I-95 Corridor Coalition

Vehicle Probe Project:
Probe Data for Arterial Performance Measures

A Case Study on US-1 in Virginia

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Abstract
This report develops the methodology for processing probe vehicle data to assess arterial performance. Probe data sources include outsourced travel time data provided by the I-95 Vehicle Probe Project and Bluetooth traffic monitoring. The methodology derives samples of the travel time distribution using percentile statistics. Individual probe data samples are combined over a multi-week period to ensure adequate data density. The travel time distribution from day to day as well as for various hours of the day is computed directly, and Cumulative Frequency Diagrams are employed to provide compact visualization of comparative performance. The methodology presented is demonstrated on both data sources, and forms the computational foundation for calculation of performance measures and future comparative analysis between two data sources for validation purposes.
Executive Summary

This report develops the methodology for processing probe vehicle data sources to assess arterial performance measures. In 2008, the I-95 Corridor Coalition launched a probe based traffic monitoring system that spanned six Mid-Atlantic states from New Jersey to North Carolina, providing travel time and speed data on a network of 1500 freeway miles using a technology that did not require the deployment of any field sensors. The data from this system, called the I-95 Vehicle Probe Project (VPP), was delivered to the Coalition from INRIX Inc. (INRIX), using a technology generically referred to as probe data. The position, speed and heading information reported by a subset of vehicles on the roadway are used as the basis to estimate travel conditions. Initially probe data came primarily from commercial fleets, but have since expanded to include crowd-sourcing and data from passenger vehicle OEM systems. The accuracy of the travel time reported by INRIX technology was rigorously verified by the I-95 Corridor Coalition during the initial months of the project, and continues to be validated on a periodic basis. As a result, several states in the Coalition were able to use the VPP data to develop travel information systems, monitor traffic within their traffic information centers, and to effectively plan for operational and infrastructure investments. The system has subsequently grown so that by 2013 the VPP spans 15 states, covering more than 7,900 miles of freeway on the eastern seaboard.

From the onset, the VPP was envisioned to provide data on both freeways as well as interrupted flow facilities, referred to in the generic sense as arterial roadways. After the validity of freeway data had been demonstrated, the Coalition embarked on a program to assess arterial data quality delivered through the VPP. Unlike the results from the freeway initiative, the effort to validate arterial data accuracy was impeded by a number of un-anticipated issues. A summary of these issues was published in a paper in October 2010 delivered to the ITS World Congress, entitled Challenges to Effective Arterial Monitoring: Lessons from the I-95 Corridor Coalition’s Vehicle Probe Project. The reader is referred to this document for a full discussion of the obstacles encountered. In short, the effort to assess accuracy of probe data on arterials was predicated on the use of methods developed on freeways. Travel time distributions on freeways are typically relatively simple, unimodal distributions which can be summarized with a measure of central tendency (such as the mean or median). Although travel time variation from day to day or hour to hour is studied and assessed in reliability metrics, the variation of travel time at any specific instance in time is not significant. In contrast, the stop and go nature of signalized operations on arterials create complex travel time distributions that are not well summarized with any single central-tendency measure as with freeways. The fundamental differences between traffic flow rendered the freeway methodology ineffective, and required a new approach capable of reflecting the complex flow on arterials. This report summarizes fundamental methodologies established to describe the traffic flow on arterials, and to eventually serve as the computational basis for assessing performance and validating data.

Probe data sources include outsourced travel time data provided by the I-95 VPP and Bluetooth traffic monitoring (BTM). Initial efforts, following the methodology used on freeways, examined arterial traffic data minute-to-minute as if in real-time, looking only at point in time measures, as well as summarizing data in 5-minute, 15-minute and hour averages as it was received. Both VPP and BTM sample only a portion of the vehicles on
the roadway, and these sample sizes are typically insufficient to fully characterize the complex distribution of travel time at any streaming time interval. The arterial methodology begins by first grouping individual data samples from the probe sources for multiple time periods. A sample of this is illustrated from BTM data in Figure ES-1 for an approximate two week period on a segment of US-1 in Northern Virginia. In this 24-hour plot all data samples are overlaid, revealing detailed travel time patterns, some the result of peak hour congestion, and some induced by signal timing on the arterial.

The second principle in the arterial methodology was to use percentile statistics to summarize the patterns revealed in the scatter plots as illustrated in Figure ES-1. Calculating the percentiles over a defined range (typically 5th, 10th, 15th, and so on up to the 95th percentile) provide a concise representation of the distribution of travel time. The percentile could then be easily visualized in Cumulative Frequency Diagrams (CFDs) showing the variation of travel time between time periods, such as hour to hour during weekday traffic periods, in a compact graphical fashion. An illustration of this is shown in Figure ES-2, highlighting the peak hour travel time characteristics as compared to other hours during the day. The right hand plot provides an ensemble of CFD curves, with the peak hour (4PM) bolded. The left plot highlights the corresponding peak hour data in the ensemble of CFD curves, each representing a different hour of the day.

Figure ES-1. Illustration of BTM data combined over a two week period from US-1
The methodology developed is applicable to both VPP and BTM data sources, and the underlying percentile calculations form the computational foundation for calculation of performance measures and, eventually, the comparative analysis between the two data sources for validation purposes.
**Introduction**

The I-95 Vehicle Probe Project (I-95 VPP) began in 2008 on a network of approximately 1,500 freeway miles and 1,000 arterial miles spanning from New Jersey to North Carolina. The network has since grown to nearly 40,000 combined freeway and arterial miles, and the system currently provides speed and travel time data on a major portion of the freeway network linking the eastern seaboard of the United States. The accuracy of the travel time data for the freeway network is validated on a near monthly basis. Non-freeway coverage has also expanded such that several states receive real-time and archive data on arterial roadways. However, the accuracy and fidelity of this arterial data is less well known.

The I-95 Corridor Coalition (I-95 CC) identified the challenge of delivering and validating traffic data on arterials (Young, 2011), with the initial effort primarily showing that the methodology implemented on freeways is ineffective for arterials. The initial findings also highlighted that the performance measures and use of traffic data for arterials is fundamentally different from freeways. Traffic control devices (primarily traffic signals) are the primary source of delay along arterials, such that methodologies of assessing free-flow travel-time, congestion, and delay derived from the analysis of freeway data fail to adequately reflect operations of interrupted flow roadways. This understanding led to the investigation into types of metrics, methodology and performance measures which would be appropriate to apply to arterial traffic data, regardless of source. This report is a continuation of that effort and investigates the use of Cumulative Frequency Diagrams - CFDs (also referred to as Cumulative Distribution Functions). This method of analysis provides a complete characterization of the travel time distribution on roadways, and provides a basis to establish accuracy metrics, validation methodology, and performance measures to apply to the traffic data obtained from I-95 VPP.

**Study Area – Route 1 in Northern VA**

A section of US Route 1 in Northern Virginia has been used as a case study to demonstrate the use of CFDs as applied to an arterial corridor. This section of roadway, shown in Figure 1, is currently monitored as part of a demonstration of real-time Bluetooth™ traffic monitoring (BTM) technology, the same technology used to validate accuracy of the I-95 VPP freeway traffic data. This real-time BTM project was funded by a Small Business Innovative Research (SBIR) grant through FHWA, and consists of 48 BTM sensors covering major freeways and signalized arterials in northern Virginia and suburban Maryland. The BTM technology was originally developed at the University of Maryland and licensed to Traffax Inc. for commercialization. The focus of the SBIR deployment was to demonstrate the use of BTM data in real-time applications. As a by-product, an archive of high-resolution traffic data was created and is available for research. This case study utilizes data from the BTM deployment on US Route 1 in northern Virginia. The case study...
applies the methodology that characterizes the travel time distribution of existing arterial flow using CFD graphs. This case study first develops the methodology using BTM data from the SBIR project, and then demonstrates the same methodology using I-95 VPP data for the same roadway.

The specific segment within the corridor under study is a southbound section of US Route 1 (also known as the Jefferson Davis Highway) between the intersections of Gordon Boulevard to the north, and Prince William Parkway to the south as shown in Figure 2, to the left. This section of US Route 1 is approximately 1.2 miles in length and has two lanes in each direction with turning bays at all intersections. This segment contains a total of four signalized intersections, one at each end, and two internal to the segment. The two internal signalized intersections are at Dawson Beach Road and Mount Pleasant Drive. The data presented is from Monday, October 17, 2011 through Saturday, October 29, 2011, representing a total of 13 full days of operations.

**Analysis using BTM Data**

The BTM scatter plot in Figure 3 shows a snapshot of the data over the two week period. Valid traversals of the study corridor are indicated in blue and data points deemed as outliers (such as stopping for services) are marked in red. Evident in this daily plot are significant evening congestion periods for all days except Saturday, October 29, 2011. Two callouts indicate a typical day and a day with light or no congestion. Friday, October 21, 2011, the first call out, is highlighted as a typical day, exhibiting a slow down during the PM peak period. Saturday, October 29, 2011, the second call out, exhibits no significant spike in travel time throughout the day.
Although the general magnitudes of travel time can be assessed in Figure 3, the fidelity and level of granularity of comparison from day to day are limited. The method of cumulative frequency diagrams is introduced to visually contrast difference in travel time patterns. Cumulative frequency diagrams (CFDs) are constructed from percentile calculations. The 5<sup>th</sup>, 10<sup>th</sup>, 15<sup>th</sup>, and up to the 95<sup>th</sup> percentile travel times are calculated for each day, and then plotted as demonstrated in Figure 4 to create a CFD representation of the data.

The data from each day of the study period is transformed to CFDs. Samples of this process are shown for Friday, October 21, 2011 and Saturday, October 29, 2011 in Figures 5 and 6. In both figures, the plot to the left is the traditional scatter plot of the traversals recorded for the Bluetooth traffic monitoring (BTM) data for a single day. Similar to the color coding from Figure 3, travel times of valid traversals are in blue, and outliers are marked in red. The plot to the right are CFDs. Shown in dark blue is the CFD of travel time data for the single day shown in the left scatter plot. In the background shown in light blue (cyan), is the ensemble of CFDs for all the other days in the study from October 17, 2011 through the October 29, 2011. Figure 5 reflects the scatter plot and CFD for Friday, Oct 21, 2011. The travel time pattern for this day is typical for the thirteen day period, as evidenced by its CFD falling within the middle of the ensemble of CFDs for all days.
The scatter plot for Friday, October 21, 2011 provides a higher granularity view of the data. The CFD for this day falls in the center of the ensemble of CFD curves for this time period, reinforcing that this is ‘typical’ operation for the segment. Note that the median travel time corresponding to the 50th percentile is approximately 4.0 minutes and the 95th percentile travel time is approximately 9.5 minutes for Friday, October 21, 2011. Both are readily discernible from the CFD plot as demarked by the dashed gray lines. Common travel time and reliability measures such as travel time index, planning time index and buffer time index can be derived directly from knowledge of the percentile distribution.

The unusual traffic activity observed on October 29, 2011 was influenced by weather. On Friday, October 29, 2011, a rare pre-Halloween snow fell on much of the Washington, D.C. area. The storm delivered up to 1.5 inches of accumulation in some of the D.C. suburbs. For this section of roadway, the early winter weather actually improved travel conditions.

As reflected in the I-95 Corridor Coalition (I-95 CC) initial report, the variance in travel time data is greatly impacted by signal operations. Although a central tendency, such as the mean or median, can be calculated for arterial roadways, the distribution about the mean is much more meaningful for observing how traffic progresses through intersections, as is the percent that are stopped on red, having to wait for the next signal cycle. Due to the pulsed flow imposed by traffic signal cycles, the progression through the corridor is more characteristically described using the percent of vehicles that progress through on all green, and those that may have to wait for two or more cycles.
In the following example, weekday data from October 17 through October 28, 2011 is combined to create a high-resolution view of the progression of traffic through the case-study segment. The quantity of data available for any given day may be insufficient to characterize the progression. For example the scatter plot from Friday, October 21, 2011, shown on the left in Figure 5, is dense enough to suggest trends to the trained eye, but generally insufficient to definitively characterize the travel time distribution. However, combining the data from all weekdays provides a high-resolution scatter diagram of the travel time for the 24 hour period as shown in Figure 7.
Figure 8 presents the same data as in Figure 7 but with several callouts.

i. During the early AM period from 5am to approximately 8am, the travel time ranges from 2 to 4 minutes. Although the variance is high, the distribution of travel time appears normal.

ii. From about 8am to 1pm, the flow still varies approximately between 2 to 4 minutes, but a distinct bi-modal pattern emerges, indicating that roughly half of the traffic progresses through in 2 minutes, while the mean of the remaining half is nearly 4 minutes.

iii. Sometime after 1pm, the travel time through this segment escalates to greater than 4 minutes, reaching to even greater than 10 minutes for a portion of vehicles near 5pm.

The change in travel time patterns is likely the result of changing signal timing plans throughout the day as well as changes in demand.

Figure 8. BTM scatter plot with travel pattern highlights

Hourly travel can be graphed as CFDs, in a similar manner as daily travel time was constructed in Figures 5 and 6. Figures 9 through 12 depict the progression of the travel time distribution throughout the day. In each figure, the portion of the hourly data is highlighted in black on the graph to the left, and the corresponding CFD is shown on the right in dark blue contrasted with the ensemble of CFD curves for each hour of the day. Figures 9 through 12 depict the CFD for 6-7am, 10-11am, 4-5pm, and 8-9pm, respectively.
The 10am-11am time frame displays a bi-modal distribution. The resulting CFD reflects a curve with two inflection points, one at approximately 2 minutes, and the other at approximately 4 minutes, corresponding to the approximate central tendency of each mode.

The period from 4pm-5pm reflects the greatest congestion for daytime traffic. The resulting CFD is furthest to the right, with a median travel time of seven minutes. Figure 12 reflects conditions from 8pm to 9pm, well after the evening rush hour. The corresponding CFD has shifted back to the far left, indicating that the majority of the traffic traverses the corridor in minimum time.
Analysis using I-95 Vehicle Probe Data

This same section of roadway was analyzed using the I-95 Vehicle Probe Data available through the Vehicle Probe Project (VPP) Suite developed by the University of Maryland CATT Lab. The VPP Suite provides easy access to I-95 VPP data in varying time aggregation formats including 1, 5, and 15 minute, and one hour summaries. The I-95 VPP data is comprised of speed and travel time data for sub-segments, referenced by Traffic Management Channel (TMC) codes. Each sub-segment, or TMC segment, generally begins and ends on access points. For this southbound section between Gordon Boulevard and Prince William Parkway, the TMC segments are comprised of two TMC segments. However, the primary TMC segment extends past the southern terminus (Prince William...
Parkway) to the next major intersection, that of State Route 642, also known as Opitz Boulevard as shown in Figure 13. This segment spans a total of 2.33 miles, as compared to 1.2 mile for the segment analyzed with the small business innovative research (SBIR) Bluetooth traffic monitoring (BTM) data. Attributes of the TMC segments are provided in Table 1.

![Figure 13. VPP study segment extents](image)

Table 1. TMC Segments for Case Study

<table>
<thead>
<tr>
<th>TMC</th>
<th>ROAD</th>
<th>DIRECTION</th>
<th>ENDING INTERSECTION</th>
<th>MILES</th>
<th>MAP LINK</th>
</tr>
</thead>
<tbody>
<tr>
<td>110N09532</td>
<td>Jefferson Davis Hwy</td>
<td>SOUTHBOUND</td>
<td>VA-123/Gordon Blvd</td>
<td>0.012</td>
<td><a href="http://goo.gl/maps/IJuko">http://goo.gl/maps/IJuko</a></td>
</tr>
<tr>
<td>110-09531</td>
<td>Jefferson Davis Hwy</td>
<td>SOUTHBOUND</td>
<td>Opitz Blvd</td>
<td>2.324</td>
<td><a href="http://goo.gl/maps/ZFU8e">http://goo.gl/maps/ZFU8e</a></td>
</tr>
<tr>
<td>Totals /</td>
<td>Common</td>
<td>SOUTHBOUND</td>
<td>-</td>
<td>2.337</td>
<td><a href="http://goo.gl/maps/7tFLF">http://goo.gl/maps/7tFLF</a></td>
</tr>
</tbody>
</table>

Data for each TMC from Sunday, October 16, 2011 through Sunday, October 30, 2011 was downloaded from the VPP Suite in one-minute archive format. A plot of the one minute travel time data is shown in Figure 14. Callouts V2 and V3 are presented in detail in Figures 15 and 16, respectively. Observations of the I-95 VPP travel time data and its comparison with BTM data include:

- The striations evident in the figure arise from the conversion of discrete speed measures to travel time. Speeds are reported to the nearest whole mph within the VPP. Travel times are obtained by dividing the discrete speeds into the segment length, creating a set of corresponding discrete travel times, though not integers.
- Traffic data is reported with a confidence score. A confidence score of 30 is considered real-time high quality data. A score of 10 or 20 relies on historical data in part or in whole to obtain an estimate of travel time. In the scatter plot in Figure 14, and subsequent scatter plots, VPP data with an aggregate score of 25 or less are highlighted in red. Any data with score less than 25 is not included in percentile calculations that support the CFD plots.
- The density of VPP data is consistent for all hours of the day because I-95 VPP provides an estimate of speed and travel time for each time increment (one-minute in the case of the displayed data), regardless of the road volume. In contrast the number of BTM discrete travel time samples is relative to the through traffic volume. When traffic is heavy such as in rush hour, more probe BTM samples are recorded. When traffic is light, such as in the overnight hours, BTM data samples are sparse.
The number of travel time samples provided by BTM is approximately 5% of the through traffic volume.

- Note that the BTM reported data between Gordon Blvd and Prince William Parkway, a distance of approximately 1.2 miles, while the southern terminus of the VPP segment extended to Opitz Blvd, for a total length of 2.3 miles. So although this methodology is demonstrated on both BTM and VPP data, the results and figures cannot be directly compared due to the differences in the base segments. This will be the objective of future case studies.

Figure 14. Scatter plot I-95 VPP travel time data for October 16-30, 2011

Parallel to the treatment of BTM data, the VPP data was transformed to CFDs to contrast the travel patterns from day to day. Figures 15 and 16 provide views of the VPP data similar to what was constructed for BTM data in Figures 5 and 6. Figure 15 portrays the traffic for Friday October 21, 2011, a typical weekday traffic pattern. Figure 16 portrays the traffic for Saturday, October 29, 2011, the day of the unusual snow fall. Similar to the BTM plots, Friday October 21, 2011 falls in the middle of the ensemble of CFD plots, indicating typical conditions for the segment of roadway. The CFD plot for Saturday, October 9, 2011 is to the far right of the ensemble, indicating better than average operation. Although similar to the BTM plots, the CFD plots created with VPP data cannot be directly compared due to the fundamental differences in sampling. The number of VPP data samples is consistent in time whereas number of BTM data samples varies with traffic volume. For this reason, the construction of the CFDs will differ between the two data sources. If the time period of analysis has relatively constant volume, such as peak hours, then the CFD graphs may be compared directly. If the traffic volume during the analysis time period is not constant, the traffic volume profile can be used to weight the VPP data so that direct comparison of CFD graphs can be made.
The CFD diagrams in Figure 15 and Figure 16 do not appear smooth like the BTM CFDs, but rather are somewhat jagged, possibly inferring multiple inflection points in the underlying data. However, this phenomenon is an artifact of the striations in the VPP data induced from truncating speed to the nearest mile per hour, and then converting to travel time. A method of filtering this visual impact is illustrated later.

In Figure 17 VPP data was aggregated by hour of the day and a scatter plot representing one-minute travel time observations is plotted for weekdays be from October 16 to 30, 2011. Similar to Figure 7, the 24-hour overlay scatter plot based on VPP data provides a visual depiction of the magnitude and distribution of travel time. However, as with earlier diagrams, striations are evident due to the conversion to travel time from speed measures rounded to the nearest integer.
In order to overcome this visual striation effect induced by reporting speed to the nearest integer, uniform random offsets between -0.5 and 0.5 mph were added to the reported speeds, and then converted to travel time. The result is shown in Figure 18, eliminating the striation effect due to discrete speed measurements. The addition of this random error does not adversely impact the accuracy of subsequent analysis because the random error is less than or equal to the error induced from rounding.
As with the BTM data, the hourly VPP data was transformed to CFDs. Figures 19 through 22 show the progression of the average weekday travel times as CFD diagrams for 6am, 10am, 4pm, and 8pm respectively. Figures 19 through 22 are created based on VPP data from Figure 17, prior to the addition of randomization as in Figure 18.

Figure 19. VPP scatter plot and CFD for 6am-7am

Figure 20. VPP scatter plot and CFD for 10am-11am
The striations in the travel time scatter plot data in Figures 19 through 22, due to discrete speed measures, create CFDs with stepped or jagged slopes, as opposed to smooth curves with the BTM data. As with the scatter plot in Figure 18, randomization was applied and the hourly CFDs were created using the same methodology to cancel the visual impact of discrete speed measures. These curves are shown for the same time periods in Figures 23 through 26.
Figure 23. Smoothed VPP scatter plot and CFD for 6am-7am

Figure 24. Smoothed VPP scatter plot and CFD for 10am-11am
Figure 25. Smoothed VPP scatter plot and CFD for 4pm-5pm

Figure 26. Smoothed VPP scatter plot and CFD for 8pm-9pm

**Summary and Discussion**

Methods to summarize and display both the central tendency and the distribution of travel times on interrupted flow arterials are critical due to the high variance, and often bi-modal distributions resulting from a portion of traffic stopped on red, while another portion progresses through on green. Cumulative Frequency Diagrams (CFDs) based on percentile calculations provide a comprehensive view of the data from which central tendency, as well as variance parameters, are easily discernible and measurable. These methods can be applied to various scenarios such as the daily travel time distributions and weekday hourly travel time distributions exhibited in this case study. These representations can be created
both with Bluetooth™ traffic monitoring (BTM) data, a form of probe data that samples approximately one in twenty through vehicles, as well as I-95 Vehicle Probe Project (VPP) data, a form of probe data derived primarily from commercial fleets which periodically report their position and trajectory.

This case study revealed some issues, and contrasts the results from the BTM and VPP data.

- Day to day travel time variation can be visually inspected and quantified using CFD plots based off of calculated percentiles. Similarly, hour to hour variation can also be analyzed and measured using the same procedure.
- Due to the fact that the number of BTM data samples vary directly with the through traffic volume, the corresponding CFD graphs and scatter plots from BTM are volume weighted. In contrast, VPP data provides speed and travel time samples once per minute, regardless of volume. The resulting CFD plots are not volume weighted. If volume is relatively constant for the time period under study, than the VPP CFDs can be compared directly with BTM CFDs. If the volume fluctuates significantly within the study time period, volume weighting can be applied to the VPP data to obtain comparable results to BTM.
- VPP data is recorded to the nearest whole mph and then converted to travel time. This process creates striations in the scatter plots and non-smooth CFD plots. This can be addressed by randomizing the input data proportional to its rounding error, as demonstrated. This process does not adversely impact the accuracy of the results.
- Base segment lengths are problematic. VPP is aligned to the electronic mapping industry Traffic Management Channel (TMC) standard, while BTM segments are determined by field deployed locations. As illustrated in the case study, care should be taken that these are aligned if direct comparisons are to be made. This case study was originally intended to compare and contrast traffic performance using two difference data sources, but the base segments from BTM and VPP did not align.

This paper illustrated a proposed method for assessing traffic performance on interrupted flow facilities, referred to generally as arterials in this discussion. The stop and go nature induced by signal control on such facilities produce complex travel time patterns which are frequently bi-modal. The performance measures and validation procedures developed for freeways often fail on arterials due to these complex travel time distributions. Additionally, the amount of probe data acquired on arterials is less than that for freeways due in part to lower volumes (for the same geometry), but also due to the many turning opportunities which diminish the quantity of through traffic. The method presented to assess hourly performance combines base probe data from multiple days, calculates percentiles on the aggregated data, and then then presents the summarized data in CFD plots. This method samples the entire travel time distribution, displays it in a concise, quantifiable method for visualization and measurement, and forms the underlying statistical framework to conduct both validation and performance assessment on arterial roadways using probe data.

This case study was originally intended to compare and contrast traffic performance using two difference data sources. However, the segments instrumented with BTM and VPP did not align. Future work will target isolating segments that align with both technologies, repeating the methodology illustrated above, and then statistically comparing the difference in performance measures calculated using the two data sources for purposes of assessing accuracy of the VPP data.
References


2. Washington Times, October 29, 2011