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Visualizations of Travel Time Performance based on Vehicle Re-identification Data

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ABSTRACT
This paper provides a visual reference of the breadth of arterial performance phenomenon based on travel time measures obtained from re-identification technology that has proliferated in the past five years. These graphical performance measures are revealed through *overlay charts* and statistical distribution as revealed through *cumulative frequency diagrams* (CFDs). By overlaying vehicle travel times from multiple days, dominant traffic patterns over a 24 hour period are reinforced, revealing the traffic behavior induced primarily by the operation of traffic control at signalized intersections. A CFD, also known as cumulative distribution functions in statistical literature, provides a method that can compare traffic patterns from varying timeframes or locations in a compact visual format that provides intuitive feedback on arterial performance. The CFD may be accumulated hourly, by peak periods, or time periods specific to signal timing plans that are in effect. Combined, overlay charts and CFDs provide visual tools to assess the quality and consistency of traffic movement for various periods throughout the day efficiently, without sacrificing detail which is a typical by-product of numeric-based performance measures. These methods are particularly effective for comparing before/after median travel times as well changes in inter quartile range to assess travel time reliability.

Keywords: Re-identification Data, Travel Time, Overlay Plot, Cumulative Frequency Diagrams, Arterial Performance

INTRODUCTION

Vehicle re-identification is a method that measures traffic performance for a segment or a corridor by sampling the travel time of vehicles that traverse the corridor. This is accomplished by identifying a vehicle at two locations using a sensor and logging the locations and exact time of observation. Re-identification data may come from a variety of technologies. The most common is re-identification data derived from Bluetooth and Wi-Fi consumer electronics. It has become the most common type of re-identification data due to the relatively low cost of equipment and deployment. (*1, 2, & 3*) License plate matching and electronic tolling equipment are other forms of vehicle re-identification but there are some disadvantages associated with them. License plate matching typically is much more costly, weather sensitive and less practical for high-speed traffic conditions and also it rises privacy issues. Re-identification techniques can also be used with data from electronic tolling equipment. However, this method requires extra caution as tolling data contains personally identifiable information associated with a customer's account (whereas Bluetooth and Wi-Fi data do not.) (*4, 5, & 6*) Also, connected vehicle data is anticipated to be a significant source of re-identification data in the future. The visualization methods presented below can be used with any source of re-identification data, however in this study re-identification data from Bluetooth technology have been used.

In Bluetooth re-identification method, Bluetooth devices carried inside vehicles observed by consecutive Bluetooth Sensors are used to sample the travel time. The Bluetooth protocol uses a unique electronic identifier called Machine Access Control (MAC). The matched MAC address of a device between two sensors are used to estimate the travel time between the stations. (*1, 2, & 3*)

To extract travel time information from the raw data collected by the Bluetooth sensors, a data clean up is needed. In this research a four-step procedure for filtering the Bluetooth data and travel time estimation explained in (*7*) have been used.

This paper shows overlay and cumulative frequency diagram as the fundamental visual performance tools and then provides a series of representative results from various traffic and signal operation phenomena that have been observed. The techniques are inspired from floating car runs employed to investigate the before/after impact of signal retiming. (*8, 9, & 10*) and random variable distribution in flow speed analysis (*11, & 12*). The samples in this research were selected to present the breadth of results that may be encountered. Samples include both common and some not-so-common results. Emphasis is placed on interpreting (or diagnosing) the broad set of conditions that may be revealed by re-identification data as a reference document for practitioners.

CONSTRUCTION OF OVERLAY AND CUMULATIVE FREQUENCY DIAGRAM

Re-identification data collected from Maryland State Route 355, as shown in Figure 1, is used to illustrate the basic visualizations of travel time overlay and cumulative frequency diagrams (CFDs). The locations of signalized intersections on this segment are indicated by the red markers while the blue markers indicate two data collection devices at the endpoints where permanent Bluetooth traffic recorders are installed. This 2.7 mile corridor is characterized by at least three traffic lanes in each direction, average annual daily traffic slightly above 50,000 vehicles, thirteen signals (not including signalized intersections at the end points), and numerous access points for businesses and side streets. Data from this installation is used as a primer for the development of overlay plots and CFDs.

The travel time data collected using Bluetooth re-identification sensors is depicted in Figure 2 for the period from October 2011 to April of 2012, which encompasses approximately 50,000 individual observations of vehicle travel time. This data set represents approximately one in twenty (5% sample) of all the vehicles that traversed the extent of the corridor during this time period. In the graph in Figure 2, one can distinguish the densest range of the travel time between 4–12 minutes as indicated by the density of the point cloud data. Travel time routinely extends to as high as 20 minutes or more. Little information beyond these general observations can be extracted about the general operating characteristics in the corridor.

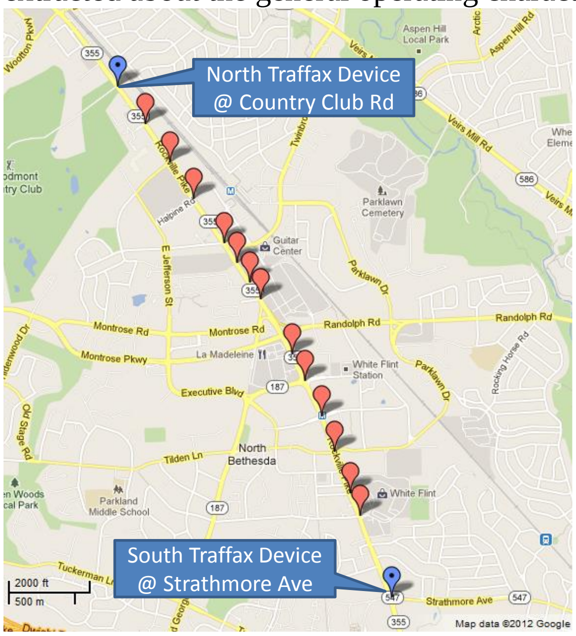

FIGURE 1 Illustrative corridor for vehicle re-identification travel times.

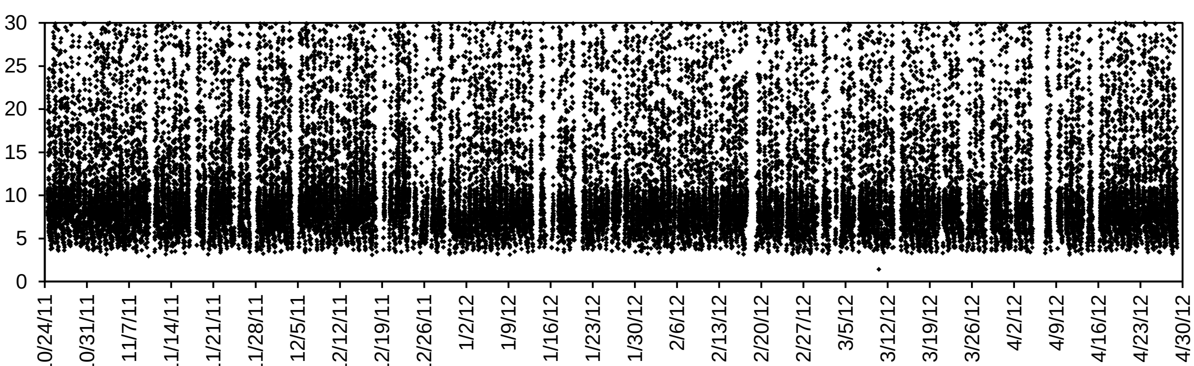

FIGURE 2 Vehicle travel time data for MD-355 over a 6-month time period.

Figure 3 shows an example of the overlay technique for a 24 hour period. Each data point in this graph is the travel time from one vehicle that was matched between the entry and exit points of the arterial on any Wednesday over the six month period. Travel times generally fall within 5 and 15 minutes, varying by time of day. Some data points (such as those in callout *a*) indicate substantially longer travel times than the majority of vehicles. Such data points represent motorists who briefly left the road (for example, at a gas station) in route to their destination. The red vertical lines show changes in signal timing at different times of the day. Note that the travel time patterns change substantially at the transition of signal timing plans.

This is most visible at 15:00 hours. Vehicle travel times appear to cluster around specific travel times, rather than being normally or uniformly distributed. The clustering of travel time creates what appears as horizontal stripes, or striations, in the data (see callout *b*). The time difference between the center of these horizontal stripes reflects the cycle length used in the corridor, since vehicles that have to stop will typically wait for about a cycle length before the next green. As traffic builds in the evening rush between 15:00 and 19:00 hours, travel times escalate. At the beginning of the evening peak period most of the vehicles progress through in six minutes. At 17:00 hours, the majority shift to the second striation of approximately 8 minutes, and close to the end of the rush hour, a significant portion of vehicles progress through in about 10 minutes. This progression to longer travel times as the rush hour progresses indicates more vehicles are stopped and forced to wait for one or more signal cycles somewhere within the corridor.

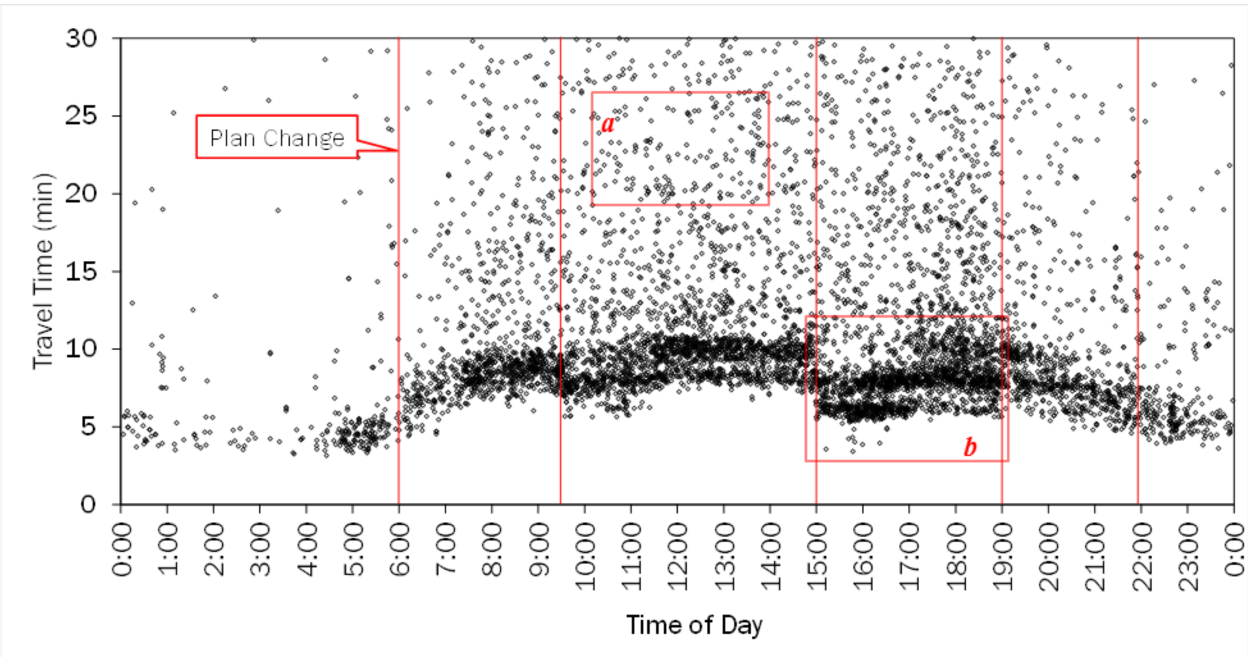

FIGURE 3 Travel times from vehicle re-identification displayed as a 24-hour overlay.

Overlay plots are useful for observing travel time trends for a single segment or corridor. Patterns in the point cloud data provide insight into the operations of the signal system and quality of traffic flow. Information that can be observed in overlay plots includes:

- Anticipated travel time through the corridor at various hours of the day
- Signal plan changes
- Cycle lengths (distance between striations)
- Mismatched cycles lengths within the corridor
- Proportion of people stopping for services within the corridor as indicated by the propensity of outliers

Although considerable insight can be gained from overlay plots, their utility is limited to observing a single corridor. Comparing the performance of multiple corridors, or performance of the same corridor at different dates or different times is not efficient with overlay charts.

Figure 4 shows the distribution of travel times observed during the AM period from 06:00 to 09:30 hour, which includes approximately 5,000 samples. Any travel time above 16.5 minutes has been removed, assuming that these travel times primarily result from vehicles stopping for services in the corridor and thus are not representative of the travel times experienced by through traffic. The data for this AM period is portrayed as a histogram, in the vertical blue bars in Figure 4, and as a cumulative frequency diagram (CFD), in the bold black curve. The number of observations for each travel time in the histogram is shown on the right axis. The cumulative frequency of travel time is plotted in black as a single line and its value is shown on the left axis. Any point on the CFD provides a measure of percentage of vehicles that traverse the corridor within a known travel time, specifically travel time percentiles. For example, in the sample graph, 0.25 (or 25%) traverse the corridor in 7.5 minutes or less, such that the 25th percentile travel time is approximately 7.5 minutes. Note that all the information pertaining to the repeatable traffic pattern between 6 AM and 9:30 AM in Figure 3, and also portrayed in the histogram in figure 4, is encoded into a single CFD curve.

The shape of the CFD curve in Figure 4 is typical for a corridor not experiencing congestion resulting in phase failures. The shape of the curve is referred to as an ‘s’ curve or sigmoid-shaped curve. An ‘s’ shaped curve can be modeled as a Gaussian (or normal) distribution with an appropriate mean and standard deviation.

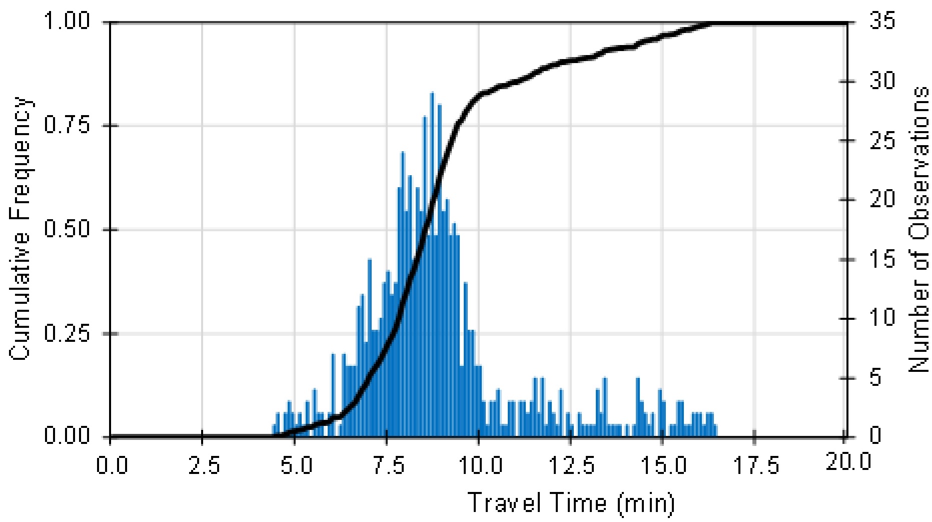

FIGURE 4 Distribution of Wednesday AM travel times on MD-355.

Cumulative frequency diagrams (CFDs) are useful to compactly portray the variation in travel time for a corridor using a single line. CFDs are suitable to compare travel time trends for multiple segments or multiple time periods on a single chart, providing not only the magnitude of travel times, but also an indication of the distribution of travel times for all the vehicles that traverse the corridor.

VARIATION OF TRAVEL TIME ON ARTERIALS USING OVERLAY AND CFD CHARTS

The following series of overlay charts and cumulative frequency diagrams (CFDs) was drawn from an archive of data collected as part of the Vehicle Probe Project validation program, sponsored and funded by the I-95 Corridor Coalition. From 2013 forward, the Coalition investigated the quality of outsourced probe data on numerous signalized corridors along the east coast, comparing the traffic patterns reported by probe data against a reference data set collected with Bluetooth traffic monitoring re-identification equipment. (*13*) The resulting archive of re-identification data provides a rich source to illustrate various traffic performance phenomenon observable with re-identification travel time data. Most of the data sets from the validation effort span a two week period. The resulting overlay plots and CFDs reflect signalized arterial traffic performance on weekdays during the two weeks of data collection. Data was filtered using standard methods as described in the Traffax BluSTATs processing manual. (*14*)

For each example, a brief description of the segment is provided. Most segments are from one to two miles in length, consistent with the validation procedures of the Coalition. The results of the comparison of re-identification with probe data are provided in reference (*13*) as well as a Coalition report (*15*), available at the Coalition web site.

Figure 5 provides an example of a multi-modal travel distribution on an arterial roadway. The roadway segment is along US-130, northbound in New Jersey between the intersection of CR-629 and NJ-413. This segment exhibits a bi-modal traffic pattern for a large majority of the day, beginning at 06:00 and lasting through 19:00 (see callout *i*). Even after 19:00 hours, a slight bi-modal pattern is discernable in the overlay plot; however, a large majority of vehicles that traverse the corridor after 19:00 do so at the faster of the two modes. The CFD plot to the right highlights the 13:00–14:00 traffic in black in comparison with the ensemble of the CFDs for the other hours of the day. The bi-modal curve, appearing as a conjoined double ‘s’ shaped curve, is characteristic of all the CFDs for the entire day, not just for the highlighted hour. The differences in the CFD for each hour are primarily vertical shifts in the curve. The inflection points for each hourly curve are roughly the same on the *x* axis, indicating the same dominant travel pattern exists throughout the day. The locations of the inflection points vary primarily with respect to the *y* axis, indicating that the portion of traffic that traverses the corridor at the faster mode versus the slower mode varies throughout the day. The magnitude of the variation is roughly 20% (see callout *iii*).

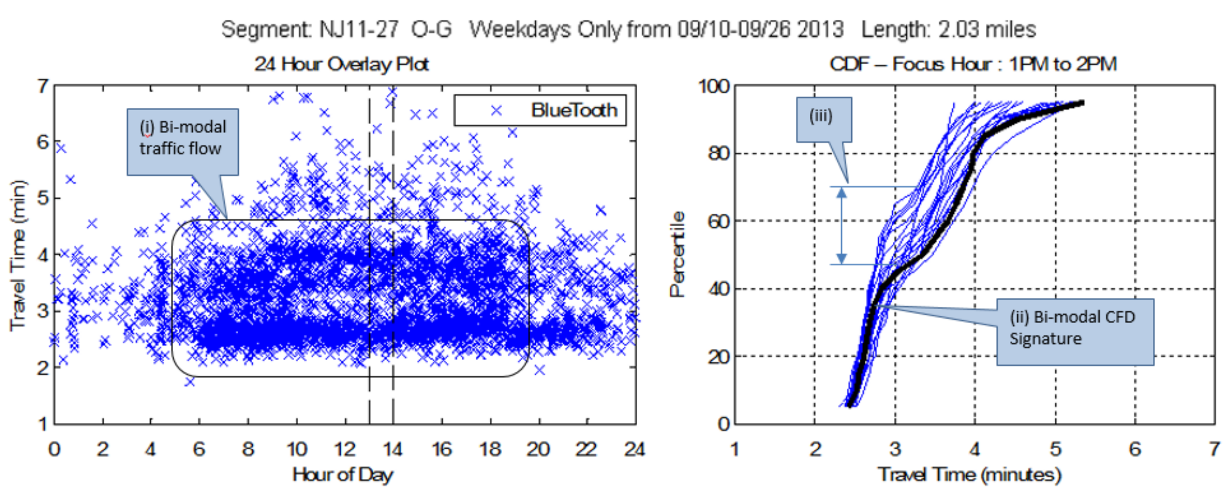

FIGURE 5 Overlay and CFD visualization of travel times for example segment on US-130.

Figure 6 provides yet another example of a multi-modal travel distribution on an arterial roadway. The roadway segment is along US Route 29 in northern Virginia, also known as Lee Highway, from the intersection with VA-123 to Jermantown Road. This segment is unusual in that four distinct travel times, or modes, are visible in the overlay plot during the course of the day as seen in Figure 6. These modes are labeled in callouts *i* through *iv* as the travel time escalates from a low of approximately 3.5 minutes, through travel times of approximately 5.0, 7.0, and finally 11.0 minutes at different times during the day. At any particular time of day, traffic is distributed between two travel times (or modes). A distribution between two modes results from a portion of the traffic stream being unable to clear the queue on green and being forced to wait an extra cycle. Throughout the day, four distinct modes are observable at various hours, but never more than two at any given time.

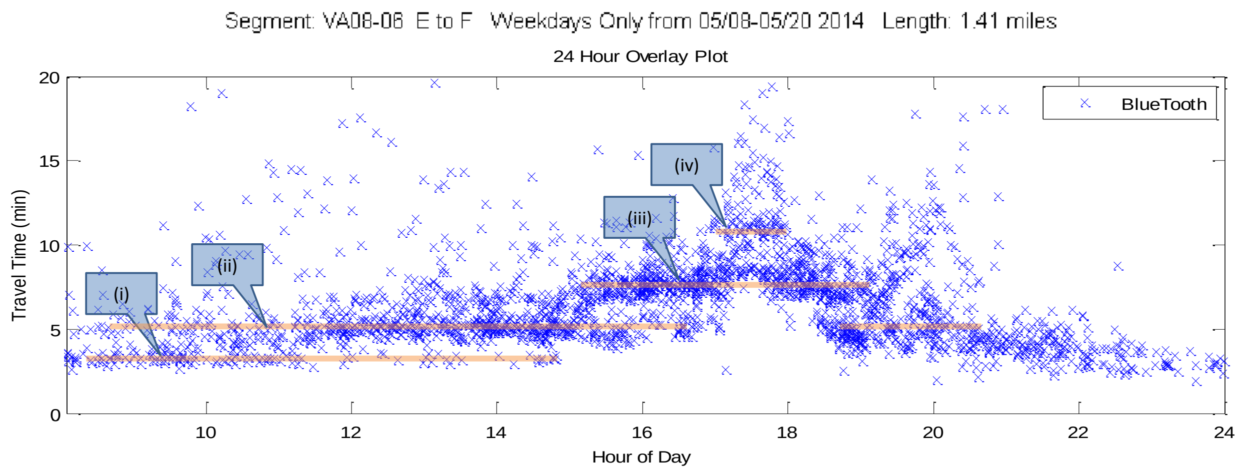

FIGURE 6 Overlay and CFD visualization of travel times for example segment on US-29.

The corresponding CFD for US-29 is shown in Figure 7. The peak evening rush hour is highlighted in black for the 17:00 to 18:00 hour (5 PM to 6 PM) timeframe. This CFD for this hour is a conjoined double ‘s’ curve. Approximately half of the traffic progresses through at the faster mode (callout *i*), and the remaining at the slower mode (callout *ii*). Many of the CFD curves from other hours of the day, shown in the diagram in blue, are also conjoined double ‘s’ shapes, indicating bi-modal distribution. Unlike the previous example plot from US-130 in New Jersey, the inflection points that demark conjoined ‘s’ curves vary horizontally as well as vertically, indicating that the travel time modes as well as their percent distributions vary throughout the day.

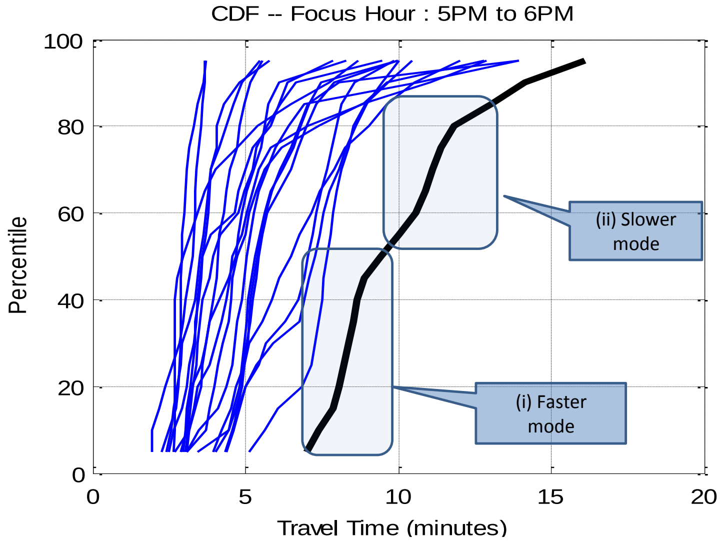

FIGURE 7 CFD visualization of travel times for example segment on US-29.

SIGNAL CONTROLLER ATTRIBUTES OBSERVABLE IN OVERLAY CHARTS

Sample plots that exhibit signal controller attributes are taken from the archive of arterial validation data collected as part of the I-95 Corridor Coalition's Vehicle Probe validation effort. These examples illustrate signal timing parameters that can be observed in travel time overlay charts. The two phenomena illustrated include signal timing changes and cycle length mismatches between adjacent signals within a corridor.

Figure 8 provides an example of signal timing change that is distinctly visible in a weekday travel time overlay chart. The roadway segment is along US Route 130 in New Jersey, southbound between the intersection of Beverly Rancocas Road and CR-629. The signal timing change is visibly evident at 15:30 hours, at callout *i*. The dominant travel time shifts from approximately three minutes to two minutes. This is due to a signal timing plan implemented for PM peak that minimized travel time for northbound traffic. A less distinct signal timing change also occurs at approximately 18:30 (see callout *ii*), in which the dominant travel time shifts back to approximately three minutes.

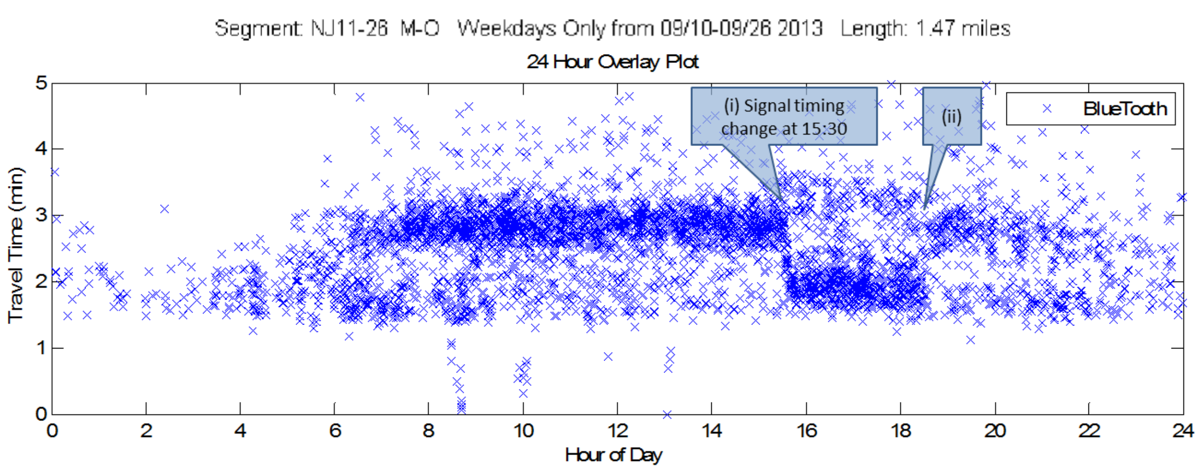

FIGURE 8 Overlay chart for US-130 northbound showing signal timing change.

Corridors with coordinated signals operate on equal cycle lengths. If cycle lengths differ, even by a second or two, the platoons from an upstream signalized intersection will arrive at different points in the cycle of the downstream signalized intersection. The difference with each cycle will grow (or diminish) depending on the relative cycle length of adjacent intersections. Mismatched cycle lengths have a distinct pattern in overlay plots. Diagonal stripes (or striations) appear as a result. Figure 9 provides an example of mismatched cycle times within a corridor visible in a weekday travel time overlay chart. The roadway segment is along US Route 130 in New Jersey, northbound between the intersections of Bridgeboro Street and Beverly Rancocas Road.

The two signals on this corridor are operated on different cycle lengths. The diagonal striations in the data indicate the phenomenon. On each successive cycle, the platoon from the upstream signal arrives at a slightly different time in the downstream cycle, causing the cyclic travel time patterns displayed in the overlay chart. This pattern is observable throughout the day, even as new signal timing plans are initiated near 15:45 and 18:30 hours. This pattern provides no indication if the mismatched cycle times were by design, as would be the case at the junction of two coordinated arterial corridors, or accidental, perhaps as a result of a data entry error. The consistency of the phenomenon in Figure 9 throughout the day suggests the former, whereas the striation pattern for only a portion of the day would suggest the latter.

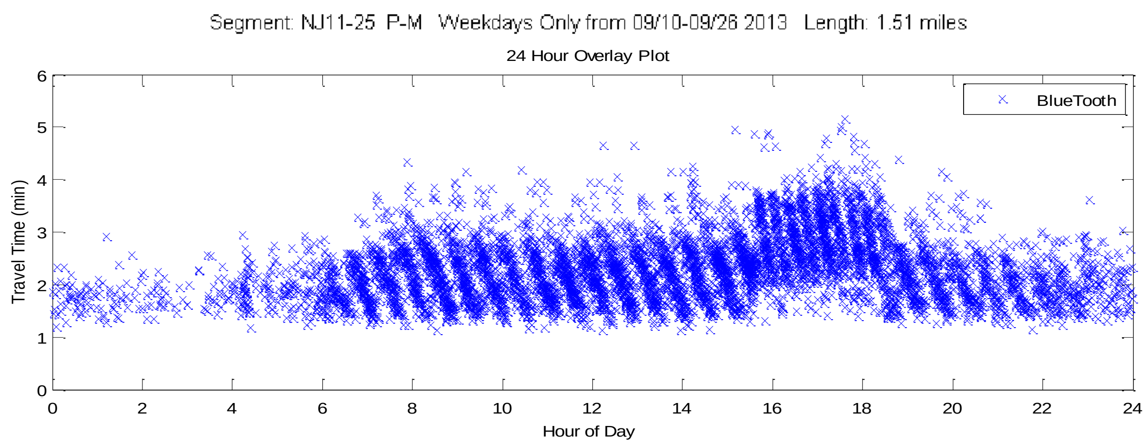

FIGURE 9 Overlay chart for US-130 segment northbound showing mismatched cycle lengths.

BEFORE AND AFTER COMPARISON WITH CFD CHARTS

The most useful attribute for CFD charts is their ability to compare traffic performance between two different roadways, or at two different times on the same roadway, or traffic performance before and after signal retiming, or the impact on traffic due to a capital improvement on the corridor or network. Comparing travel times using overlay charts is cumbersome, requiring the user to align time frames and interpret the relative density of data points. Measurements such as mean or median travel times compare only central tendencies, not the full distribution of travel time. Measures such as travel time index (TTI), buffer time index (BTI), standard deviation, or interquartile range (IQR) can characterize the magnitude of variation in the travel time, but reveal nothing of its underlying shape such as whether it is uni-modal versus bi-modal. Cumulative frequency diagrams (CFDs) fully capture traffic performance characteristics in a compact, visual format, displaying not only the change in average conditions, but also any changes in travel time variation.

The first example of comparative CFDs portrays the traffic benefit attributed to a major capital improvement. Maryland Route 200 (MD 200), more commonly known as the Intercounty Connector or ICC, is a tolled freeway in Maryland which connects Gaithersburg in Montgomery County and Laurel in Prince George's County. Although opened in stages, the portion of the ICC that allowed for connection between I-270 and I-95 opened on November 22, 2011. Two re-identification sensors were installed on the impacted network prior to the opening of the ICC. One was on I-270, north of its intersection with the ICC (sensor A in Figure 10), and the other was on I-95 between Washington DC and Baltimore (sensor E in Figure 10). Re-identification data was collected and analyzed before and after the opening of the ICC. Travel times derived from re-identification sensor A and E reflect trips between Montgomery County and Baltimore, Maryland.

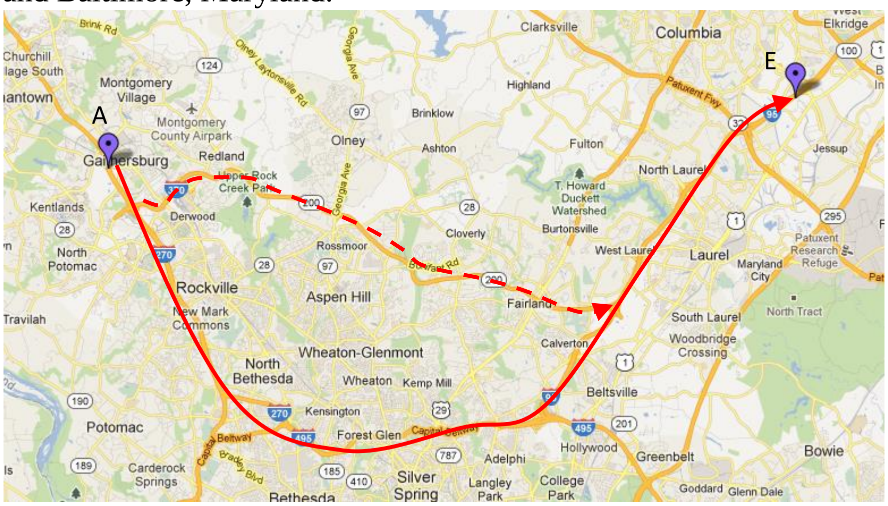

FIGURE 10 The Inter-County Connect (MD-200) in Maryland.

Even though no re-identification sensor was located directly on the ICC, sensors A and E captured the impact due to the opening of the ICC on travelers from Montgomery County to Baltimore, whether they accessed the ICC (dashed lined) or used the non-tolled route that included portions of the DC beltway (solid line). The before/after comparison of the CFDs are shown in Figure 11. Not only did the travel time lessen as indicated by the shift from right to left in the respective CFDs (see callout *i*), it also became more reliable as evidenced by shift of the curve up and to the left (see callout *ii*). This change in travel time reliability can be quantified by comparing the inter quartile range (75th percentile-25th percentile).

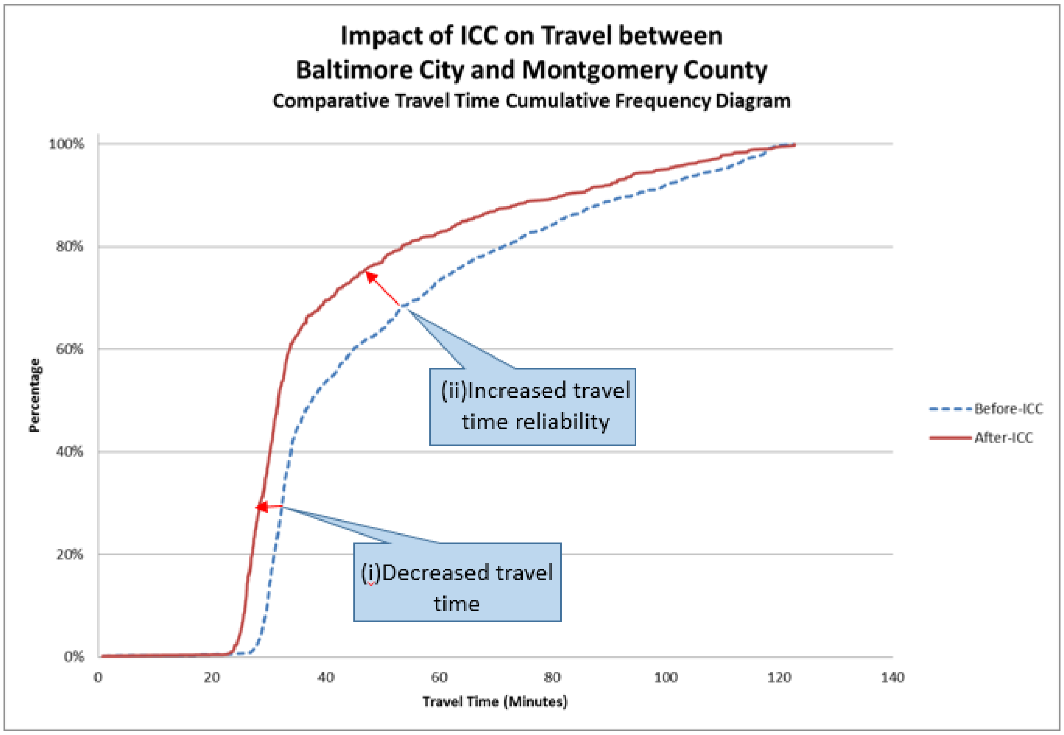

FIGURE 11 Travel time impact of the ICC.

The second example of the use of comparative CFDs reveals the improvement resulting from signal retiming. In February of 2009, Bluetooth re-identification sensors were deployed at various locations on Maryland Route 24 north of Baltimore near the intersection with Interstate 95, as shown in Figure 12. The sensors were placed to measure the impact of signal retiming.

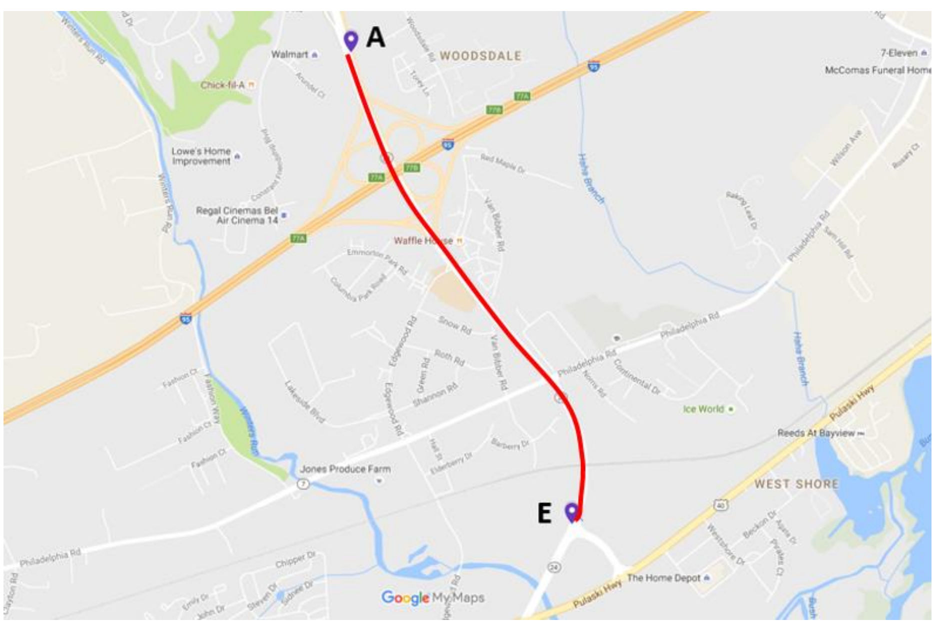

FIGURE 12 Location of Bluetooth sensors on Maryland 24.

Travel time data was captured for 2.5 days before and two days after implementation of a new signal timing plan. The before and after travel time CFDs in Figure 13 illustrate the effectiveness of the arterial signal retiming for northbound traffic during the PM peak between sensors E and A. The shift of the CFD graph to the left indicates an approximately two-minute reduction in travel time.

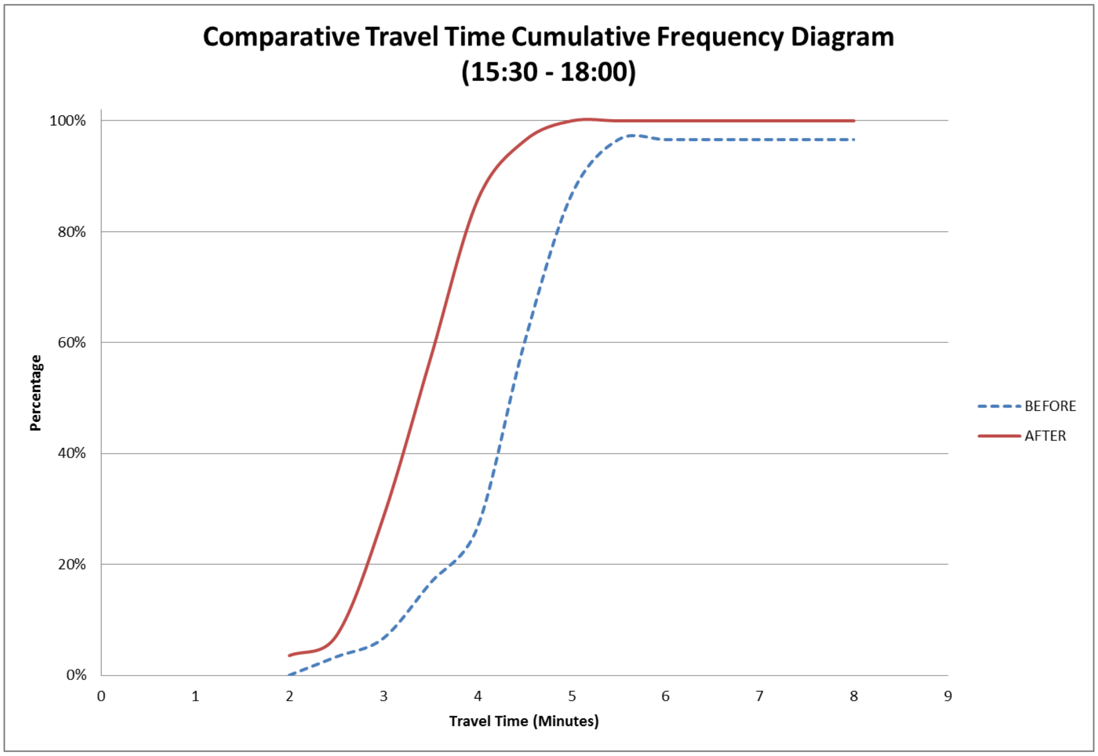

FIGURE 13 Before and after comparative CFD of travel times on Maryland Route 24.

CONCLUSION

This paper illustrates the construction and utility of overlay plots to observe travel time trends for a single segment or corridor. Overlay plots are useful to quickly determine anticipated travel time through the corridor at various hours of the day, signal plan changes, cycle lengths, mismatched cycles lengths within the corridor, and proportion of people stopping for services within the corridor. Cumulative frequency diagrams (CFDs) complement overlay charts with the ability to summarize large amounts of data into a single graphic for direct comparisons. CFDs compactly portray the variation in travel time for a corridor using a single line. CFDs are suitable to compare travel time trends for multiple segments or multiple time periods on a single chart, providing not only the magnitude of travel times, but also an indication of the distribution of travel times for all the vehicles that traverse the corridor. In other words, CFDs provide not only travel time, but also travel time reliability in a robust graphical format for ease of comparison. CFDs are appropriate for before-after studies, long term traffic trends, and comparison of performance between different facilities. These methods are particularly effective for comparing before/after median travel times as well changes in inter quartile range to assess travel time reliability.

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