Advanced Traffic Signal Control using Bluetooth/Wi-Fi Detectors

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Abstract. This paper explores the potential for using measurements from Bluetooth detectors to improve traffic signal control. More specifically this paper (1) describes the accuracy by which Bluetooth detector data (travel times and dwell times) can be used to measurement arterial traffic conditions; (2) identifies how these measures can be used to improve signal timing plans in real-time; (3) describes a field pilot project that is underway to confirm the findings obtained from simulated data.

Introduction

Signalized intersections form the capacity bottlenecks within urban arterial road networks and consequently are responsible for a significant fraction of the delay, fuel consumption, and tail pipe emissions (iTRANS, 2006). There are three categories of traffic signal control systems: fixed time, actuated, and traffic responsive. Fixed time systems are the least costly, but are unable to adapt to changes in traffic patterns. Actuated systems include traffic sensors (usually inductive loop detectors) for certain movements, and are able to respond to changes in traffic demands on those movements (Koonce et al., 2008). Traffic responsive systems include a much larger number of sensors and therefore are able to respond to changes in traffic demands; however these systems are also much more costly to deploy and operate.

Although this research is currently in the simulation stages, this paper uses Hespeler Road between Highway 401 and Highway 8 in Cambridge as the source for its simulations. This roadway was selected as it was identified in a 2009 Incident Management study as a key strategic initiative for the Region of Waterloo. A more recent ITS Strategic Planning Study identified a set of priority projects, including the Hespeler Road Corridor Traffic Management System, which will deploy advanced traffic detection and surveillance technologies to provide enhanced traffic management capabilities along the corridor.

The initial phase of this research involves the investigation of using Bluetooth/Wi-Fi detectors as part of the technology for monitoring traffic conditions along the corridor and their ability to identify appropriate traffic signal response plans. In this initial phase, a custom simulation software platform was developed and used to simulate an arterial corridor including loop detectors, Bluetooth sensors, time varying traffic demands, transit routes, heavy vehicles, and signalized and unsignalized intersections.

The purpose of the simulation study was to determine the accuracy by which Bluetooth or Wi-Fi data can be used to measure arterial traffic conditions, and to identify how these measures can be used to improve signal timing plans in real-time. The findings of this study are described in this paper. The next steps in the research involve conducting a field study to confirm the findings from the simulation study. This paper also describes the field study.

Background

This paper explores the initial stages in developing a Traffic Responsive Plan Selection (TRPS) system using Bluetooth or Wi-Fi detectors. TRPS has long been a technique available to traffic engineers, although there has been challenges associated with implementing it and ensuring its effectiveness (Hanbali & Fornal, 1997). There has been work in recent years exploring ways to make the systems more accessible (Abbas & Sharma, 2004) the procedure is still quite difficult to implement. However, Abbas and Abdelaziz (2013) have shown that when properly implemented there is a significant benefit associated with TRPS on arterial performance. This research examines the possibility of using newer traffic sensing technology as a way of simplifying the implementation and maintenance associated with the conventional TRPS.

The use of Bluetooth detectors as a data source is a recent development within the field of traffic engineering (Quayle et al., 2010). Bluetooth detectors allow Bluetooth enabled vehicles or vehicles containing Bluetooth devices to act as probe vehicles for a corridor. Bluetooth detectors have been used to effectively estimate the travel times that motorists would experience on arterials (Moghaddam & Hellinga, 2013). In addition, Bluetooth detectors have the potential to be a lower cost option than the other existing tools primarily due to their ease of installation and maintenance. The goal of this research is to determine if data collected by Bluetooth detectors can be used to improve the performance of actuated traffic signal systems on an arterial corridor.

In addition to the recent increased use of Bluetooth detectors as a data source, Wi-Fi detectors are beginning to gain popularity by operating in a similar way to Bluetooth detectors (Abbott-Jard et al., 2004). The detectors allow for vehicles that are either Wi-Fi enabled or have a Wi-Fi enabled device to act as probe vehicles on a corridor (Musa & Eriksson, 2012). The original focus of the research was focused on the use of Bluetooth detectors, however access to a new Wi-Fi based system for the field study has resulted in the ability to field test these detectors. The existing simulation tools were focused on the Bluetooth technology, and as such the Wi-Fi detectors are only discussed in the section regarding the field study.

Simulation Tools

Microsimulation Software

Microsimulation models consider every network user as an individual unit, using car-following models and other similar models to determine the actions of each user every small time step (typically on the order of every 0.1 to 0.5 seconds).

PTV's Vissim 7 (Vissim) was selected as the microscopic traffic simulation software for this project. Vissim is capable of modelling the behaviour of private vehicles, heavy vehicles, public transit, and pedestrian traffic. The simulations in Vissim include a graphical component, through which users can observe and interact with the simulation in real-time. This feature allows users to confirm that vehicles are modelled in a way that would match their expectations; **Figure 1** shows a sample of a signalized intersection, Hespeler Road at Eagle and Pinebush, in Vissim. The graphical interface depicts individual vehicles (scaled to their length), traffic signal head status, location of detectors, lane configuration, etc.

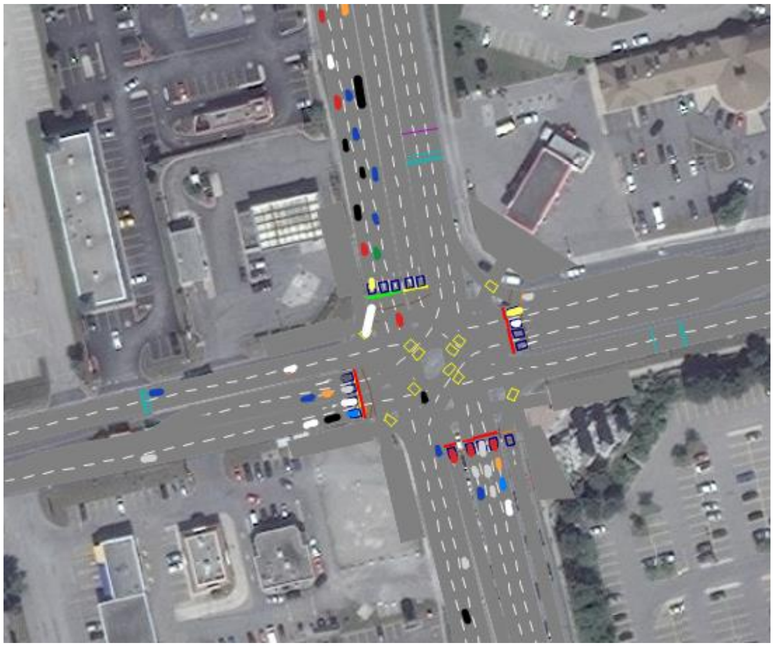


Figure 1 – Screenshot of Vissim 7 simulation display.
(Background image from Bing Maps)

In order to create a microsimulation model, the network or intersection that is being modelled must be well defined. The key items that are required to define the network are: (1) the network geometry, (2) traffic signal timings, and (3) the traffic demand. Vissim has several models for the behaviour of vehicles, and as such these are not required inputs, but can be modified as part of the calibration process. The network geometry is modelled by mapping links on top of an aerial image of the network, which ensures the correct lane configuration and geometry. The traffic signal timings can be entered directly or can be imported from other software include Synchro Studios, which is commonly used to create and save signal timings. The traffic demand can be either estimated or obtained from turning moving counts of the network.

Vissim is capable of providing a large amount of information about many aspects of the simulated network. This information includes network level statistics such as average vehicle delay; road section data such as individual vehicle or aggregated travel times between designated locations; traffic sensor data such as loop detector outputs; signalized approach measures such as average or maximum queue lengths; and data from individual vehicles, including complete vehicle trajectories. The vehicle trajectories consist of the vehicle location and speed at every simulation step. This high-resolution data is analogous to having perfect GPS data for all vehicles in the network every 0.1 second (this value can change depending on the size of the simulation step). Vissim cannot directly model Bluetooth detectors. As part of previous research the UW team developed a custom software module to simulate Bluetooth detectors. This software, described in the next section, is used in combination with the Vissim software to provide an off-line evaluation platform.

Bluetooth Simulation Tool

Bluetooth Detectors

Bluetooth is a wireless communication standard that has been adopted in many consumer electronic products (e.g. cell phones) to enable direct wireless communications between paired devices.

In order to identify possible devices, Bluetooth transceivers continuously transmit their unique 48 bit ID (address) known as Media Access Code (MAC). Each Bluetooth detector continuously performs inquiry scans in specific radio frequencies. The Bluetooth devices which are in discovery mode may be detected while they are passing the detection zone (the radius of this detection is on the order of 100m for Class 1 Bluetooth devices) of the detector even when they are already engaged in communication with another device. The detector records the MAC and the time of detection of the Bluetooth devices. Each record (i.e. MAC address and time of detection is referred to) as a “hit”. Each unique Bluetooth device can be detected several times during the time it takes to pass the detection zone (which allows for multiple hits for a device).

In recent years, Bluetooth detectors have been widely considered as an efficient and straightforward tool for measuring travel time and average travel speed both on freeways and arterials (**Figure 2**).

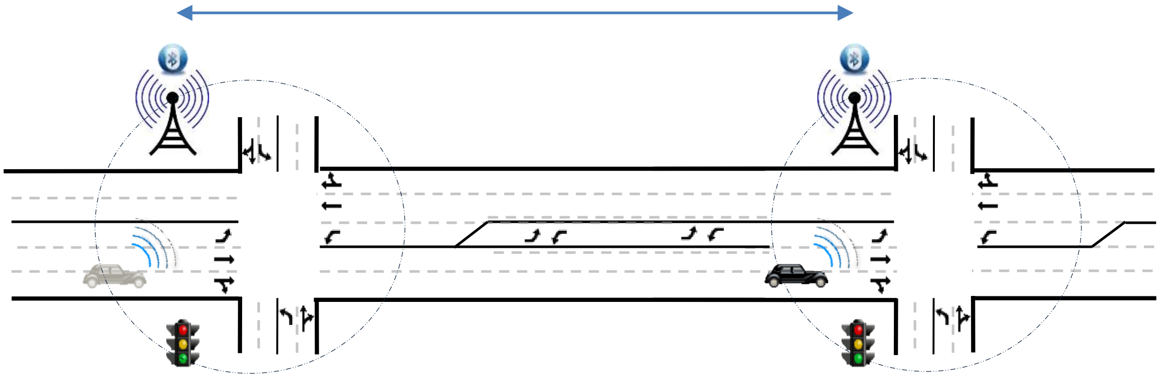


Figure 2 – Travel time measurement using Bluetooth scanners

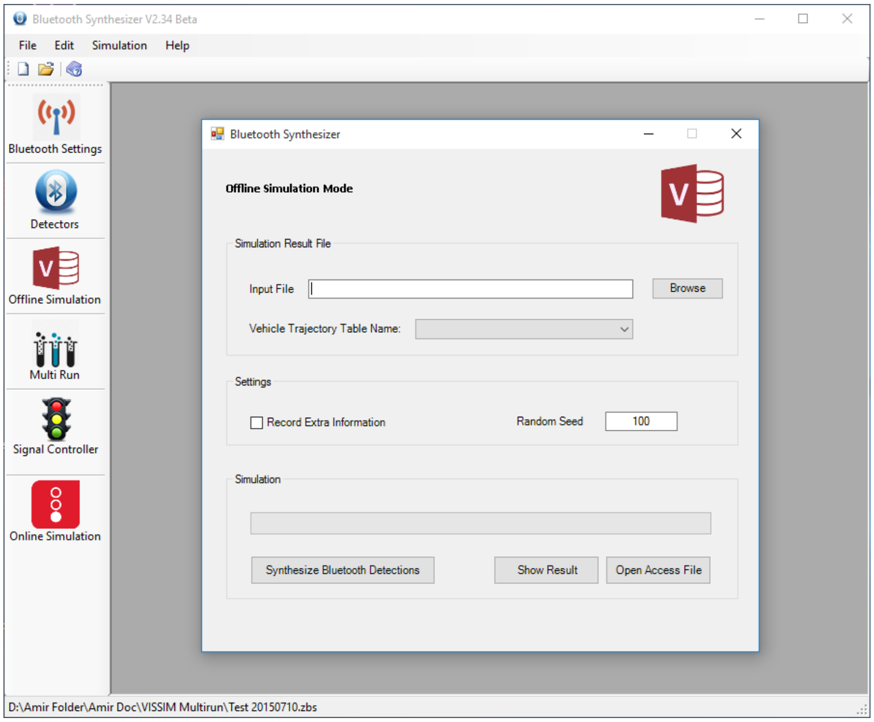
In addition to these data it is possible to extract additional information from Bluetooth detections. The time stamp of the hits for each Bluetooth device as well as the number of hits provide additional information regarding the dwell time (e.g. the difference between the time stamps of the first and last hits for a Bluetooth device that traversed the detection zone) and the experienced delay for different movements in intersections.

Software Description

The location and time of detection of a Bluetooth device is highly dependent on the pattern of the vehicle trajectory which is a function of the traffic characteristics and the interaction of

Bluetooth detectors and Bluetooth devices. Therefore, a simulation software was developed to model the detection process.

This software, BlueSynthesizer, utilizes Vissim micro-simulation model for simulation of signal control and traffic conditions. This software utilizes the vehicle trajectories produced by the Vissim simulation (e.g. location and speed of vehicles at each time step) as an input and generates Bluetooth hits and detection records similar to what happens in reality. **Figure 3** shows a screenshot of the developed software.



☐ Record Extra Information

Random Seed 100

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Figure 3 – Screenshot of BlueSynthesizer Software

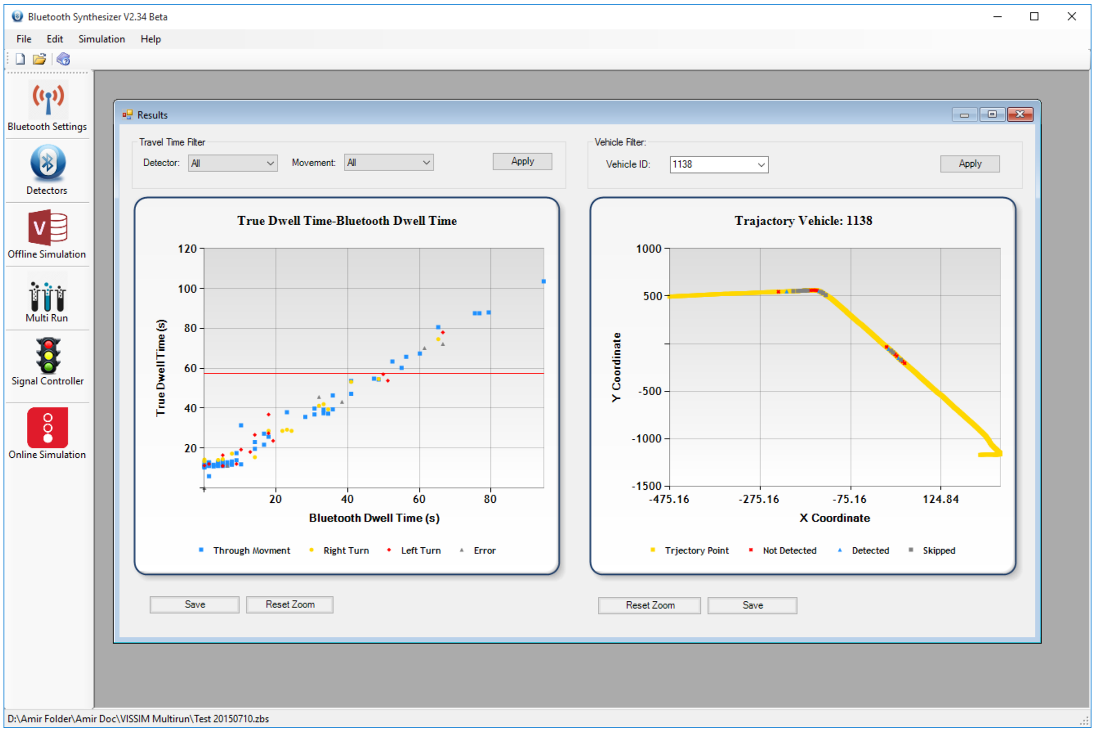
Simulation Process and Results

Once the simulation is started, based on the level of market penetration (i.e. the proportion of vehicles in the traffic stream which are assumed to have Bluetooth enabled devices), a subset of vehicles in the simulation is marked as Bluetooth enabled vehicles. At each scanning interval of Bluetooth detectors, the location of each individual Bluetooth enabled vehicle is extracted from the vehicle trajectory data. Using the location-based probability of detection, we determine whether the vehicle is detected (Bluetooth hits) and the location and time of each simulated Bluetooth hit is recorded in the output database.

The times at which each vehicle entered the detection zone for each detector is recorded, along with when it passes the sensor, and exited the detection zone. Moreover, the location and time of the first and last Bluetooth hit is recorded. These data form a Bluetooth detection record. These data are used to calculate the Bluetooth dwell time which is the basis for calculation of delay. **Figure 4** shows a sample of output charts from the software that shows a trajectory of the vehicles and location of Bluetooth hits as well as Bluetooth dwell time.

Travel time is calculated by the time difference of the matched MAC at successive detectors and average speed is computed on the basis of the travel time and the distance between the successive detectors.

As a result, this software is capable of calculating traffic measurements, simulating Bluetooth detectors and Bluetooth enabled vehicles and generating Bluetooth hits and detections.



Detector: All

Movement: All

Vehicle ID: 1138

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Figure 4 – Sample output of the BlueSynthesizer

Bluetooth Measures of Performance

Bluetooth detectors have been used to measure the travel time in a variety of applications in recent years. Often this information is used as a way to inform travellers of their expected travel times or to provide information to a traffic agency about network performance. Thus, it has already been established that Bluetooth measurements may be used to assess the performance of a network.

This study seeks to expand how this measurement could be used, specifically by considering how it could be used in a Traffic Responsive Plan Selection (TRPS) signal control system. TRPS requires information about the traffic state on the network in order to identify which signal plan to select from a predetermined library of plans. Historically, embedded loop detectors were used to measure the volume and occupancy at key points in the network. These measures can be seen as surrogates for the level of congestion at an intersection.

Traditional TRPS systems require extensive calibration to operate, due to the fact that the traditional measurements are only surrogates for the network conditions rather than a direct measurement of delay. This is one of the reasons that Bluetooth measurements are being considered as a data source for TRPS. Bluetooth sensors as the detection tool allows for direct information about the network to be extracted. The proposed MOPs are defined in this section, along with the rational for selecting them.

Before defining the suggested MOPs the following terminology is defined:

- Double detector measurement: Bluetooth measurement which requires a vehicle to be detected at two (an upstream and downstream) Bluetooth detector locations.
- Single detector measurement: Bluetooth measurement which requires at least one detection at any detector.
- Upstream detector: The first Bluetooth detector at which a vehicle is detected, or the first detector that vehicles would encounter for a given direction of travel.
- Downstream detector: The next Bluetooth detector at which a vehicle is detected, or the next detector that vehicles would encounter for a given direction of travel.
- Time lag: The delay associated with double detector measurements or to determine the directionality of a single detector measurement. It is equal to the time it takes for a vehicle to travel from the upstream to the downstream detector.

Bluetooth Travel Time

The first MOP that is proposed for use is the conventional measurement obtained from Bluetooth detectors, travel time (TT_B). This is a double detector measurement, defined as the difference between the time of detection at an upstream Bluetooth detector and a downstream Bluetooth detector for a given vehicle. It is typically calculated using the following formula:

$$TT_B = \textit{Time of First Detection Upstream} - \textit{Time of First Detection Downstream} \qquad \textbf{Equation 1}$$

Equation 1 indicates that the travel time is calculated using the first-first methodology. However, for arterial applications, Bluetooth detectors are typically installed at the signalized intersection due to the availability of power). If the objective is to measure travel time for vehicles on the approach link, then this measure should exclude any signal delay at the upstream intersection but include the signal delay at the downstream intersection. Thus, under these conditions it is advantageous to compute travel time using last-last rather than first-first. Furthermore, if the upstream detector is located mid-block, then the travel time should be computed at average-last (where “average” is the average time of the first and last hit). The difference in the travel time measurement definitions is illustrated in **Figure 5**, where a simple time-space diagram shows a single vehicle approaching a signalized intersection. In this case the traffic signal changes to red as the vehicle approaches, however the first detection at the downstream Bluetooth detector occurs before the vehicle experiences any of the delay caused by the traffic signal. In comparison, the average-last detection allows for a travel time estimate much closer to the true travel time that the vehicle experiences. Note that the true travel time is defined as the time when the vehicle passes the centre point of the upstream detection zone, to when it passes the stop line at the downstream intersection.

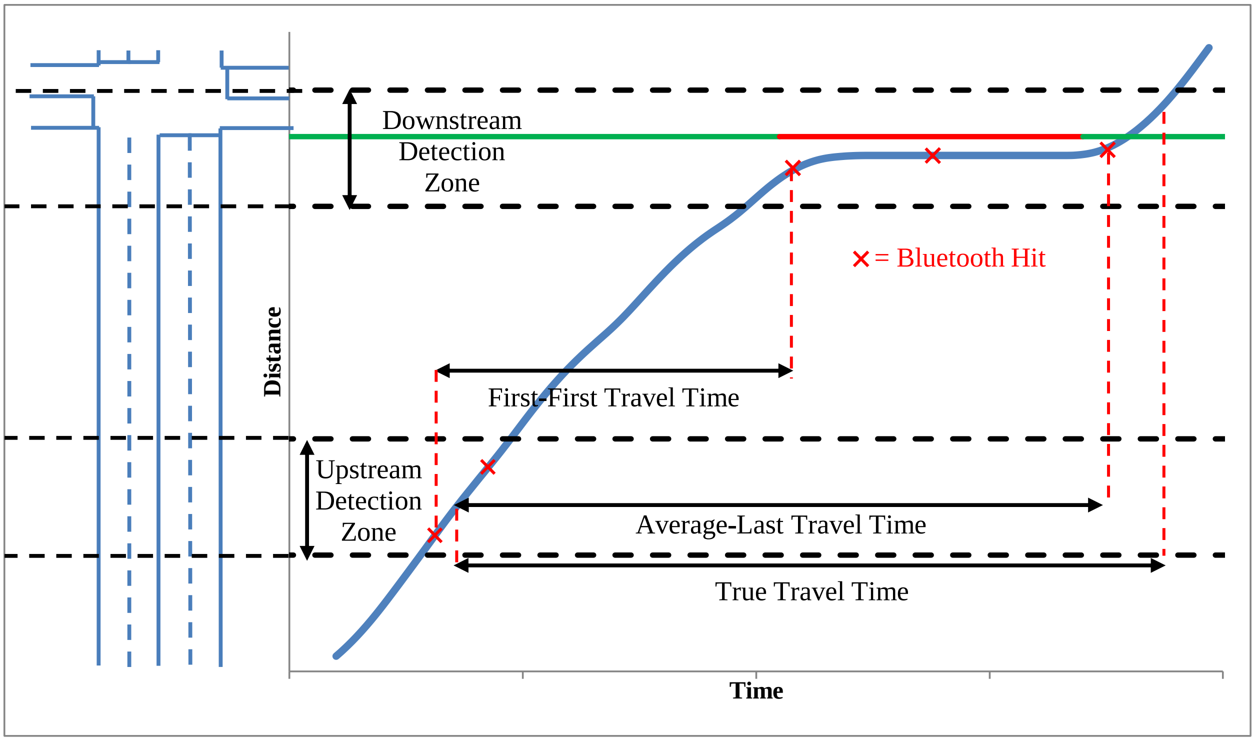


Figure 5 – Comparison of First-First, Average-Last Bluetooth, and true travel times at signalized intersection

Bluetooth Dwell Time

The next proposed MOP is the Bluetooth Dwell Time (β), a single detector measurement that approximates the travel time across a detection zone for a given vehicle. Bluetooth Dwell Time is calculated using the following equation:

$$\beta = Time\ of\ First\ Hit - Time\ of\ Last\ Hit \qquad \textbf{Equation 2}$$

Note that **Equation 2** is only valid in cases where a vehicle is detected more than once at the same Bluetooth detector. Additionally, as it is a single detector measurement, the direction of the measurement can only be determined if there is information from more than one detector, which means that unless a vehicle was detected upstream, there is a time lag associated with the measurement.

Figure 6 shows how dwell time would be calculated for a Bluetooth enabled vehicle that is detected more than one time. The concept of True Dwell Time is illustrated to show that the Bluetooth measurement should only be seen as an estimate for the time a vehicle spends in the detection zone, which may not be the same as the delay that the vehicle experiences on the approach due to the traffic signal operations.

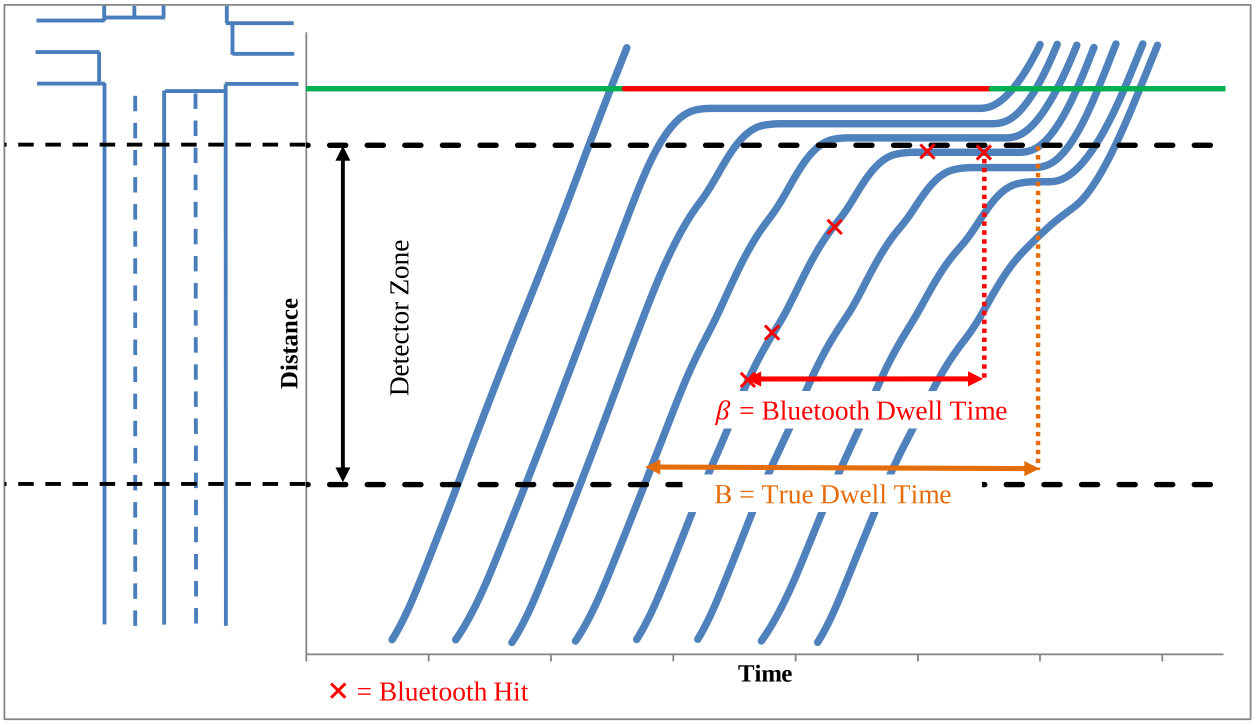


Figure 6 – Time-space diagram of vehicles progressing through detection zone

Bluetooth Dwell Time was considered as a potential MOP as it was assumed that if vehicles were consistently experiencing a long travel time across a detection zone (usually a small segment of road) and there are no nearby traffic signals, it would be likely that a queue is present in the detection zone. It could even be of use at an intersection, as if a given approach only has enough green time to clear queues that are shorter than range of the detection zone, an increase in dwell time could indicate oversaturation.

Proposed True Measure of Performance

The base objective of a TRPS system is to reduce the delay experienced by vehicles on one or more approaches at intersections that are part of the system. To this end, it is proposed that travel time is used as the true MOP when considering the simulation experimentation. This is due to the ability of Vissim to easily output the travel time between any two points for all vehicles in the network.

Although the objective is to reduce the delay experienced by road users, travel time is used to simplify the analysis. The concept of Total Travel Time is introduced in the below equation and illustrated in **Figure 7**:

$$\textit{Total Travel Time} = \textit{Base Travel Time} + \textit{Delay} \qquad \textbf{Equation 3}$$

Where,

Base Travel Time = Time between any two points in space based on a constant desired speed.

Delay = Time in excess of the Base Travel Time.

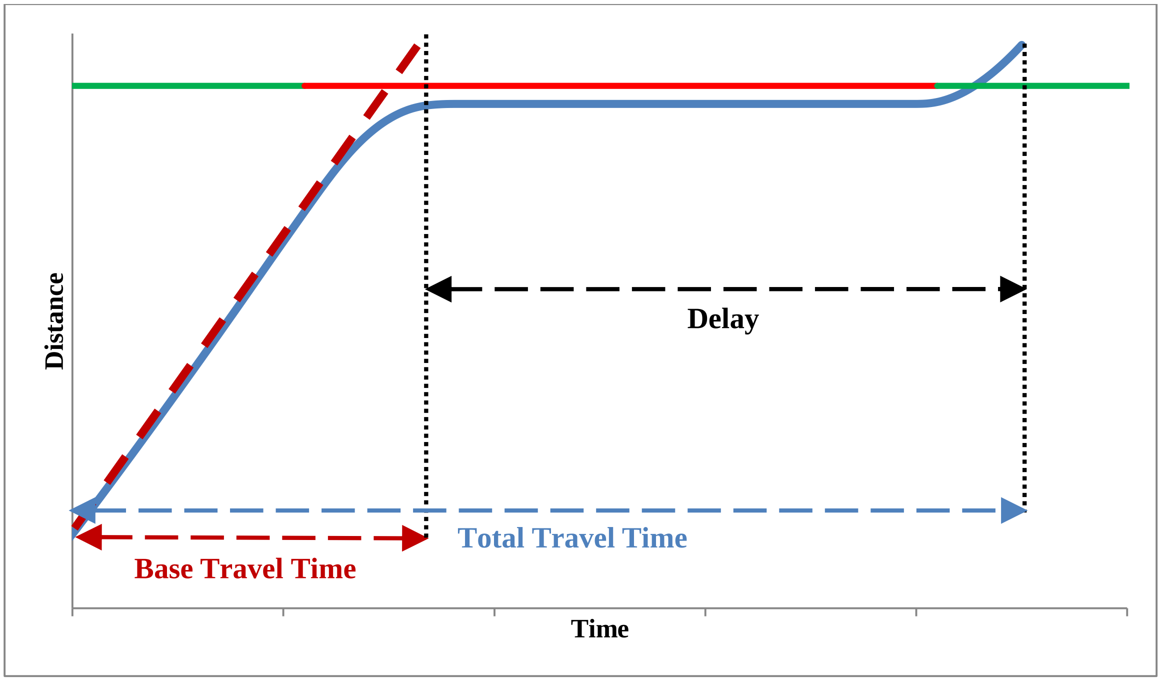


Figure 7 – Representation of Total vs Base Travel Time

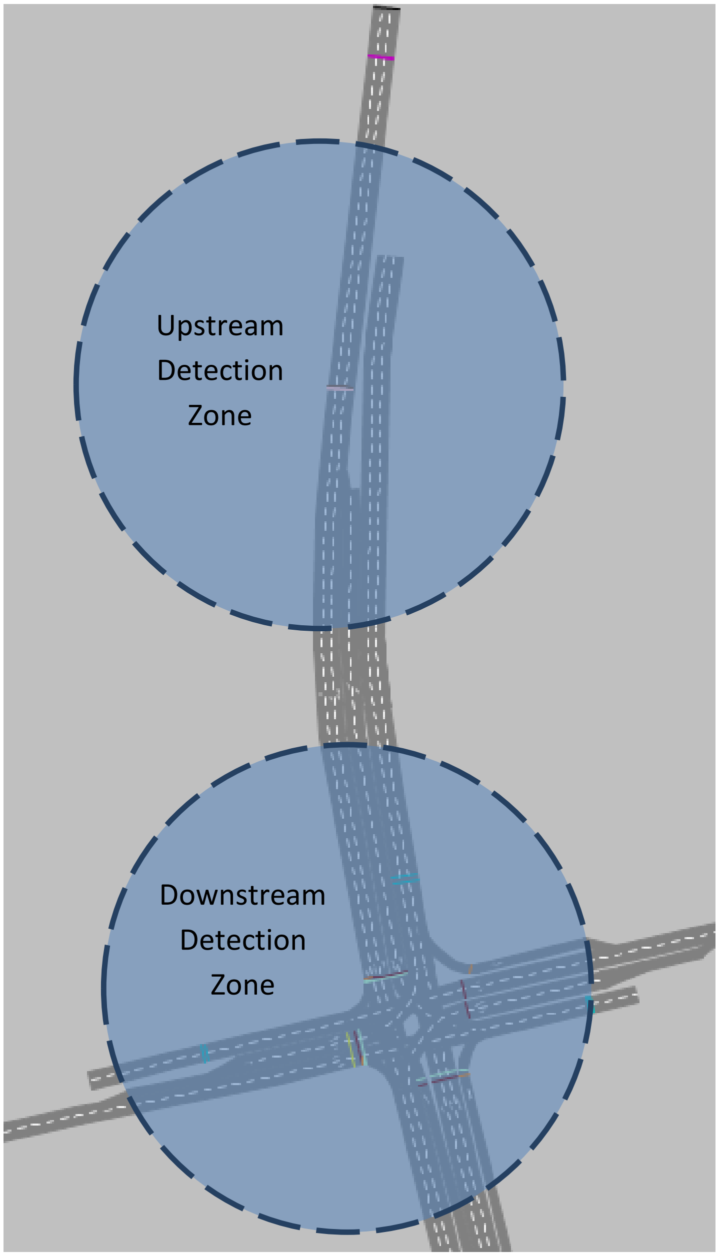
The above figure shows delay that would be associated with a traffic signal, but the delay could come from anything else that impedes travel. From an operational standpoint, having the Base Travel Time behave as a constant value gives the Total Travel Time the property that any reduction in Total Travel Time is automatically a reduction in delay. In terms of the Bluetooth experiment, associating the Bluetooth MOPs with the Total Travel Time (henceforth true travel ime) allows for a greater chance of correlation between the measurements.

Simulation Experiments

Two experiments have been completed to address the objectives of this paper, one which focuses on the relationship between the Bluetooth MOPs and the True MOPs, and the other which examines the ability to discern between two traffic states for a signalized intersection.

Both of the experiments used the same test network and Bluetooth detector positioning. **Figure 8** shows the Vissim network and the location of the Bluetooth detectors that were simulated in BlueSynthesizer. This simulated segment was based on the intersection of Hespeler Rd and Eagle St N/Pinebush Rd.

Figure 8 – Simulated intersection with Bluetooth detector zones overlaid.



The following sections explore the simulation settings as well as the results. For these experiments the following parameters were constant for both:

- An aggregation time of 5-minutes
- The level of market penetration of Bluetooth devices was assumed to be 10%
- The Bluetooth detectors were assumed to have an effective radius of 100m
- The southbound approach true travel time was measured from the location of the upstream Bluetooth detector (located approximately 250 metres upstream of the stop line) to just downstream of the intersection stop line.

Experiment #1: Comparison of Bluetooth Measurements to Truth

A total of 12 hours of conditions were simulated by varying the traffic demands on the southbound approach on an hourly basis. The traffic demands were chosen to ensure that there were periods of under and oversaturation. The turning percentages were held constant at 20% turning right, 60% turning through, and 20% turning left. No vehicles were modelled on other approaches.

The existing signal operates with an actuated 8-phase timing plan (protected left turns and protected through/right-turn phases for each approach). Consequently, the simulations were carried out using a similar 8-phase timing plan, but operating as fixed-time (**Table 1).**

Table 1 – Summary of signal parameters for southbound direction

Parameter	Time (seconds)
Cycle Length	110
Amber	4
All Red	3
Southbound Left Green	11
Southbound Through-Right	34

Once the simulation was completed, the Bluetooth detections and travel times were simulated using BlueSynthesizer. The true travel time and dwell time were produced from data supplied by the Vissim simulation. These measurements were then aggregated in 5-minute intervals, resulting in 144 observation pairs.

Figure 9 shows that the aggregated 5-minute true travel time and the estimated travel times as a function of simulation time. It can be observed that for approximately the first 5 hours of the simulation, the approach is under-saturated and approach travel times average approximately 60 seconds. As a point of context, the average vehicle delay for the approach was estimated to be 46 seconds using the methodology in the Canadian Capacity Guide for Signalized Intersections and the existing signal timing plan and base volumes. For most of the remaining 7 hours of the simulation, the approach is oversaturated and travel times are much longer.

It can also be observed that, as expected, Bluetooth travel times using the first-first methodology tend to under predict the true travel time and both the first-last and the average-last methodologies are much more accurate.

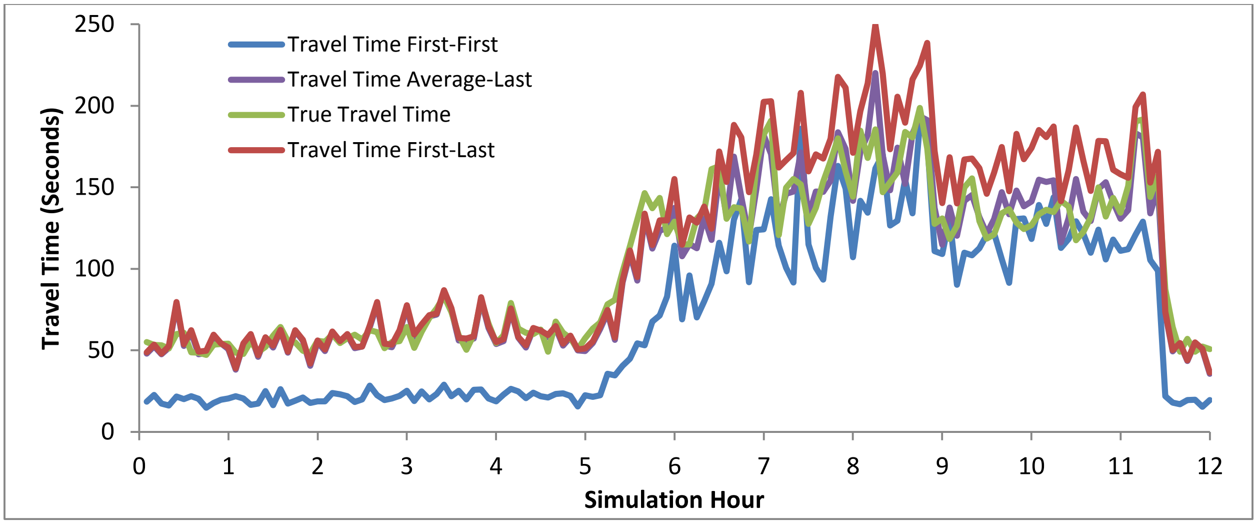


Figure 9 – Comparison of Travel Time measurements for study approach.

Figure 10 shows the relationship between the average-last travel time and the true travel time for the approach. A linear regression was performed and the intercept value was not statistically significant and therefore set to zero. The resulting linear regression (dashed red line in figure) has a slope which is very close to 1.0 suggesting that the Bluetooth estimated travel times provide an accurate and unbiased estimate of the true travel times even when the level of market penetration is 10% and a relatively short aggregation time period of 5 minutes is used.

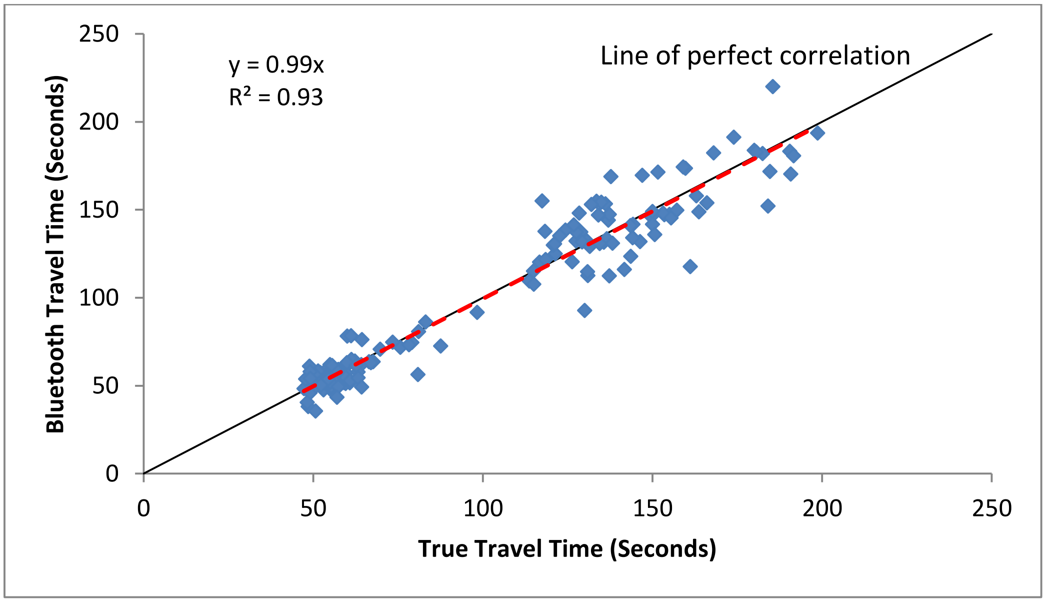


Figure 10 – True travel time vs. Bluetooth Average-Last travel time for study approach.

Figure 11 shows the relationship between the Bluetooth dwell time and the true dwell time at the detector located at the signalized intersection. The intersection detector was selected over the upstream detector as it captures the cyclic nature of queuing at the intersection that would not be observable at the upstream detector.

Again a linear regression was calibrated to the data and the intercept was not statistically significant. The R^2 value of 0.82 indicates that the linear model explains a large portion of the variability in the observed data. However, the slope is much less than 1.0 indicating that the Bluetooth dwell times tend to under-estimate the true travel time. This under-estimation occurs because the Bluetooth dwell time is computed as the difference between the first and the last hits. Due to the nature of the Bluetooth communication protocol, these hits do not always occur immediately when the vehicle enters the detection zone or just before the vehicle exists the detection zone. As such, the Bluetooth dwell time always underestimates the true dwell time.

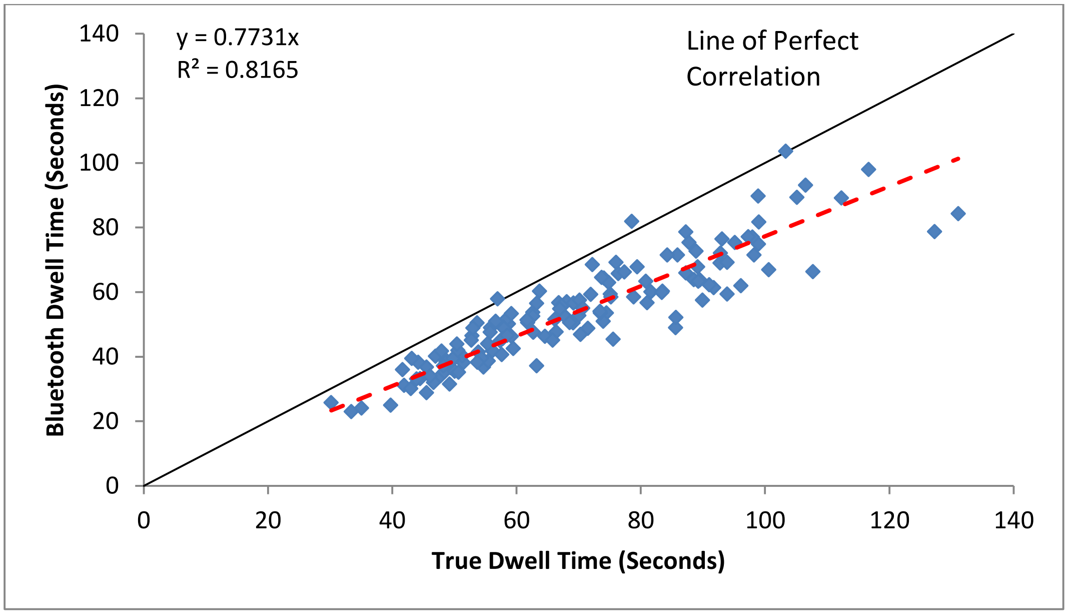


Figure 11 – True dwell time vs. Bluetooth dwell time for measurements at the intersection

The dwell time measurements were also compared to the true travel time, **Figure 12**. When compared to the other plots the overall relationship is quite weak, with an almost flat relationship between the Bluetooth dwell time and the true travel time. This is expected, as the dwell time measurements can only capture the time that the vehicle spends within the detection zone of the downstream detector which extends approximately 100m upstream of the stop line. When the approach becomes oversaturated, and the queue extends more than 100m upstream of the stop line, the delay that is experienced by the vehicle in the queue upstream of the Bluetooth detection zone cannot be captured in the Bluetooth dwell time measurement. Consequently, the dwell time under-estimates the true travel time and this under-estimation becomes large when queues and delays on the approach are large.

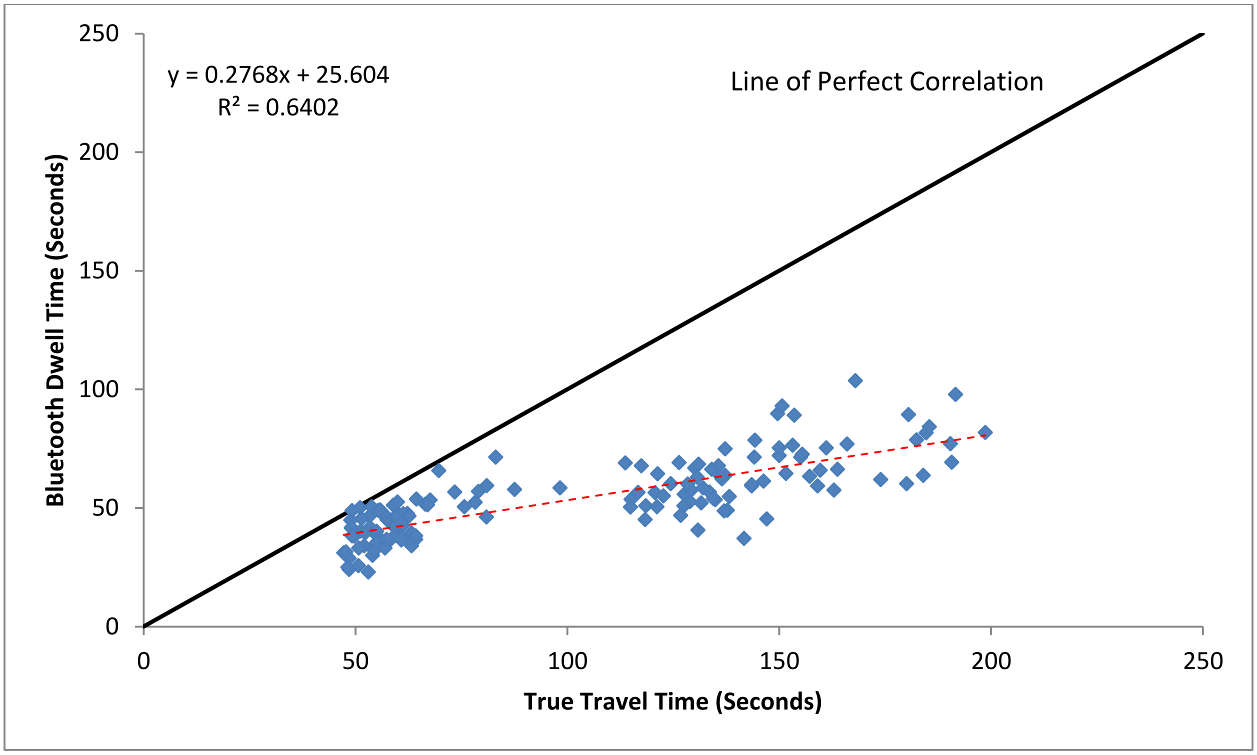


Figure 12 – True travel time vs. Bluetooth dwell time

Form these results, we can make the following observations:

1. This experiment shows that, at least under ideal conditions, the Bluetooth measured travel times can accurately reflect the true travel times when the travel times are computed in an appropriate manner (i.e. in this case as average-last).
2. Bluetooth dwell times are highly correlated with the true dwell times, but they underestimate the true dwell times.
3. The Bluetooth dwell times are not a reliable estimate of the approach travel time when queues on the approach extend upstream of the detection zone.

The next steps for examining the relationship between true measurements and Bluetooth measurements would be placing the upstream detector at a signalized intersection or include an intermediate intersection that would introduce additional variability into the travel times. Field data would be beneficial to validate the results, as currently they are only from simulated data.

Experiment #2: Traffic State Identification using Bluetooth MOPs

The second experiment focused on the potential for the Bluetooth MOPs to identify the traffic state at an intersection. To accomplish this, two traffic demand scenarios were created, a base case and a case with increased southbound left turning traffic (**Table 2**). Synchro was used to develop two fixed time signal timing plans that were optimized for each of the scenarios.

Table 2 – Summary of southbound volumes by movement for test scenarios

Scenario	Movement	Volume (vph)
Base Volume	Southbound Left	300
	Southbound Through	980
	Southbound Right	304
Increased Southbound Left Volume	Southbound Left	600
	Southbound Through	980
	Southbound Right	304

The traffic demands were held constant for each simulation run, and each traffic demand was run with each signal timing plan, for a total of four combinations. Each simulation was run for 4 hours, resulting in 48 observations at 5-minute aggregation.

The mean and standard deviation of travel times for these four scenarios were calculated to assess whether or not there was a difference in the travel times for the two volume cases for each signal timing plan. **Table 3** shows the results for the truth and Bluetooth travel times (average-last) respectively.

Table 3 – True and Bluetooth travel times for southbound approach

Travel Times (seconds)		Base Volume		Increased Southbound Left Volume	
		True	**Bluetooth**	**True**	**Bluetooth**
Base Signal Plan	Mean	51.8	51.3	196.9	178.7
	Standard Deviation	4.3	9.4	24.9	56.4
SBL Signal Plan	Mean	49.5	51.4	52.1	53.5
	Standard Deviation	4.1	9.6	4.0	7.7

The mean and standard deviation were then used to create normal distributions (the mean ± 3 standard deviations) of the travel time as a way of visually representing the difference in the travel time measurements between the two traffic demand scenarios for a given signal plan (**Figure 13).**

From the figure it is easy to observe that there is a discernible difference between the travel times associated with the two traffic demand scenarios for the true travel times. There is also a discernable difference between the Bluetooth measured travel times, however, the Bluetooth travel times exhibit a larger variance and consequently there is some overlap between these two distributions.

Thus, if in a 5-minute interval the average Bluetooth travel time was measured to be 110 seconds, and we are currently operating the Base signal timing plan, then we can safely conclude that the traffic demands are substantially different from the base traffic demands and a different traffic signal timing plan should be selected.

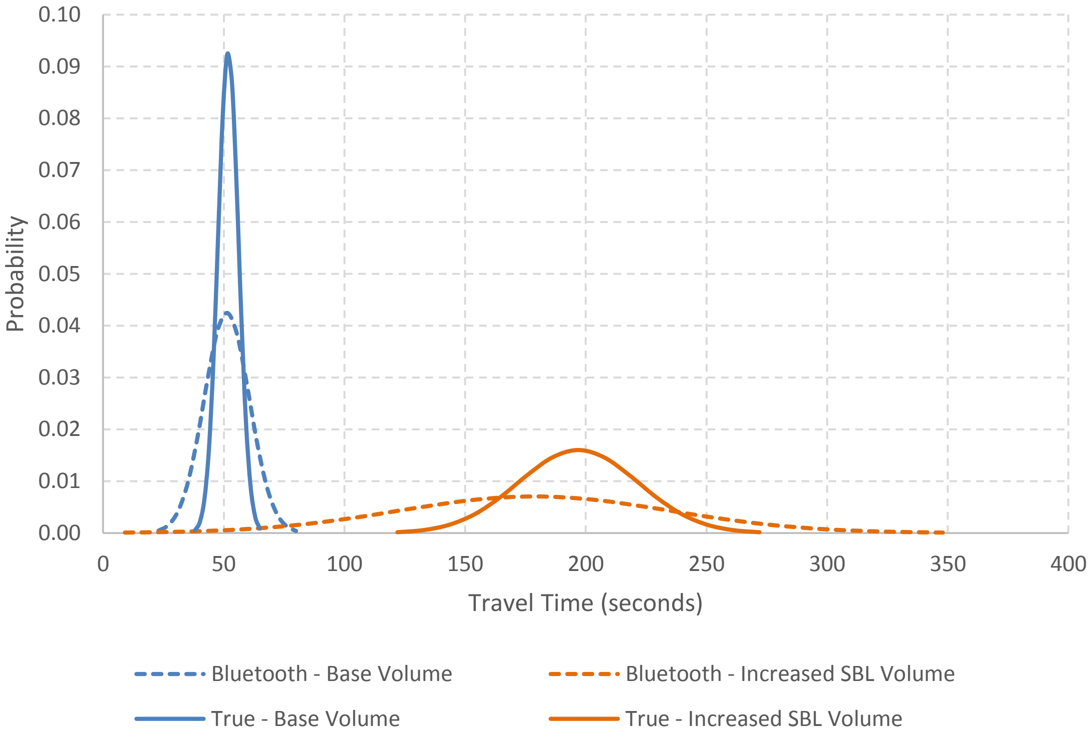


Figure 13 – Distribution of True travel times for base signal timing plan

The goal of this experiment was to identify the potential for a change in traffic state to be identified as a pre-requisite step to using Bluetooth detector measurements as a means for selecting traffic signal timing plans in a Traffic Responsive Plan Selection system.

Given that the simulation studies have demonstrated the feasibility of using Bluetooth data, the project team has initiated a field pilot study which is described in the next section.

Pilot Study Investigation

In collaboration with the Regional Municipality of Waterloo, Transport Canada, and CIMA+, a field pilot study is being conducted at two locations on Hespeler Rd in Cambridge, Ontario. Location 1 is the intersection of Hespeler Rd and Eagle St N/Pinebush St, located at the north end of the corridor just south of Highway 401. The second location is the intersection of Hespeler Rd and Bishop St N, which is approximately the halfway point of the study corridor. The pilot study involves both Bluetooth detectors and Wi-Fi detectors from multiple vendors to maximize the areas that can be instrumented. Wi-Fi detectors operate under the same concept as Bluetooth detectors, and this pilot will allow for comparison of these two detection technologies.

The Wi-Fi detectors were a recent addition to the pilot study, and there was no existing simulation software to generate sample results. As the type of information provided by Wi-Fi detectors is very similar Bluetooth detectors, the same MOPs are going to be used for the pilot study. Once the study is complete and comparison of the two detection technologies is complete, this assumption will be revisited.

The corridor is equipped with traffic sensor pucks that provide the volume and occupancy for incoming approaches. Video cameras mounted on utility or signal poles are used as a way to validate if the intersections are experiencing congestion. **Table 4** is the legend for **Figure 14** and **Figure 15**, which depict the equipment layout for the two pilot locations respectively.

Table 4 – Legend for detection instrumentation

Symbol	Instrument
●	Traffic Sensor Puck Station
◀	Video Camera
D	Bluetooth Detector
W	Wi-fi Detector

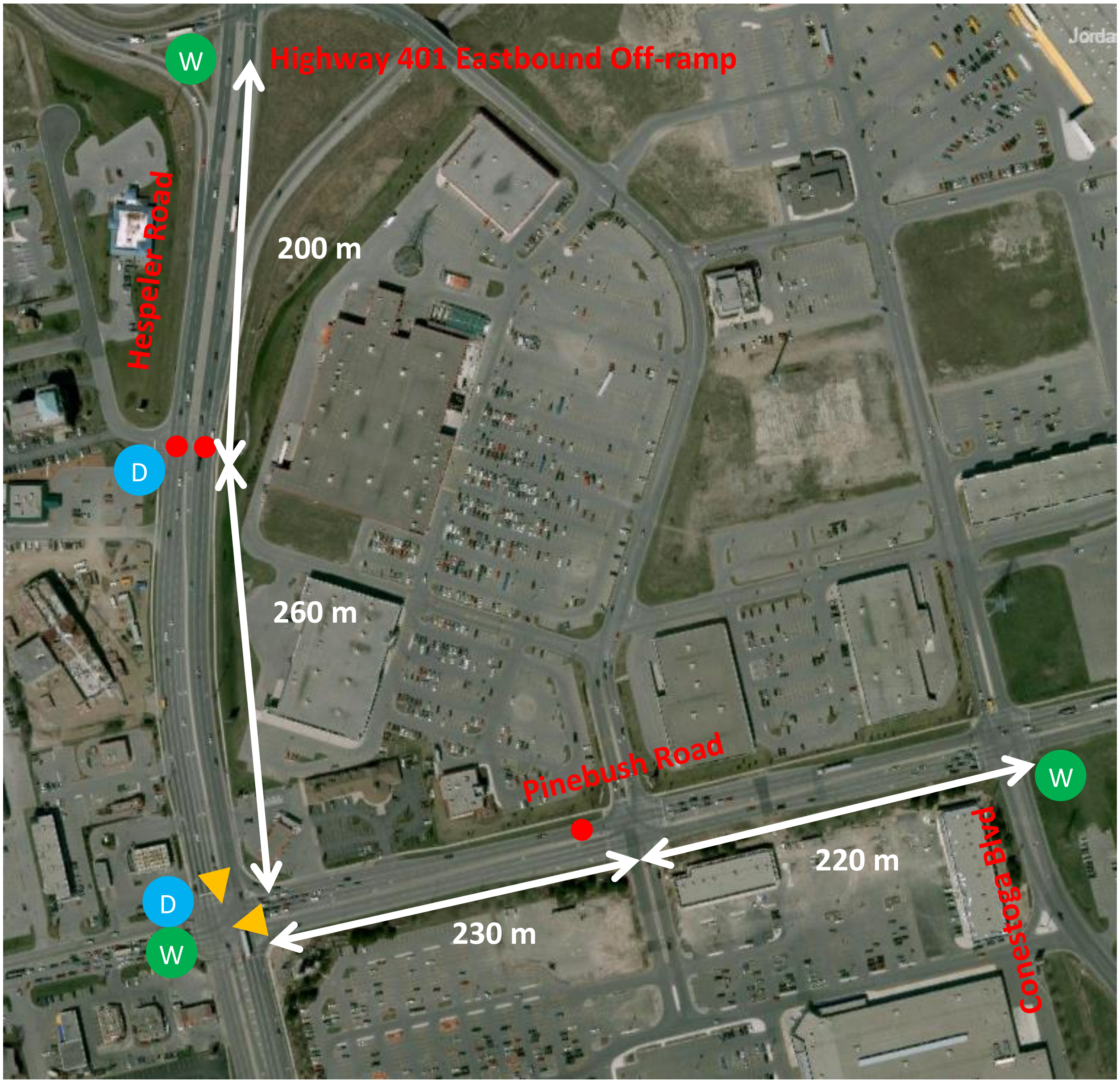


Figure 14 – Overview of first pilot intersection (Image from Google Maps)

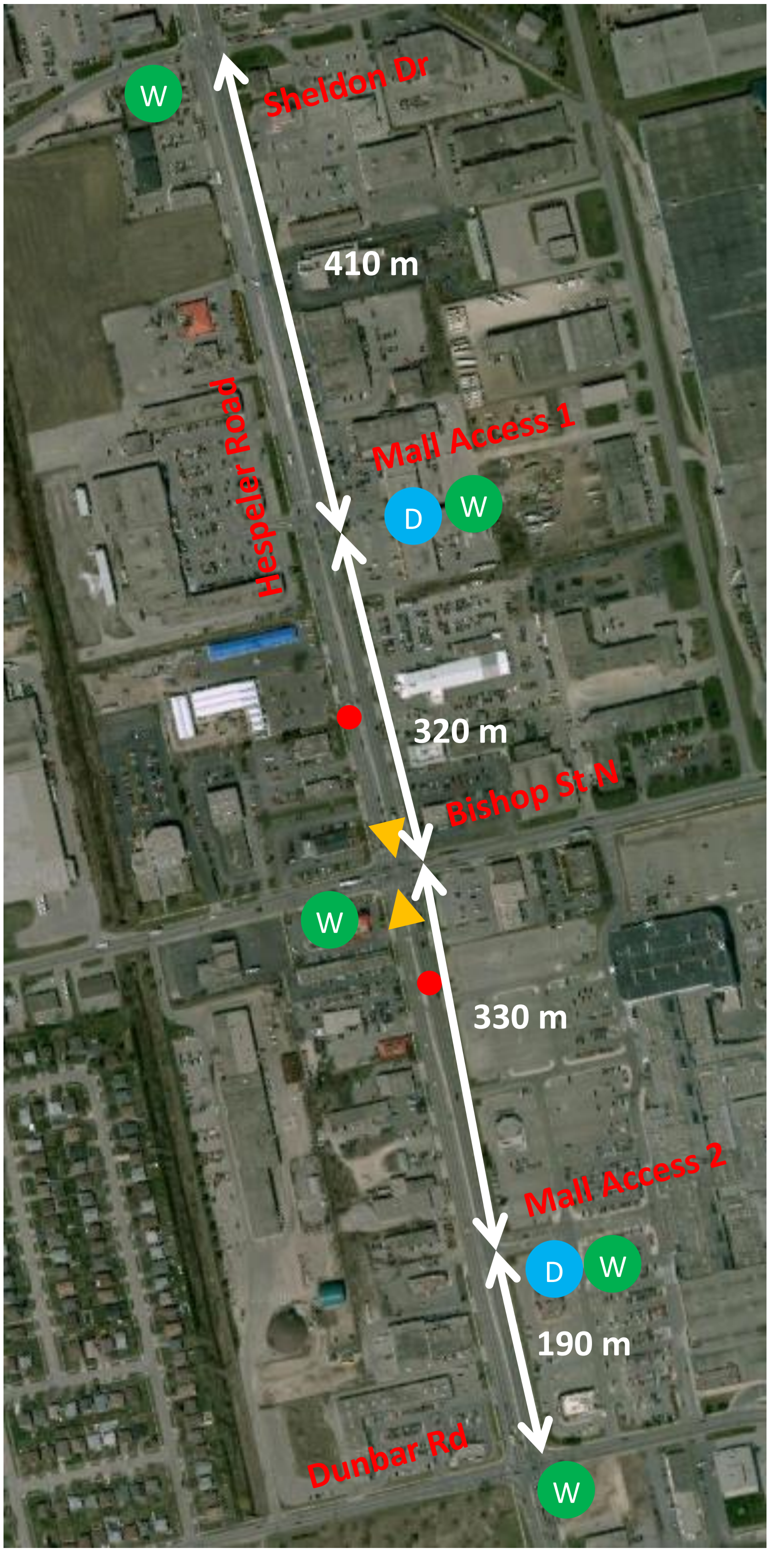


Figure 15 – Overview of the second pilot intersection (Image from Google Maps)

The data collected as part of this pilot study will provide the opportunity to validate the initial simulation results presented in this paper as well as a larger set of simulation investigation which are underway. The pilot intersections also include several detection configurations, such as the presence of an intermediate intersection between two detector pairs, and detector pairs where both are located at an intersection.

Conclusions and Recommendations

This paper has described the initial findings of the work done to use Bluetooth detectors as a data source for TRPS signal control. The results from the first rounds of simulation has shown that the identified Bluetooth MOPs are very closely related to the corresponding true measurements. Evidence was also presented that demonstrated the theoretical way that the system could detect a difference between two traffic states.

The pilot study outlined in this paper will allow for initial validation of simulation results, and provide information on how the system could be implemented on the Hespeler Rd corridor. The data from the pilot study will be used to inform the following items that have been identified as the next stages of the project:

- Impact of an intermediate intersection between detectors
- Aggregation period study and assessment of Level of Market Penetration
- Suitability of Wi-Fi detectors as a data source relative to Bluetooth detectors

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References

Abbas, M., & Sharma, A. (2004). Configuration of traffic-responsive plan selection system parameters and thresholds: Robust bayesian approach. *Transportation Research Record: Journal of the Transportation Research Board*, (1867), 233-242.

Abbas, M., & Abdelaziz, S. (2009). Evaluation of Traffic Responsive Control on the Reston Parkway Arterial Network.

Abbott-Jard, M., Shah, H., & Bhaskar, A. (2013). Empirical evaluation of Bluetooth and Wifi scanning for road transport. *Australasian Transport Research Forum (ATRF), 36th, 2013, Brisbane, Queensland, Australia* (p. 14).

Hanbali, R., & Fornal, C. (1997). Methodology for evaluating effectiveness of traffic-responsive systems on intersection congestion and traffic safety. Transportation Research Record: Journal of the Transportation Research Board, (1603), 137-149.

iTRANS 2006, *Costs of Non-Recurrent. Congestion in Canada. Final Report*, Ottawa.

Koonce, P., Rodegerdts, L., Lee, K., Quayle, S., Beaird, S., Braud, C., ... & Urbanik, T. (2008). Traffic signal timing manual (No. FHWA-HOP-08-024).

Moghaddam, S., & Hellinga, B. (2013). Quantifying Measurement Error in Arterial Travel Times Measured by Bluetooth Detectors. *Transportation Research Record: Journal of the Transportation Research Board*, (2395), 111-122.

Musa, A. B. M., & Eriksson, J. (2012, November). Tracking unmodified smartphones using wi-fi monitors. In *Proceedings of the 10th ACM conference on embedded network sensor systems* (pp. 281-294). ACM.

Quayle, S., Koonce, P., DePencier, D., & Bullock, D. (2010). Arterial performance measures with media access control readers: Portland, Oregon, pilot study. *Transportation Research Record: Journal of the Transportation Research Board*, (2192), 185-193.

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