2.7	31	90.3	96.8
I-405 NB	2.56	1.28	4.3	4.8	-2.1	1.0	21	100.0	100.0
I-405 SB	2.28	0.57	8.3	10.6	-4.2	2.3	21	95.2	100.0
US 26 EB	6.21	1.24	12.6	13.5	-7.1	3.0	20	80.0	100.0
US 26 WB	6.21	1.55	7.6	8.5	3.9	1.9	20	100.0	100.0

Highways I-5 and OR-217 were selected for detailed analysis due to reasonable detector infrastructure, lack of construction and level of interest. A brief description of travel time accuracy on each of these segments is provided below.

I-5 South of Downtown

The I-5 NB (South of Downtown) segment begins at the Carman DMS (milepost 290.9) and extends to the junction of I-5 and I-405 (milepost 299.7). In this segment, there is large detector spacing (2.37 miles) between the stations at Terwilliger Blvd. (milepost 297.33) and Macadam Ave. (milepost 299.7). Further, this section of freeway is curved and known to be congested. Figure 3 shows a speed plot of a high-error run (Run 254 at 15:55:59 on April 19, 2007) on this segment. The speed plot shows a plot of probe vehicle speeds, detector speeds and real-time detector speeds. The probe vehicle speeds are the speeds recorded by the probe vehicle as the vehicle traveled through the segment; the detector speeds are the instantaneous detector speeds recorded at the time the probe entered the segment – these are the speeds used for travel time estimation; finally, the real-time speeds are the speeds recorded by the detector at the time the probe passed the detector. The real-time speeds are not used in generating real-time travel time estimates since they represent measurements taken after the probe entered the segment; however, they can be used for offline analysis and to help understand sources of errors. Probe speeds are shown as small black dots, instantaneous detector speeds are shown as grey circles and real-time detector speeds are shown as dark grey squares. The large detector spacing is evident in Figure 3. It was theorized that additional detection in this region would improve accuracy.

The I-5 SB (South of Downtown) segment stretches from the DMS at milepost 298 to the intersection of I-5 with Tualatin/Sherwood Rd. (milepost 290). The problematic section of this segment is the area between mileposts 293 and 291 where there is a large spacing of almost two miles between detectors. Complicating matters, OR-217 merges into I-5 SB in this section of freeway, leading to a situation where there is a large, recurrent bottleneck, but no nearby detectors to capture the congestion. All runs with absolute error greater than 20% are underestimations and exhibit problems in this region. Run 217 (April 16, 2007, 16:19:12), shown in Figure 3, illustrates this issue. Additional detection upstream of the bottleneck would be expected to improve estimation accuracy.

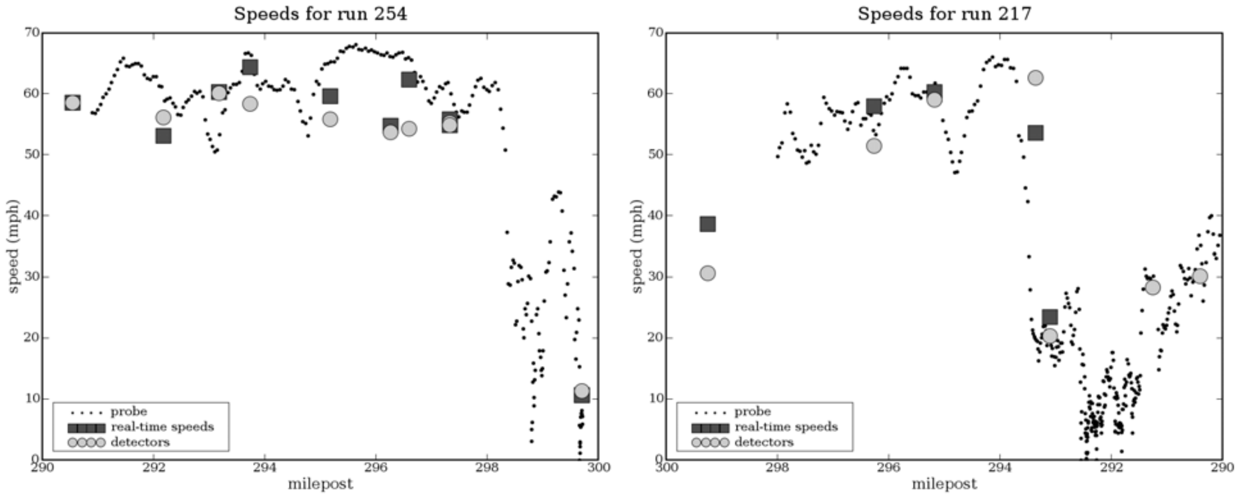

FIGURE 3 High error runs for I-5 NB and SB (south of downtown).

I-5 North of Downtown

The north segment of I-5 starts near downtown Portland and extends up to the Columbia River, between mileposts 299.99 and 307.46. The analysis of errors on this segment revealed an overestimation bias. Visual analysis of speed and trajectory plots for this segment appeared to show that many runs were affected by changes in traffic conditions after the probe started its run. In addition, some of the runs were negatively affected by detector failure. Figure 4 shows a speed plot for run 307, which took place on April 24, 2007 at 17:47:00. The error for this run was due to congestion clearing after the probe entered the segment, as can be seen from the difference between the instantaneous detector speeds and the real-time speeds in Figure 4, leading to an overestimation.

The I-5 SB North of Downtown segment extends from the Columbia River to downtown Portland (over the double deck Marquam Bridge) between mileposts 307.47 and 299.83. On this segment, underestimation errors occurred predominantly in the afternoon peak. The high-error runs in the PM peak consistently showed problems in the areas between mileposts 304 and 299. This area is characterized by high congestion and complex traffic patterns because of the highway-to-highway connections that exist in this section. Figure 4 shows the speed plot for run 166 which was a high-error run that occurred on February 15, 2007 at 17:13:33. As is apparent from Figure 5, the speed dropped and oscillations occurred between milepost 304 and 299. To reduce error, additional detection may be necessary on this segment.

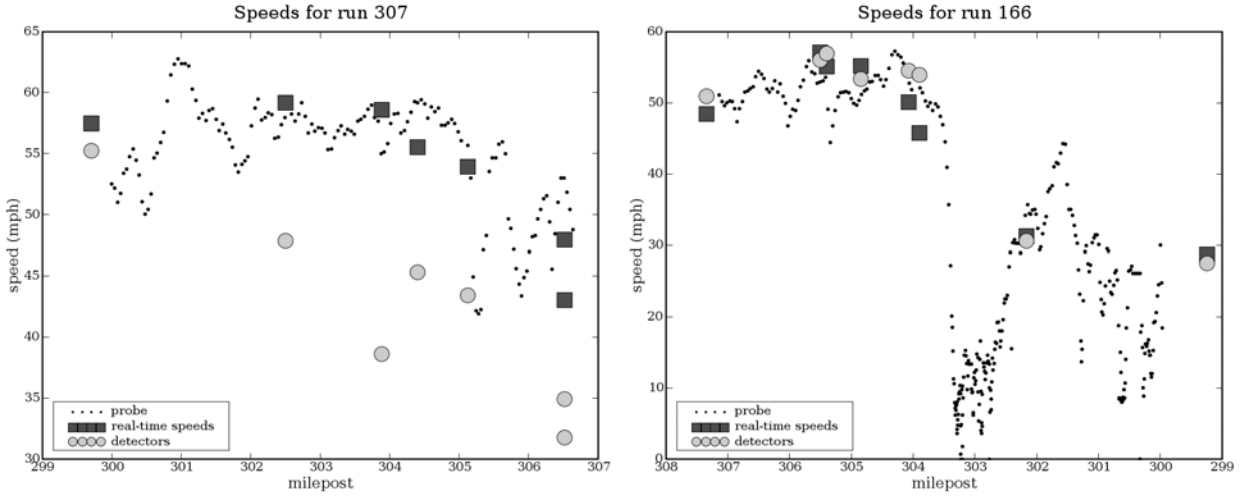

FIGURE 4 High error run on I-5 NB and SB (north of downtown).

Oregon 217

The northbound segment spans from Lake Oswego to US 26. Of runs with error greater than 20% all but one were underestimations, further the statistical analysis shows an underestimation bias. All the runs on this segment had one or two non-functional detectors. One can observe that the first portion of this segment, near milepost 7 is problematic. Figure 5 shows the speed plot for run 267 which occurred on April 16, 2007 at 16:16:05. For this run, two detectors at mileposts 6.61 and 2.16 were not functional. Had the detector at 6.61 been functional, the error might have been lower. However, other runs show high error near the start of the segment even with a functioning detector at milepost 6.61 (72nd Ave.). Therefore, an additional detector between milepost 6.61 and 7.25 may contribute toward reducing the error further.

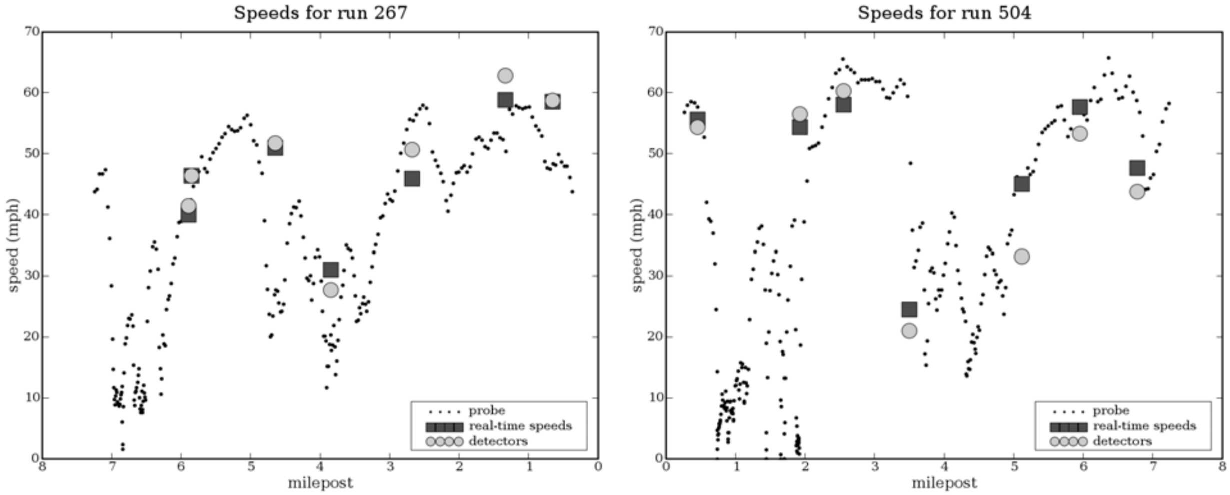

FIGURE 5 High error runs on OR- 217 NB and OR-217 SB.

The OR 217 SB segment spans between US 26 and I-5. The larger errors were predominantly underestimates. Similar to 217 NB, detector failure played a role in the estimation error on this segment. The detectors at milepost 0.76 and milepost 4.35 were not functional for all runs on this segment. In addition, the detector at milepost 3.12 was not functioning for some runs. Figure 5 shows speed plot for run 504 on April 19, 2007 at 7:52:09. There are speed drops at the beginning of the segment between mileposts 0 and 2, which are not captured because of the lack of a functioning detector.

Understanding the sources of estimation errors is crucial to fixing those errors. For this purpose, this study analyzed the high-error runs on the I-5 and OR-217 segments in detail. We elaborate on the types of errors found in those segments in the following section.

SOURCES OF ESTIMATION ERRORS

A review of the high error runs for the I-5 and OR-217 segments showed three main sources of errors which are outlined below.

Errors due to Changes in Conditions

The midpoint algorithm used by ODOT for real-time travel time estimates is static in nature and uses speeds measured from each detector at the time a vehicle enters the segment to estimate travel times. Therefore, in case of real-time estimation, the current algorithm does not attempt to correct for changes in conditions that occur after a vehicle enters the segment. Thus, while the algorithm performs well under steady traffic conditions, it is likely to fail under transition conditions. Figure 4, run 307, illustrates this type of error; the real time speeds deviate significantly from the instantaneous speeds indicating that conditions have changed after the probe vehicle started the run. In such cases, potential solutions involve using of short-term trending and historical data. Varying the length of the real-time average used as input to the estimations was investigated, including 1-, 3-, 6- and 9-minute averages; however no significant accuracy differences were observed.

In severe congestion, traffic states are relatively stable and travel time estimation algorithms are expected to perform well. In this study, 61% of runs with average probe speed less than 30 mph and 40% of runs with average speed less than 20 mph exhibited an absolute error percent of less than 20%, indicating that some highly-congested runs did indeed have low error.

Errors Due to Non-functioning Detectors

Inductive loop detectors are often subject to failure which can impact the accuracy of the travel time estimation process either in small or large magnitude depending upon the severity of failure. The non-functioning detectors affect the accuracy of the real time estimates by artificially increasing the spacing between the functioning detectors. In this study, a vast number of the runs had at least one non-functional detector station and some runs had two or more detector stations that were not working during the course of the runs. Note that a detector station is a set of detectors (one detector per lane) at a specific location on a highway. Figure 5, runs 267 and 504, illustrate this type of error.

Even with regular maintenance and increase in communication bandwidth, the mal-functioning of detectors cannot be completely eliminated. In such cases, using historical data from the missing detector or adding low-cost portable detectors in periods of extended downtime might help reduce the error.

Errors Due to Large Detector Spacing

In addition to changing conditions and detector and communication mal-function, another cause of estimation error was large detector spacing. This type of error is illustrated in Figure 3, runs 254 and 217. On I-5 SB South of Downtown, a bottleneck exists at the merge of OR-217 into I-5 SB. Unfortunately; there is no detector near this bottleneck as shown in Figure 3, run 217. As a result, the congestion from this bottleneck must propagate for 2.11 miles until it can be detected. In Figure 3, run 254, a spacing of 2.37 miles exists between the last two detectors, within which a significant speed drop takes place, leading to errors in estimation due to the inability of the widely spaced detectors to capture these conditions. In both cases, additional detection should help in reducing errors.

REDUCING ESTIMATION ERROR

The analysis in the previous section showed a significant percent of travel time runs with errors over the 20% threshold. In this section, reducing those errors through the use of additional detection and alternative algorithms is explored.

Effect of Additional Detection

The location and density of detectors are critical to accurate travel time estimation. Detector location is important because errors often occur during transition conditions when queues are forming and dissipating. If detectors are located such that they can capture queue changes, estimation errors will be lower. Conversely detectors in locations where traffic is generally free-flowing will have a limited affect on estimation error for recurrent congestion; such detectors may help estimation error under incident conditions. High density of detectors, which implies small spacing between detectors, is ideal for reducing errors in travel time estimation. However, close detector spacing is not always realistic due to detector installation and maintenance costs.

In Portland, the freeway loop detectors were installed for the purpose of ramp metering, so detector spacing varies widely, depending on the location of on-ramps, with an average detector spacing of approximately 1.2 miles. Additional detectors are needed for accurate travel time estimation in Portland; however, funds are limited. Therefore, it is important to understand the effects of additional detectors on estimation errors so that detector installation can be prioritized appropriately. To attempt to understand the error reduction because of adding detection, addition of detectors on I-5 and OR-217 were simulated using probe vehicle speeds. Simulated detectors were added at two different locations on each of our six selected segments. The location of the detectors was determined based on the existing detector infrastructure, traffic patterns and queues on each segment, including use of speed plots such as were shown in the previous section. The locations of the additional detectors are listed in Table 2.

TABLE 2 Locations of Additional Detectors

Segment Description	Length of Segment (mi.)	Average Detector Spacing (mi.)	Additional Detector Location 1 Milepost	Additional Detector Location 2 Milepost
I-5 NB (SoD)	8.80	0.88	298.0	295.5
I-5 SB (SoD)	8.00	1.14	292.0	292.48
I-5 NB (NoD)	6.71	0.96	300.5	300.8
I-5 SB (NoD)	7.31	0.73	306.5	301.25
OR-217 NB	6.99	0.78	6.9	4.3
OR-217 SB	6.99	0.78	1.00	3.00

The speeds for the simulated virtual detector were drawn from the probe vehicle speed at that location, recognizing that the probe vehicle speed would be similar to the real time speed that would have been measured if a detector had been present at the location of the virtual detector. Travel times were estimated with the presence of simulated detectors using the simulated detector speeds, as just described, and real-time detector speeds. Recall, real-time detector speeds are the speeds measured by detectors at the time the probe passes a detector, as opposed to the instantaneous speeds that are recorded by each detector at the time the probe vehicle enters the segment. Comparing the travel times with additional detection with the midpoint-instantaneous travel times is not reasonable because, the instantaneous speeds for the simulated detectors are not available. Therefore, travel times with the additional detectors are compared to the travel times estimated with real-time speeds since this is a better comparison. Table 3 shows summary statistics for instantaneous-midpoint, real-time midpoint and real-time midpoint with detectors added at two locations. The instantaneous-midpoint travel times are provided in order to assess the improvement in errors that results from using real-time speeds as opposed to instantaneous speeds.

TABLE 3 Effects of Additional Detectors on Errors

Segment Description	Midpoint Error (%)			Real Time Error (%)			Real Time Error with Detector at Location 1 (%)			Real Time Error with Detector at Location 2 (%)		
	MAPE	SDPE	SE	MAPE	SDPE	SE	MAPE	SDPE	SE	MAPE	SDPE	SE
OR 217 NB	13.12	11.98	1.65	9.66	10.52	1.35	9.67	13.11	1.46	9.37	10.41	1.39
OR 217 SB	11.39	12.99	1.56	12.19	15.01	1.80	12.10	19.97	2.40	12.02	15.1	1.81
I-5 NB SoD	8.14	11.37	1.13	6.72	9.46	0.97	5.43	7.76	0.76	6.78	9.44	0.95
I-5 SB SoD	10.75	14.09	1.20	11.47	15.11	1.29	7.39	9.68	0.81	10.19	13.87	1.26
I-5 NB NoD	17.05	32.03	3.27	15.40	26.93	2.56	10.60	15.35	1.29	11.24	15.89	1.31
I-5 SB NoD	13.37	16.43	1.09	14.38	17.49	1.17	11.73	14.55	1.11	13.55	15.43	1.10

As seen from Table 3, for each segment, when additional detectors are added at locations mentioned in Table 2, mean absolute percent error (MAPE) is lower than the error of the real-time travel time estimate (real-time speeds with existing detectors). The addition of detectors at the particular locations seemed to show more benefit on I-5 in terms of error reduction than OR – 217. Figure 6 shows a histogram of mean absolute percent error. The MAPE values represented in the above table are for all runs on each segment. The standard error of the mean (SE) represents the variability or error in the mean. The standard error along with the MAPE can indicate the region where the mean of the whole population can be expected to fall. Therefore from the above table, the addition of detectors in location 1 for three out of four segments of I-5, has significantly reduced estimation error as compared to the real-time estimates with existing detectors.

Performance of Alternative Algorithms

Several algorithms are in use by various Departments of Transportation around the United States. These algorithms are similar to the standard midpoint algorithm; however, they vary the definition of detector influence area. The following describes three such algorithms and compares them to the standard midpoint algorithm.

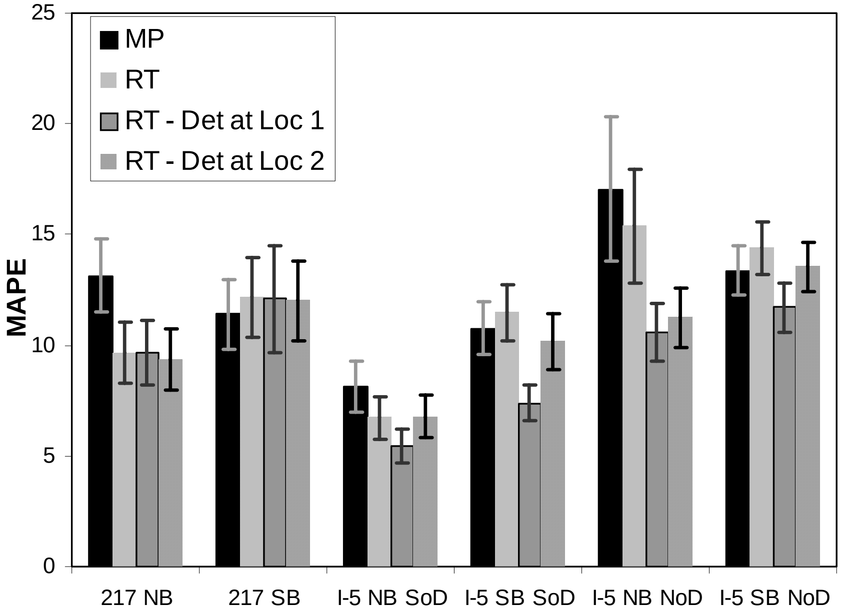

FIGURE 6 Mean absolute percent error with standard error bars.

The Washington Department of Transportation has developed an algorithm for real-time travel time estimation. In this algorithm, travel time is estimated as the ratio of distance between the detectors to the average speed obtained from the detectors. The algorithm used by WSDOT to display travel times on the web includes an historical component which was not considered for this analysis (*7*).7 The travel times estimates used in San Antonio are calculated by using the lower of the speeds recorded by detectors at either end of a segment, to estimate speed for that segment. (*8*). The Mn/DOT has studied an algorithm that divides the freeway segments into thirds. The upstream detector speed is used to estimate speed for the first third; the downstream detector speed for the last third; and the average of the two detector speeds is used for the middle third of the segment (*9*).

Table 4 provides a statistical a comparison of estimation errors using standard midpoint algorithm, WSDOT algorithm and the San Antonio algorithm on the I-5 NB south of downtown segment. Note that this table does not necessarily reflect on the accuracy of the WSDOT algorithm as the WSDOT algorithm also incorporates historical data. In general, the Midpoint, WSDOT and Minnesota algorithms have similar performance; due to its nature the San Antonio algorithm has an overestimation bias. The Mn/DOT algorithm has the lowest error numbers; however, the difference does not appear to be significant.

This project evaluated only algorithms used in practice; a recent paper by Kothuri *et al*. provides a more complete review of travel time estimation algorithms (*10*). In addition, a recent NCHRP publication provides information about freeway performance metrics including travel time and reliability (*11*).

TABLE 4 Statistical Algorithm Comparison

	Standard Midpoint	San Antonio	WSDOT (Real-time portion)	Mn/DOT
MAPE	12.50	22.64	11.74	11.88
SDPE	20.81	38.25	16.34	19.26
MPE	1.59	19.33	-5.69	-0.76
SE	0.99	2.17	0.75	0.91

CONCLUSIONS

The primary objective of this paper was to identify and understand the sources of errors for real-time travel time estimation in Portland, Oregon. The analysis of travel time estimates revealed that estimation accuracy was good with mean absolute percent error of 11.3% over all runs and 85% of the runs exhibiting errors less than 20%. An in-depth study of the high-error runs revealed that transition conditions in traffic, detector failure and detector spacing were the main causes for high errors. Transition conditions such as change in traffic state from congested to uncongested and vice versa cannot be captured by using instantaneous speeds for travel time estimation. Historical data or trends should be incorporated into the travel time estimation to improve accuracy during transition conditions. Detector failure was found to be another major cause for high errors. A potential solution is to incorporate historical data from the detector or use gap filling techniques to account for the data loss. States can also explore the possibility of portable low cost detection when detectors are not functional for extended periods of time. Detector spacing was another key factor that affected the accuracy of the estimates. High detector density is critical in locations where transitions and bottleneck occur. Therefore, it is critical to study traffic patterns on highways and identify locations of high errors and review detector density in these critical locations and augment with additional detection where necessary. The benefits of additional detection namely error reduction should be traded off against cost of installing and maintaining the detectors to achieve desired accuracy.

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