The Eastern Transportation Coalition Vehicle Probe Project: HERE, INRIX and TomTom Data Validation

Report for Pennsylvania
Freeway Validation: Pennsylvania #12
Tunnel and Work Zone Scenarios

Data Collection: October/November 2021
Report Date: May 2022

Prepared by:
Zachary Vander Laan, Stanley Young, Romina Jahangiri
University of Maryland, College Park

Acknowledgements:
The research team would like to express its gratitude for the assistance it received from the state highway officials in Pennsylvania during the data collection phase of the validation effort.

1. Table of Contents

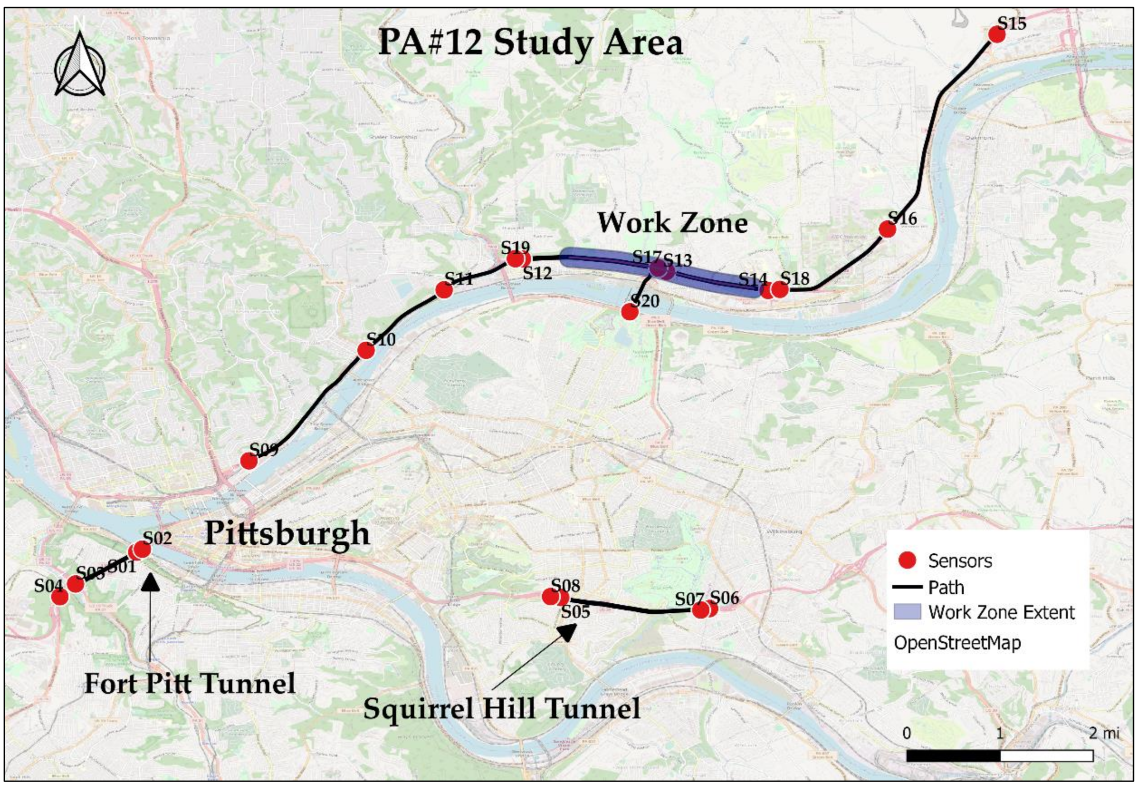
List of Tables

List of Figures

Executive Summary

This report provides the results of validation activities for the Eastern Transportation Coalition's (TETC's) Vehicle Probe Project in which multiple vendors provide travel time and speed data to our members for operations, planning and performance measures purposes. Wireless re-identification traffic monitoring (WRTM) technology (Bluetooth and/or Wi-Fi) is used to evaluate the quality of speeds reported by probe data vendors on selected validation road segments.

This freeway study focuses on two scenarios in Pittsburgh, PA: **tunnels** and w**ork zones** (see ES Figure 1 and ES Table 1 for location details). The study area consists of road segments that pass through two tunnels, Fort Pitt and Squirrel Hill, as well as others that capture a long-term work zone along PA-28 and nearby roadways that were expected to be impacted by the resulting congestion. In total, the study area encompasses approximately 20 directional freeway miles with Average Annual Daily Traffic (AADT) values around 54k (work zone) and 96k (tunnels).



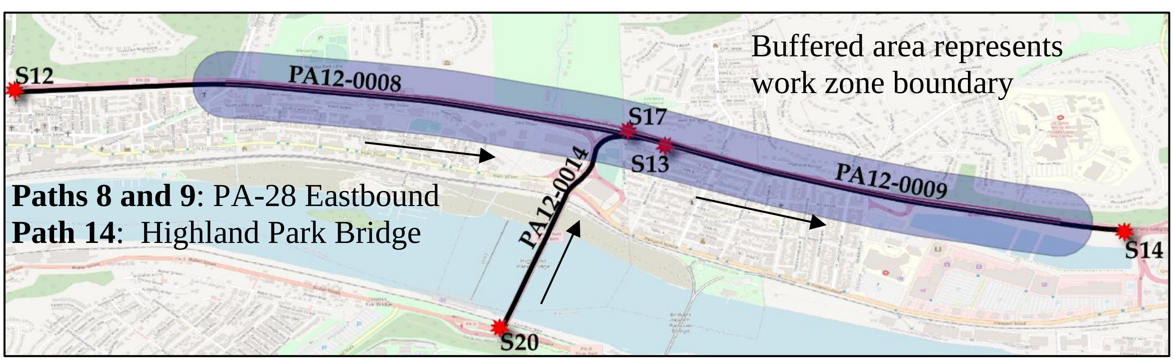
ES Figure 1 – Study area containing two tunnels and a work zone

ES Table 1 – Freeway Corridor Description			
Corridor Name	**Number of Lanes**	**AADT**	**Speed Limit**
I-376 (Tunnels)	2-4	95.8k	50-55 mph
PA-28 (Work zone)	1-4	54.0k	45-55 mph

Tunnels were selected as an evaluation scenario because an earlier validation study from 2017[1] found that probe data quality had trouble in these conditions – possibly due to challenges with GPS and cellular data signals. The 2017 study focused on two tunnels in Maryland (Baltimore Harbor and Ft McHenry) and found that all vendors reported speeds significantly lower than the reference data when traffic was operating at high speeds (60 mph+), resulting in consistent errors around 6-18 mph in the highest speed bin. The tunnels selected for the current PA study are shown below in ES Figure 2, and experience both recurrent and non-recurrent congestion.

ES Figure 2 – Fort Pitt (left) and Squirrel Hill (right) tunnels

The work zone along PA-28 was selected in consultation with Pennsylvania DOT. Based on local experience, road segments were selected within the boundaries of the work zone, and additionally upstream of the work zone in both directions of travel. ES Figure 3 shows an example of the study area in the immediate vicinity of the work zone (only one direction is shown for simplicity). Paths 8 and 9 represent Eastbound traffic along PA-28 (within the work zone), while Path 14 is defined along the Highland Park Bridge and entrance ramp that leads to PA-28 Eastbound. This bridge was included in the study area because it is upstream of the work zone, and thus can be impacted by congestion on PA-28. Many of the work zone segments had regular congestion events throughout the data collection period, thus providing opportunities to evaluate vendor data in conditions that may differ from historical patterns and to see whether vendors can capture the progression of congestion along multiple segments.



ES Figure 3 – Work zone boundary and example segments in the immediate vicinity

[1] Masoud Hamedi, Sanaz Aliari: I-95 Corridor Coalition Vehicle Probe Project: HERE, INRIX and TOMTOM Data Validation, Report for Maryland #11, Baltimore Harbor and Ft McHenry Tunnels, I-95 Express Lanes (link)

The primary method used to quantify vendor data accuracy in this report is the "traditional analysis", which involves comparing reported probe speeds to (a) the mean WRTM speed, and (b) the 1.96 Standard Error of the Mean (SEM) band for each 5-minute time interval. These comparisons are quantified in terms of two error metrics: Average Absolute Speed Error (AASE) and Speed Error Bias (SEB), which are calculated separately for different speed ranges. In this report, we also summarize the error measures separately for tunnel and work zone scenarios. Additionally, the validation team investigated the trace data visually to see how well the vendors responded to congestion events and understand the extent to which they were able to capture the progression of congestion along the work zone corridor.

Unlike recent validation studies where the validation team cautioned against over-reliance on the traditional analysis error measures (e.g., in very low-volume settings and urban arterial roads with many access points) as noted in VT#01, NC#10 and GA#12 reports, **this study area is well-suited for the traditional analysis, which was designed for freeway facilities and higher speeds**. All road segments for tunnel and work zone scenarios fall on freeways where ample Bluetooth samples were acquired, and ground truth travel time and speed conditions were captured with a high degree of fidelity. While some aspects of these scenarios are challenging, this validation is not considered an edge case, as was the previous validation in urban regions of Atlanta.

The AASE and SEB measures are summarized below for each vendor. All three vendors were within contract specs in all speed bins for both Tunnel and Work Zone scenarios.

ES Table 2 – HERE Traditional Analysis Summary

Speed Bin	Average Absolute Speed Error (<10mph)		Speed Error Bias (<5mph)		Number of 5 Minute Samples
	1.96 SEM Band	Mean	1.96 SEM Band	Mean	
Tunnel					
0-30	0.92	1.87	0.55	0.72	1293
30-45	2.15	4.22	1.56	2.84	2811
45-60	1.46	4.64	1.26	3.52	5702
60+	1	4.77	-0.73	-2.56	720
All Speeds	1.55	4.2	1.12	2.58	10526
Work Zone					
0-30	2.01	4.78	1.71	3.51	734
30-45	1.63	4.44	1.29	2.74	1931
45-60	1.02	3.73	0.62	1.42	13106
60+	0.95	4.73	-0.79	-3.49	3859
All Speeds	1.1	4.04	0.45	0.67	19630

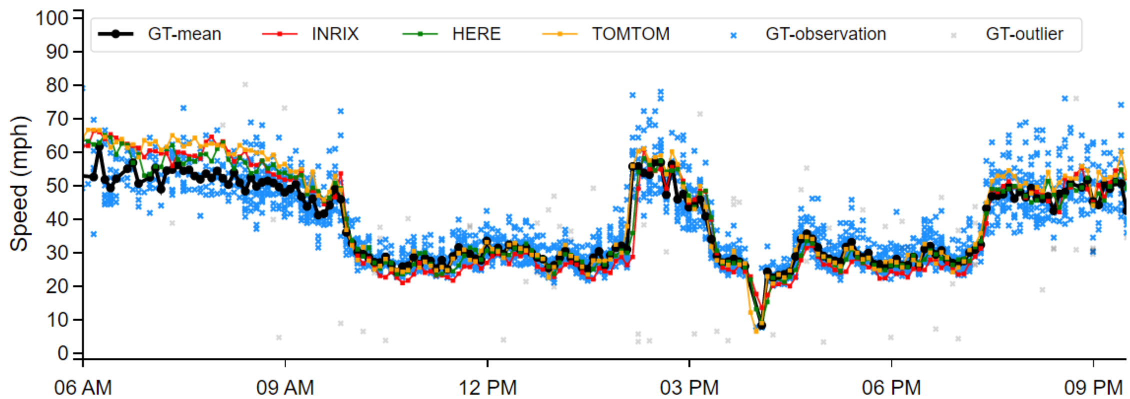
ES Table 3 – INRIX Traditional Analysis Summary					
Speed Bin	Average Absolute Speed Error (<10mph)		Speed Error Bias (<5mph)		Number of 5 Minute Samples
	1.96 SEM Band	Mean	1.96 SEM Band	Mean	
Tunnel					
0-30	1.48	2.59	-0.63	-1.27	1293
30-45	2.51	4.65	1.05	2.01	2893
45-60	1.84	5.27	1.63	4.3	5717
60+	0.69	4.01	-0.41	-1.5	720
All Speeds	1.9	4.69	1.06	2.6	10623
Work Zone					
0-30	2.17	4.75	1.92	3.35	726
30-45	1.69	4.57	1.04	2.26	1925
45-60	1.09	3.87	0.69	1.53	13105
60+	0.86	4.5	-0.78	-3.36	3857
All Speeds	1.15	4.09	0.48	0.71	19613

ES Table 4 – TomTom Traditional Analysis Summary					
Speed Bin	Average Absolute Speed Error (<10mph)		Speed Error Bias (<5mph)		Number of 5 Minute Samples
	1.96 SEM Band	Mean	1.96 SEM Band	Mean	
Tunnel					
0-30	0.44	1.3	-0.07	-0.24	1303
30-45	2.27	4.32	2.05	3.52	2864
45-60	2.79	6.51	2.73	6.13	5714
60+	0.68	4.09	0.01	0.59	720
All Speeds	2.22	5.12	2.02	4.26	10601
Work Zone					
0-30	1.38	3.78	1.14	2.33	734
30-45	2.09	5.31	2	4.67	1932
45-60	1.71	4.78	1.63	3.94	13124
60+	0.71	4.01	0.18	0	3866
All Speeds	1.54	4.64	1.36	3.18	19656

Findings

- **All three vendors demonstrated excellent average accuracy in tunnels**. As shown in ES Tables 2-4, each vendor was within specification for AASE and SEB metrics in all four speed bins for tunnels, demonstrating significant improvement relative to the previous 2017 tunnel study. All vendors had minimal bias in the 60+ mph speed bin (within 1-2 mph), which was the problem area from the 2017 study (errors in the 6-18 mph range).

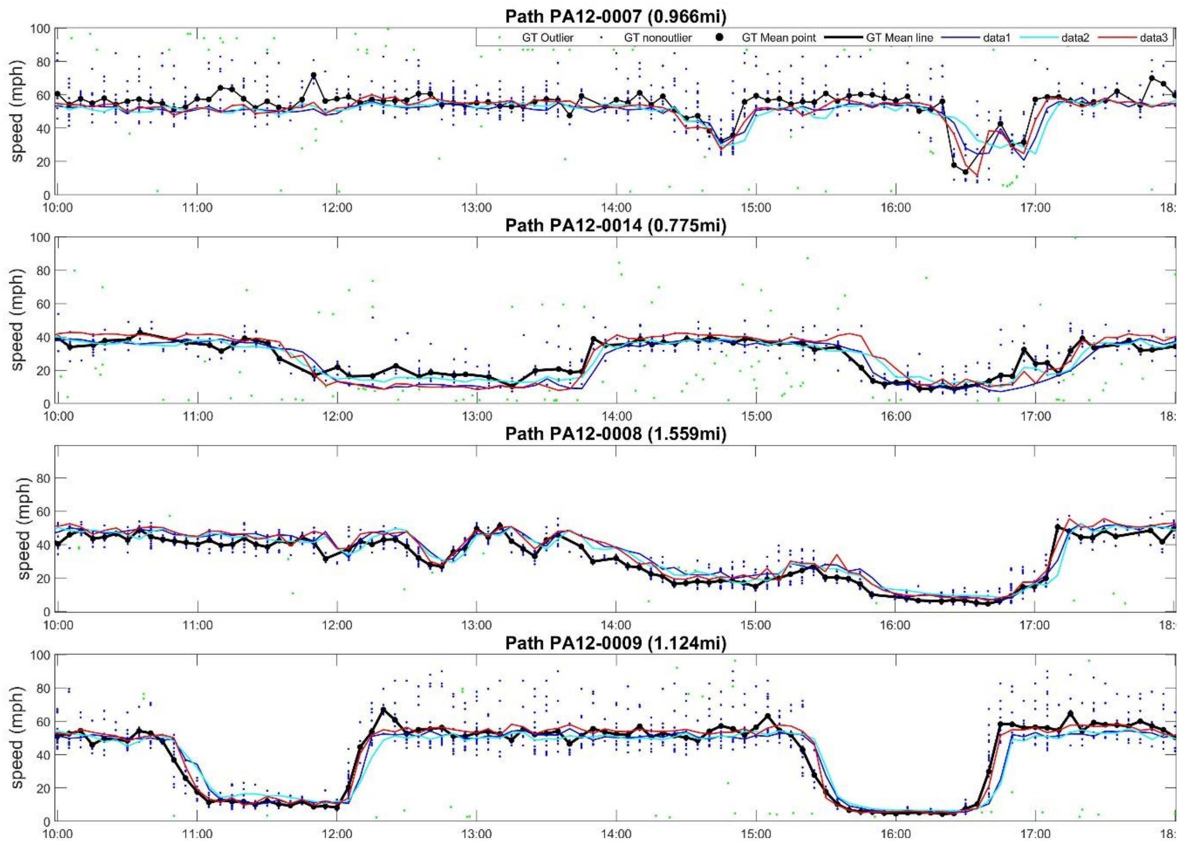
  Additionally, visual inspection of the trace data corroborates the high accuracy demonstrated by the AASE and SEB error measures. ES Figure 4 shows a representative example of data along the Squirrel Hill Tunnel in which all three vendors closely track the reference data as speeds change throughout the day.



ES Figure 4 – All vendors track reference data closely in a representative tunnel scenario.

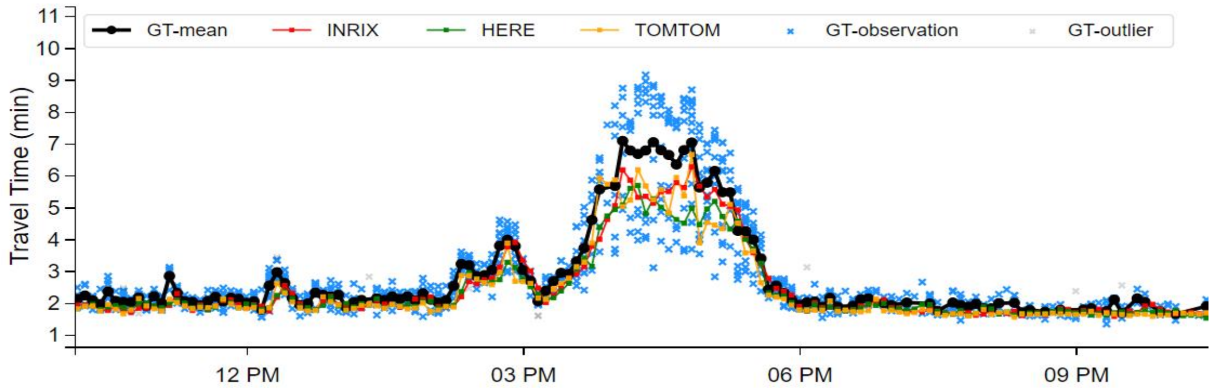
- **All three vendors showed high average accuracy in work zones and demonstrated the ability to capture the progression of congestion patterns.** As was the case with tunnels, ES Tables 2-4 showed excellent AASE and SEB values for each vendor in all speed bins, while visual inspection of the data highlighted the fact that the vendor data regularly identified congestion patterns. Accuracy in work zones is notable because congestion can occur during times and locations that differ from historical patterns, making it difficult for vendors to fall back on historical knowledge of the location.

  ES Figure 5 illustrates how the vendors capture work-zone related congestion patterns, focusing on paths 7, 8, 9 and 14. ES Figure 3 (shown earlier in the Executive Summary) illustrates this area; Path 9 represents the downstream part of the work zone area on PA-28, while Path 8 represents the upstream part of the work zone and Path 14 is the Highland Park Bridge that is also directly upstream of Path 9. Path 7 (not shown in ES Figure 3) is directly upstream of Path 8. After speeds on Path 9 drop from 55 mph to 5-10 mph twice during the day (11am and 3:30pm) speed reductions make their way upstream (with some time lag) onto Path 14 (bridge) during both periods. However, on Path 8 (directly upstream of Path 9 on PA-28) the speeds remain high until about 1:30pm, after which they drop, realizing their minimum value during and immediately following the afternoon speed drop on Path 9. The congestion seen on Path 8 also briefly progresses upstream onto Path 7, but speeds recover quickly and there is not extended congestion on this path. During each of these patterns, all three probe vendors track the reference data closely and thus capture the progression of congestion with high fidelity.

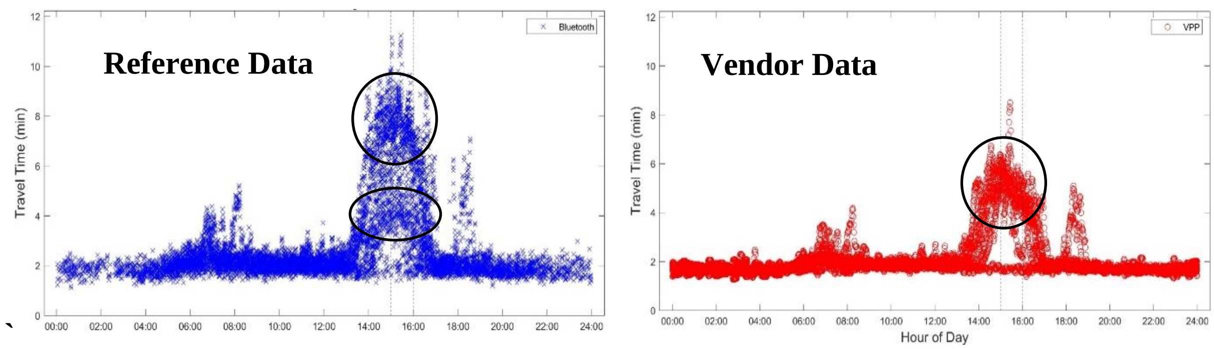


ES Figure 5 – All vendors capture congestion progressing upstream from work zone

- **Bimodal travel time patterns were observed along some work zone segments**, likely reflecting lanes moving at different speeds. In such cases, the reference mean travel time / speed sometimes tracked one mode more closely than the other (or fell in between the two modes), and the vendors all produced reasonable values, often tracking the more optimistic mode. This scenario highlights the inherent limitation of probe data reporting only a single average speed. ES Figure 6 shows an example of bimodal data during a single congestion event, while ES Figure 7 illustrates how bi-modal patterns emerge in the reference data when overlaying all weekday travel time observations. In this case the vendor data consistently reported a value in between the two modes, although closer to the more "optimistic" higher-speed mode.



ES Figure 6 – Example of bimodal travel times during a period of congestion.



ES Figure 7 – Ref data reveals bi-modal pattern while vendor reports between modes (9 weekdays)

- **There were a few isolated examples of latency, but overall, all three vendors responded to congestion with minimal delay.** To evaluate latency properly it is necessary to log vendor data in real-time – a process that is currently only possible for one vendor due to data delivery constraints. Future validation work will seek to develop a mechanism for such recording, which will likely involve setting up a logging system to query and record the data being produced by vendors in real time.

Introduction

The University of Maryland (UMD), acting on behalf of the Eastern Transportation Coalition (previously the I-95 Corridor Coalition), was given the responsibility of evaluating the quality of Vehicle Probe Project (VPP) data at the inception of the project in 2009. To assess the quality of travel time and speed data, UMD developed a methodology using wireless re-identification traffic monitoring (WRTM) technology, which is documented in detail in the previously referenced full report: I-95 Corridor Coalition Vehicle Probe Project: Validation of INRIX Data (link).

At a high level, WRTM equipment is deployed at strategic locations along selected road segments and identifies – and later re-identifies – unique signals emitted by in-vehicle electronic equipment via Bluetooth, Wi-Fi and other technologies, thus allowing direct measurement of travel times from a sample of vehicles. Initial research conducted by UMD shows that this sampling approach is capable of accurately characterizing travel times (speeds); therefore, WRTM data serves as the ground-truth data source against which reported probe speeds are compared.

In 2014, the project moved to a second phase (VPPII), during which a probe data marketplace was created. Currently there are three data vendors that provide travel time and speed data through this marketplace: HERE, INRIX, and TomTom. The purpose of this report, which is produced on a regular basis, is to continue to rigorously assess the accuracy of speeds reported by each vendor on various road segments from the Eastern Transportation Coalition member states.

Probe Data Vendors

Three probe data vendors are evaluated in this report: HERE, INRIX, and TomTom. Each vendor provides travel time and speed data along the road segments and time periods of interest, which are subsequently compared to ground truth WRTM observations in order to assess data accuracy.

Specifically, each vendor reports travel time and speed data in one-minute intervals either along road segments defined by the WRTM sensor locations (i.e., validation segmentation) or Traffic Message Channel (TMC) segments. In the latter case the TMC-based speeds must first be transformed to equivalent speeds on validation segments before a direct comparison can be made.

Methodology

The primary means of evaluating the vendor data is through the traditional validation analysis, which is documented in the original report (I-95 Corridor Coalition Vehicle Probe Project:

Validation of INRIX Data July-September 2008) and summarized below. Additionally, supplemental analyses may be conducted depending on the road type being evaluated and observed data characteristics. The most common supplemental analysis is the slowdown analysis, which evaluates probe data quality during major congestion events on arterials.

Traditional validation analysis

Overview

The traditional validation analysis consists of comparing ground truth (i.e., WRTM) speeds against vendor speeds over five-minute intervals and quantifying the discrepancy in terms of two error metrics defined in the contract specifications.

Obtain vendor speed data along validation road segments

Road segments used for validation are defined based on WRTM sensor locations – often resulting in different segment definitions than those typically reported by the probe vendors. Accordingly, vendors may either report speeds directly on the validation road segmentation used for evaluation, or report speeds based on standard Traffic Message Channel (TMC) segments. In the latter case, equivalent vendor speeds must be obtained for the geometry specified by the WRTM sensors, which is accomplished via a trajectory reconstruction algorithm. This algorithm is described in another report[2] and works by (a) identifying the portions of vendor road segments that correspond to the validation segment, and (b) using the speeds reported on the vendor's segments during multiple time intervals to calculate the equivalent speed.

Filter and aggregate ground truth data

Raw travel time (speed) observations are first filtered to remove outliers. The filtering step is necessary because WRTM sensors sometimes re-identify vehicles that stop between sensors or record travel times from pedestrians or non-motorized vehicles that are not representative of actual traffic conditions. After the outlier observations are removed, the remaining representative observations are aggregated for each segment over five-minute intervals, and intervals with too few observations or excessive variation are discarded.

The remaining intervals are deemed suitable for evaluation of vendor probe data and are summarized in terms of (a) space-mean speed and (b) confidence band around the mean. The space-mean speed captures average ground truth traffic behavior, while the confidence band accounts for sample size and variation in the observed speeds.

---

[2] Ali Haghani, Masoud Hamedi, Kaveh Farokhi Sadabadi, Estimation of Travel Times for Multiple TMC Segments, prepared for I-95 Corridor Coalition, February 2010 (link)

Several statistical measures were initially evaluated to define the width of this uncertainty band, all of which are described and reported in the original report. Ultimately, the standard error of the mean (SEM) measure was selected due to its simplicity and sensitivity to both variability and number of observations used for calculations. The SEM is calculated as the standard deviation (SD) of the WRTM speeds divided by the square root of the number WRTM data points (n) taken for a given time. In other words, $\text{SEM} = \frac{SD_{WRTM}}{\sqrt{n}}$. The confidence band based on this statistic (i.e., the SEM band) narrows when there is a higher degree of confidence in the ground truth data (i.e., more observations or less variation) and widens when there is less confidence, serving as a proxy for a 95% confidence interval of ground truth speeds.

Compute Error Metrics

A statistical analysis of the data is conducted for four defined speed bins, where each five-minute interval is associated with a speed bin based on its corresponding ground truth space-mean speed (0-15 mph, 15-30 mph, 30-45 mph, 45+ mph for arterials; 0-30 mph, 30-45 mph, 45-60 mph, 60+ mph for freeways). Reported probe speeds are compared to both the space-mean and SEM band ground truth speed for each five-minute time interval, and the discrepancies are quantified in terms of two error metrics: Average Absolute Speed Error (AASE) and Speed Error Bias (SEB), which are reported separately for each speed bin. According to contract specifications, AASE and SEB values must be within 10 mph and 5 mph, respectively, when compared with the SEM band.

AASE is calculated by summing up the absolute difference between probe vendor speeds (S_P) and ground truth speeds (S_{GT}) for each time interval and taking the average over n observations. That is, $\text{AASE} = \frac{1}{n}\sum_{i=1}^{n}|S_P - S_{GT}|$. Because the absolute value is used, positive and negative errors cannot cancel, and the result is always positive. Speed Error Bias is calculated similarly, with the difference that the absolute value of the errors is not taken. In other words, $\text{SEB} = \frac{1}{n}\sum_{i=1}^{n} S_P - S_{GT}$. Thus, positive and negative errors can cancel each other out, and the resulting value can provide insight into whether there is a consistent positive or negative error.

Data Collection

Travel time samples were collected along 14 directional freeway validation segments near downtown Pittsburgh, PA from October 26 – November 6, 2021. This freeway study focuses on two scenarios in Pittsburgh, PA: **tunnels** and w**ork zones** (see Figure 1 and Table 1, below for more details). The study area consists of road segments that pass through two tunnels, Fort Pitt, and Squirrel Hill, as well as others that capture a long-term work zone along PA-28 and nearby roadways that were expected to be impacted by the resulting congestion.

Table 1 contains the summary information for each data collection segment, including WRTM sensor latitude/longitudes and an active map link, which can be followed to view each data collection segment in detail. Please note that the configuration of the test segments is often such that the endpoint of one segment coincides with the start point of the next segment, so that one WRTM sensor covers both data collection segments.

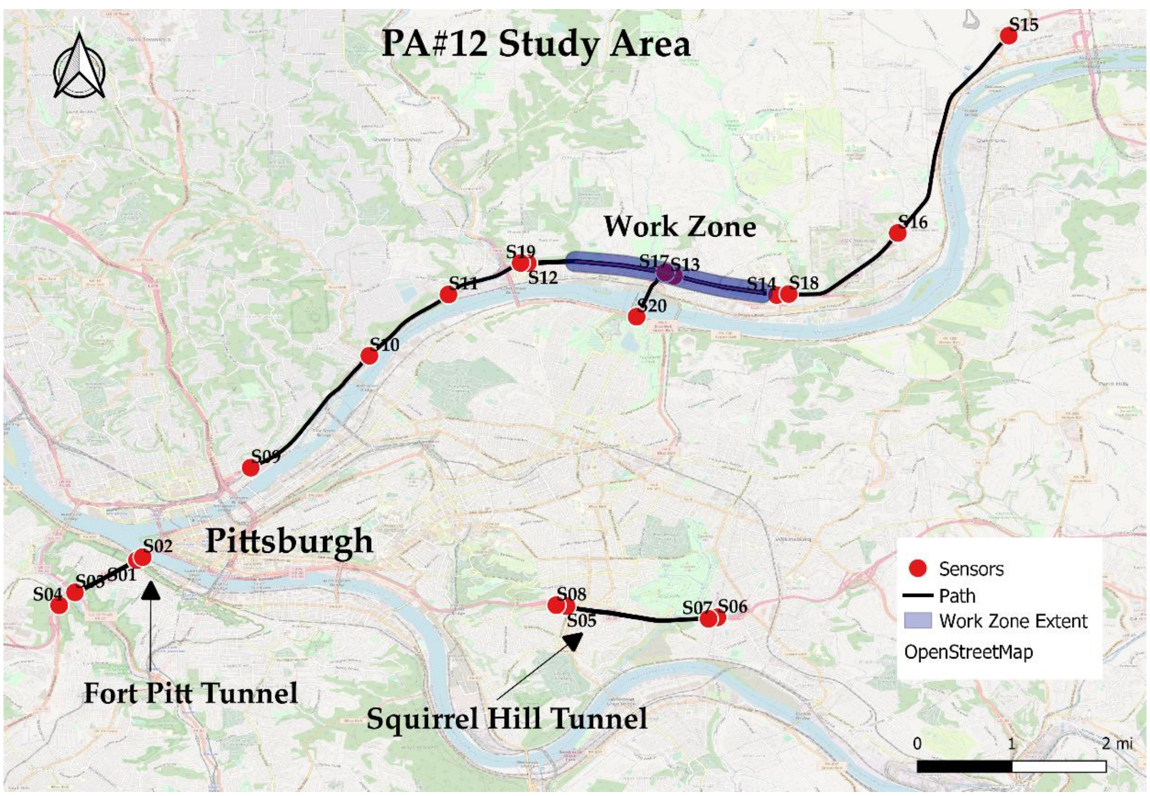


Figure 1 – WRTM Sensor locations

Table 1 - Validation Segment Attributes

Segment (Map Link)	DESCRIPTION: Highway / Direction	Starting at / Ending at	Min / Max Lanes	AADT	Access Points / Speed Limit	Deployment: Begin Lat/Lon / End Lat/Lon		Length (mi)
A1 PA12-0001	I-376 Westbound	W Carson St. Saw Mill Run Blvd	2 2	104694	0 50	40.43761 40.43102	-80.01383 -80.02628	0.799
A2 PA12-0002	I-376 Eastbound	SW of Saw Mill Run Blvd W Carson St.	2 4	99795	2 50	40.42874 40.43808	-80.02949 -80.01274	1.095
A3 PA12-0003	I-376 Eastbound	W of Forward Ave W of Braddock Ave	2 2	92291	0 55	40.42863 40.42589	-79.92937 -79.89899	1.628
A4 PA12-0004	I-376 Westbound	W of Braddock Ave W of Forward Ave	2 3	92228	0 55	40.42608 40.42835	-79.8972 -79.92755	1.621
A5 PA12-0005	28 Eastbound	E of Chestnut St Evergreen Rd.	2 3	48851	5 45	40.45621 40.47901	-79.99099 -79.96661	2.062
A6 PA12-0006	28 Eastbound	Evergreen Rd. W of Washington ST	2 3	48480	1 45	40.47901 40.49081	-79.96661 -79.95112	1.161
A7 PA12-0007	28 Eastbound	W of Washington ST Ravine St.	2 4	48102	3 45	40.49081 40.49705	-79.95112 -79.93516	0.966
A8 PA12-0008	28 Eastbound	Ravine St. W of Center Ave.	2 3	51344	2 45	40.49705 40.4947	-79.93516 -79.90594	1.559
A9 PA12-0009	28 Eastbound	W of Center Ave. W of Fox Chapel Rd	2 2	58534	3 55	40.4947 40.49081	-79.90594 -79.88528	1.124
A10 PA12-0010	28 Westbound	E of Indianola Rd E of Gamma Dr	2 3	59119	1 55	40.54283 40.50299	-79.83841 -79.86107	3.071
A11 PA12-0011	28 Westbound	E of Gamma Dr Fox Chapel Rd	2 3	64010	3 55	40.50299 40.49088	-79.86107 -79.88289	1.507
A12 PA12-0012	28 Westbound	Fox Chapel Rd W of Center Ave	2 3	60341	2 45	40.49088 40.49537	-79.88289 -79.90764	1.347
A13 PA12-0013	28 Westbound	W of Center Ave W of Levine St	1 3	42855	1 45	40.49537 40.49707	-79.90764 -79.93672	1.547
A14 PA12-0014	Highland Park Bridge Eastbound	Washington Blvd W of Center Ave	1 2	37892	5 45	40.48661 40.4947	-79.91323 -79.90594	0.775

Validation Results

Traditional Validation Results

HERE

Table 2 summarizes the error metrics computed between ground truth (i.e., WRTM) and HERE speeds, reporting results for three scenarios: Overall (across all paths), Tunnels (across only paths in tunnels), and Work zones (across only paths in the work zone).

Both Average Absolute Speed Error (AASE) and Speed Error Bias (SEB) measures are within specification for all speed bins across all scenarios (Overall / Tunnel / Work Zone) – a result that remains true whether the 1.96 SEM Band or Mean is used for calculations.

Table 2 – HERE data quality measures by scenario

Speed Bin	Average Absolute Speed Error (<10mph)		Speed Error Bias (<5mph)		Number of 5 Minute Samples
	1.96 SEM Band	Mean	1.96 SEM Band	Mean	
Overall					
0-30	1.32	2.93	0.97	1.73	2027
30-45	1.94	4.31	1.45	2.8	4742
45-60	1.15	4.01	0.82	2.06	18808
60+	0.96	4.74	-0.78	-3.34	4579
All Speeds	1.26	4.09	0.69	1.33	30156
Tunnel					
0-30	0.92	1.87	0.55	0.72	1293
30-45	2.15	4.22	1.56	2.84	2811
45-60	1.46	4.64	1.26	3.52	5702
60+	1	4.77	-0.73	-2.56	720
All Speeds	1.55	4.2	1.12	2.58	10526
Work Zone					
0-30	2.01	4.78	1.71	3.51	734
30-45	1.63	4.44	1.29	2.74	1931
45-60	1.02	3.73	0.62	1.42	13106
60+	0.95	4.73	-0.79	-3.49	3859
All Speeds	1.1	4.04	0.45	0.67	19630

Table 3 reports the same error metrics on individual validation segments. Note that some segments and time bins only have a few observations, and thus may not be representative of the overall performance in each speed bin.

Table 3 – HERE data quality measures by validation segment

Path	Scenario	Speed Bin	Data Quality Measures for AASE 1.96 SEM Band	AASE Mean	SEB SEM Band	SEB Mean	No. of Obs.
PA12-0001	Tunnel	0-30	6.19	8.26	5.94	7.79	13
		30-45	2.94	5.37	2.77	5.01	1088
		45-60	1.17	4.25	0.98	3.07	1732
		60+	0.85	5.09	-0.85	-4.46	99
PA12-0002	Tunnel	0-30	0.65	1.56	0.36	0.57	855
		30-45	1.42	3.3	0.83	1.58	610
		45-60	1.12	4.61	0.86	2.8	838
		60+	1.92	7.67	-1.84	-7.1	79
PA12-0003	Tunnel	0-30	3.17	4.46	3.04	3.85	57
		30-45	2.56	4.82	2.36	4.34	259
		45-60	1.83	4.94	1.77	4.6	1955
		60+	0.71	3.8	-0.25	-0.54	399
PA12-0004	Tunnel	0-30	1.04	1.99	0.4	0.35	368
		30-45	1.56	3.24	0.29	0.53	854
		45-60	1.48	4.77	1.13	2.91	1177
		60+	1.42	5.67	-1.35	-4.39	143
PA12-0005	Work Zone	0-30	1.88	3.17	1.5	2.01	36
		30-45	2.21	4.25	0.79	1.53	79
		45-60	0.54	2.55	0.22	0.79	1980
		60+	1.3	4.46	-1.3	-4.14	101
PA12-0006	Work Zone	0-30	1.85	2.84	1.85	2.78	13
		30-45	3.72	5.85	3.68	5.44	39
		45-60	1.5	4.31	1.43	3.8	2241
		60+	0.69	3.43	-0.56	-2.24	123
PA12-0007	Work Zone	0-30	1.34	4.01	1.03	2.32	79
		30-45	1.28	5.45	-0.2	-0.45	56
		45-60	0.43	3.22	-0.16	-1.38	938
		60+	1.35	6.9	-1.35	-6.81	547
PA12-0008	Work Zone	0-30	2.41	4.73	2.41	4.68	303
		30-45	3.08	6.12	3.04	5.87	560
		45-60	1.06	3.94	0.96	3.18	826
		60+	2.6	6.07	-2.6	-4.61	10
PA12-0009	Work Zone	0-30	2.11	3.65	1.35	2.06	32
		30-45	4.41	9.69	4.19	8.92	27
		45-60	0.53	3.49	0.23	-0.25	1889
		60+	1.89	8.8	-1.89	-8.78	273
PA12-0010	Work Zone	0-30	4.51	7.53	4.51	7.53	5
		30-45	1.11	3.18	0.57	1.27	23
		45-60	0.87	3.32	0.71	2.5	448
		60+	0.56	2.98	-0.24	-0.87	1723

Path	Scenario	Speed Bin	Data Quality Measures for				No. of Obs.
			AASE		SEB		
			1.96 SEM Band	Mean	SEM Band	Mean	
PA12-0011	Work Zone	0-30	3.38	6.88	3.14	4.82	19
		30-45	5.58	10.33	5.52	9.57	35
		45-60	2.04	5.13	1.94	4.76	1397
		60+	0.74	4.44	-0.65	-3.27	676
PA12-0012	Work Zone	0-30	1.01	3.82	0.93	2.89	174
		30-45	0.81	3.88	0.57	1.46	143
		45-60	0.6	3.67	-0.29	-2.17	1506
		60+	2	8.46	-1.98	-8.36	310
PA12-0013	Work Zone	0-30	3.31	8.83	-0.82	-5.7	8
		30-45	7.25	11.63	2.84	3.61	22
		45-60	1.31	3.73	0.52	1.85	1853
		60+	0.92	3.98	-0.82	-2.96	96
PA12-0014	Work Zone	0-30	2.96	9.03	1.36	3.27	65
		30-45	0.45	2.92	0.15	0.85	947
		45-60	3.05	7.79	-3.05	-7.79	28
		60+	-	-	-	-	-

INRIX

Table 4 summarizes the error metrics computed between ground truth (i.e., WRTM) and INRIX speeds, reporting results for three scenarios: Overall (across all paths), Tunnels (across only paths in tunnels), and Work zones (across only paths in the work zone).

Both Average Absolute Speed Error (AASE) and Speed Error Bias (SEB) measures are within specification for all speed bins across all scenarios (Overall / Tunnel / Work Zone) – a result that remains true whether the 1.96 SEM Band or Mean is used for calculations.

Table 4 – INRIX data quality measures by scenario

Speed Bin	**Average Absolute Speed Error (<10mph)**		**Speed Error Bias (<5mph)**		Number of 5 Minute Samples
	1.96 SEM Band	Mean	1.96 SEM Band	Mean	
Overall					
0-30	1.73	3.37	0.29	0.39	2019
30-45	2.18	4.62	1.05	2.11	4818
45-60	1.32	4.29	0.98	2.37	18822
60+	0.84	4.42	-0.73	-3.07	4577
All Speeds	1.41	4.3	0.68	1.37	30236
Tunnel					
0-30	1.48	2.59	-0.63	-1.27	1293
30-45	2.51	4.65	1.05	2.01	2893
45-60	1.84	5.27	1.63	4.3	5717
60+	0.69	4.01	-0.41	-1.5	720
All Speeds	1.9	4.69	1.06	2.6	10623
Work Zone					
0-30	2.17	4.75	1.92	3.35	726
30-45	1.69	4.57	1.04	2.26	1925
45-60	1.09	3.87	0.69	1.53	13105
60+	0.86	4.5	-0.78	-3.36	3857
All Speeds	1.15	4.09	0.48	0.71	19613

Table 5 reports the same error metrics on individual validation segments. Note that some segments and time bins only have a few observations, and thus may not be representative of the overall performance in each speed bin.

Table 5 – INRIX data quality measures by validation segment

Path	Scenario	Speed Bin	Data Quality Measures for AASE 1.96 SEM Band	AASE Mean	SEB SEM Band	SEB Mean	No. of Obs.
PA12-0001	Tunnel	0-30	4.34	6.63	3.81	5.77	14
		30-45	2.9	5.32	2.62	4.66	1170
		45-60	1.8	5.22	1.69	4.58	1746
		60+	0.41	4.23	-0.34	-2.51	99
PA12-0002	Tunnel	0-30	1.07	2.13	-0.85	-1.59	855
		30-45	1.82	3.86	-0.12	0.04	610
		45-60	0.97	4.42	0.53	2.14	838
		60+	2.73	8.7	-2.73	-8.67	79
PA12-0003	Tunnel	0-30	2.93	4.51	2.53	3.19	49
		30-45	2.85	5.2	2.46	4.49	261
		45-60	2.25	5.56	2.19	5.32	1956
		60+	0.38	2.97	0.03	0.49	399
PA12-0004	Tunnel	0-30	2.11	3.25	-0.71	-1.4	375
		30-45	2.36	4.14	-0.71	-0.99	852
		45-60	1.83	5.45	1.41	3.71	1177
		60+	0.63	4.19	-0.44	-2.37	143
PA12-0005	Work Zone	0-30	4.36	5.67	3.61	3.84	36
		30-45	2.63	4.83	0.19	1.09	77
		45-60	0.59	2.64	0.21	0.85	1978
		60+	1.53	4.77	-1.52	-4.54	101
PA12-0006	Work Zone	0-30	1.4	2.43	0.77	1.58	13
		30-45	4.23	6.51	3.84	5.45	39
		45-60	2.14	5.22	2.1	4.99	2241
		60+	0.26	2.81	-0.24	-1.05	123
PA12-0007	Work Zone	0-30	1.65	4.19	0.96	1.7	75
		30-45	1.82	6.52	-0.75	-2.36	55
		45-60	0.56	3.28	-0.13	-0.69	938
		60+	1.18	6.32	-1.18	-6.2	546
PA12-0008	Work Zone	0-30	1.66	3.76	1.62	3.37	300
		30-45	2.73	5.66	2.45	4.85	560
		45-60	1.01	3.73	0.77	2.66	826
		60+	1.49	5.39	-1.46	-5.21	10
PA12-0009	Work Zone	0-30	3.19	4.9	2.62	3.7	32
		30-45	4.51	9.7	4.06	8.84	27
		45-60	0.55	3.65	0.08	-0.9	1889
		60+	2.14	9.41	-2.14	-9.41	273
PA12-0010	Work Zone	0-30	1.25	3.73	1.25	3.73	5
		30-45	1.75	3.95	-0.77	-1.38	23
		45-60	0.79	3.15	0.57	1.87	449
		60+	0.39	2.73	-0.23	-0.8	1721

Path	Scenario	Speed Bin	Data Quality Measures for				No. of Obs.
			AASE		SEB		
			1.96 SEM Band	Mean	SEM Band	Mean	
PA12-0011	Work Zone	0-30	13.46	17.31	13.46	17.25	19
		30-45	6.24	11.31	5.96	10.64	35
		45-60	1.8	4.96	1.73	4.64	1397
		60+	0.54	3.82	-0.5	-2.82	677
PA12-0012	Work Zone	0-30	0.96	3.66	0.73	1.22	174
		30-45	1.87	5.52	-0.47	-0.96	142
		45-60	0.76	4.01	-0.58	-2.74	1506
		60+	2.49	9.01	-2.49	-9	310
PA12-0013	Work Zone	0-30	7.65	13.08	7.65	13.08	8
		30-45	4.56	8.27	4.55	6.98	22
		45-60	1	3.34	0.83	2.33	1853
		60+	0.86	3.79	-0.86	-3.15	96
PA12-0014	Work Zone	0-30	2.9	8.26	2.56	5.53	64
		30-45	0.54	3.1	0.19	0.92	945
		45-60	2.47	6.61	-2.47	-6.61	28
		60+	-	-	-	-	-

TomTom

Table 6 summarizes the error metrics computed between ground truth (i.e., WRTM) and TomTom speeds, reporting results for three scenarios: Overall (across all paths), Tunnels (across only paths in tunnels), and Work zones (across only paths in the work zone).

Both Average Absolute Speed Error (AASE) and Speed Error Bias (SEB) measures are within specification for all speed bins across all scenarios (Overall / Tunnel / Work Zone) when the 1.96 SEM band is used for calculations.

Table 6 – TomTom data quality measures by scenario

Speed Bin	**Average Absolute Speed Error (<10mph)**		**Speed Error Bias (<5mph)**		Number of 5 Minute Samples
	1.96 SEM Band	Mean	1.96 SEM Band	Mean	
Overall					
0-30	0.78	2.2	0.37	0.68	2037
30-45	2.2	4.72	2.03	3.98	4796
45-60	2.04	5.31	1.97	4.6	18838
60+	0.7	4.02	0.16	0.09	4586
All Speeds	1.78	4.81	1.59	3.56	30257
Tunnel					
0-30	0.44	1.3	-0.07	-0.24	1303
30-45	2.27	4.32	2.05	3.52	2864
45-60	2.79	6.51	2.73	6.13	5714
60+	0.68	4.09	0.01	0.59	720
All Speeds	2.22	5.12	2.02	4.26	10601
Work Zone					
0-30	1.38	3.78	1.14	2.33	734
30-45	2.09	5.31	2	4.67	1932
45-60	1.71	4.78	1.63	3.94	13124
60+	0.71	4.01	0.18	0	3866
All Speeds	1.54	4.64	1.36	3.18	19656

Table 7 reports the same error metrics on individual validation segments. Note that some segments and time bins only have a few observations, and thus may not be representative of the overall performance in each speed bin.

Table 7 – TomTom data quality measures by validation segment

Path	Scenario	Speed Bin	Data Quality Measures for AASE 1.96 SEM Band	AASE Mean	SEB SEM Band	SEB Mean	No. of Obs.
PA12-0001	Tunnel	0-30	1.79	3.72	1.36	3.09	14
		30-45	3.82	6.28	3.74	6	1138
		45-60	2.79	6.58	2.72	6.29	1743
		60+	0.21	3.13	-0.12	-0.77	99
PA12-0002	Tunnel	0-30	0.35	1.19	-0.12	-0.36	856
		30-45	1.11	2.98	0.75	1.7	610
		45-60	0.67	3.86	0.53	2.69	838
		60+	1.81	7.57	-1.81	-7.52	79
PA12-0003	Tunnel	0-30	0.87	1.78	0.17	0.41	58
		30-45	2.27	4.57	2.24	4.39	262
		45-60	3.85	7.6	3.81	7.52	1956
		60+	0.64	3.86	0.49	3.01	399
PA12-0004	Tunnel	0-30	0.53	1.4	-0.03	-0.21	375
		30-45	1.04	2.59	0.66	1.24	854
		45-60	2.56	6.5	2.5	6.01	1177
		60+	0.48	3.49	-0.22	-0.75	143
PA12-0005	Work Zone	0-30	0.57	1.63	-0.51	-0.76	36
		30-45	1.37	3.11	1.1	1.91	79
		45-60	1.62	4.55	1.58	4.36	1980
		60+	0.11	1.84	-0.09	-0.55	101
PA12-0006	Work Zone	0-30	0.67	1.49	0.4	0.75	13
		30-45	2.82	4.94	2.73	4.52	39
		45-60	2.22	5.49	2.21	5.4	2241
		60+	0.15	1.75	-0.15	-0.6	123
PA12-0007	Work Zone	0-30	0.42	2.46	0.12	0.24	79
		30-45	0.56	4.42	-0.35	-1.15	56
		45-60	0.47	3.32	0.28	1.54	938
		60+	0.45	4.17	-0.45	-3.91	547
PA12-0008	Work Zone	0-30	1.69	3.79	1.68	3.58	303
		30-45	3.39	6.51	3.38	6.43	560
		45-60	1.62	4.95	1.62	4.78	826
		60+	0.51	3.48	-0.51	-3.48	10
PA12-0009	Work Zone	0-30	0.5	1.75	0.15	0.66	32
		30-45	6.76	12.18	6.76	12.08	27
		45-60	0.94	3.87	0.92	2.82	1889
		60+	0.85	5.72	-0.84	-5.66	273
PA12-0010	Work Zone	0-30	2.78	5.09	2.78	3.93	5
		30-45	1.53	3.62	-0.35	-0.26	24
		45-60	1.73	4.57	1.59	4.24	460
		60+	0.96	3.95	0.87	3.25	1723

Path	Scenario	Speed Bin	Data Quality Measures for				No. of Obs.
			AASE		SEB		
			1.96 SEM Band	Mean	SEM Band	Mean	
PA12-0011	Work Zone	0-30	3.18	7.18	3.06	6.65	19
		30-45	7.05	11.46	7.05	10.81	35
		45-60	4.18	8.01	4.18	7.97	1403
		60+	0.34	3.26	0.06	0.35	683
PA12-0012	Work Zone	0-30	0.21	2.2	0.04	0.02	174
		30-45	0.4	3.12	0.16	-0.21	143
		45-60	0.4	3.08	0.04	-0.71	1506
		60+	0.97	6.31	-0.97	-6.2	310
PA12-0013	Work Zone	0-30	4.37	8.07	4.37	8.03	8
		30-45	6.05	9.93	6.05	9.93	22
		45-60	1.87	4.75	1.83	4.48	1853
		60+	0.29	2.35	-0.18	-0.83	96
PA12-0014	Work Zone	0-30	4.3	10.62	3.25	5.93	65
		30-45	1.29	4.7	1.28	4.5	947
		45-60	0.47	3.48	-0.47	-3.48	28
		60+	-	-	-	-	-