Sensitivity of Transportation Performance Measures to Changes in Reference Speed

by

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ABSTRACT

Reference speed reflects free-flow (unconstrained) travel conditions and is used as a benchmark for calculating system performance measures. The choice of reference speed can affect reported delay and reliability measures. This paper examines performance measure sensitivity to changes in reference speed on freeways and arterial street facilities. The measures examined in this paper include travel delay, Travel Time Index (TTI), 80th percentile Planning Time Index (PTI_{80}) and 95th percentile Planning Time Index (PTI_{95}).

It was found that, to a large extent, performance measure sensitivity to changes in reference speed depended on facility type and urban area size. Overall, delay was more sensitive to changes in reference speed than any of the performance indices (TTI, PTI_{80} and PTI_{95}). Delay sensitivity decreased on freeway facilities as the urban area size increased because any reference speed changes affected freeway delay values more in smaller urban areas. Arterial street delay remained largely unaffected by urban area size. For a given urban area, arterial streets were more sensitive than freeways for any measure (delay or any of the three indices) because of the presence of mid-day delay along with the fact that delay accrues faster at lower operating speeds. All measures indicated that the speed limit values were lower (between 2 to 3 mph) than the reference speeds derived from travel data. The paper highlights the importance of using appropriate reference speed in mobility measurement and the observed effects of using a higher or lower value (e.g., speed limit based proxy) for reporting performance measures.

Keywords: system performance measurement, reference speed, sensitivity, delay, Travel Time Index, and Planning Time Index

INTRODUCTION AND BACKGROUND

Reference travel speed is used as a benchmark for calculating delay, mobility and reliability statistics in industry and research. These reference speeds reflect free-flow (unconstrained) travel conditions on transportation facilities. "Reference" speed is a term used by public agencies and third-party speed data providers to identify a common comparison standard. The choice of reference speed can affect reported delay and reliability measures *(1)*. Different agencies adopt different proxies to assign reference speeds to their facilities while conducting performance measurement and monitoring *(2-15)*. Previous studies show that depending on the magnitude of difference in actual and adopted reference values, the reported measures can mis-approximate mobility measures by 20-25% and even higher for reliability measures *(16)*.

Jha et al. *(2)* recommend procedures for deriving reference speed from probe-based travel time data sets. The current paper examines delay and reliability measure sensitivity to changes in reference speeds on freeways and arterial streets. Sensitivity is approximated by the percent change in performance measure values when the reference speed is increased or decreased. Reference speeds are also compared with speed limit values to assess the associated effects on measures. This exercise highlights the importance of using appropriate reference speed in mobility measurement and the possible effects of using a higher or lower value for reporting performance measures.

Table 1 provides an overview of key recommendations for determining reference speed from travel speed database as outlined by Jha et al. *(2,3)*. Building on these reference speed determination procedures, the current paper examines transportation system performance measure sensitivity to reference speed changes on uninterrupted flow (freeway) and interrupted flow (arterial street) facilities. Depending on an urban area's size this can be a vast network of facilities, and changing the reference speed by even a small amount can affect reported measures. The measures examined in this paper include travel delay, Travel Time Index (TTI), 80th percentile Planning Time Index (PTI_{80}) and 95th percentile Planning Time Index (PTI_{95}).

TABLE 1 Snapshot of Reference Speed Determination Procedures [Jha et al. *(2)*]

<table>
<tr><th>Data Availability during 9PM-6AM Time Window</th><th>Recommended Reference Travel Time Window</th><th>Recommended Reference Speed Percentile</th><th>Notes</th></tr>
<tr><td>Equal to or greater than 50 percent</td><td>9 PM – 6 AM weekdays (Mon-Fri)</td><td rowspan="2">85th percentile of average speeds within chosen time window</td><td>Consistent, less variable data; conformity to normal distribution</td></tr>
<tr><td>Less than 50 percent</td><td>9 PM – 6 AM weekdays (Mon-Fri) + 11 AM – 4 PM weekdays (Mon-Fri)</td><td>Left skew in speed distribution; low data availability and high variability during nighttime period</td></tr>
</table>

Note: For more detailed information based on facility type, refer to "Determining Reference Speed from Probe-Based Travel Speed Data," K. Jha, Master's Thesis, Texas A&M University (3)

Travel measures for several urban areas in Texas are calculated and percent changes in each measure are observed for change increments of 1 mph and 2 mph in reference speeds. It was found that, to a large extent, performance measure sensitivity to changes in reference speed is dependent upon facility type and urban area size. Delay was more sensitive to changes in reference speed than any of the performance indices, and delay sensitivity decreased on freeway facilities as the urban area size increased because any reference speed change affected freeway delay values more in smaller urban areas. Arterial street delay remained largely unaffected by urban area size. For a given urban area, arterial streets were more sensitive than freeways for any measure (delay or any of the three indices) because of the presence of mid-day delay along with the fact that delay accrues faster at lower operating speeds. All measures indicated that the speed limit values were lower (between 2 to 3 mph) than the reference speeds derived from travel data.

METHODOLOGY AND DATA DESCRIPTION

This analysis uses probe-based travel speed data from INRIX®, a private-sector data provider, for calendar year 2016 for 32 urban areas in Texas. This INRIX® XD™ database for Texas consisted of 10,584 freeway segments and 17,057 arterial segments. Figure 1 shows the roadways on the state map of Texas for all facility types used in this paper. The XD segments, as denoted by INRIX®, are similar in nature to traffic message channels (TMCs) but typically are shorter and have higher spatial resolution (up to 820 feet [250 meters] on major roads) compared to typical TMC resolutions of 1-3 miles. The recorded travel times consists of "point-paired" data, which capture vehicle travel times between points of detection and thus are representative of vehicle space mean speeds.

Reference speeds were derived from 15-minute aggregated average travel times for each road segment based on all-day data availability as outlined in Table 1. All performance measures (delay and all three indices) were calculated for all-year travel using these derived reference speeds. While delay was calculated for all-day travel, the three indices were calculated for morning and afternoon peak periods (6 AM-9 AM and 4 PM-7 PM respectively). Therefore, for 15-minute data aggregation, the annual peak period PTI_{80} uses the 80^{th} percentile of 120 "cells" of average-week-of-the-year data (4 fifteen-minute intervals per hour*6 hours of AM and PM peak period*5 weekdays) on each segment, and the annual peak period PTI_{95} uses the 95^{th} percentile of the same dataset.

Throughout this document, the term "base measure" refers to the area-wide measure calculated using the reference speed derived using procedures detailed in Jha et al. *(2)* and summarized in Table 1. Equations 1 through 4 provide basic mathematical equations for all four performance measures examined in this paper.

$$Annual\ Delay = Observed\ Travel\ Time - Reference\ Travel\ Time \tag{1}$$

$$Average\ Peak\ Period\ TTI = \frac{Annual\ Average\ of\ Peak\ Period\ Average\ Travel\ Times}{Reference\ Travel\ Time} \tag{2}$$

$$Peak\ Period\ PTI_{80} = \frac{80^{th}\ Percentile\ of\ Peak\ Period\ Average\ Travel\ Times}{Reference\ Travel\ Time} \tag{3}$$

$$Peak\ Period\ PTI_{95} = \frac{95^{th}\ Percentile\ of\ Peak\ Period\ Average\ Travel\ Times}{Reference\ Travel\ Time} \tag{4}$$

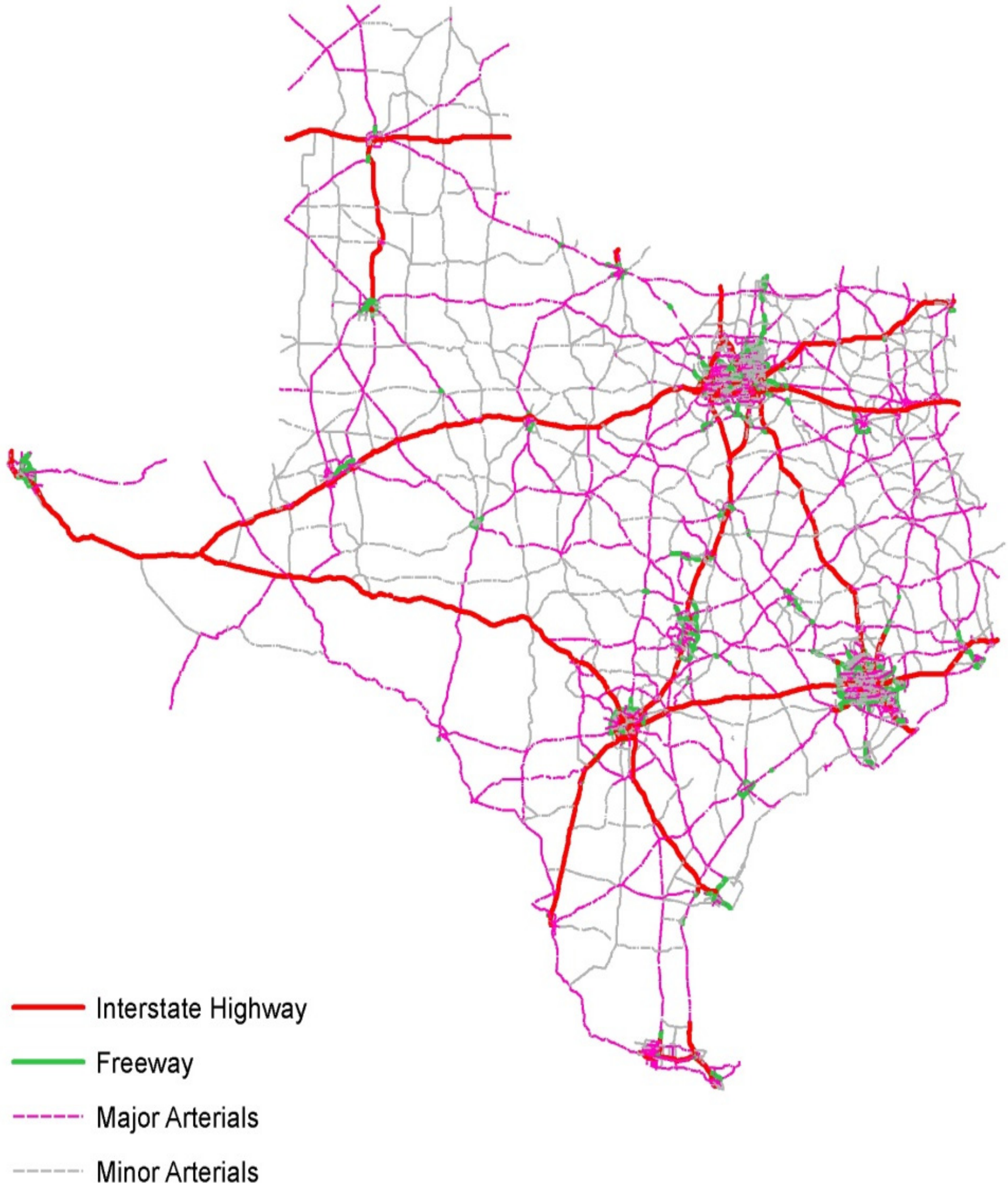

FIGURE 1 Texas state map showing all roadway segments used in the study.

To examine any measure's sensitivity to changes in reference speeds, percent changes in the performance measure are calculated after raising or lowering the reference speed by 1 mph or 2 mph, and also at the speed limit. All sensitivity values represent percent changes in the value of the performance measure for these incremental changes. Table 2 provides an overview of how the different values m_1, m_2, p_1, p_2, and sp are calculated for an example case when the reference speed is 60 mph.

TABLE 2 Term Definitions for Sensitivity Based on Example Reference Speed of 60 mph

Metric	Calculated value (percent)
Sensitivity, $\mathbf{m_1}$	$\left(\frac{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{59\ mph}}{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{60\ mph}} - 1\right) * 100$
Sensitivity, $\mathbf{m_2}$	$\left(\frac{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{58\ mph}}{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{60\ mph}} - 1\right) * 100$
Sensitivity, $\mathbf{p_1}$	$\left(\frac{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{61\ mph}}{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{60\ mph}} - 1\right) * 100$
Sensitivity, $\mathbf{p_2}$	$\left(\frac{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{62\ mph}}{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{60\ mph}} - 1\right) * 100$
Sensitivity, **sp**	$\left(\frac{Area\ wide\ measure\ @\ \mathbf{speed\ limit}}{Area\ wide\ measure\ @\ reference\ speed\ \mathbf{60\ mph}} - 1\right) * 100$
Base measure	$Area\ wide\ measure\ @\ reference\ speed\ \mathbf{60\ mph}$
Change in base measure	$Area\ wide\ measure\ @\ modified\ reference\ speed - Area\ wide\ measure\ @\ reference\ speed\ 60\ mph$

The numerical values for sensitivities m_1 and m_2 are negative because all studied measures (e.g., delay) decrease as the reference speed is lowered. Similarly, values for sensitivities p_1 and p_2 are positive because delay increases as the reference speed is raised. It is also observed that sensitivity "sp" is always negative, indicating that speed limits are typically lower than observed reference speeds. Delay and index calculations suggest that speed limits are typically between 2 to 3 mph lower than derived reference speeds, and the differences between speed limit and reference speed are higher on freeways than arterial streets. The difference in values varies from one road segment to another. Using the speed limit as reference speed can "eliminate" some delay (result in much lower reported values), particularly on freeways where vehicles travel slightly higher than speed limit. Arterial streets are not similarly affected; vehicles travel closer to, or under, the speed limit, even in low volume conditions. This phenomenon can result in high freeway delay and index sensitivity in smaller urban areas where freeway base delay and index values are low. This observation supports previously documented inferences regarding the use of data-deduced reference speeds instead of fixed proxies such as the speed limit for performance measurement purposes as discussed in detail in Jha et al. *(2,3)*.

RESULTS

This section summarizes the results on sensitivity variation for each performance measure. It is found that, to a large extent, performance measure sensitivity to changes in reference speed depends on facility type and urban area size. The following general observations are based on the results:

- **Overall**:
  - Delay is more sensitive to changes in reference speed than any of the performance indices (TTI, PTI_{80} and PTI_{95}).
  - Delay sensitivity decreased on freeway facilities as the urban area size increased because any changes in reference speed affected freeway delay values more in smaller urban areas. Arterial street delay remains largely unaffected by the size of urban area.
  - For a given urban area, arterial streets are more sensitive than freeways for any measure (delay or any of the three indices) because of the presence of mid-day delay along with the fact that delay accrues faster at lower operating speeds.
    - exception: Small urban areas with low freeway mileage. Freeway sensitivity is much higher here because of low base values for freeway delay or index.
  - All measures indicate that the speed limit values are lower (between 2 to 3 mph) than the reference speeds derived from travel data.
- **Large urban areas** (population more than 1,000,000):
  - Freeway *delay* is the least sensitive in these areas (avg. sensitivity 9%) among all urban area sizes; Arterial streets are still more sensitive (avg. sensitivity 15%) than freeways.
  - *Index* sensitivity, though still low (avg. sensitivity 2% on freeways and 4% on arterials) compared to delay sensitivity (9% on freeways and 15% on arterials), is slightly higher than in smaller urban areas.
  - Area wide *index* sensitivity is low (avg. sensitivity 2% on freeways and 4% on arterials); Individual corridor indices can still show moderate sensitivity (up to 5% on freeways and 9% on arterials).
- **Medium urban areas** (population between 250,000 and 1,000,000):
  - Freeway *delay* is more sensitive in these areas (avg. sensitivity 15%) than in large urban areas; Arterial streets are still more sensitive (avg. sensitivity 19%) than freeways.
  - Area wide *index* sensitivity (avg. sensitivity 1% on freeways and 3% on arterials) is lower than in large urban areas; Individual corridor indices can still show moderate sensitivity (up to 6% on freeways and 10% on arterials).
- **Small urban areas** (population less than 250,000):
  - Freeway *delay* is the most sensitive in these areas (avg. sensitivity 70%) among all urban area sizes; Arterial streets are marginally more sensitive (avg. sensitivity 20%) than in medium size areas.
  - Area wide *index* sensitivity (avg. sensitivity 1% on freeways and 2% on arterials) is lower than in large urban areas; Individual corridor indices can still show moderately high sensitivity (up to 6% on freeways and 14% on arterials).

Tables 3 and 4 provide a snapshot of sensitivity variation of different performance measures with urban area size. The values m_1, m_2, p_1 and p_2 represent percent changes of performance measures to minus 1, minus 2, plus 1 and plus 2 mph changes in reference speed. For easier visual search, sensitivity values below 3% in magnitude (-3% to 3%) are categorized as "Not sensitive" and are in unshaded cells and regular font, 3% to 10% as "Moderately sensitive" in light grey shaded cells and Italic font, and above 10% in magnitude as "Very sensitive" in dark grey shaded cells and bold font.

TABLE 3 Performance Measure Sensitivity on Freeway Facilities for Different Urban Area Types

Perf Measure	Urban Area	Sensitivity (percent change)			
		m_1	p_1	m_2	p_2
Delay	Very Large (Houston, DFW)	*-6.6*	*8.9*	**-12.3**	**18.1**
	Large (San Antonio, Austin)	*-7.0*	**10.2**	**-13.0**	**20.5**
	Medium	**-14.7**	**15.5**	**-23.4**	**35.3**
	Small	**-19.4**	**71.5**	**-34.1**	**142.9**
TTI	Very Large (Houston, DFW)	-1.4	1.7	-2.6	*3.3*
	Large (San Antonio, Austin)	-1.3	1.6	-2.4	*3.3*
	Medium	-1.1	1.6	-2.0	*3.3*
	Small	-0.8	1.6	-1.3	*3.3*
PTI_{80}	Very Large (Houston, DFW)	-1.6	1.6	-2.9	*3.2*
	Large (San Antonio, Austin)	-1.5	1.5	-2.9	*3.1*
	Medium	-1.4	1.6	-2.6	*3.2*
	Small	-1.1	1.3	-1.8	2.8
PTI_{95}	Very Large (Houston, DFW)	-1.6	1.6	*-3.1*	*3.3*
	Large (San Antonio, Austin)	-1.5	1.5	-3.0	*3.1*
	Medium	-1.5	1.6	-2.9	*3.3*
	Small	-1.2	1.4	-2.2	3.0

TABLE 4 Performance Measure Sensitivity on Arterial Street Facilities for Different Urban Area Types

Perf Measure	Urban Area	Sensitivity (percent change)			
		m_1	p_1	m_2	p_2
Delay	Very Large (Houston, DFW)	**-16.3**	**18.1**	**-30.9**	**37.0**
	Large (San Antonio, Austin)	**-14.1**	**15.4**	**-27.0**	**31.2**
	Medium	**-15.6**	**18.6**	**-27.5**	**36.0**
	Small	**-13.7**	**19.4**	**-26.7**	**31.4**
TTI	Very Large (Houston, DFW)	-2.9	3.0	*-5.6*	*6.0*
	Large (San Antonio, Austin)	-2.9	3.0	*-5.6*	*6.0*
	Medium	-2.7	2.8	*-5.1*	*5.6*
	Small	-2.5	2.7	*-4.8*	*5.5*
PTI_{80}	Very Large (Houston, DFW)	-3.0	3.0	*-6.0*	*6.1*
	Large (San Antonio, Austin)	-3.0	3.0	*-6.0*	*6.1*
	Medium	-2.8	2.8	*-5.5*	*5.6*
	Small	-2.7	2.8	*-5.4*	*5.5*
PTI_{95}	Very Large (Houston, DFW)	*-3.1*	*3.1*	*-6.1*	*6.2*
	Large (San Antonio, Austin)	*-3.1*	*3.1*	*-6.0*	*6.2*
	Medium	-2.8	2.8	*-5.5*	*5.6*
	Small	-2.8	2.8	*-5.5*	*5.6*

The findings for delay sensitivity are discussed below followed by discussion on sensitivity variation of all three indices (TTI, PTI_{80} and PTI_{95}).

Delay

Table 5 provides details on delay sensitivity with respect to reference speed changes and urban area size. The values for “Change in base delay” (columns 3 to 7) and “Sensitivity” (columns 8 to 12) are calculated as defined in Table 2. The last two rows for both freeways and arterial streets in Table 5 consist of a number of smaller sized urban areas categorized by the presence or absence of Interstate highways crossing them. The following general observations are made from these results:

- To a large extent, delay sensitivity to changes in reference speed depends on facility type and urban area size.
    - For freeways, delay sensitivity decreases as the size of an urban area’s transportation network increases. This is shown in greater detail in Figure 2 and Figure 3.
    - For arterial streets, the delay measure is not as sensitive to the size of urban area as for freeways. Overall, although the sensitivity decreases slightly as the size of the urban area increases, the effect is not very strong with arterial streets. This is shown in Figure 4 and Figure 5.
- <u>*Table 5 (freeways), columns 8 to 12, rows E and F*</u>:
  Delay measures are most sensitive to changes in reference speed in smaller urban areas with low to moderate Interstate and freeway mileage. Because the base delay is relatively low in such cases, any changes in reference speeds result in high percent changes (sensitivity) in those base delay values.
- <u>*Table 5 (arterial streets), columns 9 and 11, rows A to F*</u>:
  Delay sensitivity on arterial streets does not change significantly with urban area size. This can be explained by an inherent amount of delay caused by signalization, traffic turning from cross streets and driveways, and various other causes. This ‘base amount’ of delay does not fluctuate widely with changes in reference speed. Compared to freeways, there is also a higher midday delay. Therefore, changes in reference speed do not affect delay measures to the same extent with increasing size of urban area as they do on freeways.
- <u>*Table 5, columns 8 to 12, corresponding entries for freeways and arterial streets in each urban area (rows A to D)*</u>*:*
  For the same urban area, delay sensitivity as a whole is higher on arterial streets than freeways.
  For a given change in reference speed, delay accrual is faster at lower operating speeds. For example, the same increment of 2 mph in base reference speed has a higher effect on delay at an operating speed of 30 mph than at 60 mph. The travel rate (minutes per mile) is 1.0 at 60 mph operating speed and 2.0 at 30 mph operating speed. For the same 2 mph increment in reference speed, the travel rate changes from 1.0 at 60 mph base speed to 0.97 at 62 mph. It changes from 2.0 at 30 mph base speed to 1.88 at 32 mph. Therefore, the same magnitude change in reference speed results in 0.03 change in travel rate at 60 mph and 0.12 change in travel rate at 30 mph operating speed.

Therefore, for the same urban area, delay sensitivity is higher on arterial streets than freeways. There can be situations where a freeway section has extremely low operating speeds during the peak periods and delay will accumulate rapidly, but these tend to be limited in number throughout a region. Another reason for the arterials accruing delay faster is the presence of mid-day delay along with morning and evening peak-period delay. Consequently, any changes in reference speeds have a higher cumulative effect on arterials because more of the operating speeds are below reference speeds throughout the day.

- *Table 5 (freeways or arterial streets), numbers in columns 11 and 12 are higher in magnitude than corresponding numbers in columns 9 and 10 respectively*: For a given facility type (freeway or arterial street), sensitivity is higher for upward changes in reference speed (when the reference speed is higher than base reference speed) than downward changes (when the reference speed is lower than base reference speed). Delay starts accruing faster when the reference used to measure the delay is set higher because more instances of lower operating speeds are now observed relative to the reference speed and delay accrues quicker at lower speeds (higher value of travel rate in minutes per mile).
- Delay does not increase linearly with increments in reference speed. For example, the average sensitivity for all urban areas to a 1 mph increment in reference speed is 14% on freeways and 16% on arterial streets, while the same values for a 2 mph increment in reference speed are 32% and 42% respectively. Therefore, delay adds up faster as the reference speed goes up, even in the same increment.

Figures 2 through 5 provide a visual representation of the effect of facility type and urban area size on delay sensitivity. Urban areas are categorized by population size. Areas with population over 1 million are categorized large, between 250,000 and 1 million categorized medium, and less than 250,000 are categorized small. The x-axis ("increase in base delay") is representative of urban area size because larger urban areas have larger magnitude of base delay.

For freeways, as shown in Figure 2, delay sensitivity decreases considerably as the urban area size increases. Figure 3 represents the delay values on a logarithmic scale in which the values are more distributed for easier interpretation. For arterial streets, as shown in Figure 4 and Figure 5, delay sensitivity has limited variation with the urban area size. As discussed earlier in this section, the sensitivity hovers around an average value, decreasing only marginally for larger urban areas. The delay appears to grow commensurate to the size of the urban area, thereby keeping the percent change around the same level.

TABLE 5 Delay Sensitivity by Urban Area Size and Type

Delay Sensitivity for Freeway Facilities

S. No. *(1)*	Urban Area *(2)*	Change in base delay (million hours)					Sensitivity (percent change in delay)				
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*	m_1 *(9)*	m_2 *(10)*	p_1 *(11)*	p_2 *(12)*
A	Houston	-12.98	-6.48	-11.84	8.36	16.64	**-14.9**	*-6.1*	**-12.1**	*7.8*	**17.5**
B	Dallas-Ft. Worth	-10.90	-6.19	-10.85	9.36	18.68	**-13.8**	*-7.3*	**-13.0**	**11.7**	**21.4**
C	San Antonio	-3.98	-2.27	-3.93	3.43	6.84	**-18.1**	*-9.9*	**-17.1**	**14.9**	**29.8**
D	Austin	-1.91	-1.09	-1.98	1.95	3.87	*-7.5*	*-7.1*	*-9.6*	*7.4*	**14.7**
E	Other w/ Interstates (avg. values)	-0.29	-0.14	-0.23	0.25	0.49	**-32.8**	**-16.4**	**-26.8**	**28.4**	**56.8**
F	Other w/o Interstates (avg. values)	-0.06	-0.03	-0.04	0.09	0.17	**-71.6**	**-40.8**	**-60.4**	**122.1**	**243.4**

Delay Sensitivity for Arterial Street Facilities

S. No. *(1)*	Urban Area *(2)*	Change in base delay (million hours)					Sensitivity (percent change in delay)				
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*	m_1 *(9)*	m_2 *(10)*	p_1 *(11)*	p_2 *(12)*
G	Houston	-29.33	-13.76	-26.73	13.86	27.27	**-32.9**	**-15.4**	**-30.0**	**15.5**	**30.6**
H	Dallas-Ft. Worth	-24.58	-12.02	-22.89	12.40	24.52	**-37.5**	**-18.3**	**-34.9**	**18.9**	**37.4**
I	San Antonio	-7.33	-3.71	-7.12	3.79	7.47	**-34.3**	**-17.4**	**-33.3**	**17.7**	**35.0**
J	Austin	-7.99	-3.75	-7.28	3.79	7.49	**-27.3**	**-12.8**	**-24.8**	**12.9**	**25.6**
K	Other w/ Interstates (avg. values)	-0.42	-0.24	-0.51	0.29	0.86	**-25.7**	**-13.0**	**-24.5**	**15.1**	**78.9**
L	Other w/o Interstates (avg. values)	-0.32	-0.23	-0.41	0.27	0.72	**-38.5**	**-18.5**	**-35.5**	**19.7**	**88.7**

**note: numbers in parentheses in all column headers are the column number*

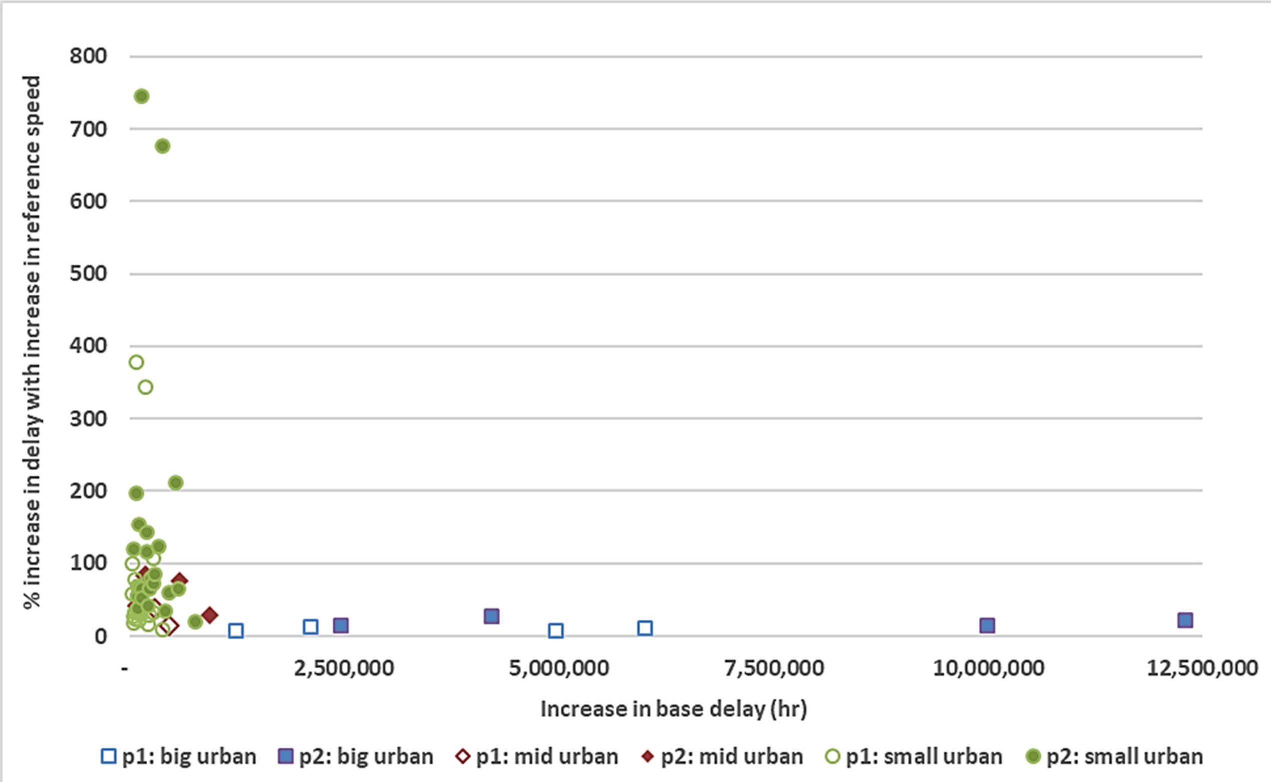

FIGURE 2 Variation of sensitivity with magnitude of delay for freeways.

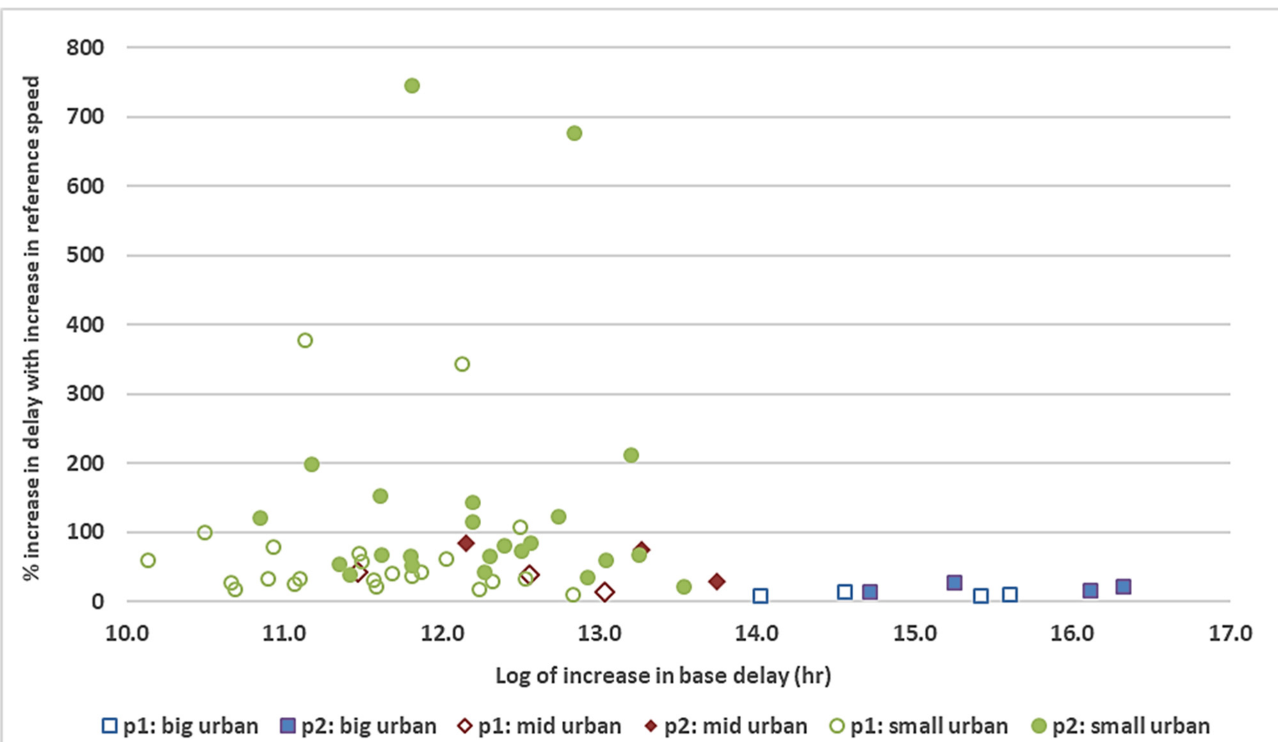

FIGURE 3 Variation of sensitivity with magnitude of delay for freeways (shown on logarithmic scale).

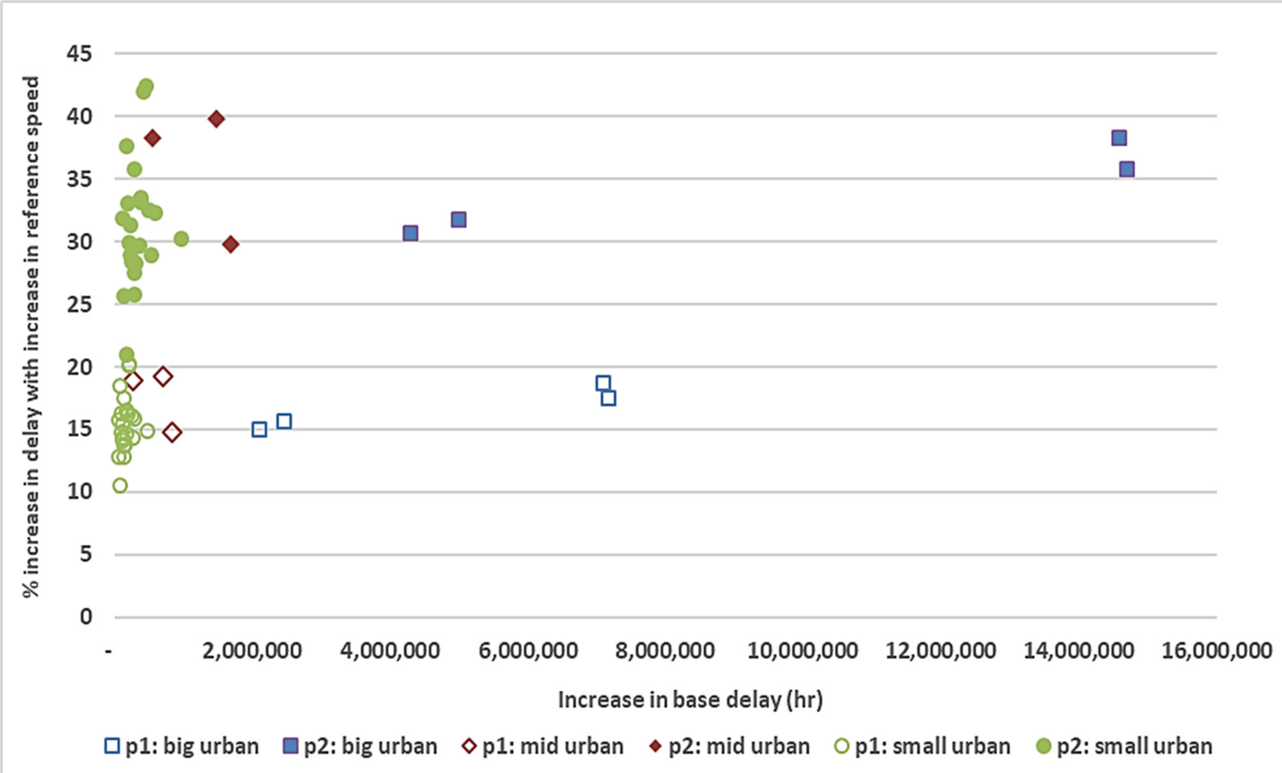

FIGURE 4 Variation of sensitivity with magnitude of delay for arterial streets.

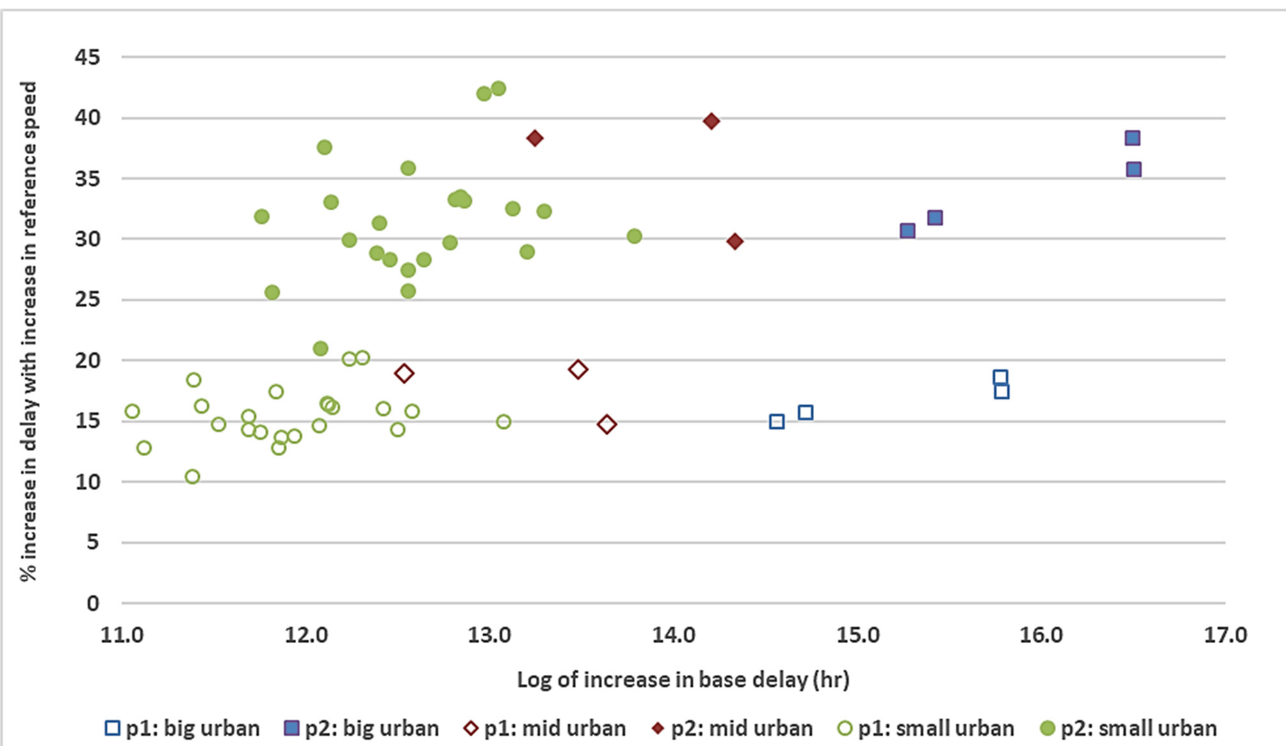

FIGURE 5 Variation of sensitivity with magnitude of delay for arterial streets (shown on logarithmic scale).

Travel Time Index, 80th Percentile and 95th Percentile Planning Time Indices

Table 6 through Table 11 provide details on index sensitivity to reference speed changes for all three chosen indices. These are categorized by urban area size and facility type (freeway vs. arterial street). The values for "Average change in Index" (columns 3 to 7) represent absolute numerical changes in indices averaged over the urban area, and "Sensitivity" (columns 8 to 12) values are calculated as defined in Table 2. Rows E and F in tables 6 through 11 consist of a number of smaller sized urban areas categorized by the presence or absence of Interstate highways crossing them while the last two rows (G to H) show urban areas categorized based on population thresholds as discussed earlier. The following general observations are made from these results:

- To a large extent, all three indices (TTI, PTI_{80} and PTI_{95}) show low sensitivity to changing urban area size, however, their sensitivity decreases slightly as the urban area size increases. This may occur because of the following reasons:
    - With increasing urban arterial network size, the TTI assumes a slightly higher value and becomes less sensitive to changes in reference speeds. In a smaller urban area, relatively lower magnitude changes can generate high percent changes.
    - PTI_{80} and PTI_{95} show lower differences in sensitivity with changes in urban area size. This can be because these are both measures of unusually bad conditions. They are influenced by occurrence of rare events rather than by small changes in reference speed.
- *Table 6 and Table 7 (or 8 & 9, and 10 & 11), columns 3 to 12, corresponding entries for each urban area in rows A to D and urban area types in rows E to H:*
  For the same urban area or urban area type, any index sensitivity is higher on arterial streets than freeways. Both the average and the maximum sensitivity values for all three indices are higher for arterial streets than freeways.
  For a given change in reference speed, travel time accrual is faster at lower operating speeds. This is based on how the same changes in reference speed have different effects on travel rate at different base operating speeds. This effect is discussed in more detail in the earlier section on delay sensitivity.
  Therefore, for the same urban area, the index sensitivity of any of the three indices (TTI, PTI_{80} and PTI_{95}) as a whole is higher on arterial streets than freeways. There can be situations where a freeway section has extremely low operating speeds during the peak periods and travel time will accumulate rapidly, but these tend to be limited in number throughout a region. Another reason for the arterials accruing travel time faster is the presence of mid-day delay along with morning and evening peak-period delay. Consequently, any changes in reference speeds have a high cumulative effect on arterials because more of the operating speeds are below reference speeds throughout the daytime period.
- *Any of Table 6 to Table 11, numbers in columns 11 and 12 are higher in magnitude than corresponding numbers in columns 9 and 10 respectively*:
  For a given facility type (freeway or arterial street), sensitivity is higher for upward changes in reference speed (when reference speed is increased compared to base reference speed) than downward changes (when reference speed is lowered compared to base reference speed). Delay (and therefore any index) starts accruing faster when the reference used to measure the delay is set higher because more instances of lower

operating speeds are now observed relative to the reference speed and delay accrues quicker at lower speeds (higher value of travel rate in minutes per mile).

- *Table 6 and Table 8 (or Table 6 and Table 10), columns 4 and 6, and 9 and 11, rows A to H*:
  PTI_{80} and PTI_{95} sensitivity is only slightly higher than TTI sensitivity. This can be because these indices (PTI_{80} and PTI_{95}) are both measures of unusually bad conditions. They are influenced by occurrence of rare events than by small changes in reference speed. Therefore, their values are less likely to exhibit high sensitivity.
- *Any of Table 6 to Table 11, numbers for "avg" (average) and "max" (maximum) in columns 8 to 12*:
  The average sensitivity values (values in "avg" column) are relatively low for all indices. The "max" numbers (cells shaded in grey) show that some road segments are affected relatively higher than others with same changes in reference speed. These road segments are typically the ones with a lower base index value. These magnitude changes are larger in PTI than with TTI. This is because the numerator for any PTI value (80th or 95th percentile travel time) is much higher than for TTI (average travel time). Therefore, any changes to the denominator (reference travel time) have a greater effect on PTI values than TTI values. This is shown in a numerical example in Figure 6. The "updated reference travel time" is the travel time at the changed reference speed [in this example case, an increase in reference travel speed (therefore, a decrease in reference travel time)]. The same 0.2-minute decrease in reference travel time causes a 0.22 change in TTI and 0.56 change in PTI_{95}.

$$TTI = \frac{Average\ travel\ time}{Reference\ travel\ time}$$

$$PTI_{95} = \frac{95th\ percentile\ travel\ time}{Reference\ travel\ time}$$

Base reference travel time = 2 min
Updated reference travel time = 1.8 min
Average travel time = 4 min
95th percentile travel time = 10 min

Measure	Value at base reference travel time	Value at updated reference travel time	Change in value
TTI	$\frac{4}{2} = 2.0$	$\frac{4}{1.8} = 2.22$	0.22
PTI_{95}	$\frac{10}{2} = 5.0$	$\frac{10}{1.8} = 5.56$	0.56

FIGURE 6 Different magnitude changes in TTI and PTI_{95} with the same change in reference travel time (speed).

TABLE 6 Travel Time Index (TTI) Sensitivity for Freeway Facilities by Urban Area Size and Type

S. No. *(1)*	Urban Area *(2)*	Average change in TTI					Sensitivity (percent change in TTI)									
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*		m_1 *(9)*		m_2 *(10)*		p_1 *(11)*		p_2 *(12)*	
							avg	max	avg	max	avg	max	avg	max	avg	max
A	Houston	-0.04	-0.02	-0.04	0.02	0.04	-2.6	-12.2	-1.4	-5.7	-2.7	-9.0	1.7	8.1	3.3	16.2
B	Dallas-Ft. Worth	-0.03	-0.02	-0.03	0.02	0.04	-2.4	-9.6	-1.3	-2.9	-2.4	-5.7	1.6	3.0	3.2	5.9
C	San Antonio	-0.03	-0.02	-0.03	0.02	0.04	-2.4	-11.5	-1.4	-3.2	-2.6	-6.4	1.6	3.3	3.3	6.7
D	Austin	-0.03	-0.02	-0.03	0.02	0.04	-2.0	-7.5	-1.2	-2.5	-2.2	-5.1	1.6	2.6	3.2	5.3
E	Other w/ Interstates (avg. values)	-0.02	-0.01	-0.02	0.02	0.04	-1.5	-12.2	-1.0	-4.1	-1.6	-8.1	1.6	4.2	3.3	8.4
F	Other w/o Interstates (avg. values)	-0.01	-0.01	-0.01	0.02	0.03	-0.9	-17.2	-0.7	-6.0	-1.1	-11.5	1.7	6.3	3.4	12.7
G	Medium size (250k<population<1M)	-0.02	-0.01	-0.02	0.02	0.04	-1.9	-17.2	-1.1	-6.0	-2.0	-11.5	1.6	6.3	3.3	12.7
H	Small size (population<250k)	-0.01	-0.01	-0.01	0.02	0.03	-1.1	-14.3	-0.8	-5.7	-1.3	-11.4	1.6	5.7	3.3	11.4

**note: numbers in parentheses in all column headers are the column number*

TABLE 7 Travel Time Index (TTI) Sensitivity for Arterial Street Facilities by Urban Area Size and Type

S. No. *(1)*	Urban Area *(2)*	Average change in TTI					Sensitivity (percent change in TTI)									
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*		m_1 *(9)*		m_2 *(10)*		p_1 *(11)*		p_2 *(12)*	
							avg	max	avg	max	avg	max	avg	max	avg	max
A	Houston	-0.08	-0.04	-0.07	0.04	0.08	-6.5	-21.8	-3.0	-8.0	-5.9	-15.3	3.1	9.1	6.2	18.4
B	Dallas-Ft. Worth	-0.07	-0.03	-0.07	0.03	0.07	-6.0	-18.8	-2.8	-9.0	-5.3	-17.5	2.8	9.1	5.7	18.2
C	San Antonio	-0.07	-0.03	-0.07	0.04	0.07	-5.8	-17.3	-2.8	-8.5	-5.5	-15.0	3.0	9.5	6.0	19.0
D	Austin	-0.08	-0.04	-0.07	0.04	0.08	-6.4	-20.4	-2.9	-6.9	-5.6	-11.8	3.0	7.7	5.9	15.4
E	Other w/ Interstates (avg. values)	-0.06	-0.03	-0.05	0.03	0.06	-4.8	-20.5	-2.3	-9.1	-4.5	-14.8	2.5	9.9	7.7	20.0
F	Other w/o Interstates (avg. values)	-0.06	-0.03	-0.06	0.03	0.06	-5.2	-23.1	-2.5	-12.1	-4.8	-19.1	2.7	14.8	5.5	29.6
G	Medium size (250k<population<1M)	-0.07	-0.03	-0.06	0.04	0.07	-5.6	-20.5	-2.7	-9.1	-5.1	-14.8	2.8	9.9	5.6	20.0
H	Small size (population<250k)	-0.06	-0.03	-0.05	0.03	0.06	-5.0	-23.1	-2.5	-12.1	-4.8	-19.1	2.7	14.8	5.5	29.6

**note: numbers in parentheses in all column headers are the column number*

TABLE 8 80th Percentile Planning Time Index (PTI_{80}) Sensitivity for Freeway Facilities by Urban Area Size and Type

S. No. *(1)*	Urban Area *(2)*	Average change in PTI_{80}					Sensitivity (percent change in PTI_{80})									
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*		m_1 *(9)*		m_2 *(10)*		p_1 *(11)*		p_2 *(12)*	
							avg	max	avg	max	avg	max	avg	max	avg	max
A	Houston	-0.05	-0.02	-0.05	0.03	0.05	-3.0	-17.2	-1.6	-8.6	-3.0	-17.2	1.6	8.6	3.3	17.2
B	Dallas-Ft. Worth	-0.04	-0.02	-0.04	0.02	0.05	-2.8	-10.4	-1.5	-3.0	-2.8	-6.0	1.5	3.4	3.1	6.8
C	San Antonio	-0.04	-0.02	-0.04	0.02	0.05	-2.8	-13.0	-1.5	-3.5	-3.0	-7.0	1.6	3.5	3.2	7.0
D	Austin	-0.04	-0.02	-0.04	0.02	0.05	-2.4	-7.7	-1.4	-2.8	-2.7	-5.5	1.4	2.8	2.8	5.5
E	Other w/ Interstates (avg. values)	-0.02	-0.01	-0.02	0.02	0.03	-2.1	-12.4	-1.3	-4.5	-2.3	-8.9	1.4	4.5	3.0	8.9
F	Other w/o Interstates (avg. values)	-0.01	-0.01	-0.02	0.01	0.03	-1.4	-22.1	-1.0	-6.4	-1.6	-12.9	1.2	6.4	2.6	12.9
G	Medium size (250k<population<1M)	-0.03	-0.02	-0.03	0.02	0.04	-2.5	-22.1	-1.4	-6.4	-2.6	-12.9	1.6	6.4	3.2	12.9
H	Small size (population<250k)	-0.02	-0.01	-0.02	0.01	0.03	-1.6	-14.3	-1.1	-5.7	-1.8	-11.4	1.3	5.7	2.8	11.4

**note: numbers in parentheses in all column headers are the column number*

TABLE 9 80th Percentile Planning Time Index (PTI_{80}) Sensitivity for Arterial Street Facilities by Urban Area Size and Type

S. No. *(1)*	Urban Area *(2)*	Average change in PTI_{80}					Sensitivity (percent change in PTI_{80})									
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*		m_1 *(9)*		m_2 *(10)*		p_1 *(11)*		p_2 *(12)*	
							avg	max	avg	max	avg	max	avg	max	avg	max
A	Houston	-0.10	-0.04	-0.08	0.04	0.08	-7.1	-23.1	-3.1	-9.4	-6.2	-18.9	3.1	9.4	6.3	18.9
B	Dallas-Ft. Worth	-0.09	-0.04	-0.08	0.04	0.08	-6.7	-23.3	-2.9	-9.1	-5.8	-18.2	2.9	9.1	5.8	18.2
C	San Antonio	-0.08	-0.04	-0.08	0.04	0.08	-6.5	-20.1	-3.0	-9.5	-6.0	-19.0	3.0	9.5	6.1	19.0
D	Austin	-0.10	-0.04	-0.09	0.04	0.09	-7.0	-23.1	-3.0	-7.8	-6.0	-15.6	3.0	7.8	6.0	15.6
E	Other w/ Interstates (avg. values)	-0.07	-0.03	-0.06	0.03	0.06	-5.5	-28.6	-2.5	-10.4	-4.9	-18.6	2.5	10.4	18.7	20.8
F	Other w/o Interstates (avg. values)	-0.07	-0.03	-0.07	0.03	0.07	-6.0	-29.8	-2.7	-14.8	-5.4	-25.8	2.8	14.8	5.6	29.7
G	Medium size (250k<population<1M)	-0.09	-0.04	-0.08	0.04	0.08	-6.3	-28.6	-2.8	-10.4	-5.5	-18.6	2.8	10.4	5.6	20.8
H	Small size (population<250k)	-0.07	-0.03	-0.06	0.03	0.07	-5.9	-29.8	-2.7	-14.8	-5.4	-25.8	2.8	14.8	5.5	29.7

**note: numbers in parentheses in all column headers are the column number*

TABLE 10 95th Percentile Planning Time Index (PTI_{95}) Sensitivity for Freeway Facilities by Urban Area Size and Type

S. No. *(1)*	Urban Area *(2)*	Average change in PTI_{95}					Sensitivity (percent change in PTI_{95})									
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*		m_1 *(9)*		m_2 *(10)*		p_1 *(11)*		p_2 *(12)*	
							avg	max	avg	max	avg	max	avg	max	avg	max
A	Houston	-0.06	-0.03	-0.06	0.03	0.06	-3.1	-16.8	-1.6	-8.4	-3.2	-16.8	1.6	8.4	3.3	16.8
B	Dallas-Ft. Worth	-0.05	-0.03	-0.05	0.03	0.05	-2.9	-10.4	-1.5	-3.4	-3.0	-6.8	1.6	3.4	3.2	6.8
C	San Antonio	-0.05	-0.03	-0.05	0.03	0.06	-2.9	-13.0	-1.6	-3.5	-3.1	-7.0	1.6	3.5	3.2	7.0
D	Austin	-0.05	-0.03	-0.06	0.03	0.06	-2.5	-7.7	-1.4	-2.8	-2.8	-5.6	1.4	2.8	2.9	5.6
E	Other w/ Interstates (avg. values)	-0.03	-0.02	-0.03	0.02	0.04	-2.5	-12.4	-1.4	-4.5	-2.6	-8.9	1.5	4.5	3.1	8.9
F	Other w/o Interstates (avg. values)	-0.02	-0.01	-0.02	0.01	0.03	-1.7	-22.2	-1.1	-6.4	-2.0	-12.9	1.3	6.4	2.8	12.9
G	Medium size (250k<population<1M)	-0.03	-0.02	-0.03	0.02	0.04	-2.8	-22.2	-1.5	-6.4	-2.9	-12.9	1.6	6.4	3.3	12.9
H	Small size (population<250k)	-0.02	-0.01	-0.02	0.02	0.03	-2.0	-14.3	-1.2	-5.7	-2.2	-11.4	1.4	5.7	3.0	11.4

**note: numbers in parentheses in all column headers are the column number*

TABLE 11 95th Percentile Planning Time Index (PTI_{95}) Sensitivity for Arterial Street Facilities by Urban Area Size and Type

S. No. *(1)*	Urban Area *(2)*	Average change in PTI_{95}					Sensitivity (percent change in PTI_{95})									
		sp *(3)*	m_1 *(4)*	m_2 *(5)*	p_1 *(6)*	p_2 *(7)*	sp *(8)*		m_1 *(9)*		m_2 *(10)*		p_1 *(11)*		p_2 *(12)*	
							avg	max	avg	max	avg	max	avg	max	avg	max
A	Houston	-0.11	-0.05	-0.09	0.05	0.09	-7.2	-25.0	-3.1	-9.5	-6.3	-18.9	3.1	9.5	6.3	18.9
B	Dallas-Ft. Worth	-0.10	-0.04	-0.08	0.04	0.08	-6.8	-25.1	-2.9	-9.1	-5.8	-18.2	2.9	9.1	5.8	18.2
C	San Antonio	-0.09	-0.04	-0.08	0.04	0.09	-6.6	-20.0	-3.0	-9.5	-6.0	-19.0	3.0	9.5	6.1	19.0
D	Austin	-0.11	-0.05	-0.10	0.05	0.10	-7.1	-23.1	-3.0	-7.8	-6.0	-15.6	3.0	7.8	6.0	15.6
E	Other w/ Interstates (avg. values)	-0.08	-0.04	-0.07	0.04	0.07	-5.6	-33.7	-2.5	-10.4	-5.0	-20.1	2.5	10.4	18.0	20.8
F	Other w/o Interstates (avg. values)	-0.08	-0.04	-0.07	0.04	0.07	-6.2	-29.7	-2.8	-14.8	-5.5	-29.7	2.8	14.8	5.6	29.7
G	Medium size (250k<population<1M)	-0.10	-0.04	-0.09	0.04	0.09	-6.3	-33.7	-2.8	-10.4	-5.5	-20.1	2.8	10.4	5.6	20.8
H	Small size (population<250k)	-0.08	-0.04	-0.07	0.04	0.07	-6.1	-29.7	-2.8	-14.8	-5.5	-29.7	2.8	14.8	5.6	29.7

**note: numbers in parentheses in all column headers are the column number*

CONCLUSIONS

Reference speed represents unconstrained travel conditions on transportation facilities. Reported delay, mobility and reliability measures are influenced by the selected reference speed values. This paper examined the relative effects of changes in reference speeds on four performance measures – delay, TTI, PTI_{80} and PTI_{95}. The analysis was performed on freeway (uninterrupted flow) and arterial street (interrupted flow) facilities in urban areas of different population sizes.

The results indicated that travel delay sensitivity to changes in reference speed is dependent upon the transportation facility type and urban area size.

- Uninterrupted flow facilities (Interstates and freeways) where delay becomes less sensitive to reference speed change as the urban area size increases.
- Small urban areas with low high-speed facility mileage (e.g., Interstate mileage) typically show high sensitivity because they have very low initial base delay.
- Arterial street delay sensitivity is not significantly affected by urban area size. Streets experience some delay all day caused by signalization, traffic turning from cross streets and driveways, and various other causes. This ‘base amount’ of delay does not fluctuate widely with changes in reference speed.

However, within a particular urban area, arterial streets were more sensitive to changes in reference speeds than Interstates and freeways because they incur mid-day delay along with peak period delay. This is compounded by the fact that for a given change in base reference speed, delay accrual is faster at lower operating speeds because of higher travel rate (minutes per mile). Consequently, any changes in reference speeds have a higher cumulative effect on arterial streets as they operate at lower speeds.

Other indices (TTI, PTI_{80} and PTI_{95}) showed lower effect of urban area size on their sensitivity. Additionally, like delay, the three indices were more sensitive to changes in arterial street reference speeds than freeway. This is because both delay and travel time accrue faster at lower operating speeds.

All measures indicated that the speed limit values are lower than the reference speeds derived from travel data. Delay and index calculations suggested that speed limits are typically between 2 to 3 mph lower than derived reference speeds. Using speed limit values resulted in lower estimates of all measures (delay and all three indices) than those obtained using reference speed. These differences are higher on freeways where vehicles travel slightly higher than speed limit. Arterial streets are not similarly affected; vehicles travel closer to, or under, the speed limit, even in low volume conditions. This can result in high freeway delay and index sensitivity in smaller urban areas where freeway base delay and index values are low. This result also indicates that widely reported delay measures may typically remain under-reported on freeway facilities when using posted speed limit (PSL) as reference speed and over-reported when using posted speed limit plus five (PSL+5) as reference speed, particularly in small and medium size urban areas. The impact may be less so in larger urban areas.

The paper highlights the importance of using appropriate reference speed in mobility measurement and the observed effects of using a higher or lower value (e.g., fixed proxies of reference speed based on speed limit) for reporting performance measures. These fixed proxies may be unable to capture field-observed operating characteristics of traffic and remain updated on a timely basis for continual system performance measurement compared to a recorded travel time data driven approach. This may result in under- or over-estimated reported performance measures as discussed in this paper.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: K. Jha, D. Schrank, W. Eisele, M. Burris; data collection: D. Schrank, K. Jha; analysis and interpretation of results: K. Jha, T. Lomax, D. Schrank; draft manuscript preparation: K. Jha, T. Lomax, D. Schrank, W. Eisele, M. Burris. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Moving Ahead for Progress in the 21st Century (MAP-21). *Performance Management*. Federal Highway Administration, US Department of Transportation. http://www.fhwa.dot.gov/map21/factsheets/pm.cfm. Accessed March 7, 2018.
2. Jha, K., M.W. Burris, W.L. Eisele, D.L. Schrank, and T.J. Lomax. Estimating Reference Speed from Probe-based Travel Speed Data for Performance Measurement. Presented at 97th Annual Meeting of the Transportation Research Board, Washington, D.C., 2018.
3. Jha, K. Determining Reference Speed from Probe-Based Travel Speed Data. *Master's Thesis, Texas A&M University, College Station, TX*, Texas A&M University Electronic Theses and Dissertations Repository, 2017. Available from https://oaktrust.library.tamu.edu/handle/1969.1/161455
4. Washington Department of Transportation. *WSDOT Gray Notebook*. http://www.wsdot.wa.gov/accountability/graynotebook.pdf (accessed 08.20.2016)
5. National Research Council. *HCM 2010: Highway Capacity Manual*. Transportation Research Board, Washington D.C., 2010.
6. Cambridge Systematics, Inc., Kittelson & Associates, Inc. and Texas A&M Transportation Institute. *Comparison of Performance Measurement Approaches*. February 2014.
7. Florida Department of Transportation. *Multimodal Mobility Performance Measures Source Book*. 2015. http://www.dot.state.fl.us/planning/statistics/sourcebook/2015.pdf
8. Texas A&M Transportation Institute. *Synthesis of U.S. Performance Measurement Activities*. Technical Memorandum Prepared for the Mobility Measurement in Urban Transportation (MMUT) Pooled Fund Study, March 2014.
9. Washington Department of Transportation. *2013 Corridor Capacity Report*. http://wsdot.wa.gov/publications/fulltext/graynotebook/CCR13.pdf (accessed 06.22.2016)
10. California Department of Transportation. *California Mobility Performance Reporting and Analysis Program*. http://www.dot.ca.gov/trafficops/mpr/ (accessed 08.25.2016)
11. Maryland State Highway Administration. *2013 Maryland State Highway Mobility Report*. http://www.roads.maryland.gov/OPPEN/2013_Maryland__Mobility.pdf (accessed 06.22.2016)

12. Missouri Department of Transportation. *Tracker - Measures of Departmental Performance*. January 2014. http://www.modot.org/about../documents/January2014TrackerReduced.pdf (accessed 08.20.2016)

13. Wisconsin Department of Transportation. *2016 MAPSS Performance Improvement Report*. April 2016. http://wisconsindot.gov/Documents/about-wisdot/performance/mapss/perf-report.pdf

14. Chicago Metropolitan Agency for Planning (CMAP). *Regional Transportation Performance Measurement*. http://www.cmap.illinois.gov/mobility/roads/cmp/performance-measurement (accessed 08.20.2016)

15. New York Metropolitan Transportation Council. *Congestion Management Process Report: 2013 Status Report*. https://www.nymtc.org/project/CMS/cms.html (accessed 06.25.2016)

16. Cambridge Systematics, Inc., Dowling Associates, Inc., System Metrics Group, Inc., and Texas Transportation Institute. *NCHRP Report 618: Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability.* Transportation Research Board of the National Academies, Washington, D.C., 2008.