Estimating Route Choice and Travel Time Reliability with Field Observations of Bluetooth Probe Vehicles

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Route choice is often assessed with either a modeling technique or field observations. Field observations have historically used a variation of license plate matching. The proposed technique assesses route choice and travel time that uses an anonymous Bluetooth media access control (MAC) address sampling technique as a surrogate for license plate matching to assess route choice. The Bluetooth sampling technique was used to evaluate the impact of an unexpected bridge closure in northwest Indiana, including an assessment of the proportion of vehicles using each of four alternate routes. The Bluetooth technology also provided a means to collect travel time data for each alternate route; these observed travel times were also compared with travel time estimates obtained by route classification and link distance. In general, the route choice behavior was consistent with observed travel time estimates. The Bluetooth sampling technique is cost-effective to deploy, and although results are approximate, direct measurement of travel times and route choice is useful for public agencies to assess mobility and travel time reliability along alternate routes.

The selection of routes and the assignment of traffic volumes to alternate routes is a classic transportation problem that has been the topic of study and research for decades. The principles of equilibrium, in which trips are assigned to alternate routes on the basis of the minimum travel time, were put forth almost 60 years ago and still provide the foundation for describing how drivers will select from alternate routes (*1*). Researchers have continued to develop the topic both in a theoretical framework, with stochastic and deterministic models (*2*), and in an applied framework, with data collection ranging from surveys and trip diaries to license plate studies and, more recently, data collection on the basis of the Global Positioning System (GPS) (*3*). With the increasing availability of route guidance information and real-time traffic information, the framework for route choice is becoming increasingly sophisticated.

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Route choice is of particular interest during road construction or closures, in which case agencies may identify a detour route (*4*) and motorists may elect to take the official detour route or another route of their own choosing. Just as agencies conduct performance assessments to evaluate the management of roadway work zones (*5*), it is appropriate for agencies to evaluate the impact of detours, with respect to both the impact on motorists displaced from the main route and the impact on operations for the signed detour and local bypass routes.

A sampling technique is described for leveraging the modest penetration of consumer electronic devices with discoverable Bluetooth identifiers in passing vehicles to collect data on route choice as well as travel time data on alternate routes. The technique is described in the context of a case study evaluating the impact of a bridge closure in northwestern Indiana.

MOTIVATION

Nationwide, agencies routinely inspect their infrastructure as a part of a comprehensive asset management program and to provide early detection of potential structural problems. On November 13, 2009, the Cline Avenue bridge on Indiana State Road (SR) 912 was unexpectedly closed because of deteriorating structural conditions (Figure 1*a*). The bridge handled an annual average daily traffic of 30,500 vehicles. With no feasible repairs and an estimated replacement cost of $150 million, the closure caused state and local officials to be concerned with how it would affect both official and unofficial detour routes. Specific concerns included assessing potential congestion on the official and unofficial detour routes, including operations on local streets, and estimating the route choices for motorists diverting because of the closed bridge.

OBJECTIVES

Three objectives were identified in an effort to examine the impact of the bridge closure: to develop travel time plots and identify any resulting congestion choke points, to identify reference points in the network that had significant traffic between them, and to estimate the distribution of traffic on the four alternate routes. This information was needed to assess resulting traffic patterns and the impact of the diverted traffic on the network; it also allowed identification of any specific locations that experienced excessive delay.

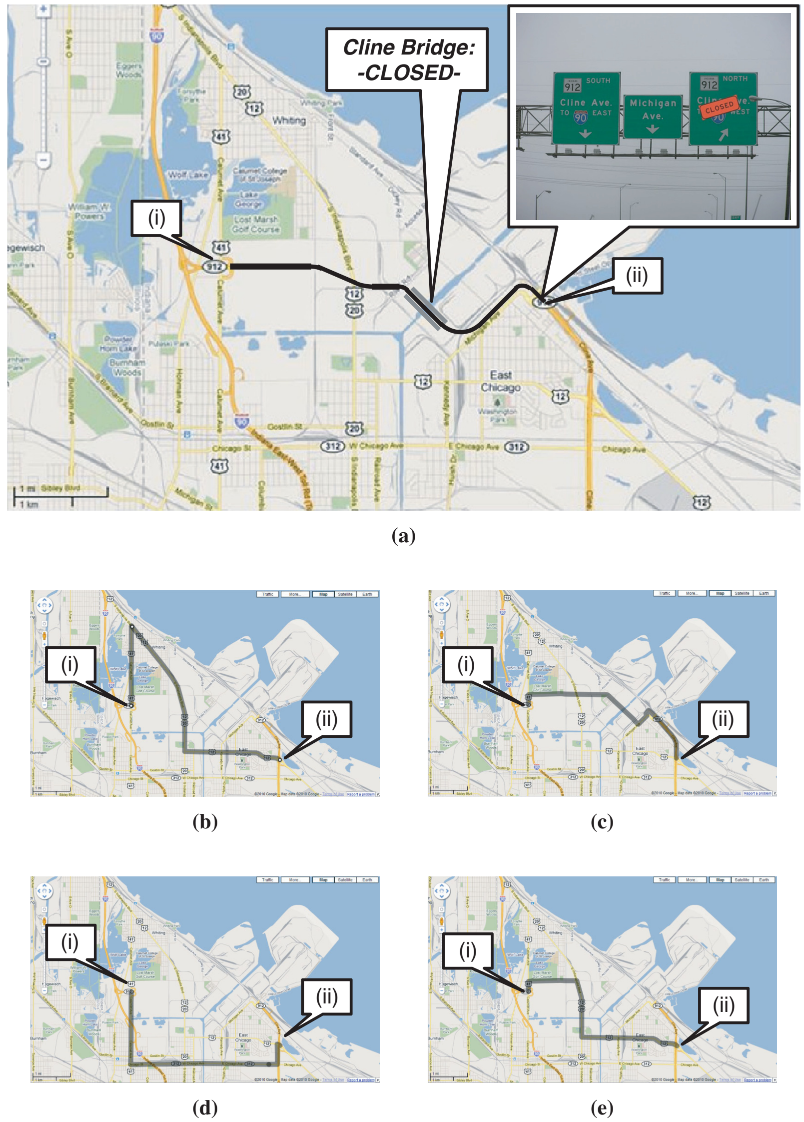


FIGURE 1 Study area [(i) = west end of Indiana SR 912 detour junction and (ii) = east end of Indiana SR 912 detour junction]: (*a*) Indiana SR 912 before Cline Avenue bridge closure, (*b*) Indiana DOT official detour, (*c*) unofficial route, (*d*) local route, and (*e*) hybrid route.

SAMPLING TECHNOLOGY AND STRATEGY

Rather than a model of the network impact using traditional planning analysis tools, a field sampling technique was used to assess route choice and travel time. Traditional techniques such as videotaping of license plates would have provided high-quality data but were cost-prohibitive. A lower-cost alternative technique based on matching unique media access control (MAC) addresses from Bluetooth-enabled devices was used (*6–8*).

In March 2010, preliminary Bluetooth monitoring stations (BMSs) were deployed to assess travel time characteristics on four critical routes, as shown in Figure 1. These routes are referred to as the Indiana Department of Transportation (DOT) official detour route (Figure 1*b*), the unofficial route (Figure 1*c*), the local route (Figure 1*d*), and the hybrid route (Figure 1*e*). Preliminary investigation and discussions with state and local officials resulted in development of a detailed data collection plan for deploying BMS stations at 12 locations to record unique identifiers for vehicles on the four routes for the period of May 7 to May 17, 2010. The BMS locations are shown in Figure 2. Segments between adjacent BMS locations are referred to as links. A link is identified by the numbers of the BMS at each end of the link. Figure 3 shows a battery-powered BMS station that houses the receiver. Routes were described by one or more links, depending on the complexity and location of the route in conjunction with the field-deployed BMS.

The Bluetooth data collection units record the time stamps of unique MAC addresses associated with consumer electronic devices within passing vehicles. MAC addresses are unique 48-bit addresses that are assigned by manufacturers of many consumer electronic devices such as cell phones, laptops, hands-free headsets, MP3 players, and GPS devices that have Bluetooth capability. These time-stamped MAC addresses can then be matched between data collection stations. For example, if MAC address “00:15:b9:6f:e2:16” were observed at BMS-16 at 14:00:05 and subsequently observed at

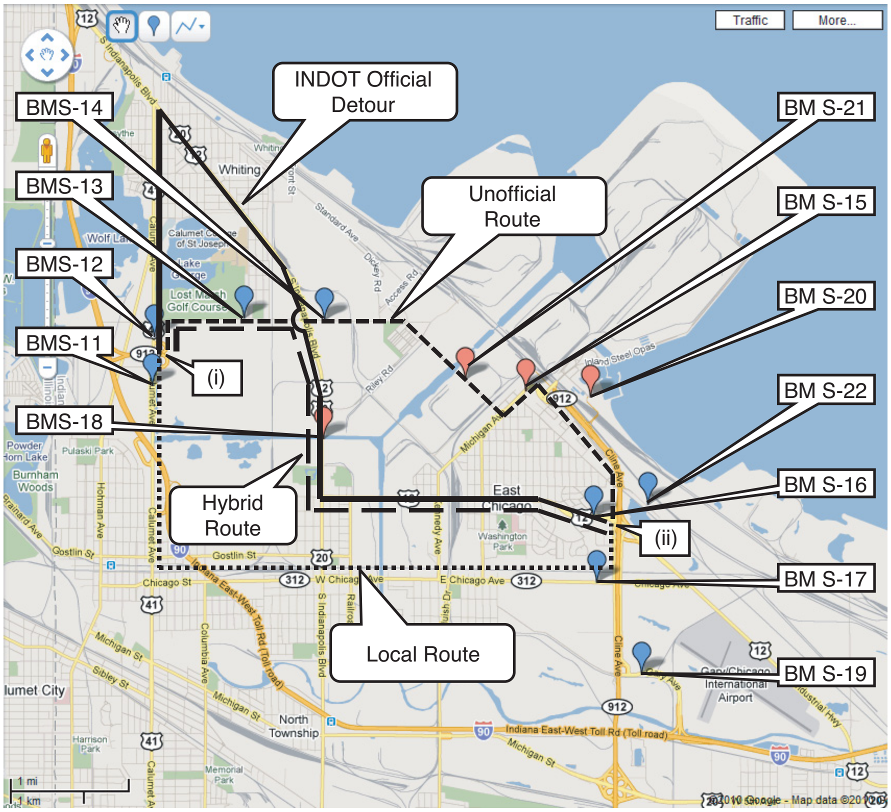


FIGURE 2 Placement of BMS to capture traffic routes between (i) west end and (ii) east end of Indiana SR 912 (INDOT = Indiana Department of Transportation).

BMS-18 at 14:05:11 (Figure 2), one would estimate the link travel time between those points to be 5 min 6 s (306 s).

Travel Time Information

By applying this matching technique to station pairs of interest in Figure 2, high-quality estimates of travel time can be derived for BMS pairs (*6, 7*). Table 1 provides insight into which BMS pairs had relatively high (and low) match rates. For example, a high number of matches were observed between BMS-11 and BMS-12 as well as between BMS-12 and BMS-11 (4,766 and 4,773, respectively). A plot of the travel time for this half-mile segment over the course of the week is shown in Figure 4. One very short-duration, nonrecurring congested period is shown just after 6:00 p.m. on May 7, 2010.

Figure 5 shows an example of a link with an increase in travel time for a short duration during the a.m. and p.m. peak periods on a few of the weekdays between Stations BMS-15 and BMS-21. These short-duration increases in travel times are associated with changes in shifts at local industrial plants. Also, what might look like additional delay attributable to higher traffic volumes might be caused by drivers with Bluetooth-enabled devices who pass by one BMS location, stop at a local business and enter, and then continue down the road past a second station. This type of operation will be plotted as a longer travel time and could be incorrectly interpreted as delay. Aside from these two pairs of BMS locations near the local plants, there were no other indications of increases in travel time that could be attributed to substantial congestion along any of the four alternate routes evaluated.

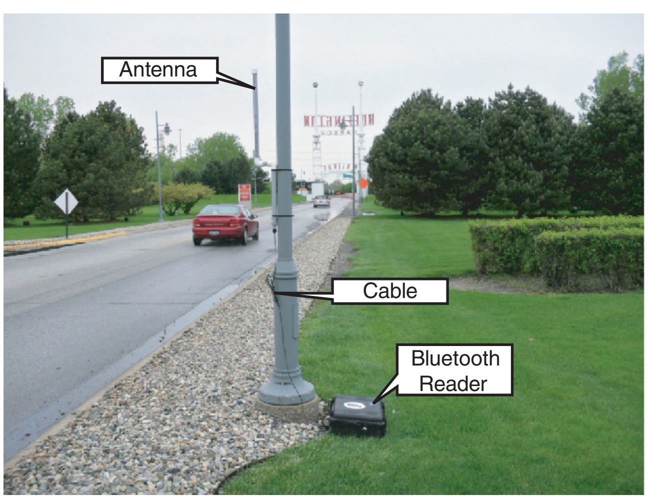


FIGURE 3 BMS placed on light pole.

Travel Patterns

To address the second objective, which was to identify BMS pairs that had significant traffic between them, a summary origin–destination table with the total number of MAC address matches for each BMS pair was created as shown in Table 1. The number of MAC address matches was used as an approximate indicator of the relative traffic volume between stations but did not provide route choice information. These matches were only a relative indicator of traffic

TABLE 1 Number of Matches Between Bluetooth Stations, May 9 and May 15, 2010

	Destination											
Origin	BMS-11	BMS-12	BMS-13	BMS-14	BMS-15	BMS-16	BMS-17	BMS-18	BMS-19	BMS-20	BMS-21	BMS-22
BMS-11	—	4,773	789	437	89	95	138	131	97	77	108	73
BMS-12	4,766	—	944	555	137	113	114	182	67	76	181	84
BMS-13	646	788	—	929	259	124	40	286	17	87	368	76
BMS-14	311	404	837	—	778	324	137	963	65	258	1,168	190
BMS-15	85	139	307	1,149	—	392	455	183	456	483	2,557	176
BMS-16	52	77	118	440	309	—	1,164	1,353	692	580	248	940
BMS-17	58	49	16	108	200	491	—	117	846	197	158	228
BMS-18	128	165	290	1,129	79	1,300	215	—	77	237	108	329
BMS-19	66	44	23	161	484	768	612	111	—	551	358	510
BMS-20	29	41	75	316	439	765	383	261	460	—	325	295
BMS-21	89	149	380	1,476	2,064	273	296	116	269	288	—	160
BMS-22	30	33	52	190	214	1,036	296	324	470	450	162	—

volume, because only 7% to 10% of passing vehicles had discoverable Bluetooth MAC addresses (*8*).

Also, sampling bias may have been introduced because of slight variations in the setback and height of the BMS from the roadway (*8*). With any sampling approach, there are always opportunities to introduce bias. This sampling approach assumes that the Bluetooth-enabled devices are randomly distributed across various vehicle types, demographics, commercial purposes, and so forth. For example, vehicles with multiple Bluetooth-enabled devices (perhaps representing affluent individuals) may affect the measured travel time. The strength of the device, the height of the vehicle, and the location of the device within the vehicle all have an opportunity to influence the amount of devices discovered. Despite these potential biases, Bluetooth MAC address matching provides a much more cost-effective mechanism for capturing route choice information than traditional license-plate-matching techniques.

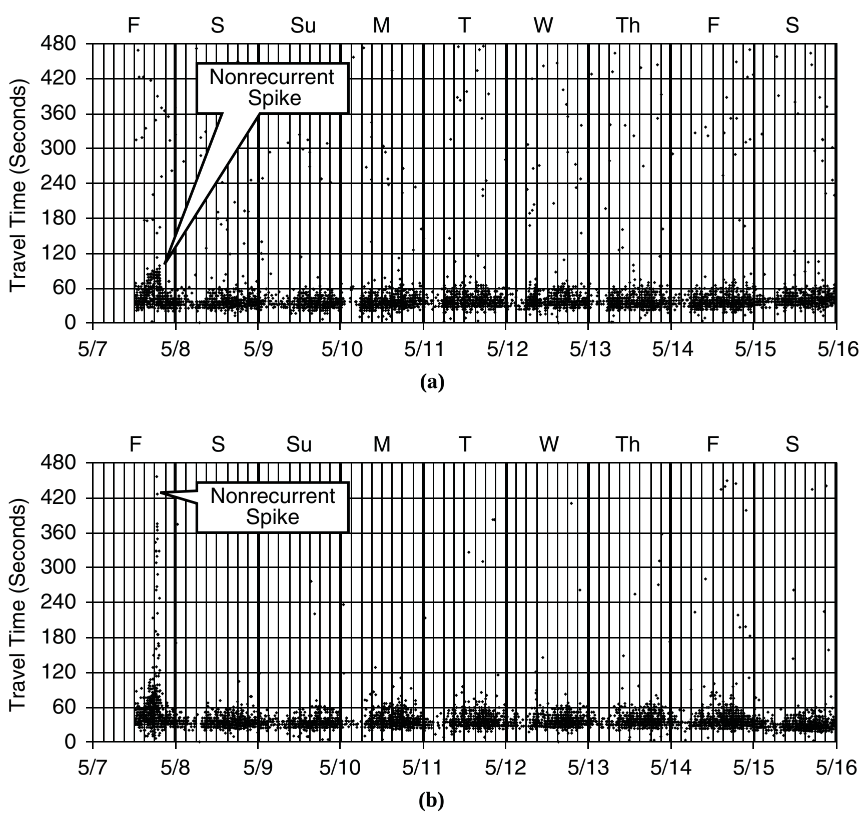
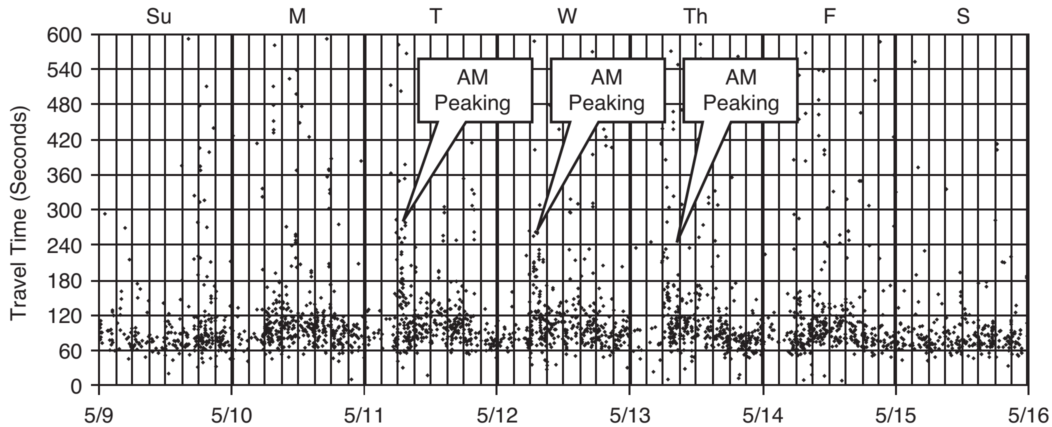
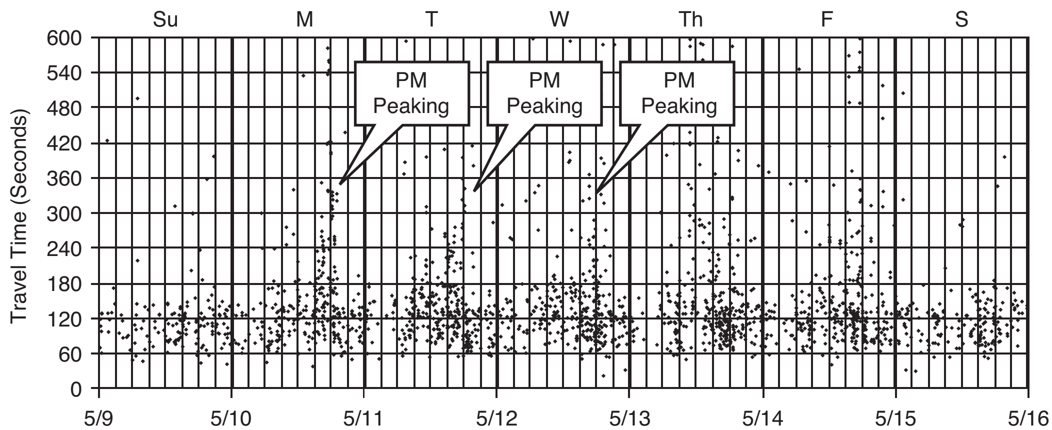


FIGURE 4 Travel times (s) showing example of nonrecurrent congestion: (*a*) northbound (Stations BMS-11 to BMS-12) and (*b*) southbound (Stations BMS-12 to BMS-11).



(a)



(b)

FIGURE 5 Travel times (s) showing congestion during peak periods due to local plant shift change: (*a*) westbound (Stations BMS-15 to BMS-21) and (*b*) eastbound (Stations BMS-21 to BMS-15).

Route Choice

To address the third objective, which was to estimate the distribution of traffic on the four alternate routes, the link data were combined to describe the routes of interest. By creating queries in the structured query language database for conditionally matching BMS locations, the routes could be described by a series of links inclusive or exclusive of BMS. Figure 6 shows a schematic example of the Indiana DOT official detour. This route includes Bluetooth MAC address matches between any BMS in Group a to any BMS in Group b with the condition of being detected by the BMS at Group c. To further distinguish between this route and the hybrid route, another condition was used in which vehicles that were detected by the BMS at Group d were excluded, to indicate that vehicles did not utilize the stretch of road where BMS-13 was located. The other three routes were described with similar conditional statements.

Once these travel times were associated with a route, Figure 7 was generated to compare the 25th, the 50th, and the 75th percentile travel times. The 25th and 75th percentiles provide a convenient mechanism for filtering outliers caused by either excessive speed or stops associated with trip chaining or other activities. In addition, the spread between the 25th and 75th percentile is called the interquartile range and can serve as a travel time reliability indicator.

An example of how these percentile travel times were calculated for the eastbound local route on Monday through Friday (Figure 7*a*) is derived from the cumulative frequency diagram for that route shown in Figure 8. For example, the 25th, 50th, and 75th percentile values of 12.2, 14.8, and 19.9 min (Figure 8) are plotted in Figure 7*a*, with 12.2 and 19.9 min defining the limits of the interquartile range (indicated by the bar) and 14.8 as the mean (indicated by ×) for Monday through Friday on the local route.

The route choice proportion for each route is shown below each route in Figures 7*a* and 7*b*. For example, Figure 7*a* shows that 57.4% of the eastbound motorists selected the local route. Comparing the route choice percentage on each route with the magnitude of the travel times provides an opportunity to check for validity of the assumption that the route with the lowest travel time would have the largest percentage of traffic. In this case, the local route had nearly the shortest travel time and the largest percentage of diverting traffic for both directions. The corollary to this concept is also shown in Figure 7: the Indiana DOT official detour has the largest measured travel time and the lowest utilization rate for both directions.

Unfortunately, with the rapid and unforeseen closure of the bridge, it was not possible to collect travel times before the closure. Travel times as suggested by Google were an alternative used in place of field-collected data. Although this choice is not perfect, it does suggest that travel time equilibrium was maintained.

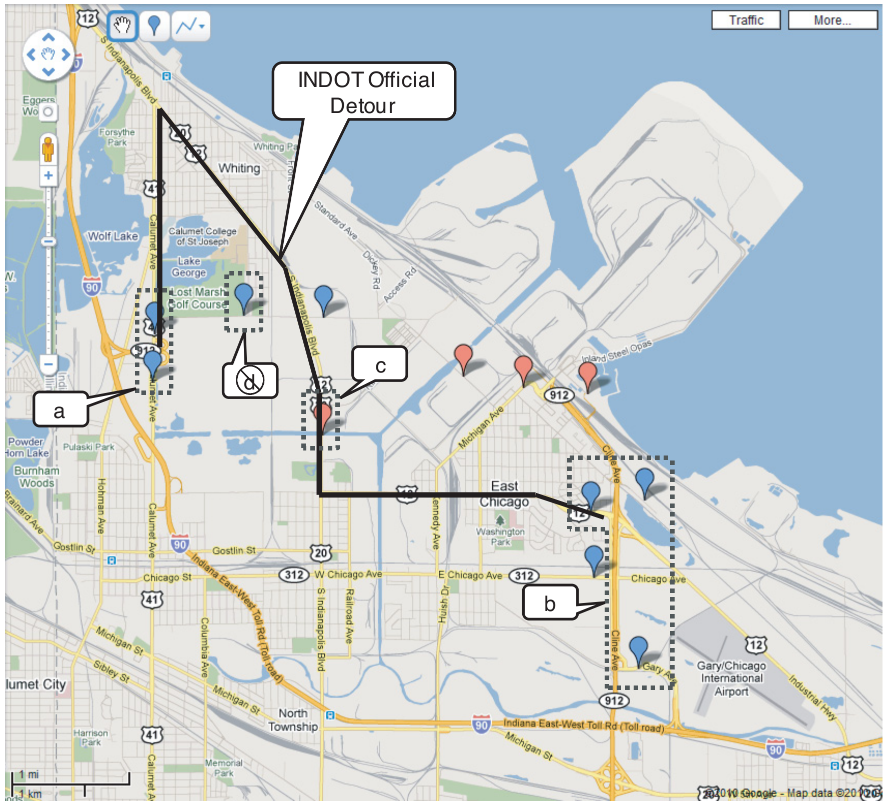


FIGURE 6 Bluetooth station groups used to describe Indiana DOT official detour: (*a*) westbound (Stations BMS-15 to BMS-21) and (*b*) eastbound (Stations BMS-21 to BMS-15), and (*c*) Station BMS-18 only.

OBSERVATIONS

Travel time plots between all 12 BMS pairs were generated, resulting in 132 travel time plots (12 ∗ 12 − 12). The plots showed almost no substantial increases in travel times, indicating acceptable performance on the links. Figure 4 shows an example of a nonrecurrent substantial increase in travel time in both directions between BMS-11 and BMS-12, although the delay is more significant in the southbound direction. The isolated nature of the travel time increase implies that it is associated with a nonrecurrent event, such as a crash or a disabled vehicle, rather than a recurring or systematic problem.

As one would expect, an examination of the number of Bluetooth MAC address matches between every pair of BMS locations (Table 1) showed match rates varying in a roughly inverse proportion to distance. For example, the number of matches between BMS-11 and BMS-12 is high because this pair of BMS locations are in close (although not overlapping) proximity. The other pair of BMS locations with a high number of matches were BMS-15 and BMS-21, which captured the traffic associated with the local plants, as previously discussed.

The route choice analysis in Figure 7 indicated that the majority of the diverting traffic (57% eastbound, 44% westbound) used the local route (Figure 1*d*). With regard to the unofficial route (Figure 1*c*, 14% eastbound, 18% westbound) the Bluetooth MAC address matches between the individual link from BMS-15 to BMS-21 include both base traffic and traffic diverting from the closed bridge; this link had 4,321 MAC address matches between May 9 and May 16, 2010, whereas the entire unofficial route that includes this link only had 62 MAC address matches during the same time period. So although Figure 7 indicates that between 14% and 18% of the diverted traffic chose the unofficial route, it is estimated that this diverted traffic only included about 2% of the traffic on this segment. Also, although Figure 5 exhibits some modest morning and afternoon congestion, diverting traffic is unlikely to be a huge contributor to the congestion.

Another interesting finding was that the majority of drivers did not use the official detour but apparently selected their routes on the basis of either local knowledge or perhaps information provided by a mapping program or GPS navigation system. This finding emphasizes the importance of analyzing all reasonable routes in a route choice study. Originally, only the official detour (Figure 1*b*) and the unofficial route (Figure 1*c*) were considered when potential routes that diverting drivers might take were being chosen. Subsequently, two BMS locations were used to define the local route. Figure 7 shows that although the hybrid route has a shorter median travel time than the local route, the local route is still the most used (57% eastbound, 44% westbound). Similarly, although the Google-estimated travel times for the official route and the local route are approximately equal (as shown in Figure 7), the local route is utilized by more than six times as many drivers as the official route. Both of these results illustrate that although many planning methods assign traffic loads to alternate routes on the basis of the travel time, factors other than travel time can substantially influence motorist route choice decisions. Furthermore, even if travel times are used to assign traffic, it may be difficult to select a single travel

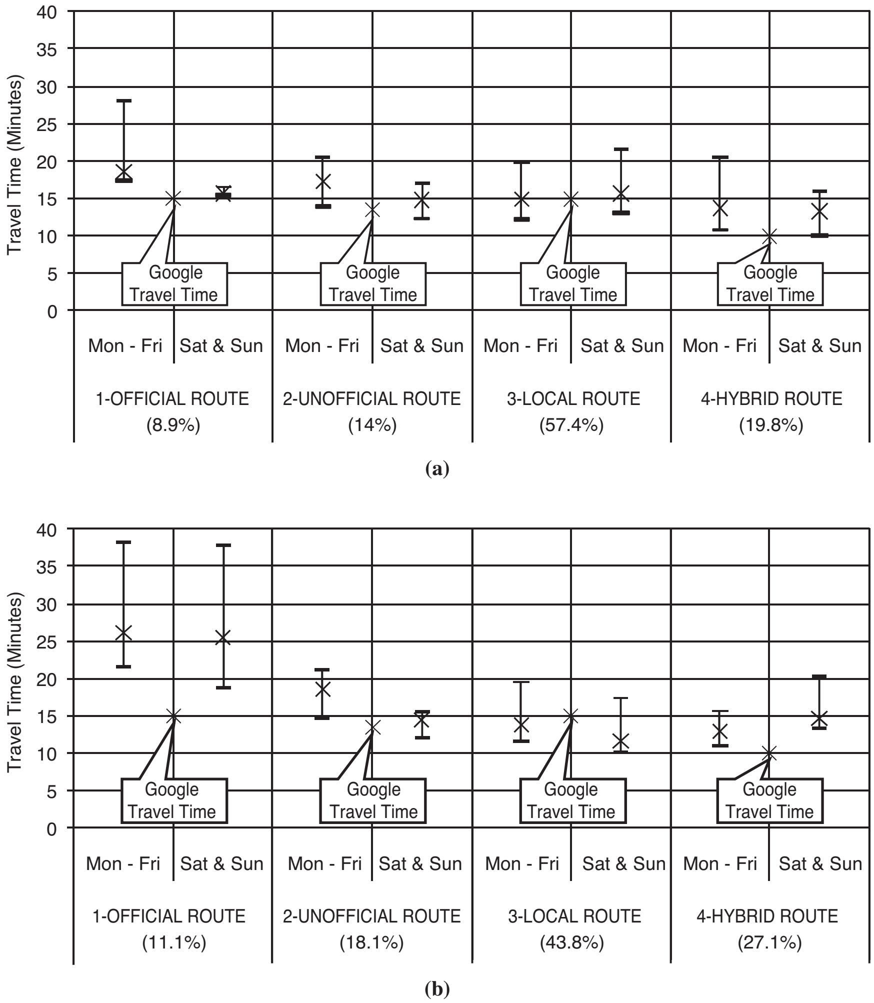


FIGURE 7 Measured 25th, 50th, and 75th percentile travel times between May 10 and May 14, 2010: (*a*) eastbound route and (*b*) westbound route.

time for any given route, since travel times may vary significantly throughout the day, as shown in Figure 5. All of these factors confirm the value of collecting travel time and route choice information by using a methodology such as the one described here rather than by relying on the results of models that are based on assumed travel times.

CONCLUSIONS

The results of this study illustrate the viability of utilizing data obtained from Bluetooth technologies to assess operations after an unexpected bridge closing in northwestern Indiana. The Bluetooth data were successfully used to assess travel times on four alternate routes. Although the Bluetooth data did successfully capture isolated occasional congestion, analysis suggests that the brief periods of congestion observed on links were due to local traffic rather than to traffic that diverted from the closed route.

The Bluetooth data were also successfully used to estimate distribution of traffic on the four alternate routes. The data indicated the following distribution of traffic: only 9% of drivers took the official Indiana DOT detour along state routes (Figure 1*b*), 20% of drivers took the hybrid route (combination of official route and unofficial route), 57% of drivers took the local route, and 14% took the unofficial route. These findings illustrate that Bluetooth technology can be used to successfully capture route choice for detours. The fact that relatively few drivers took the official detour may be explained by the observations of travel times, which indicate that the official detour may be substantially longer than the other alternate routes at some times of day.

The success of this project suggests that Bluetooth technology and this methodology are appropriate for use in the future. This study emphasizes the importance of instrumenting all reasonable alternate routes and giving careful consideration to placement of Bluetooth receivers for maximum utility of data. Ideally, to enhance the comparisons with the baseline conditions, it would be preferable to collect data before a closure; this collection would be practical for a planned construction detour but is obviously not feasible in the event of an unexpected bridge closure. The use of Bluetooth probe data is continuing to have increasing applications in transportation, and this research has successfully documented its utility for verifying operating conditions and for providing meaningful and cost-effective information regarding route choice.

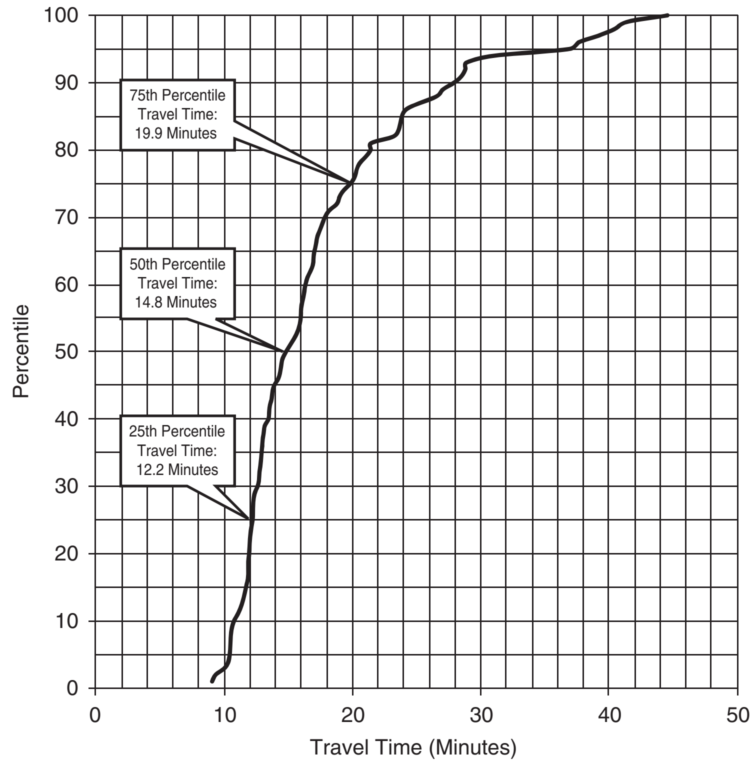


FIGURE 8 Cumulative frequency diagram for weekday (Monday–Friday) eastbound travel time on local route between May 10 and May 14, 2010 (sample size = 117).

Although a technique for using Bluetooth probe data to assess route choice decisions was demonstrated and documented, it would be desirable to conduct a comparison of the Bluetooth probe data technique with traditional license-plate-matching techniques in a future research effort.

ACKNOWLEDGMENTS

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