Microscopic Control Delay Modeling at Signalized Arterials Using Bluetooth Technology

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ABSTRACT

Real-time control delay estimation is an important performance measure for any intersection to improve the signal timing plans dynamically in real-time and hence improve the overall system performance. Control delay estimates helps to determine the level-of-service (LOS) characteristics of various approaches at an intersection and takes into account deceleration delay, stopped delay and acceleration delay. All kinds of traffic delay calculation especially control delay calculation has always been complicated and laborious as there never existed a low-cost direct method to find them in real-time from the field. A recent validated technology called Bluetooth Median Access Control (MAC) ID matching traffic data collection technology seems to hold promise for continuous and cost-effective traffic data collection. Bluetooth traffic data synchronized with vehicle trajectory plot generated from GPS probe vehicle runs has been used to develop control delay models which has a potential to predict the control delays in real-time based on Bluetooth detection error parameters in field. Incorporating control delay estimates in real-time traffic control management would result in significant improvement in overall system performance.

DEDICATION

To my mother, K Valsalakumari, who taught me to dream and to believe in myself.

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TABLE OF CONTENTS

ABSTRACT ii
DEDICATION iii
ACKNOWLEDGEMENT iv
LIST OF FIGURES ix
LIST OF TABLES xi
LIST OF ABBREVIATIONS xii
1 INTRODUCTION 1
  1.1 Research Objectives 3
  1.2 Thesis Contribution 3
  1.3 Thesis Layout 3
2 BACKGROUND AND LITERATURE REVIEW 4
  2.1 Current Traffic Data Collection Techniques 4
  2.2 Overview of Bluetooth Technology 5
  2.3 Bluetooth Technology in Traffic Field Data Collection 9
    2.3.1 Bluetooth Data Collection Unit 12
    2.3.2 Bluetooth Antenna Selection 14
    2.3.3 Method Validation 15
    2.3.4 Approximate Location Estimation Using Overlapping Bluetooth Antennas 16
    2.3.5 Privacy issues 17
    2.3.6 Advantages and Applications 17
3 BLUETOOTH UNIT DEVELOPMENT, TESTING AND DATA COLLECTION 19
  3.1 Bluetooth Traffic Data Collection Unit 19
  3.2 Bluetooth Unit Testing and Pilot Study 20

3.3 The Study Network 22

3.4 Data Collection – Bluetooth and GPS Data 24

3.5 Data processing 25

3.5.1 Bluetooth data 25

3.5.2 GPS Data 26

3.6 Vehicle Trajectory Development 27

4 MICROSCOPIC MODELING OF CONTROL DELAY AT SIGNALIZED INTERSECTIONS BASED ON BLUETOOTH AND GPS DATA 29

4.1 Abstract 29

4.2 Introduction 30

4.3 Bluetooth Unit Development and Data Collection 32

4.4 Development of Vehicle Trajectory 35

4.5 Control Delay Formulation 37

4.6 Control Delay Modeling Based on Bluetooth Hits (n) 39

4.7 Calibration of Control Delay Model Based on n 40

4.8 Conclusion 42

4.9 Future Research 43

4.10 References 44

5 CONTROL DELAY MODEL VALIDATION AND APPLICATION IN AN ARTERIAL NETWORK 46

5.1 Abstract 46

5.2 Introduction 47

5.3 Experimental Setup and Control Delay Model 48

5.4 Control Delay Model Validation 51

5.4.1 Model Analysis 51

5.4.2 Model Validation 53

5.5 Control Delay Estimation Using Delay Model ... 54
5.6 Conclusion ... 60
5.7 Future Research ... 60
5.8 References ... 61
6 CONTROL DELAY MODELING BASED ON TIME DURATION BETWEEN BLUETOOTH TRAFFIC DETECTIONS ... 63
6.1 Abstract ... 63
6.2 Introduction ... 64
6.3 Investigation of the Developed Delay Model Based on ‘n’ ... 65
6.4 Motivation for the research study ... 66
6.5 Data collection and extraction ... 67
6.6 Correlation Analysis - T, n and D ... 68
6.7 Formulation of Delay model based on T ... 70
6.7.1 Variation in data for T based on direction of traffic ... 70
6.7.2 Control Delay Model Development ... 71
6.8 Validation and Calibration Results for Delay models based on T ... 73
6.9 Conclusions ... 76
6.10 Future Research ... 76
6.11 References ... 78
7 CONCLUSIONS AND FUTURE RESEARCH ... 80
7.1 Conclusions ... 80
7.2 Future Research ... 80
8 REFERENCES ... 82
APPENDIX A - 'BLUETOOTH UNIT' COMPONENTS ... 87
APPENDIX B - ‘BLUETOOTH UNIT’ – CONNECTION OF THE COMPONENTS ... 91

APPENDIX C - NETBOOK PREPARATION FOR BLUETOOTH TRAFFIC COLLECTION..........92

APPENDIX D - RUNNING THE BLUETOOTH PROGRAM – ‘Bluetooth_capture.sh’ ..95

LIST OF FIGURES

Figure 1: Process of Bluetooth Inquiry (Fair Use)..8
Figure 2: Principle of Bluetooth Detection Technology in Traffic Data Collection (Fair Use)....10
Figure 3: Bluetooth unit chipset design with GPS+GSM [4]..13
Figure 4: Bluetooth Unit with Solar Energy Capability [17] 14
Figure 5: Vehicle location with overlapping antennas (Fair Use) 16
Figure 6: Bluetooth Unit [29, 31-33] 20
Figure 7: Blacksburg Main Street Study Network with Installed Bluetoth Units [34].................21
Figure 8: Bluetooth sensor location configuration for capturing all traffic movements at an intersection (Fair Use) 23
Figure 9: Reston Parkway study network with Bluetooth unit locations [34] 24
Figure 10: GPS data collection study network [34]...25
Figure 11: Vehicle trajectory plot with superimposed Bluetooth detections (Fair Use) 28
Figure 12: Illustration of ideal and worst-case Bluetooth detections (Fair Use)..........................32
Figure 13: Bluetooth unit installation in field (Fair Use)...34
Figure 14: GPS study network [34] 35
Figure 15: Vehicle trajectory graph with Bluetooth unit detections (Fair Use) 36
Figure 16: Field detection range box plots for Bluetooth units 3, 9 and 5 (Fair Use) 37
Figure 17: Time period division for delay analysis (Fair Use)..38
Figure 18: Delay fit curves for EB and WB traffic direction (Fair Use) 40
Figure 19: Calibration of model based on n for EB Traffic (Fair Use)..41
Figure 20: Calibration of model based on n for WB Traffic (Fair Use) 42
Figure 21: Comparison of current practice and n model control delay errors (RMSE) (Fair Use) 42
Figure 22: GPS data collection location in Reston Parkway Network [34].................................49
Figure 23: Bluetooth detections plotted on vehicle trajectory plot from GPS data (Fair Use) 50
Figure 24: Normal Probability Plot (Fair Use) 52
Figure 25: Scatter Plot of Actual and Estimated Control Delay (Fair Use) 52
Figure 26: Model validation results for WB traffic (Fair Use)..53
Figure 27: Model validation results for EB traffic (Fair Use)...54
Figure 28: Bluetooth unit configuration to capture all eight NEMA movements (Fair Use) 55

Figure 29: Color Coded Control Delay Network Map (Fair Use) 57
Figure 30: Peak Control delay at Intersection 9 (Fair Use) 59
Figure 31: Relation between T and control delay (Fair Use) 67
Figure 32: Intersections 3 and 9 and 5 locations in GPS study network [34] 68
Figure 33: Graphical representation of correlation analysis results (Fair Use) 69
Figure 34: Variation in EB and WB traffic for D vs. n and D vs. T data (Fair Use) 71
Figure 35: Polynomial fit curve of degree 2 (Fair Use) 72
Figure 36: Linear model fit curve (Fair Use) 73
Figure 37: Validation results for delay models based on T (Fair Use) 74
Figure 38: Calibration results for delay models based on Linear T model (Fair Use) 75
Figure 39: Calibration results for delay models based on Non-linear T model (Fair Use) 75
Figure 40: RMSE error comparison for delay models (Fair Use) 76
Figure 41: Lenovo S10 Netbook [32] 87
Figure 42: SENA Parani UD100 Bluetooth Adapter [29] 87
Figure 43: SENA 1dBi Stub Antenna [29] 88
Figure 44: SENA 5dBi Dipole Antenna [29] 89
Figure 45: USB Extension Cable [31] 89
Figure 46: Connection of Various Components of a 'Bluetooth Unit' 91
Figure 47: Screenshots of Running Bluetooth Program step-by-step 97

LIST OF TABLES

Table 1: Bluetooth Device Class and Approximate Range [10]..6
Table 2: Sample Bluetooth Data..11
Table 3: Blacksburg Main Street Pilot Study Results..22
Table 4: Bluetooth sensor data to match for obtaining various traffic movements.......................24
Table 5: Details of Bluetooth traffic data..26
Table 6: Details of GPS data 27
Table 7: Latitude and Longitude for Intersections 3, 9 and 5..27
Table 8: Antenna range test results..34
Table 9: Correlation analysis for D, n and T 69

LIST OF ABBREVIATIONS

ALPRS – Automatic License Plate Recognition Systems

AVL – Automatic Vehicle Location

DSRC - Dedicated Short-Range Communication

EB – Eastbound

EST – Eastern Standard Time

FFS – Free Flow Speed

GPS – Global Positioning System

GSM – Global System for Mobile communications

HCM – Highway Capacity Manual

IEEE – Institute of Electrical and Electronics Engineers

ISM – Industrial, Scientific and Medical

LOS – Level of Service

MAC – Median Access Control

MOE – Measures of Effectiveness

OD – Origin Destination

OS – Operating System

RSSI – Received Signal Strength Indicator

SIG – Special Interests Group

USB – Universal Serial Bus

V2I - vehicle-to-infrastructure

V2V - vehicle-to-vehicle

WB – Westbound

WLAN – Wireless Local Area Networks

wubi – Windows Ubuntu Installer

1 INTRODUCTION

Travel time, traffic speed and delay constitutes three of the seven basic and important measures of effectiveness (MOEs) to be estimated to determine traffic system performances [1]. Although average travel time and hence traffic speed can be measured accurately and directly from the field by various existing methods (e.g., Automatic License Plate Recognition Systems (ALPRS), floating car methods, toll tag reading etc.), its continuous measurement is inhibited by the high cost of permanent field implementation of such technologies. Delay is a derived MOE mainly based on travel time as the difference in ideal travel time and actual travel time [1]. Delay can be of various types, out of which control delay helps in analyzing the effectiveness of existing traffic control strategies. Control delay at an intersection due to the presence of a signal control is a combination of deceleration delay, stopped delay and acceleration delay, thus making it difficult to be directly measured from the field. Various methods have been developed in the past to estimate delay based on several other MOEs [2, 3]. These tend to be static computations based on complex analysis of several performance measures. Traffic delay changes with change in traffic patterns based on time of the day and day of the week and with respect to special traffic patterns. Control delay is an essential measure to analyze the effectiveness of exiting traffic control systems. Control delay also helps us to determine the existing level-of-service (LOS) for each approach at an intersection. Hence, control delay and travel time are two important performance measures which helps to analyze the existing traffic control and operation efficiency, and to improve traffic signal timing plans for better and more efficient traffic flows.

Bluetooth technology is familiar to most of us as the ‘wireless technology’ in our laptops, mobile phones and other electronic devices capable of sharing videos, photos, and other information between two connected devices wirelessly. Recently, Bluetooth technology has been validated for its potential in traffic data collection. Every Bluetooth device has an in-built unique Median Access Control (MAC) address used during pairing with another Bluetooth device for establishment of wireless connection and information sharing. This concept has been applied to traffic engineering data collection by installing roadside Bluetooth sensors/units to collect MAC address of Bluetooth devices in vehicles passing by it. Collecting MAC address does not pose privacy threats as it is an anonymous hexadecimal address which is not maintained in any database linking it to a specific Bluetooth device or owner. When the collected MAC data from many such roadside Bluetooth sensors are matched and analyzed, we can measure the real-time average travel times of the traffic and network origin-destination (OD) of the vehicles. Bluetooth technology being low power consuming and cost effective can be used for permanent implementation in fields for continuous and real-time traffic data.

One important issue with Bluetooth traffic data collection technique is its lack of location data for the vehicle detections. The location of a vehicle while it is detected at a roadside Bluetooth sensor can be anywhere in its antenna range. An increase in antenna range for increasing the Bluetooth detections and hence quantity of the Bluetooth traffic data will result in higher spatial error in Bluetooth detections. An optimal antenna range to satisfy both the above conditions adequately is complicated due to the frequency hop structure and hence random detection error of the Bluetooth technology. Several Bluetooth detections for a same Bluetooth device can be made while it is in its antenna range. Hence, the current practice has been to match the same index number of Bluetooth detections from each roadside Bluetooth sensor data to determine travel time and delay. Travel time estimations when averaged over a large sample size gives reasonably accurate results to match the actual field travel times. But delay estimated by the current practice leads to large overestimation or sometimes underestimation due to the random detection errors of the Bluetooth technology. Although there has been many studies related to the Bluetooth travel time error estimation [4] and forecasting [5], none of them have tried to look at the Bluetooth detection error which is a major factor for travel time and delay estimation errors. This study looks at two important Bluetooth detection error parameters namely number of Bluetooth detections and time duration between first and last Bluetooth detections for a vehicle. These parameters are measured directly from the Bluetooth traffic data and would include un-quantified random errors in Bluetooth technology detections. A GPS probe vehicle study has been conducted to accurately estimate the vehicle trajectory and actual control delays experienced in the field. The Bluetooth detections were then synchronized with the vehicle trajectory plot to spatially place Bluetooth detections and obtain the required Bluetooth detection error parameters for formulating delay models. These control delay models can then be used to estimate the control delays in the field in real-time, given only Bluetooth traffic data.

1.1 Research Objectives

The main objectives of this research are:

- ✓ Develop a basic Bluetooth traffic data collection unit to be directly used in the field.
- ✓ Estimate Bluetooth detection error parameters from synchronized vehicle trajectory plots and Bluetooth traffic data
- ✓ Formulate control delay prediction models based on Bluetooth traffic data

1.2 Thesis Contribution

A novel idea for estimating control delay based on Bluetooth MAC ID matching traffic data collection technique is studied in this thesis. Bluetooth technology has the potential to deliver continuous traffic data and hence this potential is utilized to estimate performance measures like dynamic travel time and control delay in the field. The delay models developed in this thesis based on Bluetooth technology would help in real-time control delay estimation and hence help in enhanced traffic control system performance.

1.3 Thesis Layout

This thesis is organized into seven chapters. The current chapter gives an introduction, the research objectives and thesis contribution. Chapter 2 presents a comprehensive literature review and background on Bluetooth traffic data collection technique. Chapter 3 describes the Bluetooth data collection unit, its testing and data collection. Chapter 4 gives in detail the methodology used for the formulation of control delay models based on Bluetooth and GPS data. Chapter 5 describes the control delay model validation and its application to a signalized arterial intersection. Chapter 6 presents two more control delay models developed based on time duration between Bluetooth detections and its detail model validation process. Chapter 7 gives the conclusion by summarizing the findings in this thesis and future research.

2 BACKGROUND AND LITERATURE REVIEW

Accurate, continuous and cost-effective traffic data is essential for all traffic monitoring and traffic management systems. Although accurate methods like Automatic License Plate Recognition Systems (ALPRS), toll tag reading etc., exist, their high cost of installation and maintenance inhibits their permanent installation in a road network. Hence, availability to continuous real data has always been a challenge to transportation engineers until the emergence of Bluetooth Median Access Control (MAC) ID detection technique. This technique is highly cost effective making it feasible for permanent roadside installation for continuous traffic data sampling. Traffic data collected through this method commonly referred to as ‘Bluetooth data’ is very efficient in providing origin-destination (O-D) and travel time for various traffic network links. This method has been successfully validated by many past studies by taking ALPRS data, toll tag reader data, Global Positioning System (GPS) probe vehicle data etc., as ground truth references [6-8].

Although this technique has been found to be very accurate for travel time and traffic speed data, it gives erroneous results while calculating various traffic performance measures like traffic control delay. This is due to the lack of vehicle location information in a Bluetooth data as well as the random detection errors due to frequency hop structure of the Bluetooth technology. Traffic delay is an important factor for the design of optimal signal timing plans and effective traffic management systems. Hence, a comprehensive microscopic methodology is required to model the control delay based on the Bluetooth detections and its associated errors, and total time duration between the first and last Bluetooth detections for each Bluetooth sensor.

2.1 Current Traffic Data Collection Techniques

Some of the most common methods of traffic data collection include Floating car technique, GPS probe vehicle data, Automatic License Plate Recognition System (ALPRS), Cellular phone tracking, Vehicle Video Imaging, and Automatic Vehicle Location (AVL) [9]. All the above listed techniques apart from cellular phone tracking technique have a common disadvantage of high cost. This makes it infeasible for continuous data collection, an important factor for efficient design of traffic management systems.

Floating car method, although very easy to collect data, is highly labor-intensive, error-prone and low on traffic data sample size. Embedding GPS technology to the floating car probe vehicle will greatly improve the accuracy of the data collected but cost of the GPS equipment as well as labor requirements makes it a less preferred method for continuous traffic data collections. ALPRS provides accurate traffic data but the cost of the equipment, its restriction of being able to collect only through-traffic data, and privacy issues due to the collection of license plate information makes it a less preferred method my many transportation engineers and transportation government departments. Another method with high privacy issues is cellular phone tracking. Vehicle video imaging and matching technique is sometimes used in cases where all the above listed methods become unviable or unavailable. Although a very low-cost method, it requires huge amounts of time matching the vehicles in video and if done through manual matching, this method adds on to the labor cost requirements too. An alternative approach of AVL provides highly accurate data where the test vehicles have attached transmitters which transmit its location at continuous intervals of time to a receiver. This method incurs high installation charges and gives small sample size making the benefit to cost ratio very small.

One promising technique which addresses most of the issues mentioned above like high cost of implementation/maintenance, small and discontinuous data samples, and privacy issues is Bluetooth MAC address matching technique. This technique is a recently developed and a highly researched method gaining its importance with the improvement and increased market penetration rate of Bluetooth technology embedded electronic devices.

2.2 Overview of Bluetooth Technology

Bluetooth is a short-range wireless technology using the unlicensed Industrial, Scientific and Medical (ISM) frequency band of 2.4 GHz to 2.485 GHz. It follows a frequency hopping structure designed to minimize interference with other radio signals using the same frequency spectrum making it a robust technology for short range communication. The idea of Bluetooth technology was conceived and developed in 1994 by engineers at Ericson, a Swedish company, mainly as a cable replacement technology to connect and communicate between various devices [10]. Currently, more than 15,000 companies jointly maintain and develop the specifications of the Bluetooth technology under the name of Bluetooth Special Interests Group (SIG)[11].

Bluetooth technology falls under IEEE 802.11 standards for wireless local area networks (WLANs) [12].

The potential of Bluetooth technology is magnified by the fact that it is available everywhere and works the same way in all the places unlike other wireless technologies. Also, non-requirement of a line-of-sight for the Bluetooth signal to travel makes it more versatile. A Bluetooth device consumes very low power and has a low price tag attached to it making it affordable to many consumers in small as well as large scales. The detection range of a Bluetooth device can vary with manufacturer but an approximate range is mentioned in the Bluetooth specification based on the class of the device used as given below in Table 1**.**

Device Class	Approximate Range (m)
Class 1	~ 1
Class 2	~ 10
Class 3	~ 100

Table 1: Bluetooth Device Class and Approximate Range [10]

Every Bluetooth device has a unique identifier address called the Median Access Control (MAC) address. It is a 48-bit unique identity for a Bluetooth device with groups of hexadecimal digits arranged as in 00:25:67:D8:BE:85[1]. Bluetooth technology follows a master-slave structure where the Bluetooth device initiating or searching for other Bluetooth devices in range becomes the ‘master device’ and the devices which are discovered by the master device are known as ‘slave devices’. The master device hops using a technique called ‘adaptive frequency hopping’ within the 79 available channels of 1 MHz width each in the ISM frequency band of 2.4 GHz to 2.485 GHz, every 625µs. A group of slave devices (up to 7 slave devices at a time) and a master device connected together make up a ‘piconet’ [12]. All the slave devices in a piconet are synchronized with the clock and frequency hop structure of the master device so that Bluetooth connection between them is maintained as long as the devices are in each other’s range. Connection between two Bluetooth devices goes through a series of steps to maintain security and minimize interference. Bluetooth uses a ‘packet-based protocol’ for transmitting information or data within Bluetooth devices [12]. The master device enters the ‘inquiry state’ and will send ‘inquiry packets’ searching for Bluetooth devices (slave devices) in range while it hops between

---

[1] Author’s MAC ID

various frequency channels [13]. A discoverable Bluetooth device in the ‘inquiry scan state’ would send an ‘inquiry response packet’ to the master device with the MAC address and clock information. According to Bluetooth specifications, an inquiry state can last for approximately 10.24 sec although the master device can abort an inquiry and begin a fresh one if programmed to do so. From Figure 1, we can see that at time period ‘t’, there is a master device in ‘inquiry state’ and two slave devices in discoverable ‘inquiry scan state’. All are hopping with random different frequency hops. The various color coding represents difference in the hopping frequency. At time period ‘t+1’, the master device and one slave device have the same frequency and hence the slave device successfully receives the ‘inquiry packet’ from the master and responds with an ‘inquiry response packet’ with MAC ID and clock information.

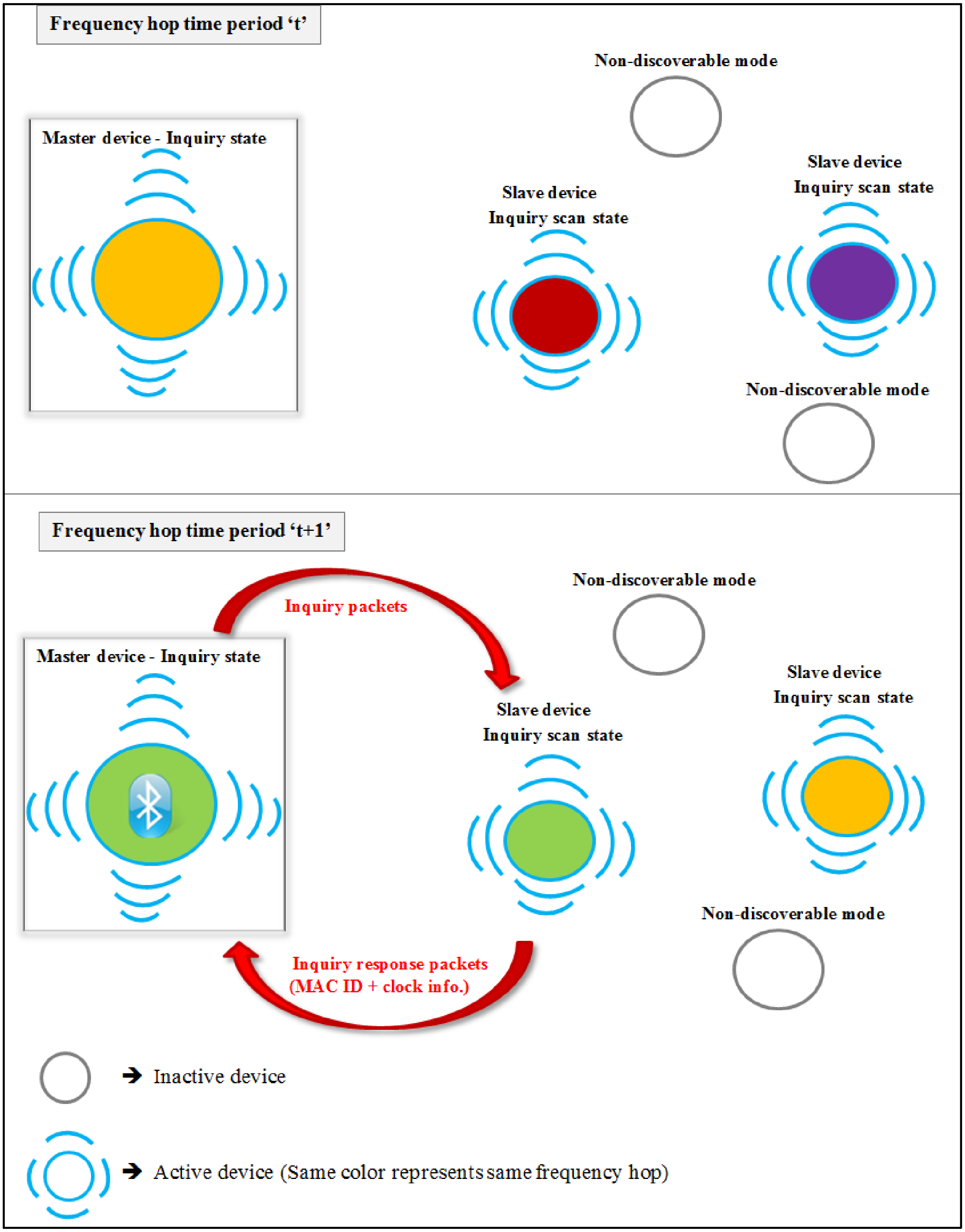


Figure 1: Process of Bluetooth Inquiry (Fair Use)

After the inquiry response process is complete, the master device proceeds to the 'page substate' as a preceding action to ultimately establish a connection with the slave device. In traffic engineering studies using Bluetooth technology, since we do not need to establish a connection between Bluetooth devices, the master device (positioned Bluetooth roadside sensor) is programmed to collect the MAC addresses of the incoming slave devices and then abort the inquiry phase to start a fresh one at the earliest possible time. Bluetooth technology is so widespread that most of electronic devices like mobile phones, in-car navigation systems etc. has Bluetooth in-built in it. Hence, the probability of detecting a Bluetooth device on a vehicle is increasing each day making Bluetooth technology based traffic data collection a potential method for actual in-field traffic data collections. All detected MAC addresses are time-stamped and stored in a database for traffic data analysis.

2.3 Bluetooth Technology in Traffic Field Data Collection

The roadside Bluetooth sensor unit detects, time-stamps and stores all the detected MAC addresses of the discoverable Bluetooth devices in its range. This dataset can include MAC IDs from stationary Bluetooth devices in nearby areas, or of passing Bluetooth devices associated with pedestrians/vehicles. When a number of such roadside Bluetooth sensors are installed at various locations, same MAC IDs detected at various sensors at various times will give us the dataset of mobile MAC IDs. An effective filter algorithm based on the time taken for the detections in various time periods will help us differentiate between pedestrian and vehicle MAC IDs. Figure 2 shows a MAC ID detection of a Bluetooth device in a vehicle at Bluetooth sensor 1 at time 10:02:23 AM. The same vehicle after it enters the detection range of Bluetooth sensor 2 is detected at time 10:03:00 AM. In this case, the time between the two detections will represent the travel time of the vehicle from Bluetooth sensor 1 to Bluetooth sensor 2.

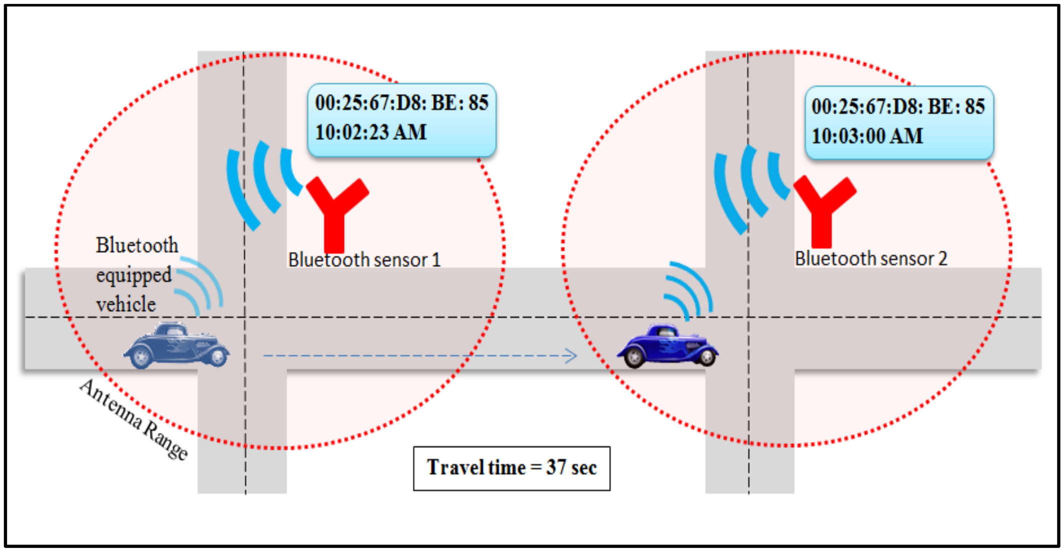


Figure 2: Principle of Bluetooth Detection Technology in Traffic Data Collection (Fair Use)

We can install a number of roadside Bluetooth sensors at various locations and matching the MAC IDs between all the Bluetooth sensors would give us the route a vehicle takes in our network. This helps us to determine the network origin-destination (O-D) for each vehicle detected. While a vehicle is passing through the detection range of a roadside Bluetooth sensor, a series of random detections are made and time-stamped with each ‘inquiry process’ of the sensor device. The frequency of these detections is random due to the frequency hopping structure of the Bluetooth technology. Hence, while matching MAC IDs between various sensors, we will get a series of matches for the same MAC ID with different time-stamps as it was passing by the sensor as seen from Table 2 for an actual Bluetooth data sample. In this particular case, one MAC ID was detected at Bluetooth sensor 3 from 1:12:25 PM Eastern Standard Time (EST) to 1:13:21 PM EST, at Bluetooth sensor 9 from 1:13:48 PM EST to 1:14:26 PM EST, and at Bluetooth sensor 5 starting at 1:14:31 PM EST.

Date: December 11, 2011			
Time-stamp	**Bluetooth Sensor**		
Eastern Standard Time (EST)	**Bluetooth Sensor 3**	**Bluetooth Sensor 5**	**Bluetooth Sensor 9**
1:12:25 PM	3		
1:12:30 PM	3		
1:12:51 PM	3		
1:12:56 PM	3		
1:13:01 PM	3		
1:13:06 PM	3		
1:13:11 PM	3		
1:13:16 PM	3		
1:13:21 PM	3		
1:13:48 PM			9
1:13:54 PM			9
1:13:59 PM			9
1:14:14 PM			9
1:14:20 PM			9
1:14:25 PM			9
1:14:26 PM			9
1:14:31 PM		5	
1:14:35 PM		5	
1:14:36 PM		5	
1:14:40 PM		5	

Table 2: Sample Bluetooth Data

One disadvantage of using Bluetooth technology is that we do not know the exact location of the vehicle while it is being detected. We only know the approximate range in which the vehicle can be detected depending on the range of the Bluetooth sensor antenna. Bluetooth works on frequency hopping principle and hence Bluetooth detections tend to be random in nature. At any given instant in time a device is in range, the detection can be thought of as a random event with values 0 or 1; 0 representing no detection and 1 representing a detection. Hence, a Bluetooth device is in range need not necessarily mean it will be detected by the sensor unit and if detected, it does not mean the device was detected exactly at the location of the sensor unit. Bluetooth detections depends on a lot of factors like frequency hopping nature of Bluetooth, interference by other radio waves using the same ISM frequency band, strength of the Bluetooth signals, distance of the device from the sensor unit etc. Due to the above factors, both detection at any time and continuity of detections of a Bluetooth device in range are random events. Therefore, referring to Figure 2, the detection of a Bluetooth device at Bluetooth sensor 1 need not necessarily mean the device is detected exactly as it passes the sensor unit. It can be detected anywhere within the range of the Bluetooth sensor. Consequently, the challenge would be to decide which detection to consider for calculation of traffic measures of effectiveness (MOEs) like the travel time, travel speed etc. The current practice is to choose among first detections, last detections or middle detections and then use it consistently throughout the study [6, 14]. Since the Bluetooth devices in the vehicles on the road has to be in discoverable mode for the roadside sensors to pick up its MAC ID, the current penetration rate of Bluetooth devices in field does not represent the actual traffic volume in the field. But, the Bluetooth traffic data does give us a significant sample size, if collected for long intervals of time, to accurately detect the travel time and travel speed for a network link under consideration [8, 15].

2.3.1 Bluetooth Data Collection Unit

The main part in a Bluetooth traffic data collection study is the roadside Bluetooth sensor unit or the ‘Bluetooth data collection unit’. An important component in the basic design of a Bluetooth unit consists of a good Class 1 Bluetooth adapter with an expandable Bluetooth antenna port. The Class 1 Bluetooth adapters come with a default range of around 100m which can be expanded according to our requirements using externally attachable antennas. Any normal netbook available in the market can be used for running the Bluetooth inquiry program for the connected Bluetooth adapter and storing the collected MAC IDs and time-stamps. This unit setup was observed to have ‘clock drifts’ for the netbook time and hence the time being time-stamped for the Bluetooth equipped vehicle detections, as the clock is not synchronized continuously with an external time source [6]. Another challenge in this design is the requirement for a continuous power supply for the Bluetooth unit. However, this design is still widely used by traffic engineers using Bluetooth data collection technique as the cost of implementation is the minimum. The problem of continuous power supply and weather protection for the Bluetooth unit can be solved instantly if the Bluetooth unit is installed inside a traffic cabinet. External batteries can also be provided but is unreliable for longer periods of data collection. Only the

Bluetooth antenna needs to be installed outside the traffic cabinet by extending it by using an USB cord as the radio signals cannot propagate inside a metal box.

An effective improvement to the Bluetooth unit to solve the problem of clock drift is by embedding and connecting it to a GPS device to constantly synchronize the system clock with a common time reference [16, 17]. One another major advantage of using Bluetooth traffic data collection technique is that it can be setup even in areas considered inaccessible by other data collection techniques. In such areas, access to a continuous power source becomes a challenge and hence the Bluetooth unit as a chipset design (Figure 3) connected to a solar energy panel (Figure 4) has been studied [7, 17-20]. Although Bluetooth technology is known for low-power usage, the reliability of a solar source to power the Bluetooth unit for long durations is yet to be studied. Expanding the capabilities of Bluetooth traffic data collection method, Global System for Mobile communication (GSM) feature has been added to the Bluetooth unit to transfer collected data in real-time [16, 17]. With GSM feature, the data collected by the Bluetooth unit is transferred in real-time to a data processing center where the data is processed to find traffic performance measures like travel time, traffic speed etc., and made available to the public in near real-time. Currently, there are a number of commercially marketed Bluetooth units by various manufacturers under various trade names (BluFax [17], BluTOAD [20], StreetWAVE [19], Acyclica [7] etc.).

Figure 3: Bluetooth unit chipset design with GPS+GSM [4]

Figure 4: Bluetooth Unit with Solar Energy Capability [17]

With each additional feature, the Bluetooth unit capability increases but the cost also goes up. Therefore, it actually depends on the objectives of the study, accuracy of the traffic data required for the study, type of unit installation (temporary or permanent), budget available for the study, and speed with which the processed data is required, in deciding the type of Bluetooth unit and features to be included with it.

2.3.2 Bluetooth Antenna Selection

Another important part in any Bluetooth unit design is the Bluetooth antenna and its detection range, type of detection direction and signal strength. One of the initial researches in Bluetooth traffic data collection technique has been on types of Bluetooth antennas and its suitability for various traffic studies. Basically, two types of antennas were considered for the studies; omnidirectional and directional antennas. Omni-directional antennas transmit radio signals equally in all the directions in a horizontal (horizontally polarized) or vertical (vertically polarized) plane. Directional antennas have higher signal strength concentrated in a specified direction improving the antenna gain in that particular direction.

Although directional antennas have lower spatial errors in the detection of Bluetooth equipped vehicles, they were found to give very less data sample size resulting in large errors in the travel time and traffic speed calculations [14]. They were also found to be biased towards slow moving vehicles due to their smaller detection ranges [14]. On the other hand, omni-directional antennas gave better results and lower error values due to their high traffic data sample sizes [14]. The detection range of the omni-directional antenna is comparatively more than directional antennas leading to higher spatial errors in the detection of Bluetooth equipped vehicles. However, while taking the average value over a large sample size, the results for omni-directional antennas were found to be comparable to the real traffic data. Studied were also done on various types of omni-directional and directional antennas with different polarizations. An omni-directional antenna with vertical polarization was found to perform the best in traffic monitoring studies using Bluetooth technology [21]. Although, the quality and quantity of data collected depends on the antenna polarization, gain, detection range and the specific field conditions, a vertically polarized omni-directional antenna has been recommended for Bluetooth traffic data collection studies [14, 21]. Detection delay and conflict due to the installation of two sensors simultaneously has been investigated to be minimal although detection conflicts in case of more than two sensors as well as its use in improving the Bluetooth detection rate is yet to be fully studied [14]. Number of Bluetooth detections is inversely proportional to the distance from the sensor unit and other radio interference factors/technologies in the field using the same ISM frequency band. Hence, the location of the Bluetooth antenna with respect to the field is also an important factor to be considered [9]. Further research needs to be done to exactly classify the antenna type to be used with specific field conditions for maximum performance.

2.3.3 Method Validation

Any new traffic data collection method needs to be validated with existing ‘ground truth’ technologies before it can be implemented for regular field data collection. Accuracy of the collected data and its percentage error with respect to the actual value in the field is the major criteria considered for any validation techniques. Bluetooth technology has been successfully validated by various ground truth methods like Floating car data, ALPRS etc., to provide very close travel time and traffic speed estimates [6, 8, 14]. Bluetooth data is found to be continuous for 24 hours a day with a large sample size. Consequently, Bluetooth data collection method is found to be more complete and seen to predict the state of traffic (e.g., congestion level and average travel times) better than GPS-based floating car method due to the smaller sample size [6]. Bluetooth method also proves to be an alternative replacement method for highly priced methods like ALPRS, toll tag readers etc., as Bluetooth traffic data provides comparatively close travel time estimates [14]. An attempt at solving the issue of lack of location information in Bluetooth traffic detection technique has been to use Received Signal Strength Indicator (RSSI) of the Bluetooth antenna. RSSI helps to find the approximate location of the vehicle but there has been no validation studies done for the receiver sensitivity, RSSI value update rate capability for each device, and the cost of RSSI instrument [22].

2.3.4 Approximate Location Estimation Using Overlapping Bluetooth Antennas

There have been few studies in the past which have attempted to approximately estimate the location of an object using Bluetooth sensors [23, 24]. Most of such studies have tried to use a combination of Received Signal Strength Indicator (RSSI) and theoretical Bluetooth antenna ranges to locate a Bluetooth equipped object within a narrow location range. The idea of approximate location estimation based on RSSI has been used in a past study to determine the worker proximity to hazards [25]. Another concept of overlapping antennas has been applied to in-building Bluetooth device detection. This concept has not been applied to traffic engineering yet. The basic idea of this concept applied to traffic data collection based on overlapping antennas is as shown in Figure 5. In the case where two roadside Bluetooth sensor units are kept close enough so that their antenna ranges overlap, if a Bluetooth equipped vehicle is detected at both the sensor units at the same time, then the location of the vehicle can be narrowed down to the overlapping antenna range (hatched portion in Figure 5).

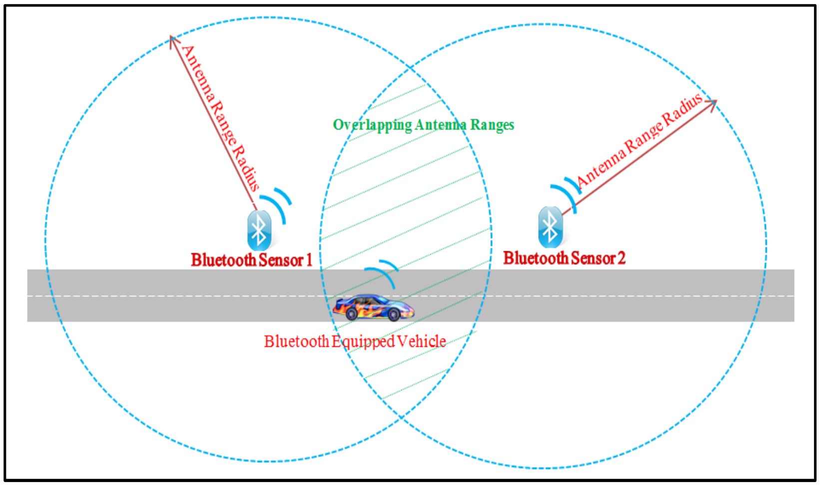


Figure 5: Vehicle location with overlapping antennas (Fair Use)

Although the concept appears simple, more research needs to be done to see the consistency of overlapping detections before this can be implemented in field. Also, overlapping antennas will give rise to unwanted complications in the otherwise more direct travel time and Origin-Destination (O-D) estimations. Hence, efficient algorithms to address the above issues should be developed before attempting to apply the overlapping antenna concept to determine approximate vehicle locations in field.

2.3.5 Privacy issues

The 48-bit Median Access Control ID is a unique identifier address, consisting of groups of hexadecimal digits, for each Bluetooth device in the market. It is using this address that the Bluetooth devices try to communicate and connect with other discoverable Bluetooth devices in range. The manufacturer generates and embeds this unique ID to each Bluetooth device being manufactured but do not maintain any database relating a MAC ID to a specific Bluetooth device and its purchaser. Hence, it is not possible to match and track down a MAC ID to a particular device unless one personally knows the MAC ID of a device. Moreover, only the MAC IDs of Bluetooth devices in the 'discoverable mode' are collected. The owner of a device can set the device to 'indiscoverable mode' at any time to avoid detection.

A method adopted in the current practice to provide extra privacy protection is to clip some digits of the MAC address so that it still remains unique to match MAC IDs, but impossible to find the original full MAC address from it [6, 21]. Another efficient method to completely hide the actual MAC ID is to encrypt it before storing it for data analysis [5, 7]. An efficient encryption algorithm would still be able to match the encrypted MAC IDs but makes it impossible for anyone to decipher the actual MAC ID from it.

2.3.6 Advantages and Applications

Bluetooth data can be collected continuously 24 hours a day and 365 days a year with minimal installation and maintenance cost. Bluetooth technology has been designed to consume minimum power possible and hence the challenge of high power requirement does not exist in Bluetooth traffic data collection method unlike for other alternative methods in practice (ALPRS, AVL etc.). Its low power consumption makes it feasible to use solar power when implemented in areas inaccessible to any external power supply. Bluetooth data collection technology can be successfully implemented in areas considered inaccessible to other methods like a ramp entry/exit, middle of a freeway section etc. This method does not need any changes to be made to existing road infrastructure making it economically viable for immediate implementation in the system for continuous data collection in real-time.

The listed advantages makes it a potential alternative to use in various ITS studies and data collection until Dedicated Short-Range Communication (DSRC) designed for ITS vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications is fully implemented and functional in the field. DSRC is defined for high-level accurate V2V and V2I communications as a step forward to highway automation which will take more years to become a reality. Bluetooth traffic data collection has been successfully tested for freeway and arterial travel times [8, 26]. The same concept of Bluetooth data collection has been applied to find the proximity of workers to hazards (noise and dust) with reasonable accuracy. This uses Bluetooth signal strength measurement with respect to the linear distance between the Bluetooth equipped worker and the hazard [25]. Route choice and travel time reliability in cases of sudden induced congestion (e.g., closing of a bridge) has been investigated to be representative of the actual field values [27]. Different moving average techniques and Kriging method has been evaluated for travel time and traffic speed prediction ahead of time under uncongested conditions [28]. Kriging method of prediction has been found to provide reasonable data under congested conditions too. Kalman filter approach has also been studied for travel time forecasting and time dependent O-D matrices [5]. Bluetooth technology has also been successfully applied to pedestrian traffic for finding the passenger screening time from the non-sterile side before security screening to clear the security checkpoint and reach the sterile side.

3 BLUETOOTH UNIT DEVELOPMENT, TESTING AND DATA COLLECTION

3.1 Bluetooth Traffic Data Collection Unit

The Bluetooth unit used for this study was designed in the VT-SCORES Lab in Virginia Tech. Designing the unit posed a lot of challenges in the beginning due to the lack of literature review and proper guidelines for the development of a Bluetooth unit, in the relatively newly researched field of 'Bluetooth MAC ID detection traffic data collection method'. All possible alternatives for a system design from a basic netbook-Bluetooth adapter design to Bluetooth chipset design were considered. Considering the budgetary constraints, a netbook-Bluetooth adapter unit was proposed to be developed. The next challenge included in finding a good Bluetooth adapter which had antenna extension capability to increase the range of detection. Finally, a Bluetooth USB adapter 'Parani UD 100' by SENA technologies was found to meet the study requirements precisely [29]. A 5dBi antenna by the same manufacturer was used in this study which had a specified range of about 600m in open field but lesser achievable range in real test fields which may not be open and which may have interference from other radio signals [30]. The Bluetooth unit was decided to be kept inside the traffic cabinet for continuous power supply as well as weather protection for the system. The Bluetooth antenna had to be kept outside the traffic cabinet as propagation of radio signals is affected inside a metal box. A USB extension cord (length ≤~ 5m) was found to have no signal loss unlike an antenna extension cord. Signal strength is crucial in this study as signal strength and hence the number of data points (Bluetooth detections) captured is inversely proportional to the distance from the Bluetooth sensor. Hence, the Bluetooth adapter wrapped in a weather proof material connected to the Bluetooth antenna was kept outside on top of the signal cabinet extended through a USB extension cord connected to the netbook. A netbook cooler was also provided to mitigate problems due to the overheating of the netbook inside the traffic cabinet. The whole Bluetooth unit developed is as shown in Figure 6.

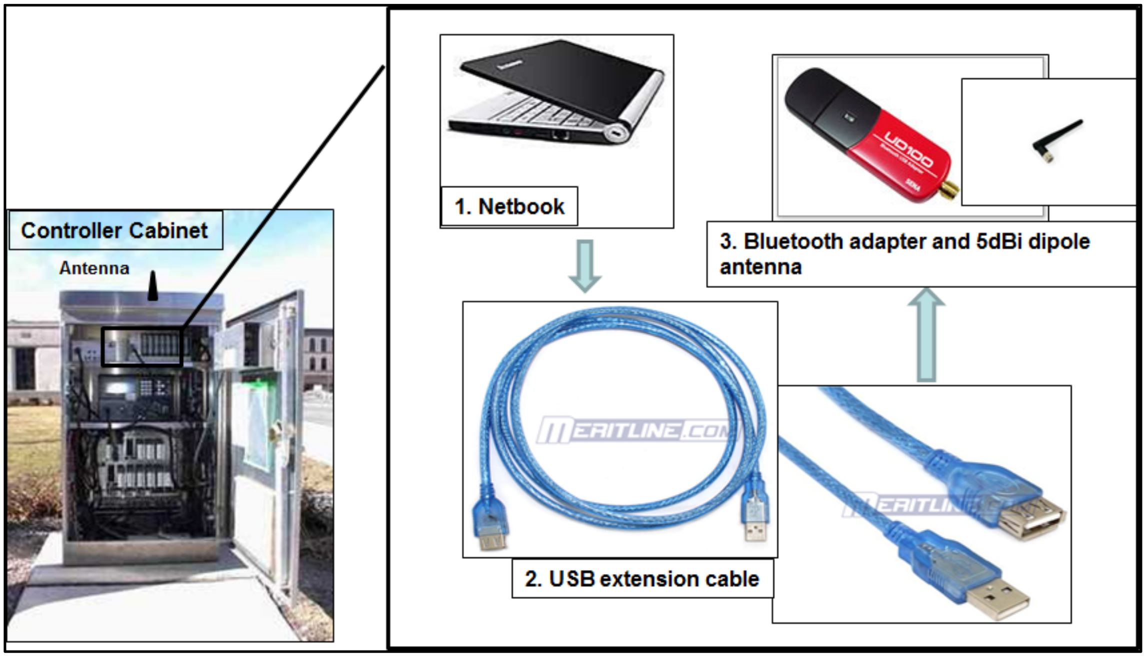


Figure 6: Bluetooth Unit [29, 31-33]

3.2 Bluetooth Unit Testing and Pilot Study

A pilot study in Main Street Blacksburg was done to test the developed Bluetooth unit for required functionality. Six major locations were identified near Virginia Tech Campus in North Main Street, Blacksburg for testing (Figure 7). The basic objective of this pilot study was to determine the feasibility of the Bluetooth unit to collect the vehicle data in an actual roadway setting.

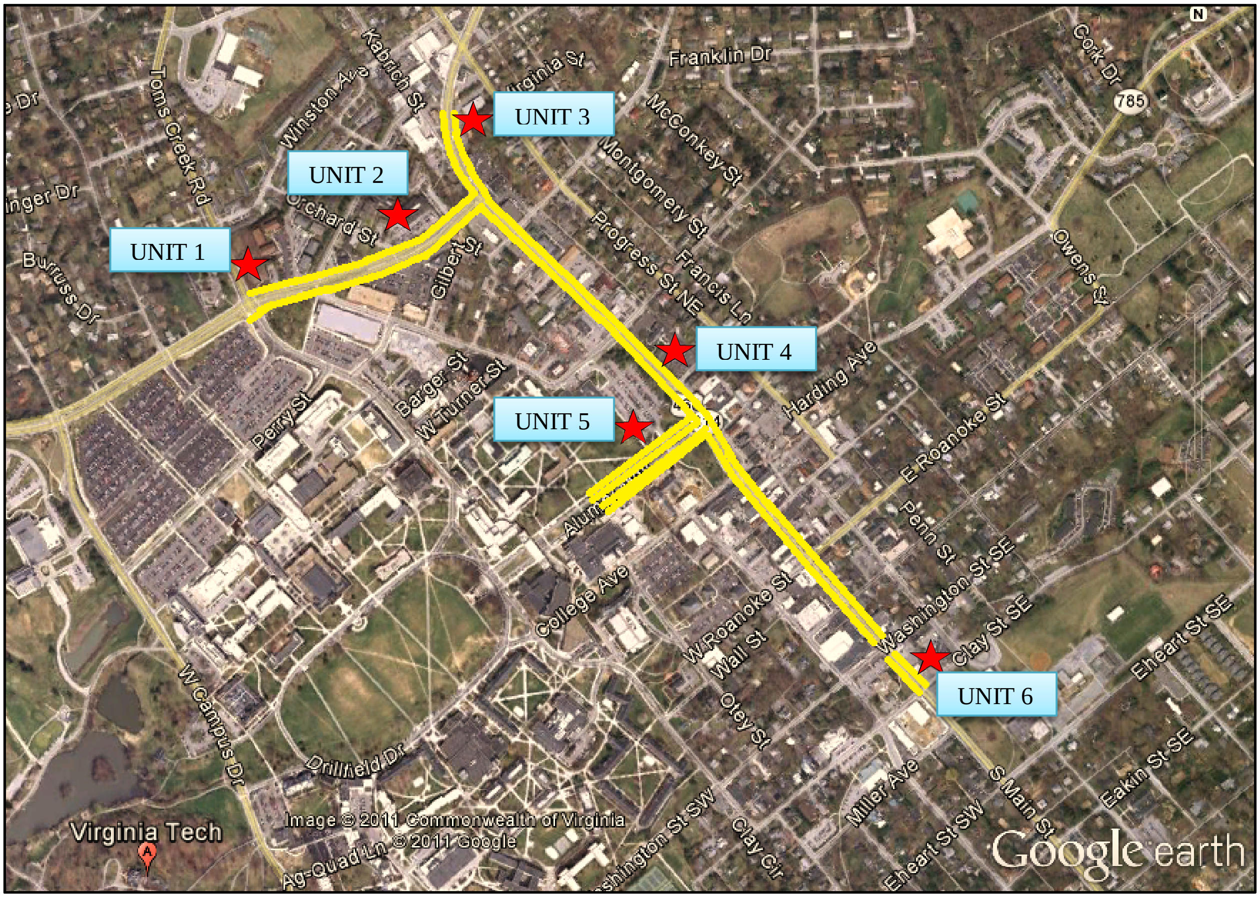


Figure 7: Blacksburg Main Street Study Network with Installed Bluetoth Units [34]

The data was collected for 1 hour from 3:30pm to 4:30pm on 29 October, 2010. A 1dBi stub antenna was used for this study. Successful MAC ID matches were obtained at five locations out of the total six Bluetooth unit locations considered for the study as shown in Table 3. The MAC ID matches obtained might have been lower than actual due to the ongoing roadway improvement work in certain parts of North Main Street, Blacksburg, during that time. The location where no Bluetooth MAC ID matches were observed (Alumni Mall, unit 5) was found to be affected due to its closeness to the roadway improvement work mentioned above and consequent vehicle detours.

			Bluetooth Link O-D					
Bluetooth Unit	**Location**	**Matched MAC IDs originating from unit**	**Tom's Creek/Prices Fork Intersection**	**Prices Fork**	**N Main Street**	**Alumni Mall**	**E Roanoke Street (near Church Street)**	**Clay Street/ N Main Int.**
1	Tom's Creek/Prices Fork Int.	**14**		2	2	1	1	8
2	Prices Fork	**6**	5		1	0	0	0
3	N Main Street	**8**	1	2		1	1	3
4	Alumni Mall	**0**	0	0	0		0	0
5	E Roanoke Street (near Church Street)	**6**	0	0	1	0		5
6	Clay Street/N Main Int.	**15**	5	0	7	0	3	

Table 3: Blacksburg Main Street Pilot Study Results

3.3 The Study Network

Reston Parkway is an arterial network in Reston, Virginia consisting of 14 signalized intersections with an approximate total length of 16572 feet (Figure 9). The traffic, especially the peak hour traffic, in Reston Parkway is oversaturated with building vehicle queues and occasional spillbacks. The surrounding area is highly active with mainly office spaces and hence morning, afternoon and evening peak-hour traffic during the regular weekdays become congested and unmanageable. The arterial is also connected to East Bound and West Bound high-speed Toll Roads to Washington Dulles Airport with three on-ramps and two off-ramps. Signal timing design, coordination and optimization is a challenging task without the knowledge of the critical route network O-Ds and intersection control delays in the oversaturated Reston Parkway. Bluetooth method of traffic data collection looked promising to get quality data at a very minimal cost.

A Bluetooth unit configuration as shown in Figure 8 will help us acquire details about all the 12 traffic movements in an intersection. Table 4 gives details about which Bluetooth roadside sensors needs to be matched for obtaining a particular traffic movement. But, collecting data for all traffic movements in all the major intersections of Reston Parkway was infeasible due to budget constraints on the number of Bluetooth units. Hence, major critical routes which most of the vehicles traverse during oversaturation periods observed from a previous study at VT-SCORES Lab were used to determine the location of the 9 Bluetooth units developed so that all critical routes causing oversaturation during peak-hours are captured in the data collection.

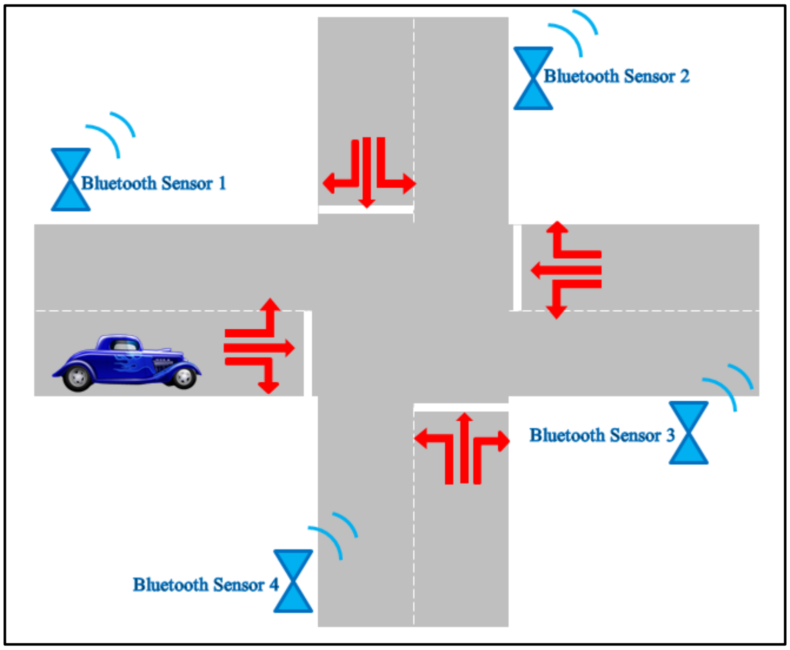


Figure 8: Bluetooth sensor location configuration for capturing all traffic movements at an intersection (Fair Use)

Direction of Traffic	Movement	Bluetooth Sensors to Match
EB	Left	1 to 2
	Through	1 to 3
	Right	1 to 4
WB	Left	3 to 4
	Through	3 to 1
	Right	3 to 2
NB	Left	4 to 1
	Through	4 to 2
	Right	4 to 3
SB	Left	2 to 3
	Through	2 to 4

	Right	2 to 1

Table 4: Bluetooth sensor data to match for obtaining various traffic movements

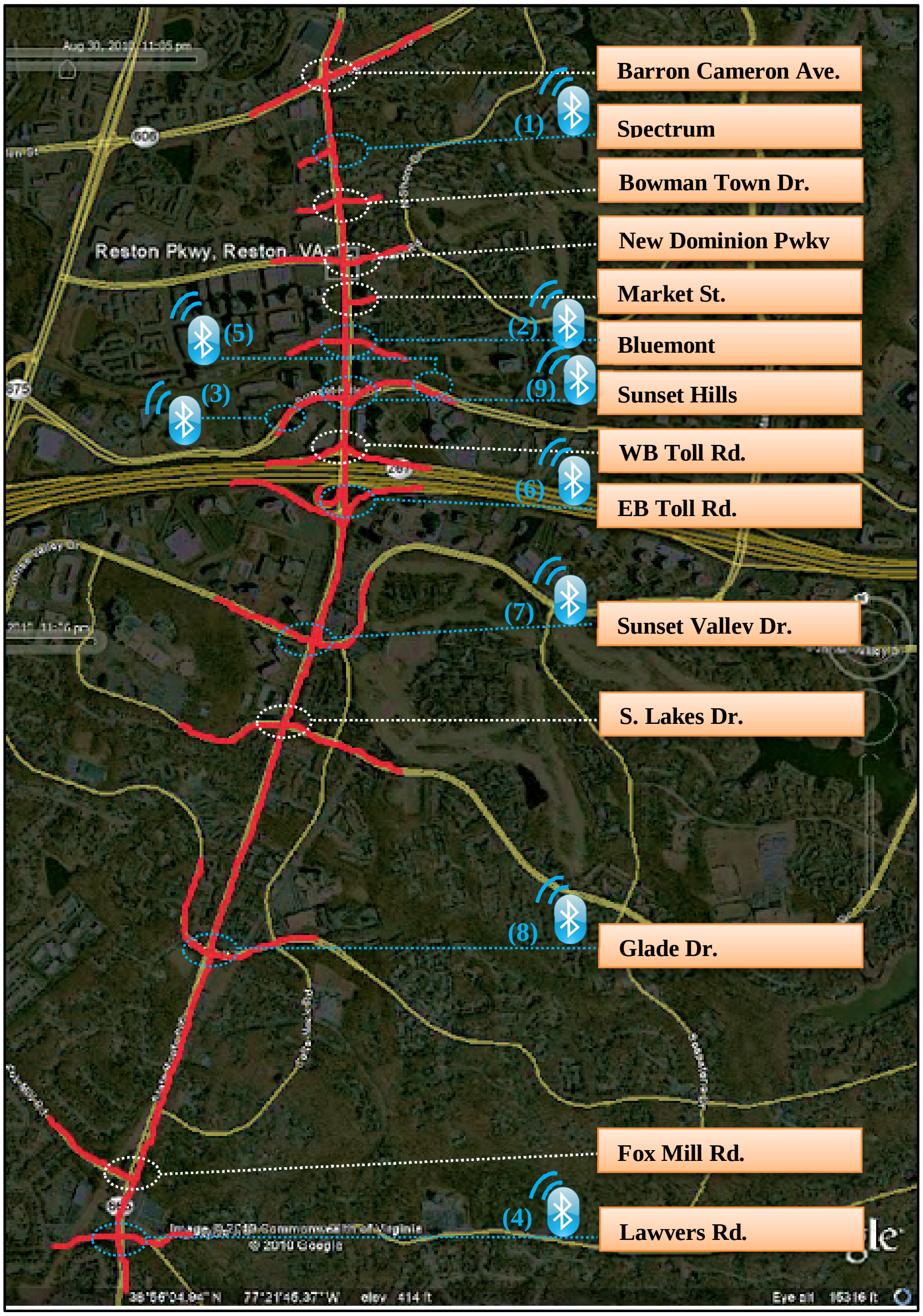


Figure 9: Reston Parkway study network with Bluetooth unit locations [34]

3.4 Data Collection – Bluetooth and GPS Data

Traffic data was collected using 9 Bluetooth units installed at the Reston Parkway Network. The data was collected for 18 days (excluding unit installation and removal days) from November 24, 2010 to December 11, 2010.

For validating the Bluetooth data collected as well as for developing microscopic delay models from synchronized Bluetooth and GPS data, GPS probe vehicle runs were made and data collected on December 11, 2010 from around 1:00pm to 5:00pm. The GPS probe vehicle had an in-car navigation system with Bluetooth capability. Hence, Bluetooth and GPS data for the same vehicle was collected for synchronization and validation purposes. GPS probe vehicle runs were done covering mainly three intersections as shown in Figure 10. Sunset Hill intersection (labeled Bluetooth unit 9) is one of the busiest intersections prone to oversaturation frequently in the Reston Parkway Network.

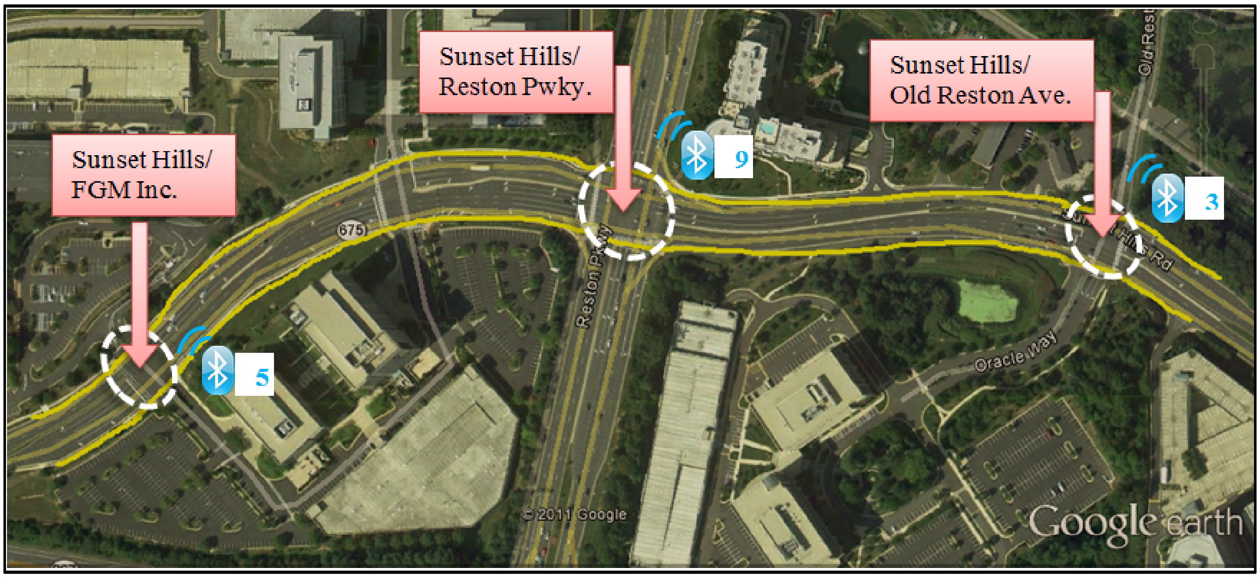


Figure 10: GPS data collection study network [34]

3.5 Data processing

3.5.1 Bluetooth data

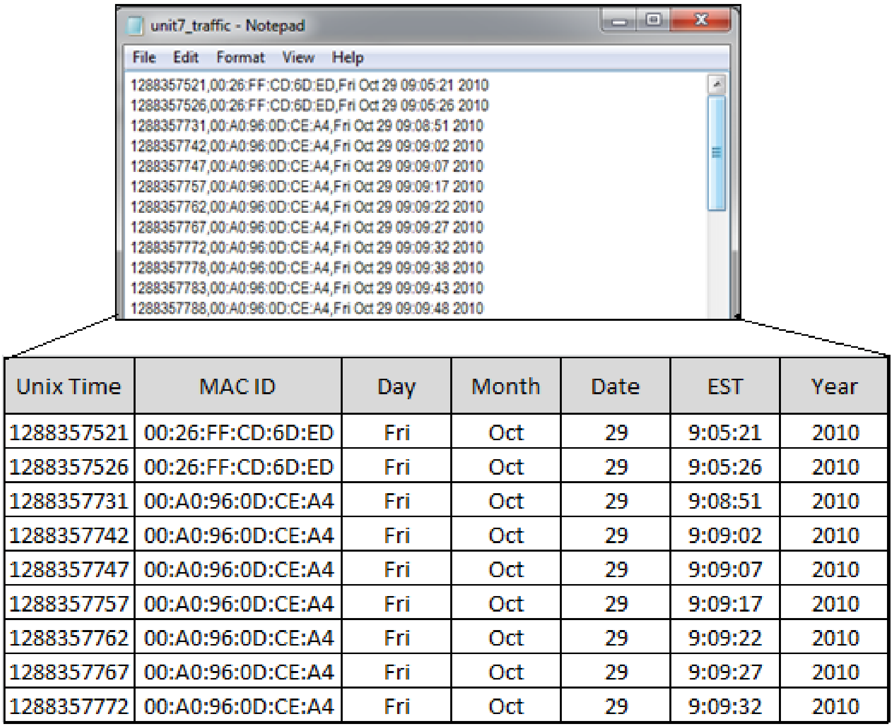
Bluetooth data for December 11, 2011 was processed to validate it with the GPS probe vehicle runs done on the same day at intersections with Bluetooth sensors 3, 9 and 5. Bluetooth data was also processed for December 10, 2011 (Friday) to calculate the control delay using the microscopic delay model developed based on the Bluetooth number of detections/hits.

The Bluetooth data collected has the following information as shown in Table 5:

1. Unix time
2. MAC ID

3. Date
4. Time in EST
5. Year

Unix time is defined as the number of seconds elapsed since midnight Coordinated Universal Time (UTC) of Thursday, January 1, 1970 [23]. Unix time is widely used by the research world as it is easier in computations of time.



```
1288357521,00:26:FF:CD:6D:ED,Fri Oct 29 09:05:21 2010
1288357526,00:26:FF:CD:6D:ED,Fri Oct 29 09:05:26 2010
1288357731,00:A0:96:0D:CE:A4,Fri Oct 29 09:08:51 2010
1288357742,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:02 2010
1288357747,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:07 2010
1288357757,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:17 2010
1288357762,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:22 2010
1288357767,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:27 2010
1288357772,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:32 2010
1288357778,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:38 2010
1288357783,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:43 2010
1288357788,00:A0:96:0D:CE:A4,Fri Oct 29 09:09:48 2010
```

Unix Time	MAC ID	Day	Month	Date	EST	Year
1288357521	00:26:FF:CD:6D:ED	Fri	Oct	29	9:05:21	2010
1288357526	00:26:FF:CD:6D:ED	Fri	Oct	29	9:05:26	2010
1288357731	00:A0:96:0D:CE:A4	Fri	Oct	29	9:08:51	2010
1288357742	00:A0:96:0D:CE:A4	Fri	Oct	29	9:09:02	2010
1288357747	00:A0:96:0D:CE:A4	Fri	Oct	29	9:09:07	2010
1288357757	00:A0:96:0D:CE:A4	Fri	Oct	29	9:09:17	2010
1288357762	00:A0:96:0D:CE:A4	Fri	Oct	29	9:09:22	2010
1288357767	00:A0:96:0D:CE:A4	Fri	Oct	29	9:09:27	2010
1288357772	00:A0:96:0D:CE:A4	Fri	Oct	29	9:09:32	2010

Table 5: Details of Bluetooth traffic data

3.5.2 GPS Data

The GPS data collected on December 11, 2011 was processed to synchronize with the Bluetooth data and validate it. The GPS raw data collected has the following information as shown in Table 6:

1. Date
2. Time
3. Latitude
4. Longitude

DATE	TIME	Latitude	Longitude
121110	122454	3857.336	-7721.33
121110	122455	3857.324	-7721.34
121110	122456	3857.319	-7721.34
121110	122457	3857.316	-7721.34
121110	122458	3857.313	-7721.34
121110	122459	3857.311	-7721.34
121110	122500	3857.309	-7721.34
121110	122501	3857.308	-7721.34
121110	122502	3857.308	-7721.34
121110	122503	3857.307	-7721.34

Table 6: Details of GPS data

The format of the obtained raw GPS data is as follows:

1. Date: DDMMYY without space in between
2. Time: Hours, Minutes and Seconds without space in between.
3. Latitude: The first two digits are in degrees and the rest are in minutes. Positive value implies north of equator and negative implies south of equator. E.g., if latitude data is collected as 3857.307, it means latitude is 38^{o} 57.307′North
4. Longitude: Same format as for latitude. Negative longitude value implies west and positive value implies east of prime meridian respectively. E.g., if longitude data is collected as -7721.33, it means longitude is 77^{o} 21.23′ West

3.6 Vehicle Trajectory Development

GPS data is recorded every second for the vehicle as it maneuvers through intersections 3, 9 and 5, back and forth. The latitude and longitude values for the center point of all the three intersections under consideration were found from Google Earth as shown in Table 7.

Bluetooth unit no.	Intersection	Latitude (in deg.)	Longitude (in deg.)
3	SUNSET HILLS/FGM Inc.	38.95427	-77.359
9	RESTON/Sunset Hills	38.95516	-77.35547
5	SUNSET HILLS/Old Reston Ave.	38.955	-77.35191

Table 7: Latitude and Longitude for Intersections 3, 9 and 5

The distance of the vehicle with respect to intersections 3, 9 and 5 were calculated at each second using the spherical law of cosines as given below:

Spherical law of cosines:

$$\boldsymbol{d} \;=\; \boldsymbol{acos}(\boldsymbol{sin}(\boldsymbol{lat_1}).\boldsymbol{sin}(\boldsymbol{lat_2}) + \boldsymbol{cos}(\boldsymbol{lat_1}).\boldsymbol{cos}(\boldsymbol{lat_2}).\boldsymbol{cos}(\boldsymbol{long_2} - \boldsymbol{long_1})).\boldsymbol{R}$$

$$where, R\ is\ earth's\ radius\ (mean\ radius\ =\ 6{,}371km)$$

Intersection 9 (Sunset Hills/Reston Parkway) was taken as the base and assigned a distance of zero. Distance of the vehicle from unit 9 to unit 3 was taken as negative and to unit 5 was taken as positive to plot the trajectory of the vehicle using GPS data. The Bluetooth detections for units 3, 9 and 5 were super imposed on the GPS vehicle trajectory plot by matching the time of detection to the GPS time as shown in Figure 11.

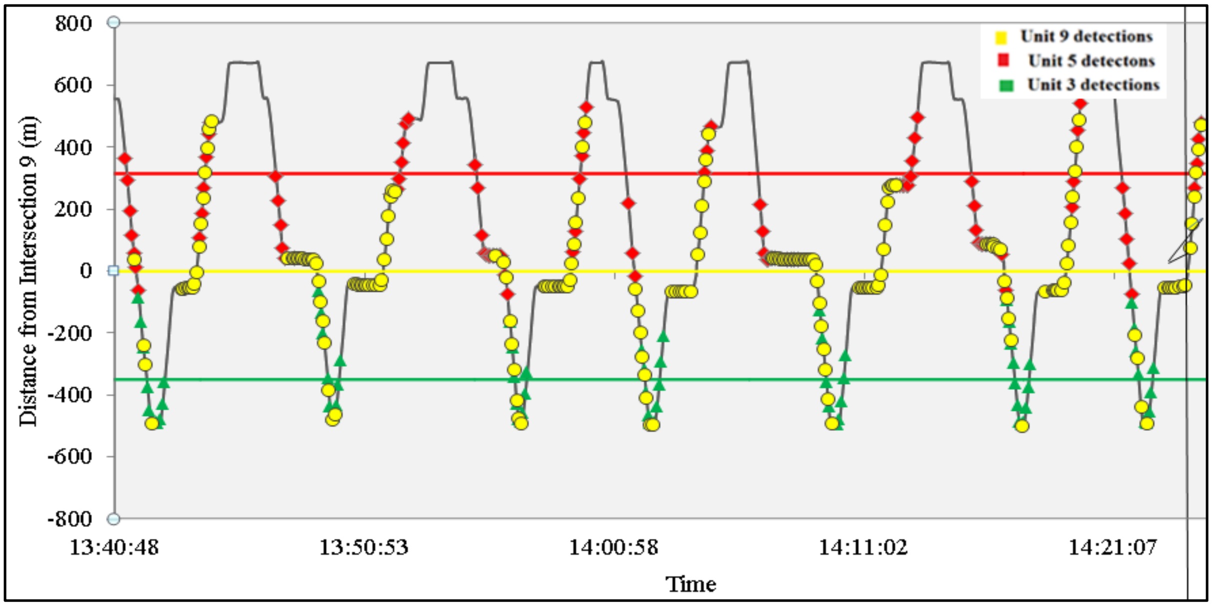


Figure 11: Vehicle trajectory plot with superimposed Bluetooth detections (Fair Use)

There were a total of 32 GPS runs done in each east-bound (EB) and west-bound (WB) direction of the traffic. The stopped delay and total control delay can be read directly from the Bluetooth superimposed GPS vehicle trajectory plot. The actual delay of the GPS probe vehicle was found by the above method. The number of Bluetooth detections/hits for each run and the total time duration between first and last detections for each run can also be extracted from the above plot. This information was used in the microscopic modeling of control delay with respect to Bluetooth hits and Bluetooth detection duration as explained in the subsequent chapters.

4 MICROSCOPIC MODELING OF CONTROL DELAY AT SIGNALIZED INTERSECTIONS BASED ON BLUETOOTH AND GPS DATA

4.1 Abstract

Bluetooth Median Access Control (MAC) ID detection method has been proven to be an effective technique for near real-time traffic monitoring. Moreover, its continuous data collection capability by sampling the actual traffic makes it feasible for permanent installation in the road with minimal cost and better data, both qualitatively and quantitatively. The traffic data obtained through this method referred to as ‘Bluetooth data’ has been successfully validated by various methods in the past studies for direct traffic travel time and speed measurements. However, the delay calculated with simple matching of MAC IDs has some inherent errors due to the frequency hop structure of Bluetooth detections. The detections of a Bluetooth device in a traveling vehicle can be thought of as random events varying in space and time. This study deals with the development of a microscopic methodology to calculate traffic control delays by quantifying the detection errors with synchronized Bluetooth and GPS probe vehicle data.

Keywords Bluetooth-GPS data synchronization; Bluetooth detection errors; Traffic delay analysis

4.2 Introduction

Cost-effective and robust methods to collect continuous traffic data for various Traffic Management Systems have always been the top priority of transportation researchers and professionals. Bluetooth MAC ID detection techniques has emerged as a promising alternative during the last few years attributed to its various advantages such as data collection even in inaccessible areas, temporary or permanent installation capability, minimal to no privacy intrusions compared to existing techniques like Automatic License Plate Recognition Systems (ALPRS) and toll tag reading, etc. Bluetooth communication works on the globally open Industrial, Scientific and Medical (ISM) frequency band of 2.402 GHz and 2.480 GHz, requiring no changes to the existing infrastructure. Currently, the need to standardize the technique to make it more viable in every day traffic monitoring has gained an increasing attention in the research world.

Bluetooth traffic monitoring technique gains its importance due to its robustness and low cost. The designing of the 'Bluetooth unit' has come a long way from the basic netbook-Bluetooth adapter unit to a more advanced Bluetooth compact chipset with solar energy capabilities for continuous power [4] and GPS+GSM capabilities for real-time data processing [4, 17]. The range of an antenna highly depends on each specific product although a vertically polarized [21] omni-directional antenna [14] is preferred for a Bluetooth study due to its higher matching rates and lower travel time errors.

Bluetooth MAC ID detection technology data collection method has been validated in many previous studies with various existing methods such as floating car data [6, 8] and Automatic License Plate Recognition System (ALPRS) [14] to establish as a ground truth in future ITS studies. However, there are many issues related to the random detection nature of Bluetooth which should be addressed before its successful implementation as a ground truth data collection method in the field. Received Signal Strength Indicator (RSSI) has also been used to locate the approximate location of the vehicles with a Bluetooth device in it [22] but there has been no validation for the receiver sensitivity, RSSI value update rate capability for each device found, and cost of RSSI instrument. Although there has been many studies related to the Bluetooth travel time error estimation [4] and forecasting [5], none of them have tried to look at the Bluetooth detection error which is a major factor for travel time and delay errors. Apart from finding travel time and space mean speed, Bluetooth MAC ID technique can be used for various other applications like estimating route choice [35], worker proximity to construction health hazards [25], passenger screening time at security checkpoints in airports [15] etc.

Hence, detection error in data collection due to the random nature of Bluetooth detections is an important factor affecting the accuracy of travel time and delay calculations. The detection of an inquiry-scan Bluetooth device within the range of an inquiring Bluetooth device can be thought of as a random event which can take two values; 1 – a detection is made and 0 – no detection is made. In addition, any detection made is again a random event varying in time and space. Hence, calculation of travel time and delay based on matching MAC IDs only is prone to huge errors as current Bluetooth MAC ID detection technique gives us only the time and the Bluetooth detection unit number. To illustrate the point, Figure 12 shows three different Bluetooth detection situations. The first section of the figure shows a situation where the vehicle with the Bluetooth device is detected exactly at each intersection, giving us a correct travel time of 25 seconds. The second two sections of the figure show two probable situations due to the random error in Bluetooth detections, where the device can be detected before the vehicle reaches the second intersection or after the vehicle have crossed the intersection, providing travel time of 19 seconds and 33 seconds, respectively. In fact, in some situations observed in the field at closely-spaced intersections, some of the Bluetooth detections at the second intersections were observed before the first intersection, leading to negative travel time estimates.

Hence, modeling the detection error is of prime importance to accurately find the delay at intersections. This paper concentrates on quantifying the Bluetooth detection error to estimate and validate the control delay at intersections by using GPS probe vehicle data.

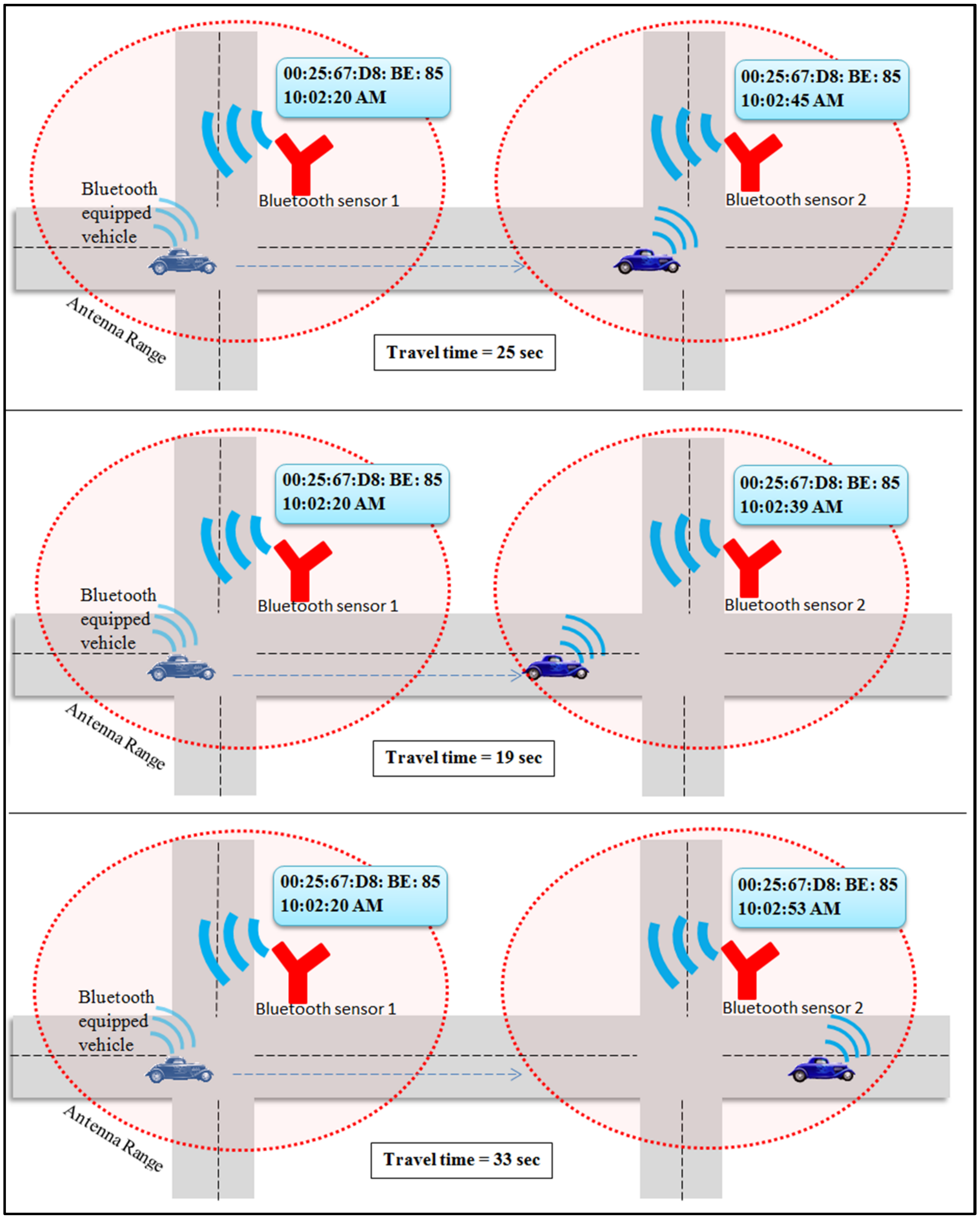


Figure 12: Illustration of ideal and worst-case Bluetooth detections (Fair Use)

4.3 Bluetooth Unit Development and Data Collection

This Bluetooth study is part of a signal timing improvement project for the Reston Parkway network in Northern Virginia (Figure 9). A Bluetooth study was found to be the most feasible method to sample the network Origin-Destination (O-D) matrix and to find the major traffic movements for signal timing improvements for the oversaturated Reston Parkway. Bluetooth units developed at the VT-SCORES Lab, Virginia Polytechnic Institute and State

University (Virginia Tech) were installed at 9 chosen intersections of the total 14 intersections of the Reston Parkway network for continuous and quality traffic data. Being a temporary installation with budget constraints, basic netbook-Bluetooth adapter unit format was adopted. SENA Parani UD-100 Bluetooth adapters with 5dBi omni-directional antennas were used for the entire study. The Bluetooth device inquiry software was developed in the Linux platform and set to minimum feasible detection cycle length. The average device detection rates were noted from the study to be 5 seconds. The Bluetooth units were placed inside the signal traffic cabinet (Figure 13) for weather protection and continuous power supply. USB extension cables of less than 5 meters were found to have no signal loss and hence were considered instead of an antenna extension cable.

As the performance of any Bluetooth unit depends on various factors like the gain and polarization of antenna used, signal strength and surrounding environment, a pilot study to test the unit as a whole was completed on Main Street, Blacksburg, VA. The study was successful with about 4-5% detection matching rate. An antenna range field test was also conducted for SENA UD 100 1dBi and 5dBi antennas with and without USB cable extension chord in two locations of the Virginia Tech Campus: Burruss Hall Bus stop which has a lot of bus traffic with students boarding/alighting and an open ‘Drillfield’ which was the closest open space accessible for testing although surrounded by multiple buildings. The results of the approximate ranges obtained for both the antennas matched the manufacturer specifications. The use of USB cable was not found to affect the range or the quality of the data collected indicating no signal loss in the process. The antenna with a gain of 5dBi was selected for the main study in Reston Parkway based on the antenna range measured in the field. Table 8 shows the Antenna test results in Virginia Tech campus. The ranges observed were less than what was expected. Virginia Tech campus is a busy campus with lots of activity and hence the possibility of interfering radio waves is also more. There could have been other unknown interferences or manual error in the antenna range test experiment conducted which resulted in such small range values than expected.

Bluetooth data collection was conducted for slightly more than two weeks from November 23, 2010 to December 12, 2010 in the Reston Parkway network (Figure 9).

Figure 13: Bluetooth unit installation in field (Fair Use)

GPS probe vehicle runs were done on December 11, 2010 for the purpose of validating the delay analysis. Figure 14 shows the three intersections used for the GPS probe vehicle runs labeled as intersection 3, 9 and 5.

Sl. No.	Test No.	Type of Environment	USB Cable Attached (Yes/No)	Antenna Type	Range Radius
1	Test 1	Crowded (Burruss Bus stop)	No	1dBi	71 m
2	Test 2	Crowded (Burruss Bus stop)	Yes	1dBi	69 m
3	Test 3	Crowded (Burruss Bus stop)	No	5dBi	127 m
4	Test 4	Crowded (Burruss Bus stop)	Yes	5dBi	135 m
5	Test 5	Open Field (Drillfield)	No	1dBi	70 m
6	Test 6	Open Field (Drillfield)	Yes	1dBi	72 m
7	Test 7	Open Field (Drillfield)	No	5dBi	170 m
8	Test 8	Open Field (Drillfield)	Yes	5dBi	167 m

Table 8: Antenna range test results

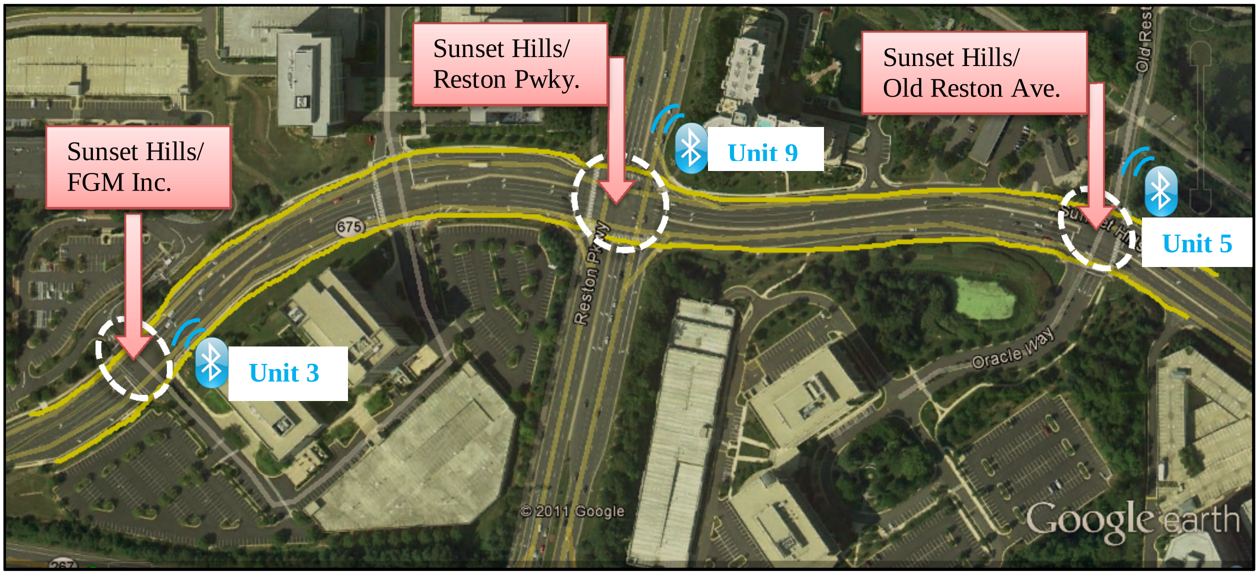


Figure 14: GPS study network [34]

4.4 Development of Vehicle Trajectory

With the help of the GPS data, the Bluetooth detections for each of the three units were plotted in the vehicle trajectory graph to locate the distance of the Bluetooth detections with respect to intersection 9.

Trajectory graphs were plotted relative to Intersection 9 taking Intersection 3 at negative distance from Intersection 9 and Intersection 5 at positive distance from Intersection 9 (Figure 15). Figure 15 shows the vehicle trajectory graph with the locations of the Bluetooth detections made with all the three Bluetooth units.

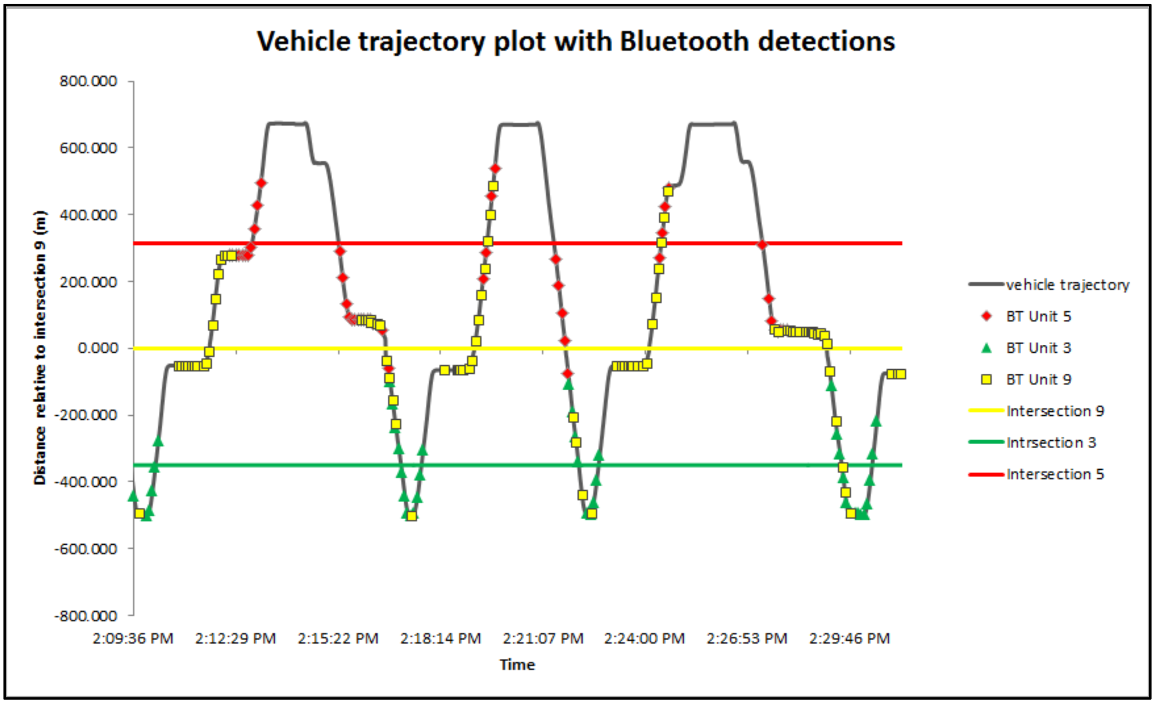


Figure 15: Vehicle trajectory graph with Bluetooth unit detections (Fair Use)

The antenna range observed in the field is found to be noticeably more than what was obtained in the antenna range test prior to field implementation (Table 8). Figure 16 shows the detection ranges of first and last detections in the field for all the three units. The antenna range differs with specific location and related device concentration and interference. This helps us to understand the actual detection ranges in the specific study field and compare with the theoretical antenna range. A Bluetooth detection range test would be useful to examine the extent of interference in the field approximately.

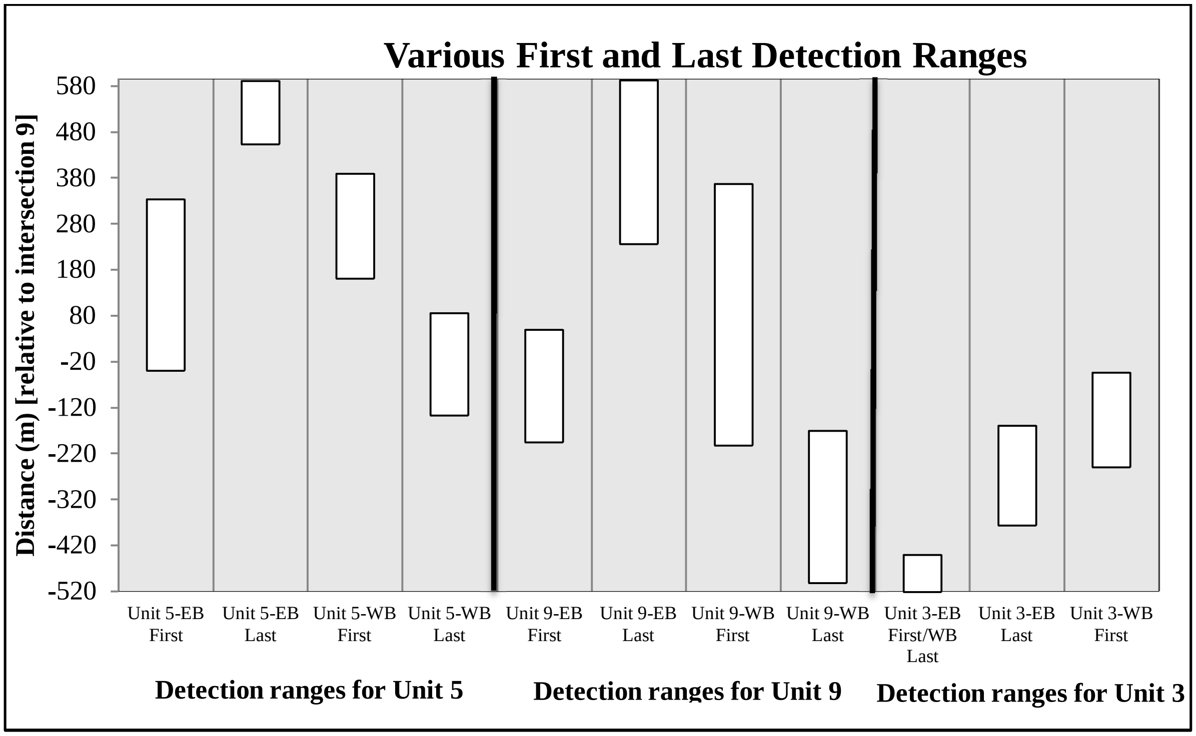


Figure 16: Field detection range box plots for Bluetooth units 3, 9 and 5 (Fair Use)

4.5 Control Delay Formulation

The Bluetooth MAC ID detection technique provides us with two parameters: detection time and detection Bluetooth unit. As the Bluetooth detection follows a random pattern, calculating travel time and delay by matching the detections and taking the time difference would lead to large errors.

Without placing the vehicle spatially, travel time and delay calculations will have random errors. Hence, error modeling is a feasible solution to solve the random error. In this study, we used a GPS probe vehicle to get the location and time during the same Bluetooth data collection study period.

32 GPS runs were made for EB traffic direction and 33 runs were made for WB traffic direction on December 11, 2010 from 1:00:00 PM to 4:50:00PM. The Bluetooth detections were overlapped in the vehicle trajectory plot with GPS data to visualize the location of the Bluetooth detections with time. Intersection 3 and 5 shows minimal control delay resulting in insufficient samples for control delay modeling. Sunset Hills/Reston Parkway intersection (intersection 9) has heavy congestion especially during morning, afternoon and evening peak hours. As

expected, intersection 9 was observed to have large control delays in most of the runs with an increased number of Bluetooth detections. This confirms the theory that Bluetooth better detects slow moving or stopped vehicles. The control delay at intersection 9 was divided into three zones as shown in Figure 17.

Notations in Figure 17:

t_1 = duration of time lost due to deceleration from free flow speed (FFS) to a complete stop (deceleration curve)

t_0 = time duration during which the vehicle is at complete stop at an intersection

t_2 = duration of time lost due to acceleration from complete stop to FFS (acceleration curve)

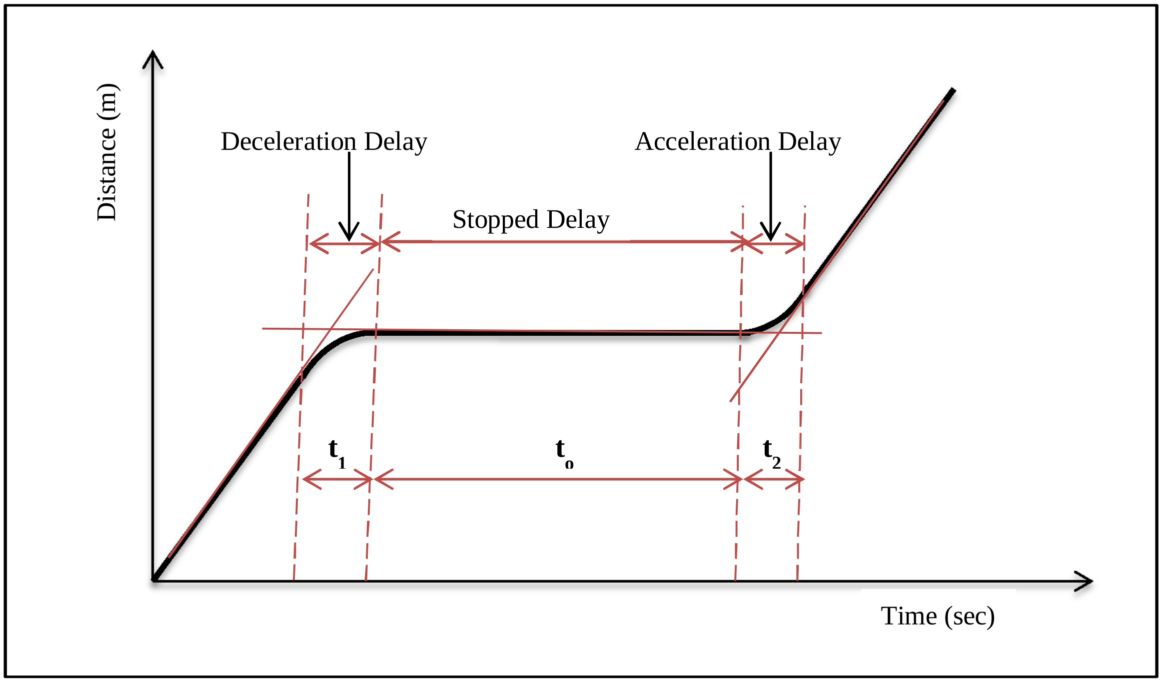
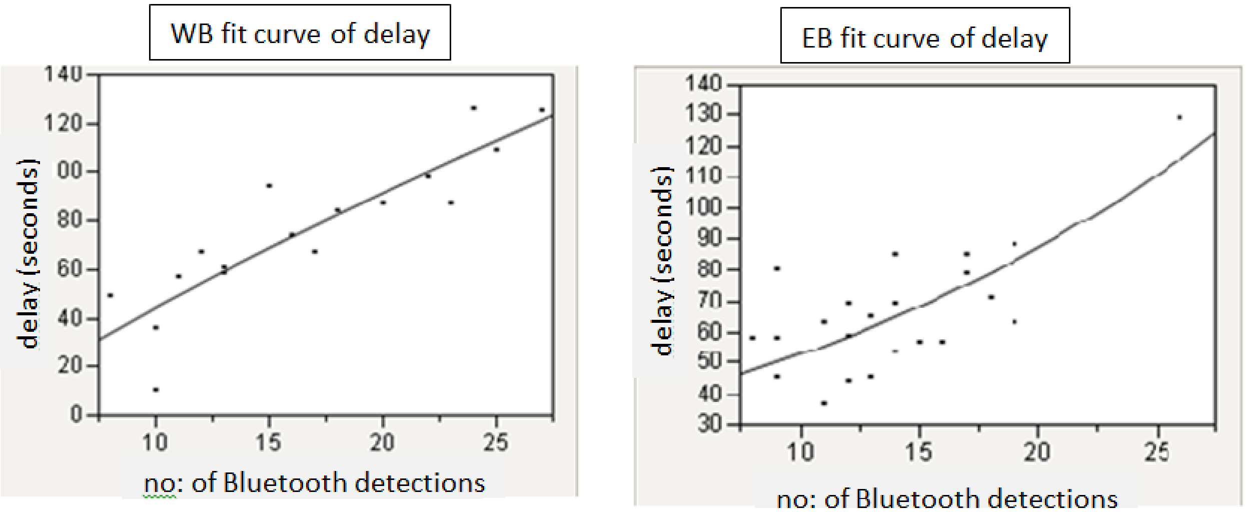


Figure 17: Time period division for delay analysis (Fair Use)

Number of detections in each of these time periods were noted for intersection 9 from the Bluetooth unit detections imposed GPS vehicle trajectory plot. Time period t_0 was observed to have a concentration of detections attributed to the increased detections during the stopped delay. The GPS runs were divided into EB and WB to distinguish between the delays in each direction. The actual delay was calculated from the GPS vehicle trajectory plot by taking the sum total of the time periods t_1, t_0, and t_2. The delay from the Bluetooth data was calculated by using the current practice of matching the first detections between units. The aim is to formulate a model for calculating the control delay by relating the number of total detections for each traffic direction. Time period, t_0 which represents the stopped delay was observed to have the majority of the detections.

4.6 Control Delay Modeling Based on Bluetooth Hits (n)

The total control delay observed ($t_1 + t_0 + t_2$) for intersection 9 for each GPS run was modeled with the number of Bluetooth detections made for each run. The delay equations for both EB and WB direction are modeled as follows. A constant, 'n_0', representing the minimum detections in a no-delay situation, was defined to consider the probable detection errors in each run. Two calibration parameters, α and β were also defined in the development of the delay model. This general model with its three calibration parameters is intended to model the delay in relation to the number of Bluetooth hits that any vehicle would receive as it spends more time around the intersection. The α and β parameters should account for the overestimation or underestimation of the delay estimates due to missed or repeated detections with different Bluetooth hopping frequency. It should be noted that calibration of the model to different approaches might deviate from the physical meaning to provide better estimation of delay (e.g., the EB delay model where n_0 was calibrated to a large negative number), whereas in other situations, the physical meaning of the model can be held intact (e.g., the WB calibrated model presented in Figure 18).



WB traffic delay equation:

$$delay, D = \alpha\,(\mathrm{n} - n_0)^{\beta}$$

$$with\ R^2 = 0.79$$

$where,$

$\alpha = 8.8127$

$n_0 = 2.8648$

$\beta = 0.8239$

EB traffic delay equation:

$$delay, D = \alpha\,(\mathrm{n} - n_0)^{\beta}$$

$$with\ R^2 = 0.54$$

$where,$

$\alpha = 3.996$

$n_0 = -134.403$

$\beta = 7.465$

Figure 18: Delay fit curves for EB and WB traffic direction (Fair Use)

Curve fitting was done for the GPS delay taken as the actual delay and the number of Bluetooth detections (Figure 18). The modeled delay equation was then calibrated with the actual control delay obtained from the GPS data. Also, the delay obtained from the modeled equation was compared with the current practice of Bluetooth delay estimation method which is, deducting the travel time at posted speed limit from the obtained travel time. Control delay model developed based on EB traffic was found to perform inadequately with large errors and hence was excluded from further analysis and validation studies.

4.7 Calibration of Control Delay Model Based on n

The delays obtained from the modeled equation were calibrated with the current practice of Bluetooth delay estimation method. Figure 13 shows the comparison for the control delay obtained from the model, actual control delay obtained using GPS data and the control delay using the current practice. The delay model developed based on n was applied to both EB and WB directions. It is noted that the existing method of Bluetooth delay analysis underestimates the delay time mainly due to the practice of taking ideal travel time as the posted speed limit based travel time. Ideal travel time and control delay are dynamic in nature which should be accounted for while estimating control delay values. The control delay models developed performs well for estimating control delay values for various approaches compared to the current practice of control delay estimation (Figure 19, Figure 20). The calibration results point towards the potential usefulness of the control delay models developed in predicting dynamic control delays. The n model predicted control delay is found to have lesser errors than using the current practice (Figure 21).

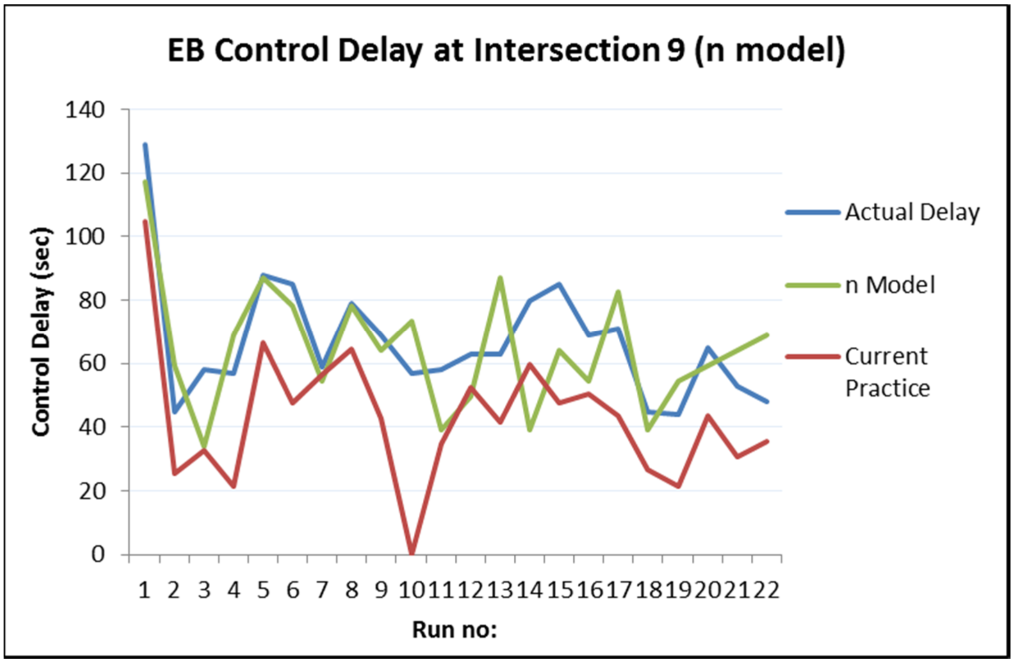


Figure 19: Calibration of model based on n for EB Traffic (Fair Use)

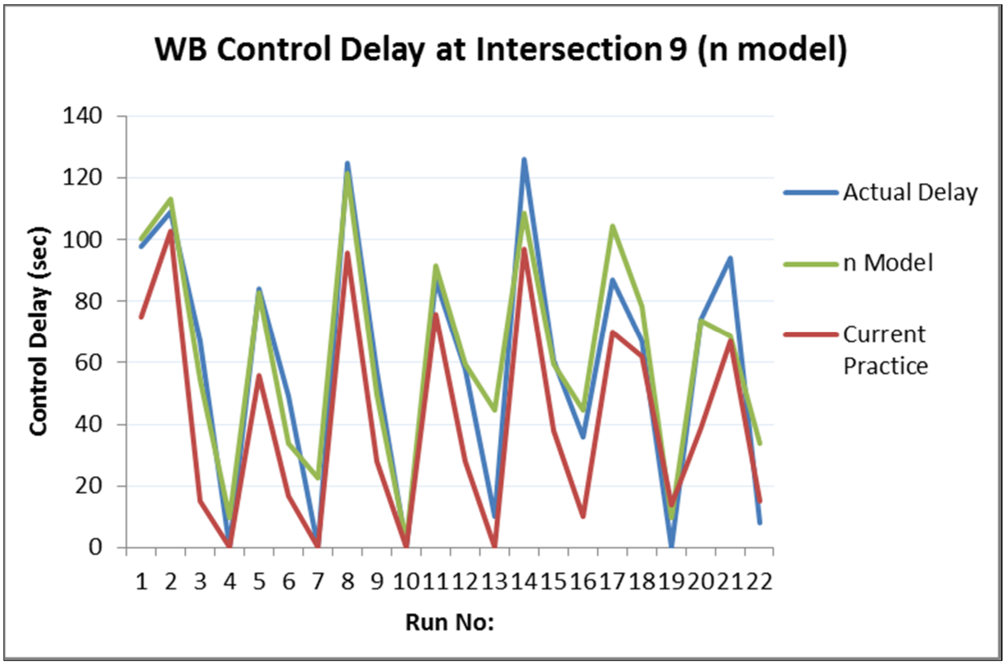


Figure 20: Calibration of model based on n for WB Traffic (Fair Use)

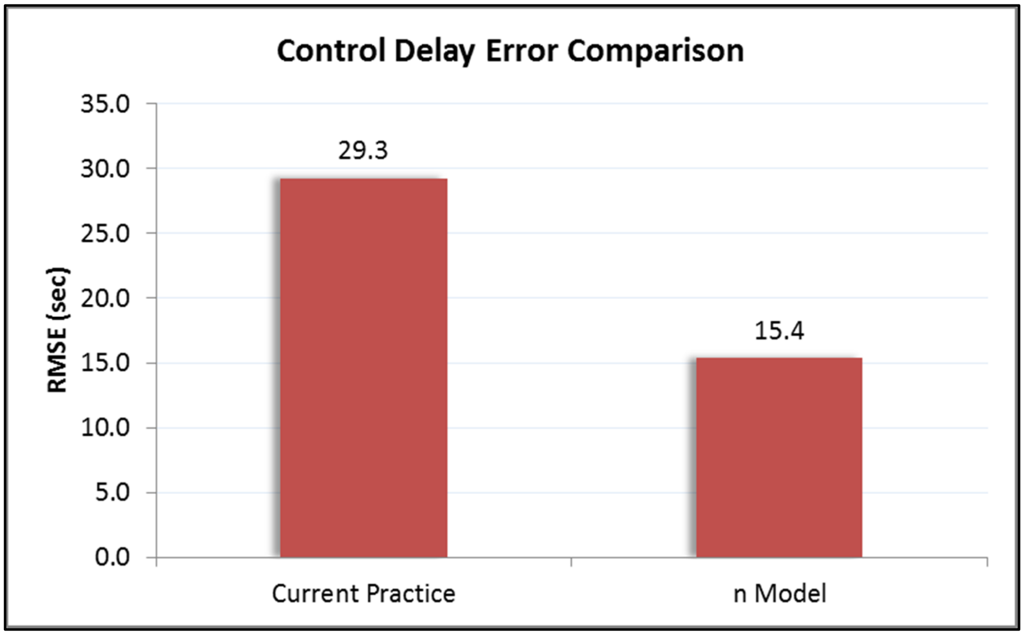


Figure 21: Comparison of current practice and n model control delay errors (RMSE) (Fair Use)

4.8 Conclusion

Within the given limitations of the Bluetooth data, it is not possible to find the control delay for an intersection without incurring a large error. The existing method calculates the delay by matching the first-to-first or last-to-last MAC matching time and then subtracting the travel time derived from the posted speed limit. This method suffers from large random errors induced due to the random nature of Bluetooth detection and time-logging. Bluetooth data gives us the time of detection, number of detections and detection unit number. A novel idea is presented to model the number of detections observed with the control delay which has been found to be more accurate than the existing method.

4.9 Future Research

Bluetooth detections have a lot of random error associated with it. Hence, exploring the many factors contributing to this error would help better model the delay equation. Reducing the randomness would help to improve the R^2 value of the delay equation. Future research should also focus on estimating the total control delay at an intersection, considering the Bluetooth vehicle location in the traffic and the estimated Bluetooth penetration rate.

4.10 References

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5 CONTROL DELAY MODEL VALIDATION AND APPLICATION IN AN ARTERIAL NETWORK

5.1 Abstract

Continuous and cost-effective traffic data for near real-time traffic monitoring seems to be an achievable goal with the emergence of Bluetooth Median Access Control (MAC) ID detection technique. Although various other methods like Automatic License Plate Recognition Systems (ALPRS), toll tag reading, etc. with high accuracy levels exists; their permanent installation in a road network in a wide scale is infeasible due to the high cost factor. Validated by previous studies, Bluetooth MAC ID method gives continuous network Origin Destination (O-D) and travel times data. However, the current approach of simple matching of the Bluetooth MAC IDs for finding the control delay has some inherent errors due to the random nature of Bluetooth detections. Bluetooth MAC ID data lacks location information for the vehicle which makes it very difficult for various traffic performance measure evaluations. Traffic delay is an important performance measure with wide applications in effective traffic management systems and optimal traffic signal timing operations. This paper deals with the validation of a microscopic methodology developed in our previous study to find average control delay by quantifying the Bluetooth detection errors with synchronized Bluetooth and GPS probe vehicle data. The validated control delay model is then applied to the Bluetooth MAC data to find average control delay for each traffic movement at the intersections. A continuous color-coded level of service (LOS) network map based on the average vehicle delay per movement helps to quickly analyze and control traffic congestions and traffic signal timing inadequacies in near real-time.

Keywords: Bluetooth-GPS data synchronization, control delay model, LOS based network map

5.2 Introduction

With the increase in traffic management complexity, the need for continuous real-time traffic data has become essential for accurate performance measure evaluations and hence better traffic operations management. Existing techniques like Automatic License Plate Recognition Systems (ALPRS) and toll tag reading gives accurate traffic data but their high cost factor limits their installation on a wide scale, consequently affecting the traffic data sample size. A newly researched area of Bluetooth MAC ID detection method holds promises with its cost-effective and continuous data collection capability. ‘Bluetooth units’ used for continuous MAC ID detections works on low-power and is easy to install even in areas considered inaccessible by existing methods. Bluetooth communication works on the globally open Industrial, Scientific and Medical (ISM) frequency band of 2.402 GHz and 2.480 GHz, requiring no changes to the existing infrastructure. The privacy issues remain negligible as the manufacturers do not maintain any record of a MAC ID with a specific device and hence cannot be traced to any individual device directly.

Being a recent advancement in transportation engineering field, the Bluetooth MAC ID detection method needs a lot of research to standardize it. There has been many studies conducted in the recent past to validate the method as a ground truth with various existing methods such as floating car data [6, 8], and Automatic License Plate Recognition System (ALPRS) [14] for future studies. Bluetooth antenna characterization is also extremely important as the type and range of antenna affects the quality and quantity of the Bluetooth detections. A vertically polarized omni-directional antenna has been found to be the optimal for traffic data collections [14, 21]. In the case of non-existence of a nearby power source, solar energy has been tested to be an adequate source due to low power requirements of a Bluetooth unit [18]. GPS+GSM technology addition to the Bluetooth unit has made real-time traffic data transfer feasible [4, 36] for near real-time traffic management. Bluetooth MAC ID method has already been found to have many applications like estimating route choice [27], worker proximity to construction health hazards [25], passenger screening time in airports [15], etc.

Currently, the Bluetooth data gives us the Bluetooth unit of detection and the time of detection. Spatial movement of the Bluetooth devices and hence the corresponding location of the vehicles in the roadway network remains unknown. The possibility of a Bluetooth device detection anywhere within the range of the Bluetooth antenna leads to huge spatial errors. No cost estimation or validation has been done for a study which attempted to find the approximate location of the Bluetooth device with the help of a Received Signal Strength Indicator (RSSI) [22]. Apart from the travel time error estimation [4, 5], there is a need to quantify the random error in Bluetooth detections due to its frequency hop structure. While analyzing Bluetooth traffic data, the general practice is to match the MAC ID first or the last detection at one Bluetooth unit with the corresponding first or last detection at the next Bluetooth unit. This results in a lot of undefined random error especially while calculating control delay at intersections, an important performance measure input for traffic operations. Bluetooth detections have been found to be efficient for slow moving traffic and hence the number of Bluetooth detections is an important factor in control delay estimation.

This paper deals with the validation of a microscopic control delay analysis model developed from a previous study by the authors, based on the quantification of Bluetooth detections and its associated errors with the help of synchronized Bluetooth and GPS data. This validated model has then applied to the Bluetooth data without any supporting GPS data to find the traffic movement-wise average control delay at the intersections. A color coded network map based on the LOS per movement for each 15 minute interval time period gives a quick method to analyze the intersections with continuous congestions and hence to suggest any traffic signal plan changes.

5.3 Experimental Setup and Control Delay Model

Network Origin-Destination (O-D) matrix would help to optimize the traffic signal timings based on critical movements with change in time period. Compared to the traditional methods like road-side survey to find network O-D information, Bluetooth MAC ID detection method would give a more complete and continuous travel time and O-D data for analysis.

Reston Parkway Network in Northern Virginia consisting of fourteen intersections with a total length of 16572 ft. was the study location. Out of the installed Bluetooth units at major intersections throughout the Reston Parkway Network, eight Bluetooth unit traffic data from December 10, 2010 (Friday) and December 11, 2010 (Saturday) were used in this study to capture the control delay variations during a weekend. GPS probe vehicle runs were done simultaneously on December 11, 2010 from 1:00:00 PM to 4:50:00 PM for three intersections considered to be significant in the control delay modeling. Figure 22, shows the location of the three intersections (numbered 3, 9 and 5 for analysis purposes) used for the GPS data collection in the Reston Parkway Network.

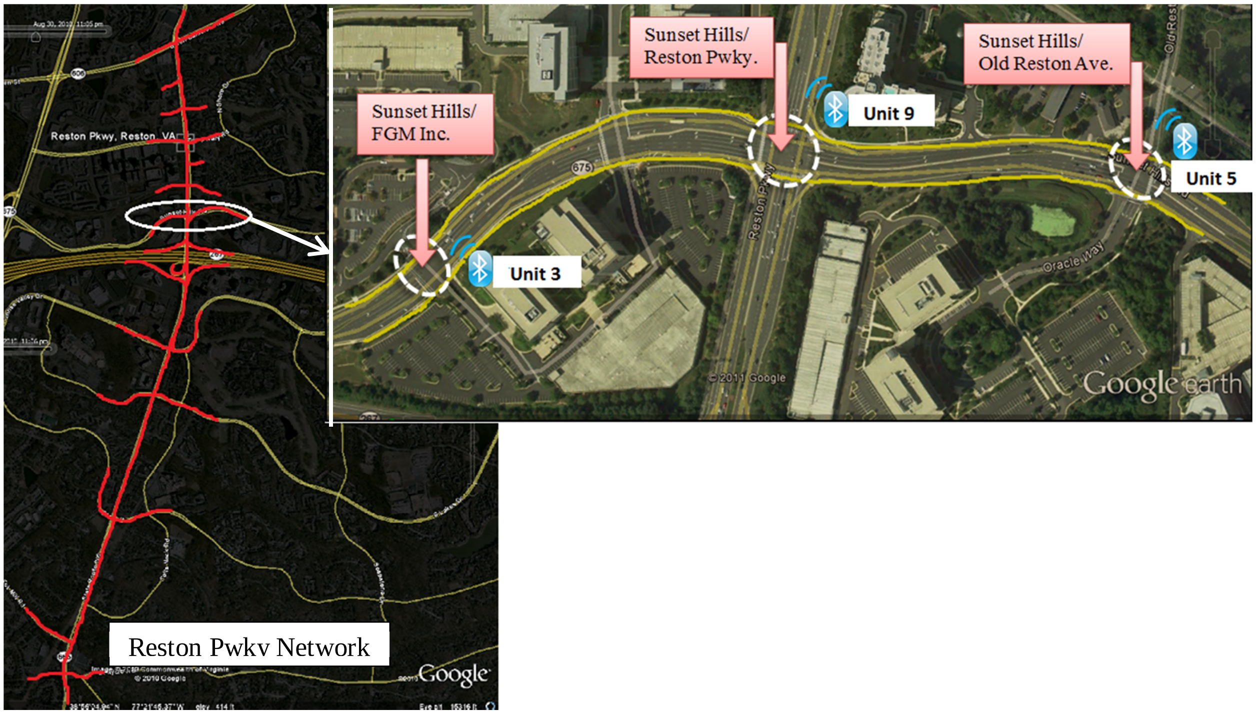

Figure 22: GPS data collection location in Reston Parkway Network [34]

The Bluetooth traffic data was synchronized with the GPS probe vehicle run data for the corresponding three intersections and was plotted as a vehicle trajectory plot as shown in Figure 23. Intersection 9 (Sunset Hills/Reston Parkway intersection) is taken as the reference point with distance 0 in the plot and the distance from intersections 3 and 5 are plotted as shown with intersection 5 drawn in the negative y axis.

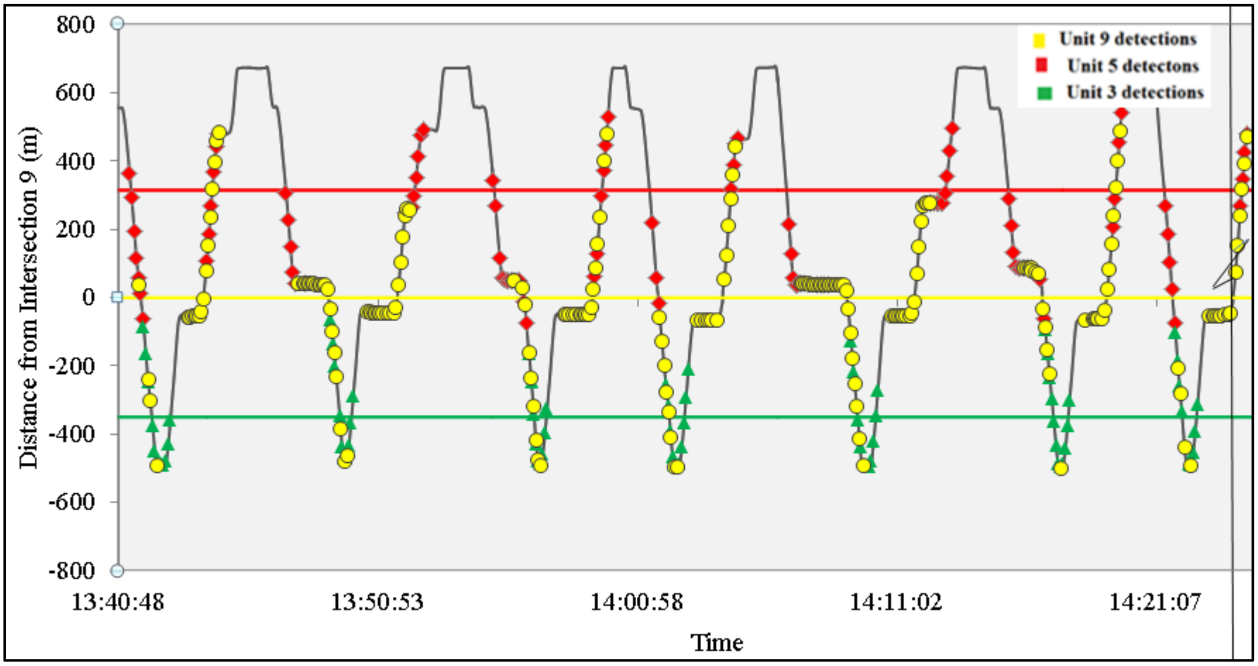

Figure 23: Bluetooth detections plotted on vehicle trajectory plot from GPS data (Fair Use)

Actual control delay was calculated as the sum of deceleration delay, stopped delay and acceleration delay from the vehicle trajectory plot. Only intersection 9 was found to have sufficient delays to provide adequate sample size for the control delay modeling and hence the total number of Bluetooth detections at intersection 9 was obtained from the vehicle trajectory plot. The equation below shows the control delay model developed based on the number of Bluetooth detections by a vehicle while passing through a Bluetooth unit [13].

$$\boldsymbol{D = \alpha\,(n - n_o)^{\beta}}$$

$with\ R^2 = 0.79$

$where\ D = delay$

$n_o = no{:}\ of\ minimum\ expected\ Bluetooth\ detections = 2.8648$

$\alpha,\ calibration\ parameter = 8.8127$

$\beta,\ calibration\ parameter = 0.8239$

A constant, ‘n_0’ representing the minimum detections in a no-delay situation were defined as shown in the above equation to consider for the probable detection error in each runs. Calibration parameters, α and β were also defined in the development of the delay model. Number of Bluetooth detections for any Bluetooth device in a vehicle are assumed to have a direct proportionality with the amount of delay time the vehicle faces at an intersection as detection rate is higher for slower vehicles. This general model with its three calibration parameters is intended to model the control delay in relation to the number of Bluetooth detections made as the vehicle spends more time around the intersection. The α and β parameters should account for the overestimation or underestimation of the delay estimates due to missed or repeated detection due to the Bluetooth frequency hop structure.

5.4 Control Delay Model Validation

5.4.1 Model Analysis

The control delay model was validated with actual delay observed in the field. The total GPS probe vehicle data collections resulted in 32 GPS runs for EB and 33 runs for WB traffic directions. 22 GPS runs of each EB and WB traffic data were used for control delay modeling. Visual analysis of the prediction capability of the control delay model developed has been performed by comparing the predicted delay and the actual control delay for 22 runs used for modeling. Also, GPS probe vehicle run data not used for the modeling of the delay model was used for validation purposes. As a high R^2 (coefficient of determination) does not guarantee a better model, a validation was thought necessary for the developed model. Graphical model validation method was adopted due to its ability to look into complex details easily. The Actual control delay in field and the estimated control delay from the model was plotted to check the normality of the value. Figure 24 shows some deviation from normality line but this can be attributed to the random errors due to unknown parameters in Bluetooth traffic data collection. The estimated values from the developed control delay model satisfy the normality requirements and hence can be used for delay estimation. Further research to find other parameters affecting control delay estimation in Bluetooth traffic data collection would further reduce the random error and hence improve the model accuracy.

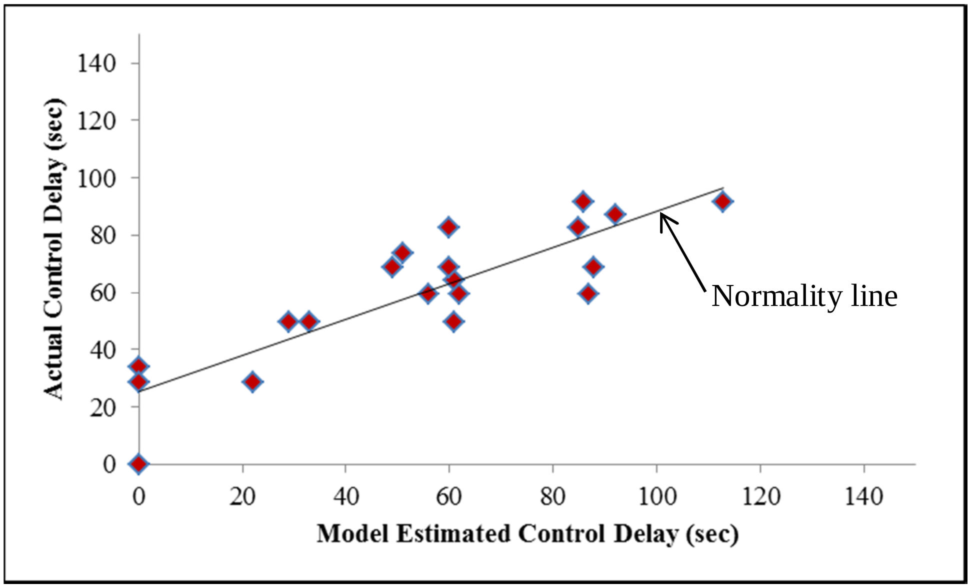

Figure 24: Normal Probability Plot (Fair Use)

A scatter plot of model estimated control delay against number of Bluetooth detections were overlapped with that of the actual delay observed in the field for validation purposes (Figure 25). The model developed was found to predict the control delay with the number of Bluetooth detections as input satisfactorily. From Figure 25, we can see that the model predicts the trend in the control delay very reasonably.

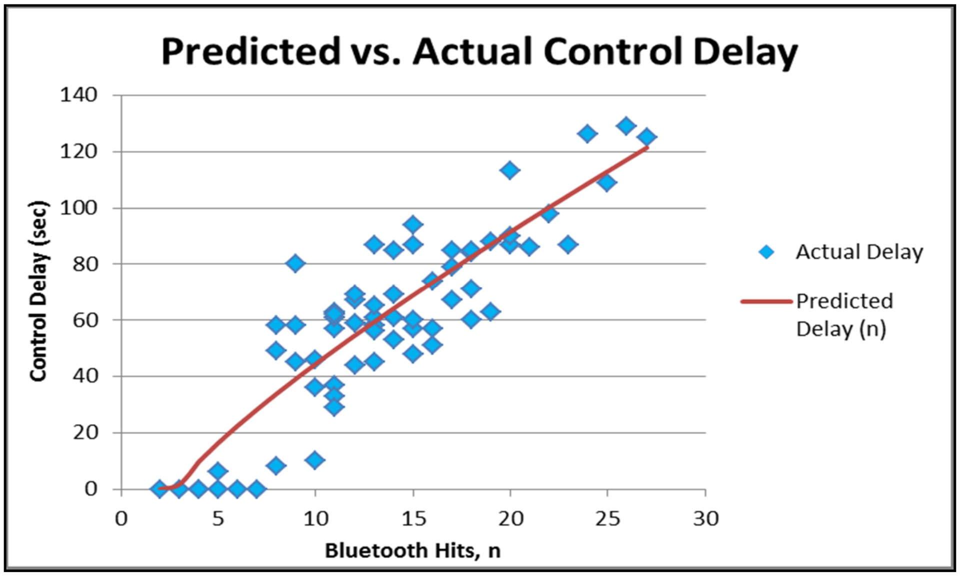

Figure 25: Scatter Plot of Actual and Estimated Control Delay (Fair Use)

5.4.2 Model Validation

The developed control delay model was validated using the remaining GPS runs not used for the modeling part. Hence, 11 GPS run data for WB and 10 GPS run data for EB traffic direction was used to study the prediction accuracy of the developed delay model based on Bluetooth hits (n). Figure 26 shows the model validation results for WB traffic. The model was found to estimate the control delay reasonably well although it overestimates higher control delay values and underestimates lower control delay values. The delay model developed for WB traffic discussed in this study was applied to the EB traffic data. The validation results (Figure 27) show very good prediction accuracy and hence the developed delay model was found fit to be used for all approaches within the given limitations of actual data.

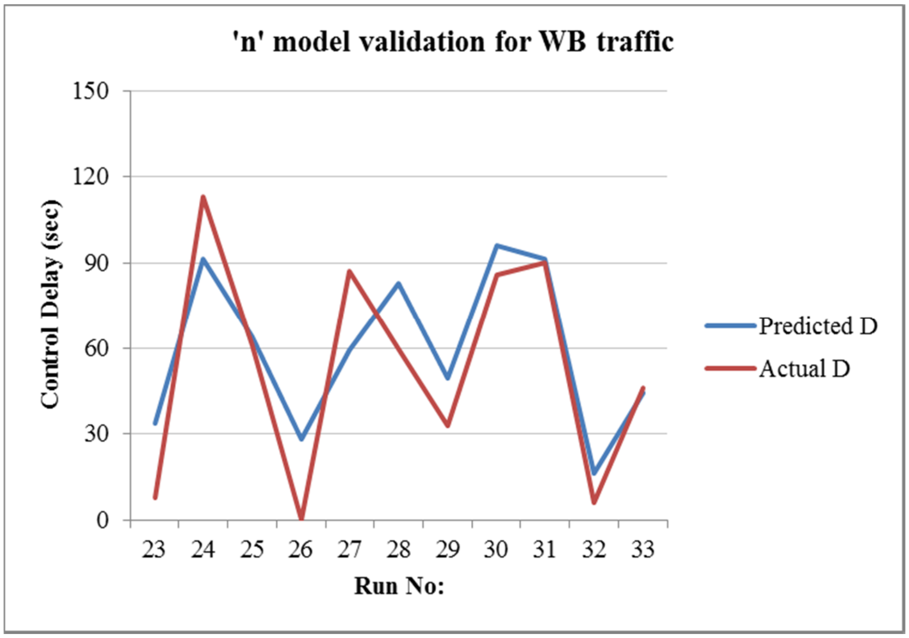

Figure 26: Model validation results for WB traffic (Fair Use)

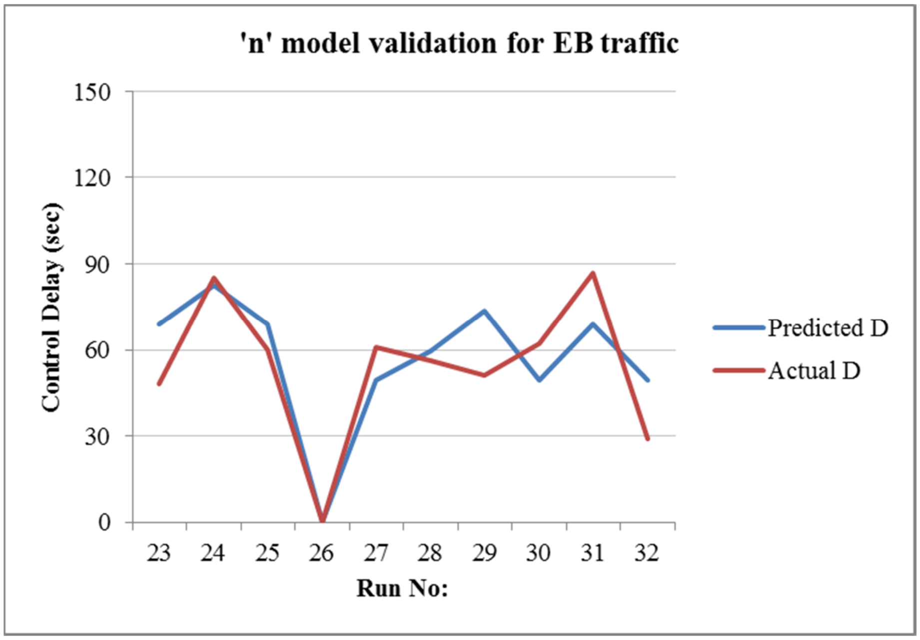

Figure 27: Model validation results for EB traffic (Fair Use)

5.5 Control Delay Estimation Using Delay Model

Control delay is an important performance measure to estimate the effectiveness of any traffic operation system. The developed control delay model was used to estimate the control delay at all the eight major intersections in Reston Parkway Network where Bluetooth units were installed. The control delay estimate provides a quick assessment of the existing congestion levels and any changes in the traffic signal timing plans required to improve the traffic network performance.

Bluetooth traffic data from eight intersections in the Reston Parkway network was used for the control delay analysis. NEMA traffic movement naming pattern was adopted for the control delay analysis. The number of Bluetooth detections during the evening peak-hour (4pm to 7pm) for each traffic movement at all the eight intersections were calculated as the input for the control delay model developed. Bluetooth data for a weekday and a weekend was analyzed to see the change in pattern in the delays. Also, the Bluetooth traffic data for the evening peak-hour was divided into 15-minute intervals data to capture the change in control delay more accurately.

To capture all the eight traffic movements at an intersection, there should be four Bluetooth units located at the four ends of an intersection. In urban road network, there will be many parallel roads and a vehicle can have same origin and destination without passing through the expected intersection. Hence, a Bluetooth unit at the intersection is also required to confirm the vehicle passed through the expected intersection and not take any other route to reach the destination. Figure 28 below shows the required Bluetooth units configuration to capture all the twelve traffic movements.

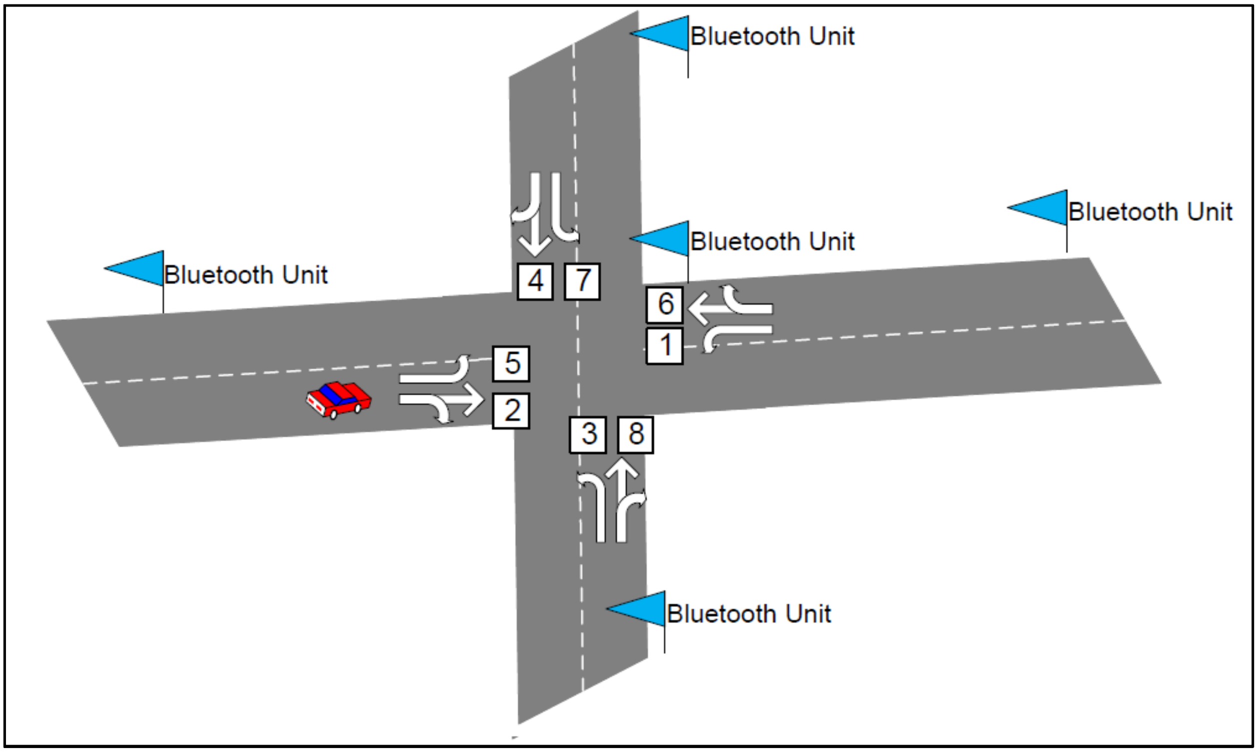

Figure 28: Bluetooth unit configuration to capture all eight NEMA movements (Fair Use)

The objective of the current study was to capture the critical movements in the fourteen-intersection Reston Parkway Network to solve the congestion issues faced. Hence, the control delays of the critical movements at eight major intersections were estimated using the developed model. A color coded network map showing the control delays of the critical movements at the selected intersections were made for quick visual analysis of the congestion levels and the efficiency of the existing traffic signal timing plans for a 15minute interval basis. Level of service was selected as the standard for grouping the delay levels for color coding. Figure 29 shows a sample of the network map with estimated control delays of major movements for the time interval 5:30 PM to 5:45 PM on December 11, 2010. Some of the vehicle O-Ds and hence the traffic movements were predicted from the obtained Bluetooth traffic data by using a deeper analysis of the data. For instance, if a first Bluetooth detection from a vehicle was made at an intersection under consideration but failed to be detected at previous intersections, then the probable movements which could have resulted in the observed O-D is analyzed. Wherever possible, the O-Ds of vehicles obtained near to the vehicle under consideration were observed and based on the signal timing plans, the traffic movement most probable to be true was selected for control delay estimations.

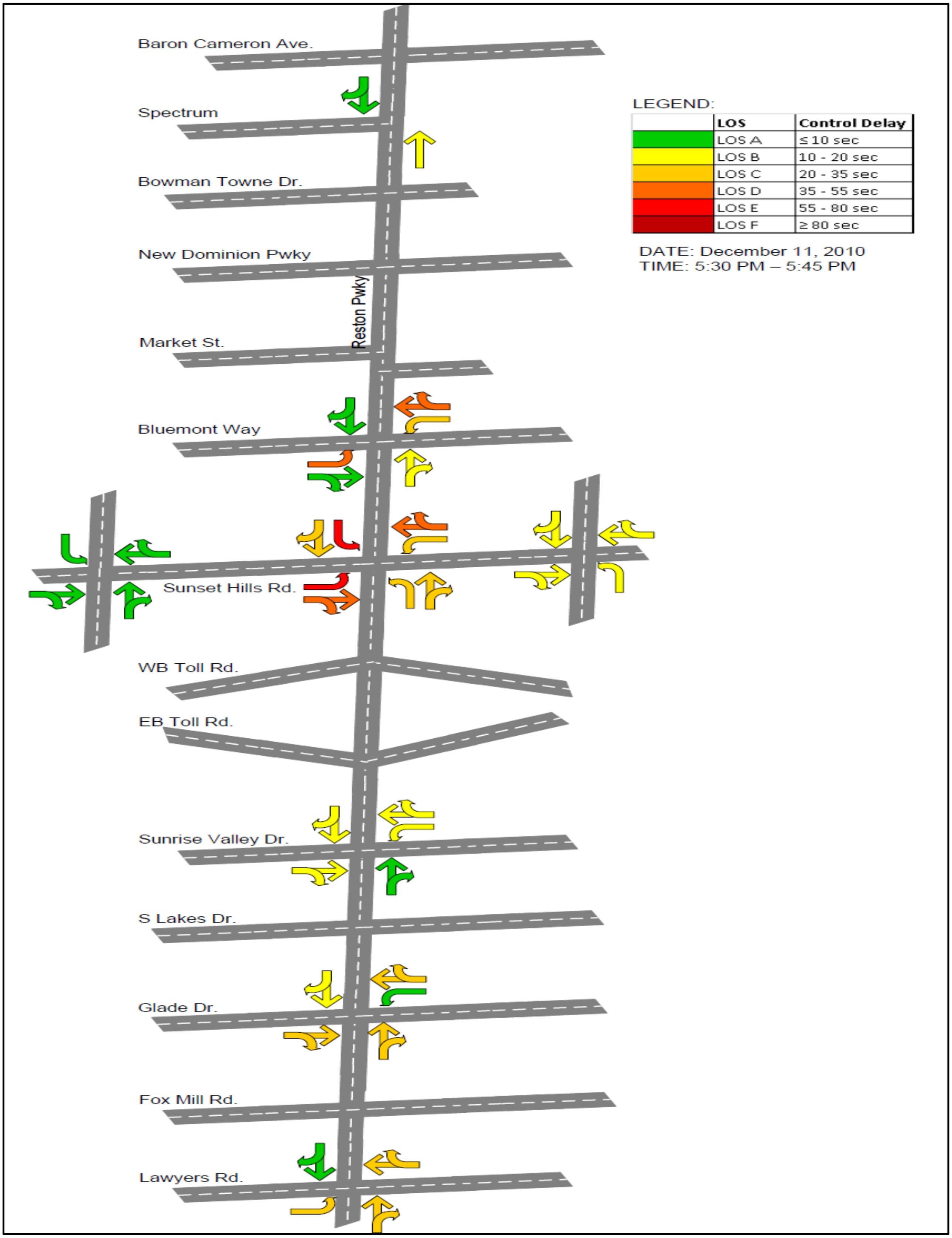

Figure 29: Color Coded Control Delay Network Map (Fair Use)

The data was screened to avoid pedestrians while calculating the control delay from number of Bluetooth detections. This would give us more accurate results necessary for the control delay estimation in real world. Another observation made during the study was, the number of MAC detections were higher for traffic movements nearest to the installed Bluetooth unit. Hence we get higher sample of data for the movements near to the Bluetooth unit and hence get better estimate the number of the vehicle O-Ds in a movement. Color coded control delay maps implemented in near-real time would help to analyze and control congestions and incidents in a better way. Average control delay plot were made for all the available NEMA movements for all the intersections. Intersection 9 was observed to be a part of many critical routes in the Reston Parkway Network and hence the Bluetooth units were so installed that we can capture all the eight movements at intersection 9. Figure 30 shows the average control delay values obtained for both the days under consideration at intersection 9 for all the movements for the peak hour traffic. It can be noted that most of the through + right movements had a LOS D or LOS C with occasional rise to LOS E temporarily. This can be avoided with some fine tuning of the signal timings plans at the intersection. The left turn movements were found to have irregular and high control delays for the two days. The south-bound movement 4 for vehicles which are continuing its way through the Reston Parkway network was found to have a constant delay with an approximate LOS of C. On the other hand the, the north-bound movement 8 needs adjustments to its signal timing due to its highly irregular control delays.

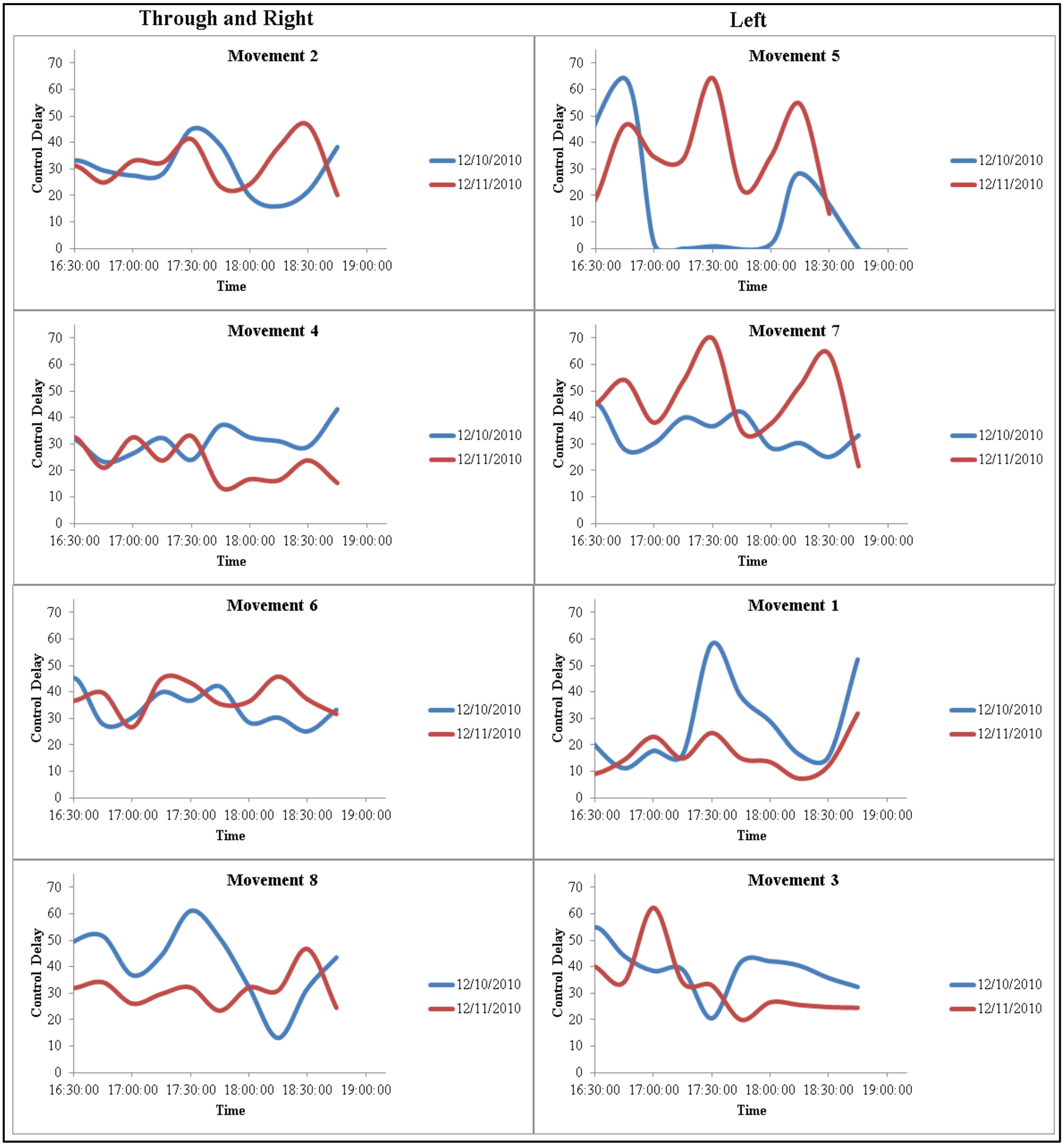

Figure 30: Peak Control delay at Intersection 9 (Fair Use)

The delay model developed was found to have acceptable error ranges and hence can be used to find the control delay at intersections with just the Bluetooth traffic data. The model would need more research to incorporate other factors affecting the variation in the Bluetooth detections in time as well as space.

5.6 Conclusion

Bluetooth data collection technique currently employed gives us only the Bluetooth detection time and Bluetooth unit of detection. The state of the art practice is to find the control delay at intersections by direct matching the Bluetooth detections. One major limitation of the Bluetooth traffic data collection method is that it does not provide any kind of spatial data to find the location of the Bluetooth detections. With the concept of higher Bluetooth detections for slow moving vehicles, a model was developed in a previous study by the authors to find the control delay at intersections using the number of Bluetooth detections. This paper dealt with the validation of the model as well as its application to find average control delays in an arterial network. The development of any model for delay analysis using Bluetooth traffic data collection method is bound to have large errors due to the current limitations of this method. This paper helps to put forward the idea of using a Bluetooth detection based delay model which has a huge potential if future research is able to reduce the random errors associated with it.

5.7 Future Research

Exploring methods to reduce the randomness of the errors related to the delay model would highly improve its accuracy for analyzing the control delays in real-time. Hence, future research should focus on finding the parameters which can be incorporated in the delay model to improve its accuracy. More study should be done to find the factors affecting the Bluetooth rate of detection and number of detection with the change in study road network (E.g., arterial network, interstate etc.). The model developed needs to be tested and calibrated in other test sites and field conditions for standardizing it. The effect of time duration of the total Bluetooth detections can also be factor which can be tested for incorporation in the delay model. The effect of penetration rate of Bluetooth detections in the estimation of the delays can also be a good area to work on.

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6 CONTROL DELAY MODELING BASED ON TIME DURATION BETWEEN BLUETOOTH TRAFFIC DETECTIONS

6.1 Abstract

Control delay is an important performance measure for any signalized intersection, useful for signal timing plan optimization and improvement. Direct determination of control delay from the field has always been complicated and erroneous as control delay is a combination of deceleration delay, stopped delay and acceleration delay. Although an important performance measure, control delay estimation from direct field data has been laborious, costly and complicated due to which its determination has been commonly done through simulation techniques. This paper looks into a potential microscopic method of control delay estimation based on Bluetooth traffic data. Bluetooth traffic data has been proved to be inexpensive and continuous in the recent past and hence its application in finding real-time control delay trends would significantly improve the overall system performance through improved signal timing plan control and optimization.

Keywords: Control delay model, Bluetooth-GPS data synchronization, model validation

6.2 Introduction

Accurate control delay estimation is essential for improved and optimized signal timing plan formulation. It also helps to improve the equilibrium flow in traffic assignment models [48]. Control delay is also an important performance measure to determine the level of service (LOS) of various approaches at an intersection [49]. Existing control delay estimation calculations using highway capacity manual (HCM) and other techniques tend be expensive, labor oriented and time-inefficient [2, 3]. A relatively easier and highly accurate method is using GPS data for developing vehicle trajectories [49]. This method, although efficient and accurate, tends to be expensive for large scale implementation. This makes control delay data for intersections scare and most of the time unavailable for analyzing real-time intersection performances. Bluetooth MAC detection technology is a novel methodology for traffic data collection developed in the recent years. Application of Bluetooth data for control delay modeling and estimation holds a high potential for real-time and continuous implementation in the field.

Bluetooth data collection technique is continuous and cost-effective. This method of traffic data collection has been validated by a lot of past studies with existing and already validated alternative methods (e.g., automatic vehicle detection (AVL), automatic license plate recognition systems (ALPRS), toll tag readers etc.) most of which are expensive to be implemented in the field for permanent installations [6, 8]. The Bluetooth data collection is done through a ‘Bluetooth unit’ which basically has a Bluetooth class 1 adapter, a Bluetooth antenna for obtaining higher detection ranges, a Bluetooth device code for running the ‘inquiry process’ of Bluetooth repeatedly, and a data storage device to store the continuously collected data. The Bluetooth unit can be expanded to include a variety of features such as GPS, GSM, solar energy capability etc., according to the study requirements [4, 7, 17, 18]. Previous studies have also concentrated on the type of Bluetooth antenna to be used for optimal traffic data collection in the field [14, 21].

Bluetooth detections for a vehicle in its antenna range can be made several times until it leaves the detection range. Installing Bluetooth sensors at different parts of a road network would yield us the link travel time and traffic speed by simple matching of the first Bluetooth detection at sensor 1 to first Bluetooth detection at the next sensor unit [6, 8, 50]. This current practice when applied directly to delay calculations does not yield satisfactory results. Hence, many studies have looked at travel time error estimation and forecasting in an attempt to address this issue [4, 5]. These methods tend to make control delay calculations tedious and indirect. In one of our past studies, we had developed a novel methodology for microscopically formulating a control delay model based on the Bluetooth detection errors [51]. This simple yet potential method developed with the help of a combination of Bluetooth traffic data and an initial GPS probe vehicle run data was found to be predicting the control delay for various approaches at an intersection reasonably well. A vehicle trajectory analysis was done to accurately determine the actual control delays from the GPS data and the Bluetooth detection error parameters discussed later in this paper from Bluetooth data [1]. The actual control delay calculated included deceleration delay, stopped delay and acceleration delay [52]. Such models have very high potential for real-time implementation in the field to improve the existing signal control strategies. This paper attempts to microscopically analyze the errors in Bluetooth detection and theoretical Bluetooth antenna ranges by studying the time duration between the first and the last Bluetooth detections for a Bluetooth equipped vehicle at a roadside Bluetooth sensor. This concept is then incorporated into the control delay model to analyze the minimization of Bluetooth prediction errors and hence to predict control delays for various approaches at an intersection.

6.3 Investigation of the Developed Delay Model Based on ‘n’

A novel methodology for finding the control delay based on number of Bluetooth hits/detection was developed in our previous study. The control delay model developed based on the number of Bluetooth detections by a vehicle while passing through a Bluetooth sensor is as shown below [51].

$$\boldsymbol{D = \alpha\,(n - n_o)^{\beta}}$$

$with\ R^2 = 0.79$

$where\ D = delay$

$n_o = no{:}\ of\ minimum\ expected\ Bluetooth\ detections = 2.8648$

$\alpha,\ calibration\ parameter = 8.8127$

$\beta,\ calibration\ parameter = 0.8239$

This model was found to predict the control delay at an intersection reasonably well but still included a lot of random errors due to the Bluetooth hop frequency randomness. Another variable which might have a direct relationship to the control delay is the time duration between first and last Bluetooth hits. Let ‘T’ represent the total time elapsed between the first Bluetooth detection and last Bluetooth detection made for a vehicle.

6.4 Motivation for the research study

If the free flow speed (FFS) of a vehicle is known, the time taken to cover a known distance on the roadway becomes the travel time (TT) of the vehicle under ‘no delay’ conditions. Suppose, the vehicle encountered control delay due to a traffic signal within the known distance, the new time taken to cover the same distance would include FFS Travel Time + Control Delay. Hence, the difference between the two would yield us the control delay for the vehicle.

Applying the same concept to the Bluetooth traffic data, let us assume an ideal case where the first detection of a Bluetooth equipped vehicle happens as soon as it enters the range of the roadside Bluetooth sensor antenna. Also, let the last detection of Bluetooth equipped vehicle occur just before the vehicle leaves the range of the Bluetooth sensor antenna. Referring to Figure 31, for scenario 1, where the vehicle has no control delay, the FFS travel time of the Bluetooth equipped vehicle becomes the difference in time between the first and the last Bluetooth detections. Now, for scenario 2, where the vehicle experiences control delay, the travel time calculated as the difference between the first and the last Bluetooth detections includes the control delay. Hence, the duration between the first and the last Bluetooth detections, T, would automatically include any control delay experienced by the vehicle and hence is directly related to the control delay, D.

In an actual condition, the first Bluetooth detection need not occur as soon as the Bluetooth equipped vehicle enters the Bluetooth sensor antenna range. Similarly, the last Bluetooth detection need not occur just before the vehicle leave the detection range of the Bluetooth sensor antenna. Hence, because of the random frequency hopping structure of Bluetooth detections, the first and last detections can occur anywhere within the range of the Bluetooth sensor antenna, making ‘T’ a randomly varying variable. Nevertheless, a strong direct proportionality is expected to be present between variables T and D.

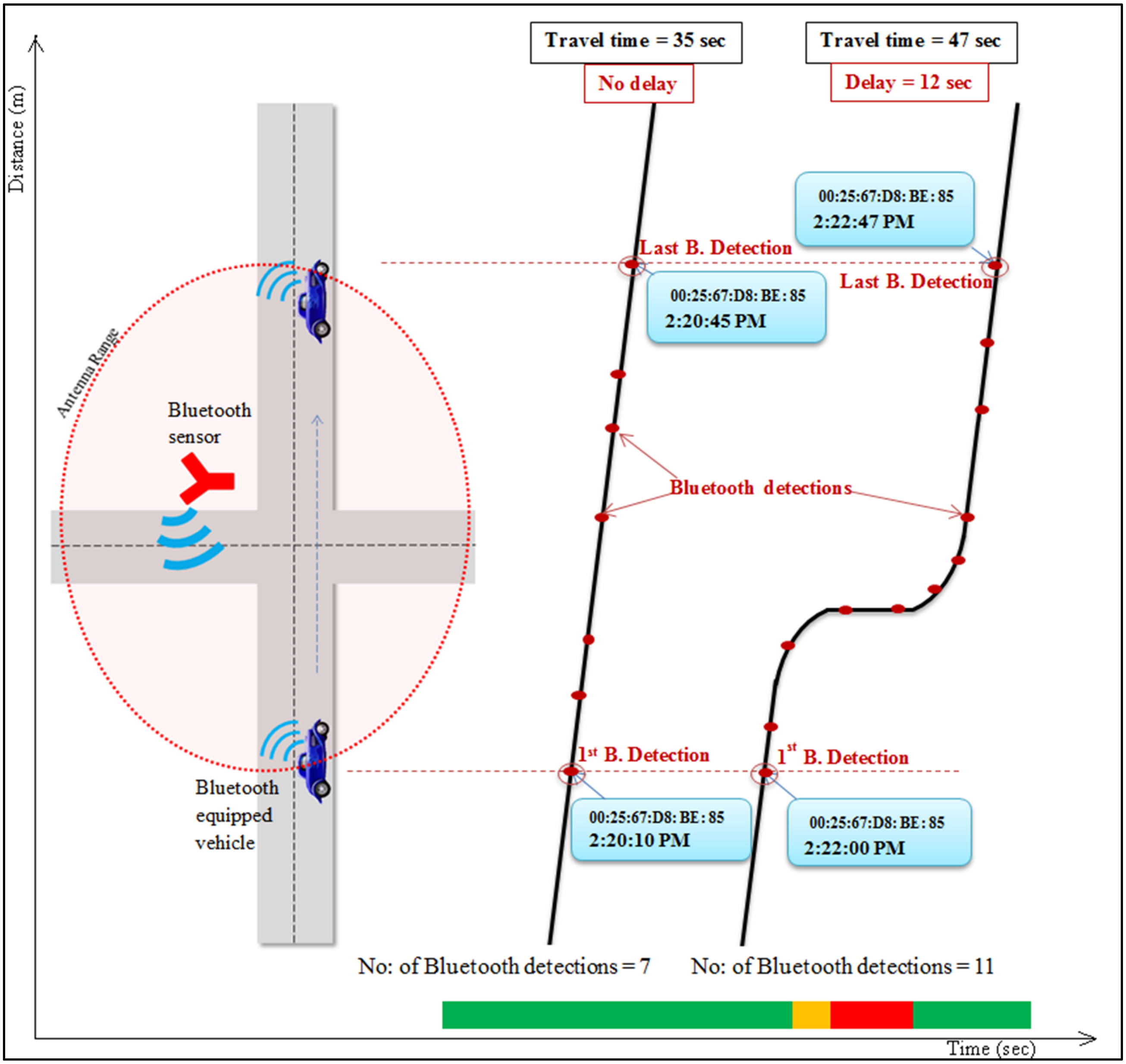

Figure 31: Relation between T and control delay (Fair Use)

6.5 Data collection and extraction

Reston Parkway is a 14-intersection long network with complicated and unique traffic patterns and critical routes. Sunset Hills is one of the intersections in Reston Parkway which is highly oversaturated during peak-hours and has a lot of incoming and outgoing traffic from the nearby Dulles Toll roads. GPS runs were conducted for three intersections including Sunset Hills (Figure 32) to determine the traffic patterns and delays for EB and WB traffic directions at

Sunset Hills. The intersections have been named 3, 9 and 5 for Bluetooth unit installation and data processing purposes as shown in Figure 32. Close to thirty-two GPS probe vehicle runs each were done for EB and WB traffic on December 11, 2011. Out of this available data, 22 runs each from EB and WB were used for the modeling of control delay model. The rest GPs runs were kept reserved for the model validation purposes.

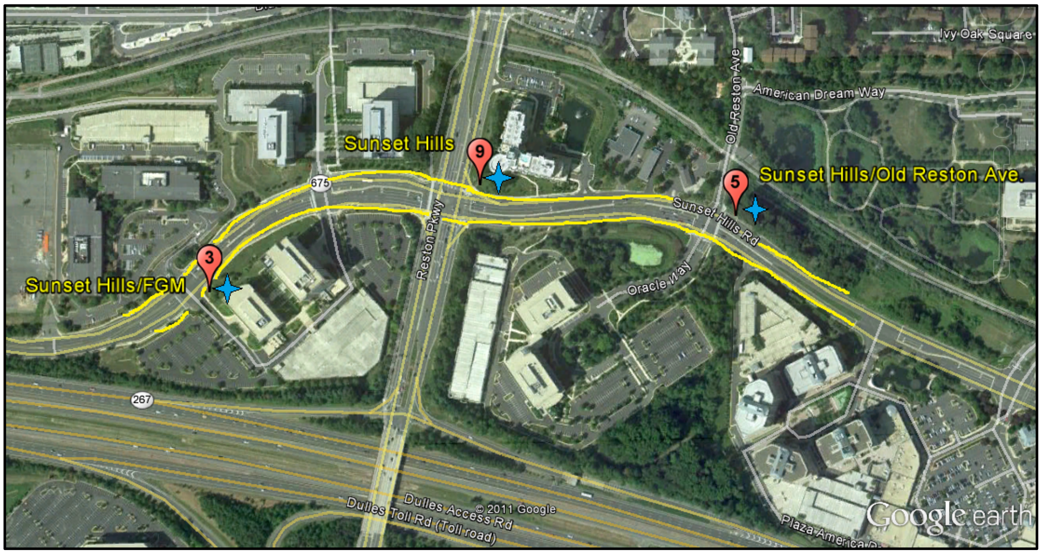

Figure 32: Intersections 3 and 9 and 5 locations in GPS study network [34]

Simultaneous Bluetooth traffic data collection was being done when the GPS probe vehicle runs were being made. Thus both data were combined to develop a vehicle trajectory plot to accurately estimate the actual control delay (D) experienced by the vehicle for the various runs as well as to determine the required Bluetooth data (total no: of Bluetooth detections (n), time duration between first and last Bluetooth detections for each link O-D (T)) for the model formulation.

6.6 Correlation Analysis - T, n and D

As a high proportionality between 'Duration between first and last Bluetooth hits (T)' and 'Control Delay (D)' is expected, the first instinct would be to include the variable 'T' in the delay model already developed based on 'Bluetooth hits (n)' and model again to see the change. But, before this is attempted, a correlation analysis between T, D and n is deemed necessary as any multivariate model with high correlation between its supposedly independent variables would show complex sensitivity to slight changes to its variable values. Hence, it is necessary that correlation, if any, between variables in model be within defined allowable limits.

A correlation analysis between D, n and T was performed using the statistical software JMP. The results are as shown in Table 9. Figure 33 shows the correlation graph between D, T and n. There is a high correlation observed between T and n and hence cannot be used in the same delay model. Also, a slightly higher proportionality between D and T was observed than between D and n. Therefore, developing another delay model based on T was considered right.

At this point, we cannot make the conclusion that a D vs. T model would perform better than a D vs. n model as the correlation results are based on our research study alone. More studies of the similar type are considered necessary before a generalization can be made.

	D (in sec)	**T (in sec)**	**n**
D (in sec)	1	0.944222	0.883734
T (in sec)	0.944222	1	0.872339
n	0.883734	0.872339	1

Table 9: Correlation analysis for D, n and T

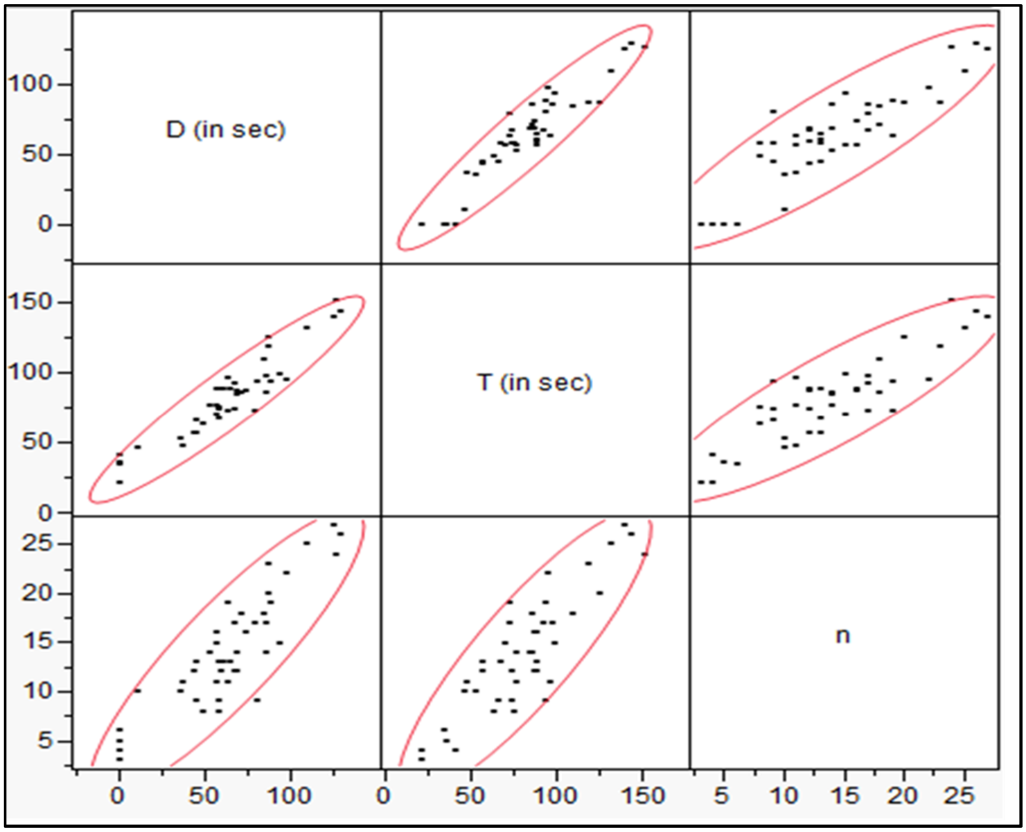

Figure 33: Graphical representation of correlation analysis results (Fair Use)

6.7 Formulation of Delay model based on T

This research study for GPS probe vehicle runs on the field on December 11, 2011 resulted in 32 runs for each Eastbound (EB) and Westbound (WB) traffic directions. Out of the available 32 runs, first 22 runs in each EB and WB direction were decided to be used for the model development and the remaining 10 runs each for EB and WB direction were reserved for the model validation purposes as mentioned earlier in this paper. Any model is considered ‘potential’ only with accompanying successful validation studies. The purpose of not using the last 10 GPS runs for the model development part was to provide a ‘new and unused data’ for the model validation part later in the study.

6.7.1 Variation in data for T based on direction of traffic

The first step performed was to look at the variation in the D and T data based on the direction of traffic (EB and WB). The delay model developed based on Bluetooth hits (n) was modeled separately for both EB and WB traffic due to the variation observed in the data for EB and WB (Figure 34) [51]. As can be observed from Figure 34, for the D vs. T plot, there is minimal variation between EB and WB traffic data and hence the data can be combined while developing the delay model based on T. The sample size increases to 33 (WB data) + 32 (EB data) = 65 data points for use in the development of the delay model based on T and its validation. Hence, 44 data points were used for model development and the rest 21 data points were used for the model validation part.

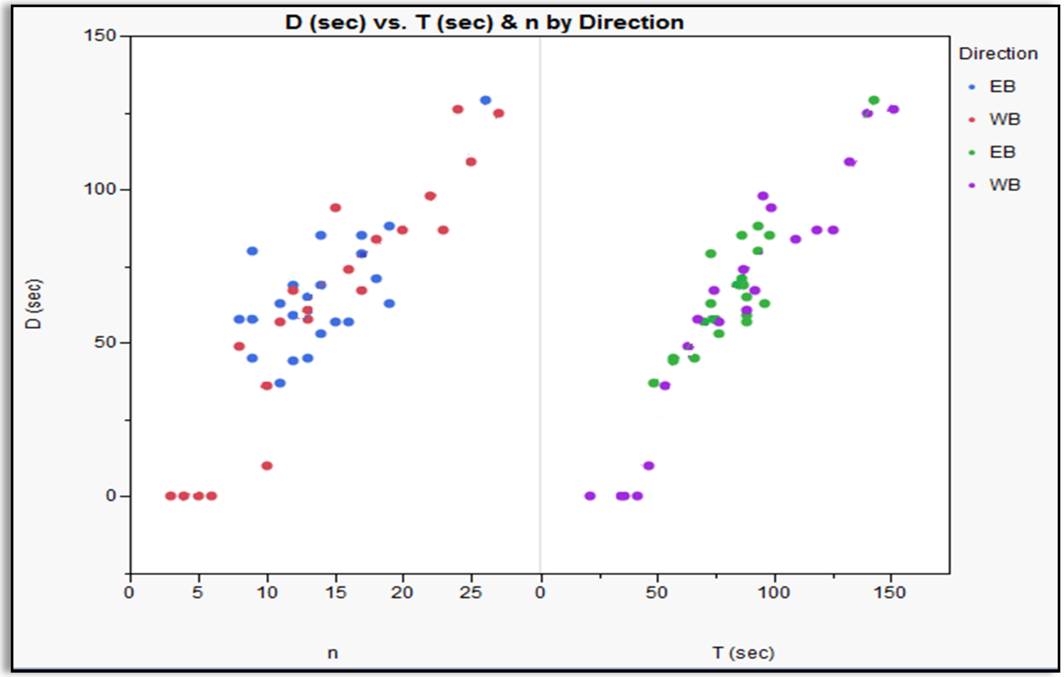

Figure 34: Variation in EB and WB traffic for D vs. n and D vs. T data (Fair Use)

6.7.2 Control Delay Model Development

For any model development, accurate prediction capability of the model for real data is more important than its precision in fitting a curve for the data used for modeling. The time duration between the first and the last Bluetooth hits (T) recorded at a roadside Bluetooth sensor will have a lot of random variation due to random frequency hop structure of the Bluetooth technology. Hence, a non-linear model was first attempted with the available data. Delay modeling based on Bluetooth data becomes challenging due to lack of any previous works on the same concept in the literature. Bluetooth technology for traffic data collection is very recent hence modeling for delay based on Bluetooth data had a lot of trial-and-error for an appropriate delay prediction model. The results from the non-linear model development discussed below as well as the D vs. T plot (Figure 34) showed a relatively linear relationship and hence a linear model between D and T was also developed for comparison.

6.7.2.1 Non-linear Delay Model Based On 'T'

Various non-linear models were attempted for the D vs. T data and finally a polynomial model of degree 2 was found to predict the data very well.

The polynomial delay model developed is as given below:

$$\boldsymbol{D = \delta T - \varepsilon(T-\gamma)^2 - C}$$

$$with\ R^2 = 0.90$$

$$where, \delta = 1.0422$$

$$\varepsilon = 0.00275$$

$$\gamma = 81.0682$$

$$Constant, C = 19.5881$$

$\delta, \varepsilon, and\ \gamma$ are model calibration parameters and C is a constant. Model calibration parameter γ and constant C determine the minimum value of T until which the control delay is zero. Hence, it defines the threshold value of T below which the control delay (D) is zero.

The polynomial fit curve of degree 2 for this model is as shown in Figure 35.

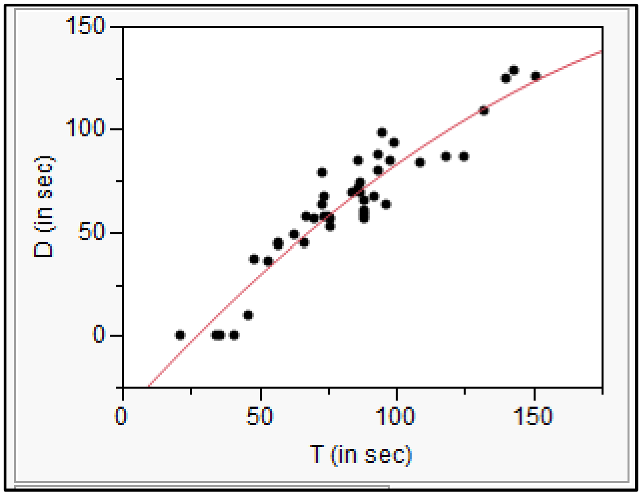

Figure 35: Polynomial fit curve of degree 2 (Fair Use)

6.7.2.2 Linear Delay Model Based On ‘T’

A simple linear model was developed based on the available data for Time duration between first and last Bluetooth hits (T) and Control Delay (D). This linear model primarily was developed to compare with the already developed non-linear model based on T and determine its predictability strength. The developed model is as given below:

$$\boldsymbol{D = \mu T - C}$$

$$R^2 = 0.89$$

$$where, \mu = 1.0241$$

$$C = 20.566$$

μ is a model calibration parameter and C is a constant. In this linear model, C determines the threshold value of T below which the control delay is zero. Figure 36 shows the fit curve for the linear model. The linear fit model obtained an R^2 value of 0.89, very close to that obtained from the polynomial fit model developed with an R^2 value of 0.90.

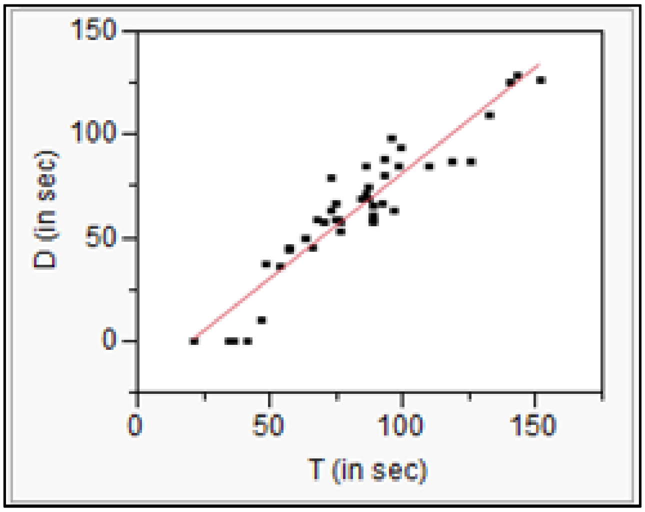

Figure 36: Linear model fit curve (Fair Use)

6.8 Validation and Calibration Results for Delay models based on T

A total of 21 GPS run data points for T (10 EB and 11 WB GPS runs) and corresponding control delay values were used for the validation of the delay model based on T. Both linear and polynomial control delay models developed based on T had almost same R^2 value and hence both models were decided to be used in the validation study. Predicted control delay based on both polynomial and linear models were tested with respect to the actual delays obtained from the GPS runs data extraction. The results from the validation study for both the models are as given in Figure 37.

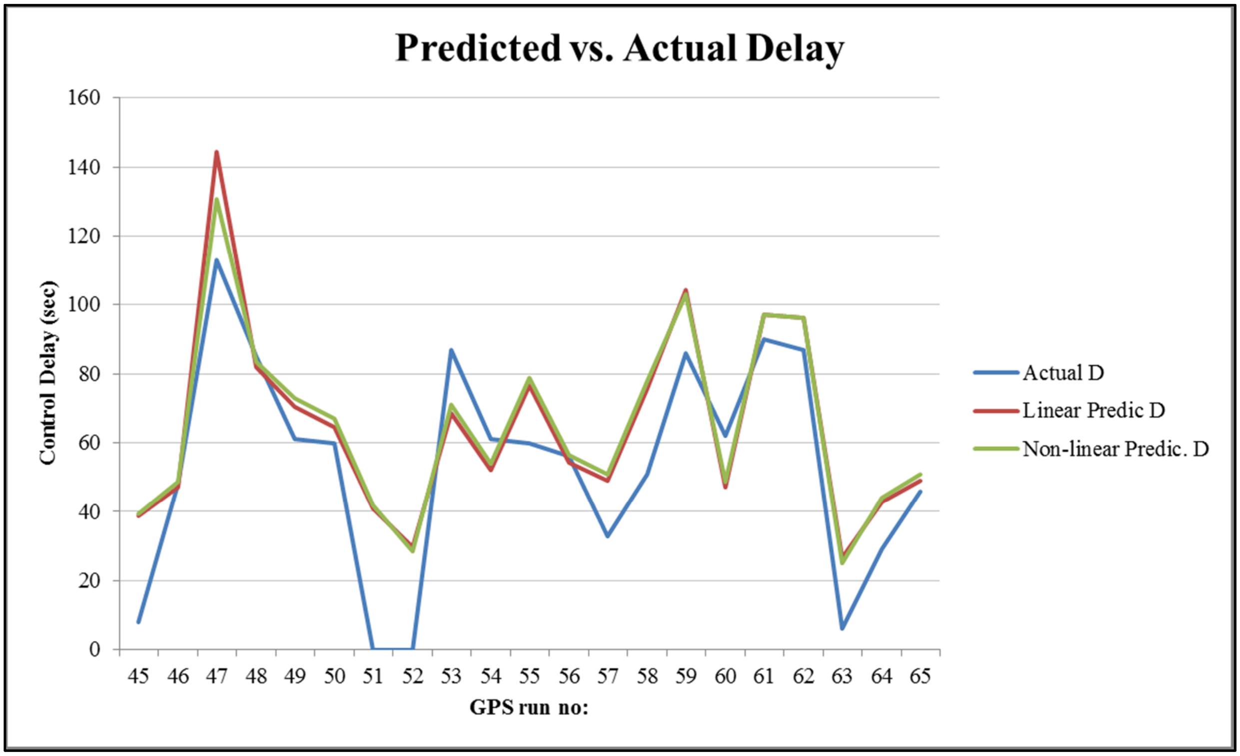

Figure 37: Validation results for delay models based on T (Fair Use)

As can be seen from Figure 37, the polynomial model and the linear model was found to perform comparably well in the validation study. Overall, both the models were found to overestimate the local maximum control delay values and underestimate the local minimum control delay values. The linear model overestimated slightly higher than the polynomial model for very high delay values.

The developed models were also calibrated using the delays obtained by using the current practice of subtracting ideal travel time from the Bluetooth travel time. The model predicted delays were found to perform better than the delay predicted using the current practice (Figure 38, Figure 39). The current practice is to calculate the ideal travel time based on the posted speed limit. This tends to underestimate the travel time and consequently control delays in case of oversaturation. Figure 40 shows the root-mean-square (RMSE) error for control delay estimation using linear and non-linear T models, current practice of control delay estimation, and n model. The non-linear T models has the lowest error and the current practice has the highest error values.

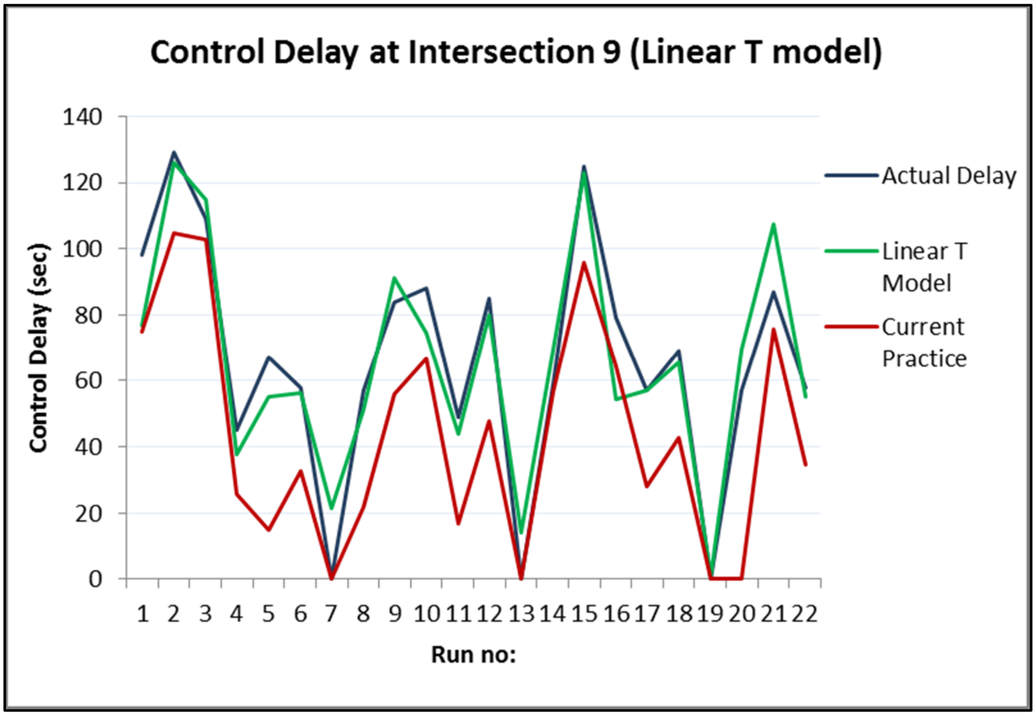

Figure 38: Calibration results for delay models based on Linear T model (Fair Use)

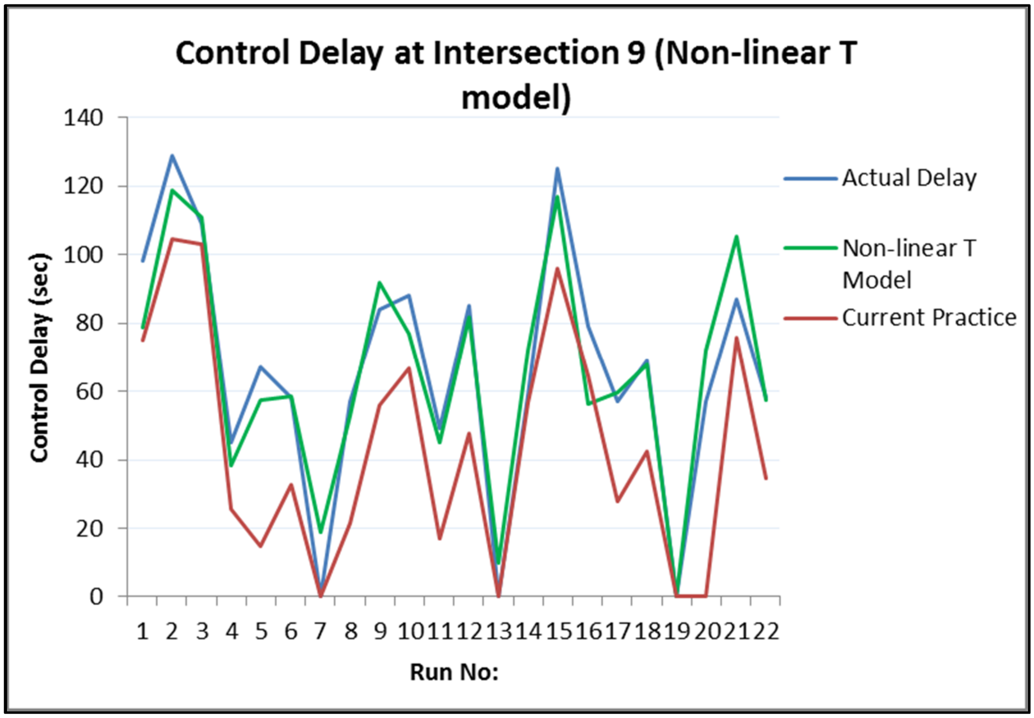

Figure 39: Calibration results for delay models based on Non-linear T model (Fair Use)

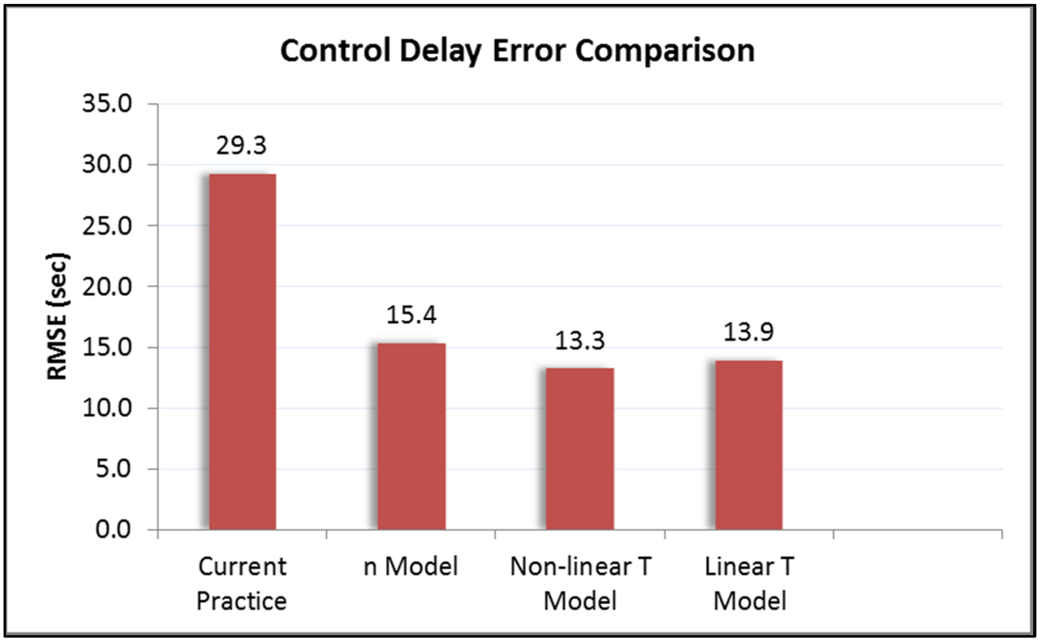

Figure 40: RMSE error comparison for delay models (Fair Use)

6.9 Conclusions

Overall, both the polynomial and linear models developed were found to estimate delay with reasonable accuracy. In this study, the Bluetooth antenna used was a 5dBi omni-directional antenna with a range of approximately 600m. Higher antenna range will increase the spatial error in the Bluetooth detections and hence the variation in the measured T value. Using smaller range Bluetooth antenna which will have enough range to give an adequate Bluetooth detection sample size at the same time reducing the variability in the measured T value might give us better control delay prediction. Furthermore, this paper illustrates a control delay estimation methodology which has the potential for real-time field implementation for improving the intersection performances.

6.10 Future Research

Continued research to explore the various factors contributing to the random error in Bluetooth traffic data will significantly reduce the prediction error of the control delay models and hence enhance the potential for permanent field implementation of control delay to improve overall system performance. Similar researches to model control delay using number of Bluetooth detections or time duration between first and last Bluetooth detections would help determine the model prediction parameters more accurately and hence will help generalize the model. Model prediction parameters represent the prediction errors in the Bluetooth traffic data due to the random frequency hopping structure of the Bluetooth technology. Hence its accurate determination is crucial for control delay model generalization.

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7 CONCLUSIONS AND FUTURE RESEARCH

7.1 Conclusions

This research validates the potential application of Bluetooth technology in traffic engineering data collection. It also develops a novel methodology for control delay modeling based on Bluetooth traffic data collection technique. Control delay is an important performance measure which is neglected most of the time by the traffic engineering professionals due to its complicated analysis procedures and continuous data unavailability. Control delay estimation is required for proper and efficient designing of traffic control systems and approach LOS calculations.

Bluetooth technology works on a frequency hop structure to minimize interference with other radio waves using the same ISM frequency band as Bluetooth technology. This has resulted in a lot of Bluetooth detection errors which affects the traffic data extracted from the Bluetooth traffic data collection technique significantly. Hence, the Bluetooth detection errors are studied in detail and detection error parameters are formulated to develop control delay models. This thesis also looks into the shortcomings of the current Bluetooth traffic data analysis practices and formulates simple and effective control delay models based on Bluetooth traffic data which has the potential to be implemented in the field for real-time delay estimates. The validation result from this research study shows the reliability of these control models to predict actual field control delays within reasonable prediction error limits.

7.2 Future Research

Bluetooth traffic data collection technique lacks vehicle location information. Addition of vehicle location information into the Bluetooth traffic data collection technology would significantly enhance the potential of this technology to be considered for permanent installation in a large scale. Use of a combination of overlapping antenna ranges with RSSI would help to locate the vehicle approximately within acceptable error ranges. Location information would help estimation of the traffic performance measures like travel time, traffic speed, and control delay with a high level of accuracy. It might also solve many of the issues due to the random Bluetooth detection errors. Improved Bluetooth inquiry algorithms to increase the vehicle detection certainty would also help to significantly reduce the Bluetooth detection errors. Currently, the control delay model developed is field specific as the Bluetooth detection errors and Bluetooth signal interferences tend to be field specific. Similar researches in various types of study networks would help determine the Bluetooth detection error parameters and hence the model prediction parameters with better accuracy. This would help generalize the control delay models developed to be applied to any field setting for real-time control delay estimations.

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APPENDIX A - 'BLUETOOTH UNIT' COMPONENTS

The Bluetooth unit used for traffic data collection consists of the following parts:

1. Netbook
2. Bluetooth adapter
3. Bluetooth antenna
4. USB extension cord
5. Netbook cooler

A.1 Netbook

Figure 41: Lenovo S10 Netbook [32]

The Lenovo S-10 netbooks were chosen for the Bluetooth traffic data collection study (Figure 41). The netbooks were a main component of the 'Bluetooth unit' as these supplied the power necessary for the Bluetooth adapter and antenna, and acted as a device to store the traffic data collected by the same. The netbook settings were changed to adapt to the requirements of his study and for continuous data collection, details of which are discussed later in this report.

A.2 Bluetooth Adapter

Figure 42: SENA Parani UD100 Bluetooth Adapter [29]

Bluetooth adapters play a major role in the quality of the Bluetooth data collected in the field. After a thorough search of the Bluetooth adapters available in the present market, it was decided to choose SENA Parani UD-100 Class -1 Bluetooth adapter, due to its various advantages (Figure 42). This Bluetooth adapter has been well tested for operation and storage in extreme temperature conditions. It is compatible with Windows, MAC and Linux OS. It has a comparatively good receiver sensitivity and data transfer rate. This Bluetooth USB adapter comes with a 1dBi stub antenna with a default range of about 300m in clear and open space. The working distance of the adapter can be increased by using higher range antennas with an RP-SMA connector. Due to its higher range than usual Bluetooth adapters, it has been found to be better for industrial and special applications and hence found suitable for traffic data collection study. A detailed review of the specifications for this at: http://www.sena.com/products/industrial_bluetooth/ud100.php.

A.3 Bluetooth Antenna

Various studies conducted on Bluetooth traffic data collection suggested the use of omni-directional antennas. Omni-directional antennas have higher spatial error than a directional antenna but the data sampling rate was found to be much higher due to higher data collection range. Hence, the performance measures calculated with omnidirectional antenna data were found to be more accurate than that for directional antennas.

In our study, we used the 1dBi dipole antenna to do a proof-of-concept study before going to the actual field (Figure 43). A 5dBi dipole antenna was used for the actual study at Reston Parkway Network in Northern Virginia to obtain higher data collection range (Figure 44).

Figure 43: SENA 1dBi Stub Antenna [29]

Figure 44: SENA 5dBi Dipole Antenna [29]

A.4 USB Extension Cable

After careful study to decide between an USB extension cable and an antenna extension cable, we finally came to the conclusion of using an USB extension cable (Figure 45). An antenna extension cable acts as a connector between the Bluetooth antenna and the Bluetooth adapter. This was found to have loss in signal strength directly proportional to the length of the extension cable. On the other hand, an USB extension cable was found to have zero loss in signal strength for the 6m cable used for the study.

Figure 45: USB Extension Cable [31]

The netbook was kept inside the signal control cabinet with the USB extension cable used to extend the length between the netbook and the Bluetooth adapter. Hence, the only disadvantage that can be under consideration is that with an USB extension cable, the Bluetooth adapter + Bluetooth antenna connected to the adapter will have to be kept outside the signal cabinet exposed to the weather conditions. But with proper weather proofing, this disadvantage was accounted for.

A.5 Netbook Cooler

One accessory which would prove to be useful while using the netbook included Bluetooth unit is the netbook cooler especially while being used for extended hours. Our study lasted almost two weeks and hence netbook coolers were found necessary to avoid any overheating of the netbooks.

APPENDIX B - ‘BLUETOOTH UNIT’ – CONNECTION OF THE COMPONENTS

The following figure shows the connection of the various components of the Bluetooth unit:

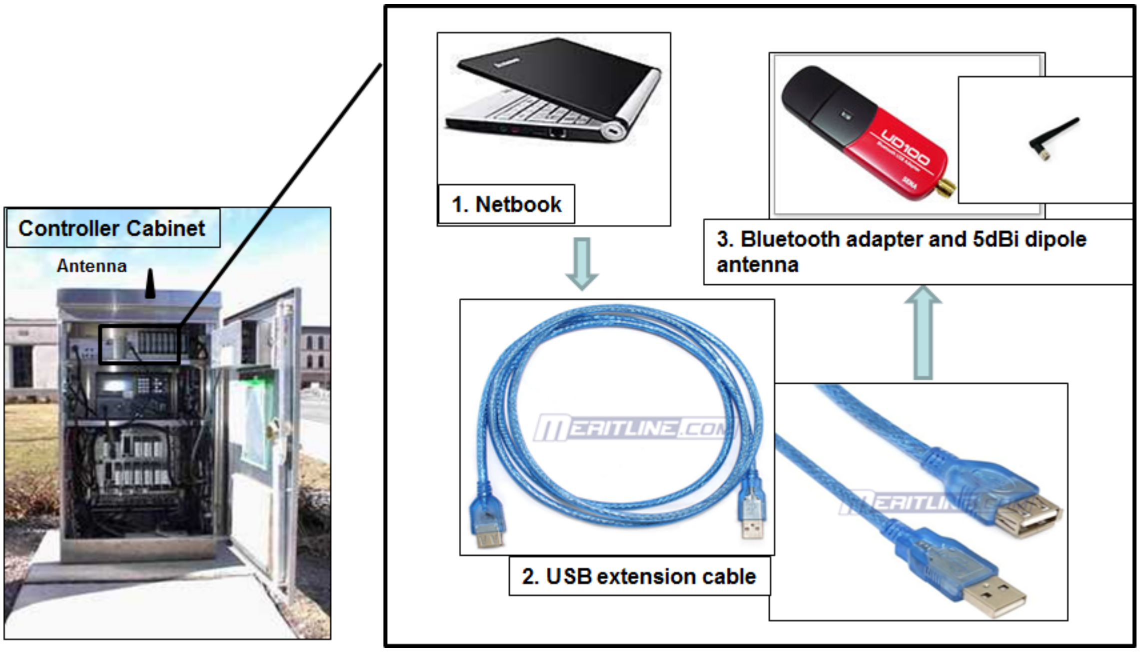


Figure 46: Connection of Various Components of a 'Bluetooth Unit' [29, 31-33]

First the netbook is connected to the USB extension cable which is then connected to the Bluetooth adapter. The Bluetooth adapter default stub antenna is removed and replaced with the 5dBi dipole antenna. The netbook + netbook cooler are kept inside the signal control cabinet. The Bluetooth adapter and Bluetooth antenna are secured in a weather proof case and kept on top of the cabinet. Only the base of the Bluetooth antenna which is connected to the Bluetooth adapter is enclosed in the weather proof case and the main Bluetooth antenna part is left uncovered to avoid any interference with the signal strength and data collection.

APPENDIX C - NETBOOK PREPARATION FOR BLUETOOTH TRAFFIC COLLECTION

The netbooks have to be adjusted for the system settings for uninterrupted data collection during the Bluetooth traffic data collection study. Because we will have a number of 'Bluetooth Units', it would be easier to set up all the netbooks in a row with all of them powered on at the same time. The following steps can be used to prepare the system for the study:

C.1 Linux Installation:

The data collection software application is written in Linux platform and hence first we need to install Linux OS in the netbooks (the netbooks came with a preinstalled Windows OS). One method can be to install Windows Ubuntu Installer (wubi) instead of installing the full Linux OS in the netbooks. Wubi is faster and easier to install. Go to download wubi to download and install wubi. Remember to keep enough memory space allotted to the Linux OS as we would be storing the collected data in Linus OS. For example, give about 100GB of space while partitioning for Linux OS in case one plans to collect Bluetooth data for weeks.

C.2 Update Manager

Check for any up-dates and install the necessary updates. Unlike in Windows, in Linux, the update manager checks the internet for system compatible updates and software downloads. After the system is up-to-date, un-toggle all automatic update options to prevent any update manager pop-ups during the data collection.

C.3 Time Synchronization

After installing wubi, synchronize the time in the system. On the top left corner of the desktop, go to:

System → Administration → Time and Date

In the 'Time and Date' window, select the time zone according to one's location (America/New York in this study and select the configuration as 'keep synchronized with internet servers'. When prompted for install 'NTP support', select install.

After the time has been synched to the internet server, select ‘Time and Date’ settings again and change the configuration to ‘manual’ as there would not be internet connection out in the field.

C.4 Hardware Clock – System Clock synchronization

In a Linux platform, there are two clocks – a system clock and a hardware clock.

a) **System Clock** – This is the time which is maintained in the Linux kernel and is active only when Linux is running.
b) **Hardware Clock** – This is the clock maintained by the system even when the system is shut down. This is maintained by a clock battery which keeps a record of the time. When the system is rebooted, the system clock takes the time from the hardware clock while starting.

Sometimes, when we are running Linux, we can see that the time displayed on the system is incorrect. This would be the time recorded by the Bluetooth adapter while it detects any Bluetooth devices during the study and hence has to be correctly maintained and synchronized between all the netbooks. The following can be the reasons of the wrong time display in Linux based systems:

a. The time configuration is keep as manual and not as synchronized with the internet servers.
b. Un-synched hardware clock and system clock.
c. Drift in time due to lesser strength battery maintaining the hardware clock.

If the time configuration is kept manual and not synched with the internet time servers, there can be a change in time due to hardware clock drift. In our study, as there won’t be any internet connection, the configuration is always set to manual to avoid unnecessary notifications which might interfere with the smooth data collection.

If the first option is not the reason, then it can be due to the fact that the hardware clock and system clock are not synched. Perform the following steps to correct this situation:

a. In the top left corner of the desktop, click on *Application → Accessories → Terminal*
b. Type as follows:
    i. *Sudo su → enter*

ii. *password → enter* (enter the password)

iii. *#hwclock --systohc* (synch hardware clock to system clock)

iv. *#hwclock --show* (show the hardware clock and check if it has been set to the correct system time)

C.5 Suspend Screensaver

The netbooks should not go into screensaver activation/sleep/hibernation as the netbooks would be in the field for a long time.

a. For disabling screensaver, on the top left corner of the desktop, go to *System → Preferences → Screensaver.* Un-toggle ‘activate screen saver when computer is idle’.

b. Click on ‘Power Management’ on the bottom of the screensaver preferences window. For both AC Power and Battery tabs, set the computer sleep settings to ‘never’. Also, un-toggle ‘spin down hard disks when possible’ option.

c. On the ‘general’ tab, set the ‘when power button is pressed’ option to ‘Ask me’ so that even if someone accidently presses the power button, the system will ask us what to do instead of going into suspend/shut down mode.

C.6 Disable Network Connection

After the update manager is run and the time synched, we do not need internet connection for running the Bluetooth data collection software. Also, the field might have a number of wireless networks around and hence to prevent any unnecessary wireless network notifications, disable the network connections by right clicking on the wireless connection icon on the top right corner of the desktop. In case the netbooks come with in-built Bluetooth drivers, uninstall them through the windows platform as an extra measure.

APPENDIX D - RUNNING THE BLUETOOTH PROGRAM – ‘Bluetooth_capture.sh’

(Bluetooth inquiry code courtesy: John Paul Dunning, Virginia Tech)

The Bluetooth software is written in the Linux platform. The folder ‘btwatcher’ has the ‘bluetooth_capture’ code file, make file, and a log folder. The data collected approximately every 5 seconds is stored in this log file. After we stop the program, the data for the entire duration is concatenated and stored in the ‘btwatcher’ folder as ‘filename.traffic’ where filename is the name we give while initializing the Bluetooth program in each netbook. In this study, for convenience, we have given the unit number of the netbook as the filename.

D.1 Opening Procedure for Bluetooth Data Collection Units:

i. Power-on the netbook and connect one end of the USB extension cable to it.
ii. Connect the Bluetooth antenna to the Bluetooth adapter and connect it to the other end of the USB extension cable.
iii. Boot the system to Linux OS (wubi in our case).

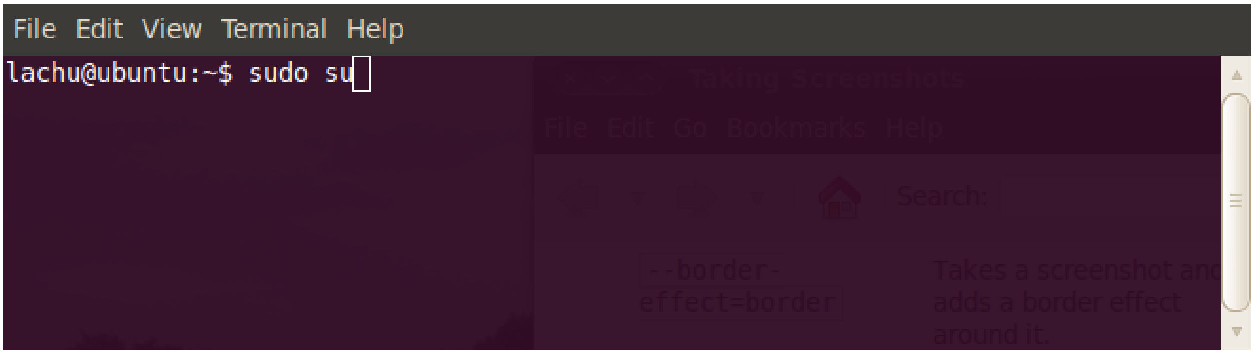
D.2 Procedure for running the Bluetooth Data Collection Program (follow step-by-step):

Sl. No.	Commands	Comments
Step 1	*Open Applications → Accessories → Terminal*	//Open ‘Terminal’ window
Step 2	*sudo su → enter*	//switching the user to access permission for changing directory and running the Bluetooth program.
Step 3	*password → enter*	//enter password. (passwords are not be displayed in the Terminal window when typed)
Step 4	*cd Desktop/btwatcher → enter*	//changing directory
Step 5	*./bluetooth_capture.sh → enter*	//compiling and running code
Step 6	*hci0 → enter*	//interface name number ZERO, not letter ‘O’
Step 7	*unit# → enter*	// without SPACE enter YOUR unit no: in place of ‘#’

Step 8	*Ctrl+C → enter*	//to stop the Bluetooth code

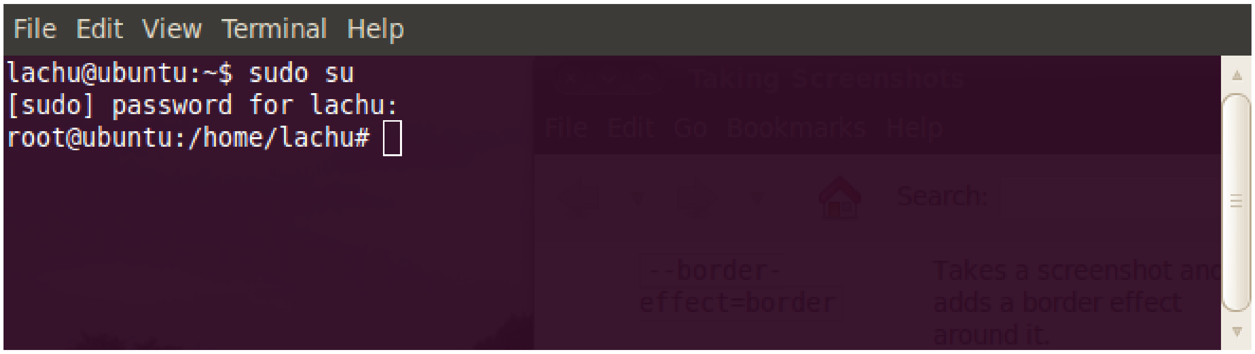
The following screenshots will illustrate the step-by-step procedure mentioned above:

STEP 1:



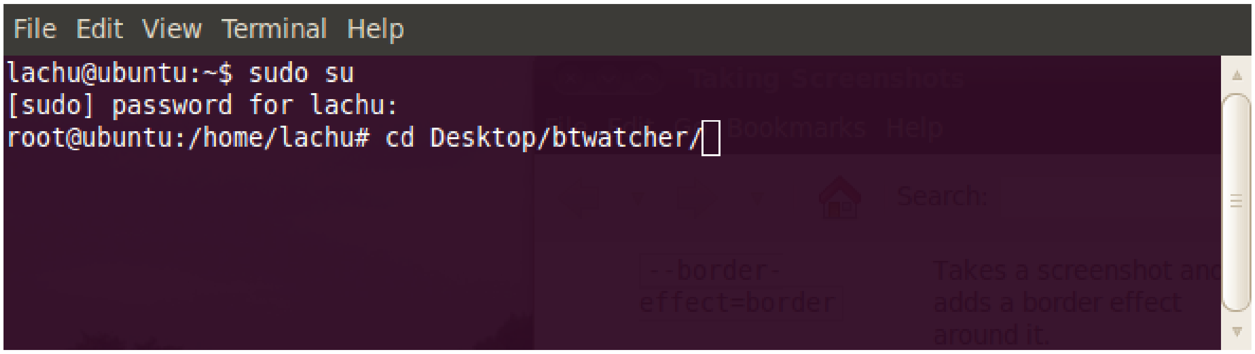
```
lachu@ubuntu:~$ sudo su
```

STEP 2:



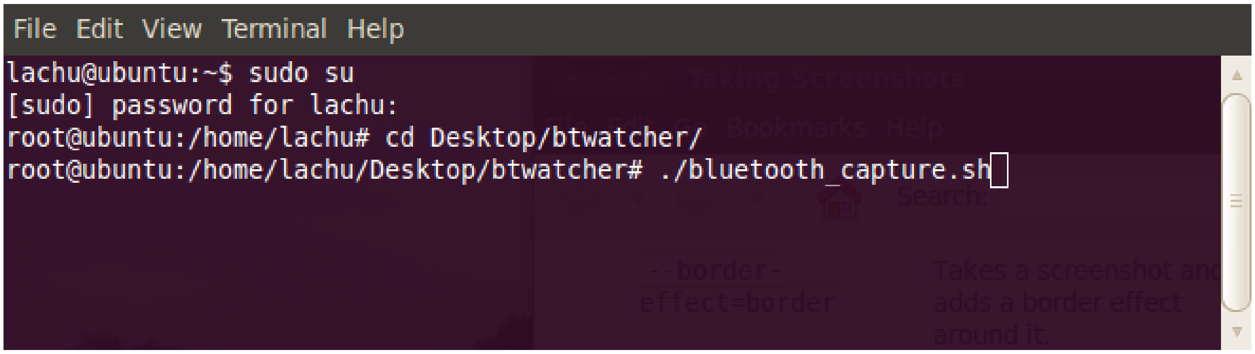
```
lachu@ubuntu:~$ sudo su
[sudo] password for lachu:
root@ubuntu:/home/lachu#
```

STEP 3:



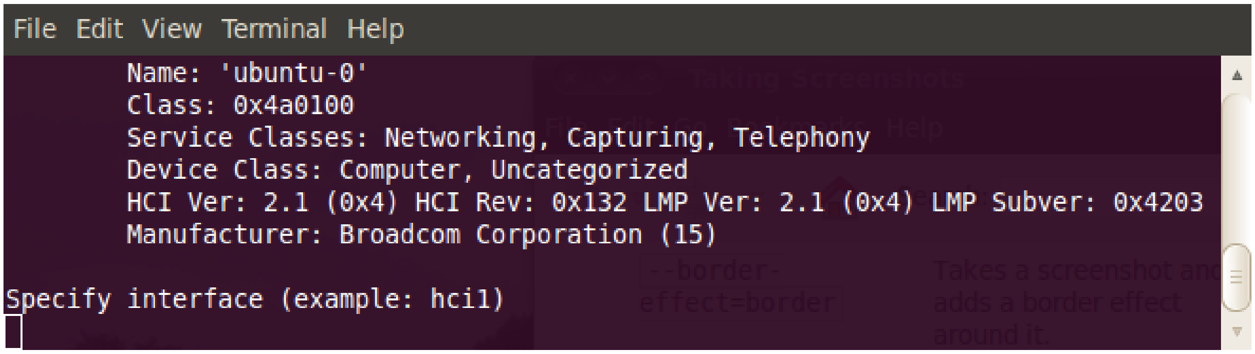
```
lachu@ubuntu:~$ sudo su
[sudo] password for lachu:
root@ubuntu:/home/lachu# cd Desktop/btwatcher/
```

STEP 4:



```
lachu@ubuntu:~$ sudo su
[sudo] password for lachu:
root@ubuntu:/home/lachu# cd Desktop/btwatcher/
root@ubuntu:/home/lachu/Desktop/btwatcher# ./bluetooth_capture.sh
```

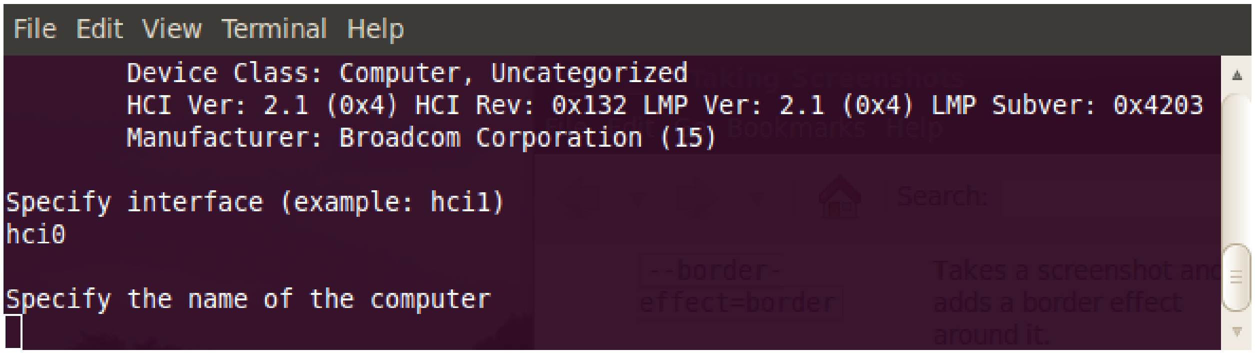
STEP 5:



```
        Name: 'ubuntu-0'
        Class: 0x4a0100
        Service Classes: Networking, Capturing, Telephony
        Device Class: Computer, Uncategorized
        HCI Ver: 2.1 (0x4) HCI Rev: 0x132 LMP Ver: 2.1 (0x4) LMP Subver: 0x4203
        Manufacturer: Broadcom Corporation (15)

Specify interface (example: hci1)
```

STEP 6:

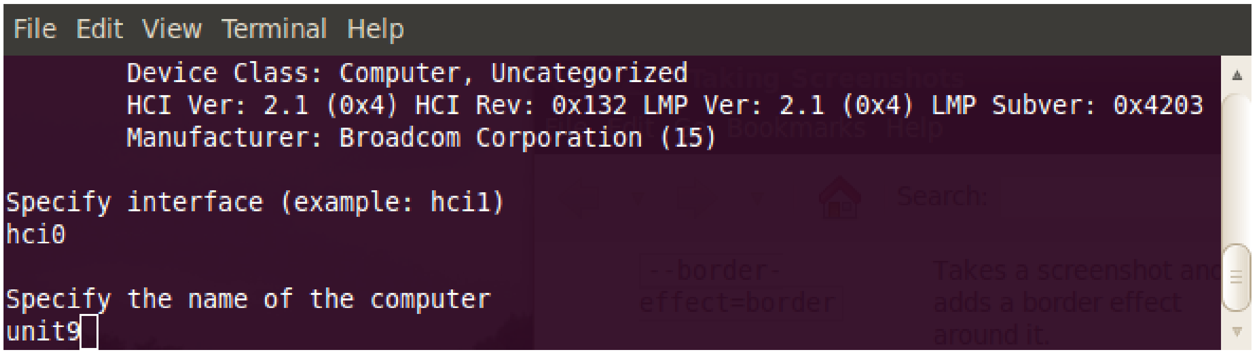


```
        Device Class: Computer, Uncategorized
        HCI Ver: 2.1 (0x4) HCI Rev: 0x132 LMP Ver: 2.1 (0x4) LMP Subver: 0x4203
        Manufacturer: Broadcom Corporation (15)

Specify interface (example: hci1)
hci0

Specify the name of the computer
```

STEP 7:



```
        Device Class: Computer, Uncategorized
        HCI Ver: 2.1 (0x4) HCI Rev: 0x132 LMP Ver: 2.1 (0x4) LMP Subver: 0x4203
        Manufacturer: Broadcom Corporation (15)

Specify interface (example: hci1)
hci0

Specify the name of the computer
unit9
```

Figure 47: Screenshots of Running Bluetooth Program step-by-step(Fair Use)

NOTES:

i. Plug in the adapter only after Linux has loaded.

ii. Do not press Ctrl+Z instead of Ctrl+C.
Ctrl+Z will stop the code without concatenating the files!

iii. Be careful not the touch the power button while handling the netbook as making the computer sleep will result in errors in data collection.

iv. Before starting to run the code anew and start a new data collection – please do not forget to delete the following files in the btwatcher folder in the desktop:
   1) Single file named unit#.traffic inside the btwatcher folder
   2) All files inside btwatcher -> log folder

D.3 Closing procedure for Bluetooth data collection units:

i. In the computer terminal screen, press CTRL+C.

ii. Wait till the message – '**finished concatenating files**' is displayed on the screen. It will only a few seconds.

iii. Close the terminal window and shutdown the computer.

iv. Disconnect Bluetooth USB cable connecting laptop to the Bluetooth adapter & antenna.

v. Remove the rest of the accessories (laptop charger + laptop cooler).