Bluetooth based dynamic critical route volume estimation on signalized arterials

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ABSTRACT

Bluetooth Data collection technique is recently proven as a reliable data collection technique that provides the opportunity to modify traditional methodologies to improve system performance. Actual volume in the network is a result of the timing plans which are designed and modified based on the volume which is generated using existing timing plans in the system. This interdependency between timing plan and volume on the network is a dynamic process and should be captured to obtain actual traffic states in the network. The current practice is to calculate synthetic origin destination information based on detector volume that doesn’t necessarily represent the volume scenario accurately. The data from Bluetooth technology can be utilized to calculate dynamic volume on the network which can be further used as input for signal timing design. Application of dynamic volume improves the system performance by providing the actual volume in system to design optimal timing plans. This thesis proposes a framework that can be used to integrate data obtained from the Bluetooth technology with the traditional methods to design timing plans. The proposed methodology utilizes the origin destination information obtained from Bluetooth data, detector data, characteristics of intersections such as number of lanes, saturation flow rate and existing timing plans as a basis for the calculation of the dynamic volume for the various movements at each intersection. The study shows that using the Bluetooth based OD matrix to calculate accurate dynamic volumes results in better system performance compared to the traditional way of using the static detector volume alone.
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DEDICATION

I dedicate this thesis to my Father, Ananta Gharat, whose love, support, patience, and encouragement provided me with the strength and perseverance I needed to achieve my goal.
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1 Introduction

Efficient operation of signalized intersections is typically achieved through optimal design of timing plans as well as the mode of operation, such as time of the day or traffic responsive control. Timing plans are optimized using various software packages such as PASSER and Synchro. In order to develop optimal timing plans, an accurate representation of traffic states is needed. The optimization is carried over to yield better signal performance in terms of delay, number of stops, or other objectives.

The accuracy of designed and optimized timing plans is based on the accuracy of traffic states representation. Traffic state in this context refers to the existing traffic pattern for all approaches at a certain point in time. Traffic state for an arterial consist of major external movement, cross street movements and internal movements as illustrated in Figure 1. The first two movements describing traffic states and internal movements are generally calculated.

Traditionally, internal movements in an arterial are obtained from either manual counts or system detector logs. Alternatively, if the OD distributions are known, then internal movements can be
calculated based on the summation of relevant OD pairs passing through each link. However, none of these two methods take into account the metering effect of timing plans at the peripherals of the network.

Traffic engineers has been limited to static estimation of internal movements due to the lack of resources and detailed OD knowledge at the intersection level. However emerging technology brought new solutions to this challenge. Conventionally the origin destination information was calculated using different statistical approaches. Synthetic OD estimation is one among the popular approaches. The statistical approaches are based on various assumptions which reduce their reliability. Introduction of Bluetooth technology in traffic data collection introduced advanced features in data collection. It has various significant applications like travel time calculation, speed calculation, etc. This technology provided solutions to various challenging problems; obtaining actual origin destination information was one of the major solutions brought by this technology.

Bluetooth Data collection technique collects OD data using Bluetooth Units that capture information from vehicles equipped with any Bluetooth device. It detects the unique MAC Address associated with Bluetooth device and time of detection. By installing number of Bluetooth detection unit at different desired location, it is possible to track the path followed by a vehicle. If the detection units are located at every entrance and exit of an arterial, it is possible to collect the origin destination information of each detected vehicle. Traffic patterns can be derived from collection of origin destination information for significant period of time.

Here, OD information provided by Bluetooth data is applied to calculate the volume associated with internal movement. The distribution of the volume is majorly affected by the green time provided for the respective phase. The volume is dependents on timing plans and the timing plan optimization is based on volume. This interdependency leads to dynamic volume for internal movements.

Dynamic critical route volume associated with network is the continuous changing volume due to change in timing plans provided for the network. Calculation of dynamic volumes involves distribution of external volume. This distribution is based on the OD matrix obtained from Bluetooth data and capacity. Capacity is calculated by using timing plans, amount of green time and saturation flow rate.

1.1 Thesis Objective
The main objectives of this thesis are:

- To develop stepwise procedure to obtain Origin Destination Matrix from Bluetooth data
- To formulate the concept for calculation of Dynamic critical route volume applying OD information obtained from Bluetooth data
- To Design a framework for timing plans optimization based on dynamic critical route volumes.

1.2 Thesis Contribution

This thesis aims at using the Bluetooth technology to design effective timing plans. Traffic signal system performance is predominantly dependent on the selection of accurate mode of operation and selection of precise timing plans. The common practice is to design timing plans with the help of synthetic origin-destination analysis utilizing detector counts obtained from loop detectors. The detector counts are based on the current timing plans. Objective of modification of timing plans is to protect the oversaturated links and inflate the volume in links with higher storage. This metering is based on capacity and it reflects in the form of actual volume which passes through the intersection. The optimization of timing plan should be based on this actual volume which can be calculated by applying Origin Destination information derived from Bluetooth data and demand capacity ratios. This thesis focuses on the development of a stepwise procedure which uses the benefits from the new world technologies to improve the current practice.

1.3 Thesis Layout

The thesis is organized into five chapters. This chapter presented an introduction, research objectives, and contribution of the thesis. Chapter 2 presents the literature review for the concepts used. Chapter 3 describes the development of the methodology used for the implementation of the Bluetooth data to obtain critical routes based on Origin destination matrix for the network. Chapter 4 describes implementation of dynamic critical volume to design and optimization of timing plan. Chapter 5 presents the study conclusions and recommendations for further research.
2 Literature Review

2.1 Overview

Bluetooth Technology proved its application in the traffic management field. It provides the information which was very difficult to obtain for traffic engineers. Using Bluetooth technology it is possible to track vehicle equipped with Bluetooth devices. This Detection of vehicle provides data with unique id and time of detection. The data is used to obtain Origin Destination information within the network. This information is used to highlight Critical route on the network.

In the process of design of timing plans for signalized intersection, the accurate calculation of volume is required. Volume distribution on network is dynamic. It changes with changes in time plans. This change in volume is identified by using origin destination data. The use of dynamic volume in the process of timing plan design and optimization would help to increase the accuracy of the existing methods. This chapter presents the basics of Bluetooth technology, Origin Destination concept, Design and optimization of timing plans.

2.2 Bluetooth data collection technique

Bluetooth is Short-range open wireless communication technology which Works on frequency hopping principle in which random frequency is chosen for each time slot of transmission. Every Bluetooth device has a 48-bit unique address known as Median Access Control (MAC) address-12 digits long. As example: “00:03:6E:21:C6:92”. While detection Bluetooth adapter searches for all discoverable Bluetooth devices in range. This state is termed as Enquiry state. MAC address is sent and received during device inquiry stage[2]. Received MAC addresses are time-stamped and stored. This Bluetooth detection mechanism is explained in following figure.
The Bluetooth data collection units are available in market for purchase or on rent by several different vendors[3]. Along with data collection units some vendors provide the service for collection of data.

The Bluetooth data collection has benefits over other techniques as following:

• It gives Direct measurement of travel time, speed, OD data
• It has Minimal privacy intrusions as only MAC -Median Access Control address is stored[4]
• It doesn’t need addition/modification to existing road infrastructure
• It’s possible to collect continuous 24 hours database compared with other methods like Automatic License Plate Recognition (ALPR), Toll tag reading, etc.
• It is more economical than existing methods (e.g., ALPR, Road-side surveys, etc.)
• It is possible to perform data collection in locations inaccessible to other types of sensors

The Bluetooth data collection technique provides the MAC address which is equivalent to unit identification number and time of detection of the devices which pass through the range of detection over the period of collection[5].

The most useful application of Bluetooth data is to measure travel time and to estimate origin-destination matrices[6]. Traditional technologies, such as inductive loop detectors, do not usually produce measurements of the quality required by real-time applications.
Bluetooth technology has some drawbacks like it only captures a fraction of vehicles in the traffic stream which has Bluetooth unit. To obtain true representation of field Origin destinations, large amount of data should be collected. Several efforts have been taken to check the reliability and accuracy of media access control (MAC) technology. Bluetooth technique is tested by measuring travel time using MAC readers and comparing with traditional floating-car method[7]. The effort have been taken to evaluate work zone mobility performance by the automated collection and processing of Bluetooth probe data from multiple field collection sites, communicating travel delay times to the motoring public, assessing driver diversion rates, and developing proposed metrics for a state transportation agency.

2.3 Loop detector data applications

The design and selection of timing plans which are best suitable to the traffic states is important tsk in improvement of the performance of overall system. The data used by practitioners to design timing plans is generally detector data collected by various detection techniques such as loop detector, Video Detection, Microwave, Radar, Sonar, Magnetic field detection[8]. The most commonly used data is loop Detector data. The loop detector detection is basically electromagnetic communication and detection system. The vehicle detections loops are generally located near the stop line and also at certain important point on roadway at which the detector data need to be monitored. In this method an insulated electrically conducting loop is installed under the road and electric current circulate through the loop at all times. When a ferrous body which can be iron of steel passes close to the wire loop it results in change in inductance of loop and the vehicle is detected. The loop detector data collection method provides with vehicle count, occupancy and speed of vehicle for specific interval of time based on which controller decides the traffic state and mode of operation the operation[9]. The loop detector data significant applications while dealing congestion problems and travel time calculation.

2.4 Significance of O-D information in process of Signal time plan optimization

The design of signal timing is based on the accurate identification of traffic state. Using loop detector data the volume associated with external movement is calculated. The external volume required to be distributed to obtain volume belongs to internal movement. This distribution involves assumption of equal attraction between two nodes which is unrealistic. The distribution is dependent of origin destination matrix for the network. To obtain the distribution either the simulation need to be done or the actual O-D need to be obtained[4]. The several mathematical approaches are taken to calculate dynamic O-D flow[10]. This is a high-dimensional problem and needs to be decomposed into smaller sub-problems at the intersection and corridor levels. Several schemes have been proposed to decompose this complex problem[11].
3 Validation of Critical routes utilizing Origin-Destination Matrices in Reston Parkway Using Bluetooth Data Collection Methods

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ABSTRACT

Bluetooth-based data collection techniques have been recently proven as effective and reliable traffic data collection methods. Several research efforts have been undertaken to utilize Bluetooth information for various important applications, such as travel time and speed estimation. This article aims to add an application of Bluetooth technique to estimate origin-destination matrices thereby to obtain the critical routes on urban arterials, along with the procedure for installation of cost-effective Bluetooth data collection system in the field. The information about critical routes for an oversaturated signalized arterial plays a significant role in the process of designing the signal control system. By applying the information about the origin-destination pairs for an arterial, it is possible to obtain the traffic pattern which provides the fundamental information to identify the critical routes on the arterial. The prioritization of these identified critical routes facilitates the application of traffic signal control strategies. By applying the Bluetooth technique, it is possible to keep track of vehicles equipped with Bluetooth devices such as mobile phones, hands-free kits, global positioning system onboard units, and laptops. The data obtained from detection of these Bluetooth equipped vehicles at various Bluetooth detection unit locations at an arterial was used for identification of critical routes using origin-destination trip matrices for different times and days. The variation observed between these matrices is utilized to validate the critical routes obtain by detector data and presented in this paper to highlight the importance of using such information in designing effective control strategies.

*Keywords: Bluetooth data, Origin Destination, Traffic Signal Control*
3.1 Introduction

Bluetooth-based traffic data collection is an innovative and reliable method for data collection and travel time calculation [2]. Using this evolving data collection method can provide a viable and cost-effective alternative for laborious and time-consuming traditional data collection methods, such as probe vehicles and roadside surveys. Bluetooth data collection methods have already seen an increasing level of interest for estimating travel time on freeways [3][12]. The Bluetooth equipment on moving vehicles has a relatively low penetration rate at the moment (8-10%), but is expected to increase with time[13]. There is limited literature describing analytical application and use of Bluetooth technology in transportation [14][13]. Implementation of Bluetooth data collection methods is mostly facilitated by several companies in the market for installation and service cost. The cost to implement this technique is high at present, which limits its frequent use by traffic professionals and agencies. However, this is expected to change as the cost of implementation reduces with time. In this paper, we apply a time-offset searching technique to extract and tabulate O-D matrices during different times and dates. This O-D information is useful to understand and design effective control strategies for an arterial network. The last section of the paper explains how this information could be used for this purpose.

![Figure 3 Application of Bluetooth Technology](image-url)
Bluetooth wireless capabilities are available in most electrical devices in today’s market. These devices utilize a Bluetooth protocol with an electric identifier known as the Media Access Control Address (MAC Address)[15]. This MAC Address is unique for any device and can be treated similar to vehicle signature. Each Bluetooth device in the vehicle has a unique MAC Address. A vehicle can therefore be tracked by tracking the MAC Address of any device in the vehicle. The Mac Address can be detected by roadside Bluetooth detection units, along with the time of detection. This information can be utilized as traffic data for various applications as shown in Figure 3. The direction of travel of a vehicle can be obtained by observing the order of detection at consecutive units. Travel time can be estimated by calculating the time difference between detection at two consecutive units. The speed of vehicles can be obtained using the estimated travel time and the distance between units.

3.2 Reston Parkway Arterial

We implemented our Bluetooth data collection technique along Reston Parkway. Reston Parkway is located in the Fairfax County in the state of Virginia, USA. The network has a total of 13 intersections as shown in Figure 4. The length of the entire network is 16,572 feet. The maximum link length is 3,800 feet and the minimum link length is 621 feet. The speed limit for the main arterial is 45 mph, and it ranges between 15 mph and 45 mph for the side streets.
Figure 4 Reston Parkway Network with Intersections

The traffic condition of Reston Parkway is fairly oversaturated during peak hours, especially at closely spaced intersections such as Sunset Hill Road and Bluemont. The Reston Parkway network overpasses the Dulles Toll Road with two intersections from the on- and off-ramp. This configuration results in atypical O-D matrices that are not usually observed in normal arterial networks which in turn justifies the need to obtain accurate measures of O-D matrices for traffic patterns on the Reston Parkway.

Field observation and loop detector data is applied to obtain various volume profiles along each movement as shown in sample volume profiles in figure 3. The obtained volume profiles suggested some primary critical paths on the network as shown in Figure 5.

A critical path is defined as a series of intersections along which the traffic volume shows a high value or variation throughout the time of day. System detectors installed in Reston Parkway were used to obtain the total number of vehicles passing through or originating from any particular link in the network. The primary critical routes are studied and utilized to decide the location of Bluetooth detection units. The number of Bluetooth units is restricted due to the cost factor. Hence the number of Bluetooth units to be installed was decided based on the criteria that the location of a Bluetooth unit should cover the maximum number of critical routes without confounding the information obtained from each unit (i.e., any significant traffic origin or destination should be covered by one unit to allow the analyst to trace down the source of significant sink or source of traffic on the network).
The location of Bluetooth units is fixed based on the entrance and exit of the critical routes. The number of Bluetooth units used for this implementation was 9 units that were located and numbered as shown in Figure 7.
3.3 Bluetooth Data Collection Setup

There are several types of Bluetooth data collection units that are available in the market. Some of these units require an external electric power supply. It would be a difficult and costly process to provide an external electric power supply in the field at the required locations. There are some Bluetooth equipments which have solar panels embedded, but the cost of these are high, exceeding the available budget of the project. Hence the whole setup of the Bluetooth detection unit was developed to meet the cost requirement and other influencing factors such as the power supply and security of equipment after installation. The data collection unit is developed using the following components shown in Figure 8:

1. Controller Cabinet
2. Netbook (a)
3. Bluetooth adapter (b)
4. Antenna - 5dbi dipole (d)
5. USB extension cable (c)
The Bluetooth technique implementation was part of a project funded by Virginia Transportation Research Council and for the Virginia Department of Transportation, which facilitated the access to the controller cabinet.

Traffic signal controller cabinets are generally located near the intersection where the data collection is required. The controller cabinet is chosen for the installation location of the Bluetooth unit because it has an uninterrupted power supply and it provides security of the installed units to ensure large data collection period.

The netbook with a Bluetooth adapter was used as a data collection unit. The netbook has a Linux operating system, which can run Bluetooth sniffing code to obtain the data. A 5dbi dipole antenna was used to amplify the range of detection. This allowed a range of 100 meters on each side of the road. The netbook with a Bluetooth adapter was kept inside the controller cabinet and the antenna was fixed outside of the cabinet using the USB extension cable. A continuous electrical supply was provided using the plug point available inside the cabinet. Cooling pads were used to reduce the chances of damaging the netbooks due to heat and/or continuous use.

The provided range of the antenna was to maintain a sufficient gap between the detection zones of Bluetooth units which reduces the chances of dual detection. The Bluetooth units were installed at every location and data was collected for 16 consecutive full days.

### 3.4 Raw Data and Primary Data Processing

Bluetooth data was collected for 18 days, including the day of installation and the day of the collection of units. The days for which the units were installed and collected were excluded from the analysis for data coordination purposes. Hence the complete data set was available for 16 consecutive full days. The total data collection contains 4.5 million data points.

<table>
<thead>
<tr>
<th>MAC ID</th>
<th>Unix Time</th>
<th>Date</th>
<th>Time</th>
<th>Unit No</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:1B:DC:50:14:76</td>
<td>1291004260</td>
<td>11/28/2010</td>
<td>11:17:40 PM</td>
<td>1</td>
</tr>
<tr>
<td>00:1B:DC:50:14:76</td>
<td>1291004266</td>
<td>11/28/2010</td>
<td>11:17:46 PM</td>
<td>2</td>
</tr>
<tr>
<td>00:1B:DC:50:14:76</td>
<td>1291004274</td>
<td>11/28/2010</td>
<td>11:17:54 PM</td>
<td>3</td>
</tr>
</tbody>
</table>

The raw data was obtained in log files and was extracted to excel file format as shown in Table 1. The first column in Table 1 contains the MAC Address. A single MAC Address will get detected several times at any particular unit. The frequency of enquiry sent by the Bluetooth unit was once every 5 seconds. If the vehicle stays in the range for a large period of time, it can get detected several times.
The second column consists of the time in UNIX time format, which can be converted to date and normal time format using simple formulae. The formulae were applied to the entire dataset. The unit number (ID) was also included in respective data sets for O-D analysis.

Data sets were extracted for each day for each unit and were combined to get the Bluetooth data for each day.

3.5 **O-D Estimation Methodology**

The collected dataset consisted of all detected MAC Addresses with its time of detections at different units. This information was analyzed to get O-D pairs for the network. Figure 8 explains the methodology applied to extract the O-D pairs. As shown in Figure 8, every vehicle follows a particular path and as a result it gets detected at every unit it passes through. The number of detections at each unit depends on the speed of the vehicle. In our preliminary analysis, the first detection for any particular MAC address at any unit was extracted and arranged in ascending order. This will give the sequence of intersections that the vehicle has passed through. The intersection at which the vehicle appeared first was considered as the origin and the intersection at which it appeared last was considered as the destination. After getting detected at the destination, a vehicle leaves the network. This concept is used to get the O-D pair for each MAC Address. The large number of MAC Addresses are analyzed in an excel sheet using pivot tables to extract the O-D pair for each time period.
Detailed observation of the data provided very significant information that there are more O-D pairs available for some MAC Addresses. This is due to the fact that the location of the experiment is basically a commercial zone and most of the vehicles belong to commuter traffic. Hence it was logical that they would have at least two trips a day, one trip is when they drive to work and another trip is when they return home (or any other destination). Any particular O-D pair was associated with a 15-minute time period corresponding to the time of its first detection. The total number of origins present in every 15-minute time period is calculated. Each MAC address is scanned in the network within two time periods to determine the last time it appeared. Two time periods (30 minutes) was deemed enough (and was later validated) to clear the 3-mile long network during congested conditions. This time-offset searching technique resulted in extracting the first O-D pair for any vehicle. The procedure was repeated again by starting with the latest time a MAC address was observed in the network. This latest time was considered as the destination for the second trip. A time-offset search within the previous two periods resulted in the determination of the origin for the second trip. If a vehicle made only one trip on the network, this procedure will result in extracting two identical trips for the vehicle, for which one of them was discarded as a redundant trip.

Table 2 Output from analysis: O-D Matrix

<table>
<thead>
<tr>
<th>YEAR</th>
<th>MONTH</th>
<th>DATE</th>
<th>ORIGIN UNIT</th>
<th>TIME PERIOD</th>
<th>DESTINATION UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Start</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>2010</td>
<td>November</td>
<td>23</td>
<td>1</td>
<td>12:00AM</td>
<td>2 0 3 4 2 1 3 1 1</td>
</tr>
<tr>
<td>2010</td>
<td>November</td>
<td>23</td>
<td>1</td>
<td>12:15AM</td>
<td>1 3 4 2 1 1 2 2 1</td>
</tr>
<tr>
<td>2010</td>
<td>November</td>
<td>23</td>
<td>1</td>
<td>12:30AM</td>
<td>2 1 2 3 4 2 0 2 2</td>
</tr>
</tbody>
</table>

The 15 minute time period interval was used to match the loop detector data tabulation that was originally used to find the initial critical routes. The MAC Addresses were not considered after this stage in the analysis. The final output of the analysis was conducted in Excel and consisted of summing the total number of O-D pairs for each time period and for each day as illustrated with the example in Table 2.
The output of the final analysis is presented in Figure 8 as obtained from SAS JMP Software. In Figure 10, the analyst can observe that certain O-D pairs do not change significantly over time or over different days. These movements can be treated as a background or base layer of traffic in the network. This critical movements obtained using Bluetooth data are coincides with the critical movement observed using field condition and loop detector data. This observed critical movements that change significantly during the day or during different days emphasize the need for the analyst to address them by designing different timing plans that change in response to changes in these movement (either by a time-of-day or traffic responsive control mechanisms).

In addition, knowing that a critical route has significant number of trips can justify applying certain control strategies. For example, an upstream through movement could be coordinated with a downstream left movement, rather than the through movement if that is what defines the critical route (O-D).
3.6 Conclusions and Further Research

The Bluetooth technique provides a cost effective and high quality traffic data collection method by which the origin destination information of trips within a network can be estimated. The MAC Address obtained is accurately used to obtain data that is otherwise very difficult to obtain. The final output obtained is critical route information based on O-D Pair Matrices for the network during different time periods and days. The information obtained can be utilized in various ways to improve traffic control systems, including optimal design and activation of optimal control strategies.

Future research includes the utilization of real-time O-D estimation in optimal control, as well as the robust analysis of synthetic O-D estimation techniques that are currently used in commercial planning software.

3.7 References

7. Stan Young, (2008), Bluetooth traffic monitoring Technology concept of operation and development guideline, Center for Advanced Transportation Technology, University of Maryland, Maryland, USA
4 Detector data Analysis

4.1 Preliminary Analysis

System detector data was provided by VDOT for Reston Parkway Network of signalized intersections situated at Fairfax County in Northern Virginia. The data consisted of Count, Occupancy, and Speed for every fifteen minutes time period interval. The preliminary study is done for database of eight month.

The Objective for preliminary study on detector data was to observe traffic variability during different months of year, different days of month and different hours of day. It is possible to derive the traffic patterns based on the variability of the traffic. The initial critical routes are based on this observed traffic patterns.

Figure 11 Sample Traffic variation Plots
The Figure 11 indicates the variation during time of day and also during day of week. The high variation routes are decided observing plots for all thirteen intersections. The critical routes obtained in preliminary study are used to decide the location for Bluetooth Units.

4.2 Detector Data Based Common Origin Trips Calculation

The objective of performing penetration analysis is to verify the reliability of Bluetooth data. The analysis is performed using detector data. The detector data contains the vehicle count for detectors associated with particular lane. The vehicle count for particular movement can be calculated by adding data from all detectors associated with that particular movement.
All movements belonging to the network are differentiated as inbound movements and outbound movements. The inbound movements at each intersection are basically the turning movements entering the network. In this way that intersection will become origin for all the vehicles which are associated with these movements. Using this concept the number of vehicle that originates from each intersection can be calculated. The addition of vehicle count for all movements starting from particular intersection will provide the total number of vehicle originated from it.

This procedure applied to calculate the number of vehicles originate at each intersection with bluetooth unit and travel to north or south. The addition of South bound and North bound provide total vehicle trip originated from each intersection with bluetooth unit.Following table shows the total number of trips started from intersection consisting Bluetooth unit.The data mentioned start from 24th of November 2010 to 7th December 2010.

<table>
<thead>
<tr>
<th>Based on Detector data</th>
<th>Origin Unit No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
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</tr>
<tr>
<td>24</td>
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<tr>
<td>25</td>
<td>6658</td>
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</tr>
<tr>
<td>27</td>
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<tr>
<td>29</td>
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<td>30</td>
<td>14603</td>
</tr>
<tr>
<td>1</td>
<td>14290</td>
</tr>
<tr>
<td>2</td>
<td>14937</td>
</tr>
<tr>
<td>3</td>
<td>15877</td>
</tr>
<tr>
<td>4</td>
<td>14536</td>
</tr>
<tr>
<td>5</td>
<td>11193</td>
</tr>
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<td>14326</td>
</tr>
<tr>
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<td>14660</td>
</tr>
</tbody>
</table>

4.3 Bluetooth Data Based Common Origin Trips Calculation

The basic sample of O-D Matrix is shown in following table.It is modified to make it comparable to the table obtained from the Detector data.The Bluetooth O-D are added for every day.
Table 4 Bluetooth Based Sample O-D table for each time period

<table>
<thead>
<tr>
<th>Date</th>
<th>Origin Unit</th>
<th>Time period</th>
<th>Destination Unit</th>
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<td>1</td>
<td>2</td>
</tr>
<tr>
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<td>1</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>24</td>
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<td></td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>10</td>
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</tr>
<tr>
<td>24</td>
<td>1</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Following is O-D matrix summerised for 24th November 2010.

Table 5 Bluetooth Based O-D table for a Day

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<th>Destination unit</th>
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</tr>
</tbody>
</table>

<table>
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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
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<td>41</td>
<td>43</td>
<td>49</td>
<td>68</td>
<td>68</td>
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<td>25</td>
<td>657</td>
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<td>2</td>
<td>76</td>
<td>209</td>
<td>60</td>
<td>101</td>
<td>107</td>
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<td>82</td>
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<td>67</td>
<td>67</td>
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<td>154</td>
<td>24</td>
<td>28</td>
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<td>61</td>
<td>549</td>
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<td>63</td>
<td>67</td>
<td>46</td>
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<td>23</td>
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</table>

22
Then the O-D starting for one origin are added together daywise to obtain the following table.

### Table 6 Bluetooth Unit Based Origin Trips

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<tr>
<th>Date</th>
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<th>3</th>
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<th>6</th>
<th>7</th>
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<td>559</td>
<td></td>
</tr>
</tbody>
</table>

### 4.4 Penetration Rate

The Penetration Rate is the percentage trip obtained by Bluetooth dat compared to Detector Data.

Penetration rate = Bluetooth based trip Count Detector based trip Count × 100

Penetration Rate Calculated for each installed using above formulation.
Table 7 Calculated Penetration Rate in Percentage

<table>
<thead>
<tr>
<th>Date</th>
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<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
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<td>8.26</td>
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<td>5.80</td>
<td>4.22</td>
<td>8.33</td>
<td>6.21</td>
<td>3.06</td>
<td></td>
</tr>
</tbody>
</table>

The results indicate that the obtained penetration rate is very high at unit 6 which is 13.3%. The location of unit 6 was very near to the freeway which has exit and entrance on both side also there is an over bridge on the freeway which results in large number of vehicle detection. For rest of the units the average penetration rate ranged is 3 % to 9 %.
5 Framework for dynamic critical route volume estimation on signalized arterials

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ABSTRACT

Traffic signal system performance is predominantly dependent on the accurate mode of operation and best selection of timing plans. Recent development in signal timing indicates that it is desirable to design timing plans utilizing synthetic origin-destination information from loop detector counts. Detector movement counts are result of amount of green time allotted to associated phase ultimately to timing plan provided. The relationship between timing plans and traffic counts is dynamic. Hence the change in volume due to improved timing plans should be taken into account while optimizing for best suitable timing plans. The change in volume due to modified timing plans is significant for critical routes. Critical routes are those routes on a particular network which has higher volumes or higher variability in volume or combination of both compared to other routes on the same network. The relevant change in volume for critical route due to modification in timing plan is termed as dynamic critical route volume. This paper proposes the procedure to derive dynamic critical route volume by applying Bluetooth technology. The data obtained from detection of Bluetooth equipped vehicles at various Bluetooth detection unit locations at an arterial was used for identification of critical routes by using origin-destination trip matrices for different times and days. Prioritization of identified critical routes facilitates the application of traffic signal control strategies. The prioritization can be done by calculating dynamic volume with the help of amount of OD passing through this route and capacity for the movement associated with it. The calculation of dynamic volume is proved effective in generation for timing plans and in process of selecting best suitable timing plans based on performance evaluation.
5.1 Introduction

Bluetooth-based traffic data collection is an innovative and reliable method for data collection and travel time calculation [2]. Using this evolving data collection method can provide a viable and cost-effective alternative for laborious and time-consuming traditional data collection methods, such as probe vehicles and roadside surveys. Bluetooth data collection methods have already seen an increasing level of interest for estimating travel time on freeways [3][10]. The Bluetooth equipment on moving vehicles has a relatively low penetration rate at the movement (8-10%), but is expected to increase with time [11] There is limited literature describing analytical application and use of Bluetooth technology in transportation [12][11]. Implementation of Bluetooth data collection methods is mostly facilitated by several companies in the market for installation and service cost. The cost to implement this technique is high at present, which limits its frequent use by traffic professionals and agencies. However, this is expected to change as the cost of implementation reduces with time. In this paper, we apply a time-offset searching technique to extract and tabulate O-D matrices during different times and dates. This O-D information is useful to understand and design effective control strategies for an arterial network[16]. The last section of the paper explains how this information could be used for this purpose.

Bluetooth Data Collection Technique

Bluetooth wireless capabilities are available in most electrical devices in today’s market. These devices utilize a Bluetooth protocol with an electric identifier known as the Media Access Control Address (MAC Address)[13]. This MAC Address is unique for any device and can be treated similar to vehicle signature. Each Bluetooth device in the vehicle has a unique MAC Address. A vehicle can therefore be tracked by tracking the MAC Address of any device in the vehicle. The Mac Address can be detected by roadside Bluetooth detection units, along with the time of detection. This information can be utilized as traffic data for various applications in traffic management. The direction of travel of a vehicle can be obtained by observing the order of detection at consecutive units. Travel time can be estimated by calculating the time difference between detection at two consecutive units. The speed of vehicles can be obtained by using the estimated travel time and the distance between units.
Introduction of Reston Parkway

Bluetooth data collection method was implemented along Reston Parkway. Reston Parkway is located in the Fairfax County in the state of Virginia, USA. The network has a total of 13 intersections as shown in Figure 11. The length of the entire network is 16,572 feet. The maximum link length is 3,800 feet and the minimum link length is 621 feet. The speed limit for the main arterial is 45 mph, and it ranges between 15 mph and 45 mph for the side streets.
Field observation and loop detector data is applied to obtain various volume profiles along each movement. The obtained volume profiles suggested some primary critical paths on the network as shown in Figure 14. A critical path is defined as a series of intersections along which the traffic volume shows a high value or variation throughout the time of day. System detectors installed in Reston Parkway were used to obtain the total number of vehicles passing through or originating from any particular link in the network. The primary critical routes are studied and utilized to decide the location of Bluetooth detection units. The number of Bluetooth units is restricted due to the cost factor. Hence the number of Bluetooth units to be installed was decided based on the criteria that the location of a Bluetooth unit should cover the maximum number of critical routes without confounding the information obtained from each unit (i.e., any significant traffic origin or destination should be covered by one unit to allow the analyst to trace down the source of significant sink or source of traffic on the network).

The location of Bluetooth units is fixed based on the entrance and exit of the critical routes. The number of Bluetooth units used for this implementation was 9 units that were located and numbered as shown in Figure 14.
5.2 Stepwise procedure dynamic critical route volume
Dynamic Volume is the actual volume which pass through the intersection in the given green time. This volume is based on the capacity, O-D Distribution and Demand. The flowchart shown in Figure 13 explain the stepwise procedure to calculate the Dynamic Volume.

The detector data give certain volume for each time period but that volume might not be same if the time plan is changed. If the green time for particular phase is changed, it will affect the capacity of the movement associated with that phase. Based on the capacity the volume which will actually pass through will change dynamically. Here the bluetooth data is used to calculate O-D Distribution factor which will be multiplier for the volume. Detector data provide the volume which termed as demand. Existing time plans and Network characteristics such as number of lanes, desired speed, saturation flow rate are used to calculate the capacity. The dynamic volume is calculated for all outbound movement which are affected by the capacity and O-D Distribution. Following sections are consist of the explanation of the above procedure stepwise in detail.

**Estimation of Origin Destination for Network**
The collected dataset consisted of all detected MAC Addresses with its time of detections at different units. This information was analyzed to obtain O-D pairs for the network. Figure 15 explains the methodology applied to extract the O-D pairs. As shown in Figure 16, every vehicle follows a particular path and as a result it gets detected at every unit it passes through. The number of detections at each unit depends on the speed of the vehicle. In our preliminary analysis, the first detection for any particular MAC address at any unit was extracted and arranged in ascending order.

Table 8 Output from Analysis – O-D MATRIX

<table>
<thead>
<tr>
<th>YEAR</th>
<th>MONTH</th>
<th>DATE</th>
<th>ORIGIN UNIT</th>
<th>TIME PERIOD</th>
<th>DESTINATION UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>2010</td>
<td>November</td>
<td>23</td>
<td>1</td>
<td>12:00AM</td>
<td>12:15AM</td>
</tr>
<tr>
<td>2010</td>
<td>November</td>
<td>23</td>
<td>1</td>
<td>12:15AM</td>
<td>12:30AM</td>
</tr>
<tr>
<td>2010</td>
<td>November</td>
<td>23</td>
<td>1</td>
<td>12:30AM</td>
<td>12:45AM</td>
</tr>
</tbody>
</table>
This will give the sequence of intersections that the vehicle has passed through. The intersection at which the vehicle appeared first was considered as the origin and the intersection at which it appeared last was considered as the destination. After getting detected at the destination, a vehicle leaves the network. This concept is used to get the O-D pair for each MAC Address. The large number of MAC Addresses are analyzed in an excel sheet using pivot tables to extract the O-D pair for each time period.

Detailed observation of the data provided very significant information that there are more O-D pairs available for some MAC Addresses. This is due to the fact that the location of the experiment is basically a commercial zone and most of the vehicles belong to commuter traffic. Hence it was logical that they would have at least two trips a day, one trip is when they drive to work and another trip is when they return home (or any other destination). Any particular O-D pair was associated with a 15-minute time period corresponding to the time of its first detection. The total number of origins present in every 15-minute time period is calculated. Each MAC address is scanned in the network within two time periods to determine the last time it appeared. Two time periods (30 minutes) was deemed enough (and was later validated) to clear the 3-mile long network during congested conditions. This time-offset searching technique resulted in extracting the first O-D pair for any vehicle. The procedure was repeated again by starting with the latest time a MAC address was observed in the network. This latest time was considered as the destination for the second trip. A time-offset search within the previous two periods resulted in the determination of the origin for the second trip. If a vehicle made only one trip on the network, this procedure will result in extracting two identical trips for the vehicle, for which one of them was discarded as a redundant trip.

The 15 minute time period interval was used to match the loop detector data tabulation that was originally used to find the initial critical routes. The MAC Addresses were not considered after this stage in the analysis. The final output of the analysis was conducted in Excel and consisted of summing the total number of O-D pairs for each time period and for each day as illustrated with the example in Table8.

**Distribution of Origin Destination for Movements**

The obtained origin destination pairs are utilized to distribute the percentage of O-D pair for each movement in the network. The inbound movement are all movement by which vehicles are entering in the network and outbound movement are the movement which are leaving the network. A particular outbound movement is considered to be contributed by various inbound movements. The Table 9 shows the combination of inbound movement for particular outbound movement. The contributing inbound movements are seperated by northbound and southbound as shown in Figure16 and Figure17.

As an example If outbound movement no 7 is considered, which is southbound right at 3rd intersection. This movement has input listed as 1 and 5. Here movement number 1 is southbound through at 2nd intersection and movement number 5 is southbound right at 2nd intersection. Here movement 4 is not taken as the intersection 2 is T-Intersection and movement 4 is absent. Also the reason for absence of movement 6 is that movement 6 and 7 are belong to same OD Pair.
Table 9 Combination O-D Inbound and Outbound Movements

| ORIGIN UNITS | 1 | 2 | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|--------------|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1            | 1.5| 7.8,9,10,11 | 1.5 | 12.13 | 1.5 | 15.16 | 1.5 | 18.19 | 1.5 | 20.11,22.23 | 1.5 | 24.25,26,27,28 |
| 2            | 6.7,8,9,10,11 | 6.7,8,9,10,11 | 12.13 | 6.7,8,9,10,11 | 15.16 | 18.19 | 6.7,8,9,10,11 | 20.11,22.23 | 6.7,8,9,10,11 | 24.25,26,27,28 |
| 5            | 18,19,20,21 | 1.5,7,8,9 | 18,19,20,21 | 10.11 | 18,19,20,21 | 12.13 | 18,19,20,21 | 16 | 18,19,20,21 | 20,11,22.23 | 18,19 | 24.25,26,27,28 |
| 7            | 25,27,28 | 1.5,7,8,9 | 25,27,28 | 10.11 | 25,27,28 | 12.13 | 25,27,28 | 16 | 25,27,28 | 18,19,20,21 | 25,27,28 | 22.33,24,25 |

Figure 17 Inbound Movement for O-D Distribution
The table is used to distribute the 9X9 combination of O-D pair as a fraction into 28X28 combination of movement.

### Table 10 Bluetooth Unit based sample O-D Table

<table>
<thead>
<tr>
<th>Origin</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>...</th>
<th>9</th>
<th>9</th>
<th>...</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destination</td>
<td>1</td>
<td>2</td>
<td>...</td>
<td>9</td>
<td>...</td>
<td>1</td>
<td>2</td>
<td>...</td>
<td>9</td>
</tr>
</tbody>
</table>

### Table 11 Movement based sample O-D Table

<table>
<thead>
<tr>
<th>Inbound</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>...</th>
<th>28</th>
<th>28</th>
<th>...</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outbound</td>
<td>1</td>
<td>2</td>
<td>...</td>
<td>28</td>
<td>...</td>
<td>1</td>
<td>2</td>
<td>...</td>
<td>28</td>
</tr>
</tbody>
</table>
The Distribution of O-D pair from unit wise to movement wise is done by utilizing the combination given in Table 9. The originally the Unit wise O-D are shown in Table 10 and output after distribution is shown in to Table 11.

**Example:** O-D count for unit 2 to unit 1 is used to calculate movement wise O-D of all combinations using 10 and 11 as origin and 1, 5, 7, 9, 8 as destination movements, referring to figure19, O-D value belongs to Origin 2 and Destination 1 is considered and further it is divided by five as this O-D has five numbers of outbound movements in total. The O-D value obtained is converted in to percentage value for each origin.

![Figure 20 Sample O-D Distribution](image)

The distribution factor for combination of movements is used as a multiplier for the volume for the outbound movements.

**Outbound Dynamic Volume Calculation**

The significant inputs needed to calculate the dynamic volume consists of capacity associated with particular movement. The capacity is calculated by using the equation from HCM (Highway Capacity Manual)

Capacity Equation from HCM,

\[ c = \times s \]

Where,

\( c \) = Lane Group Capacity

\( s \) = Adjusted Saturation Flow Rate
g = Effective Green Length

C = Cycle Length

**Formulation for Dynamic Volume calculation**

The formulation is used to calculate the dynamic volume for outbound movements is shown below:

\[
\frac{V_{kT}}{=1} \forall \ U \ \forall \ D = -1
\]

Where,

\( V_{kT} \) = Dynamic Volume for intersection number k and time period T

\( T \) = Time period

\( \forall \) = Intersection number for which the volume is calculated

\( \forall \) = Number of upstream Intersection to the Intersection for which the volume is calculated

\( U \) = Upstream intersection

\( D \) = Downstream Intersection

\( = \) Capacity of corresponding movement m

\( = \) Demand of corresponding movement m

\( = \) Distribution factor of Origin Destination

The above formula would provide the dynamic volume for outbound movement, which consists of turning movements leaving the intersection and through movement at last intersection leaving the network. The formula takes into account the OD Distribution and Capacity Demand Ratio for movement at the intersection and at movements at previous Intersections that contribute the movement for which the formula is applied.

The volume is calculated for all outbound movements leaving the network for each time period of 14 days. The combination of this new volume for outbound movements and the original volume for inbound movements gives the actual volume scenario for the Network.

**5.3 Implementation on the Reston Parkway Network**
The formulation is applied to the selected four intersections at Reston Parkway. The dynamic volume is calculated for south bound left (SBL) movement at fourth intersection shown in red color in the above figure. The green color movements are the contributing movement for SBL AT fourth intersection. The timing plans are obtained from passer V simulating the vehicle count from detector data. West bound movement at second intersection is absent as it is T-intersection.

![Network use for Implementation](image)

**Figure 21 Network use for Implementation**

Following are the green times according to the three timing plans provided for all movements of four intersections.

**Table 12 Timing plans (Green time in seconds) by PasserV**
Saturation flow rate is 1770 and Cycle Length is 100 seconds is used to calculate capacity. Following table consist of capacity based on above timing plans and demand for three different time period of day contributing movement.
Using above parameters the volume is calculated using the proposed formulation and respective OD Distribution Factors. Following are the internal volumes obtained:

**Table 14 Calculated Dynamic Volumes (Vehicle/hr)**

<table>
<thead>
<tr>
<th>Intersection 4</th>
<th>Time Period 1</th>
<th>Time Period 2</th>
<th>Time Period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TP1</td>
<td>TP2</td>
<td>TP3</td>
</tr>
<tr>
<td>SBR</td>
<td>109</td>
<td>131</td>
<td>150</td>
</tr>
<tr>
<td>SBL</td>
<td>109</td>
<td>131</td>
<td>150</td>
</tr>
<tr>
<td>SBT</td>
<td>1630</td>
<td>1645</td>
<td>1553</td>
</tr>
</tbody>
</table>

The observation of calculated internal volume for 4th intersection indicates that the volume varies significantly if the time period is changed. The reason for this is the OD distribution factor for the contribution movement change due to change in OD Count per period. Here the volume is same for south bound left and south bound right as the contribution movements are same and the O-D distribution factors are same. The volume show changes for change in time period also change in timing plan.
Figure 22 Variation of Volume

Figure here shows that the volume variations for different time period are higher than variations for different timing plans. The O-D distribution factor varies significantly and affects the internal volume during different time period. This proves the significance of actual O-D calculation while calculating internal volume as a part of timing plan design process.

5.4 Conclusions and Future Research

This paper proposes a method that can be used to integrate the Bluetooth data to improve the timing plan generation. Thirteen intersections of the Reston Parkway arterial were considered for this study and the use of detector volume was compared with the use of proposed Bluetooth based dynamic volume for generation and optimization of timing plans.
It was found that the calculated dynamic volume change significantly for various timing plans. So, this change in volume should be considered while designing timing plans. While optimizing timing plans, selection of the time plan is based on the evaluation parameters such as delay, stops and it varies with change in volume. The values of evaluation parameters select the best suitable timing plan based on the traffic state.

Future work includes the implementation of this proposed method in design and optimization of timing plans. The integration of dynamic volume calculation process with design and optimization of timing plan would give us a sound methodology of obtaining time plan which can be then further applied for various modes of operation. It is now possible to study many traffic scenarios with real volume distribution using many different plans. Other than this, to further study the effectiveness of the proposed system, the timing plans of the traffic can be calculated by using optimization soft wares such as Syncro, PasserV etc. and compared with the timing plans generated by the integrated system using the proposed method of volume calculation.

5.5 References


6. Young, S., "Bluetooth traffic monitoring Technology concept of operation and development guideline", 2008, Center for Advanced Transportation Technology, University of Maryland, Maryland, USA.


6 Summary and Conclusion

6.1 Summary

Traffic management system consists of efficient working of signalized intersection. Effective design of timing plans play major role in efficient working of intersection. Design and optimization of timing plans is based on the volume of various movements of intersection in the network. The volume for external movement and cross street is obtained by detector data vehicle counts. The distribution of volume within the network is assumed as equally distributed considering equal attraction in different nodes. In the field the distribution vary according to origin destination of trip within the network. To obtain the actual origin destination information was challenging due to limitation of traditional data collection techniques. Introduction of the Bluetooth data collection technique provides a way to obtain this information from field at reasonable cost and efforts.

Bluetooth technology based data collection technique has proved contribution to existing data collection techniques such as probe vehicle, loop detector data, video detection. This technique has several applications in calculation of travel time, speed. This thesis proposes application of Bluetooth data in designing timing plans. The description of implementation of Bluetooth data collection technique in field to is provided. The setup of Bluetooth unit and procedure to decide the location of units in field based on analysis of detector data is discussed.

The methodology to derive the origin destination matrix from data collected by using Bluetooth is the explained. The main objective of the research is to develop stepwise procedure to calculate dynamic volume distribution for the signalized arterial based on this obtained origin destination information.

The proposed procedure needs capacity calculation using various parameters such as existing time plans which provide green time and cycle length, saturation flow rate for the network. It also needs demand for every approach of all intersections. Demand is calculated by using detector counts. For every approach number of lanes and associated detector are identified. Demand for particular approach is obtained by adding up the vehicle counts belongs to all detectors associated with that approach. After calculating capacity demand ratio for all intersection the formulation is applied to calculate dynamic volume for all internal movement. The volume obtain is compared with the volume calculated assuming equal distribution. The calculated dynamic volume is the true representation of field scenario. The application of this volume while designing and optimizing timing plans would be more realistic compare to current assumption based methodology.
Conclusion

Use of Bluetooth technology in traffic data collection technique solved various challenges in traffic management field. Bluetooth data has an ability to provide information that would be useful in improving the existing traffic management methodologies and approaches. The reliability and accuracy are the major issues while practicing the traditional methodologies. Traditional mythologies are based on various assumptions due to the absence of efficient technology to assist in obtaining required information to implement the methodologies. Designing and optimizing time plans for signalized arterial is significant task in process of traffic management. These timing plans are based on traffic state on an arterial. The traffic state is defined by the volume associated with all approaches at certain point in time. In the process of designing efficient timing plan it is required to input the accurate volume. These volumes are associated with three movements external movements, cross street movements and internal movements. Among these three volumes the external movement volume and cross street volumes are available directly from vehicle counts. The volume associated with internal movements is obtained by assuming equal internal distribution of volume. This assumption is not based on any practical observation and that reduce the reliability of the entire process of designing optimal timing plans. The distribution is based on the origin destination of trips within the network. To obtain the actual origin destination information of the traffic was a challenging task due to limitation of traditional data collection technique.

This research proposes the application of the recently proven Bluetooth data collection technique to obtain the origin destination information of trips within the network. The study shows that using the Bluetooth data it is practically possible to calculate the number of trips from particular origin and destination within the network. The thesis proposes a formulation to obtain the volume distribution among the internal movement of the arterial. With the help of collecting data Reston parkway arterial the proposed formulation is tested and it is observed that the amount of distribution is based on actual O-D obtained in field.

The ultimate aim of any methodology is to decrease the error in existing system and improve the overall efficiency by suggesting the feasible alternatives. The thesis covers the new concepts of calculation of O-D with the network from data obtained applying Bluetooth technique.

The results indicate that the proposed method has a potential to provide the significant input in current practice of designing timing plans.
References


6. Young, S., "Bluetooth traffic monitoring Technology concept of operation and development guideline", 2008, Center for Advanced Transportation Technology, University of Maryland, Maryland, USA.


