

1 **Beyond Corridor Reliability Measures: Analysis of Freeway Travel Time Reliability at the**
2 **Segment Level for Hotspot Identification**

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1 **Abstract.** Travel time based performance measures are widely used for transportation systems and particularly
2 freeways. However, it has become evident that travel time reliability, taking into account the variability in travel
3 times, may be a more important metric for evaluating the performance of a freeway over time and space. The
4 objective of this paper is to build upon previous work performed at the directional corridor level for planning
5 purposes and analyze the ways in which travel time reliability can be measured at the segment level, aimed at
6 operational solutions and hotspot identification. This was accomplished using archived loop detector data from the
7 Interstate 5 freeway in Portland, Oregon as a case study. Breaking the overall 24-mile northbound I-5 freeway
8 corridor into shorter segments on the order of one mile long, this study shows how reliability can vary across
9 freeway segments (space) and over time. Corridor travel time variance of correlated segments versus uncorrelated
10 segments is also discussed. To explore the inconsistency among existing commonly used travel time reliability
11 indicators, several reliability measures are examined using differential reliability maps and compared with travel
12 time based measures. Finally several reliability measures are used to prioritize freeway segments according to travel
13 time reliability which is beneficial in regional transportation planning, operations, and bottleneck prioritization.
14

15 INTRODUCTION

16 In recent years, travel time reliability as a key freeway performance measure has become an important topic for
17 researchers, practitioners and policy makers around the world. Researchers have used a range of definitions for
18 travel time reliability and developed several metrics to report it. Travel time reliability can be defined as the
19 probability that a certain trip (from a given origin to a given destination) can be made successfully within a specified
20 interval of time (1). Small et al. introduced reliability as the uncertainty about arriving at one's destination at a
21 predicted time (2). The Florida DOT defines reliability as the percent of travel that takes no longer than the expected
22 travel time plus a certain acceptable additional time (3). Travel time reliability can capture the variability
23 experienced by individual travelers (4), and it is an indicator of the operational consistency of a facility over an
24 extended period (5). Reliability of travel time can also be used as a measure of quality of service (6). The standard
25 deviation, median, coefficient of variation, buffer time, 95th percentile of travel time, buffer index, planning time
26 index, misery index, skew and width, and congestion frequency are some of the other metrics used to measure travel
27 time reliability. Given a large freeway data archive as a platform where travel time variability can be directly
28 computed, the objective of this research is to extend previous work (7) done at a directional freeway corridor level
29 with a segment level analysis of travel time reliability over a 24-mile freeway in Portland, Oregon (northbound
30 Interstate 5). Using historical measured data, the aim is to develop a tool that can identify the points in time and
31 space where notable reliability patterns emerge. This is important for planning and operational purposes and takes
32 advantage of this high resolution freeway data archive.
33

34 LITERATURE REVIEW

35 Previous studies have pointed to the usefulness of using travel time reliability as a performance measure (4, 6, 7, 8)
36 for planning and operations. Researchers use a range of definitions of travel time reliability in different contexts.
37 Reliability is expressed by Nam et al. (4) in terms of standard deviation and maximum delay that is measured based
38 on a triangular distribution. Their analysis revealed that reliability is an important factor affecting mode choice
39 decisions. Since values of reliability were higher than values of time, the benefits from improving travel time
40 reliability were greater than merely reducing the travel time at the same level of improvement. In a previous study,
41 Emam et al. defined travel time reliability as the variability of travel time experienced by individual travelers and as
42 an indicator of the operational consistency of a facility over an extended period (5).

43 Travel time is a useful measure of freeway service quality and level of service (LOS). Chen et al. found that
44 under LOS A through E, the travel time is low and consistent; under LOS F, the travel time can be up to three times
45 longer than during freely flowing conditions, and the standard deviation is also larger (6). Travel time reliability can
46 also be used as a measure for improving real-time transportation management and traveler information systems.
47 Metropolitan planning organizations (MPOs) can use travel time reliability to prioritize freeway corridors and
48 roadway segments (7). Reliability measures can also be used to highlight corridors and segments that are good
49 candidates for operational measures such as traveler information, focused incident management, or ramp metering.
50 In a previous study Lyman and Bertini (7) used the buffer index to prioritize directional freeway corridors in the
51 Portland metropolitan region. In this study a similar methodology is used to prioritize individual freeway segments,
52 and to help identify hotspots. In this analysis, a directional freeway corridor is made up of a collection of segments
53 arranged and designed to achieve desired functions with acceptable performance and reliability. The relationship
54 between the freeway corridor system reliability and the reliability of its individual segments is the subject of this
55 analysis.
56

1 **EXISTING TRAVEL TIME AND RELIABILITY MEASURES**

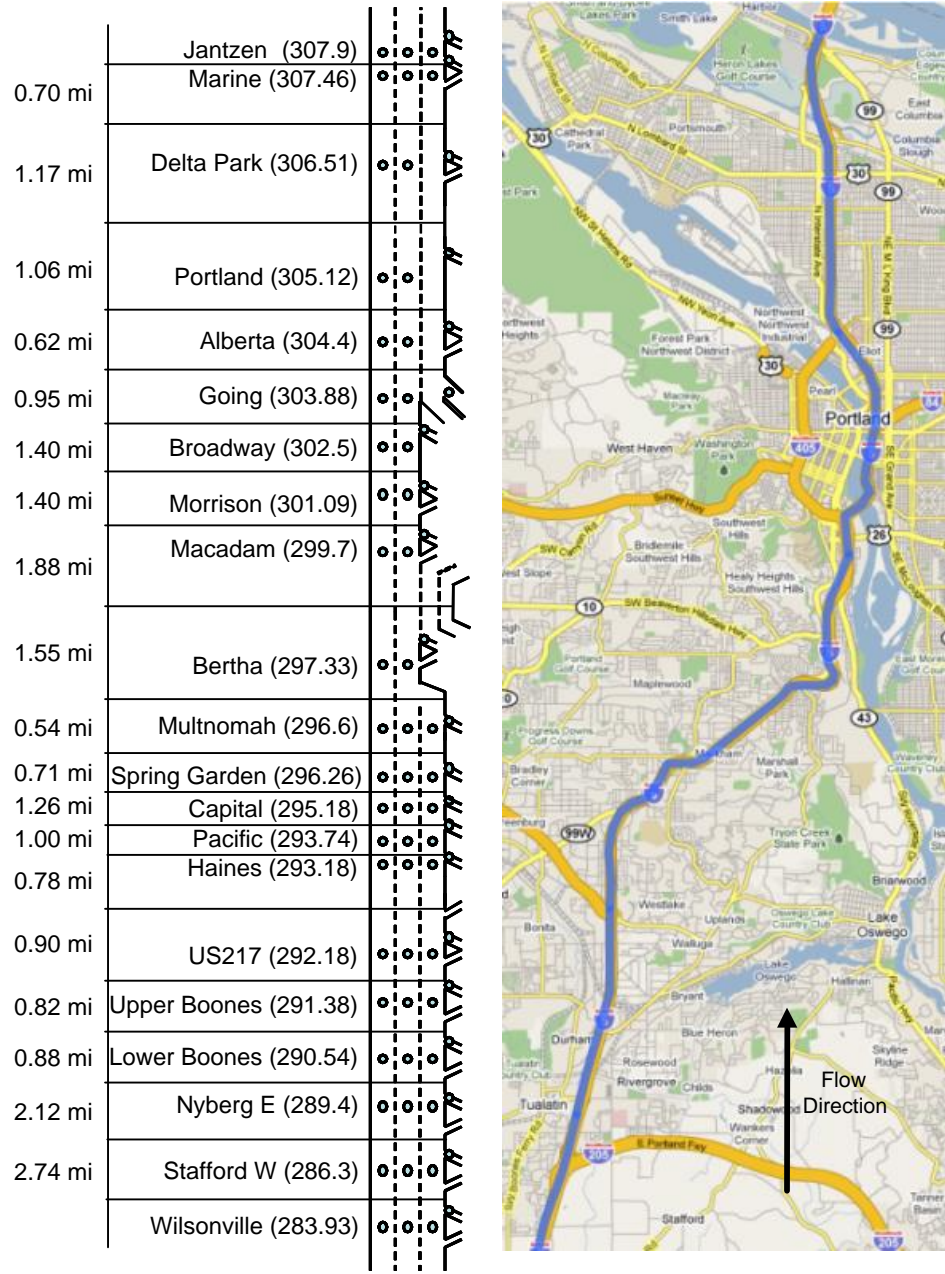
2 Travel time related performance measures are usually constructed from measurements of speed, volume and/or
3 travel time. For example, the travel time index is usually computed as the mean travel time divided by an assumed
4 free flow travel time. In addition, measures that incorporate travel time reliability have been proposed and
5 demonstrated under different circumstances. The following lists some reliability measures that are commonly used:

- 6 • 90th or 95th percentile travel time
 - 7 • Standard deviation of travel time
 - 8 • Coefficient of variation: computed as standard deviation of travel time divided by mean travel time.
 - 9 • Buffer index: computed as difference between 95th percentile travel time and mean travel time, divided by
10 mean travel time.
 - 11 • Planning time index: computed as 95th percentile travel time divided by assumed free-flow travel time.
 - 12 • Misery index: computed as difference between mean travel time for worst 20% of trips and overall mean
13 travel time, divided by mean travel time.
 - 14 • Skew of travel time distribution: computed as the difference between 90th and 50th percentile travel time,
15 divided by the difference between 50th and 10th percentile travel time.
 - 16 • Width of travel time distribution: computed as the difference between 90th and 10th percentile travel time,
17 divided by the 50th percentile travel time.
 - 18 • Congestion frequency: percent of time that mean speed drops below a particular speed.
 - 19 • Lateness and earliness indices: can be based on the log-normal distribution (9)
- 20

21 **METHODOLOGY**

22 The Portland Oregon Regional Transportation Archive Listing (PORTAL) is the official archived data user service
23 (ADUS) for the Portland region. Currently, the Oregon Department of Transportation (ODOT) uses the standard
24 midpoint algorithm to generate travel time estimates from 20-second time mean speed data measured by dual
25 inductive loop detectors. For this analysis, archived loop detector data aggregated over 5-minute intervals over all
26 the lanes for weekdays in February and March 2007 from PORTAL are used to estimate travel time reliability.
27 Breaking the overall northbound I-5 freeway corridor into 22 segments between milepost 283.93 and milepost 307.9
28 (one detector station per segment, segment boundaries established at the midpoints between detectors), travel time
29 reliability was computed for each segment during each time interval. The average segment length is about 1.2 mile
30 (1.9 km). There is a High Occupancy Vehicle (HOV) lane between mileposts 302.5 and 307.46 operating between
31 15:00 and 18:00 on weekdays. Data from the HOV lane were not included in the data analysis. Data from the
32 milepost 291.38 were not available in the study time period. So the segment associated with this milepost was
33 removed from the analysis.

34 Figure 1 shows a map of the I-5 freeway. Unreliable segments and time periods were identified by plotting
35 a travel time index map and reliability maps based on standard deviation, coefficient of variation, buffer index,
36 planning time index, and congestion frequency. Finally, the buffer index, planning time index, coefficient of
37 variation, and congestion frequency were used to prioritize freeway segments according to their travel time
38 reliabilities.
39



1
2 **FIGURE 1 Map of I-5 Freeway in Portland, Oregon**
3

4 **CORRIDOR AND SEGMENT TRAVEL TIME CHARACTERISTICS**

5 The northbound I-5 freeway is a major corridor through Portland, Oregon. Individual segment travel times in this
6 corridor are measured using dual inductive loop detector data. If we consider a corridor that is composed of n
7 segments, then the corridor travel time can be computed as the summation of the individual segment travel times
8 along the corridor as:

9

$$\bar{t}_R = \sum_{i=1}^n \bar{t}_i \quad (1)$$

10 **Corridor travel time variance of uncorrelated segments**

11 One reason for the use of the variance in preference to other measures of dispersion is that the variance of the sum
12 (or the difference) of uncorrelated segments is the sum of their variances. Using the Bienaymé formula, it is often

1 made with the stronger condition that the segments are independent, but uncorrelatedness also suffices. Therefore,
 2 the travel time variance of the corridor can be computed as:

$$\text{var}(t_R) = \sum_{i=1}^n \text{var}(t_i) \tag{2}$$

3
 4 **Corridor travel time variance of correlated segments**

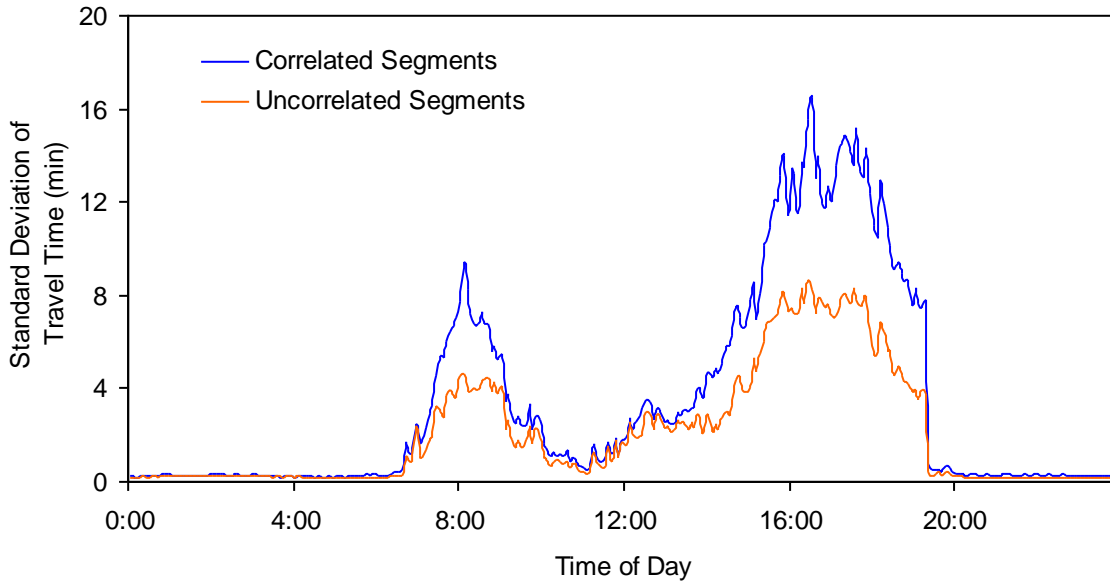
5 In general, if the individual segments are correlated, which is the case on congested freeways where queues
 6 propagate across segments, then the variance of their sum is the sum of their covariances. Therefore, the travel time
 7 variance of the corridor can be computed as:

$$\text{var}(t_R) = \sum_{i=1}^n \sum_{j=1}^n \text{cov}(t_i, t_j) \tag{3}$$

8
 9 This by definition includes the variance of each segment, since $\text{cov}(t_i, t_j) = \text{var}(t_k)$ when $i = j = k$. Equation
 10 3 can also be rewritten as:

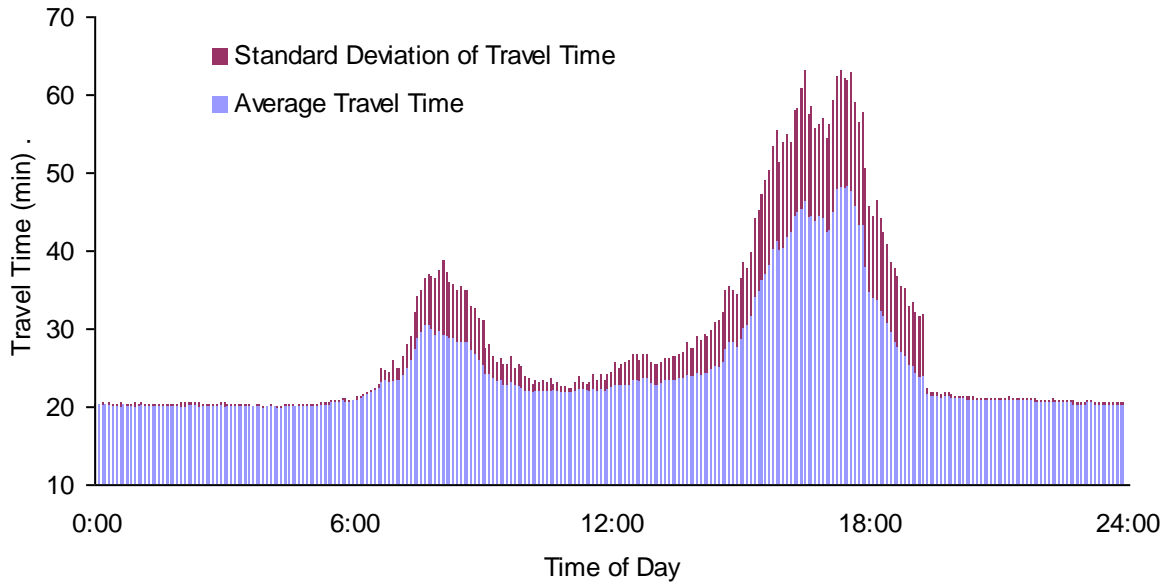
$$\text{var}(t_R) = \sum_{i=1}^n \text{var}(t_i) + 2 \sum_{i < j} \text{cov}(t_i, t_j) \tag{4}$$

11
 12 Here cov is the covariance, which is zero for independent segments (if they exist). Thus the variance of a
 13 sum is equal to the sum of all elements in the covariance matrix of the components. In this study, for each assumed
 14 “departure time” (5-minute time interval) a 21×21 covariance matrix was created. Therefore 288 covariance
 15 matrices were created to study the correlations among the individual segments. Covariance is a measure of how
 16 much two variables change together. If two variables tend to vary together (that is, when one of them is above its
 17 expected value, then the other variable tends to be above its expected value too), then the covariance between the
 18 two variables is positive. Alternatively, if one variable tends to be greater than its expected value when the other
 19 variable is less than its expected value, then the covariance between the two variables will be negative. If two
 20 variables are independent, then their covariance is zero.



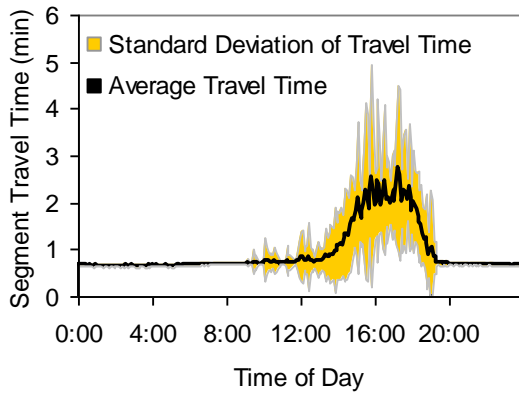
21
 22 **FIGURE 2 Corridor Travel Time Standard Deviation Assuming Correlated and Uncorrelated Segments**

23
 24 Figure 2 shows the corridor travel time standard deviation considering both scenarios: correlated and
 25 uncorrelated segments. As shown in the figure, for off-peak hours the two travel time standard deviations are nearly
 26 superimposed. As soon as the standard deviation of the travel time increases during peak hours, the difference
 27 between the two travel time standard deviations increases as well. This means that for off-peak hours we can assume
 28 that the segments are uncorrelated and therefore corridor travel time variance can be simply computed as the
 29 summation of the segment travel time variances. But for peak hours, it is shown that segment correlation has a
 30 notable impact on corridor travel time variance and should not be ignored.
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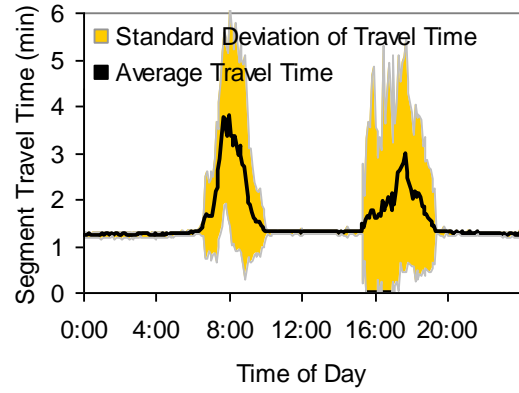


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2 **FIGURE 3 Mean plus Standard Deviation of Travel Time for the I-5 NB Corridor**

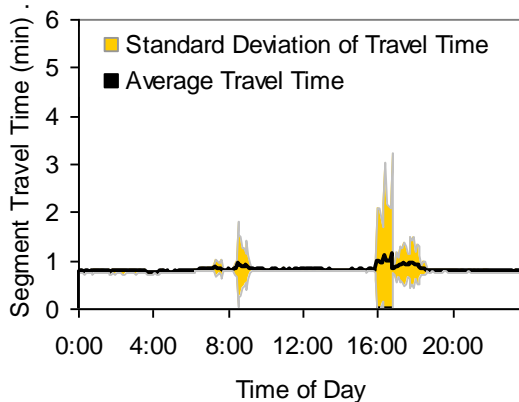
3
4 Figure 3 shows the mean and standard deviation of travel time for the northbound I-5 corridor as stacked
5 bars, assuming correlated segments. As shown in the figure, the free flow travel time is about 21 minutes. There is a
6 jump in the mean travel time during the morning and afternoon peak hours. The figure also shows that as the travel
7 time increases, the standard deviation of travel time (travel time variability) also increases.
8



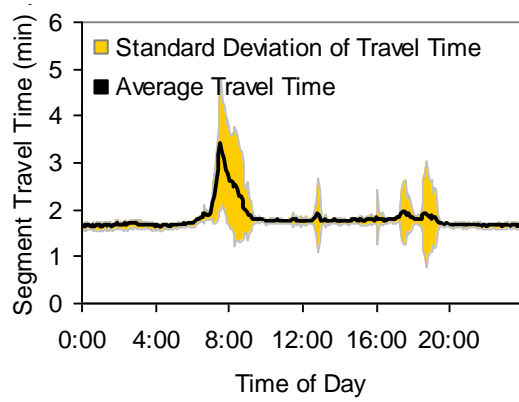
9 (a) Marine Dr. (Milepost 307.46)



10 (b) Capitol Highway (Milepost 295.18)



11 (c) Milepost 293.18 (Haines Street)



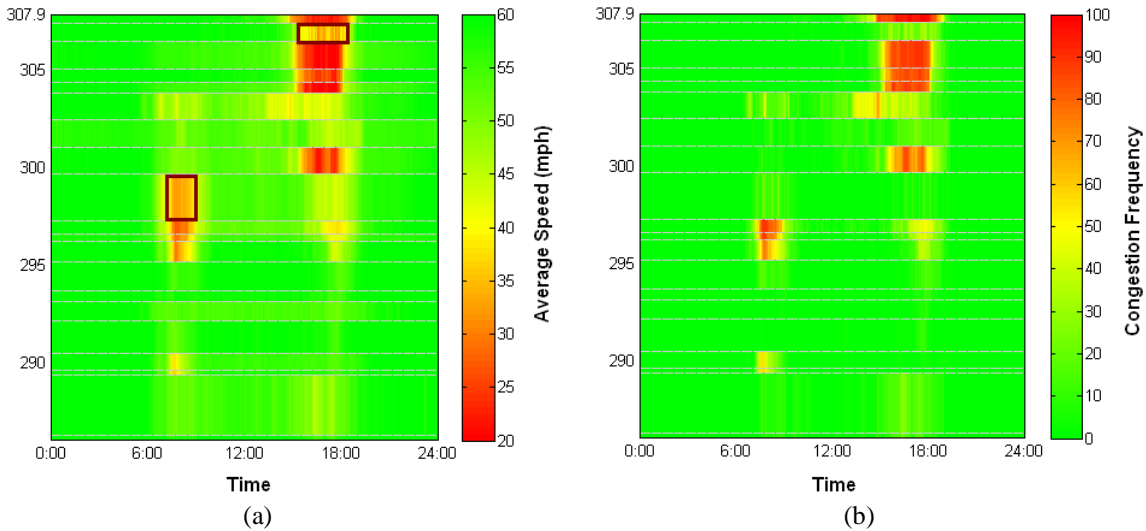
12 (d) Milepost 289.4 (Nyberg Street)

13 **FIGURE 4 Mean Plus and Minus Standard Deviation of Travel Time at Different Segments**

1 ODOT divides the Interstate 5 freeway corridor into 22 individual segments. Figure 4 shows average travel
 2 time plus standard deviation of travel time for different segments (defined by milepost) on I-5. Figure 4(a) shows
 3 travel time data at the Marine Dr. segment (milepost 307.46) which is 0.70 mile in length. The data here are for
 4 weekdays in February and March 2007. The figure illustrates that the travel time across this segment varies
 5 considerably throughout the day, and that the variability of travel time increases during the afternoon peak. Figure
 6 4(b) shows travel time data (mean and plus/minus one standard deviation) at Capitol Highway (milepost 295.18), a
 7 1.26 mile segment. The figure shows that the mean and the standard deviation of travel time both increase during the
 8 morning peak and afternoon peak periods. Figure 4(c) illustrates travel time data at Haines Street (milepost 293.18),
 9 a 0.78 mile segment. This figure shows that there is not a notable change in mean travel time over this segment
 10 throughout the day, but the standard deviation of the travel time increases noticeably during the afternoon peak
 11 hours. Figure 4(d) shows travel time data at Nyberg Street (milepost 289.4), a 1.67 mile segment. This figure shows
 12 that the mean travel time and the standard deviation of travel time are both higher in the morning peak hours than all
 13 the other times of the day. It can clearly be seen that these four segments, as examples, have different travel time
 14 characteristics throughout the day. Each of these locations will affect the travel time characteristics of the whole
 15 corridor differently, with respect to both the mean travel time and the travel time reliability.
 16

17 **SEGMENT LEVEL TRAVEL TIME RELIABILITY**

18 Figure 5 shows an average speed map, with time on the *x*-axis, distance along the freeway on the *y*-axis, and a range
 19 of “color” associated with average speed. The figure also shows a similar time-space map of congestion frequency
 20 for the I-5 corridor; both panels use 5-min data measured on weekdays during February and March 2007. Figure 5(a)
 21 shows that in the morning the average speed drops between 7:00 and 8:00 between mileposts 295 and 300 and in the
 22 afternoon it drops between 16:00 and 18:00 at about milepost 300 and between mileposts 304 and 307.9. Figure 5(b)
 23 illustrates the congestion frequency of this corridor using an arbitrary congested speed threshold of 40 mph. There
 24 are some highlighted areas on the speed map that are not visible in the congestion frequency map. When the speed
 25 map indicates that a segment is congested based on average speed at a certain time period and at a segment, this
 26 does not necessarily mean that it also experiences frequent congestion. Although the following two graphs are very
 27 similar to each other, there are some congested areas in the speed map that are not frequently congested according to
 28 the congestion frequency map; an example is the segment between mileposts 298 and 300 in the morning.



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 30
 31 **FIGURE 5 (a) Average Speed Map and (b) Congestion Frequency Map of the I-5 NB Corridor**
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33 Figure 6 shows a travel time index map (time space diagram, where the *x*-axis is time and the *y*-axis is
 34 distance along the freeway) and three normalized reliability maps of the I-5 corridor based on reliability measures:
 35 buffer index, planning time index, and coefficient of variation. To normalize the reliability measures, each of them is
 36 divided by their own statistical range which is the maximum value minus minimum value of the measure. Figure
 37 6(a) shows a normalized reliability map on the basis of buffer index for the overall northbound I-5 corridor. As
 38 shown, travel time reliability drops considerably on the segment between mileposts 293.74 and 295.18 between
 39 8:00–9:00 and between 17:00–19:00. The segment between mileposts 301.09 and 302.5 is also deemed unreliable by
 40 this metric during a long period between 12:00–19:00. It can clearly be seen that the entire corridor is not unreliable
 41 over all segments and throughout the day. Figure 6(b) illustrates a normalized reliability map on the basis of the

1 planning time index for the study corridor. Segments between mileposts 293.74 and 295.18 are still shown as
2 unreliable segments during the morning and afternoon peak hours. This figure shows that the segment between
3 mileposts 303.88 and 306.51 is highly unreliable during the afternoon peak hours, in contrast with the reliability
4 map based on the buffer index above, which shows the segment between mileposts 301.09 to 302.5 as the most
5 unreliable segment in the afternoon. The differences between these two travel time reliability measures are due to
6 their definitions. The buffer index is computed as the difference between the 95th percentile travel time and the
7 mean travel time, divided by the mean travel time while the planning time index is computed as the 95th percentile
8 travel time divided by the assumed free-flow travel time (in this case assumed to be 60 mph). The planning time
9 index is biased by congestion because it is based on the difference between actual travel time and free flow travel
10 time. Figure 6(c) shows the normalized travel time index map which is a more typical performance measure that
11 does not include any reliability considerations. The travel time index is computed as the mean travel time divided by
12 the assumed free flow travel time. Figure 6(d) illustrates the normalized reliability map based on coefficient of
13 variation. The coefficient of variation is computed as the standard deviation of travel time divided by the mean
14 travel time. Although the standard deviation of travel time and reliability measures based on the standard deviation
15 tell only half of the story (8), this figure indicates that the coefficient of variation shows roughly the same trend as
16 the buffer index, rather than being similar to the planning time index or the pattern revealed by plotting the travel
17 time index. These figures indicate that each index would show approximately the same trends along the corridor and
18 throughout the day. Note that the travel time index (without reliability considerations) seems to heighten the trends
19 more than planning time index.
20

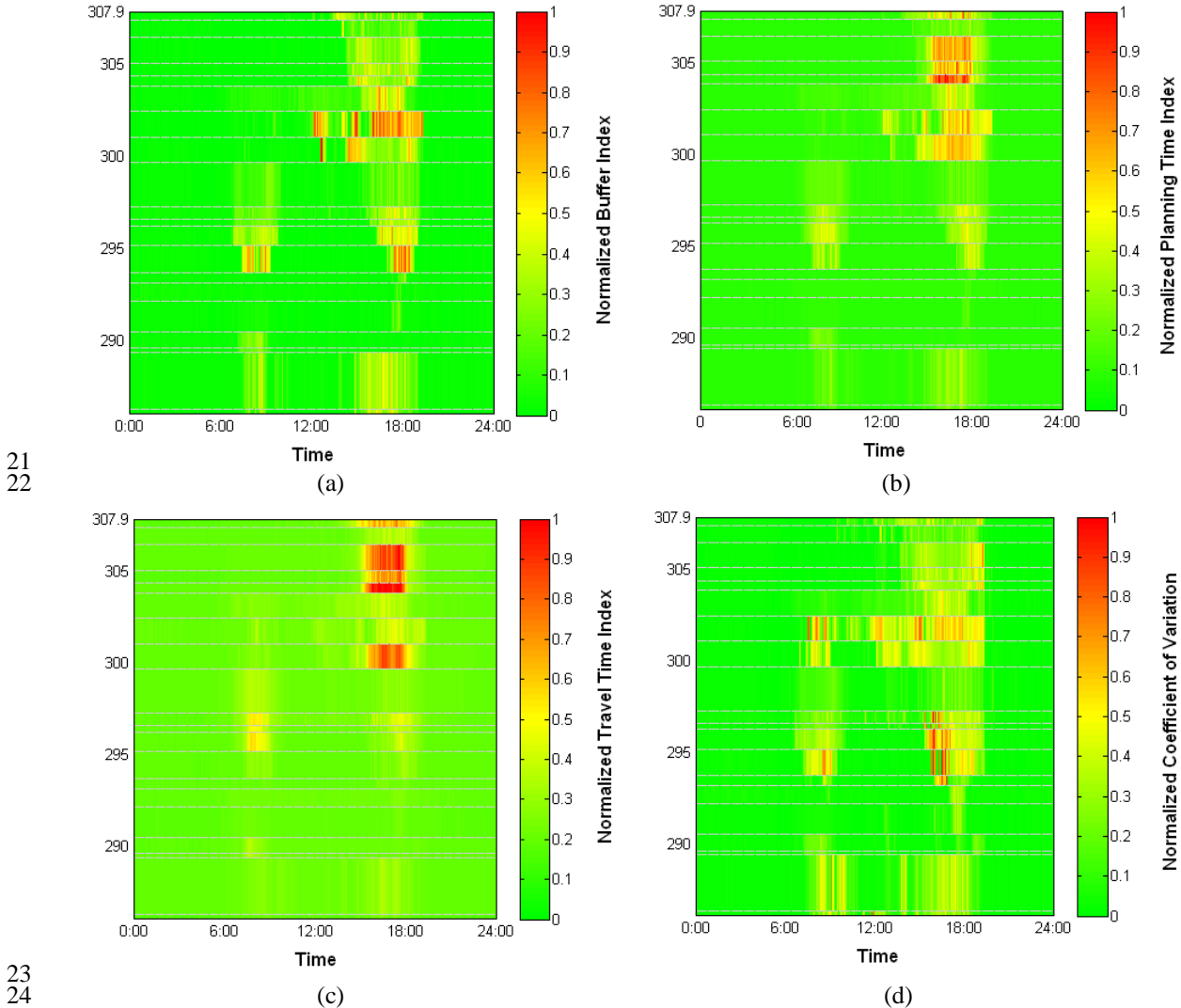
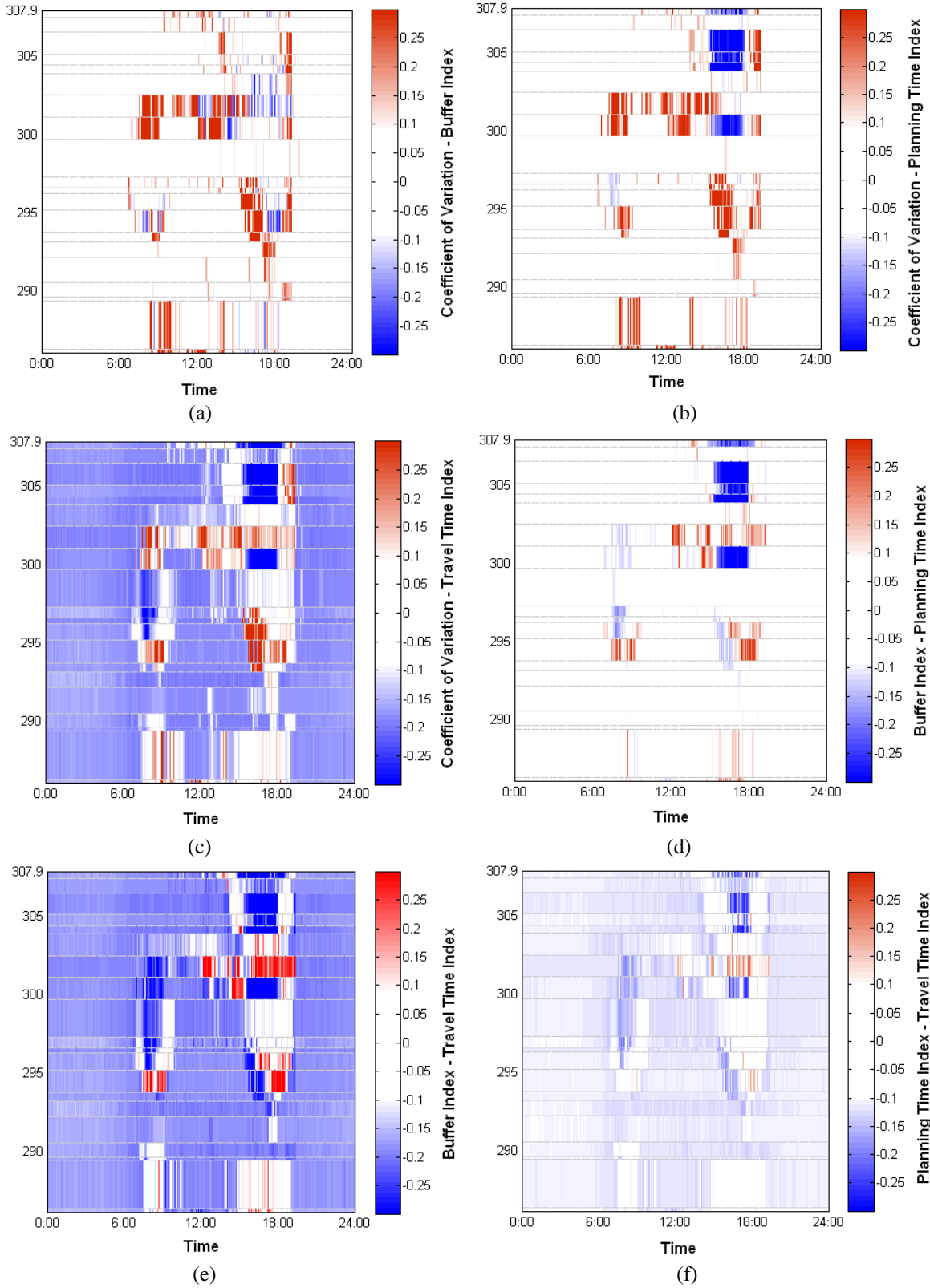


FIGURE 6 Normalized Reliability Maps of the I-5 NB Corridor Based on Different Measures

1
2 The notion of segment level travel time reliability is often misunderstood. For example, the following
3 statement is false: “a segment which is congested is unreliable.” Congestion is only one of the causes of
4 unreliability. A congested segment is not necessarily unreliable. Segments that are unreliable according to the
5 planning time index are almost the same as segments that are unreliable according to congestion frequency. A
6 segment can become more reliable if the congestion frequency in the segment moves toward 100%. The segments
7 identified as unreliable by the buffer index are less frequently congested compared to unreliable segments identified
8 by the planning time index.

9 By subtracting panels from Figure 6 from one another, Figure 7 shows a set of “differential maps” that
10 compare different reliability measures (coefficient of variation, buffer index and planning time index) with one
11 another and with the travel time index. . Figure 7(a) shows the difference between normalized coefficient of
12 variation and the normalized buffer index over time and space. For most of the day, as well as congested segments
13 and times, shown in Figure 5, the coefficient of variation and buffer index are fairly consistent. For segments and
14 timeframes not exhibiting frequent congestion, the coefficient of variation reveals more unreliability than the buffer
15 index. When a segment is frequently congested (congestion frequency of more than 80%), the coefficient of
16 variation and buffer index are consistent with one another, but when a segment is less frequently congested
17 (congestion frequency less than 80%), the coefficient of variation captures more unreliability than the buffer index.
18 Figure 7(b) shows the difference between the normalized coefficient of variation and the planning time index.
19 Similarly for most of the day, these two reliability measures are fairly consistent. For frequently congested segments
20 and times, the coefficient of variation reveals less unreliability than the planning time index but for less frequently
21 congested segments and times, the coefficient of variation shows more unreliability than the planning time index.
22 Figure 7(c) illustrates the difference between the normalized coefficient of variation and the normalized travel time
23 index. Distinct from previous differential maps, it is shown that during most of the day the coefficient of variation
24 shows more extreme values of unreliability along different segments than those identified as being congested using
25 the travel time index. For frequently congested segments and times, the normalized coefficient of variation is lower
26 in magnitude than the travel time index while for less frequently congested areas in time and space, the coefficient
27 of variation and the travel time index reveal roughly consistent features. In Figure 7(d), the difference between the
28 normalized buffer index and the normalized planning time index is shown. For frequently congested segments and
29 times, the normalized buffer index is smaller than the normalized planning time index while for most of the rest of
30 the day and over most segments they are roughly consistent. Figure 7(e) illustrates the difference between the
31 normalized buffer index and the normalized travel time index. Similar to Figure 7(c), that during most of the day the
32 buffer index highlights areas of low unreliability in different segments than the congested regions indicated by the
33 travel time index. For frequently congested segments and times, the normalized buffer index is lower in magnitude
34 than the travel time index while for less frequently congested areas in time and space, the regions highlighted by the
35 buffer index and those highlighted by the travel time index are roughly consistent. In Figure 7(f), the difference
36 between the normalized planning time index and the normalized travel time index is shown. During most of the day
37 the planning time index shows slightly more extreme values of unreliability in locations similar to those revealed by
38 the travel time index. In conclusion, it is found that the buffer index and the coefficient of variation have more
39 consistency in comparison to other examined reliability measures and they are powerful tools to highlight segments
40 and times where congestion is not highly frequent. The planning time index is more focused on frequently congested
41 areas in time and space. Results confirm what is mentioned earlier in the paper that according to the buffer index and
42 the coefficient of variation a segment which is congested is not necessarily unreliable while according to the
43 planning time index unreliable segments are more frequently congested.
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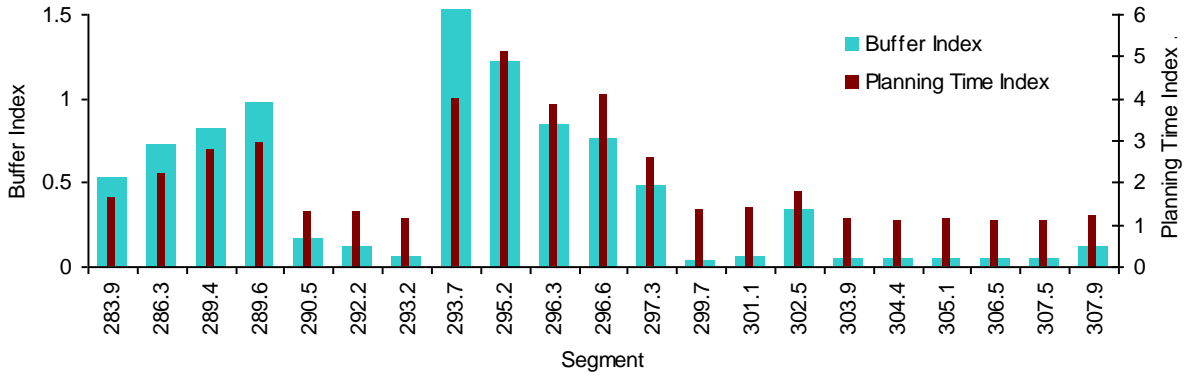


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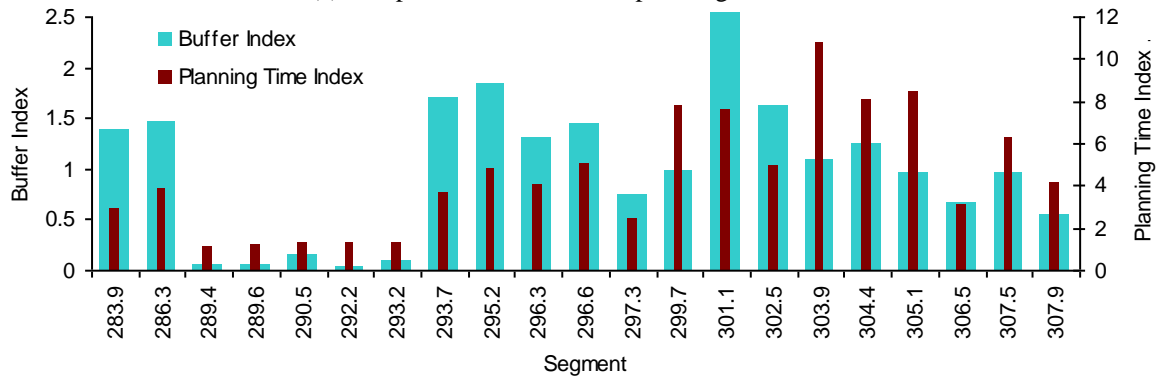
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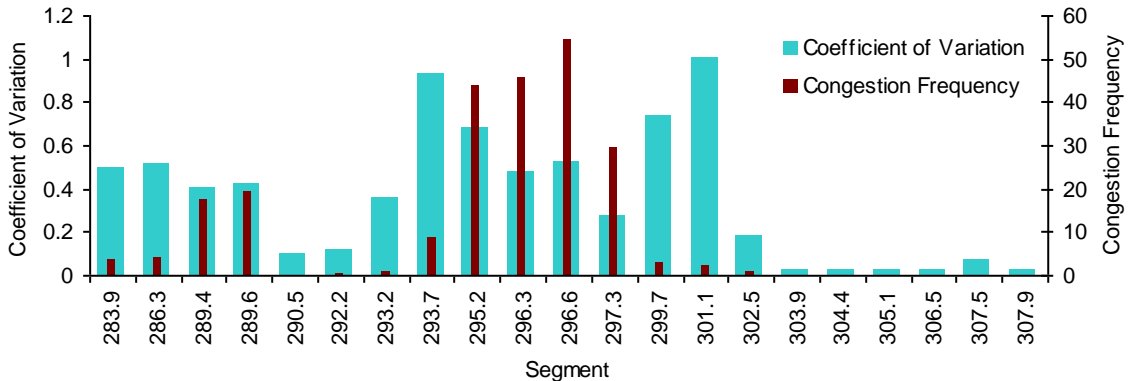
FIGURE 7 Differential Reliability Maps of the I-5 NB Corridor Based on Different Measures



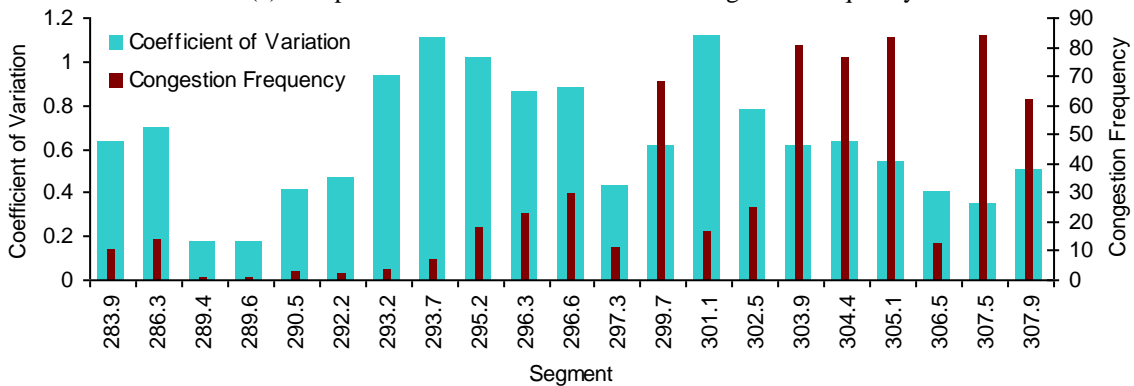
(a) AM peak buffer index and planning time index



(b) PM peak buffer index and planning time index



(c) AM peak coefficient of variation and congestion frequency



(d) PM peak coefficient of variation and congestion frequency

FIGURE 8 I-5 NB Freeway AM and PM peak Buffer Index, Planning Time Index, Coefficient of Variation, and Congestion Frequency

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1 SEGMENT PRIORITIZATION

2 The buffer index and the coefficient of variation are used here as the primary measures of travel time reliability
3 because they appear to reveal more than the other measures. The buffer index better represents the percentage of
4 extra travel time that drivers need to add to their trip in order to ensure on-time arrival. All 22 segments of the
5 northbound I-5 corridor were studied using data from weekdays over a two month period (February–March 2007).
6 There were no data available for the Upper Boones Ferry Road segment (milepost 291.38) because of
7 malfunctioning loop detectors. Therefore, this segment was excluded from the study.

8 Figure 8 details the buffer index, planning time index, coefficient of variation, and congestion frequency
9 values for each segment for AM and PM peak hours. In Figure 8(a), the segments with the worst reliability based on
10 their buffer index ratings (highest buffer index) were Pacific Highway (milepost 293.7), Capitol Highway (milepost
11 295.2), and Nyberg Street (milepost 289.6). The segments with the worst reliability based on their planning time
12 index ratings (highest planning time index) were Capitol Highway (milepost 295.2), Multnomah Boulevard
13 (milepost 296.6), and Pacific Highway (milepost 293.7). This analysis suggests that these segments could be
14 considered for further, detailed analysis for planning, operations strategies or prioritization purposes. Figure 8(b)
15 shows the buffer index and planning time index values for each segment for PM peak hours. Morrison Bridge
16 (milepost 301.1), Capitol Highway (milepost 295.2), and Pacific Highway (milepost 293.7) had the highest buffer
17 indices in the afternoon peak hours. Going Street (milepost 303.9), Portland Boulevard (milepost 305.1), and
18 Alberta Street (milepost 304.4) had the highest planning time indices during the same time period. Similarly in
19 Figure 8(c) and 8(d) the most unreliable segments according to the coefficient of variation and the congestion
20 frequency for the AM and PM peak hours can be found. It is shown that the results of the congestion frequency
21 metric differ substantially from the results using the coefficient of variation. The segments with the lowest reliability
22 in the morning peak hours based on their coefficient of variation ratings (highest coefficient of variation) were
23 Pacific Highway (milepost 293.7), Morrison Bridge (milepost 301.1), and Capitol Highway (milepost 295.2).
24 Multnomah Boulevard (milepost 296.6), Spring Garden Street (milepost 296.3), and Capitol Highway (milepost
25 295.2) had the highest congestion frequency during the same time period. Results confirm previous findings in this
26 paper that the buffer index and the coefficient of variation have a high consistency among other measures. Also the
27 planning time index and the congestion frequency seem to follow similar trends.
28

29 CONCLUSIONS

30 This paper has reviewed ways in which travel time reliability is measured. The analysis used archived freeway data
31 to analyze changes in travel time reliability and extend the previously proposed methodology in (7) for prioritizing
32 freeway segments. In conclusion, travel time reliability, no matter which measure we use, varies substantially across
33 freeway segments. However the relationship between the travel time reliability on each of the segments and the
34 reliability over the entire corridor still requires further research. Given that the PORTAL database contains more
35 than five years' worth of data, it would also be useful to expand this analysis over a longer timeframe. It is shown
36 that freeway segment correlations highly influence the variability of corridor travel time and should not be ignored.
37 It is also found that different reliability measures present different portraits of the reliability aspects of a freeway
38 corridor. Differential reliability maps were used to visually explore locations and times where different reliability
39 measures have consistency and inconsistency. It is found that the buffer index and the coefficient of variation have a
40 high consistency among other measures. Also the planning time index and the congestion frequency seem to follow
41 similar trends. However more quantitative analysis is required. Finally, the authors recommend the use of segment
42 travel time reliability measures in regional transportation planning and operations to evaluate and prioritize roadway
43 segments. Travel time reliability measures both at the corridor level and segment level can be used to highlight
44 corridors or segments that are candidates for operational improvements.
45

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