12-1-2013

Performance Measure for Transportation Network: A Study in Travel Time Dynamics

Anuj Nayyar

University of Nevada, Las Vegas, anuj818@gmail.com

Follow this and additional works at: https://digitalscholarship.unlv.edu/thesesdissertations
Part of the Electrical and Computer Engineering Commons, and the Transportation Commons

Repository Citation
https://digitalscholarship.unlv.edu/thesesdissertations/2014

This Thesis is brought to you for free and open access by Digital Scholarship@UNLV. It has been accepted for inclusion in UNLV Theses, Dissertations, Professional Papers, and Capstones by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.
PERFORMANCE MEASURES FOR TRANSPORTATION NETWORK: A
STUDY IN TRAVEL TIME DYNAMICS

by

Anuj Nayyar

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science - Electrical Engineering

Department of Electrical and Computer Engineering
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
December 2013
We recommend the thesis prepared under our supervision by

Anuj Nayyar

entitled

Performance Measures for Transportation Network: A Study in Travel Time Dynamics

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering
Department of Electrical and Computer Engineering

Pushkin Kachroo, Ph.D., Committee Chair
Rama Venkat, Ph.D., Committee Member
Emma Regentova, Ph.D., Committee Member
Haroon Stephens, Ph.D., Graduate College Representative
Kathryn Hausbeck Korgan, Ph.D., Interim Dean of the Graduate College

December 2013
ABSTRACT

PERFORMANCE MEASURES FOR TRANSPORTATION NETWORK: A STUDY IN TRAVEL TIME DYNAMICS

by

Anuj Nayyar

(Pushkin Kachroo), Examination Committee Chair
Professor of Electrical Engineering
University of Nevada, Las Vegas

Arterial Performance Measurement and Monitoring is one of the leading goals of any transportation agency. The complexity of the differences between performance measures is highlighted and the various data collection methodologies are highlighted. A major performance measure that impacts end users and traffic planners is travel time. This study presents defining a mathematical system for modeling travel time. The modeling in real-time is presented and methods are proposed to evaluate it using vehicle trajectories. Also comparative results are presented between the actual sensor data sets and simulated data to study the effectiveness of the system developed.
ACKNOWLEDGEMENTS

I would like to express my sincere thanks and gratitude to my advisor Dr. Pushkin Kachroo for inspiring, motivating and guiding me throughout my research. I am also grateful to my committee members Dr. Haroon Stephen, Dr. Rama Venkat and Dr. Emma Regentova for their insightful remarks.

I would also take this opportunity to show my appreciation towards the love of my parents Mr. Naresh K. Nayyar, Mrs. Kiran Nayyar and my sister Shruti. I am also indebted by the blessings showed by my grandparents.

A special gratitude is extended to the help in research provided by my colleagues Victor Molano and Sergio Contreras. I am also grateful to the support and motivation provided by my friends Pratik Verma, Sourabh Srim, Atul Sancheti, Sergio Contreras, Shaurya Agarwal and Romesh Khaddar during my work.

This material is based upon work supported by the National Science Foundation (NSF) under Grant No. 0928744. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.
# TABLE OF CONTENTS

**ABSTRACT** iii

**ACKNOWLEDGEMENTS** iv

**LIST OF TABLES** vii

**LIST OF FIGURES** viii

<table>
<thead>
<tr>
<th>Chapter</th>
<th>INTRODUCTION</th>
<th>Performance Measures</th>
<th>Literature Surveys</th>
<th>Data Collection Methodologies</th>
<th>Architecture for Data Processing</th>
<th>Smartphone Data Collection App</th>
<th>Travel Time Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.2.1 Arterials vs Freeways</td>
<td>3.2 Minnesota</td>
<td>4.2 Bluetooth Sensor Data</td>
<td>5.2 Designing Mathematical Models</td>
<td></td>
<td>7.1.1 Conservation Laws</td>
</tr>
<tr>
<td>2</td>
<td>2.1 Performance Measures</td>
<td></td>
<td>3.3 Denver</td>
<td>4.3 Automatic Vehicle Locator (AVL) Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.4 AirSage</td>
<td></td>
<td>3.5 SENSYS Networks</td>
<td>4.4 Smartphone Application Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.6 Texas Performance Measurement System</td>
<td></td>
<td>3.7 Sensys Berkeley</td>
<td>4.5 Crash Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.7 Sensys Berkeley</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.1</td>
<td>Comparative Results of the Observed Travel Time and the Calculated Travel Time (in minutes) over repeated travel runs</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.2</td>
<td>Percentage Change in the observed travel times over the calculated travel times</td>
<td>61</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.3</td>
<td>The comparison results for computed travel time for different time averaged data</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>A block diagram depicting the various performance measures related to reliability and performance</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>A Typical Road Network</td>
<td>9</td>
</tr>
<tr>
<td>4.1</td>
<td>BlueTOAD(Bluetooth) Data Processing</td>
<td>25</td>
</tr>
<tr>
<td>4.2</td>
<td>iPhone Application for data collection</td>
<td>27</td>
</tr>
<tr>
<td>4.3</td>
<td>Sample of crash data demonstrating the missing location coordinates</td>
<td>29</td>
</tr>
<tr>
<td>6.1</td>
<td>iPhone Application for data collection</td>
<td>34</td>
</tr>
<tr>
<td>7.1</td>
<td>Infinitesimal Section</td>
<td>43</td>
</tr>
<tr>
<td>7.2</td>
<td>Travel Time Function Derivation for Discrete Space Systems</td>
<td>46</td>
</tr>
<tr>
<td>8.1</td>
<td>A sample tabular result of a query made on the developed interface</td>
<td>52</td>
</tr>
<tr>
<td>8.2</td>
<td>A sample map result of a query made on the developed interface</td>
<td>53</td>
</tr>
<tr>
<td>8.3</td>
<td>Traffic Density Profile Contour plot</td>
<td>54</td>
</tr>
<tr>
<td>8.4</td>
<td>Vehicle trajectories with Density Profile Contour plot</td>
<td>55</td>
</tr>
<tr>
<td>8.5</td>
<td>The locations of Freeway Sensors installed in Las Vegas Area by NVFAST</td>
<td>56</td>
</tr>
<tr>
<td>8.6</td>
<td>A screenshot of the app running on the iPhone showing the parameters being collected</td>
<td>59</td>
</tr>
<tr>
<td>8.7</td>
<td>Bar graph comparing the observed and calculated travel times (in minutes)</td>
<td>60</td>
</tr>
<tr>
<td>8.8</td>
<td>Percentage Change in the observed travel times over the calculated travel times</td>
<td>61</td>
</tr>
<tr>
<td>8.9</td>
<td>A comparative set of obtained results showing the travel time obtained (in seconds) for various $x_0$, $t_0$ and $k$</td>
<td>66</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Motivation and Research Goal

In the U.S. nearly 40% of all miles traveled by vehicles are on arterial roads. Thus, in many urban settings, arterials provide considerable mobility for commuters. Observing and controlling arterials is useful to both the public and transportation engineers. Arterials, however, are more difficult to study than freeways for several reasons. Vehicle flows are complicated by traffic signals, which cause queues and dissipation. Also, there are many users with different starting and destination points. Consequently, an arterial performance measurement system is needed to inform travelers of the best routes, help traffic engineers manage the transportation system, and inform the public of traffic conditions and reliability of routes on arterials.

Arterial Performance Measurement and Monitoring is one of the leading goals of any transportation agency. The current work done by focuses on doing a research on the existing state of the arterial monitoring, and the studies that have been done in other regions. The current report documents the studies that were done, some of the methodologies that were developed for arterial management and the solutions implemented.

Most of the study currently done by the transportation departments is restricted to
the freeways. The performance of the arterial networks, being very complicated is not usually handled at a large scale. The study being conducted deals with capturing actual traffic conditions on major and minor arterials in the Las Vegas region; and then evaluate and present the performance measures. It will also analyze the currently used data collection schemes and come up with suggestions about the possible changes that need to be made to improve the data collection process.

The current work deals with more than just collection of data and calculating the performance measures. It is more about providing optimum solutions to the targeted user groups. It also deals with identifying the areas or regions that may be affecting the performance on the arterials and suggest solutions for the same. The complexity of providing solutions to user groups can be largely attributed to the complicated traffic parameters and the users with numerous different origins and destinations.

1.2 Introduction

1.2.1 Arterials vs Freeways

There are some notable ways in which arterial performance monitoring differs from freeway monitoring\[1\]. First, while urban freeways such as those in the Seattle area are often equipped with a dense network of sensors, arterial sensor density can vary significantly. Arterials can also have varying types of instrumentation, ranging from sophisticated sensors and signal systems to very basic sensors or no sensors at all. While well instrumented arterials can collect a broad array of data, making them easier to monitor, arterial performance on the significant number of lane-miles of sur-
face streets with less extensive or less sophisticated sensors can be more difficult to evaluate. Because one of the goals of this effort was to develop a versatile method, the research described in this paper focuses on the feasibility of monitoring performance in common arterial scenarios that use sensors with basic data collection capabilities, e.g., inductive loops (and alternative sensors which provide similar data), while imposing minimal requirements for sensor density and placement.

Second, signalized intersections introduce inherent variability in arterial road performance, as vehicles slow and stop for red lights, then resume travel when the light changes. Unlike freeway flows that commonly exhibit fluid state changes, at least under recurring congestion conditions, arterial flow, by its very nature, displays frequent uneven fluctuations in performance over time, even during uncongested conditions. Even under those conditions, the methodology described in this paper proposes that one can still make use of detectors such as those commonly found on freeway (and arterial) systems, based on the reasonable assumption that as congestion varies on a roadway, corresponding sensor values (e.g., the occupancy percentage) will generally vary in a consistent way in response. This is not a new idea; the same basic concept is currently used for freeway applications by methods such as TRACFLOW, and previous research has explored the use of sensor data for a variety of arterial performance analysis applications using various levels of existing instrumentation. For example, Luyanda, et. al., and Gettman, et. al., describe a research effort to employ detector data to develop adaptive signal control algorithms that can be used for arterial signal timing analyses and timing adjustments (2,3). Of particular note is the focus of that
research on the development of methods that can be applied to existing closed-loop signal control systems in a cost-effective manner, using typical detector configurations and common detector data types. That objective of developing a versatile method that is designed to adapt to existing equipment in commonplace field conditions, using commonly available data types, is one that is shared with the research described in this paper.

Third, the interrupted nature of arterial flow, caused by such factors as signal operations and associated queue buildup and dissipation, means that the utility of detector data will be affected by the detectors position relative to the sources of flow interruption (e.g., stop bar detector vs. advance detector). For example, the relationship between detector occupancy percentage and arterial roadway performance is affected by the location of vehicle queues that form while waiting for a red light, relative to the location of that detector. For stop bar detectors, a single vehicle stopped at the associated red light creates an occupancy value of 100 percent until the light changes to green and the vehicle departs. If the detector is placed 100 feet back from the stop bar, and again only that one vehicle is present, detector occupancy is zero for the same roadway performance scenario. Thus, depending on detector location, the same roadway performance can generate completely different occupancy values. The use of alternate or supplementary detector locations has been demonstrated to be useful in addressing this ambiguity.

A major arterial performance measure that is studied in various studies is travel time. It is the one of major concern to the user of the road segments as less traveling
time is one of the most important features of planning a journey. Most of the work
done on travel time is estimation based on the sensor data. This study broadly
focuses on the development of a travel time estimation mathematical model. The
model discusses the formulation of the travel time partial differential equation and
the use of vehicle tracking models for indirect measurement of travel time in real time.
Moreover, the results are compared with results obtained from software simulations
and actual traffic sensor data and the results are analyzed.
CHAPTER 2

PERFORMANCE MEASURES

2.1 Performance Measures

Performance measure is an estimate of a certain parameter that can be used to judge the effectiveness of a certain road segment. The parameter can range from reliability to shortest travel time, minimum delays, shortest distance and so on. The performance measures can vary from the perspective of the user groups or the factors being given higher priority. The performance measures can be broadly classified into following categories

- Performance and Reliability
- Safety
- Environmental Factors

The measures relating to performance and reliability are the ones that describe the factors relating to how good an arterial is for commuting. As shown in the Figure 2.1 various performance measures such as travel time, speed, delays, volume, occupancy etc. are counted as performance measures describing performance and reliability.

The performance measures relating to safety can be listed as - number of accidents, fatalities, etc. Some of the performance measures related to environment are emission
Figure 2.1: A block diagram depicting the various performance measures related to reliability and performance rates, air toxicity levels and so on.

Moreover the classification of the performance measures can be done as direct and indirect performance measures. Direct measures are the ones, that are directly observed from a sensor or calculated using sensor fusion from various sensors that are used to observe the same parameter (as discussed in subsequent subsections). Some of the direct performance measures can be listed as -

- Travel Time
- Travel Delay
- Speed
- Traffic Volume
On the other hand, the indirect performance measures are the ones, which are calculated using the other parameters, and are not a direct consequence of a measured parameter. Some of the indirect performance measures can be listed as -

- Level of Service (LOS)
- Congestion Levels
- Travel Pattern Information
- Real Time Traffic Information

Another way in which the performance measures can be classified, is on the basis of the user groups they are aimed at. The user group may belong to any of the following categories.

- Drivers and users
- System engineers
- Traffic planners
- Governing bodies

As discussed earlier, the complexity of the performance measures for the arterials can be attributed to the complexity of the arterials themselves. The road network is a complex entity that is composed of various entities such as -

- Nodes
A typical small road network can be illustrated as shown in Figure 2.2. As seen in the figure, the road network has multiple possibilities of routing from one point to the other. This makes it extremely difficult for the performance measures to be evaluated between points on such a complex network.
CHAPTER 3

LITERATURE SURVEYS

Before undertaking the work, an extensive study of similar work done by various transportation departments and universities was conducted. This chapter covers the literature survey that covers this work. The points of interest noted from the studies were technologies used, possible scope and benefits of the study.

3.1 Real-Time Arterial Traffic Signal Performance Measures - Purdue Libraries

This study conducted by Purdue University [4] focuses on the collection of performance measures at a traffic signal. This work focuses primarily on measures that can be extracted and logged in real time by an automatic traffic signal controller using information about detector actuations and phase information. This study has two objectives:

- To serve as part of the general effort toward improving data collection at traffic signals by investigating methods that could be applied feasibly within the existing technology
- To investigate a body of performance measures that could be calculated on a
cycle-by-cycle basis using events recorded in real time, and interpreted by a traffic engineer to evaluate the performance of the signal.

**Goals and Guidelines of Study:**

The major objective of the study was signal coordination and to identify the level of service at intersections. The data was collected for three weeks to obtain a trend in performance measures at the signalized intersections. The measured performance measures for state of intersection, performance of intersection and vehicle progression were compared pair wise for further study. This process helped in generalizing the trends, and build pair wise and aggregate statistical comparison.

**Data Collection Technologies Used:**

The traffic data that was collected was dependent upon what data was available at the test intersection. The types of data that were available were phase information of the traffic signals and vehicle arrivals. For getting the data for vehicle arrivals, pulse mode detection was used. The data was logged using the Autoscope Solo Pro cameras, each of which was capable of recording up to eight digital inputs. The vehicle phase information was captured by recording information about the red indication. For vehicle arrivals, only the detector on time was recorded.

**Performance Measures Calculated:**

- **State of Intersection:** Cycle length, Green duration, volume
- **Performance of Intersection:** Service flow rate, Estimated and observed capacity, Volume to Capacity (v/c) ratio
• Signal performance in coordination with vehicle progression: Percentage of arrivals on green, Arrival type

3.2 Minnesota

In this project [5], a system for high-resolution traffic signal data collection is successfully built. The system, named as SMART-SIGNAL (Systematic Monitoring of Arterial Road Traffic and Signals), is an arterial data collection and performance measurement system, which simultaneously collects "event-based" high-resolution traffic data from multiple intersections and generates arterial performance measures in real time. In the SMART-SIGNAL system, a complete history of traffic signal control, including all signal events such as vehicle actuations on detectors and signal phase changes, is archived and stored.

**Goals and Guidelines of the Study:**

The need for addressing the deficiency of traffic signal data collection, and performance monitoring inspires this project. The goal of this project is to develop a real-time arterial performance measurement system, which can automatically collect and archive high-resolution traffic signal data, and build a rich list of performance measures. The system is designed for the closed-loop signal control system, which represents 90% of the traffic signal systems in the nation. The objectives of this project are then two-fold:

• To develop a data collection system where high-resolution traffic signal data can be collected, archived, and preprocessed
To develop a set of methodologies that can use the collected data to calculate traffic signal performance measures, including queue length, delay, level of service (LOS) and turning movement proportion (TMP) for individual intersections and travel time and number of stops for an arterial corridor.

**Data Collection Technologies Used:**

The proposed SMART-SIGNAL (Systematic Monitoring of Arterial Road Traffic Signals) system is a cohesive event based data collection, storage, and analysis system. The system can be scaled to an isolated intersection, an arterial, or a network of signalized intersections. The SMART-SIGNAL System has three major components; including event-based data collection system, performance measure calculation system and user interface (Internet Access).

**Performance Measures Calculated:**

- For Intersection: Occupancy, volume, green time, red time, yellow time, cycle length, queue length, turning movement proportion (TMP), queue size, intersection delay, level of service (LOS)
- For Arterial: Travel time, number of stops, average speed, delay, level of service (LOS)

### 3.3 Denver

The objective of this project [6] was to develop an understanding of what performance-related information local traffic system operators need in order to assist in the man-
agement of their traffic systems, identify the means and methods to accurately collect
the appropriate data, and to develop a plan on how the data would be disseminated
to both the traffic system operators and to the public.

**Goals and Guidelines of the Study:**

- Identify arterial performance measures that would be of the most use to traffic
  signal operators; ones that can also be presented to the public

- Develop a concept of operations for the pilot implementation that can be ex-
  panded to other arterial streets throughout the DRCOG region

- Determine the best-suited approaches for collecting the data that the operating
  agencies find most useful

- Develop a pilot program to test data gathering techniques and their effectiveness

**Objectives of the Study:**

- Provide traffic signal operators with the tools to better monitor their signal sys-
  tems and the data necessary to make informed and timely operational decisions

- Provide planning information to other stakeholders such as City and regional
  transportation planners, transportation boards or City Councils

- Disseminate useful traveler information to the public that can be derived from
  the performance measures data

**Data Collection Technologies Used:**
Based on queue length:

1. Hybrid Input-Output Technique

2. Non-Intrusive Detection Technique

Based on Travel Time:

1. AVI Transponders (Tolltag) Technique

2. RTD AVL Technique

3. Traffic Flow Characteristics Technique

Performance Measures Calculated:

- Queue length
- Travel time
- Mid-block traffic volume by lane

3.4 AirSage

This memorandum provides an overview of the analysis performed on travel time data collected on Interstate 10 (I-10), US 27, US 319, and Capital Circle in Tallahassee from three sources between May 3, 2010, and May 6, 2010. The goal of the analysis is to validate the travel time system data provided by AirSage for travel time reporting purposes.
Goals and Guidelines of the Study:

FDOT wanted to look at two innovative traffic data collection methods - data collection via GPS probes and cell phone probes. They tried the GPS probes in 2008 and Cell phone probes (AirSage) in 2009 for arterial and highway data collection. The goal was to compare the AirSage data with available methods for reliability.

Data Collection Technologies Used:

- AirSage Data: Records the re-identification of a cell-phone at different coordinates along a roadway

- License Plate Reader System: Records the timestamp, average speed, total volume, and travel time for each LPR segment, reported as average of every 15 min.

Performance Measures Calculated:

- Absolute Average Speed error

- Average Speed bias

- Absolute Average Travel Time Error

- Travel Time bias

- Percentage of time at specific mode

- Percentage of time that data is changing
3.5  SENSYS Networks

This presentation discusses advancing the traffic management systems such as adaptive signal control, traveler information, planning and asset management, and optimized signal timing based on Arterial Performance Measures resulting from accurate, reliable, and cost effective data.

**Goals and Guidelines of the Study:**

- Advance Traffic Management Systems
  - Adaptive signal control
  - Traveler information
  - Planning and asset management
  - Optimized signal timing

- Provide feedback mechanism for optimizing transportation Networks
  - Reduction of traffic congestion - reduction of emissions
  - Enhanced safety through smoother traffic
  - Improved emergency vehicle routing and response
  - Lower traveler stress from unpredictable commutes
  - Better budget utilization based on valid project prioritization

**Data Collection Technologies Used:**

Measurement and reporting real-time travel times. The process involved in the performance measures calculation are -
• It uses the unique vehicle magnetic signatures

• Re-identifies vehicles to provide accurate travel times and vehicle density

• It is easily scalable from one intersection to an entire city

• Calculates and delivers a complete distribution of vehicle travel times along an artery

• Provides volume and occupancy data

A one re-identification array is equivalent five sensors across a lane. Arrays are placed 40 feet downstream of the intersection and the maximum distance between arrays is 1.5 mile.

Performance Measures Calculated:

• Complete distributions of travel time

• 80th percentile travel time

• Median travel time

• Level of service

• Vehicles in segment

• Volume and occupancy

• Speed
3.6 Texas Performance Measurement System

The overall goal of this project [9] was to examine current and innovative methods of collecting measures that Texas Department of Transportation (TxDOT) can use to assess traffic operations at intersections and the performance of their traffic signals. The objectives of the project were as follows:

- Through interviews, identify how TxDOT engineers and traffic signal technicians assess performance of traffic operations and signals in the field.
- Assess the capabilities of the existing detection and traffic signal controller technology to provide these measures.
- If necessary, propose new and innovative measures for evaluating traffic operations and signals. The objectives of the second year of this project, the primary focus of this report, were as follows:
- Develop a system for collecting signal timing and traffic operations performance measures directly from the inputs of the traffic signal controller and the vehicle detection system inside the traffic signal cabinet.
- Install the system at several field locations as a proof-of-concept of the system.
- Collect information to assess the effectiveness of the system to produce effective and meaningful performance measures.

Goals and Guidelines of the Study:

Using hardware-in-the-loop simulation, assess the accuracy and effectiveness of the
built-in performance monitoring capabilities of the Eagle EPAC 300 Actuated Traffic Signal Controller, given TxDOT’s traditional surveillance and control design at a typical intersection. To provide guidelines and recommendations for setting up the controller and designing the detection system for utilizing this built-in feature reports specifically on the green interval utilization on a cycle-by-cycle basis.

**Data Collection Technologies Used:**

Hardware in-the-loop simulation to assess the accuracy and effectiveness of the Eagle® MOE reporting features. With hardware-in-the-loop, a microscopic traffic simulation model is tied to a real traffic signal controller through a controller interface device. The traffic simulation model generates vehicle arrivals at the intersection provide detector inputs to controller through controller interface devices (CID). The controller has a capacity to store up to 60 Cycle Reports.

**Performance Measures Calculated:**

- Volume
- Stops
- Delays
- Utilization

### 3.7 Sensys Berkeley

The Arterial Travel Time System (ATTS) is described. It accurately estimates travel time distributions in real time, and derives various performance measures,
including delay, LOS, emissions. ATTS uses measurements from wireless magnetic sensors. Results from ATTS deployments in Chula Vista, CA, New York City are discussed. With signal phase information, ATTS can help improve signal settings, and identify vehicles running a red light or speeding.

**Goals and Guidelines of the Study:**

- Design a system to measure traffic condition in cities.
- Provide data for performance measures
- Comprehensive performance measurement system

**Data Collection Technologies Used:**

- ATTS (Ariel Travel Time System) using Wireless Magnetic Sensors
- License Plate Recognition (LPR)
- Electronic Toll Collection Readers (ETC)
- Bluetooth
- GPS Phones

**Performance Measures Calculated:**

- The following performance measures were used while using ATTS for data collection:
  - Travel Time Distribution
• Free flow travel time

• Delay per vehicle

• Total Delay

• Queues at signals

• Fuel and emissions at intersections
CHAPTER 4

DATA COLLECTION METHODOLOGIES

The work done currently deals with collection of the data from various sources, and analyzing the data to come up with performance measures. One of the most important steps in developing an arterial performance management and monitoring system is to deploy data collection sensors to cover a broad range of parameters. The data that is used in the evaluation of performance measures is either historical data or the real-time data collected using the sensors. The sensors used can be either automatic or manual. The manual sensors involve the use of sensors at specific times, when the sensors are activated; which lead to sampled and limited data. On the other hand, the automatic sensors installed at particular locations are a source of continuous data collection, and provide more reliable data that can be used for real-time monitoring. On the other hand, the advantage of manual data collection is that we can collect data at various locations spread out spatially; but with the automatic data sources, the data collection is restricted to specific locations. Most of the sources that are discussed in the study are automatic data sources.

The data sources that were monitored during the study are -

- Traffic Signal System Data
• Bluetooth Sensor Data

• Automatic Vehicle Locator (AVL) Data

• Smartphone Application Data

• Crash Data

A thing to note is that more number of parameters does not guarantee more performance measures. To select the most optimum data sources, it is necessary to identify the relations between parameters and performance measures to remove redundant data sources and minimize the input cost in setting up the system.

4.1 Traffic Signal System Data

The traffic controllers installed at various intersections in the city of Las Vegas are an important source of the signal timing and usage data, which can greatly contribute in evaluation of performance measures for the arterials. The software used in the controllers (NextPhase) allows polling of data every five minutes, but the data cannot be saved.

4.2 Bluetooth Sensor Data

The bluetooth sensors that are used in the study involved the sensors that were set up by BlueTOAD in a few selected arterials. The Figure: 4.1 demonstrates the process of collection and processing of the bluetooth sensor data. The fixed bluetooth sensors on the arterials identify any bluetooth device that is present in a passing vehicle.
Once the vehicle passes the other fixed sensor, placed ahead on the road, the unique ID assigned to the device that passed the first sensor is matched and data is recorded.

If no match is found in a particular time interval, the data is discarded. Out of the matched data, the parameters like the travel time and speed are calculated, as the distance between the sensors is fixed.

### 4.3 Automatic Vehicle Locator (AVL) Data

The Automatic Vehicle Locator (AVL) data is the GPS data that is collected from the transit vehicles which ply on various routes in the Las Vegas region, which is collected by the Regional Transportation Commission (RTC), Las Vegas. The two specific routes that were targeted in the current study are the 202 and 110. Only a sample of the data (for a few days) was available and used in the current study. The aim was to identify the performance measures that can be evaluated using the data.
from the AVL sources.

The major parameters that are noted from the sensors are listed below:

- Date and time stamp
- Coach and trip number
- Time of arrival at the stops
- Delay at each stop from the stipulated times

The data from the AVL sources can be used to evaluate the total delay that is experienced during the trip. This data, over a period of time can be used to identify the time of the day when the transit service is most and least efficient, which can be used by passengers.

4.4 Smartphone Application Data

The smartphone application for data collection for arterials is developed by University of Las Vegas for iPhone and Android platform to be used in vehicles as a driver drives along. The application when started, will record various at timed intervals, which can be set according to the resolution required. The standard resolution that was set for data collection was 5 seconds, which provides a very high resolution of data. An illustration of the application used in data collection is shown in Figure: 6.1. The data is sent via wireless connection to a server which is maintained by TRC, where entries are saved with an identifier to recognize the device from which the data
Figure 4.2: iPhone Application for data collection

is sent. A large number of parameters are collected and saved, some of which are listed below:

- Date and Time stamp
- GIS data(latitudes and longitudes)
- Instantaneous Speed
- Total distance traveled
- Accelerometer data(for all 3 coordinates)
- Gyroscope data(for all 3 coordinates)
Some of these parameters are used to calculate the direct performance measures, while others can be used for evaluating the indirect performances. An application is the use of the gyroscope and accelerometer data to evaluate the ride quality, which directly relates to the road surface quality.

4.5 Crash Data

The crash data and incident report data is collected by various agencies for the Las Vegas area (LVMPD, NHP, etc.), which is maintained by the Nevada Department of Transportation (NDOT). This extensive data is fed into the system database, where the parameters required for arterial safety are extracted. A system for real-time crash data reporting to the database is established for the freeways, but there is still a three month gap before the data for the arterials is fed into the system. Thus only historical data is available for the safety analysis. The major parameters that are recorded in the crash data are:

- Crash date and time
- Collision description
- Crash location coordinated - MISSING
- Crash location (primary and secondary streets)
- Number of fatalities and injuries, Crash location coordinates - MISSING
- Crash location (primary and secondary streets)
Figure 4.3: Sample of crash data demonstrating the missing location coordinates

- Number of fatalities and injuries

The crash data that is currently available has a major loophole, as the location coordinates for the accident sites is missing as demonstrated from the screenshot of a sample data ??.
CHAPTER 5

ARCHITECTURE FOR DATA PROCESSING

When calculating the performance measures from various data sources, the results are not a direct consequence of the values that are observed from the various sensors. There is a need to fuse the data from various data sources, and do some processing on them to get the best estimate from the observed values. Some of the techniques that are proposed to be used for the calculation of performance measures are discussed below in the following sections.

5.1 Sensor Fusion Approach

Sensor fusion is the combining of sensory data or data derived from sensory data from disparate sources such that the resulting information is in some sense better than would be possible when these sources were used individually. The term better in this case can mean more accurate, more complete, or more dependable. The different sensors that are used to collect the information need not be identical.

There might also be a difference in the duration or the stages at which the information is recorded by the different sensors. The techniques may be classified as low, intermediate or high depending on the stage at which the processing takes place. The
currently observed data may also be fused with the previously recorded and stored historical data to get the best possible results. The expectation from the process is that the fused data is more informative, accurate and synthetic than the original values that are fed into the system.

An example of this is estimating the speed for a certain arterial, that is monitored by various sensors. The bluetooth sensors that are fixed provide us with a timed average (15 minutes) of the speed for various vehicles that go through the segment over that time interval. On the other hand, the on-vehicle sensors, i.e. the smartphone application gives us the values of the speeds at a very high resolution (approximately 5 seconds), and also for every individual vehicle, rather than the average of various vehicles. So, to obtain the best possible approximate of the speed parameter, the values from the different sensors have to be processed to get a single value that can be used in further calculations.

The different levels of sensor fusion can be listed as -

- Data alignment
- Entity assessment
- Situation assessment
- Impact assessment
- Process refinement
• User refinement

The common techniques that are used for sensor fusion are Kalman Filters and Bayesian Networks, which are discussed below in detail.

5.2 Designing Mathematical Models

When it comes to extracting the performance measures, the first step to be followed is sensor fusion to get the best approximate value of the observed value from various sensors. As an example, if the performance measure is to be measured in terms of road performance, the individual parameters like volume, speed, travel time, etc. have to be combined to give an overall performance measure. Based on what is of maximum priority, a formula combining the different values has to be formulated. An example can be shown as:

\[ PM = \sum_{i=1}^{n} w_i x_i \]  

(5.1)

where: \( PM \) is the performance measure \( x_i \) are the different parameters used in the calculation \( w_i \) are the weights assigned to the parameters in the model \( n \) is the number of parameters used in the model

This example is just one of the simplest models which can be used to calculate the performance measures. There could be more complex models that can be developed to calculate the performance measures, depending on the requirements.
CHAPTER 6

SMARTPHONE DATA COLLECTION APP

This chapter briefly discusses the smartphone application developed at Transportation Research Center (TRC), UNLV and highlight its varied use for data collection by exploiting the various sensors equipped in the device. The applications [2] developed for the iOS and Android platforms were used for data collection for use in various studies.

The idea being having a smartphone application for data collection is for the ease with which the data can be collected. Another advantage of having smartphone based data collection is to allow data to come in through various users (large volume of data) and the cost-effectiveness as no additional sensors need to be deployed and maintained. The applications also allow the real time and Lagrangian data to be collected and studied, since the GPS data is available along the motion of the vehicle from which the data is recorded. This allows more granular data availability and allow user-specific studies to be done for traffic solutions.

The applications have the ability to continuously collect data as the vehicle moves along. The standard time resolution used for data collection is 5 seconds, but it can be adjusted based on the utility or the accuracy or redundancy of data required. On initialization of the application, the GPS sensors in the smartphone allowed the vehicle
position to be recorded for each stamp with the preset resolution. Also parameters like speed are evaluated and recorded by the app using the accelerometer sensor in the smartphone. The high resolution data recorded is sent wirelessly to a remote server located and maintained at the TRC, UNLV.

The data is saved with identifiers for each run with a unique time stamp and identifier to recognize the device from which the data is obtained. The database maintained stored a large number of parameters, some of which are listed below -

- Date and Time stamp
- GIS data(latitudes and longitudes)
• Instantaneous Speed

• Total distance traveled

• Accelerometer data(for all 3 coordinates)

• Gyroscope data(for all 3 coordinates)

These parameters allow various traffic parameters to be evaluated, which can be classified as - direct or indirect. The direct results that can be inferred from the data are speed, heading, accuracy; while the indirect ones are road surface quality, travel time or so on.

6.1 Arterial Performance Measurement System

Though highways are the primary roads traveled, arterials are important as well. Traffic condition measurement has been successful for highways, but arterials are more difficult to study than freeways for several reasons. Vehicle flows are complicated by traffic signals, which cause queues and dissipation. There are many users with different starting and destination points. Also, installing the same equipment that is used on highways on arterials is expensive.

An arterial performance measurement system is needed to inform travelers of the best routes, help traffic engineers manage the transportation system, and inform the public of traffic conditions and reliability of routes on arterials. One of the projects at the TRC UNLV was on this subject, APMS. The main goal was to use
different measurement data, such as bluetooth and bus locations, for studying APMS. A smartphone application can also be another source for study. The data must be transferred remotely as well. To be compatible with real time APMS applications, this data must be transmitted instantaneously. The data is sent to the TRC server where it is put into a database. The information that is received can then be processed.
CHAPTER 7

TRAVEL TIME CALCULATIONS

A major part of the work was to develop a theory for the calculation of travel time for vehicles. Although real-time traffic data is now widely available in most of the urban areas in the US, accurate estimation of route travel times still requires a robust and theoretically sound technique that can make efficient use of this raw traffic data obtained from sensors. This paper attempts to develop a robust methodology that is based on the fundamentals of traffic flow theory by taking advantage of the bivariate relationship between speed and density, speed and flow, and flow and density. Moreover, instead of treating traffic as a point process, it models traffic as a continuous process by employing the well-known fluid flow analogy of traffic. This spatial treatment of the traffic process using fluid flow analogy for estimating route travel times departs from most of the travel time estimation techniques proposed in the past that model traffic as a point process by using time-series or other statistical models.

The current work presents a detailed discussion of the proposed travel time estimation methodology and the theory employed to develop this methodology. The other major concern of this research is the study of the resulting system of partial differential equations. We discuss the type of the system, well posedness of the solution
and also discuss a few numerical schemes that can be used to solve the system. The corresponding results obtained are also shown.

7.1 Traffic System Modeling

The first step in the design of estimators for travel time is to model the system dynamics appropriately. There are various traffic flow models that can be used for this, the three main models commonly used for the study are -

1. Microscopic Model: This model treats every vehicle as an individual, each of which can be modeled using ordinary differential equations. The road can be discretized into cells and the cells can be then assumed to contain a vehicle, moving with its corresponding velocity.

2. Macroscopic Model: This model uses the idea of fluid dynamics and treats the traffic flow as one entity. Rather than treating each vehicle as a separate entity, properties like density of traffic, the mean velocity, etc. are studied and modeled using partial differential equations.

3. Mesoscopic Model: This model uses the idea of defining a probabilistic function which expresses the chances of having a vehicle at a certain position at a certain time, running with a certain velocity.

For our study, the macroscopic model is used, where we consider one dimensional traffic flow, i.e. traffic flowing in one direction (and overtaking not allowed).
7.1.1 Conservation Laws

To model the traffic, the wave model of traffic flow is considered. It follows the model where we consider the movement of vehicles in a single lane, which does not permit them to overtake one another. Considering this, we assume that we know the density of the vehicle flow, given by $\rho(t,x)$ on a roadway length over position $x$ and time $t$. We can assume $x$ as $x \in [0,L]$ and the time $t > 0$. For a particular spatial interval $(x_1, x_2)$, at a particular time $t$, the number of cars can be given by

$$\int_{x_1}^{x_2} \rho(x,t)\,dx$$

Let $v(x,t)$ be the velocity. At a particular time and instant, the flow of traffic $q(x,t)$ can be given by the product of the velocity and the density at that instant. It can be shown mathematically as

$$q(x,t) = \rho(x,t)v(x,t) \quad (7.1)$$

Now since the rate of change of number of cars in $(x_1, x_2)$ is given by the difference in flows at $x_1$ and $x_2$. Hence the relation between traffic density and traffic flow can be stated in a differential equation as

$$\int_{x_1}^{x_2} \rho(x,t_2)\,dx - \int_{x_1}^{x_2} \rho(x,t_1)\,dx = \int_{t_1}^{t_2} q(x_1,t)\,dt - \int_{t_1}^{t_2} q(x_2,t)\,dt \quad (7.2)$$

Alternatively, the above equation can be stated in double integral form as

$$\frac{d}{dt} \int_{x_1}^{x_2} \rho(x,t)\,dx = q(x_1,t) - q(x_2,t) \quad (7.3)$$
Consequently, the equation can be restated as

\[ \int_{x_1}^{x_2} [\rho(x, t_2) - \rho(x, t_1)] dx = \int_{t_1}^{t_2} [q(x, t_1) - q(x, t_2)] dx \]  \hspace{1cm} (7.4)

If \( \rho(x, t) \) and \( q(x, t) \) are differentiable functions, then we have

\[ \rho(x, t_2) - \rho(x, t_1) = \int_{t_1}^{t_2} \frac{\partial}{\partial t} \rho(x, t) dt \]  \hspace{1cm} (7.5)

and

\[ q(t, x_2) - q(t, x_1) = \int_{x_1}^{x_2} \frac{\partial}{\partial x} q(x, t) dx \]  \hspace{1cm} (7.6)

Using equations 7.5 and 7.6, we get the equation

\[ \int_{x_1}^{x_2} \int_{t_1}^{t_2} \left\{ \frac{\partial}{\partial t} \rho(x, t) + \frac{\partial}{\partial x} q(x, t) \right\} dt dx = 0 \]  \hspace{1cm} (7.7)

Since this must hold for all intervals of \( x \) and \( t \), the integrals can be dropped to get the differential form of conservation law as

\[ \frac{\partial}{\partial t} \rho(x, t) + \frac{\partial}{\partial x} q(x, t) = 0 \]  \hspace{1cm} (7.8)

This traffic model is known as the Lighthill-Whitham-Richards Model[11] and since \( q(x, t) = \rho(x, t)v(x, t) \), the law can be restated as

\[ \frac{\partial}{\partial t} \rho(x, t) + \frac{\partial}{\partial x} [\rho(x, t)v(x, t)] = 0 \]  \hspace{1cm} (7.9)
7.1.2 Greenshield’s Model

Macroscopic stream models represent how the behavior of one parameter of traffic flow changes with respect to another. Most important among them is the relation between speed and density. The first and most simple relation between them is proposed by Greenshield. Greenshield model assumes a linear relationship between speed and density.

The equation for the model is given by

$$v(x,t) = v_f - \left(\frac{v_f}{\rho_j}\right) \rho(x,t)$$  \hspace{1cm} (7.10)

where $v(x,t)$ is the mean traffic speed at density $\rho(x,t)$; $v_f$ is the free flow speed and $\rho_j$ is the jam density. As evident from the equation (7.10) when density becomes zero, speed approaches the free flow speed (i.e. $v \to v_f$ as $\rho \to 0$); and when speed becomes 0 (vehicles are stationary), the density approaches the jam density (i.e. $\rho \to \rho_j$ as $v \to 0$). Once the relationship between speed and density has been established, the relationship between density and flow can also be established.

Using equation (7.1) and the Greenshield’s model, we get

$$q(x,t) = v_f \rho(x,t) - \left(\frac{v_f}{\rho_j}\right) \rho(x,t)^2$$  \hspace{1cm} (7.11)

These equations depict a parabolic relationship between density and flow of traffic. Combining the Greenshield’s model with the Lightwill-Whitham-Richards model, the conservation law can be stated as
\[
\frac{\partial}{\partial t} \rho(x, t) + \frac{\partial}{\partial x} v_f \rho(x, t) \left(1 - \frac{\rho(x, t)}{\rho_j}\right) = 0 \quad (7.12)
\]

7.2 Travel Time Calculations

Travel time estimation algorithms and functions can be designed using the distributed or lumped parameter models of the traffic. We will develop appropriate models using the different modeling paradigms. This section will present models without forecasting that will approximate the travel time based on only the current state values. The next section will present more accurate estimators that will use forecasting.

7.2.1 Travel Time - Definition

It is a performance measure used in transportation used to define the time taken to reach a certain fixed point (destination) from an initial position. The quantity depends upon the other parameters that define the system parameters such as density \( \rho \) and flow \( q \) which are both functions of position \( x \) and time \( t \). The current methodologies used to compute the travel time broadly fall in two categories -

1. **Link Measurement Approach** - using active test vehicles between points of interest

2. **Point Measurement Approach** - inferred indirectly from other sensors, such as loop detectors or video cameras
These methods can be classified as being either direct or indirect methods. With the link measurement method, the travel time is the observed parameter, and hence is a direct method. On the other hand the point measurement approach is an indirect observation method as the observed parameters are used to deduce the travel time rather than directly measuring it.

7.2.2 System Assumptions

We assume that the initial density profile $\rho(0, x)$ is provided, which could be used to solve for the density for all times and position. So once the entire density profile $\rho(t, x)$ is known, we solve for the travel time function $u(t, x)$. Since $u$ is to be calculated, we fix a point $x_f > 0$ on $x$ till where the travel time is to be evaluated. We use the function $\eta(t)$ to describe the position of a vehicle at a certain time. Once the vehicle reaches $x_f$, the value of $u(t, x)$ is 0 for any $x \geq x_f$. Similarly the position $\eta$ of the vehicle after $x_f$ is assumed to be constant after it reaches that point, i.e.

$$\text{if } \eta(t^*) = x_f, \text{ for some } t^*, \text{ then } \eta(t) = x_f, \forall t \geq t^*$$ (7.13)
Since the conservation law is followed and we assume the model where the cars follow in a straight single line, the cars do not cross each other. We define a road segment \( x \in [0, x_f] \). For an infinitesimal road segment of length \( dx \) at \( x \), the time taken to traverse it would be \( du \), given by

\[
du = \frac{dx}{v(\rho(t, x))}
\] (7.14)

To calculate the function over the entire length, we integrate \( du \) over the entire segment. The velocity \( v \) is a function of the density \( \rho \), and is given by the Greenshield model. The differential model in equation 7.14 can be written as

\[
u(t + \Delta t, x + \Delta x) = u(t, x) - \frac{dx}{v_f \left(1 - \frac{\rho(t, x)}{\rho_m}\right)}
\] (7.15)

Using the Taylor series expansion of \( u(t, x) \) about \((t, x)\), ignoring higher order terms and taking the limits \( \Delta x \to 0 \) and \( \Delta t \to 0 \), we get the following equation

\[
\frac{\partial u}{\partial t} + \left(v_f \left(1 - \frac{\rho(t, x)}{\rho_m}\right)\right) \frac{\partial u}{\partial x} = -1
\] (7.16)

### 7.3 Special Cases

In case of a constant initial density profile, the solution to the density profile over time remains constant, allowing us to determine the travel time explicitly, as the velocity also remains constant. In that case of constant density \( \rho^* \), over \( x \) from 0 to \( L \), the travel time \( u(t, x) \) can be given as
\[ u(t, x) = T \left(1 - \frac{x}{L}\right) \]  

(7.17)

where \( T \) is the total travel time given by

\[ T = \frac{L}{v_f \left(1 - \frac{\rho^*}{\rho_m}\right)} \]  

(7.18)

which makes the travel time just a function of position \( x \), rather than both time \( t \) and position \( x \).

There can be certain properties that can be associated with the travel time \( u(t, x) \). Using the properties of the traffic density, the characteristics of travel time \( u(t, x) \) can be listed as

1. \( u(t, x) \) is non-negative function for all \( t \) and \( x \)

2. In case a jam occurs, the function becomes infinite, if jam does not clear

3. The function becomes linear with time \( t \) till the jam clears

4. If the function \( u \) is found to have a finite value for some \( x = x' \) at some time \( t' \), then the solution exists for all \( x > x' \), because of the conservation law followed by the vehicles, as any vehicle that is ahead of this would also reach \( L \) in finite time
7.3.1 Discrete Space Based Estimation

The discrete time based travel time estimation is done by using travel time estimation applied in a sequential fashion from upstream to downstream. To show this analysis, let us consider the figure below.

![Figure 7.2: Travel Time Function Derivation for Discrete Space Systems](image)

The travel time in section 1 is given by

\[
T_1 = \frac{d_1}{v_f(1 - \frac{\rho_1}{\rho_m})}
\]  
(7.19)

Now we need to calculate the travel time in section 2 at a time that occurs after the travel time in section 1, i.e.

\[
T_2 = \frac{d_2}{v_f(1 - \frac{\rho_2(t+T_1)}{\rho_m})}
\]  
(7.20)

In order to calculate \(\rho_2(t + T_1)\), we will solve the ODEs for a general section from upstream to downstream.
7.3.2 Discrete Time and Space Based Estimation

For discrete space and time case, the development is similar to the case above, except that we have difference equations. In order to find the travel time, we need to solve the original PDE for density profile \( u(t, x) \).

\[
\frac{\partial u(t, x)}{\partial t} + \frac{\partial f(t, x)}{\partial x} = 0 \tag{7.21}
\]

where \( f(t, x) \) is the flux function, given by

\[
f(u(t, x)) = v_fu(1 - \frac{u}{u_{\text{max}}}) \tag{7.22}
\]

We use Godunov scheme\[11\] to discretize the above equation, rather than normal Euler discretization scheme, which uses the characteristic information within the framework of a conservative method. In the method, we divide space into sections of size \( h \) and time into small parts of size \( k \), and assign a value \( U_{n}^{j} \) as solution to the problem for the grid \( x_{j-1/2} \leq x \leq x_{j+1/2} \) for time \( t_{n} \leq t \leq t_{n+1} \). We define \( U_{n+1}^{j} \) by

\[
U_{n+1}^{j} = \frac{1}{h} \int_{x_{j-1/2}}^{x_{j+1/2}} u_{n}(x, t_{n+1}) \, dx \tag{7.23}
\]

But our original equation, allows us to define \( U_{n+1}^{j} \) as

\[
U_{n+1}^{j} = U_{n}^{j} - \frac{k}{h} [F(U_{n}^{j}, U_{n}^{j+1}) - F(U_{n}^{j-1}, U_{n}^{j})] \tag{7.24}
\]

where
\[ F(U^n_j, U^n_{j+1}) = \frac{1}{h} \int_{t^n_j}^{t^n_{j+1}} f(u(x_{j+1/2}, t)) dt \] (7.25)

Also we define the travel speed of the shock wave as

\[ s(u_l, u_r) = \frac{f}{u} = \frac{f(u_l) - f(u_r)}{u_l - u_r} \] (7.26)

Using the expression for the flux \( f(u(t, x)) \), we get \( s(u_l, u_r) \) as

\[ s(u_l, u_r) = v_f(1 - \frac{u_l + u_r}{u_{max}}) \] (7.27)

and define

\[ F(U_l, U_r) = f(u^*(u_l, u_r)) \] (7.28)

Depending upon the direction of the shock wave, i.e. whether \( s(u_l, u_r) \), we take \( F(U_l, U_r) \) as

\[ f'(u_l), f'(u_r) \geq 0 \Rightarrow u^* = u_l \] (7.29)

\[ f'(u_l), f'(u_r) \leq 0 \Rightarrow u^* = u_r \] (7.30)
\[ f'(u_l) \geq 0 \geq f'(u_r) \]
\[ \Rightarrow u^* = u_l, \text{if } f' \left( \frac{f}{u} \right) > 0; u^* = u_r, \text{if } f' \left( \frac{f}{u} \right) \leq 0 \]

\[ f'(u_l) < 0 < f'(u_r) \Rightarrow u^* = u_s (\text{transonic rarefaction}) \quad (7.31) \]

In the case of transonic rarefaction, \( u^* \) is the value where we get

\[ f'(u_s) = 0 \quad (7.32) \]

which, according to Greenshield model gives us \( u_s \) as

\[ u_s = \frac{u_{max}}{2} \quad (7.33) \]

### 7.4 Vehicle Following Model for Estimation of Travel Time

In this section, we devise an alternate approach to determine the travel time. The idea of microscopic model is used for tracking the vehicle trajectory \( \eta(t) \). Since the variable \( \eta(t) \) is a function of time \( t \), the model can be described by an ordinary differential equation (ODE), rather than a PDE. Once the density profile over the segment is obtained using Godunov scheme on the initial density profile, the following
ODE can be used for modeling for vehicle trajectory.

\[
\frac{d\eta}{dt} = v_f (1 - \frac{\rho(t,x)}{\rho_m}) \tag{7.34}
\]

Since the variable \( \eta \) is also a measure of length, and is measured on the same segment of length, \( x \) in the PDE

Here \( x \) is the position along the road segment, which is same as \( \eta \). Thus the above equation can be written in terms of \( \eta(t) \) as

\[
\frac{d\eta}{dt} = v_f (1 - \frac{\rho(t,\eta(t))}{\rho_m}) \tag{7.35}
\]

The above ordinary differential equation depends on the density profile, \( \rho(t,x) \); but once the density is known from Godunov method, the position of car, \( \eta(t) \) can be determined by solving the ODE. The simple Euler forward scheme works well for solving the ODE. The results obtained for vehicle trajectory that are obtained from MATLAB simulations using piecewise initial density profile are shown in the following Chapter.
8.1 Currently Developed Integrated System

A prototype of an integrated interactive software has been developed for displaying the results of performance measures based on the data collected from different sources. The varied data sources used in the application are

1. Bluetooth Sensor Data
2. Smartphone Application Data
3. Automatic Vehicle Locator (AVL) Data
4. Crash Analysis Data

Since the timestamp and the location data are available for almost all data sources (except the bluetooth sensor data for which the location data is unavailable), the application can be used to query the data based on time and location based on the selection of the data source.

Based on the query made from the integrated historical database by making the required selection, the data is displayed in a front end graphical interface developed
in Adobe Flash. The results are shown both in a tabular form and also on the map (if possible for that data source) as shown in the above and below figures.

8.2 Vehicle Tracking Model - Simulation Results

In this section, we present the results obtained for vehicle trajectory using the model described in the previous chapter. A model is considered with an initial density profile $\rho(0, x)$ over the length of the section. The Godunov conservation numerical scheme is employed to generate the density profile over time. Once $\rho(t, x)$ is obtained, the vehicle tracking equation is numerically solved for $\eta(t)$.

The simulations for the model were done for the cases of normal traffic flow, jam
density and rarefaction. The results thus obtained are shown below. The density profiles as a function of time and position are shown as contour plots with 200 peaks (Figure 8.2). The vehicle trajectories for various initial positions are plotted in different colors as a function of time on the same plot as shown in the figure below.

8.3 Smartphone Data Collection for Travel Time Evaluation

In this section, we look at the travel time results obtained from both freeway sensor data and the smartphone (iPhone) data collection app. The scenario of observation is explained and the results from the two sources are compared. Based on the results obtained and the system conditions, comments are made about the two methods.
8.3.1 System and Data Collection Procedure

The study involved collecting data from the freeway sensors installed on the highway by the Nevada Freeway and Arterial System (NVFAST). They have installed the sensors on major freeways around Las Vegas viz as shown in figure below.

- I-15 NB
- I-15 SB
- US-95 NB
A corridor was chosen on Interstate-15 North Bound Freeway for conducting the study. The straight stretch of highway was chosen between Sunset Rd and Spring
Figure 8.5: The locations of Freeway Sensors installed in Las Vegas Area by NVFAST Mountain Rd on the I-15 NB. A total of 11 sensors were selected on the stretch where the sensor data was recorded. With the NVFAST naming, the detectors chosen can be listed as (from North to South Directions) are

- 89_2_30
- 89_1_28
- 72_1_22
- 71_2_23
- 70_2_21
- 59_2_18
8.3.2 Data Collection Procedure

The NVFAST sensors record a 15 minute average of the data at the locations and save the following parameters which are available on the NVFAST website at NVFAST Detectors:

- Lane wise Speed
- Volume
- Occupancy
- Poll_Count
- Failure

Out of these parameters, for calculation of travel time \( u \), the speed for a sensor was averaged out over the lanes at a particular timestamp. The lengths of the sections...
between the sensors was measured using the geographic co-ordinates. Repeated travel runs were conducted on the selected stretch of the freeway and data was collected using the app on the iPhone. At the same time intervals, the data from the sensors along the stretch of the freeway was obtained from the NVFAST website.

The travel time was calculated from the sensors using from the cumulative sum of the time taken to travel the individual sections, giving

$$u = \sum_{i=1}^{N} \frac{\Delta x_i}{v_i}$$  \hspace{1cm} (8.1)

where $u$ is total travel time, $\Delta x_i$ is the length of the section $i$ and $v_i$ is the measured speed for that section. For the current scenario a total of 11 $N = 10$

### 8.3.3 Smartphone App for Data Collection

As an alternative to the the freeway sensors used by NVFAST, an iPhone app was developed by Transportation Research Center(TRC), UNLV. It acts as a data collection source along the vehicle in which it is kept. It records a wide variety of parameters for the vehicle as it is driven around. A screenshot of the app running as shown in the following figure lists the parameters collected.

From the parameters, we consider the time stamps for the travel time calculation. The app is used to start recording the data when the vehicle reaches the starting point of the NB stretch on I-15 and it is used to record data at every 5 second intervals. The app is stopped once the ending point of the freeway stretch is reached.
Figure 8.6: A screenshot of the app running on the iPhone showing the parameters being collected.

time difference between the starting time and the stopping time is calculated which observes as the observed travel time. A single entry of the travel time observation from the iPhone app is not a good measure of comparing the calculating travel time and the observed travel time. Thus five travel runs were conducted at fifteen minute intervals (to coincide with the NVFAST sensors’ fifteen minute average timings), and the results were calculated and compared.
8.4 Observed and Calculated Travel Times Compared

The results for the travel time from both the data sources were evaluated, compared and conclusions were drawn on the basis of the comparisons. The travel times for the different travel runs can be listed in the table below.

These results can be explicitly shown in the bar graphs as shown in the figure below

<table>
<thead>
<tr>
<th>Run</th>
<th>Observed Travel Time (min)</th>
<th>Calculated Travel Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1</td>
<td>3.34</td>
<td>2.83</td>
</tr>
<tr>
<td>Run2</td>
<td>3.32</td>
<td>3.92</td>
</tr>
<tr>
<td>Run3</td>
<td>3.27</td>
<td>3.72</td>
</tr>
<tr>
<td>Run4</td>
<td>3.23</td>
<td>3.75</td>
</tr>
<tr>
<td>Run5</td>
<td>3.35</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Table 8.1: Comparative Results of the Observed Travel Time and the Calculated Travel Time (in minutes) over repeated travel runs

Figure 8.7: Bar graph comparing the observed and calculated travel times (in minutes)
8.4.1 Observations Made about the Data

The comparative difference between the observed and the calculated travel times can be listed in tabular form, the results for which are demonstrated in the following figure.

<table>
<thead>
<tr>
<th>Run</th>
<th>Percentage Difference in Travel Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1</td>
<td>15.39</td>
</tr>
<tr>
<td>Run2</td>
<td>18.14</td>
</tr>
<tr>
<td>Run3</td>
<td>13.86</td>
</tr>
<tr>
<td>Run4</td>
<td>13.80</td>
</tr>
<tr>
<td>Run5</td>
<td>11.93</td>
</tr>
</tbody>
</table>

Table 8.2: Percentage Change in the observed travel times over the calculated travel times

Figure 8.8: Percentage Change in the observed travel times over the calculated travel times
The variations in the observed and the calculated travel times can be attributed to a variety of reasons

- The calculated travel times utilize the averaged data of different lanes over a 15 minute period
- The iPhone app collects data at a 5 second time interval which gives a higher resolution of data

8.5 CORSIM Simulations for Travel Time Estimation

This section discusses the use of simulated traffic data from CORSim - Corridor-microscopic Simulation program, and using it for travel time estimation. CORSIM is the core simulation and modeling component of the Traffic Software Integrated System (TSIS) tool suite.

The program allows the simulation of traffic data on freeways or arterials and allow the recording of various parameters. The system used for collecting the simulation data for the study was under the following setup

- A two lane freeway with a speed limit of 65mph
- The segment for which data was simulated was 55,000 ft = 10.41667 miles long
- The road segment had 13 nodes, and hence 12 segments over which data is simulated
- For each road segment, various time averaged data sets were simulated for
varying time lengths (1 minute, 2 minute, 5 minute and 10 minute).

- The parameters being recorded and analyzed were the average travel time for the segment and the average speed over a time interval.

The simulation averages the data parameters for all the vehicles that cover the segment, which is then used for the travel time estimation. The idea of using the data is to develop an algorithm for tracking the vehicle trajectory with time and use the consequent time elapsed as the travel time to traverse till the end of the segment. The algorithm can be stated as

```plaintext
while(x0 < length(N))
    tcheck = (length(xIndex) - x0)/velocity(xIndex, tIndex);
    if tcheck + t0 < time(tIndex)
        t0 = t0 + tcheck;
        x0 = length(xIndex);
        xIndex = xIndex + 1;
    else
        t1 = time(tIndex) - t0;
        x0 = x0 + velocity(xIndex, tIndex) * t1;
        t0 = t0 + t1;
        tIndex = tIndex + 1;
    end
    tfinal = [tfinal, t0];
```
xfinal = [xfinal, x0];

end

totalTravelTime = tfinal(end) - tfinal(2);

where $x_0$ is the starting position, $t_0$ is the starting time and $k$ is the time average over which data is simulated in CORSIM.

The approach is different from the standard algorithms which use the averaged travel times or averaged speeds over time to evaluate travel times. This approach when combined with the estimation of the density profile, and hence the velocity profile can be used for future travel time prediction rather than using static sensor data.

The results are further compared for various time window sizes over which the data is averaged. The results for different $x_0$, $t_0$ and $k$ are shown in 8.5

The results can be compared visually as in figure 8.9
Table 8.3: The comparison results for computed travel time for different time averaged data

<table>
<thead>
<tr>
<th>x0 (feet)</th>
<th>t0 (seconds)</th>
<th>k (seconds)</th>
<th>Travel Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23,000</td>
<td>50</td>
<td>60</td>
<td>344.2666</td>
</tr>
<tr>
<td>23,000</td>
<td>50</td>
<td>120</td>
<td>344.6035</td>
</tr>
<tr>
<td>23,000</td>
<td>50</td>
<td>300</td>
<td>346.1381</td>
</tr>
<tr>
<td>23,000</td>
<td>50</td>
<td>600</td>
<td>345.8677</td>
</tr>
<tr>
<td>4,500</td>
<td>200</td>
<td>60</td>
<td>544.2779</td>
</tr>
<tr>
<td>4,500</td>
<td>200</td>
<td>120</td>
<td>544.3586</td>
</tr>
<tr>
<td>4,500</td>
<td>200</td>
<td>300</td>
<td>544.1217</td>
</tr>
<tr>
<td>4,500</td>
<td>200</td>
<td>600</td>
<td>544.0432</td>
</tr>
<tr>
<td>45,000</td>
<td>500</td>
<td>60</td>
<td>103.8334</td>
</tr>
<tr>
<td>45,000</td>
<td>500</td>
<td>120</td>
<td>108.3869</td>
</tr>
<tr>
<td>45,000</td>
<td>500</td>
<td>300</td>
<td>109.1560</td>
</tr>
<tr>
<td>45,000</td>
<td>500</td>
<td>600</td>
<td>108.4927</td>
</tr>
<tr>
<td>38,000</td>
<td>300</td>
<td>60</td>
<td>185.9688</td>
</tr>
<tr>
<td>38,000</td>
<td>300</td>
<td>120</td>
<td>185.568</td>
</tr>
<tr>
<td>38,000</td>
<td>300</td>
<td>300</td>
<td>184.2298</td>
</tr>
<tr>
<td>38,000</td>
<td>300</td>
<td>600</td>
<td>184.2298</td>
</tr>
<tr>
<td>50,000</td>
<td>300</td>
<td>60</td>
<td>56.4908</td>
</tr>
<tr>
<td>50,000</td>
<td>300</td>
<td>120</td>
<td>54.2519</td>
</tr>
<tr>
<td>50,000</td>
<td>300</td>
<td>300</td>
<td>54.3191</td>
</tr>
<tr>
<td>50,000</td>
<td>300</td>
<td>600</td>
<td>54.3191</td>
</tr>
</tbody>
</table>
Figure 8.9: A comparative set of obtained results showing the travel time obtained (in seconds) for various $x_0$, $t_0$ and $k$
CHAPTER 9

CONCLUSIONS AND REMARKS

9.1 Conclusions

The current work focussed on analyzing the current performance measure systems developed by various organizations. A proof of concept study performance management system was developed by using various data sources. The system uses data from sensors that are maintained by different organizations. Also a smartphone application was developed for collecting user specific data. All the sources were combined into a database which were used in a GUI. The graphical interface allows the calculation of performance measures based on a user query. The results are shown in a tabular format and also on a map.

Since travel time is a major performance measure evaluated in most studies, a theory on mathematically modeling the travel time computation is proposed. The model is fused with vehicle tracking models to evaluate the trajectories over time and space. The simulations showed good results in cases of traffic jams and free-flowing traffic as well. An analysis is performed on the travel time computation for various data sampling times. A comparative study is carried out to compare the results of travel time from highway sensor data and travel time computed by using the mathematical model from the data collected by the smartphone application. The
computed results show a low difference in the calculated and the observed travel times.

9.2 Future Work

The work discussed in this thesis can be further expanded to evaluate more performance measures. The proof of concept study can be extended to a full operational system, which the users can use for planning travels. Also solutions can be provided for specific routes based on user patterns. The travel time model can be used predicting travel times and reducing the cost of traffic sensors for data collection. The model can be used for studying traffic patterns and planning.
BIBLIOGRAPHY


VITA

Graduate College
University of Nevada, Las Vegas

Anuj Nayyar

Home Address:
3925 Cambridge St, Unit 2
Las Vegas, Nevada 89119

Degrees:
Bachelor of Science, Electrical and Communication Engineering, 2009
Indian Institute of Technology, Guwahati, India

Thesis Title: Performance Measures for Transportation Network: A study in Travel Time Dynamics

Thesis Examination Committee:
Chairperson, Dr. Pushkin Kachroo, Ph.D.
Committee Member, Dr. Rama Venkat, Ph. D.
Committee Member, Dr. Emma Regentova, Ph.D.
Graduate Faculty Representative, Dr. Haroon Stephen, Ph.D.