

**FREIGHT-SIGNIFICANT SITE MONITORING USING  
BLUETOOTH AND RFID TECHNOLOGIES: LINK SPEED  
MEASUREMENT BASED ON SIMULATION STUDY**

**By**

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## **ABSTRACT**

This Thesis presents a simulation-based evaluation study for link speed estimation using Bluetooth and RFID combined detection system.

Freight-significant sites refer to roadway sections with high freight flow. Previous studies on freight traffic performance monitoring are generally based on data collected using GPS devices installed on freight vehicles. The exclusive freight traffic data do not have sufficient information for analyzing the condition of the general traffic system. The issue which should be considered is that vehicles of different classes should not be independent from complete traffic system. The isolated data source may neglect the factors that activate traffic problems. The insufficient freight data collection and freight performance measures efforts make researches on freight-specific studies necessary.

In this study, we investigate the feasibility of using Automatic Vehicle Identification (AVI) technologies (i.e. Bluetooth and Radio-Frequency Identification (RFID) technology) to automatically collect data from freight vehicles and the general traffic. The innovation points and contribution are 1) new detection system architecture is developed for collecting all-vehicle traffic data and freight-specific data simultaneously; 2) the concept of speed estimation unit and methodology are defined; 3) an evaluation analysis under simulation situation close to the real field condition is provided; 4) some future works are foreseen that can make the propose system work

better in real-time traffic monitoring at freight-significant freeway sections.

A VISSIM-based simulation model is developed as a test bed to evaluate the Bluetooth-RFID combined system in collecting data to measure segment average speed in a short range. The traffic flow data used to calibrate the VISSIM model comes from the 5-min loop detector data collected on I-94 freeway in the urban area of Milwaukee, WI, USA. Heavy vehicle percentages are determined using 3-min CCTV traffic snapshots. The simulation results indicate that the innovative AVI-based system can be promising in freight performance monitoring.

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# **1 INTRODUCTION**

## **1.1 RESEARCH PURPOSE**

This thesis presents a simulation-based evaluation study on the monitoring traffic at several selected freight-significant sites, the detect method is focused on new AVI (Automatic Vehicle Identification) technologies, which are Bluetooth and RFID (Radio-Frequency Identification) technologies.

The developing world witnesses the importance of the efficiency of freight transport and delivery. The urban competition powers of cities rely on the high delivery rate of goods at large extent. As has been seen in past years, freight transportation tightly related to trade among regions. In academic field, more attentions are attached to the movement of people than freight transportation. Although freight transport has huge contribution to traffic congestion and environmental impact (Haider et al. 1999), more attentions are placed on the movement of people. There are plenty of studies focusing on improvement of mobility of the general traffic flow, and the key part is passenger cars, because they are main participants on the road. However, the traffic problems (mainly congestions) that suffered by passenger cars are more likely to stuck trucks which operate freight transportation because of lower speed limit and lane restriction, in adverse, freight commute always stuck people's travelling. The different vehicle classes proceed together to form the complete traffic system, so the lack of study calls for more attention on freight transport research, because the higher freight transport

efficiency would bring benefits to traffic and environment quality and overall welfares. To consider the efficiency of freight transport, we need to account for freight performance at specific time and location. To do freight performance measurements, we can then obtain useful information about the status of freight delivery.

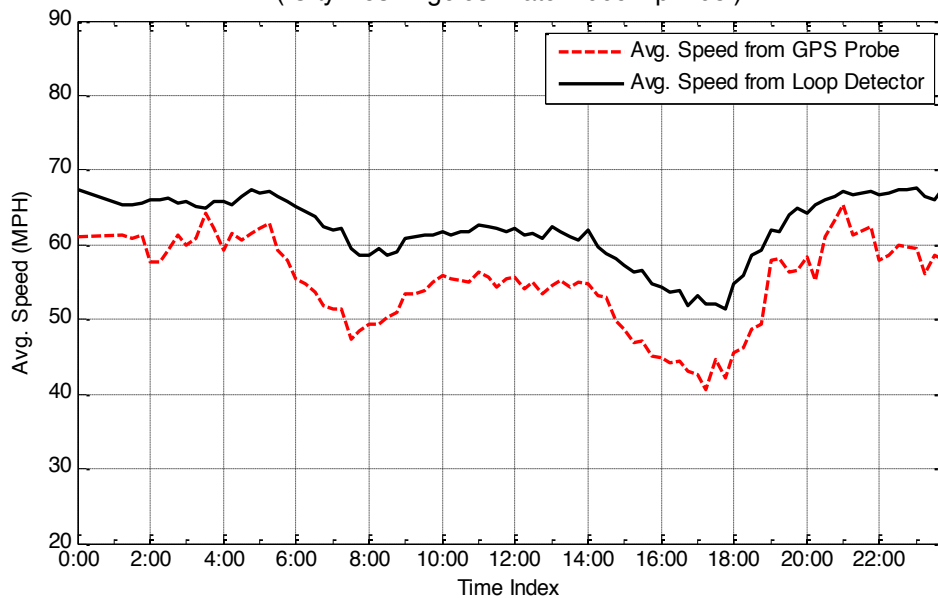
In recent years, freight transportation gradually gains attention from both academic and industrial fields, USDOT (US Department Of Transportation, 2012) and DOTs of certain states has carried out numbers of studies on freight data collection and freight performance measures. The primary focus of freight data collection has been on commodity and vehicle flows at the inter-regional level rather than the intra-urban level (Gorys and Hausmanis, 1999).

To monitor the freight performance measures, there are currently three major data sources used by Federal Highway Administration (FHWA). The first one is the FHWA Highway Performance Monitoring System (HPMS) database (FHWA). Information in the HPMS database is submitted by state DOTs and compiled by FWHA. The database is created to monitor general highway bottlenecks. Estimated truck percentage values for each highway are available to determine the truck flow. The second data source is the Freight Analysis Framework (FAF), which contains county-to-county freight flows over the national freight networks. Due to the limitations in data collection, these two databases can only provide aggregated and low-resolution data for freight bottleneck analysis. With the increase of popularity of

wireless communication device equipped in freight vehicles, the third data source, Freight Performance Measurement (FPM) database was created to collect detailed location and speed data from freight vehicles. Even though with much higher resolution than previous two databases, a major bias is that these data are exclusively collected from freight vehicles and cannot reflect the actual traffic condition of all vehicles.

The principal reason for the lack of data on truck movement is that reliable methodologies have not been developed to obtain the level of detail needed for modeling efforts and planning (Jessup et al. 2004). The FPM database system at ATRI (American Transportation Research Institute) mentioned above evolved from its previous system, which is based on GPS (Global Positioning System) software (Liao, 2008). A recent study conducted by the research team (Wang et al. 2011) shows that the bias of freight GPS probe speed and general traffic speed observed from loop detector can reach 10 mph (See Figure 1-1).

Freeway Average Speed Comparison between GPS Probe and Loop Detector Data Source  
( City: Los Angeles Date: 2009-April-08 )



**Figure 1-1 Comparison between Loop Detector and GPS Detection**

Although loop detector data is easy to access for most academic institutes, for freight transport research purpose, its accuracy cannot reach the desired level. GPS-prone data just reflect the truck driving condition such as truck speed and truck travel time, however, we always want to know the interaction between freight vehicles and passenger cars, the interaction can be important since many freight bottlenecks are also general highway bottlenecks for commuters, it is quite important to consider the interaction between the passenger vehicles and freight vehicles when analyzing the actual cause and alleviation strategies for freight bottlenecks.

This paper proposes a new method to conduct freight data collection and freight performance measures. The transportation simulation software provides a good platform to make estimation of the efficiency of the new technology. By developing a simulation model for Bluetooth and RFID technologies and evaluating the impact of

different system configurations on the accuracy of the traffic speed estimation at selected test freight-significant freeway sections, the detection outcomes can be used by engineers and planners in various academic research efforts and industrial freight transportation planning arrangements.

## **1.2 PROBLEM STATEMENT**

The problem we are now facing at freight-significant sites on freeway is that the freight-specific data is limited. Most freeways are instrumented with loop detectors, which are traditional detecting techniques with good performance in traffic count. Improved dual-loop detectors have ability to measure vehicles' speed and occupancy. However, based on this information, the vehicle classification accuracy is not enough to fulfill the need for collecting truck mobility data. GPS-probe truck data can be a robust data source for exclusive freight data collection, but it rules out other traffic inputs by magnifying trucks' roles in the whole traffic system. We are trying to balance the significance we attach on different vehicle classes, to get comprehensive data source with innovative and efficient improvement on detection system. Freight transportation is a major part in our daily transportation system, and because the transport of freight use different vehicle type, sometimes travel on separated lanes and on specific travel schedule (nightly truck shifts), the collection of freight-specific data is comparatively hard to do.

The system proposed in this paper combines Bluetooth and RFID technologies.

Certain proportion of vehicles has Bluetooth signals detectable with Bluetooth headset and other devices. Large numbers of trucks are attached with RFID tags by the truck companies. The companies use tags to track and manage their fleet. However, passenger cars rarely installed with RFID tags without specific reasons. These characteristics allow the Bluetooth detectors to sense all the vehicles whoever has Bluetooth signal detectable while RFID readers only record freight vehicle data. This effort makes all-vehicle traffic and truck data available simultaneously, and with two sets of data incorporated into one database, a much more efficient and reliable way of carrying out freight traffic study becomes realistic. This can be a much more comprehensive data source and the data user can be better served with their specific purpose.

With more accurate and comprehensive traffic data, road users get welfare. Nowadays, road users are information armed, and they are totally glad to be led by updated information. For freight-significant sections on the freeways, we care more about the freight transport capacity, so that truck companies can judge the ground condition to plan their truck scheduling and route choice. With more specific freight data, together with all-vehicle traffic information, not only truck-related entities, but also commuters get better informed about the real-time road condition. Also, with the archived data, transportation engineers and planners can achieve more reliable data source to carry out academic researches, or make their decisions.

The proposed system is implemented and evaluated in real-condition simulated environment, which delivers a good platform to test the feasibility and efficiency of the monitoring system. The questions of the study are addressed in three aspects:

1. Can AVI technology-based detection system provide a robust data source for real-time traffic travel time and speed? For the short-range travel time and average speed data processing, the effectiveness of identifier matching and the number of vehicles detected are critical effects. With the archived data successfully reflect real-time traffic situation, the data source can be regarded robust.
2. Is simulation suitable for our study? Simulation-based study is a notable way to test the feasibility and efficiency of the system without considering time and budgetary limits in field implementation. Besides, the repeatability of the same scenario with various detection system settings makes simulation study even more attractive, because the repetitions make system evaluation comparable without disturbance of actual situation changes.
3. Is there obvious difference in the results produced by AVI-based probe technique and by point sensors (e.g. loop detector)? The output comparison between point-collected data and short-range data can serve to provide more details for detecting system evaluation and to select proper detection scheme for different detecting purpose.

### **1.3 THESIS SUMMARY**

The main contents of this thesis is composed of the following chapters: (1) introduction about the study in this thesis; (2) overview of research background, summary on the existing work with related to Freight Performance Measures and technical knowledge about Bluetooth and RFID technologies; (3) major methodologies; (4) experimental design, evaluation and calibration; (5) result analysis; (6) conclusion and future work; (7) reference.

## **2 BACKGROUND**

This chapter summarizes related technological and theoretical background related to this research. The background knowledge is important for setting forth the purpose and fundament of the study. First, the condition of freight transportation in Wisconsin is described to expound our research environment. Second, the concept and category of freight bottleneck are introduced. Freight bottlenecks are freeway sections with insufficient freight transportation capacity, which are typical freight-significant sections. Third, the summarized reviews of freight performance measures (FPM) are stated. Fourth, some general overviews are given for the technological fundamentals of AVI (Automatic Vehicle Identification) technologies and other kinds of vehicle detecting technologies. Fifth, a general introduction is provided about microscopic simulation software –VISSIM, which is used as the major simulation tool for real traffic conditions in this simulation study. Finally, the VISPOC data base and its web application are introduced. The database is the ground truth data provider in this study.

### **2.1 OVERVIEW OF RESEARCH ENVIRONMENT**

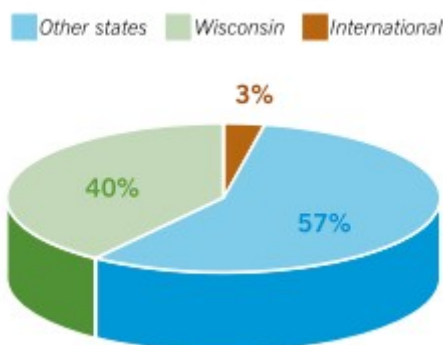
As the efficiency of freight transportation becomes critical to economic aspects, the economic environment changes have direct and indirect impacts to transportation conditions in adverse. The following section gives out a statistical description about freight transportation condition in Wisconsin. The freight-significant sites are on

selected important freeway corridor in Wisconsin, between two significant cities, Madison and Milwaukee. The general freight transportation characteristics in the state affect the situation of our study site. These sites have the name of freight-significant locations instead of freight bottlenecks because in most of the occasions, there is sufficient freight transportation capacity. But the severe congestion problems sometimes occur at these sites, the situation means these locations have potential to become freight bottlenecks. So the freight-related problems make these freeway sections vulnerable to traffic delay and stuck. However, the definition and categories of freight bottleneck is still introduced to represent the characteristics of freight-significant sites. The academic environment always presents a picture of the research condition of some specific problem. In following introduction of previous studies of freight performance measures (FPM), we find the limitation in both number and quality. That leads to the purpose of finding new method to carry out freight transportation related researches.

### **2.1.1 Truck-prone Freight Transportation in Wisconsin**

The industries in Wisconsin depend on majority of multimodal transportation network to make goods delivery. With the demand of freight delivery, this system faces harsh challenge in fulfilling the task. It was estimated by professional institute that freight delivery demand over Wisconsin system would have an additional 70 percentage through 2025. The unlimited extension of transportation facilities as expanding road, adding lanes, is an unrealistic proposal, so the increase of efficiency of transport

should be the major concern. The four categories of transport modes, rail, air, truck and water, constitutes an integrated shipping network that carries goods worth \$300 billion over the whole state (Cambridge Systematics, Inc., CFIRE, 2009). Wisconsin freight transportation has its business both inside the state, out to other states in the U.S and to other countries, although the international business is in a relatively small percentage. The pie chart below (Figure 2-1) shows the distribution of freight shipments of Wisconsin business.



**Figure 2-1 Distribution of Freight Shipments from Wisconsin Business (2002)**

Truck-prone freight transportation handle almost 74 percentage of all freight tonnage shipped from Wisconsin, which dominates among all four modes. For those categories of goods that are sensitive to delivery time variation, and the shipment distance is relatively short, truck can be regarded as the best mode. At the same time, other shipment methods need truck to be auxiliary deliver method to realize the door to door shipment service. The state has an 113,000-mile network of state highways and local roads (WisDOT, 2009), the average travel length of trucks does not occupy as high percentage as other modes because the restriction of truck travel distance.

Wisconsin's truck ton-miles represents just under one-half of the total ton-miles of goods movements with an average truck trip length of 183 miles, while other modes have definitely longer freight deliver length.

Although freight transportation congestion problem is not notable nationwide, there are certain numbers of freight significant highway locations that block traffic recurrently as freight bottlenecks, two such sections located on I-94 rank among the top 50 worst congest locations in US, and 8 rank among the top 250 (ATRI 2010). Interstate highways connect major cities in Wisconsin are exposed to severe recurrent congestion.

### **2.1.2 Concept and Categories of Freight Bottleneck**

Freight bottleneck refers to highways with insufficient freight transportation capacity (Cambridge Systematics, Inc., FHWA, Oct. 2005). Nationwide, such freight bottlenecks are increasing rapidly in number and severity due to the lag of the expansion of highway capacity behind the growth of demand in freight transportation. Such lag is expected to become more and more serious issue in the future of U.S. Economy, since the delivery is behind the demand. The Strategic Inventory Control and Warehousing fails if the delivery efficiency cannot be guaranteed. Actually, the highway bottlenecks are usually the outcome of interaction, it means they not only stuck the trucks but also passenger vehicles. Trucks are larger in its size, so they tend to wait a longer time for a suitable when changing lane or doing other actions. Also

the average speed of trucks is reasonably lower than cars, the special characteristics of trucks lead to the drop of transportation capacity. So the freight bottlenecks can always be bottlenecks for all kinds of vehicles.

The cause of freight bottlenecks can come from recurrent events, such as volume routinely exceeds capacity, and also from non-recurrent events such as incidents, work zones, extreme weather conditions, and suboptimal traffic controls. This project will focus on the recurring freight bottlenecks and more specifically, the highway bottlenecks for truck freight transportation. The recurrent events always have its pattern of occurrences, which are reasons that lead to insufficient highway capacity. According to those reasons, we can develop the categorization of freight bottlenecks.

Types of truck bottlenecks can be classified based on its constraint type (Lane-drop, interchange, intersection/signal, road geometry and etc.), roadway type (freeway, arterial, collectors, local roads), and freight route type (intercity, urban, intermodal, and etc.).

### **2.1.3 Reviews of Previous Freight Performance Measures Studies**

Freight Performance Measures (FPM) is of great interest to both transportation engineers and planners as a process to generate qualitative and quantitative indicators for measuring effects freight flow imposed on transportation mobility, traffic control, freight delivery route planning, etc.

The three currently used databases (FHWA Highway Performance Monitoring System, Freight Analysis Framework and Freight performance measure database) which are mentioned above, are either too aggregated to serve specific purpose, or exclusive to be independent from the whole traffic system. The existing data sources are not sustainable and practical for further usage and process.

The national freight performance measures (FPM) studies are launched by FHWA and ATRI (American Transportation Research Institute). The initial phase study begins in 2002, mainly concerned the data collection methods and important freight corridors identification. The later phases began to refine data collection processes and analysis methods while collecting GPS data (Harrison R. et al.). FHWA and ATRI also launched FPM effort initiative in 2002 aiming at collecting intercity truck travel time (USDOT and FHWA, 2012). In October 2011, ATRI and FHWA released their study results about FPM monitoring at 250 freight bottlenecks using GPS-based technology. The pre-action of this study is a bottleneck analysis of 100 freight significant highway locations in 2009 (ATRI and FHWA, 2012).

Besides FPM studies of national level, some states have made a push to look into FPMs or to begin some data collection actions. Minnesota is one of the most notable states looking seriously into using freight-specific performance measures in the near future. The 1999 study by the Minnesota Freight Advisory Committee (MFAC) recommended a series of freight-specific performance measures. Bottlenecks and impediments are mentioned in the study to provide more direct and specific measures

for planning needs. The 2005 Minnesota Statewide Freight Plan further specified the FPMs, building on data and experience from the first few years of implementation (MnDOT, 2005). New Jersey has also come up with research outcomes in their past efforts. NJTPA sponsored a 2003 study by NJIT that was distinguishable from the other states due to the level of detail, containing measures more dynamic and effective over time. At the state level, the New Jersey Department of Transportation (NJDOT) does have a Comprehensive Statewide Freight Plan with Phase 1 completed in 2004 (Parsons Brinckerhoff- QD, Inc, 2007). Collaborate with MPOs and NJTPA, the plan aims at improve freight performance measures. The Oregon Department of Transportation (ODOT) has made a strategy that performance measures have been selected to evaluate progress in twelve categories. And the Oregon statewide model is then used to determine freight delay cost and has been widely accepted as a feasible way for calculation (McMullen and Monsere, 2010). Since 2007, the Washington State Department of Transportation (WSDOT), Transportation Northwest (TransNow), and the Washington Trucking Associations(WTA) have partnered on a research effort to collect and analyze GPS truck data from commercial, in vehicle, truck fleet management systems. The WSDOT/TransNow project has evaluated the feasibility of the GPS data to support a truck performance monitoring program. The project has produced large databases of processed truck GPS data (Ed McCormack, 2011). The NCTOG (North Central Texas Council of Governments) of Texas has conducted a study about fright bottlenecks performance measures, although it has not been developed into a mature plan, it did mention several freight indicators are being used

to describe the trends in truck traffic and to identify freight bottlenecks, including percent of trucks in total traffic counts, travel time contours in the vicinity of sites that are intensive truck trip generators and trucks per day (Harrison et al., 2006).

## **2.2 OVERVIEW OF COMMONLY USED VEHICLE DETECTING TECHNOLOGIES**

This section introduces several kinds of traffic count and data collection tools that are in wide usage. With the development of technology, transportation engineers and researchers tend to make utilization of more developed technologies for vehicle identification, tracking and data extracting. In the following section, the main characteristics and the usage in FPM of the several commonly used vehicle detecting technologies are introduced, and some comparisons are made to see the advantages and disadvantages of those technologies. Traditional loop detectors are fixed-location sensors, and other well used technologies are generally in the mobile traffic sensor area. Generally speaking, mobile traffic sensors include any monitoring or data collection system with a dedicated device equipped with vehicles. In this sense, they include for example probe vehicles (such as those equipped with Electric Toll Collection (ETC) tags), cellular phones, portable GPS devices (like GPS cellular phones), GPS navigation systems, Bluetooth Mac Address Matching, vehicles in Vehicle Infrastructure Integration, etc (Ban and Gruteser, 2010). These mobile traffic sensors are also known as probe vehicle technologies, which are typically intelligent transportation system (ITS) application for real time traffic monitoring.

### **2.2.1 Loop Detectors**

Among all the vehicle detecting technologies, loop detector still dominates in its implementation on urban road intersections or freeway surveillance. Loop detectors, mainly induction loops, can provide basic traffic parameters. Vehicle counts, traffic speed, and occupancy of detector over a time interval are available data sets. The data observation and derivation between the neighboring loops can help identify freight bottlenecks (Cassidy and Bertini, 1999; Bertini and Myton, 2004). Chen et al. (2004) identify freeway bottlenecks by using aggregated five-minute speed information obtained from Freeway Performance Measurement System (PeMS). Similarly, Wiezorek et al. (2009) use the Portland Transportation Archive Listing (PORTAL) data to develop an automated tool for identifying recurrent freeway bottlenecks.

Even though loop detectors dominate in detecting technologies, for FPM study, they lack accuracy and efficiency in vehicle classification. The occupancy time of the detector triggered by passenger cars and freight vehicles have very small difference. Newer inductive-loop detector electronics units and loop configurations are capable of vehicle classification (FHWA, 2010). However, because of the installation of loops needs large amount of time and budget consumption, the upgrade of loop detectors is restricted.

### **2.2.2 Global Positioning System (GPS)**

The Global Positioning System is a satellite-based navigation system made up of 24

satellite placed into orbit by the U.S. department of defense (Garmin Ltd. 1996).

GPS technology based vehicle tracking system belongs to a category of traffic time measurement technologies called probe vehicle technologies. In recent researches and studies of FPM, Global Positioning System (GPS) technology is also widely used. A study sponsored by FHWA suggested that there are 32 states have used GPS for planning purpose. It also has served to provide traveller information and tested for travel time on main corridors. The first GPS pilot test was conducted by Cayford and Yim in 2001 and also included the analysis of cellular phone tracking. This study successfully proves that GPS can be used for travel time calculation. The 2003 TRAC study reflects more benefits for using GPS technology as freight data collection method. The strong point is that the frequency of reading is high, especially for trucks. But more numbers of vehicles equipped with GPS is needed. Compare to TRAC study, which needs high cost for data collection, the study of FHWA/ATRI has an arbitrary reading frequency, with a lower precise data. But it indicates that GPS has a great potential for planning purpose.

### **2.2.3 Cellular Probe Technology**

Cellular Probe Technology also belongs to the field probe vehicle technologies. Cellular technology began to receive attention from transportation research field just several years ago. It uses wireless communication signals to make vehicle identification and detection possible. When tracking the cellular phone signal in vehicles, the timestamp, location information of vehicles are caught. Since the

detection of phone signal in vehicle never tell the type of vehicles, the freight study with cellular probe is hard to do. However, by using wireless location technology (WLT), which has been developed for mobile phone network, cellular probe technology can be a potentially promising technology for obtaining vehicle travel information. There are plenty of studies on travel time estimation using cellular phone based system (Hillel, 2005) and obtaining general traffic information (Cayford and Johnson, 2003, Fontaine and Smith , 2007), these study receive robust results for traffic detection purpose.

#### **2.2.4 Automatic Vehicle Identification (AVI) Technology**

AVI is a general traffic surveillance tool derived from auto identification (Harrison et al., 2006), which serves institutes who want to identify items, capture information about them and somehow get the data into a computer automatically (Butani et al.). AVI has been widely used in monitoring the performance of Electronic Toll Collection (ETC) and High Occupancy Tolling (HOT) systems (Lu et al. 1997). Huston was the first city to apply AVI technology for monitoring traffic conditions (Puckett and Vickich, 2010). Because of the excellent performance of AVI application in toll station monitoring, Huston's AVI monitoring system deploys the "EZ-Tag" Embedded in the vehicles, which are used in automatic toll collection system, to be the transponder tags. AVI devices include tags placed in vehicles, and tag readers set along roadside. By recording the timestamp of vehicle passing the two readers, the travel time between readers can then be generated. AVI technologies have

not been used widely for traffic monitoring. The FPM study using AVI technology can be even more limited. The potential advantage of AVI technology over fixed-location detectors resides in its ability to collect point data as well as point-to-point data, which are expected to provide a better description of certain aspects of traffic conditions. Considering its higher efficiency and accuracy and lower cost compare to traditional plate-matching method, it is expected to fill in the gap for traffic tracking purpose, especially in freight performance monitoring. Bluetooth and Radio Frequency Identification (RFID) technologies belong to the category of AVI technologies.

#### **2.2.4.1 Bluetooth Technology**

Bluetooth is a typical short-range wireless communication technology with its functionality embedded in various electronic wireless devices, such as cell phones, MP3 players, PDAs, laptops, GPS, car radios and so on. Bluetooth-enabled devices can serve as “tags” for vehicle tracking by a unique identifier known as Media Access Control (MAC) address. Every Bluetooth device has a unique electronic address, used to identify it to other network devices (Bluetooth SIG, Inc., 2009). The traffic monitoring effort also rely on the pairwise Bluetooth readers to take down the timestamps and location information of vehicles, the readers just get anonymous IDs for privacy protection. This might be an essential characteristic for a potential data source.

The Bluetooth technology can be applied in freeway travel time arterial travel time and performance measures, traffic signal studies, pedestrian travel time, airports evacuation modeling, Transit travel time estimation, and OD studies. The exploration of these technology in traffic monitoring has been quite active recently both in academic and industry field. Case study of estimating traveler's route choice and travel time using Bluetooth probe vehicles have been conducted at the northwestern Indiana (Hainen et al., 2011) and Georgia(Center for Transportation Operations and Safety, Georgia Tech, 2011). Some commercial companies have been manufacturing Bluetooth based vehicle detectors and systems. The study of travel time and speed measuring using Bluetooth carried out by Texas Transportation Institute in Huston area is a notable study in AVI detecting field (Puckett and Vickich, 2010). In the study, the Bluetooth detection system related concepts are given and shown in graphic below.

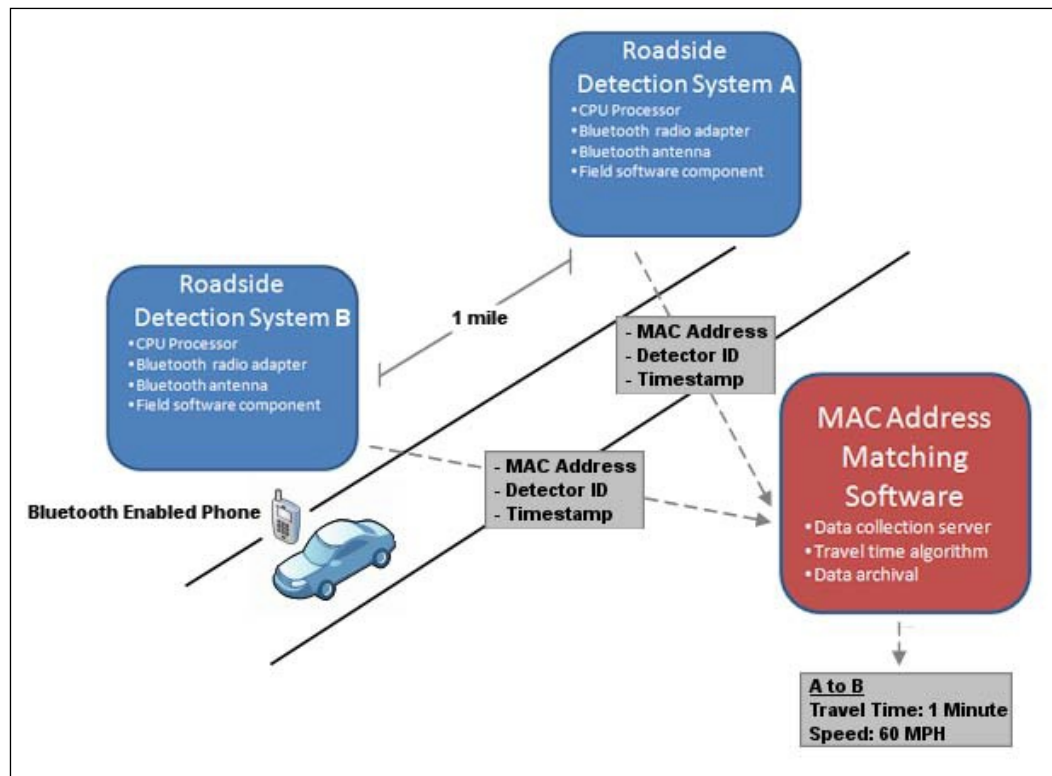


Figure 2–2 Concept of Bluetooth Detection System

#### 2.2.4.2 Radio Frequency Identification (RFID) Technology

Radio-frequency identification (RFID) is a technology that uses communication via electromagnetic waves to exchange data between a terminal and an electronic tag attached to an object, for the purpose of identification and tracking (Kaur et al. 2011).

Radio-frequency identification involves interrogators (also known as readers), and tags (also known as labels). Most RFID tags contain at least two parts. One is an integrated circuit for storing and processing information, modulating and demodulating a radio-frequency (RF) signal, and other specialized functions. The other is an antenna for receiving and transmitting the signal (Butani et al.). There are three types of RFID tags: passive RFID tags, which have no power source and require

an external electromagnetic field to initiate a signal transmission, active RFID tags, which contain a battery and can transmit signals once an external source ('Interrogator') has been successfully identified, and battery assisted passive (BAP) RFID tags, which require an external source to wake up but have significant higher forward link capability providing greater range.

There are two acquisition methods, which define the method used to read tags in the field. One is global search, the primitive command method. During the operation of acquisition, the readers just send the command to the air and every tag in the receiving area can get the request and immediately send back its ID to the reader. Another method is called inventory. This single high-level command transforms itself into a complex series of reader-tag interrogations that eventually resolve themselves into a single list of tag IDs seen by the RFID Reader.

Passive RFID is now commonly used in various fields, such as warehouse management, medical, animal identification, Usages at toll stations and parking lots have been applied in various countries. However, for objects with high speed motion, active tags should be attached to ensure the detecting range and tracking accuracy. Some major organizations such as Loggers use RFID technology to track its fleet, the 915 MHz active tags are used (RFID Journal LLC. 2005). Those tags are UHF tags so that the detection range can be up to 300ft (about 100m) (Kaur et al., 2011). Although active tags needs attached power source and thus are higher in installing budget, they are truly necessary in traffic monitoring. As the implements of RFID on freight

vehicles become more and more popular, a good vehicle identification and monitoring method become realistic.

## **2.3 OVERVIEW OF VISSIM SIMULATION PACKAGE**

In the study, we build a simulation environment that project the real world situation, so the simulation environment is a very important layer of test-bed for AVI technology detecting. The introduction about operation, limitation and data input in VISSIM are provided in following sections.

### **2.3.1 Introduction**

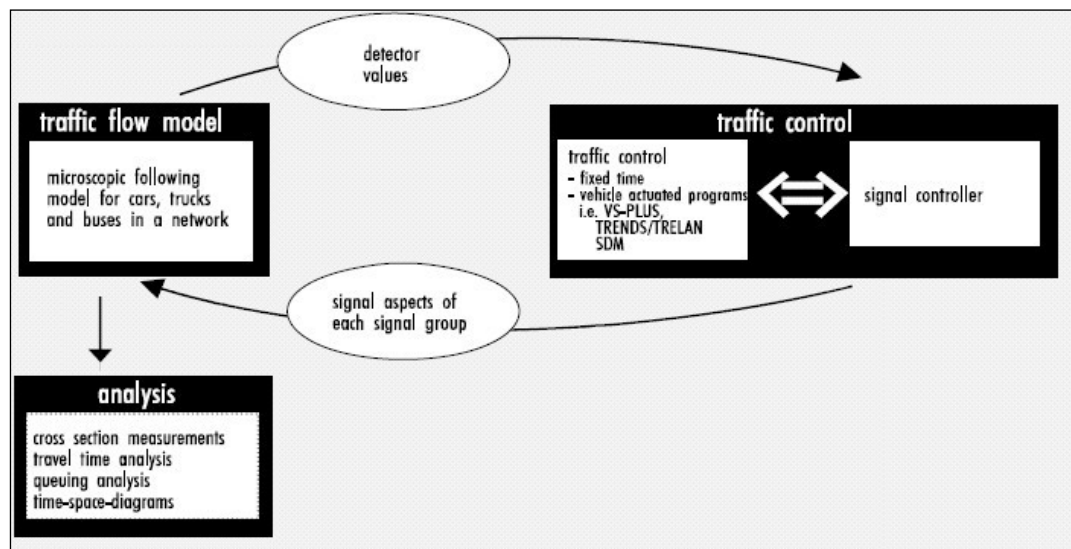
VISSIM is a microscopic, time -step and behavior based simulation model developed to model urban traffic and public transit operations. It was developed by PTV Planung Transport Verkehr AG in Karlsruhe, Germany. The software has program developed to analyze traffic operations under certain constraints provided by software users. The constraints can be lane configuration, traffic composition, driving behavior setting, etc. The software package is thus a useful tool for evaluation of various alternatives based on transportation engineering and planning measures of effectiveness (VISSIM 5.20 Manual, 2009). The repetitions allowed in simulation process makes the comparisons between alternatives in the same scenario possible. And the characteristics of VISSIM such as the ability to take down every vehicle's information and the user-defined vehicle classes make VISSIM a useful tool in this study.

### **2.3.2 VISSIM Theory of Operation**

This section only provides some basic operation features and simulation mechanism of VISSIM to avoid going too much into the technical details of the software (PTV AG, 2009).

The simulation package consists of two different programs. The simulation generates an online visualization (animation) of traffic operations and yields offline output files with statistical data such as travel times, mean speeds and queue lengths.

One program is traffic simulator. It is a microscopic traffic flow simulation model including car following and lane change logic. The other one is signal state generator, which is signal control software polling detector information from the traffic simulator on a discrete time step basis (as small as one tenth of a second). It then determines the signal status for the following second and returns this information to the traffic simulator. The interaction between detector calls and signal status is based on an interface, which is built for data sharing. The raw data after simulation process is transferred to another module for data analysis through traffic simulator. After analysis part, users can access to output files. The data transfer and module interaction process is shown in the following figure.



**Figure 2-3 Communication between traffic simulator and signal state generator (PTV AG, 2009)**

VISSIM is the representative simulation software for microscopic simulation purpose. Micro-simulation is defined as a simulation process that each entities (car, truck, bicycle, pedestrian, etc.) in reality is simulated individually. That is to say, every object in the real world has an representative in the simulation environment, and their properties are projected by the substitute. This characteristic is needed for out simulation study, because in the field implementation, every vehicle's information is recorded, so in corresponding simulation world, we need the information of every entity.

Another characteristic about VISSIM is Multi-modality. That means the software is able to simulate various types of traffic, and the features of each kind can be set separately by users. For the studies that need to focus on more than one kind of traffic, this characteristic is attractive. For the model itself, with every modes featured differently, the simulation can better present the real situation, because the

interactions among various traffic entities cannot be ignored.

The internal model quality of vehicle modeling determines the accuracy of traffic simulation model. Vehicle modeling means how vehicles move through the corridor. Generally speaking, it is defined by car following and lane changing logics. VISSIM adapts a more complex model. The psycho-physical driver behavior model used by VISSIM was developed by WIEDEMANN (1974). The basic concept of this model is that the driver of a faster moving vehicle starts to decelerate as he reaches his individual perception threshold to a slower moving vehicle. Since he cannot exactly determine the speed of that vehicle, his speed will fall below that vehicle's speed until he starts to slightly accelerate again after reaching another perception threshold. This results in an iterative process of acceleration and deceleration. The car following logic of WIEDEMANN adopted by VISSIM is like the following figure.

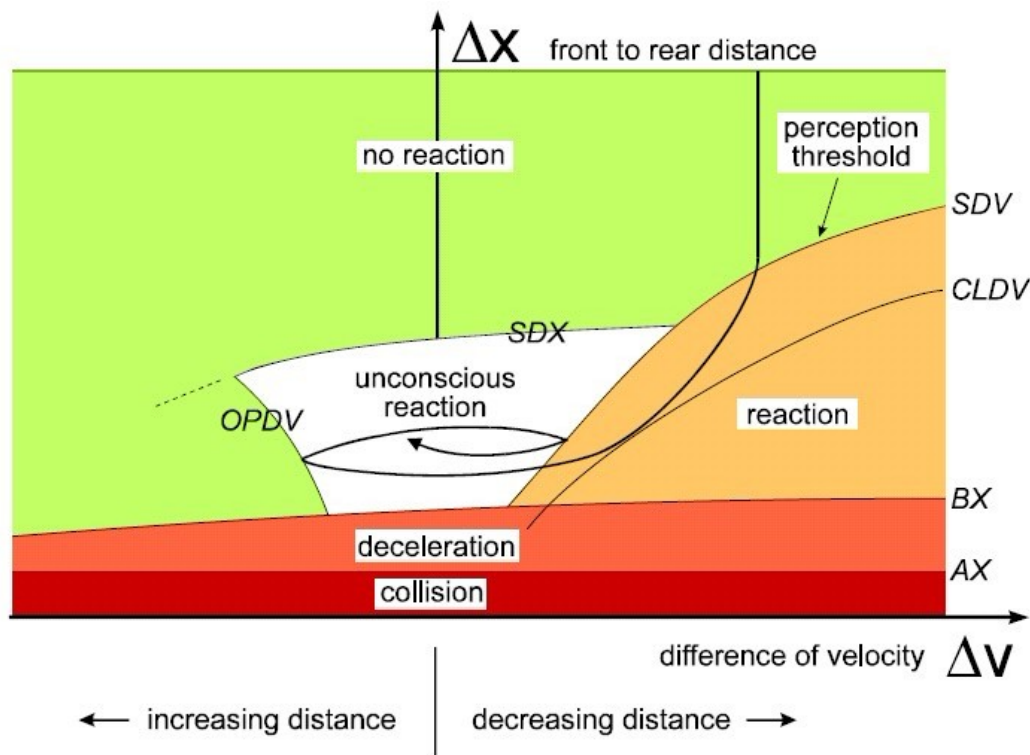


Figure 2-4 Car Following Logic (Wiedemann 1974) (PTV AG, 2009)

To interpret the model more clearly, Wiedemann's model is usually presented as "Wiedemann's four driving modes" (Liu, 2004):

- Free Driving: No influence of preceding vehicles observable, driver seeks to reach and maintain their desired speeds.
- Approaching: The process of adapting the driver's own speed to the lower speed of a preceding vehicle.
- Following: The driver follows the preceding car without any conscious acceleration or deceleration.

- Braking: The application of medium to high deceleration rates if the distance falls below the desired safety distance.

For each mode, Acceleration is the function of speed, speed difference, distance, driver characteristics and vehicle characteristics. A simplified graph that represent the four driving modes is shown below.

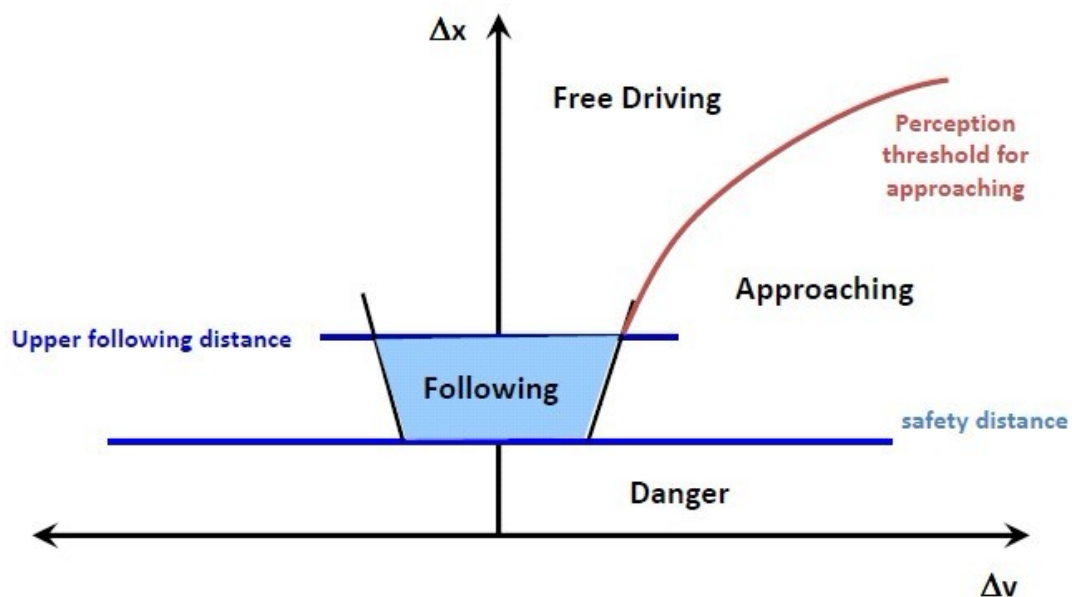


Figure 2-5 Widemann's Four Driving Modes (Liu, 2004)

The model adopted by VISSIM does not use constant speeds and simple deterministic logics, the stochastic distributions of speed and spacing features different individual driver behavior characteristics, and can be more close to ground situation. The model has been calibrated through multiple field measurements at the Technical University of Karlsruhe, Germany. Periodical field measurements and their resulting updates of model parameters ensure that changes in driver behavior and vehicle improvements

are accounted for.

VISSIM has the traffic simulator act in a more complex and realistic way. It allows simulated vehicles to interact with its preceding vehicles and vehicles on the adjacent lanes. And VISSIM model simulate traffic flow by moving “vehicle-driver-unit” through a network. So the driving behavior is combined with vehicle capabilities. The psycho-physical model represents two folds of driving behavior. The psychology part is presented as desired speeds, desired safety distances, etc. And physical part is denoted by perception limits Imperfect vehicle/throttle control.

### **2.3.3 VISSIM Simulation Data Input and Output Files**

VISSIM simulation process is a platform that transfer the base input data into analyzed statistical data based on internally applied programs. The base data provided in VISSIM falls into five categories:

- Geometry data comes from true geometric information of roadway network, usually from road information database and roadway satellite images. Typical geometry data are like grades, height and weight limitations, road curvatures, etc.
- Controls information. Traffic control strategies include signal timing, speed limit, etc. The controls information is from operating agency.

- Existing demands. This kind of information is the general traffic input in the simulation system. The demands include the O-D table, which goes to initial volume inputs and route choice process. The vehicle mix rate gives the picture of vehicle classes' composition. And turning volume is also part of route choice procedure.
- Calibration data. The calibration data need to be performance data such as speed, travel time, queues and so on. They are used for model calibrating purpose, to compare with simulation results and to minimize difference between simulation data and calibration data.
- Future demands. This kind of data is the future values of existing demands. They are for estimation and forecast purposes.

The output files are generated based on users request, generally include raw data, MOEs (e.g. mean error, mean absolute error), 2D and 3D animations, and important text files and database files. In the simulation environment, users can get whatever performance data they want, which is impossible in field inspection. That's why simulation tool is very attractive in researches.

### **3 METHODOLOGY**

In this section, the methodology used in the simulation study in this research is introduced. In order to set the simulation environment for test and evaluation purpose, we need to get clear about the whole conceptual structure and Bluetooth and RFID technologies' detection principles. And then, the details about the detection system like detection range setting, duplication rules, sample rates, and more importantly, the records matching rules and speed calculation method are taken into account. In the detection process, the detectable link is the basic speed measurement unit. The length of detectable link is determined by detection range. We may consider the optimal distribution of measurement links in the future work, but in this study, detectable link is just at the selected freight significant sections.

#### **3.1 DETECTION SYSTEM DESIGN**

##### **3.1.1 Detection System components**

The detection system set its basis on the communication between vehicle-embedded tags and roadside readers. There are generally four major components (include vehicle tags) in the whole detection system:

- In-vehicle tags. For Bluetooth detection, the in vehicle Bluetooth devices serve as tags. The Bluetooth function can be activated when drivers make Bluetooth phone calls, use Bluetooth headset, listen to music with MP3 players or have

passenger using laptop with Bluetooth on. Bluetooth devices send out radio signals in relatively short distance to fulfill data exchange purpose. The communication distance of Bluetooth signal ranges from 3ft (1m) to 330ft (100m) (Bluetooth Technology, 2011). The Bluetooth readers identify vehicles based on their MAC addresses. For RFID part, the specific active RFID tags installed on the truck cab's dashboard. The tags automatically transmit data to the interrogators (readers). Because of the automatic transmission of signals by the active tags, RFID readers would not send signal to "wake up" tags. Each RFID tag has encoded ID string, just like traditional barcode, however the reaction and data exchange time between interrogators and tags are much faster than bar code reading.

- Bluetooth and RFID Readers. In our proposed system, Bluetooth readers and RFID interrogators are roadside placed sensors. The two kinds of readers are installed together into a traffic cabinet. The readers are composed of adapters connected to laptop via USB cables. Here we avoid going too detail into the reading process of the MAC addresses and ID strings. We proposed to place readers both at upstream and downstream parts of the study sites. The adjacent readers within certain range may have radio interference. But radio interference is not a part of this research.
- Antenna and Mounting System. Except for tag frequency, the antenna is also a key for effective detection range. Certain kind of antenna corresponds to the

type of adapters. The antennas are mounted over road and connected to adapters. They are the active part in the detection process.

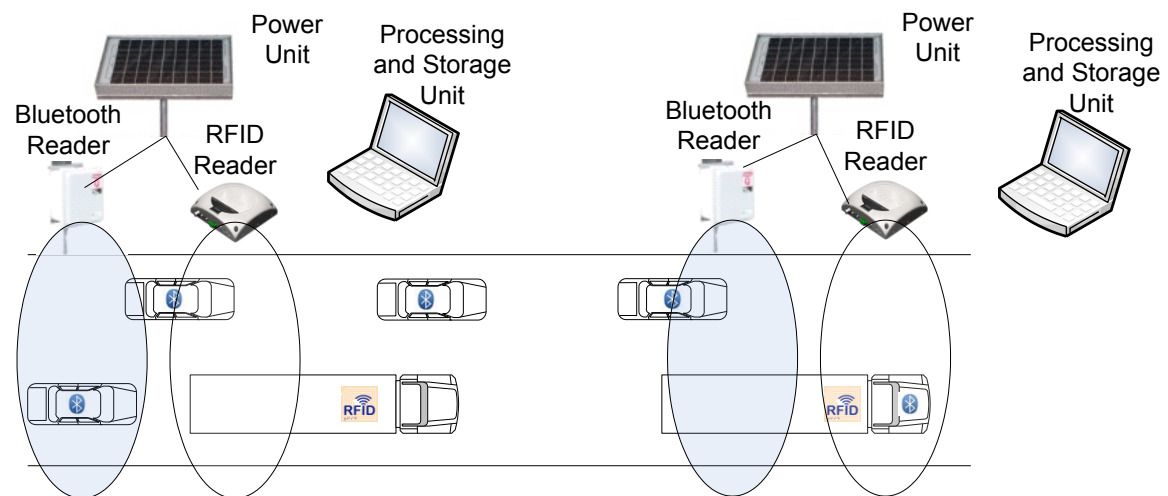
- On-site computing and data-storing unit and Local database server. The on-site calculation and data storage is realized with laptops. The computing and data processing speed of laptop is fast enough to handle the work. As taken in the real situation, one set of sensor has a corresponding computing and storing unit. The vehicle's travel information is stored and shared data with other on-site units through internet on a real-time basis. The calculated and processed performance data (travel time, speed) are archived in local database server.

### **3.1.2 Detection System Architecture**

The purpose of the proposed traffic detection system is to collect freight data and all-vehicle data at the same time, so that we can obtain two complementary sets of data. The general traffic data reflect the condition of the whole traffic system, and the freight-only data set provide corresponding freight information. Within the severe freight-capacity-insufficient situations, the two-data-sets is much better than any stand-alone data set, because the ignorance of data from any critical vehicle classes can lead to the neglect of the reasons that cause traffic problems.

The main idea has its key lies in assemble of Bluetooth and RFID readers in a roadside traffic cabinet. Vehicles pass by with Bluetooth signal or RFID tag

detectable would get their information recorded. The conceptual design of the system can be found in Figure 3-1.



**Figure 3-1 Vehicle detecting system design**

The deployment of Bluetooth technology makes it possible for vehicles to communicate with certain infrastructures in a short range. Bluetooth utilization on freeway traffic monitoring is a smart and suitable idea since freeway traffic only composes of limited vehicle classes, generally cars and trucks. For urban roads, pedestrians and bicycles always have Bluetooth signals on because of cellular phones, Bluetooth headset and MP3 players' usage. The noisy signal environment makes researches for automobiles difficult.

RFID utilization aims specifically on exclusive freight data collection because RFID tags used on truck tracking are generally active tags that send out special signals to communicate with interrogators, this kind of tags are rarely attached to personal cars. Such UHF (Ultra High Frequency) or Microwave tags usually have longer communication range.

In the detection process, RFID and Bluetooth readers are jointly considered in pairs and they communicate with their different detectable tags. The origin readers sense the MAC address as identifier of Bluetooth-enabled vehicles and tag ID string as identifier of RFID-enabled vehicles that come into detectable range and record relative information (includes timestamp and world-coordinates-represented location). The recorded data will then be shared to destination reader attached on-site calculating and data-storing unit. The units are connected with internet so that the progress of data sharing can be real time. When certain unit matches either the MAC address or tag code successfully, travel time and mean speed of the certain vehicle will be calculated and archived in the on-site computing and data-storing unit temporarily. The data will be regularly transferred to local database server for later use. One point worth mentioning is that the connection between readers can be point-to-point or multi-point, although in our study only connections between two reader sets are considered.

### **3.1.3 Concept of Combined-sensor pair and Combined-sensor Link**

In the combination of Bluetooth and RFID readers in a traffic cabinet process, each of the sensor-set is regarded as a unit. Here we call it a combined-sensor. Our study set the focus on monitoring the freight-significant sections on the freeway, so we regard two combined-sensors consecutive in roadway network as a combined-sensor pair. If a vehicle passing the study area meets the triggering condition at both combined-sensors, a measurement of travel time and speed between the two

combined-sensors can be generated. Thus we obtain a valid record of travel time or speed.

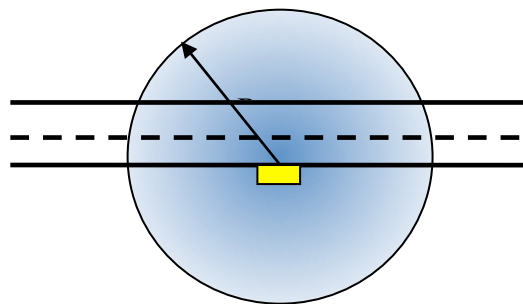
With the definition of combined-sensor, the concept of combined-sensor link is the roadway link between two combined-sensors' detection range. We know that a single combined-sensor can only get the vehicle IDs and timestamps of vehicles, that traffic information has little meaning in traffic condition analysis. The performance information needs the combined-sensor to work in pairs. Only when the vehicles' ID in two sets records took down by two combined-sensors, the travel time and speed records can be generated.

The combined-sensor link is considered to be effective with certain requirements. First, there should be no entrance and exit between the combined-sensor pair. Because the inlet and outlet of traffic would lower down the match rates and thus cut down the number of valid measurements of travel time and speed. Second, despite the radio interference, the combined-sensor link should be relatively short enough in its length. This requirement is also the consideration of higher match rates. Third, the location accuracy of the combined-sensor should be high enough. This is for the accuracy of combined-sensor link length. The accuracy of the link length is helpful in speed measure because in the real situation, the vehicle location information is unavailable.

#### **3.1.4 Concept of Detection Zone and Measurement Link**

As the determination of detection range of the reader-tag communication, we define

detection zone as a circular area where vehicles can be identified and their information can be recorded. The readers are placed in proximity to roadway to ensure the maximal usage of the detection range. On the roadway, the detection length is the double of adapted detection range. The figure below shows the detection zone of the sensors.



**Figure 3–2 Example of Detection Zone**

In the short detecting travel distance, we make an assumption that sensible vehicles are detected when they enter the detection range of the both upstream combined-sensor and downstream one. So the travel distance considered is the double detection range plus the length of combined-sensor link. Measurement link is defined with the travel distance between the two detections in the vehicle monitoring process. The travel distance in our study is short, so for Bluetooth detection, we can make sure that most of the vehicles' signals are available when traversing the two detectable area. As our assumption goes, the travel distance is calculated using the equation below:

$$D = 2R + L_c \quad (1)$$

Where

$R$  = Sensor detection radius range.

$L_c$  = Length of combined-sensor link.

The combined-sensor link and measurement link are shown in the graph below:

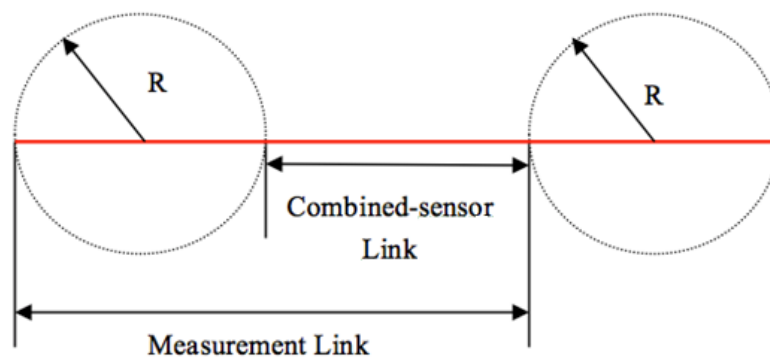


Figure 3–3 Combined-sensor Link and Measurement Link

## 3.2 RECORDS MATCHING AND SPEED MEASURE METHOD

### 3.2.1 Records Matching Rule and Method

With the update of real-time vehicle information, the processing unit needs an algorithm to match the identifier of each vehicle. We have assumed that the vehicles get detected as soon as they enter the detection zone, but when a vehicle enters the detectable area, it can be detected and recorded multiple times, so one certain vehicle may corresponds with several records. In travel time and speed measurement efforts, only one record needs to be extracted within one detection area. With our assumption, the first record should be extracted. The first record is supposed to be taken down at the very beginning of detection zone. The pseudo codes for vehicle records extracting

and matching is as follows:

```

SELECT vehicle_ID1, vehicle_ID1.timestamp1, vehicle_ID1.timestamp2,
       vehicle_ID1.coordinate1, vehicle_ID1.coordinate2

FROM

      (SELECT minimum_timestamp1, vehicle_ID1

      FROM readerN_records) AS record1,

      (SELECT minimum_timestamp2, vehicle_ID2

      FROM reader (N+1)_records) AS record2

WHERE vehicle_ID1 = vehicle_ID2

```

The assumption we made means that when vehicles traverse the entire measurement link, a valid travel time and speed observation is generated. So that's why the two first-time records are chosen as starting and finishing points.

### **3.2.2 Travel Time and Speed Measure Method**

In real monitoring cases, we usually care much more about the average speed of the traffic than one vehicle's data. When a record matching happens, a travel time observation is generated. All the travel time observations are grouped by link and by

5-minute time interval (according to the link-entering time). The travel distance of a vehicle between two detection records can be obtained by accessing the road geometry information with the two locations of combined-sensor coordinates known. Within each group, the link speed is estimated in following procedure.

First, we define some variables:

$t_l(m)$  is the random variable of individual measurement link travel time on measurement link  $l$  at time interval  $m$  (5-minute-based time interval). Assume that  $t_l(m)$  is independent and identically distributed (i.i.d).

$T_l(m)$  is the mean measurement link travel time of link  $l$  during time interval  $m$ .

$\mu_l^m$  is the sample mean of the individual travel time during time interval  $m$ .

$\sigma_l^{m2}$  is the sample variance of the individual travel time at time interval  $m$ .

Second, we can calculate the sample mean and variance of the individual travel time at a specific link as:

$$\mu_l^m = E[t_l(m)] = \frac{\sum_{i=1}^n t_l^i(m)}{n} \quad (3-1)$$

$$\sigma_l^{m2} = Var[t_l(m)] = E\{(t_l^i(m) - E[t_l(m)])\}^2 = \frac{\sum_{i=1}^n (t_l^i(m) - E[t_l(m)])^2}{n-1} \quad (3-2)$$

Where

$n$  = number of vehicles that have ID matched on link  $l$  during time interval  $m$ .

$t_l^i(m)$  = travel time of the  $i$ th vehicle having ID matched on link  $l$  during time interval  $m$ .

Third, we assume that the probability density function (PDF) of travel time on measurement link  $l$  during time interval  $m$  is represented with:

$$T_l(m) = E[t_l(m)] + \varepsilon \quad (3-3)$$

Where,  $\varepsilon$  is the estimation error. The error item can be considered with various choices, which would be talked in MOEs part later.

At last, if we only consider the detected travel time item on measurement link  $l$  during time interval  $m$ , which is the first item in equation 3-3 above. The detected travel time is:

$$\hat{T}_l(m) = E[t_l(m)] \quad (3-4)$$

So the detected measurement link speed on link  $l$  during time interval  $m$  is:

$$\hat{S}_l(m) = \frac{L_l}{\hat{T}_l(m)} = \frac{L_l}{E[t_l(m)]} = \frac{nL_l}{\sum_{i=1}^n t_l^i(m)} \quad (3-5)$$

Where,  $L_l$  is the geometric length of the measurement link.

### **3.3 PERFORMANCE RELATED PARAMETERS**

#### **3.3.1 Detection Range**

Bluetooth device and RFID tag visible distance determine reader detection range. For Bluetooth devices, there are three classes of designed permitted power, correspond with three detectable ranges. The class1 devices are most typical in the market with range of 330 ft (100 m) (Bluetooth SIG Int., 2008). Most RFID tags can be detected by detectors from over 100m and 100m tags are most attractive ones for most truck companies (8). So in the system, 330 ft (100 m) is put to use for detection range.

#### **3.3.2 Sample Rate**

Sample rate in this study is attached attention just on Bluetooth detection because of the fluctuation of Bluetooth signal availability. Sample Rate actually has the same presence with penetration rate, which is defined as the ratio of detected number of vehicles over the total traffic between two adjacent combined-sensors, and which reflect the reliability of detection. In our detection system, we actually care less about the detection rate of the single combined-sensor. Instead, the detection rate for combined-sensor pair has important relationship with records matching. Because a single-sensor record without mate has no meaning for performance measure. So we adopt detection rate of combined-sensor pair to be the sample rate in this study.

Sample rate can be affected by several factors. A study by Tarnoff revealed that about 5% to 7% vehicles in a typical traffic stream have Bluetooth-enabled devices on, and up to 42% of them are from cellular or smart phones (Tarnoff P. et al., 2009). The detection rate varies with space and time change. The high detection rate can be beneficial to our study, but the low rate situation does exist and to deal with small sample size situation is a crucial issue. As required, there is no inlet or outlet of traffic between two neighboring combined-sensors, so the number of sensors is still the major concern. The length of phone calls and the frequency of Bluetooth devices usage also play critical roles in determining detection rate.

### **3.3.3 Duplication Handling Rule**

It is always possible that a truck installs RFID tag with it and has Bluetooth device on at the same time. The duplication of detection is not a big deal in this study, because the two types of readers generate two different dataset. For example, two readers catch freight vehicle  $k$ , in Bluetooth obtained dataset,  $k$  is an entity that precedes in general traffic, and in RFID dataset,  $k$  works as a piece of freight-specific data. The analyses of two data sets are jointed, but the two obtained dataset are independent from each other.

### **3.3.4 Measures of Effectiveness (MOE)**

The users of a certain detection system have a strong desire about the effectiveness about the accuracy of traffic performance parameters' detection, which is defined as

measure of effectiveness (MOE). In our study, we care about absolute relative error between detected value and observed value.

The absolute relative error is calculated as:

$$ARE = \frac{|\hat{S}_l(m) - S_l(m)|}{S_l(m)} \quad (3-6)$$

Where,  $\hat{S}_l(m)$  is the estimate link speed of measurement link l during time interval m and  $S_l(m)$  is the observed link speed of link l during time interval m. The general evaluation of effectiveness over the whole detection process is represented with mean absolute error (MAE) and mean absolute relative error (MARE). These two MOEs are measured on link basis over the whole study process and are calculated as follows:

$$MAE = \frac{1}{m} \left( \sum_1^m |\hat{S}_l(m) - S_l(m)| \right) \quad (3-7)$$

$$MARE = \frac{1}{m} \left( \sum_1^m \frac{|\hat{S}_l(m) - S_l(m)|}{S_l(m)} \right) \quad (3-8)$$

### 3.3.5 Measures of Performances (MOP)

In another aspect, we care about how many samples in our study is enough for effectively estimating the speed. According to traffic flow theory (May, 2001), the

required sample size can be calculated using the central limit theorem.

$$n = \left( \frac{ts}{\varepsilon} \right)^2 \quad (3-9)$$

Where,

$n$  = required sample size for the study.

$s$  = observed value stand deviation.

$\varepsilon$  = a user-defined allowable error.

$t$  = coefficient of standard error of the mean that represents user defined probability level.

In order to find our standard of required sample size, we traced back to the studies of speed measurement for empirical results. Toppen and Wunderlich surveyed daily variability in several US cities (Toppen, 2003). They found that the standard deviation of speeds on freeways was approximately 8 mph for peak periods and 5mph for off-peak periods. The variability of local streets would be much higher because of the complexity of the local condition. For the observation on freeways, the specified error  $\varepsilon$  can be lower. Because it is hard to give a uniform standard deviation for all the actual links, so we obtain a simple calculation and assume the allowable error is 1/3 of

the standard deviation. The error is regulated with stand deviation determined. To unify the standard to determine the minimum sample size for speed measurement, 85% confidence level is chosen. If we want a higher accuracy of measurement, we may need to raise confidence level to 95%.

According to the normal distribution table, t value is 1.04 with the selection of 85% confidence level ( $Z_{0.8508} = 1.04$ ). t value is 1.65 with the selection of 95% confidence level ( $Z_{0.9505} = 1.65$ ). Then the required sample sizes are calculated in a low value and high value:

$$n_l = \left( \frac{t_1 s}{\varepsilon} \right)^2 = (1.04 \cdot 3)^2 = 9.73 \approx 10 \quad (3-10)$$

$$n_h = \left( \frac{t_2 s}{\varepsilon} \right)^2 = (1.65 \cdot 3)^2 = 24.5 \approx 25 \quad (3-11)$$

## **4 EXPERIMENTAL DESIGN**

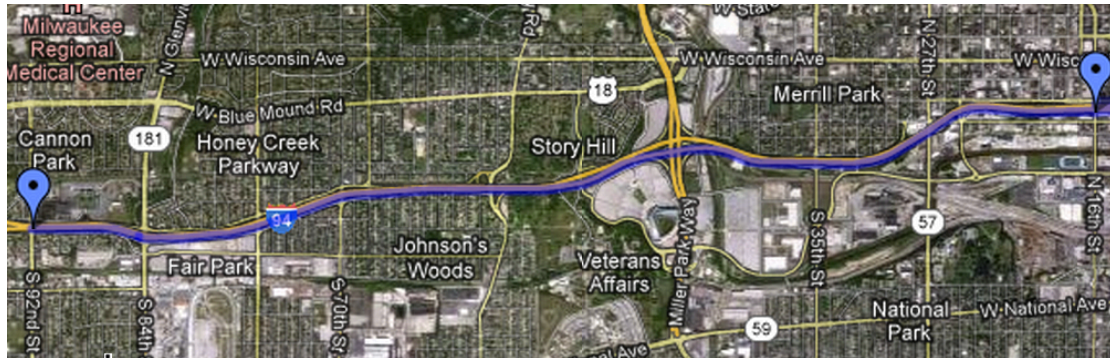
### **4.1 SIMULATION MODEL BUILDING AND CALIBRATION**

This section aims to illustrate the process of VISSIM-based simulation model building, including the network coding, parameter setting and model calibration. To begin with, a study site that is considered freight significant should be selected. Meanwhile, there should be sufficient available data to support the study. In fact, the most severe freight bottlenecks are located around big cities, such as Chicago in the east coast and Los Angeles in the west coast, so we made a trade off when choosing the study site. The study site is selected with respect of existed results on freeway freight transportation analysis. With the target site selected, an exact simulation site is built based on the road geometry. During the following steps in data input and model calibration process, the field source data is used and it relates tightly to the accuracy and efficiency of the model. The following description follows the model building and calibrating steps to show the fundamental simulation work.

#### **4.1.1 Experiment Site and Data Source**

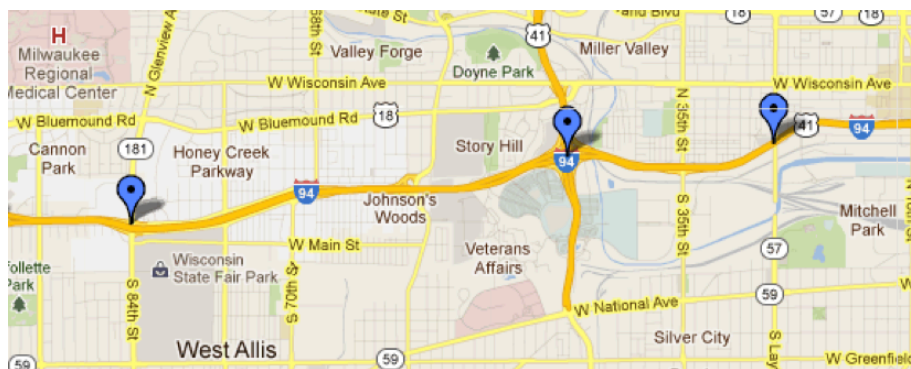
Simulation study serves as the test bed and precursor of field implementation for the proposed system. The environment is created in VISSIM and the study site is chosen to be I-94 East-West corridor between 92nd and 16th Street, which is instrumented with loop detectors. According to a previous study on freight bottlenecks of Upper Midwest Region, we define three freight-significant sites: I-94 at 84<sup>th</sup> Street, I-94 at

Stadium Interchange and I94 at 28<sup>th</sup> Street. A satellite image from Google Map shows our experiment scope below.

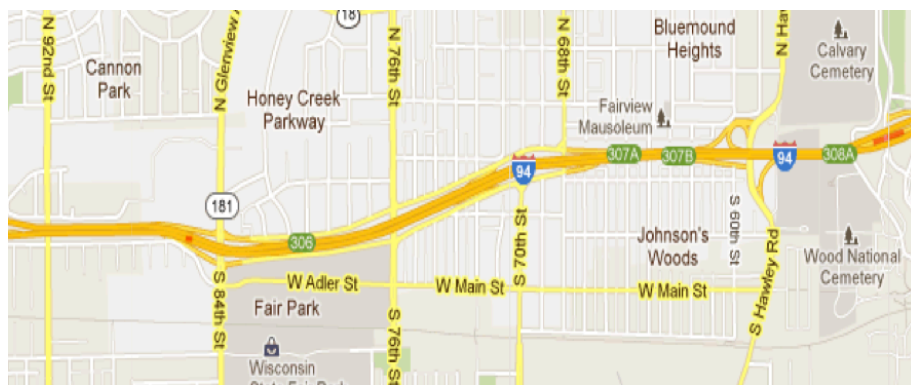


**Figure 4–1 Snapshot of Study Site to Be Evaluated**

By reviewing a previous CFIRE study on freight bottlenecks of Upper Midwest Region by Dr. Guo's group (Guo, Gong, and Obernesser, 2010), the freight significant sections on the freeway can be selected. Dr. Guo's group also provided the ArcGIS shape files that contain all the GIS information regarding those freight bottlenecks. The ArcGIS data has been converted into KML file, and imported into Google map as shown in the following figures.



**Figure 4–2 Interchange Freight Bottleneck Locations Identified by the Previous CFIRE Study**



(a)



(b)

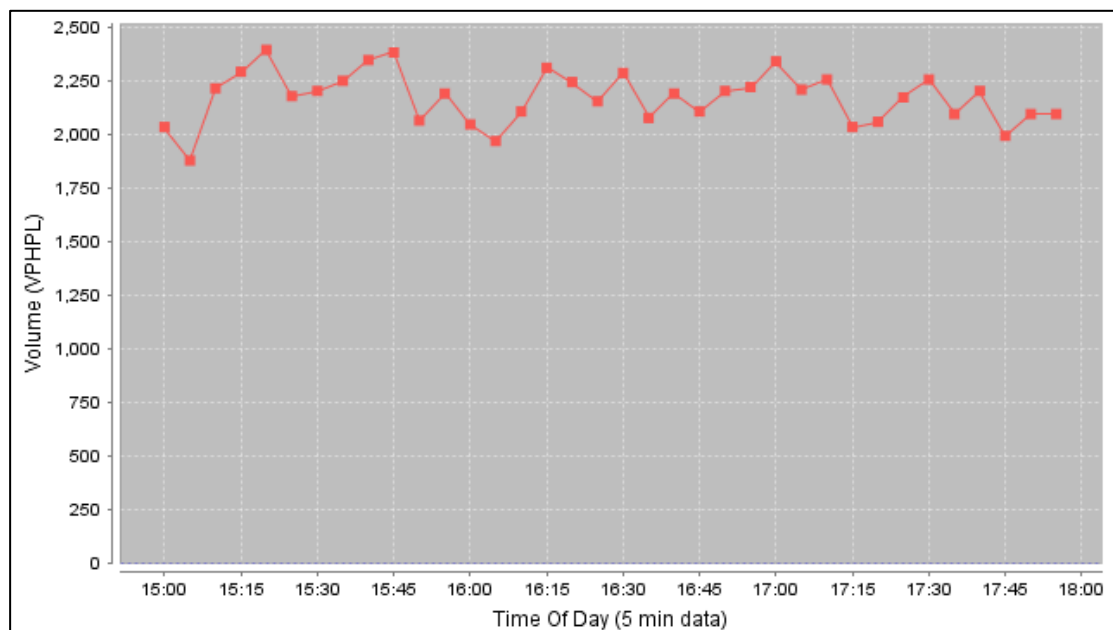
**Figure 4–3 Segment Freight Bottleneck Locations Identified in Previous CFIRE Study**

The blue place marks in Figure 4-2 indicate the locations of Interchange freight bottlenecks on I-94 corridor in Milwaukee. The red lines in the two pictures in Figure 2 denote the other three types of bottlenecks include lane drop bottlenecks, signalized intersection bottlenecks and geometry bottlenecks.

Thus, with the reviewing of all the information from Dr. Guo's group's study, we choose 84<sup>th</sup> Street section, Stadium Interchange section and 16<sup>th</sup> Street section in our experiment scope. The detail information about the detection section is introduced in section 4.4.1.

There are two data sources used in the microscopic-simulation environment development and model calibration. One is the 5-min detector data achieved in

WisTransPortal V-SPOC (Volume, Speed, and Occupancy) Application Suite developed at TOPS Laboratory (WisTransPortal); the other is CCTV images from Wisconsin Department of Transportation, the image database is in TOPS Lab server. Images are the records of truck presents on mainline I-94. The heavy vehicle percentages are deduced manually from the frames. Simulation period is selected from 3:00PM to 6:00PM in June 14th, 2011 to focus on peak hour situation. The travel demand pattern is shown in figures below.



**Figure 4-4 Traffic Flow Pattern in the Simulation Time Period**

Form the data quality report of VISPOC database, most of the loop detector data on June 14, 2010 reach to the level of larger than 85% in availability, which means the field data can generally reflect the real traffic condition on road. In the simulation process, simulation period is divided into 36 time intervals with a time elapse of 300 seconds with respond to 5-min ground truth data. The loop detector data serves as

input values. The input values are fixed during the whole simulation period.

The CCTV images are accessed on 511 Wisconsin website (WisDOT wi511), the frames are taken every three minutes to provide travelers real time information about the road condition. The target corridor locates in southeast region of Wisconsin, Milwaukee County. We can get access to the camera snapshots by entering the proper links. The window opens to general travelers is shown in 4-5.

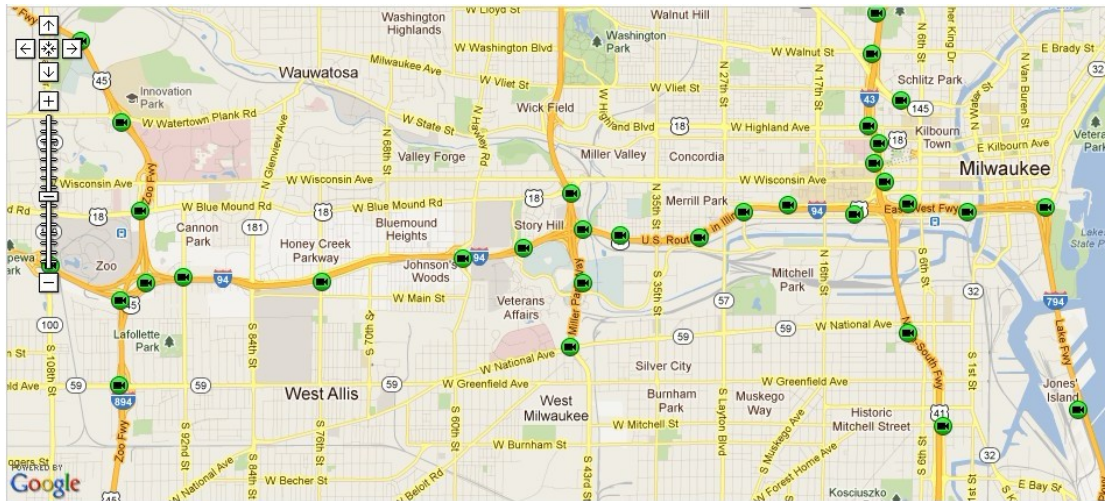
The screenshot displays the Wisconsin Department of Transportation's 511 Travel Information website. The header features the state logo, the text 'WISCONSIN DEPARTMENT OF TRANSPORTATION', and 'Travel Information'. Navigation links include Home, Traffic, Transit, Travel Services, and Help/FAQ. A '511 Wisconsin Travel Info' logo is also present. Below the header, an 'ALERTS' section shows 'No current alerts'. The main content area has a 'Printer Friendly' link and a 'Low Bandwidth Map' link. A navigation menu includes 'Map', 'Winter Road Conditions', 'Traffic Events', 'Message Signs', 'Cameras', and 'Travel Times'. The 'Cameras' tab is active, showing a filter list for 'Milwaukee' and 'I-94'. A table lists camera locations, and two camera images are displayed.

Camera Location	County	Highway	Camera Image
I-94 at 13th St	Milwaukee	I-94	
I-94 at 20th St	Milwaukee	I-94	

**Figure 4–5 Snapshot of Visual Monitoring on Wis511 Website**

Since the locations on the freeway with cameras installed are not as many as loop detectors, we have just several spots of supportive camera data, those are I94 at 92<sup>nd</sup> Street, 76th Street, Hawley Road, Mitchell Blvd, Stadium Interchange, 35th Street, 30<sup>th</sup> Street, 25<sup>th</sup> Street and 20<sup>th</sup> Street. Locations of cameras can be shown in Google

map (Figure 4-6).



**Figure 4-6 Camera Locations of the Study Corridor**

Although we can get corresponding truck percentage at each camera station, there are obvious deficiencies for the visual data source for collecting freight vehicles' percentage. First, cameras are located only on mainlines, that's a big problem in simulation modeling, since ramp data is needed for running the simulation environment. Second, because the existed CCTV images in the database reflected the road traffic updated every three minutes, we kind of missed the cases in time between. All the information we can get from the images are at a specific time point, the vehicle composition at a certain time point cannot represent the whole period, even though the period can be divided into small pieces. So the method for dealing with the missing pieces is that after collecting the truck percentage at every three-minute point, we use the average percentage to stand for the vehicle composition condition during our study period. Another problem with CCTV images: sometimes the vehicle type cannot be assured exactly. The freight vehicle percentage error is a hard problem to

solve, however, if we use simulated detector data to compare with the measurement of new proposed system, the average value can be reasonable for the study and it may have little impact on the final results.

## 4.2 SIMULATION FRAMEWORK

In the simulation process, we need to consider the simulation of traffic flow in one aspect, and consider the simulation test bed for the proposed system with Bluetooth and RFID technologies. In Jin's study (2012), he considered dividing the simulation network into three modules, which is the same situation as our study. The three modules are traffic simulation, data evaluation and new system simulation. The simulation framework has a structure shown below.

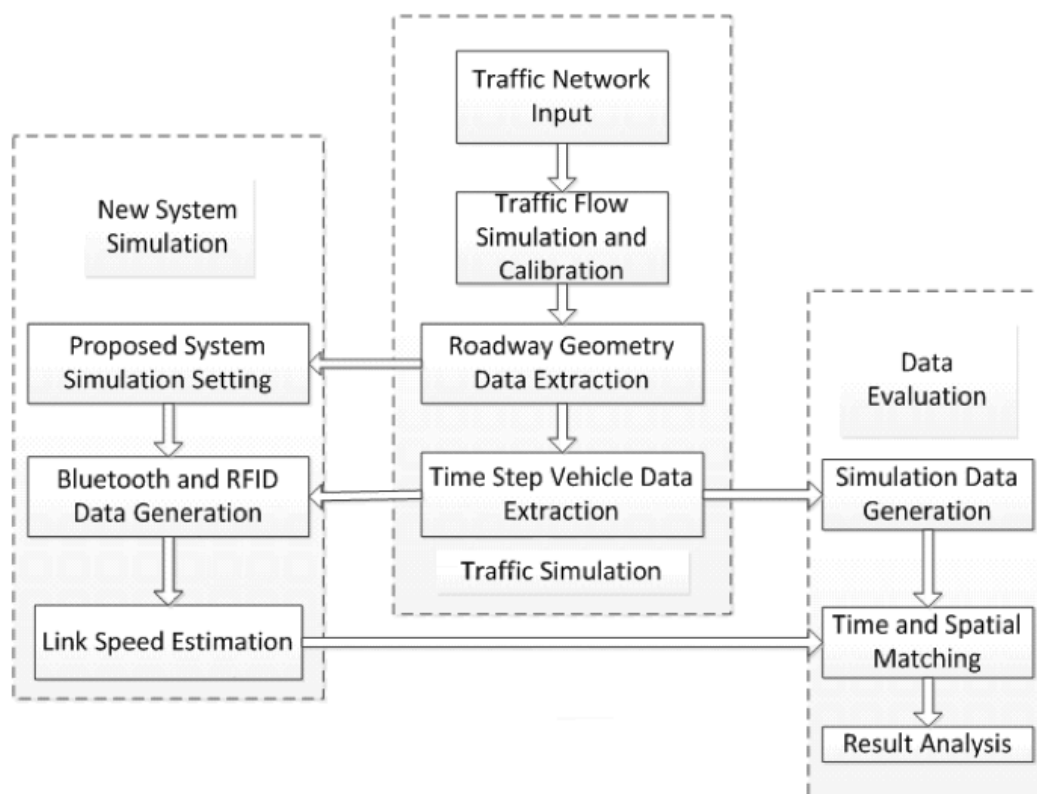


Figure 4–7 Simulation Network for New Proposed Traffic Monitoring System

In traffic simulation module, the acquired and manipulated traffic flow and speed data are applied into the roadway network. The network is built following the geometry information from satellite image. The running of VISSIM can generate time step data file and parse the time step vehicle data from VISSIM output files. The calibration process needs to minimize the difference between software-generated data and ground data. By changing specific parameters, the errors between two data series can be lower down to a tolerate level.

In new system simulation module, the location of readers is determined. With the location as the center of the circle, the detection zone is defined with detection range of 330 ft (100 m). Then the paired combined-sensors are generated. With the matching of the vehicle records, the measurement link travel time and speed are generated. Then we can project the performance data to the study sites.

The data evaluation module prepares data for each simulation and analysis step. The simulation data generated for system evaluation can well represent the real traffic system. Matched together with the data decorated with Bluetooth and RFID characteristics, the new proposed system's performance in speed estimation can be analyzed through result comparison and analysis effort.

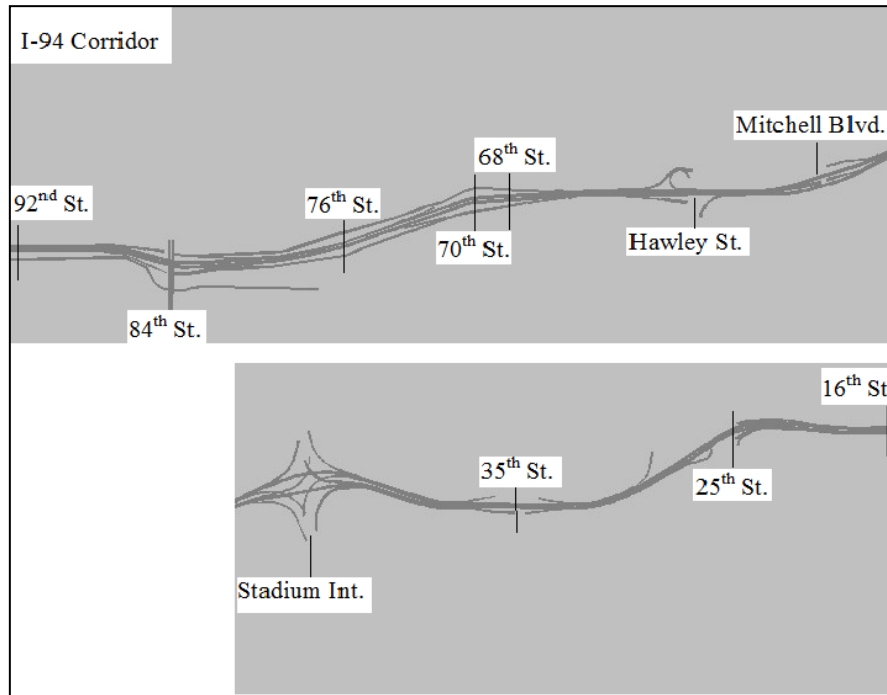
### **4.3 TRAFFIC SIMULATION**

In the efforts of doing traffic simulation, we need to build roadway network in VISSIM following the geometric design of the real road. And the real traffic volume

and freight vehicle percentage are traffic system input. These two aspects the simulation environment project the condition of the field situation. The major output files we need to use in this study is the traffic count and time step data for each individual vehicle. New proposed system simulation module uses the traffic count data at each data collection points to determine the locations of detection readers and length of measurement link, and then generate new system detected data.

### **4.3.1 Traffic Network Coding and Calibration**

The data source of traffic network is Google Map. We use the satellite image and the ruler legend provided by the map service to determine the number of lanes, curvature link length and other roadway geometry information. The figure below shows the roadway network built in VISSIM. Because of constrain in width of page, we broke the whole snap of corridor into two parts to show more clearly of the study corridor. In order to get the volume data from simulation process, we need to develop data collection points on the simulation network according to the location of pair loop detector. The location information of detectors can also be accessed in TOPS lab database.



**Figure 4–8 Study Site Snapshot in VISSIM**

The simulation environment should be implemented close to realistic environment in both geometry design and traffic flow condition. The calibration effort strives to control the volume mismatches in a tolerable range. The base scenario use default values of traffic and driving behavior parameters. During the calibration procedure, we adjust the parameters until the termination condition is met.

The procedure of the calibration in this study is conducted as following:

- 1) Adjust the traffic volumes at on-ramps and off-ramps. After traffic input, the inlet and outlet of volume is tuned.
- 2) Adjust driver behavior related global variables such as free-flow speed, headway distribution, speed distribution, etc. In order to

differentiate speeds of vehicle classes, cars obtain the desired speed of 120km/h and trucks of 80km/h.

- 3) Use Wiedemann's 1999 car following model and fit the model parameters. The freeway situation fits the Wiedemann's 99 model. Change the upper level of Look back distance to 800ft and model parameter CC0 (Standstill distance) to 1.7 to fit better for high-volume freeway situation (22). Look back distance is the distance that a vehicle can see back-wards in order to react to other vehicles behind (within the same link) (PTV, 2009). For the freeway situation, the default value of 200ft is not enough. And standstill distance defines the desired distance between stopped cars (PTV, 2009). The freeway value of standstill distance tends to be a little higher than that of urban road. So the default value 1.5 is changed to 1.7.
- 4) Changing lane-change parameter. "Waiting Time before Diffusion" is changed to 1s to make lane-change behavior reasonable in mainline freeway traffic. Because of the heavy congestion observed in the base simulation, the blockage pops out as a major problem. The modification of "waiting time before diffusion" can be helpful for easing the off-ramp blockages, thus reduces the heavy traffic load on the mainline. Vehicles that failed to make lane change quickly enough

and stopped at the emergency stop position on the mainline were immediately removed from the simulation, thereby minimizing the obstruction to the freeway. Eliminating these vehicles has little impact on the total travel time, since they are few and very close to their exit anyway. The suppose behind it is that those vehicles took lane change quickly and leave from the closest ramps. Besides, One new behavior type “freeway onramp” is added to distinguish the behaviors of vehicles trying to merge into freeway form those driving on freeway. The “waiting time before diffusion” of freeway onramp is set to 30s.

- 5) Changing connectors’ attributions. The “Emergency stop” and “Lane change” distances at off-ramp connectors are set to 20ft and 1800ft per lane separately. Emergency stop defines the last possible position for a vehicle to change lanes. With the last possible position for lane changing father away from the connectors of exits, and the lane change action took ahead, the congestion at off-ramp can be relieved at certain level. This action has a hidden assumption that drivers are quite familiar with the route and are able to make their route decision far behind the off-ramp. For daily commuters and truck drivers, this assumption is totally reasonable.

During the calibration process, the adjustments talked above are conducted in order, until the simulation volume at all the data collection points is close enough to the data

collected by field loop detectors.

### **4.3.2 Retrieving Data from VISSIM Output Files**

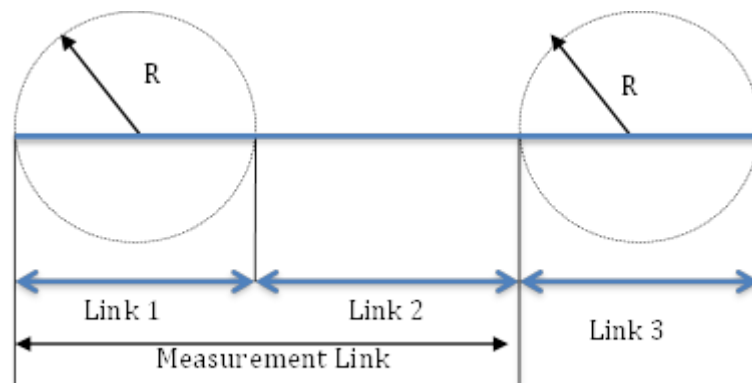
VISSIM has various output files accessible for each simulation run. Before each running process, users have to determine what kind of output they want to use in the analysis and turn the file mode on to get the specific kind of output. For traffic simulation part, we need to activate traffic count evaluation file on. The data in this file is like the real loop detector recorded data, with volume, speed and occupancy available. The compiled data is archived in .mes file.

## **4.4 BLUETOOTH AND RFID BASED SYSTEM SIMULATION**

### **4.4.1 Hypothetical Simulation Implementation for Bluetooth and RFID detection**

In the simulation process, Bluetooth and RFID data collection characteristics are developed through software-provided functionalities. In order to measure traffic mean speed at the freight-significant sites, the readers are placed in pairs at specific location. In VISSIM, an evaluation function Vehicle Record can take down the timestamp and location information of each vehicle on link basis. So we split the link at the location we want to place the reader sets, and set the link length to the detection range (i.e. 330ft). For a detection section, we split the link into three parts, as shown in the figure below. The two circles are detectable zone. The records of vehicles' time step data are taken down on link 1 and link 3. Link1 and link2 compose the measurement link. The

action makes every vehicle that enters the “detectable” link recorded. To simulate the multiple detection actions by one reader, the simulation resolution is set to 1.



**Figure 4–9 Split Link in VISSIM Simulation**

The upstream detection link and the downstream one form a pair to match vehicles’ identifiers. Vehicle records can be stored in a database, which is the same as real local database server. The first record of each vehicle at upstream detection link is extracted and then matched with the record at downstream detection link. We use the matching algorithm with pseudo code mentioned in section 3.2.1 to retrieve vehicle records and to calculate the link speed. A successful match yields a result of link travel time and mean speed set. The detection sites and range is defined in the figure below. The red dashed-line circles represent detectable areas.

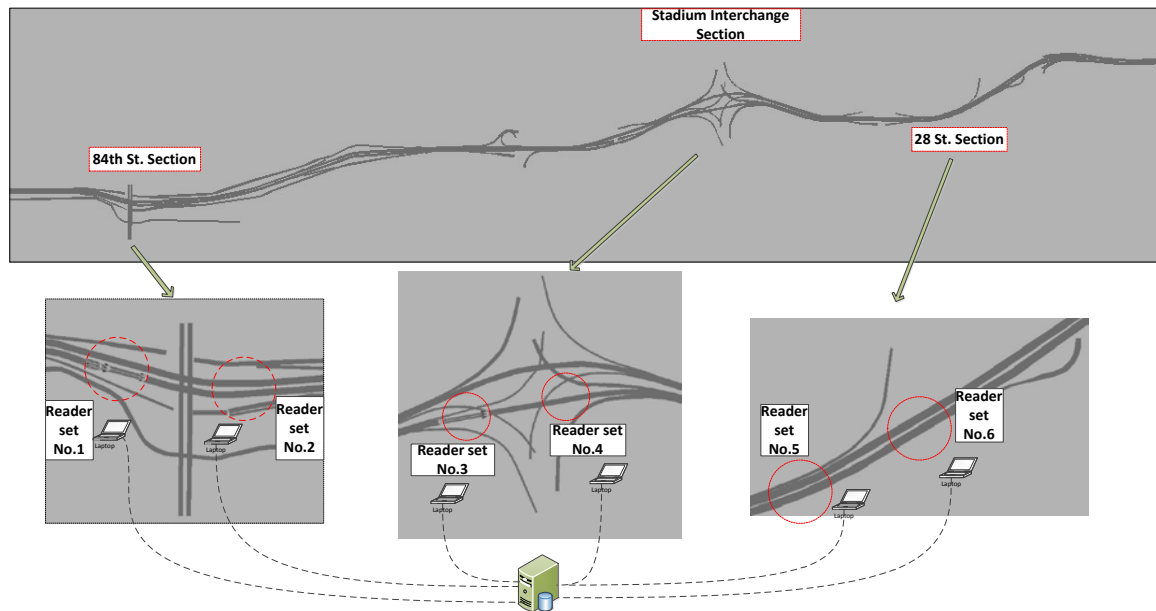


Figure 4-10 Detection Sites and Range

#### 4.4.2 Bluetooth and RFID Simulation Data Generation

In building the environment that mimic the Bluetooth and RFID based detection system we proposed, only link breaking is not enough, because all the vehicles entering the detection links can be recorded. The problem we are facing is that how do we collect different sample rate result. In the vehicle class module, we create two new vehicle classes, Bluetooth and RFID. Bluetooth class includes Bluetooth cars and Bluetooth trucks, RFID class only shares detectable heavy vehicles part. Bluetooth and RFID detection rates can be defined using relative volume in vehicle composition setting. The vehicles with class of Bluetooth or RFID in vehicle records effectively represent the data collected by real Bluetooth and RFID readers.

### 4.5 EVALUATION SCENARIOS

In the development of Bluetooth and RFID based traffic monitoring system, some

variables should be taken into consideration for various alternatives evaluation. For effect analysis, these variables are performance related parameters mentioned above, and they serve as global variables in the analysis. Among the variables, we select sample rate for effect analysis.

Sample rate is an important performance parameter. In the field implementation, we usually use sample rate to determine whether to accept a combined-sensor pair or not. In other words, if a combined-sensor pair has low sample rate in speed measurement effort, we cannot use it as a reliable data provider in the detection system. One assumption here is that each combined-sensor pair is independent from each other.

Detection range is actually a fixed value in the simulation study. This variable determines the length of measurement link. The reasonable detection range has been pre-determined, so we don't have many choices. But in the future research, with more selection of detection range available, the effect of detection range on detection accuracy can be a new scope in research.

Travel distance measure error is caused by the lack of vehicle location information during detection process. As mentioned above, we simplify the measurement link length to the sum of double detection range and length of combined-sensor link. However, when the vehicle is detected at the middle point of the detection zone, the detection travel distance would be less than the calculation-based travel distance. Such vehicles will not be in large proportion, because the test link is in short range.

But the distance measure error can be an impact on speed estimation accuracy.

Without vehicle location information, this variable would not be considered in this study.

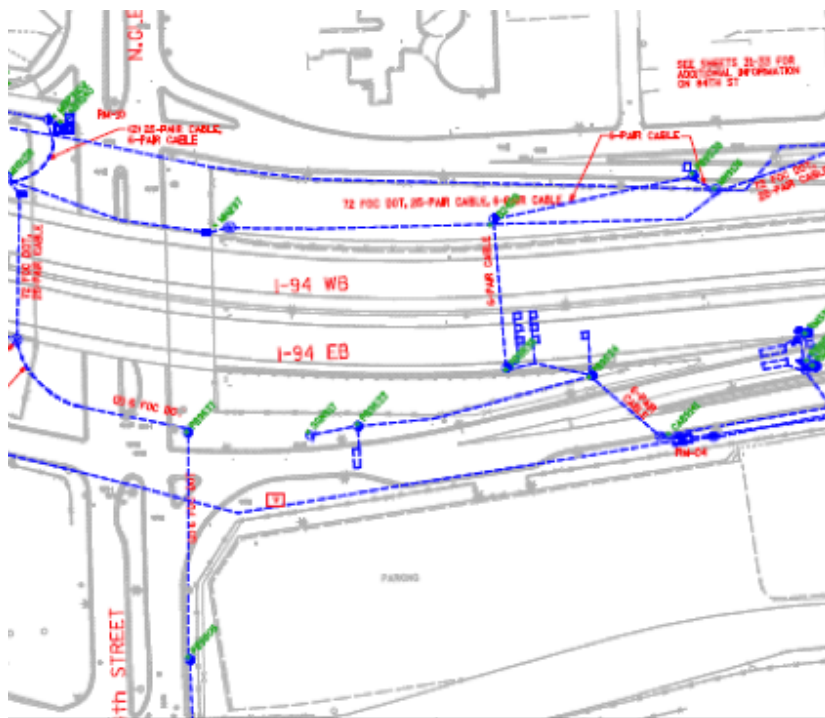
So in our study, the only parameter that we can test for the effect analysis is sample rate. We design to use 5%, 10% and 15% sample rate to make result analysis. The evaluation process has its details in Chapter 5.

## **5 RESULT ANALYSIS**

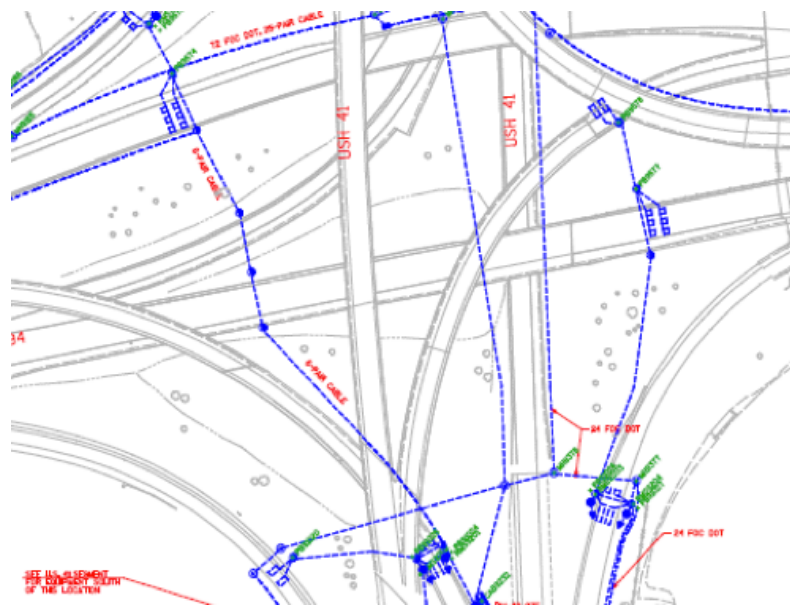
In this Chapter, a comprehensive result analysis is given. Based on results yielded by simulation model, we collect several sets of data similar to those obtained by real on-site Bluetooth and RFID data collection and processing devices. The lack of historical freight vehicle data makes it impossible to evaluate the quality of RFID-recorded data, but the real contribution of the proposed system is the collection of freight-specific data. Here presents a systematic result analysis about the traffic monitoring system on general traffic monitoring.

### **5.1 MODEL CALIBRATION RESULTS**

On our I-94 East-west bound corridor, there are 10 interchanges, with the Stadium Interchange the biggest one with busiest traffic. The data quality issue makes the lack of some on-ramp or off-ramp data. The three freight-significant sites we selected at interchanges (84<sup>th</sup> Street, Stadium Interchange and 28<sup>th</sup> Street, named with crossroads) have all the mainline, on-ramp and off-ramp data available, which is good for our evaluation study. The locations of paired loops at our study interchanges are shown in three figures below. Figure (a) is the snapshot of I-94at 84<sup>th</sup> Street, figure(b) is at Stadium and figure(c) is controller image of I-94 at 28<sup>th</sup> Street.



(a)



(b)



(c)

**Figure 5-1 Snapshots from Milwaukee Controller Map (VSPOC, 2008)**

Our simulation study imitates the ground truth traffic environment with volume difference at various data collection points not higher than tolerate values. The mismatches of volume in simulation results and real freeway volume are quantified by the index of GEH. The equation for calculating GEH is shown below (23):

$$GEH = \sqrt{\frac{2(ObsVol - SimVol)^2}{ObsVol + SimVol}} \quad (3)$$

Where

*ObsVol* = ground truth volume

*SimVol* = simulation volume

The terminate condition of calibration is that mean GEH value of each data collection site is less than 5 and the average of all sites is less than 4 (23). The calibration results are shown in following figures and tables. After four times of calibration, the volumes get close to the ground values. During the calibration process, we keep tracking GEH value until the termination condition met.

### 5.1.1 Calibration Results for All-vehicle Traffic

(1) I-94 at 84<sup>th</sup> Street Interchange

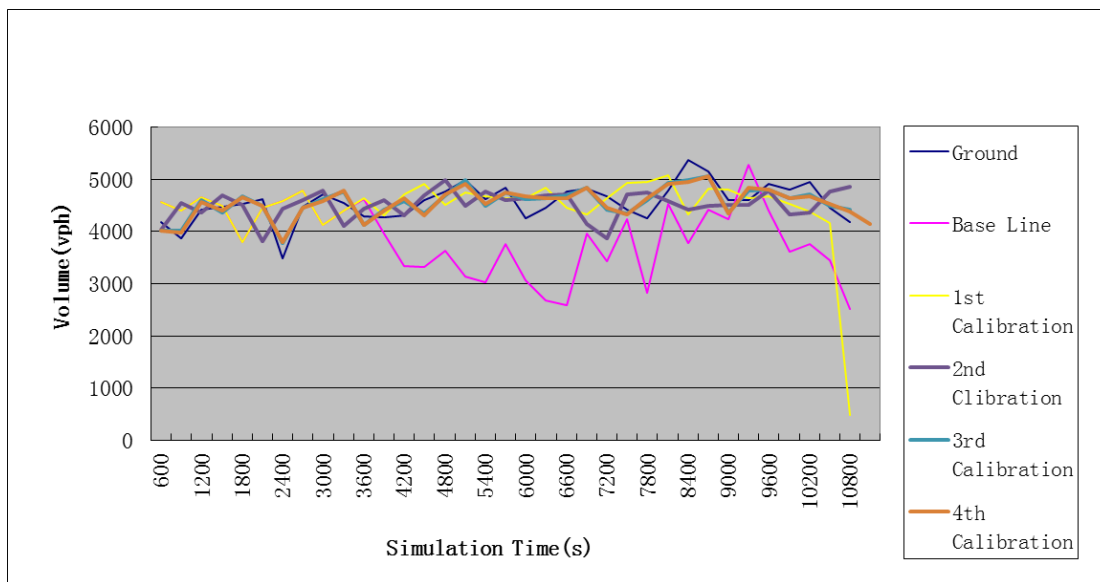


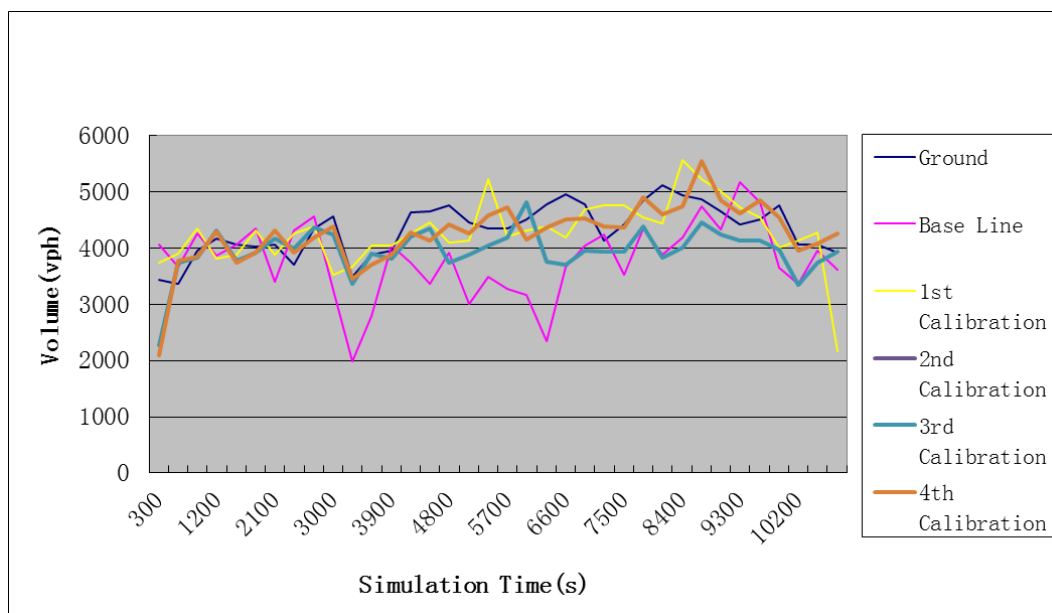
Figure 5–2 Step-wise All-vehicle Volume Calibration Result for 84<sup>th</sup> Street Interchange

Table 5-1 Mainline all-vehicle volume Calibration result for 84<sup>th</sup> street interchange.

Time Interval	Simulation Interval	Simulation 5-min Traffic Count	VSPC 5-min Traffic Count	Simulation Volume (vph)	VSPC Volume (vph)	GEH
15:05 - 15:10	300 - 600	332	323	3984	3876	1.72
15:10 - 15:15	600 - 900	381	368	4572	4416	2.33

15:15 - 15:20	900 - 1200	367	373	4404	4476	1.08
15:20 - 15:25	1200 - 1500	388	378	4656	4536	1.77
15:25 - 15:30	1500 - 1800	375	385	4500	4620	1.78
15:30 - 15:35	1800 - 2100	317	290	3804	3480	5.37
15:35 - 15:40	2100 - 2400	371	373	4452	4476	0.36
15:40 - 15:45	2400 - 2700	382	393	4584	4716	1.94
15:45 - 15:50	2700 - 3000	399	379	4788	4548	3.51
15:50 - 15:55	3000 - 3300	344	357	4128	4284	2.41
15:55 - 16:00	3300 - 3600	367	356	4404	4272	2.00
16:00 - 16:05	3600 - 3900	386	359	4632	4308	4.85
16:05 - 16:10	3900 - 4200	359	383	4308	4596	4.32
16:10 - 16:15	4200 - 4500	393	398	4716	4776	0.87
16:15 - 16:20	4500 - 4800	409	415	4908	4980	1.02
16:20 - 16:25	4800 - 5100	377	385	4524	4620	1.42
16:25 - 16:30	5100 - 5400	396	403	4752	4836	1.21
16:30 - 16:35	5400 - 5700	389	354	4668	4248	6.29
16:35 - 16:40	5700 - 6000	386	371	4632	4452	2.67
16:40 - 16:45	6000 - 6300	387	397	4644	4764	1.75
16:45 - 16:50	6300 - 6600	403	402	4836	4824	0.17
16:50 - 16:55	6600 - 6900	372	390	4464	4680	3.19
16:55 - 17:00	6900 - 7200	360	369	4320	4428	1.63
17:00 - 17:05	7200 - 7500	386	354	4632	4248	5.76
17:05 - 17:10	7500 - 7800	410	399	4920	4788	1.89
17:10 - 17:15	7800 - 8100	413	447	4956	5364	5.68
17:15 - 17:20	8100 - 8400	422	429	5064	5148	1.18
17:20 - 17:25	8400 - 8700	362	384	4344	4608	3.95
17:25 - 17:30	8700 - 9000	403	383	4836	4596	3.49
17:30 - 17:35	9000 - 9300	400	410	4800	4920	1.72
17:35 - 17:40	9300 - 9600	387	401	4644	4812	2.44
17:40 - 17:45	9600 - 9900	389	413	4668	4956	4.15
17:45 - 17:50	9900 - 10200	378	371	4536	4452	1.25
17:50 - 17:55	10200 - 10500	365	349	4380	4188	2.93
17:55 - 18:00	10500 - 10800	346	353	4152	4236	1.30

(2) I-94 at Stadium Interchange



**Figure 5-3 Step-wise All-vehicle Volume Calibration Result for Stadium Interchange**

**Table 5-2 Mainline all-vehicle volume calibration result for stadium interchange.**

Time Interval	Simulation Interval	Simulation 5-min Traffic Count	VSPOC 5-min Traffic Count	Simulation Volume (vph)	VSPOC Volume (vph)	GEH
15:05 - 15:10	300 - 600	315	281	3780	3372	6.82
15:10 - 15:15	600 - 900	321	330	3852	3960	1.73
15:15 - 15:20	900 - 1200	358	348	4296	4176	1.84
15:20 - 15:25	1200 - 1500	312	338	3744	4056	5.00
15:25 - 15:30	1500 - 1800	326	335	3912	4020	1.71
15:30 - 15:35	1800 - 2100	360	339	4320	4068	3.89
15:35 - 15:40	2100 - 2400	327	309	3924	3708	3.50
15:40 - 15:45	2400 - 2700	349	363	4188	4356	2.57
15:45 - 15:50	2700 - 3000	366	380	4392	4560	2.51
15:50 - 15:55	3000 - 3300	288	291	3456	3492	0.61
15:55 - 16:00	3300 - 3600	308	324	3696	3888	3.12
16:00 - 16:05	3600 - 3900	323	330	3876	3960	1.34
16:05 - 16:10	3900 - 4200	356	386	4272	4632	5.40
16:10 - 16:15	4200 - 4500	344	387	4128	4644	7.79
16:15 - 16:20	4500 - 4800	368	397	4416	4764	5.14
16:20 - 16:25	4800 - 5100	355	371	4260	4452	2.91
16:25 - 16:30	5100 - 5400	381	362	4572	4344	3.41
16:30 - 16:35	5400 - 5700	394	363	4728	4356	5.52
16:35 - 16:40	5700 - 6000	346	376	4152	4512	5.47
16:40 - 16:45	6000 - 6300	364	398	4368	4776	6.03
16:45 - 16:50	6300 - 6600	375	413	4500	4956	6.63

16:50 - 16:55	6600 - 6900	377	398	4524	4776	3.70
16:55 - 17:00	6900 - 7200	365	344	4380	4128	3.86
17:00 - 17:05	7200 - 7500	364	369	4368	4428	0.90
17:05 - 17:10	7500 - 7800	408	404	4896	4848	0.69
17:10 - 17:15	7800 - 8100	383	427	4596	5124	7.57
17:15 - 17:20	8100 - 8400	395	411	4740	4932	2.76
17:20 - 17:25	8400 - 8700	462	406	5544	4872	9.31
17:25 - 17:30	8700 - 9000	404	388	4848	4656	2.79
17:30 - 17:35	9000 - 9300	385	368	4620	4416	3.03
17:35 - 17:40	9300 - 9600	404	375	4848	4500	5.09
17:40 - 17:45	9600 - 9900	379	396	4548	4752	2.99
17:45 - 17:50	9900 - 10200	330	339	3960	4068	1.70
17:50 - 17:55	10200 - 10500	340	338	4080	4056	0.38
17:55 - 18:00	10500 - 10800	355	327	4260	3924	5.25

(3) I-94 at 28<sup>th</sup> Street Interchange

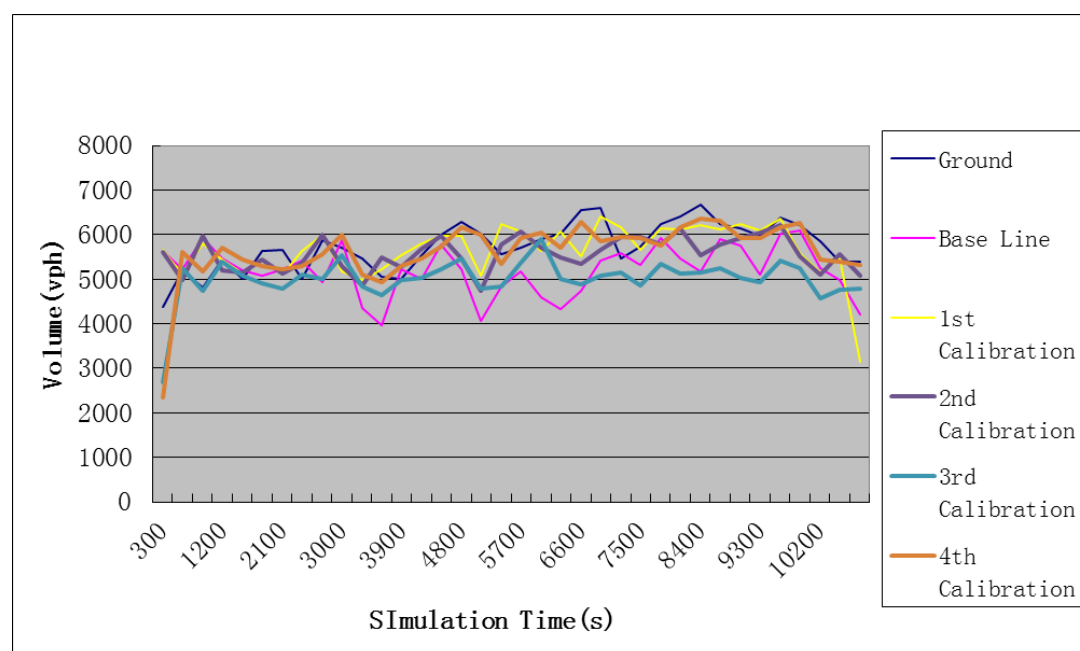


Figure 5-4 Step-wise All-vehicle Volume Calibration Result for 28<sup>th</sup> Street Interchange

Table 5-3 Mainline all-vehicle volume calibration result for 28th street interchange.

Time Interval	Simulation Interval	Simulation 5-min Traffic Count	VSPC 5-min Traffic Count	Simulation Volume (vph)	VSPC Volume (vph)	GEH
15:05 - 15:10	300 - 600	468	433	5616	5196	5.71
15:10 - 15:15	600 - 900	431	401	5172	4812	5.10

15:15 - 15:20	900 - 1200	475	454	5700	5448	3.38
15:20 - 15:25	1200 - 1500	453	417	5436	5004	5.98
15:25 - 15:30	1500 - 1800	442	470	5304	5640	4.54
15:30 - 15:35	1800 - 2100	435	471	5220	5652	5.86
15:35 - 15:40	2100 - 2400	441	418	5292	5016	3.84
15:40 - 15:45	2400 - 2700	464	490	5568	5880	4.12
15:45 - 15:50	2700 - 3000	500	476	6000	5712	3.76
15:50 - 15:55	3000 - 3300	426	455	5112	5460	4.79
15:55 - 16:00	3300 - 3600	411	421	4932	5052	1.70
16:00 - 16:05	3600 - 3900	442	418	5304	5016	4.01
16:05 - 16:10	3900 - 4200	455	461	5460	5532	0.97
16:10 - 16:15	4200 - 4500	477	500	5724	6000	3.60
16:15 - 16:20	4500 - 4800	514	523	6168	6276	1.37
16:20 - 16:25	4800 - 5100	500	501	6000	6012	0.15
16:25 - 16:30	5100 - 5400	446	463	5352	5556	2.76
16:30 - 16:35	5400 - 5700	493	475	5916	5700	2.83
16:35 - 16:40	5700 - 6000	504	492	6048	5904	1.86
16:40 - 16:45	6000 - 6300	475	502	5700	6024	4.23
16:45 - 16:50	6300 - 6600	523	546	6276	6552	3.45
16:50 - 16:55	6600 - 6900	487	549	5844	6588	9.44
16:55 - 17:00	6900 - 7200	495	455	5940	5460	6.36
17:00 - 17:05	7200 - 7500	493	478	5916	5736	2.36
17:05 - 17:10	7500 - 7800	480	520	5760	6240	6.20
17:10 - 17:15	7800 - 8100	513	533	6156	6396	3.03
17:15 - 17:20	8100 - 8400	530	556	6360	6672	3.87
17:20 - 17:25	8400 - 8700	526	520	6312	6240	0.91
17:25 - 17:30	8700 - 9000	493	511	5916	6132	2.78
17:30 - 17:35	9000 - 9300	493	497	5916	5964	0.62
17:35 - 17:40	9300 - 9600	514	532	6168	6384	2.73
17:40 - 17:45	9600 - 9900	521	517	6252	6204	0.61
17:45 - 17:50	9900 - 10200	454	487	5448	5844	5.27
17:50 - 17:55	10200 - 10500	449	449	5388	5388	0.00
17:55 - 18:00	10500 - 10800	443	449	5316	5388	0.98

The mean GEH values of the three target interchanges are 2.55, 3.80 and 3.40 separately. In our study, we calibrated the mainline volume on all the 10 interchanges.

The results of calibration are quite similar to those shown in tables above. Our last time simulation yielded the highest GEH value on single data collection point as 4.89,

and the total average value as 3.63. For truck percentage at cross-street points, the highest relative error is 5.3% and lowest is 3.8%, which can be effective enough to simulate truck flow. With the result, we believe the simulation environment provides effective volume input for ground truth condition presentation.

### **5.1.2 Calibration Results for Trucks**

For truck-only volumes, we still measure the GEH values. Because the existing loop detectors has no strategy for vehicle type distinguishing, the truck percentages collected in CCTV images are used to apply to all-vehicle volume to get truck volume. And the simulation values are then compared with the generated ground truth data to see whether the calibration requirement is satisfied. However, in truck volume calibration, we begin to check the GEH index after we get satisfied with the calibration results of all-vehicle traffic. The simplified method can save the calibration steps, because the general trends of calibration is to get close to the ground condition, as one vehicle class, the results follows the trend, so the calibration efforts would benefit all vehicle classes in the traffic system. The truck-specific results of last calibration are shown in the tables below.

#### (1) I94 at 84<sup>th</sup> Street Interchange

The average truck percentage at 84<sup>th</sup> Street Interchange is 8.2%.

**Table 5-4 Mainline truck Volume calibration result for 84<sup>th</sup> street interchange.**

Time Interval	Simulation Interval	VSPOC All-vehicle Traffic Volume	VSPOC Truck Volume (vph)	Simulation Truck Volume (vph)	GEH
15:05 - 15:10	300 - 600	3876	318	332	0.79
15:10 - 15:15	600 - 900	4416	362	373	0.57
15:15 - 15:20	900 - 1200	4476	367	358	0.47
15:20 - 15:25	1200 - 1500	4536	372	377	0.26
15:25 - 15:30	1500 - 1800	4620	379	374	0.25
15:30 - 15:35	1800 - 2100	3480	285	303	1.03
15:35 - 15:40	2100 - 2400	4476	367	365	0.11
15:40 - 15:45	2400 - 2700	4716	387	378	0.45
15:45 - 15:50	2700 - 3000	4548	373	386	0.67
15:50 - 15:55	3000 - 3300	4284	351	349	0.12
15:55 - 16:00	3300 - 3600	4272	350	361	0.57
16:00 - 16:05	3600 - 3900	4308	353	382	1.50
16:05 - 16:10	3900 - 4200	4596	377	362	0.77
16:10 - 16:15	4200 - 4500	4776	392	385	0.34
16:15 - 16:20	4500 - 4800	4980	408	402	0.32
16:20 - 16:25	4800 - 5100	4620	379	372	0.35
16:25 - 16:30	5100 - 5400	4836	397	393	0.18
16:30 - 16:35	5400 - 5700	4248	348	341	0.40
16:35 - 16:40	5700 - 6000	4452	365	375	0.52
16:40 - 16:45	6000 - 6300	4764	391	376	0.75
16:45 - 16:50	6300 - 6600	4824	396	398	0.12
16:50 - 16:55	6600 - 6900	4680	384	376	0.40
16:55 - 17:00	6900 - 7200	4428	363	359	0.22
17:00 - 17:05	7200 - 7500	4248	348	375	1.40
17:05 - 17:10	7500 - 7800	4788	393	399	0.32
17:10 - 17:15	7800 - 8100	5364	440	424	0.76
17:15 - 17:20	8100 - 8400	5148	422	419	0.15
17:20 - 17:25	8400 - 8700	4608	378	368	0.51
17:25 - 17:30	8700 - 9000	4596	377	388	0.57
17:30 - 17:35	9000 - 9300	4920	403	394	0.47
17:35 - 17:40	9300 - 9600	4812	395	379	0.79
17:40 - 17:45	9600 - 9900	4956	406	402	0.22
17:45 - 17:50	9900 - 10200	4452	365	377	0.62
17:50 - 17:55	10200 - 10500	4188	343	359	0.83
17:55 - 18:00	10500 - 10800	4236	347	342	0.29

## (2) I94 at Stadium Interchange

The average truck percentage at Stadium Interchange is 5.1%.

**Table 5-5 Mainline truck volume calibration result for stadium interchange.**

Time Interval	Simulation Interval	VSPOC All-vehicle Traffic Volume	VSPOC Truck Volume (vph)	Simulation Truck Volume (vph)	GEH
15:05 - 15:10	300 - 600	3372	172	198	1.91
15:10 - 15:15	600 - 900	3960	202	194	0.57
15:15 - 15:20	900 - 1200	4176	213	218	0.34
15:20 - 15:25	1200 - 1500	4056	207	191	1.12
15:25 - 15:30	1500 - 1800	4020	205	203	0.14
15:30 - 15:35	1800 - 2100	4068	207	224	1.13
15:35 - 15:40	2100 - 2400	3708	189	201	0.85
15:40 - 15:45	2400 - 2700	4356	222	216	0.42
15:45 - 15:50	2700 - 3000	4560	233	224	0.57
15:50 - 15:55	3000 - 3300	3492	178	176	0.16
15:55 - 16:00	3300 - 3600	3888	198	184	1.03
16:00 - 16:05	3600 - 3900	3960	202	197	0.35
16:05 - 16:10	3900 - 4200	4632	236	209	1.83
16:10 - 16:15	4200 - 4500	4644	237	214	1.52
16:15 - 16:20	4500 - 4800	4764	243	228	0.98
16:20 - 16:25	4800 - 5100	4452	227	216	0.74
16:25 - 16:30	5100 - 5400	4344	222	238	1.09
16:30 - 16:35	5400 - 5700	4356	222	241	1.24
16:35 - 16:40	5700 - 6000	4512	230	226	0.27
16:40 - 16:45	6000 - 6300	4776	244	224	1.28
16:45 - 16:50	6300 - 6600	4956	253	239	0.88
16:50 - 16:55	6600 - 6900	4776	244	235	0.55
16:55 - 17:00	6900 - 7200	4128	211	223	0.85
17:00 - 17:05	7200 - 7500	4428	226	242	1.06
17:05 - 17:10	7500 - 7800	4848	247	251	0.24
17:10 - 17:15	7800 - 8100	5124	261	242	1.22
17:15 - 17:20	8100 - 8400	4932	252	239	0.80
17:20 - 17:25	8400 - 8700	4872	248	279	1.88
17:25 - 17:30	8700 - 9000	4656	237	252	0.93
17:30 - 17:35	9000 - 9300	4416	225	237	0.78
17:35 - 17:40	9300 - 9600	4500	230	252	1.45

17:40 - 17:45	9600 - 9900	4752	242	238	0.28
17:45 - 17:50	9900 - 10200	4068	207	202	0.38
17:50 - 17:55	10200 - 10500	4056	207	212	0.36
17:55 - 18:00	10500 - 10800	3924	200	221	1.44

(3) I94 at 28<sup>th</sup> Street Interchange

The average truck percentage at 28<sup>th</sup> Street Interchange is 4.3%.

**Table 5-6 Mainline truck volume calibration result for 28<sup>th</sup> street interchange.**

Time Interval	Simulation Interval	VSPOC All-vehicle Traffic Volume	VSPOC Truck Volume (vph)	Simulation Truck Volume (vph)	GEH
15:05 - 15:10	300 - 600	5196	223	243	1.28
15:10 - 15:15	600 - 900	4812	207	222	1.03
15:15 - 15:20	900 - 1200	5448	234	244	0.63
15:20 - 15:25	1200 - 1500	5004	215	239	1.58
15:25 - 15:30	1500 - 1800	5640	243	227	1.01
15:30 - 15:35	1800 - 2100	5652	243	232	0.72
15:35 - 15:40	2100 - 2400	5016	216	235	1.29
15:40 - 15:45	2400 - 2700	5880	253	242	0.69
15:45 - 15:50	2700 - 3000	5712	246	258	0.78
15:50 - 15:55	3000 - 3300	5460	235	223	0.78
15:55 - 16:00	3300 - 3600	5052	217	220	0.19
16:00 - 16:05	3600 - 3900	5016	216	212	0.25
16:05 - 16:10	3900 - 4200	5532	238	224	0.91
16:10 - 16:15	4200 - 4500	6000	258	242	1.01
16:15 - 16:20	4500 - 4800	6276	270	247	1.42
16:20 - 16:25	4800 - 5100	6012	259	268	0.58
16:25 - 16:30	5100 - 5400	5556	239	255	1.02
16:30 - 16:35	5400 - 5700	5700	245	233	0.78
16:35 - 16:40	5700 - 6000	5904	254	257	0.20
16:40 - 16:45	6000 - 6300	6024	259	266	0.43
16:45 - 16:50	6300 - 6600	6552	282	243	2.39
16:50 - 16:55	6600 - 6900	6588	283	264	1.17
16:55 - 17:00	6900 - 7200	5460	235	253	1.17
17:00 - 17:05	7200 - 7500	5736	247	258	0.71
17:05 - 17:10	7500 - 7800	6240	268	256	0.76

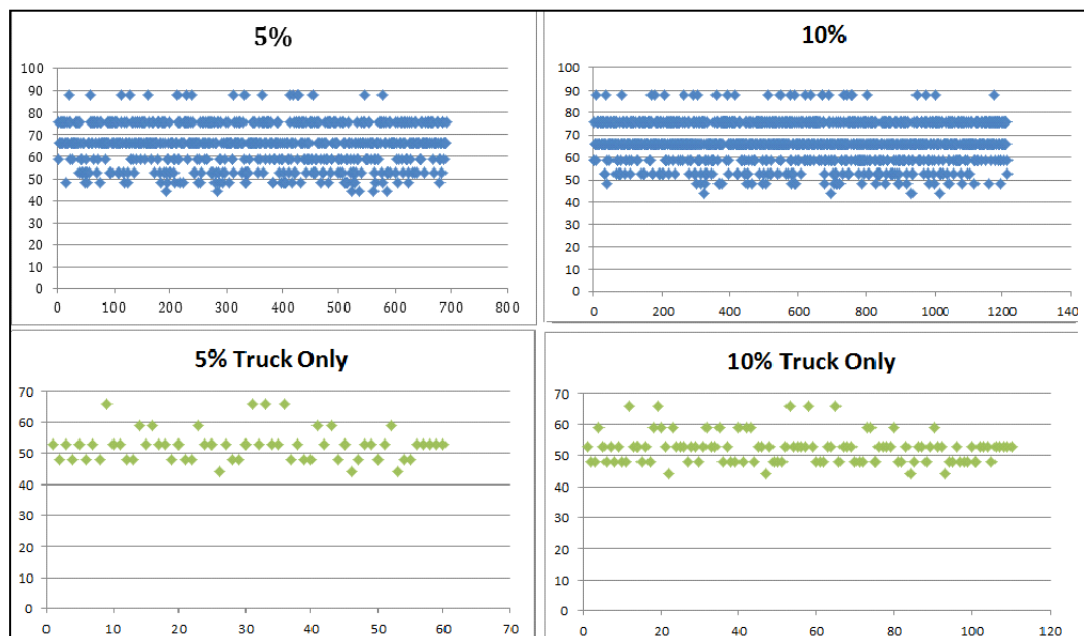
17:10 - 17:15	7800 - 8100	6396	275	244	1.93
17:15 - 17:20	8100 - 8400	6672	287	242	2.76
17:20 - 17:25	8400 - 8700	6240	268	285	1.00
17:25 - 17:30	8700 - 9000	6132	264	271	0.45
17:30 - 17:35	9000 - 9300	5964	256	255	0.09
17:35 - 17:40	9300 - 9600	6384	275	254	1.26
17:40 - 17:45	9600 - 9900	6204	267	269	0.14
17:45 - 17:50	9900 - 10200	5844	251	263	0.73
17:50 - 17:55	10200 - 10500	5388	232	242	0.67
17:55 - 18:00	10500 - 10800	5388	232	229	0.18

The mean GEH value at the three target interchanges are 0.52, 0.87 and 0.91 separately, which denotes that the truck volume in simulation environment can well reflect the real freight flow. Fortunately, the calibration of all-vehicle flow yield the satisfying results for truck flow.

## 5.2 EVALUATION RESULT

### 5.2.1 Estimated Speed Data Analysis

The on-site database and local server archive the direct results of traffic monitoring, which are travel time and mean speed for each vehicle detected. The speed of trucks can be extracted form RFID records. The figure below shows the raw speed data of 84<sup>th</sup> street section under two detection rates. The all-vehicle speed data are supposed to be collected by Bluetooth readers and truck only data collected by RFID readers. Evaluation scenarios come with different sample rate, 5% and 10%.



Note: Horizontal axis in each graph represents simulation time(s) and vertical axis represents speed (mph).

**Figure 5-5 Raw Speed Data of Overall and Freight Traffic at 84<sup>th</sup> Street Interchange**

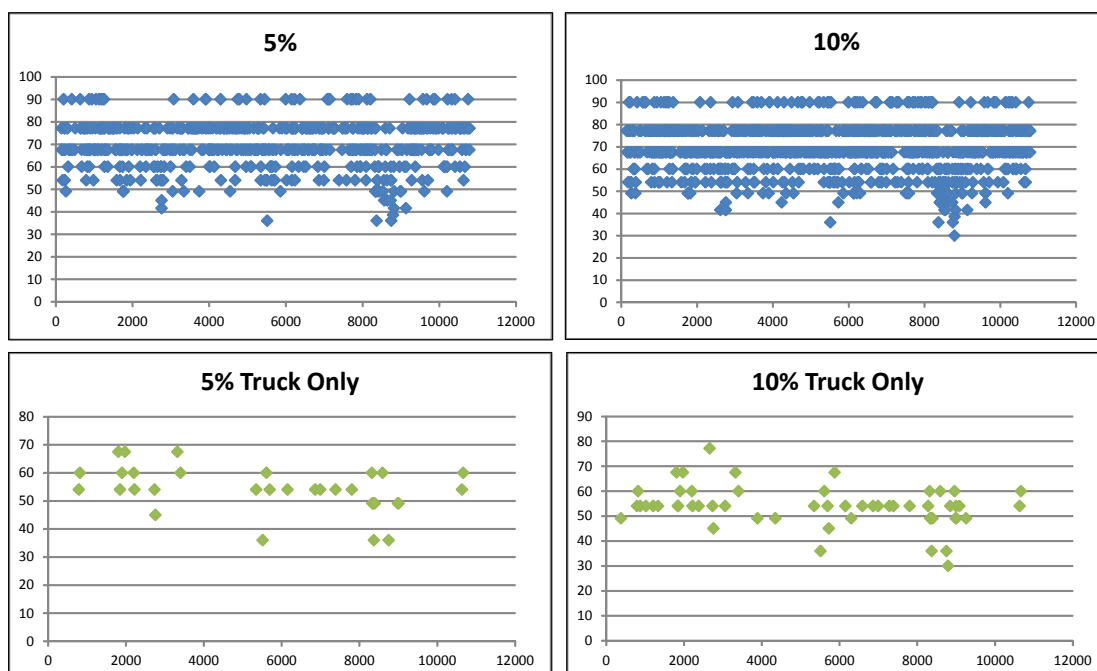
The speeds of the detected vehicles tend to be aggregated. The higher two concentration levels are at 66 mph and 76 mph, and the lower two are at 48 mph and 53 mph. Although Bluetooth does not distinguish vehicle classes, the general scan of raw data illustrates that speeds of two different vehicle classes oriented to aggregate at two ranges (the higher range for cars and lower range for freight vehicles). Truck only speed raw data graphs help to verify the truck aggregation range deduced from the overall data. With the detection rate rises from 5% to 10%, the aggregation trend becomes more obvious and the out-of range points make smaller constitution.

The two aggregated levels for each class may be caused by speed difference between overtaking lane and normal carriageway. The reason of aggregation is that the distance between one and the adjacent reader is short (less than 1200 ft), the vehicles

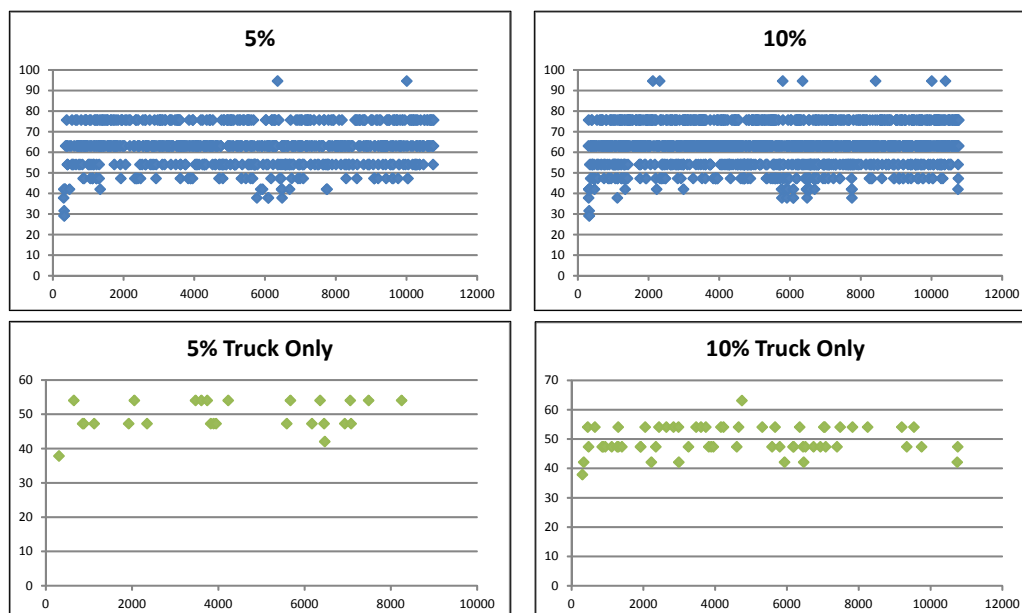
are oriented to form platoons during travelling. Also, the readers have capability to read hundreds of vehicles' identifiers at one time, so it is possible that a group of vehicles are detected at the same time at paired detection stations and obtain same travel distance and travel time.

Usually, the speed aggregation level can reflect the general traffic condition at the study site. For the all-vehicle mean speed less than 55 mph, the corridor faces insufficiency of carriage capability.

The same results come with Stadium Interchange and 27<sup>th</sup> Street Interchange, and the data points plots are listed below.



**Figure 5–6 Raw speed data of overall and freight traffic at Stadium Interchange**



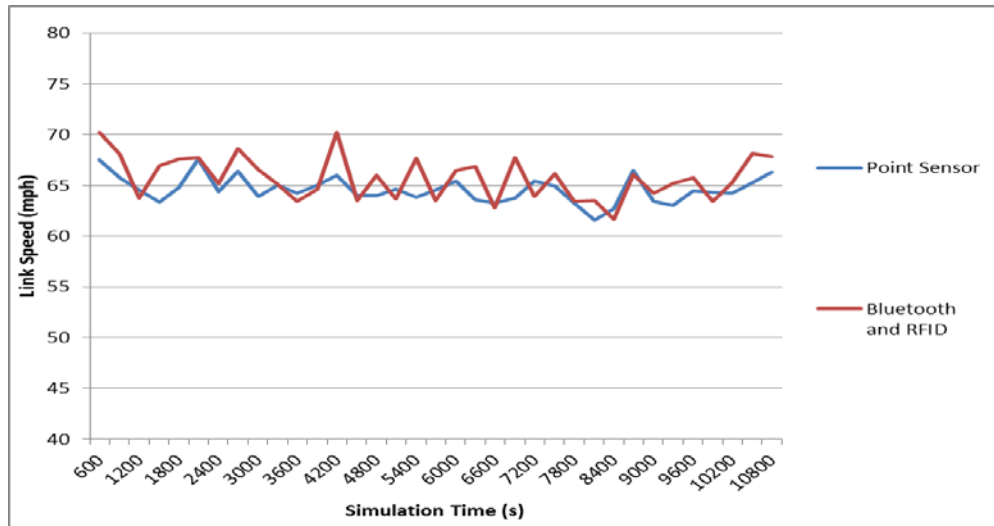
**Figure 5-7 Raw Speed Data of Overall and Freight Traffic at 28th Street Interchange**

Because the truck percentage of Stadium and 28<sup>th</sup> Street interchanges are much lower than that of 84<sup>th</sup> Street Interchange, the 5% truck only data figures cannot clearly represent the trends of aggregate. However, with higher sample rate, the trends become more obvious. That is why higher sample rate is more reliable.

## 5.2.2 Link Speed Detection Results

The following diagrams and tables show the Bluetooth and RFID combined system detection results implemented in VISSIM. The results are compared with the traffic count data from VISSIM simulated loop detectors. The detection results for one typical scenario (Sample Rate: 30%) on each study sites (the study sections are defined above) and each time interval are plot and compared as follows:

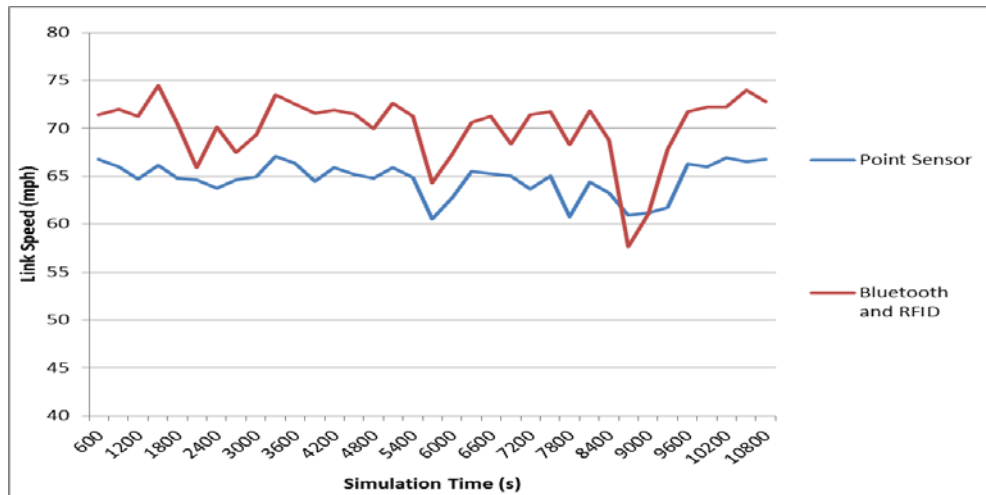
(1) I-94 at 84<sup>th</sup> Street section



**Figure 5–8 Speed Detection Result for I-94 at 84<sup>th</sup> Street Section**

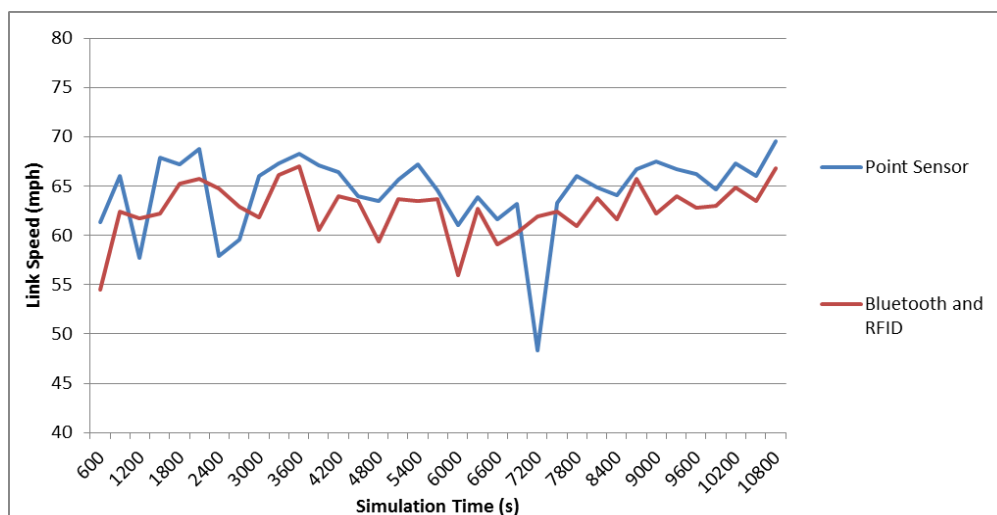
The speed results of Bluetooth and RFID based system at the first study site is very close to that of the point sensor collected results. The two detection methods match well under this condition. The reason may be that the study site is at the beginning of the built corridor. The traffic flow was just inlet into corridor, so the speed is generally not interrupted, so the short-range link speed is very close to the point speed.

(2) I-94 at Stadium Interchange Section



**Figure 5–9 Speed Detection Result for I-94 at Stadium Interchange Section**

(3) I-94 at 28<sup>th</sup> Street Section



**Figure 5–10 Speed Detection Result for I-94 at 28<sup>th</sup> Street Section**

The results of other two target sections are not as accurate as that of the first study section. The Bluetooth and RFID combined detection system yields more optimistic results at Stadium interchange section and less optimistic ones at 28<sup>th</sup> Street section. The reason behind this may be the impact from the distance of entrances and exits to the study sections. However, based on the results we get, with the same fluctuation trend, we can conclude that the Bluetooth and RFID combined detection system is a

valid one for traffic monitoring.

### 5.2.3 Detection Methods Contrast: Hypothesis Testing

In our study, we obtain the average speeds over a short range at different detection stations. The freeway is instrumented with pair loop detectors, which we developed in our simulation environment with data collection points. For experience analysis, the point detectors measure the instantaneous velocities of vehicles when passing the detection point while the Bluetooth readers in our study measure average speed in a short range (the defined freight-significant section), the two measurement methods should produce obviously different results. However, the detection results in last section (5.2.2) present that the two detection system yields similar outcomes. In order to see whether the Bluetooth and RFID detected short-range link speed are the same with the point speed within the tolerable error range, here we make a hypothesis test to see whether the difference exists:

Null hypothesis ( $H_0$ ): the results produced by two detection methods are not different.

Alternative hypothesis ( $H_1$ ): the results produced by two detection methods are different.

Define the speed measured by point sensor in  $i^{\text{th}}$  time period as  $x_i$ , and the result produced by Bluetooth reader in the same period as  $y_i$ . The difference between them as  $d_i = x_i - y_i$ .

So we can rewrite the hypothesis:  $H_0: \mu_d = 0$ ,  $H_1: \mu_d \neq 0$

We use measured speed data at 84<sup>th</sup> St. with three levels of detection rate, the confidence level is 95%, and got the statistical result in TABLE 3.

With the null hypothesis  $H_0$  rejected in all three cases, we conclude that the two detection techniques do not necessarily yield the same results. Even within short distance, point speeds are still distinguished from average speeds. Thus, different detection technology is used for different purpose. The selection of proper detection technology on research-objective basis is a critical concern.

**Table 5-7 Statistics for hypothesis testing.**

Detection Rate	p-value	$\bar{d}$	$S_d$	t-value	$H_0$
5%	1.6909	0.894	2.298	2.362	Rejected
10%	1.6909	1.153	1.703	4.003	Rejected
15%	1.6909	1.025	1.295	4.685	Rejected

#### 5.2.4 Bluetooth Truck Rate Detection

One of the major concerns of Bluetooth detection in our simulation study is the vehicle composition percentage. Although in the general evaluation study, we assume that the detection rates of all-vehicle traffic and freight-specific traffic are the same. The assumption means that the truck percentage in the whole traffic has the same ratio with the detected truck in the whole detected traffic.

Here, we want to dig a little about the impact of detection rate difference. The higher the detected truck percentage is, the lower the overall average speed for general traffic

is. The detected truck percentage has direct impact on speed measurement accuracy. In the practice, we retrieve the duplicate records to determine the detection of heavy vehicle by Bluetooth reader. The table below shows the truck detection rates under different sample rate conditions.

**Table 5-8 Truck rate detection with different sample rate.**

	Detection Rate	Actual Site Rate <sup>1</sup>	Origin Reader No.	Destination Reader No.	From Rate <sup>2</sup>	To Rate <sup>3</sup>
84 <sup>th</sup> St.	5%	8.20%	1	2	10.49%	10.41%
	10%	8.20%	1	2	10.08%	9.94%
	15%	8.20%	1	2	10.03%	9.58%
Stadium Int.	5%	5.10%	3	4	7.46%	6.45%
	10%	5.10%	3	4	5.94%	5.86%
	15%	5.10%	3	4	5.75%	5.62%
28 <sup>th</sup> St.	5%	4.30%	5	6	5.42%	4.90%
	10%	4.30%	5	6	4.88%	4.61%
	15%	4.30%	5	6	4.81%	4.73%

Note:

1. Actual site rate is the truck rate detected by point-sensor (i.e. loop detector).
2. From rate indicates the truck rate detected by origin reader.
3. To rate indicates the truck rate detected by destination reader.

With the rise of sample size, we see the trend that the detected truck rate getting closer to the actual site rate, which, as the discipline goes, tends to give out more accurate overall traffic speed measure. The higher the truck composition is, the lower the overall traffic speed is.

### **5.2.5 Speed Measurement Errors of Different Detection Rates**

Although Tarnoff's work indicated the typical sample rate of Bluetooth detection is 5% to 7% (19), the current popularity of Bluetooth headset makes the result increase to a

new higher level. One of the drawbacks of Bluetooth technology detection is that it could not get exclusive freight data, however, with RFID detection, the general truck percentage in Bluetooth detection can be extracted. In the sample rate analysis part, an important assumption is that the Bluetooth sample rate is the same for cars and trucks to make sure that in detected traffic, truck rate in general traffic is stable. For RFID detection part, certain proportions of trucks have their information recorded and their performance parameters calculated, so we assume that the sample rate has little impact on the RFID-collected data.

For evaluating the speed measurement errors of different detection rates, the speed of the whole population should be available. This is not possible in real situation. However, the beauty of simulation study is that it gives a comprehensive presentation of traffic system. We can access its statistical analysis directly from the result output. Through link evaluation, we can get the population average speed, thus we find a way to evaluation the impacts of detection rate on measurement error.

The following diagram shows the fluctuation of absolute relative error (ARE) of different sample rates at the three study sections.



Rate									
MAE	2.34	1.65	1.35	6.1	5.55	5.83	3.47	3.38	3.25
MARE	3.26 %	2.56 %	2.10 %	9.46 %	8.57 %	9.01 %	5.60 %	5.44 %	5.19 %

The fluctuation of the errors has lower level of difference with three sample rates. However, we can see the benefits in the increase of sample rate since the MAE and MARE are lower. Because the two different detection systems certainly yield different speed estimation results and the errors are in tolerable range, we can get that even with relatively low sample rate, the estimated speed can be valid data for further usage.

### 5.2.6 Sample Size and Confidence Level

Sample rate in our case has the same concept and representative meaning as detection rate. In our effort of speed measurement, we need to make sure the sample size (which is the vehicle detected in the whole traffic flow) is large enough to reach certain confidence level. The purpose is to evaluate the reliability of measurement based on detected vehicles for representing the condition of the general traffic.

In our analysis, we set the confidence level 95% (i.e.  $\alpha = 0.050$ ), the statistics and key parameters for calculation is shown in TABLE3 below.

**Table 5-10 Statistics of different detection rates.**

Measure Site	Sample rate	Population Average Speed ( $\mu$ )	Sample Size	Sample Average Speed ( $\bar{X}$ )	Sample Standard Deviation ( $S_d$ )	Confidence Interval
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84 <sup>th</sup> St.	5%	64.59	236	65.49	2.67	(65.15, 65.83)
	10%		472	64.75	2.16	(64.55, 64.94)
	15%		708	64.61	1.76	(64.49, 64.75)
Stadium Int.	5%	70.32	236	70.12	4.62	(69.53, 70.53)
	10%		472	70.03	3.51	(69.72, 70.35)
	15%		708	70.26	3.77	(69.98, 70.54)
28 <sup>th</sup> St.	5%	62.50	236	62.63	3.09	(62.23, 63.02)
	10%		472	62.70	2.68	(62.46, 67.06)
	15%		709	62.77	1.36	(62.27, 62.87)

With the population mean values fit into confidence level in all conditions, we get that our speed measurement samples can surely represent the overall traffic speed, even with 5% detection rate, the sample size is enough in confidence level of 95%, which verify that the low sample rate, the detection result can be used to reflect the traffic flow speed and for other planning or analysis purposes.

## 6 CONCLUSION AND FUTURE WORK

In this thesis, a Bluetooth and RFID combined detection system is proposed to monitor traffic condition at freight-significant freeway sections. With Bluetooth readers collecting all-vehicle traffic data and RFID readers recording exclusive freight data, the innovative system provides a more comprehensive data source for transportation planners and engineers.

Within the simulation environment, which is implemented to present the real traffic system, the Bluetooth and RFID combined system provides effective and reliable speed measurements for pre-defined freight-significant freeway segments. The results of new proposed system are compared with the traffic count results with are from simulation-implemented point sensors (e.g. loop detectors).The Bluetooth detection rate is an important issue in system evaluation and is set as the evaluation scenarios for detection system evaluation. With the increase of sample rate, the actual truck percentage can be better represented by the detected traffic, and the speed relative error can be reduced. However, small sample size condition exists at times. Fortunately, the speed measurement results show that with the lower detection rate bond, the detected measurement values can well project the condition of the whole traffic and thus monitoring traffic progressing. The system we proposed measures the average speeds within a short range, which is distinguished from traditional point sensors that measure point and instantaneous values. Although within a short range, different detection systems give out distinct results for purpose-specified research. For

studying the freight-significant sections, the Bluetooth and RFID bond system has a promising future.

Future work is foreseen in three aspects:

1. For the balance between system working efficiency and economic efficiency, the optimal detector locations should be found in long-distance corridor study. The purpose of finding optimal reader locations is to use limited numbers of readers to fulfill highest detection rate. The implementation of the optimization process using certain algorithm (e.g. Particle Swarm Optimization, PSO) can be developed using VISSIM extended COM interface.
2. For the field system implementation, final system is expected to be a floating one that can be transported between critical sites. This complementary characteristic takes both recurrent and non-recurrent traffic events into consideration so that freight performance monitoring can be done at any site that suffers from congestions. The system can do seasonally, even weekly change to fulfill monitoring needs with further accommodation of weather, incident, work zone, etc.
3. For the accuracy of speed estimation, the more accurate travel distance of each detected vehicle should be recorded. With the combination of the proposed system with GPS, the vehicle location information can be recorded together with time step data. Thus the speed can be measured in higher quality.

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