ABSTRACT
This paper reports on the manual ground-truthing of travel times collected from a wireless magnetometer signature matching system. The evaluation was conducted along a 2.2 mile corridor spanning 5 signalized intersections in Indianapolis, IN during a congested time period with rapidly varying travel times. Within the evaluated time period, each re-identified probe vehicle was manually confirmed using video images. In general, the 25th, 50th, and 75th percentile signature matching system link travel times and the ground truthed data were virtually identical.

Depending upon the approach evaluated (and mid-block turning), the proportion of confirmed link probe travel time samples was between 31% and 45% of the entering volumes. These large sampling rates provide high quality data for assessing corridor performance as well as identifying opportunities for improving traffic signal timing settings. With probe data penetration rates of this magnitude, it is possible to develop high quality statistical distributions of travel time characterizing the movement of vehicles along a signalized arterial. The paper demonstrates how those statistical distributions can be used to assess before and after conditions associated with a traffic signal retiming action. The paper concludes by recommending that traffic signal management systems augment their traditional count and occupancy data collection with emerging probe vehicle data sources to obtain more robust real-time performance measures that can be used to more effectively manage an urban or suburban traffic signal system.

INTRODUCTION
For nearly 5 decades, floating car studies have been used as a tool for assessing the performance of roadways [1, 2, 3, 4]. A major challenge with these studies has been cost-effectively scheduling a sufficient number of instrumented vehicles necessary to obtain a statistically significant comparison of mean travel time. Obtaining statistically significant results can be particularly challenging for signalized arterials where the stochastic variation in travel time can be quite high. In the past three years a variety of new vehicle re-identification technologies have emerged that can provide high quality probe vehicle data with sampling rates exceeding 40% of the traffic stream [5, 6, 7, 8]. With probe data penetration rates of this magnitude, it is possible to develop high quality statistical distributions of travel time characterizing the movement of vehicles along a signalized arterial [9, 10].

STUDY OBJECTIVE
This study evaluated the statistical accuracy of a wireless magnetometer vehicle re-identification system (WMVRS) for estimating link travel time along a signalized corridor in Indianapolis, IN (Figure 1). Figure 2 (page 49) illustrates the concept of using a WMVRS to estimated travel times for vehicles traversing a road segment. A vehicle traveling down a road passes over an array of magnetometers (Figure 2a), after traveling down the road further, the vehicle passes a second array of magnetometers (Figure 2b). The concept behind WMVRS is that these fingerprints can be matched and a travel time can be derived based on the fingerprint data and the timestamp.

For the example shown in Figure 2, the signature associated with the car passing station a at 8:25:20 is matched with the signature passing station b at 8:27:25 and a vehicle travel time of 125 seconds can be calculated for the passenger car. In this particular example, the signatures for the motorcycle and truck at station a are not shown to be matched at station b.

TRAVEL TIME TEST BED
INSTRUMENTATION
Location
Pendleton Pike, or US 36, located east of Indianapolis, IN adjacent to I-465 (Figure 1) was selected as the corridor for evaluating WMVRS. This corridor was chosen because it was newly constructed in 2010 and experiences some peak period congestion. The Pendleton Pike corridor has significant west bound traffic congestion in the morning period, going towards Indianapolis and significant east bound congestion in the PM period, leaving Indianapolis.

The segment of Pendleton Pike selected includes five signalized intersections, however only three of the intersections, Franklin, Post, and Mitthoeffer represented by a, b, and c in Figure 1, were equipped with the WMVRS. Figure 3 shows the placement of the wireless magnetometer sensors. The two intermediate intersections (Figure 1d and Figure 1e) were not instrumented with wireless

Continued on page 49
magnetometer sensors. The Mowrey Street intersection with Pendleton, callout e in Figure 1, is signalized to provide access to a semi-occupied strip mall facility and a residential neighborhood. The Sheila Drive intersection, callout d in Figure 1, is located near a distributing plant and a residential trailer home area.

**Installation**

The installation was conducted the week of August 16th, 2010, which included installation of the wireless magnetometers, repeaters, access points, cabinet racks, and cameras for each of the three intersections on Pendleton Pike. The magnetometers were installed one lane at a time by coring 4” diameter holes in the road, adjusting the height of the magnetometer, placing the magnetometer in the void, and filling the void with an epoxy compound. Figure 4a - Figure 4f (page 50) illustrates the steps associated with installing the in-pavement wireless magnetometers.

Six wireless magnetometers were used in each lane of traffic. Five magnetometers were used for the matching array and one was used as a detector to trigger for the camera used for ground truthing. Two arrays were used in the east bound direction and one array was used in the west bound direction at each intersection. The configuration and approximate location of these magnetometer arrays relative to the stop bar is shown in Figure 3. Photographs of the completed wireless magnetometers installations in the two eastbound lanes at Franklin Road is shown in Figure 5a and a similar photograph is shown for the single westbound lane installation at Franklin Road in Figure 5b.

**Test Segments**

The three intersections equipped with sensors (Figure 1: a, b, c) became the endpoints of 6 segments where travel time was calculated using the WMVRS. Figure 6 conceptually shows these six segments, covering

Continued on page 50
two lanes in the eastbound direction and one lane in the westbound direction. The locations of these segment endpoints are more precisely shown in Figure 3 a, b, and c. Distances and speed limits of the segments can be found in Table 1. There is a speed limit change on Pendleton Pike which can be seen in Figure 1. The speed is 40 mph southwest of that point in the figure and 45 mph northeast of that point. This section of US 36 has a number of access drives allowing vehicles to enter and exit between sensor locations.

The WMVRS calculated travel time data for six segments shown in Figure 6 (page 52) was subsequently evaluated using video that was collected concurrently.

**PROBE DATA AND VISUAL CONFIRMATION TECHNIQUES**

**Testing Periods**

Two test periods were used to complete this study. The eastbound direction was evaluated on November 3rd, 2010 between 1500 hrs. and 1800 hrs. The westbound direction was evaluated on December 2nd, 2010 between 0730 hrs. and 1030 hrs. These three hour periods for each direction were the peak volume time periods for the given segments because of traffic moving toward Indianapolis in the morning and away from Indianapolis in the evening. During these testing periods the WMVRS travel time data (Figure 7) (page 52) was logged concurrently with digital video from cameras located at Franklin Rd., Post Rd., and Mitthoeffer Rd. (Figure 1a,b,c). Cameras at each of those intersections were aimed in the direction of the wireless magnetometer sensors to allow visual identification of vehicles (Figure 8, Figure 9, Figure 10) (page 51).

**Eastbound Franklin to Post Lane 1 Example**

In Figure 7 a scatter plot of the entire day of November 3rd, 2010 can be seen for segment E1 (Figure 6). The evaluation period is distinguished with two black lines and a surge in travel times can be seen between the lines. In Figure 7 two callouts are pointed at two enlarged diamond points. One of those callouts has a check mark which indicates it is a confirmed match. This visually confirmed match can be seen in Figure 8, which shows time stamped images at Franklin Road (Figure 8a) and Post Road (Figure 8b) on Pendleton Pike. The unique image of the garbage truck provides an easy visual illustration to portray how video images could be used to manually calculate segment travel time and compare with the WMVRS. The other callout in Figure 7 shows an ‘X’ which indicates an unconfirmed match. This ‘X’ in the figure corresponds to the
Probe Vehicle Re-Identification Data Accuracy Evaluation . . . Continued from page 50

camera images in Figure 9 which appear to be two different vehicles. The picture from Franklin Road appears to be a white van, while the picture from Post Road appears to be a dark colored car.

Penetration Rates
Images of each of the remaining points in the evaluation period (n=683) on the scatter plot, Figure 7, were analyzed. Based upon a lane vehicle volume of 1708 and 683 estimated travel times the penetration rate for this segment was estimated to be 40%. Based upon visual inspection of the vehicles the WVMRS classified as matches, 619 vehicles (or 36.2% of the entering segment volume) could be clearly confirmed as a match. In several cases there were visual occlusions that precluded a positive visual match. Figure 10 shows an example of a lane 1 occlusion (lane closest to centerline) at a time period that the WVMRS identified a match. Due to the occlusion shown in Figure 10, the WMVR might very well have identified a correct match, but from the images shown in Figure 10, there is insufficient video evidence to classify it as correct. However, even using this conservative approach, the proportion of entering vehicles with unconfirmed matches was quite small, ranging from 1.9% to 6.4%. Table 2 summarizes these statistics for all six segments shown in Figure 6.

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Table 1: Probe Vehicle Segment Characteristics

<table>
<thead>
<tr>
<th>Segment</th>
<th>Starting Cross Street</th>
<th>Ending Cross Street</th>
<th>Length (miles)</th>
<th>Lane</th>
<th>Posted Speed (MPH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Franklin Rd</td>
<td>Post Rd</td>
<td>1.05</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>E2</td>
<td>Franklin Rd</td>
<td>Post Rd</td>
<td>1.05</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>E3</td>
<td>Post Rd</td>
<td>Mathieson Rd</td>
<td>1.17</td>
<td>1</td>
<td>40/45</td>
</tr>
<tr>
<td>E4</td>
<td>Post Rd</td>
<td>Mathieson Rd</td>
<td>1.17</td>
<td>2</td>
<td>40/45</td>
</tr>
<tr>
<td>W1</td>
<td>Mathieson Rd</td>
<td>Post Rd</td>
<td>1.17</td>
<td>1</td>
<td>45/40</td>
</tr>
<tr>
<td>W7</td>
<td>Post Rd</td>
<td>Franklin Rd</td>
<td>1.05</td>
<td>1</td>
<td>40</td>
</tr>
</tbody>
</table>

PROBE DATA STATISTICAL CHARACTERIZATION AND ANALYSIS

The statistical distribution of the visually confirmed data and the entire data set collected by the WVMRS was compared. Figure 11 (page 52) shows a stacked histogram for travel times along segment E1, illustrating that a majority of the outlier travel time data was unconfirmed (0 to 60 second travel time over 1.05 miles). Some of the unconfirmed data for travel times greater than 75 second...
Probe Vehicle Re-Identification Data Accuracy Evaluation . . . Continued from page 51

were due to occlusions in the video processing, such as shown in Figure 10. Figure 12 shows a cumulative frequency diagram (CFD) for segment E1 travel time for both the confirmed matches and every match that was provided by the WVMRS. It is important to note that between the 25th and 75th quartile of the figure the lines are nearly identical. The travel times vary by half a second or less for each of these three points. This process of plotting the CFDs of confirmed and all matches was repeated for each of the six segments and can be seen in Figure 13 (page 53). Every segment displayed very similar characteristics to E1 where there is little difference between the confirmed matches and all of the matches. Table 3 show the details regarding the 25th, 50th, and 75th percentile travel times for each segment. Table 4 (page 54) shows the percent difference between the confirmed data and all of the data. The largest percent difference between was found at the 75th percentile for segment E4 (Table 4). This point is represented by call out ‘i’ in Figure 13d. Graphically there is minimal difference between the confirmed matches and all matches.

EXAMPLE PROBE DATA APPLICATION

Probe data is valuable for identifying time periods where there are opportunities to improve a signal system performance. After initiating an improvement, probe data is then valuable in quantitatively assessing the impact (11). Examining travel time data for segment W2 on February 15th, 2011 (Figure 14a) (page 54), an increase in the travel time data during the morning peak period between 600 and 900 hours was observed. This information was relayed to the operating agency and an offset adjustment was made. After this adjustment was performed travel time data was tabulated a week later, on February 22nd, 2011 (Figure 14b). A visual improvement in travel time exists during the morning evaluation period between Figure 14a and Figure 14b. Figure 14c provides a cumulative frequency diagram (CFD) comparison of the before and after travel time for the morning period and shows a median reduction in travel time of 28 seconds in one lane over a 1.05 mile segment.

Using the median travel time reduction and the volumes collected over the three hour morning evaluation period a user costs savings can be determined. If 1700 vehicles are saving 28 seconds over the segment it would result in a total travel time savings of over 13 hours per day. Over the entire course of a year (assuming 250 business days per year) the travel time savings are over 3300 hours per lane. Since there are two lanes on this approach, and assuming a 15.47$/hr user cost, this one offset change accounts for just over $100,000 of savings in annual user costs for just segment W2. For simplicity, this example shows before/after data for just one segment. However, these techniques can easily be extended to an entire corridor. In fact a recent retiming project just north of this corridor that updated a Saturday timing...
Figure 13: Travel time (seconds) CFD comparison for reported and visually confirmed data for six segments

e) Segment W1  f) Segment W2

Table 3: Travel Time (Seconds) 25th, 50th, and 75th Percentile of All Data and only confirmed data

<table>
<thead>
<tr>
<th>Segment</th>
<th>25th Percentile</th>
<th>50th Percentile</th>
<th>75th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Confirmed</td>
<td>All</td>
</tr>
<tr>
<td>E1</td>
<td>88.9</td>
<td>89.4</td>
<td>106.8</td>
</tr>
<tr>
<td>E2</td>
<td>90.4</td>
<td>90.7</td>
<td>109.2</td>
</tr>
<tr>
<td>E3</td>
<td>94.5</td>
<td>94.7</td>
<td>104.8</td>
</tr>
<tr>
<td>E4</td>
<td>102.0</td>
<td>102.2</td>
<td>112.3</td>
</tr>
<tr>
<td>W1</td>
<td>97.8</td>
<td>97.7</td>
<td>107.0</td>
</tr>
<tr>
<td>W2</td>
<td>92.2</td>
<td>92.6</td>
<td>130.4</td>
</tr>
</tbody>
</table>

Note: Table 4 and Figure 14 are on page 54.
CONCLUSIONS

This paper reports on the evaluation and application of a WVMRS to measure travel time (Figure 2). The evaluation was performed along the Pendleton Pike corridor in Indianapolis, IN (Figure 1, Figure 3) using six study segments (Figure 6, Table 1), during peak periods. Travel time data (Figure 7) was manually ground truthed (Figure 8, Figure 9) using surveillance video to assess the accuracy of the WVMRS travel time estimates. It was determined that between 31 and 45 percent of incoming vehicles were confirmed matches downstream (Table 2). This is a significant percentage when compared to other probe vehicle data collection methods (12).

When comparing the confirmed data with all of the data collected it was determined, both graphically and numerically, that there was no substantive difference in the data sets between the 25th, 50th, and 75th percentiles (Figure 13, Table 3, Table 4).

It is recommended that traffic signal management systems augment their traditional count and occupancy data collection with emerging probe vehicle data sources to obtain more robust performance measures that can be used to more effectively identify operational problems that warrant intervention (Figure 14a), and then quantitatively assessing the impact of those improvements (Figure 14b,c). Work is underway to extend this example of quantifying before/after benefits of a

Continued on page 59

Table 4: Difference between 25th, 50th, and 75th Percentile of All Matches and Confirmed Matches

<table>
<thead>
<tr>
<th>Segment</th>
<th>25th Percentile % Difference</th>
<th>50th Percentile % Difference</th>
<th>75th Percentile % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.65%</td>
<td>0.36%</td>
<td>0.17%</td>
</tr>
<tr>
<td>E2</td>
<td>0.33%</td>
<td>0.98%</td>
<td>0.54%</td>
</tr>
<tr>
<td>E3</td>
<td>0.24%</td>
<td>0.14%</td>
<td>0.11%</td>
</tr>
<tr>
<td>E4</td>
<td>0.16%</td>
<td>0.03%</td>
<td>1.27%</td>
</tr>
<tr>
<td>W1</td>
<td>0.05%</td>
<td>0.07%</td>
<td>0.36%</td>
</tr>
<tr>
<td>W2</td>
<td>0.41%</td>
<td>0.42%</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

Continued from page 53

Figure 14: Before and after comparison of segment W2 travel time
segment to quantifying before/after benefits along the entire corridor.

ACKNOWLEDGMENTS
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REFERENCES


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