BLUETOOTH VEHICLE RE-IDENTIFICATION FOR ANALYSIS OF WORK ZONE DIVERSION

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Key words: Bluetooth, work zone traffic control, diversion, path choice

Word Count: 4402 words + 4 figures + 7 tables = 7152 words

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Abstract. Bluetooth vehicle re-identification technology has potential to improve understanding of driver route choice behavior associated with work zones. The Wisconsin Department of Transportation and the Smart Work Zone Deployment Initiative commissioned work zone diversion studies at four sites: two urban and two rural. Several Bluetooth detectors were deployed in pairs, triples and quadruples to help identify differences in route choice with and without lane closures. In spite of relatively low (and variable) detection rates, comparisons of the number of vehicles using specific routes during closure and non-closure periods revealed differences in driver behavior in urban vs. rural work zones. These techniques provide field data that can supplement conventional methods for estimating work zone diversion. The accuracy of the method can be expected to increase as the number of vehicles with onboard Bluetooth devices rises and Bluetooth detection technology continues to improve.

INTRODUCTION

Over the past decade US state highway agencies have devoted considerable resources to reducing and mitigating driver delays associated with highway construction. The selection of appropriate traffic mitigation strategies requires good estimates of the traffic volume in the work zone, which in turn depend on the amount of traffic that can be expected to divert to alternate routes. Unfortunately, methods for accurately estimating diversion have not been adequately addressed either in the professional literature or in practice.

Drivers can attempt to avoid freeway work zone congestion in a number of ways. A driver could exit the freeway, use parallel roads to bypass the work zone, and re-enter the freeway. Alternatively, a driver whose trip begins on a route that parallels the freeway could remain on that route until past the work zone, and then enter the freeway. Or a driver could use alternate routes for the entire trip.

Additional field studies could improve understanding of work zone driver behavior, but field studies often have difficulty identifying driver route choices and their effects on traffic volumes and travel times on the original and alternate routes. Automated Vehicle Identification (AVI) technologies such as Bluetooth detection provide opportunities to analyze route choices but have seldom been deployed to assess work zone diversion.

In 2011 the Wisconsin Department of Transportation (WisDOT) and the Smart Work Zone Deployment Initiative commissioned studies of work zone diversion at four sites: two urban and two rural. For these studies the authors utilized Bluetooth detection in combination with driver surveys, video observation, speed and volume detection, and floating car runs.

In this context, Bluetooth is a vehicle re-identification strategy based on passively reading and recording an electronic identifier called the Media Access Control (MAC) address. In wireless digital networks the MAC address serves as a unique identifier for each node (for example, a printer can distinguish between two computers and a digital camera). Traffic engineering applications exploit the fact that in-vehicle Bluetooth devices in "discovery mode" periodically transmit their MAC addresses, thus a Bluetooth device observed at one location can often be re-identified at subsequent locations, providing insight on travel time and route.

When Bluetooth detectors are deployed in pairs, trip times can be computed from the time differential between observations. With three or more detectors it becomes possible to infer route choices. Nevertheless, relatively few vehicles currently have detectable Bluetooth devices aboard, and not every device will be observed at every detector (Bluetooth devices go out of discovery mode and stop transmitting MAC addresses while they are being used). Consequently the "hit rate" is affected by the number and spacing of detectors and the possible existence of unmonitored highway access points.

Although the purpose of the work zone diversion studies was not to evaluate the technology itself, our experiences with Bluetooth forced us to address several questions:

- Are there technological or institutional limitations to Bluetooth that would prevent obtaining useful results on driver path choice?
- Are there any unusual steps required to analyze driver path data that is not part of a typical Bluetooth detection application?

- What types of results could others expect to obtain by deploying Bluetooth for path choice studies?

BACKGROUND ON WORK ZONE DIVERSION AND QUEUING

In Wisconsin, Horowitz et al. *(1)* conducted a study where an Advanced Traveler information System (ATIS) was giving travel time and speed to the end of the work zone. The diversion rate was nearly 10%. They concluded that the reasons for failing to divert to an alternate route under ATIS probably related to the reported amount of delay and lack of knowledge of alternate routes, which should be taken into account in future studies. Horowitz and Notbohm *(2)* conducted a different study in Green Bay, Wisconsin, where an ATIS was giving drivers information about the actual speeds ahead. Diversion from the work zone was substantial, resulting in a 36% reduction in mainline volume just ahead of the taper of the work zone.

A summary of the empirical diversion rates at rural work zones was compiled by Song and Yin *(3)*. In general the results suggest that the amount of diversion is a function of congestion severity and the specificity of the information provided about the alternate route.

Very few empirical studies have estimated diversion rates at urban work zones, due to the complexity of urban road networks. Zhang et al. *(4)* conducted empirical diversion analysis for the I-15 Devore and I-710 Long Beach freeway reconstruction projects in California. They found that most diversions happen only during peak time periods and noted a gradual traveler adjustment process over the project duration.

Chen et al. *(5)* studied four short-term work zones in Milwaukee and focused on a hybrid process (micro-simulation and logistic regression) to imitate diversion behavior upstream of work zones. The process looked at the presence of exit and entrance ramps combined with queuing. The field results showed a significant decrease in volume on entrance ramps (by up to 40%), and an increase, by as much as 12%, in exit ramp volumes. The diversion algorithm had good performance, but like other modeling, needs further research and validation before it can be integrated into a work zone planning tool. Qin et al. *(6)* further looked into the dynamics of traffic demand for short-term work zones. According to the Pearson correlation test, the following factors had a significant impact in drivers' decision to divert:

- Density of signalized intersection along the arterial route;
- Speed difference between normal and work zone conditions;
- Historical mainline traffic; and
- Alternate route distance.

Several computer programs estimate work zone queuing and diversion, but all suffer from scarcity of field data for calibrating their influencing parameters. Quadro, QUEWZ (Queue and User Cost Evaluation of Work Zones), and QuickZone are quasi-commercial software products providing numerical queue length estimates. Quadro *(7)* uses two-link equilibrium travel times and queuing theory to allocate vehicles between "main" and "diversion" routes. The QUEWZ *(8)* algorithm was created by the Texas Transportation Institute in Texas, where many freeways have frontage roads (frontage roads are less common in other states). QuickZone *(9)* is a traffic-network based tool, which can include up to two alternate routes. In an urban setting, the tail of queue must reach the diversion point before diversion takes place, which does not account for natural diversion. In a rural setting, the travel time on QuickZone's alternate route must be shorter than the original route for diversion to occur.

Another technique combines shock wave theory, an energy model, and a mathematical analogy to compute traffic queues *(10)*. The analogy consists of flow through a permeable pipe and traffic with lane closures. The flow across the permeable medium is perceived as diverted traffic. Shock wave theory is used to model the dispersion of traffic characteristics, like queues and reductions of speed, upstream of the work zone. The energy model of traffic flow is used to define the physics as the analogy relates to traffic: the queue length (and reduction in speed) creates a pressure, which represents natural diversion near the work zone. The mathematical analogy represents the urban corridor as the fluid flow through a section of the permeable pipe, where a specific corridor permeability coefficient accounts for dissipating traffic flows. In order for concepts like these to be implemented as a work zone analysis tool, more research needs to be done to address the factors that affect the "permeability" of a freeway.

Another attempt to estimate queue lengths was done by Chitturi and Benekohal *(11)* based on a previously proposed methodology *(12)*. Queue lengths were estimated considering the effects that roads and traffic have on speeds. Cars and heavy vehicles were analyzed separately because heavy vehicles were found to travel about 5 mph slower.

CONCEPT OF BLUETOOTH DETECTION FOR WORK ZONE PATH CHOICE

For this study WisDOT arranged for the authors to use several TrafficCast BlueToad detectors. The devices were equipped with cellular modems and solar panels, which provided reliable energy during the (summertime) data collection period. The system uses mobile telephony to upload raw vehicle observation data to a server where proprietary matching and filtering algorithms are applied. Processed data were then downloaded from the server in hourly time increments.

Path choice analysis requires deploying detectors in groups of three ("triples") or four ("quadruples"), but at the time of the study TrafficCast's software was only able to supply matches for detector pairs. The authors created software (Figure 1) to estimate triples and quadruples from the pair data. Table 1 shows how the software recognized triples given two sets of pairs. Quadruples could also be assembled from three sets of pairs.

FIGURE 1 Screenshot of the Software Used to Create Triples Given Pairs

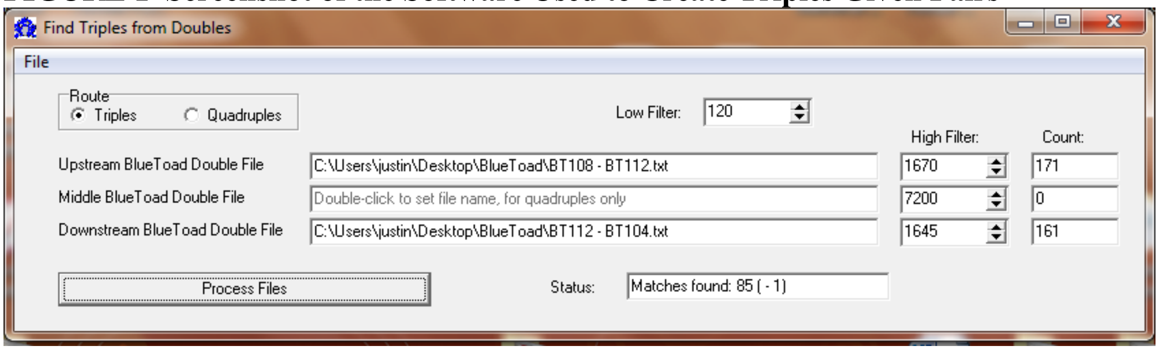

TABLE 1 Example of How the Software Recognizes Triples Given Pairs

BT1 – BT6		BT6 – BT11		
Travel Time	BT6	Calculated BT6	Travel Time	BT11
2341	2:20:22	1:34:35	2075	
1719	2:30:43	2:30:43	2188	
2465	2:58:14	3:20:18	2236	

Triples were estimated by matching time stamps at the middle detector of each triple. TrafficCast assigns the time stamp to the downstream detector of a pair, so the upstream time stamp was calculated from the travel time. Filters were applied to remove pairs where drivers made a stop exceeding 5-10 minutes (the threshold varied based on detector spacing).

False positive triples were possible because of a relay between two different vehicles. As in a foot race, a relay occurs when a vehicle is seen at the first and second Bluetooth detectors; a second vehicle is seen at the second Bluetooth detector at exactly the same time as the first vehicle, and the second vehicle proceeds to the third Bluetooth detector, while the first vehicle does not. Since time stamps are accurate to the nearest second, the two most likely situations for a false positive are (1) two vehicles side by side in adjacent lanes or (2) two vehicles moving in opposite directions on the same road. The software could estimate the false positive rate, even though it could not identify specific false positives. Such false positives were found to be unlikely, principally because the hit rate was low. For the example in Figure 1, the estimated number of false positives is shown as a negative number in the Status box. Among of the 171 upstream pairs and 161 downstream pairs in Figure 1, there were an estimated 85 triples with an expected value of 1 false positive among all the triples. False positives could have been avoided entirely if the database contained a unique identifier for each vehicle (as is possible in some competing Bluetooth detector products), but TrafficCast suppressed the MAC addresses to avoid any privacy concerns.

Another issue that has not been completely resolved to our satisfaction is the possibility of speed bias: an increased probability of detecting Bluetooth device in slow-moving vehicles. During discovery mode, Bluetooth devices generate an inquiry hopping (channel changing) sequence using a 32-channel subset of the available 79 Bluetooth channels. As noted by Woodings et al *(13),* in a strict implementation of the Bluetooth specification a full 32 channel scan requires 10.64 seconds. Consequently, detection time is random according to a uniform probability distribution.

Our BlueToad units were supplied with omnidirectional antennas with an estimated detection radius of 150 feet and were generally installed in the freeway median. Therefore, under ideal conditions a vehicle travelling at 65 mph would be in the range of the detector for approximately 3.1 seconds, whilst a 25 mph vehicle would occupy the detection zone for 8.2 seconds. Consequently, detection rates might increase during periods of congestion and drop during free-flow. As discussed later, checks for a speed bias were performed.

A Note Concerning Probability of Detection

Computation of detection rates requires contemporaneous collection of both Bluetooth and traffic volume data at each site. The complexity of the detection rate computation increases with the number of sites. The probability of detecting a single vehicle at a single location is the joint probability of a vehicle having an active Bluetooth device and the probability that the Bluetooth device's MAC address can be read. These probabilities should be independent. For pairs it is reasonable to assume that the conditional probability is close to 1.0 for a vehicle having a Bluetooth device at location B if it had a Bluetooth device at location A, but the same cannot be said about the probabilities of *reading* a MAC address for any device. The conditional probability of reading a MAC address at location B given that it was read at location A is considerably less than 1. Consequently, the probability of detecting a given triple in a traffic stream is considerably less than detecting a pair between two of the same locations, and the probability of detecting a quadruple is likely to be even less.

It is also necessary to assure that there are no site conditions which would result in unusually high (or low) concentrations of Bluetooth devices in the traffic stream. For example, at about the same time as our work zone studies, one of the authors was involved in an origin-destination study in Hudson WI, where one detector had an unusually high hit rate due a large number of Bluetooth-equipped vehicles entering and exiting a new car dealership.

THE WORK ZONES

Portage and Tomah Work Zones (Rural)

Portage and Tomah located in south-central and west-central Wisconsin, respectively. These work zones provided opportunities to evaluate the effects of lane closures on rural freeway facilities. Both work zones involved crossovers with two-way traffic running on one side of the roadbed, separated by concrete barriers. In Portage there were also concrete barriers near the outside (rightmost) lane.

The Portage work zone (Figure 3) was on I-39/90/94 between STH 60 and CTH CS and involved a reduction from 3 lanes to 2 in each direction. Normally traffic demand is well below capacity except on Fridays and Sundays when there is heavy tourist/recreational traffic.

The Tomah work zone (Figure 4) consisted of two freeway crossovers on I-90/I-94, one between CTH C and CTH PP and another between CTH ET and Embassy Rd. In both cases the number of lanes was reduced from 2 to 1 in each direction. Like Portage, the Tomah site operates well under capacity except on Fridays, Sundays, and holidays.

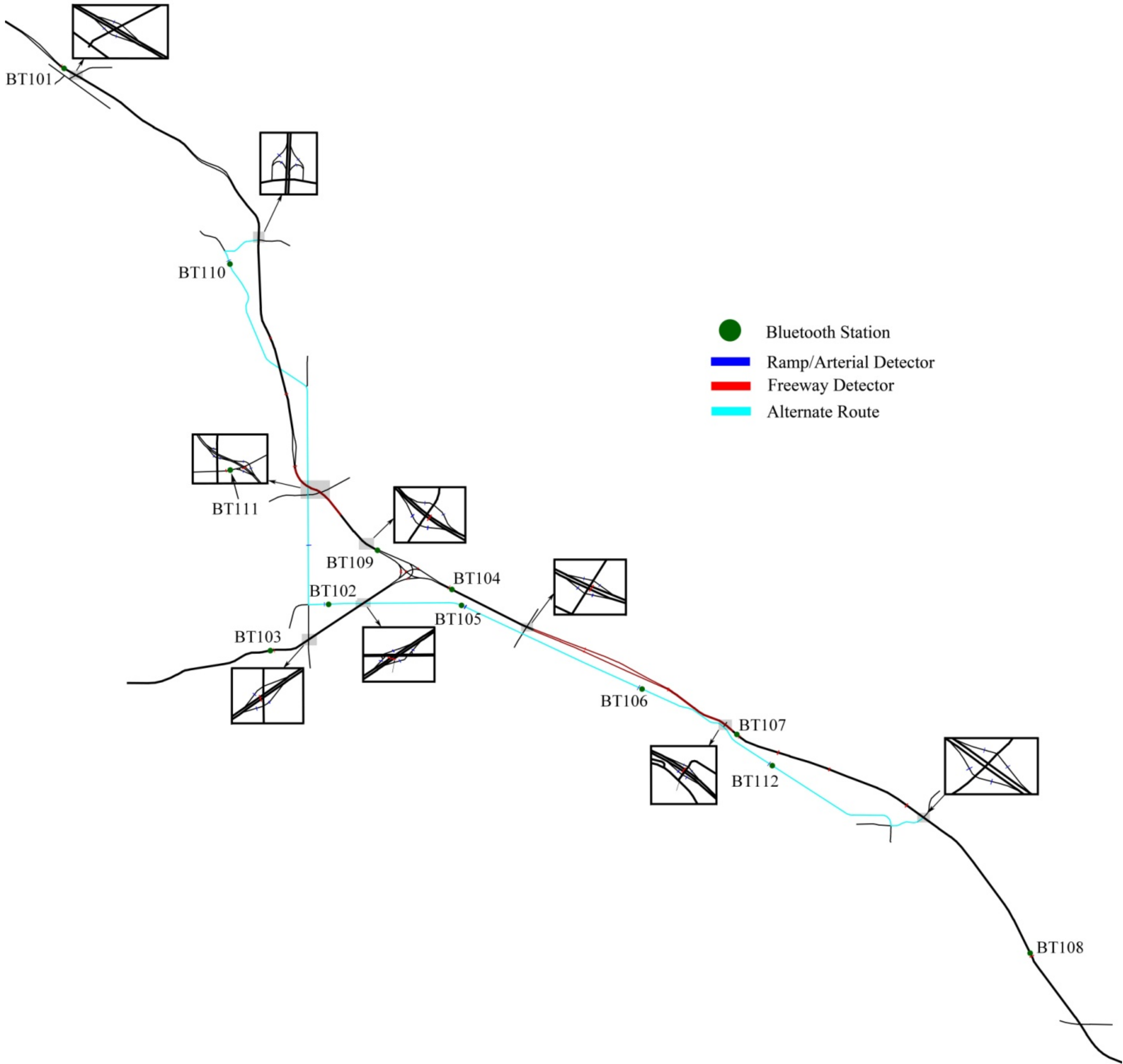

FIGURE 3 Tomah Work Zone and Bluetooth Detector Deployment

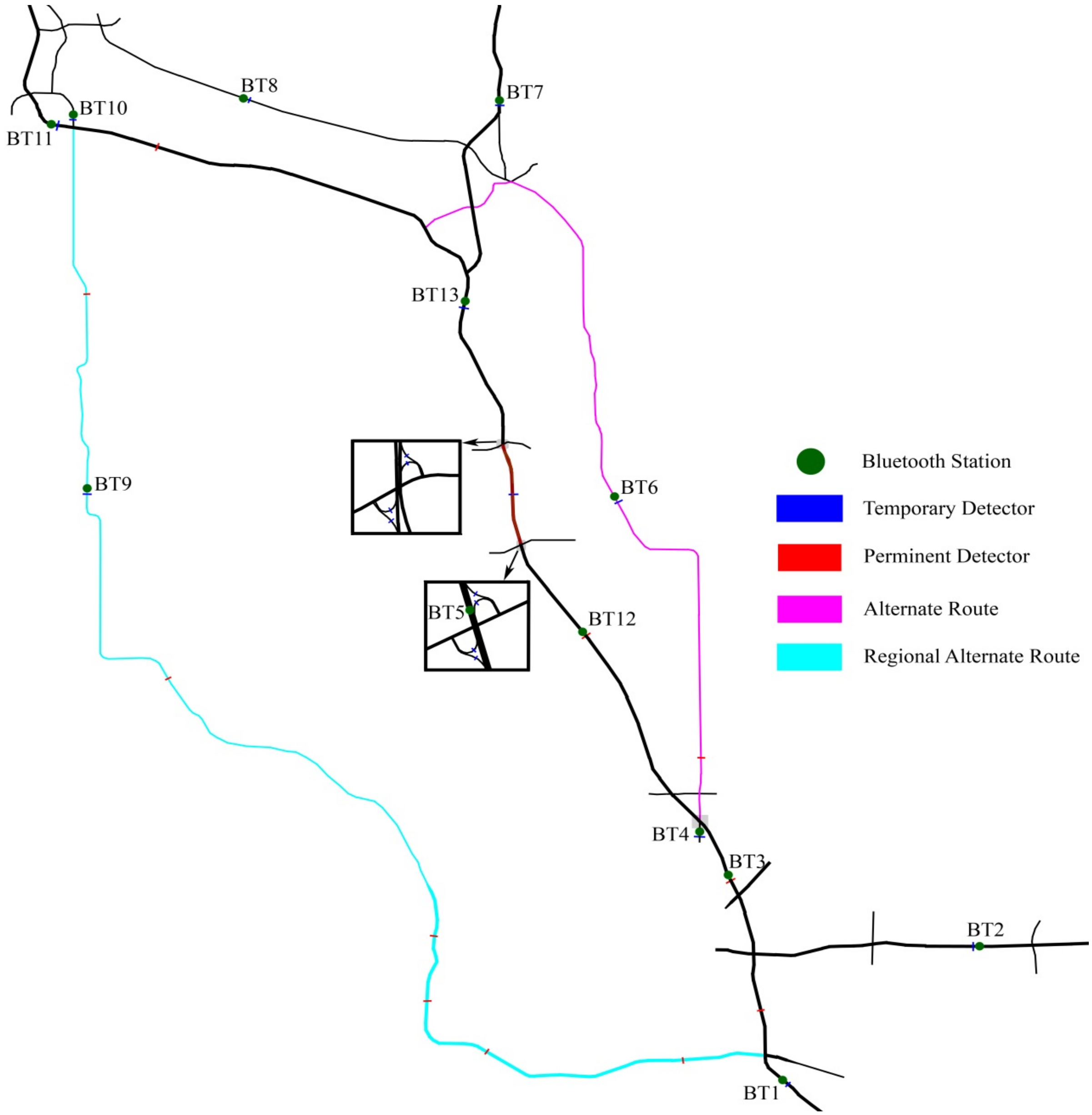

FIGURE 4 Portage Work Zone and Bluetooth Detector Deployment

Milwaukee Work Zones (Urban)

The I-94 East-West Corridor Rehabilitation Project (Figure 5) included two urban work zones: one in Milwaukee County and one in neighboring Waukesha County. The freeway normally has three lanes in each direction. Heavy weekday demand frequently results in queuing even without roadwork. A transportation management plan (TMP) developed for the project established closure locations and countermeasures intended to mitigate the anticipated congestion.

The Waukesha County repaving zone consisted of a one-lane closure (3 lanes to 2) in both directions from STH 16 to 124th Street. There were also intermittent ramp closures (mainly at night). Our empirical analysis focused on the Waukesha County work zone where the best data was available, but the Waukesha County site was influenced by upstream conditions in the

Milwaukee County repaving zone. That site had a reduction from 3 to 2 lanes between 70th and 32nd Streets, but only in the westbound direction. At the main Marquette Interchange in downtown Milwaukee, each approach was signed with advance warning of the construction. On-ramp closures were used as a mitigation technique and off-ramps were closed intermittently for repaving.

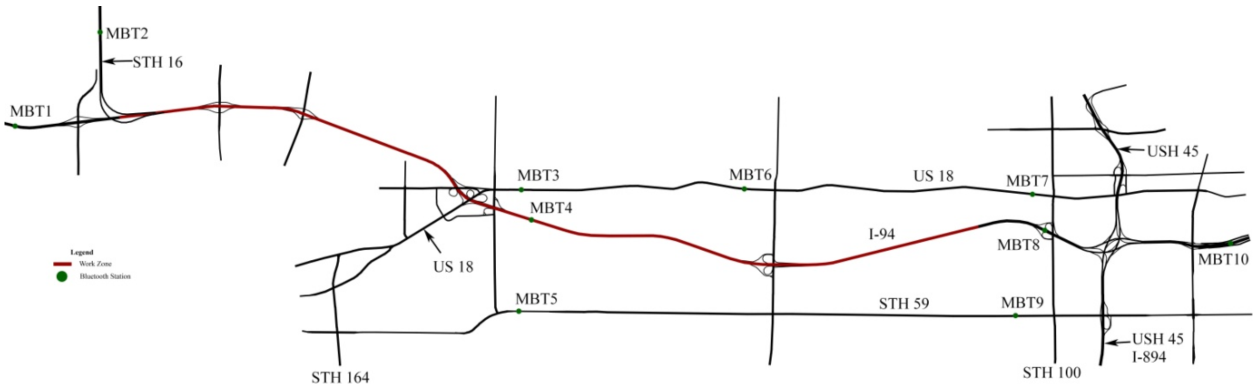

FIGURE 5 Waukesha County Work Zone Showing Bluetooth Detector Locations

Location Specific Issues

Regression analyses were performed to determine whether any unexpected local variables were influencing the number observed pairs. The regression analysis allowed these conclusions with 90% confidence:

- Higher volumes at the upstream Bluetooth detector produced a higher number of pairs.
- Distance between detectors negatively affected the number of pairs.
- A major interchange between detectors decreased the number of pairs (some vehicles exited to unmonitored locations).
- Congestion in the work zone increased the number of pairs.
- The eastbound direction produced more pairs than westbound.
- The urban setting produced fewer pairs per 1000 vehicles than the rural sites.

Speed between detectors failed to explain any variation in the number of hits, but the number of hits increased with congestion. The significance of travel direction was surprising, but might be related to the fact that there was no eastbound closure in Milwaukee County. Possible factors influencing the detection rate differences could include a higher propensity to use Bluetooth devices for longer trips, differences in the truck proportion, signal reception effects related to urban terrain and/or radio channel congestion, and/or limitations on the total number of simultaneous observations that could be processed by the detectors.

Table 2 presents some diagnostic statistics for the Tomah work zone. Pairs are listed by detector IDs. The table compares hit rate per day between closure (with the work zone) and non-closure periods and the amount of variation in the data. These results are typical of all the work zones studied. The pair hit rate varies considerably from day to day, usually by a factor of two across all days, and the amount of variation increases with construction activity.

TABLE 2 Bluetooth Pairs for the Tomah Work Zone

		Non-Closure			Closure		
Location	Distance (miles)	Hits (Avg.)	Hits/Vol (Low)	Hits/Vol (High)	Hits (Avg.)	Hits/Vol (Low)	Hits/Vol (High)
WB							
BT108 - BT107	12.5	569.2	3.0%	4.8%	295.6	0.8%	4.4%
BT108 - BT104	22.3	640.9	3.6%	5.4%	579.6	2.7%	5.7%
BT107 - BT104	9.8	673.7	3.4%	5.7%	344.4	1.1%	4.6%
BT104 - BT101	20.2	475.9	2.6%	3.7%	300.1	1.5%	2.6%
BT104 - BT109	2.0	321.1	1.5%	2.6%	238.6	1.5%	2.8%
BT104 - BT103	7.6	203.4	0.9%	1.9%	188.9	0.9%	2.0%
BT103 - BT109	7.9	44.4	0.3%	1.7%	49.9	0.2%	1.7%
EB							
BT103 - BT104	7.6	143.6	1.6%	2.3%	230.3	1.8%	5.6%
BT104 - BT107	9.8	506.0	2.2%	4.5%	324.4	0.8%	4.6%
BT101 - BT109	18.1	295.8	2.0%	4.2%	294.1	2.8%	4.7%
BT101 - BT104	20.2	315.3	2.2%	4.4%	378.4	3.6%	5.5%
BT107 - BT108	12.5	496.8	2.3%	4.6%	266.9	0.8%	3.4%
BT104 - BT108	22.2	469.1	1.9%	4.0%	536.4	2.9%	4.7%

ANALYSIS OF ROUTE CHOICE

Detection Rates

In a few instances the detector placement virtually assured that a trip between two Bluetooth detectors must pass by a third Bluetooth detector. As shown in Table 3, these situations allow estimation of the reduction in detection rates as the number of Bluetooth detectors in a chain increases.

TABLE 3 Probabilities that a Vehicle Is Detected at a Third Location Given it Is Detected at Two Other Locations on a Single Path

Work Zone	Triple	Third Location Detection Rate
Portage, EB, Non-Closure, Freeway	BT13 - BT5 - BT12	78.7%
Portage, EB, Closure, Freeway	BT13 - BT5 - BT12	80.9%
Portage, WB, Closure, Freeway	BT12 - BT5 - BT13	80.4%
Milwaukee, EB, Non-Closure, Arterial	MBT3 - MBT6 - MBT7	83.9%
Milwaukee, WB, Non-Closure, Arterial	MBT7 - MBT6 – MBT3	77.4%
Milwaukee, EB, Closure, Arterial	MBT3 - MBT6 - MBT7	77.1%
Milwaukee, WB, Closure, Arterial	MBT7 - MBT6 – MBT3	80.4%

The Table 3 data covers 16 to 21 days of data collection, depending upon the location. There was some day-to-day variation at a single location. Third-detector daily detection rates varied from 66.7% to 100% across all the locations.

Locations vary only slightly in their average detection rates, but the probability that a vehicle is detected given that it has already been detected twice is about 80%. So if this probability were to be assumed constant across a whole chain of detections and the probabilities of detection are independent, then the probability of detecting a triple is 80% of detecting a pair and the probability of detecting a quadruple is just 64% of detecting a pair. Half the pair-detected vehicles would likely disappear within a quintuple. Higher quadruple and quintuple hit rates would be possible if an assumption of independence is not perfectly accurate.

Since the detection rates were relatively low and varied significantly from site to site, the authors were not comfortable extrapolating the available data to compute the exact number of vehicles following various routes in and around each work zone. What could be confidently accomplished was to compare the number of Bluetooth hits (pairs, triples and quadruples) during closure against those during the non-closure period. The closure and non-closure periods were designed to be similar in several attributes: number of weekend days, number of weekday days, weather conditions, season, and detector locations. The main differences between scenarios were lane closures, ramp closures and the presence of construction activities.

Tomah and Portage Work Zones

A classic type of diversion occurs when a vehicle is observed exiting the freeway, bypassing the work zone, and re-entering the freeway. Tables 4 and 5 show the triple hits for such situations. The middle Bluetooth detectors (BT6, BT105, BT106 and BT112) are on parallel routes, while the endpoint detectors are on the freeway. During the non-closure period only a small number of vehicles were observed leaving and then returning to the freeway. With just one exception, more such diversions were made during the closure periods. In Tomah, this type of diversion appeared to be less common than vehicles that avoided the work zone by entering the freeway downstream of the construction.

Although not presented in the tabular data, the number of triple hits also increased as the congestion approaching the work zones increased: drivers were noticeably responding to conditions on the ground, but it is unclear whether they were responding to congestion or making decisions based on previous trips through the work zones.

TABLE 4 Portage Diversion Bluetooth Triples

EB (SB) Alternate Route (US 51)		
Triple	Non-Closure	Closure
BT11 - BT6 - BT1	0	11
BT11 - BT6 - BT2	0	4
BT11 - BT6 - BT4	0	4
BT10 - BT6 - BT1	0	2
BT10 - BT6 - BT2	0	1
BT10 - BT6 - BT4	0	1
BT8 - BT6 - BT1	1	3
BT8 - BT6 - BT2	0	0
BT8 - BT6 - BT4	0	1
BT7 - BT6 - BT1	1	5
BT7 - BT6 - BT2	0	0
BT7 - BT6 - BT4	0	9
WB (NB) Alternate Route (US 51)		
Triple	Non-Closure	Closure
BT1 - BT6 - BT11	0	1
BT1 - BT6 - BT10	1	2
BT1 - BT6 - BT8	0	2
BT1 - BT6 - BT7	0	0
BT2 - BT6 - BT11	0	1
BT2 - BT6 - BT10	0	1
BT2 - BT6 - BT8	1	0
BT2 - BT6 - BT7	1	1
BT4 - BT6 - BT11	0	1
BT4 - BT6 - BT10	0	2
BT4 - BT6 - BT8	1	7
BT4 - BT6 - BT7	0	3

TABLE 5 Tomah Diversion Bluetooth Triples and Quadruples

WB (NB) Alternate Route (US 12) East WZ		
Triple	Non-Closure	Closure
BT108 - BT105 - BT102	3	11
BT108 - BT106 - BT102	2	8
BT108 - BT112 - BT102	0	6
BT108 - BT105 - BT109	8	14
BT108 - BT106 - BT109	2	26
BT108 - BT106 - BT104	2	64
BT108 - BT112 - BT104	3	85
BT108 - BT106 - BT105 - BT103	2	10
BT108 - BT112 - BT105 - BT103	0	5
BT112 - BT106 - BT105	46	88
EB (SB) Alternate Route (US 12) East WZ		
Triple	Non-Closure	Closure
BT102 - BT105 - BT108	3	20
BT102 - BT106 - BT108	0	63
BT102 - BT112 - BT108	0	32
BT103 - BT105 - BT108	3	40
BT103 - BT106 - BT108	0	59
BT103 - BT112 - BT108	0	61
BT109 - BT105 - BT108	13	34
BT109 - BT106 - BT108	1	48
BT105 - BT106 - BT112	47	127

The results show some diversion at the Portage work zone (a marked increase in the Bluetooth triple hits during the closure period), but the numbers are small in comparison to the Tomah work zone. In Tomah there was more diversion from the east work zone that from the west work zone, which is attributable to significantly higher volumes and delays east of the fork of I-90 and I-94.

Milwaukee Work Zones

Tables 6 and 7 show similar data for the Milwaukee work zones. The data suggest that in this location many drivers stayed on the local street system, but it was rare for drivers to exit the freeway, proceed along a parallel route, and then re-enter the freeway. While there was no eastbound work zone in Milwaukee County, a small amount of eastbound diversion nevertheless occurred, suggesting the possibility of a modest reciprocal effect for the non-construction direction.

TABLE 6 Milwaukee/Waukesha Diversion Bluetooth Triples STH 59 (EB), Greenfield Ave.

EB Alternate Route (STH 59)		
Triple	Non-Closure	Closure
MBT1 - MBT5 - MBT10	1	6
MBT2 - MBT5 - MBT10	0	7
MBT1 - MBT5 - MBT11	1	1
MBT1 - MBT5 - MBT12	0	1
MBT1 - MBT5 - MBT13	0	0
MBT2 - MBT5 - MBT11	0	0
MBT2 - MBT5 - MBT12	0	1
MBT2 - MBT5 - MBT13	0	0
MBT5 - MBT9	583	1216

Table 7 gives triple hits for diversion to US 18 (Blue Mound Road) in the westbound direction, which was affected by both I-94 work zones. Whilst there were modest increases in drivers who chose to leave and reenter the freeway, a striking number of drivers chose to use USH 18 instead of I-94, resulting in a threefold increase in the number of hits for the Bluemound Road corridor.

TABLE 7 Milwaukee/Waukesha Diversion Bluetooth Triples US-18 (WB), Blue Mound Rd.

WB Alternate Route (US 18)		
Triple	Non-Closure	Closure
MBT11 - MBT6 - MBT1	2	2
MBT12 - MBT6 - MBT1	0	7
MBT13 - MBT6 - MBT1	0	3
MBT11 - MBT6 - MBT2	0	0
MBT12 - MBT6 - MBT2	3	1
MBT13 - MBT6 - MBT2	0	3
MBT11 - MBT7 - MBT3	6	10
MBT12 - MBT7 - MBT3	9	34
MBT13 - MBT7 - MBT3	3	18
MBT10 - MBT6 - MBT1	7	15
MBT10 - MBT6 - MBT2	7	4
MBT7 - MBT6 - MBT3	428	1507

A Note about Travel Times

Individual travel times between Bluetooth detectors were found to be reliable after filtering for probable stops. Since our detectors were widely spaced, the 150 foot estimated detection zone radius was acceptable, but if we had been analyzing closely-spaced urban arterials it might have been necessary to use a different antenna configuration to achieve a more focused detection zone. It was quite easy to see queuing at work zones tapers and to correlate this queuing with volumes through the taper. However, caution is warranted at this time about averaging travel times where there are large variations in speed, given our inability to completely rule out the possibility of a speed bias.

CONCLUSIONS

While evaluating changes in traffic volumes resulting from freeway work zones is relatively straightforward, it has historically been difficult to assess the routes that drivers use to divert. A set of Bluetooth detectors is one means of ascertaining this route choice. Sets of three to four detectors were generally sufficient to begin analyzing diversion routing. Many such sets are required to obtain good coverage of potential diversion routes, particularly in locations where multiple alternate routes exist. The study design needs to account for different types of diversion, since many drivers in urban areas “divert” by not using the freeway at all. And it is critical to have traffic volume data along with Bluetooth observations during both the closure and non-closure periods.

Many issues with Bluetooth traffic detection still need to be resolved. Our sampling rate was low (0.3% to 5.7% at the Tomah site) and inconsistent because of the relatively small number of vehicles with Bluetooth devices. Detection rates varied by location. Furthermore, some Bluetooth devices “disappear” between detectors, either because they are in use and stop transmitting their MAC addresses or fail to be detected for some other reason. These issues increase the difficulty of factoring up the Bluetooth sample to the entire vehicle population. Thus, it is recommended that researchers report relative changes in route choice rather than absolute numbers of trips.

In spite of these limitations, Bluetooth detection is already a valid way of obtaining path choice information and producing information that can be used to calibrate of work zone diversion estimates. The ability of the detectors to accurately estimate diversion should improve with increases in the number of automobiles with Bluetooth devices and improvements in Bluetooth detection technology.

ACKNOWLEDGEMENTS

This study was supported by the Wisconsin Department of Transportation and the Smart Work Zone Deployment Initiative. The Bluetooth detectors were provided by the Wisconsin Department of Transportation and they were installed by the Wisconsin Traffic Operations and Safety Laboratory at the University of Wisconsin - Madison.

REFERENCES

1. Horowitz, A. J., Notbohm, T., 2003. Evaluation of Intellizone: A System for Providing Speed Advisories to Drivers Entering Work Zones. [online] Ames, IA: Smart Work Zone Deployment Initiative. Available at: <http://www.intrans.iastate.edu/smartwz/reports/MwSWZDI-2003-Horowitz-Intellizone.pdf> [Accessed 11 January 2011].
2. Alan J. Horowitz, K. Ian Weisser and Thomas Notbohm, 2003. “Diversion from a Rural Work Zone Owing to a Traffic-Responsive Variable Message Signage System”, Transportation Research Record Journal, #1824, pp. 23-28.

3. Song, Z., Yin, Y., 2008. Impact of Lane Closures on Roadway Capacity, Part C: Modeling Diversion Propensity at Work Zones. [online] Gainsville, FL: Florida Department of Transportation. Available at: <http://www.dot.state.fl.us/researchcenter/Completed_Proj/Summary_RD/FDOT_BD545_61_B.pdf> [Accessed 7 August 2010].
4. Zhang, L., Levinson, D., 2008. Determinants of Route Choice and Value of Traveler Information, Transportation Research Record, 2086, pp.81-92.
5. Chen, Y., Qin, X., Noyce, D. A., Lee, C., 2008. A Hybrid Process of Micro-Simulation and Logistic Regression for Short-Term Work Zone Traffic Diversion. In: TRB (Transportation Research Board), 87th Annual Meeting. Washington, DC.
6. Qin, X., Santiago-Chaparro, K., Noyce, D. A., 2010. Traffic Demand Dynamics During Urban Freeway Short-Term Lane Closures. In: TRB (Transportation Research Board), 89th Annual Meeting. Washington DC.
7. British Highways Agency and TRL, Ltd. 2006. *Economic Assessment of Road Maintenance: The Quadro Manual,* Design Manual for Roads & Bridges Volume 14.
8. Copeland, L., 1998. *User's Manual for Quewz-98*, Report No. FHWA/TX-98/1745-2. College Station, Texas: Texas Transportation Institute.
9. Mitretek Systems, 2005. *QuickZone Delay Estimation User Guide*, Version 2.0.
10. Ullman, Gerald L., Dudek, Conrad L., 2003. Theoretical Approach to Predicting Traffic Queues at Short-Term Work Zones on High-Volume Roadways in Urban Areas. *Transportation Research Record,* 1824, pp. 29-36.
11. Chitturi, Madhav V., Benekohal, Rahim (Ray) F., 2010. Work Zone Queue Length & Delay Methodology. In: TRB (Transportation Research Board), *89th TRB annual meeting*. Washington, DC, 2010.
12. Chitturi, M.V., Benekohal, R.F., Kaja-Mohideen, A.Z., 2008. Methodology for Computing Delay and User Costs in Work Zones. *Transportation Research Record*, 2055, pp. 31-38.
13. Woodings, R., Joos, D., Clifton, T., 2002. *Rapid Heterogeneous Connection Establishment: Accelerating Bluetooth Inquiry Using IrDA*, Proceedings of IEEE Wireless Communications and Networking Conference, 2002.