ABSTRACT

XUAN, XINGYU. A Shockwave Speed Estimation Method for Freeway Facilities Based on Archived Vehicle Probe Data. (Under the direction of Dr. Billy Williams and Dr. Bastian Schoreder).

Shockwave analysis is widely used for solving bottleneck problems on freeway facilities. In macroscopic traffic analysis, a shock wave model is used to model the vehicle queue propagation. Furthermore, shock waves are considered a safety concern, because rapid deceleration that drivers must negotiate at the transition of traffic flow conditions (free-flow to breakdown) can often lead to accidents, sometimes serious ones. Understanding the formation and characteristics of shock waves is important for studying congestion patterns and impacts. Specifically, the shockwave propagation speed is one of the most important analysis metrics in freeway facility evaluation. In general, the shockwave speed can be estimated based on time-space domain vehicle trajectories or based on shockwave theory using a flow-density model associated with deterministic demand and capacity in freeway facilities. However, no research to date has focused on shockwave speed estimation based only on freeway link speed data (archived vehicle probe data). The freeway segment speed data have become commonplace in recent years and are available to most transportation agencies. Therefore, a shockwave speed estimation methodology based on time-space domain speed only data is useful and meaningful.

In the thesis, a method, estimating shockwave speed and queue length based on a converted time-space domain speed contour plots has been proposed. The methodology was developed and tested at three different routes on interstate I-40/I-440 in Raleigh Area, NC, where data are available from both INRIX (link speed data) and Traffic.com (point speed and volume data). This study also explored a shockwave theory based shockwave speed estimation
method in order to compare the results in a validation exercise. Moreover, two different queue length values estimated in different ways based on proposed method were presented and compared. Results reveal that the proposed methodology is reliable and accurate on shockwave speed estimation.
A Shockwave Speed Estimation Method for Freeway Facilities Based on Archived Vehicle Probe Data

by
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**BIOGRAPHY**

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1. Introduction & Objectives

Shockwave analysis is widely used for solving bottleneck problems. A shock wave is a boundary established at the time-space domain when one flow state changes to another. In macroscopic traffic analysis, a shock wave model is widely used to model the vehicle queue propagation.

Furthermore, shockwaves are considered a safety concern, as the transition of conditions can often lead to accidents, sometimes serious ones, specifically, shockwave speed is the most important characteristic (en.wikibooks.org). In particular, the formation and dissipation of congestion creates greater variation in speed and potentially increases likelihood of crash occurrence on freeways (B.S. Kerner 2004, E. Hauer 1971).

In general, the shock wave can be classified in terms of the following categories (C. Lee, and S. Volpatti 2010):

1. Direction of shock wave movement: forward or backward shock wave. Forward shock wave moves in the same direction as traffic flow whereas backward shock wave moves in the opposite direction to traffic flow.

2. Growth or dissipation of a queue: forming or recovery shock wave. Forming shock wave occurs as the density increases whereas recovery shock wave occurs as the density decreases.

3. Traffic state: changes in volume and density within the same traffic states (uncongested or congested regime) or between two different traffic states (from the uncongested regime to the congested regime or vice versa).

The following six shock wave types were defined based on the above categories, as shown in Figure 1.1:

Type 1: Frontal stationary shock wave
Type 2: Forward forming shock wave
Type 3: Backward recovery shock wave
Type 4: Backward forming shock wave
Type 5: Forward recovery shock wave
Type 6: Rear stationary shock wave

For a freeway facility experiencing recurring congestion during peak period, not all types of shock waves can be observed. As shown in Figure 1.2, the frontal stationary shock wave, backward forming shock wave, forward recovery shock wave and rear stationary shock wave are commonly existed at a freeway bottleneck during peak period.
Based on the shockwave analysis, the queue length and the traffic states along the roadway with a defined time-space region can be estimated, in addition to the shockwave speed. The study of shockwaves in turn requires traffic data, such as traffic stream speed over time and space. For this study, link speed data on I-40/I-440 surrounding Raleigh area were collected from the Regional Integrated Transportation Information System (RITIS 2014), which archives one-minute aggregation period speed from the INRIX probe vehicle network as a part of the I-95 Corridor Coalition Vehicle Probe Project. Further, daily speed contour plots were developed for shockwave speed estimation in this thesis.

In addition, the Highway Capacity Manual (HCM 2010) provides a freeway flow-density relationship both in undersaturated and oversaturated regime. Shockwave speed can be estimated based on shockwave theory associated with this flow-density relationship using assumed deterministic values of freeway downstream capacity and upstream demand.
Thus, the objective of this paper is to estimate speeds of *backward forming shock wave* and *forward recovery shock wave* on recurring congested freeway facility based on converted speed contour plots (time-space domain speed data) and compare these results to corresponding estimates from classical theory.

The paper presents an exploratory analysis of shockwaves on freeways, and the development and application of an algorithm estimating shockwave speed based on converted speed contour profile. The algorithm developed here is generic and can be used for shockwave speed estimation based on speed contour plots from any range of link speed data for any type of freeway sections that experiencing recurring congestion during peak period as long as reasonably accurate speed data are available.

Finally, the paper presents a comparison between estimated shockwave speeds based on the proposed algorithm and shockwave theory for validation exercise. Furthermore, the corresponding queue lengths were estimated in two different methods and the range of true queue lengths were assumed, which need further validation.
2. Literature Review

In this chapter, studies on shockwave speed estimation as well as capacity definition and estimation are reviewed.

2.1 Shockwave Analysis

Shockwaves can be defined as boundary conditions between states of traffic flow on freeway facilities (A.D. May 1990). A shock wave propagates along a line of vehicles in response to changing conditions at the front of the line. Shock waves can be generated by bottleneck generation, collisions and sudden decreases in speed caused by ramp entering vehicles, or by a number of other reasons. Basically, a shock wave exists whenever the traffic conditions change.

The basic equation that is used to estimate the propagation speed of shock waves is given below (A.D. May 1990).

\[ v_{sw} = \frac{(q_b - q_a)}{(k_b - k_a)} \]

**Equation 2-1**

Where

- \( v_{sw} \) = propagation speed of shock wave (miles/h)
- \( q_b \) = flow prior to change in conditions or upstream of bottleneck (vehicles/h/ln or pc/h/ln)
- \( q_a \) = flow after change in conditions or downstream of bottleneck (vehicles/h/ln or pc/h/ln)
- \( k_b \) = traffic density prior to change in conditions or upstream of bottleneck (vehicles/mile)
- \( k_a \) = traffic density after change in conditions or downstream of bottleneck (vehicles/mile)

From equation 2-1, the magnitude and direction of the shock wave emerge. The greater \( v_{sw} \), the faster the speed of the wave.

A negative wave speed (−), refers to a shock wave that is travelling upstream or against the traffic stream, which is equivalent to a backward forming shock wave. A positive wave speed
(+), refers to a shock wave that is travelling in the same direction of the traffic stream, which is a forward recovery shock wave. Note that for a front-clearing queue, a recovery wave speed can have a negative value.

Using this classical theory, the shockwave speed on freeways have been measured and analyzed in the past studies. Messer et al. (1976) estimated the speed of shock waves after lane-blocking incidents occurred using the combined equations of the kinematic wave model and the Greenshield’s macroscopic traffic flow models. Hurdle and Son (2000) estimated the shock wave speed using density contour maps that can display the spatial and temporal propagation of the traffic regimes with similar densities. Windover and Cassidy (2001) observed the propagation of shock waves using the re-scaled cumulative vehicle arrival curve. Suzuki & Matsunaga (2010) proposed a mathematical approach to evaluating safety of vehicle platooning based on the shockwave theory with macroscopic traffic variables such as traffic flow “q” and density “k”.

While these studies used the aggregated traffic flow data at fixed locations of freeways, Lu and Skabardonis (2007) estimated the shockwave speed using individual vehicle trajectories under congested conditions. However, none of these studies estimated shockwave speed using macroscopic link speed data. Also, since the traffic data from vehicle probe are more and more readily available in freeways, it is practical to develop a method of estimating speed of shock waves using the archived vehicle probe data.

Thus, the objective of this study is to develop an algorithm to estimate the speeds of two typical types of shock waves using archived vehicle probe data.

2.2 Capacity Definition

In order to validate the proposed shockwave speed estimation method, the author explored a shockwave speed estimation method based on classical shockwave theory associate with HCM
2010 freeway flow-density relationship using assumed deterministic values of freeway downstream capacity and upstream demand.

The HCM 2010 version provides a flow-density model both in undersaturated and oversaturated regime in freeway facilities, as shown in Figure 2.1. Knowing the upstream demand and downstream capacity in a freeway site during breakdown and recovery, the speeds of backward forming shock wave and forward recovery shock wave can be easily estimated respectively using equation 2-1 and equation 2-2.

![Highway Capacity Manual 2010 Flow-Density Relationship](image)

**Figure 2.1 Highway Capacity Manual 2010 Flow-Density Relationship**

\[
v_{fw} = \frac{(q_{arr} - q_c)}{(k_{arr} - k_c)} \quad \text{Equation 2-1}
\]

\[
v_{rw} = \frac{(q_{arr} - q_c)}{(k_{arr} - k_c)} \quad \text{Equation 2-2}
\]

Where

\[v_{fw} = \text{propagation speed of forming shockwave (miles/h)}\]
Thus, the estimated values of downstream capacity and upstream demand in a freeway site are two key parameters in the implementation of shockwave theory method. Specifically, capacity is much more difficult to estimate than demand, partly because the definition of capacity varies greatly across different sources in the literature. It is helpful to develop a clear definition of capacity in this thesis when exploring shockwave theory method.

From the literature review about capacity research, it can be found that most of researchers used their own freeway capacity definition (Jiang 1999, Maze 2000, Lorenz and Elefteriadou 2001, Bham 2011).

The Indiana Department of Transportation studied eight work zones on Interstate highways randomly selected between October 1995 and April 1997 (Jiang 1999, Jiang 1999). They followed one of the capacity definitions representing pre-breakdown condition. So, they tried to find capacity values through identifying drastic speed drop as shown in Figure 2.2.
In a study in Iowa conducted during the summer of 1998 on a rural Iowa interstate highway estimated work zone capacity averaging the ten highest free flow values (Maze 2000). The authors first identified queued conditions from speed data and then excluded flow rate under the queued conditions while averaging the ten highest free flow values as shown in Figure 2.3.

Figure 2.2 Traffic Flow and Speed Plots
A study in Missouri conducted on I-44 work zone provided both pre-breakdown flow (breakdown flow) and queue discharge rate as a capacity (Bham 2011). The study examined speed and flow rate to identify a maximum pre-breakdown, breakdown flow, maximum queue discharge rate, and average queue discharge rate as presented in Figure 2.4. They stated that both pre-breakdown and queue discharge rate would be useful in capacity definition, as the pre-breakdown capacity could be used on congestion analysis and the queue discharge rate could be used on delay analysis.
Lorenz and Elefteriadou (2001) conducted an extensive analysis of speed flow data collected at two freeway bottleneck-locations in Toronto, Canada, to investigate how the probabilistic model previously developed by Elefteriadou et al (1995) compared to field data as shown in Figure 2.4. At each of the two sites, the freeway breakdown process was examined in detail for over 40 breakdown events occurring during the course of nearly 20 days. Based on field observations, the authors defined breakdown to occur:” The authors also defined the breakdown flow rate as: “the flow rate (expressed as a per-lane, equivalent hourly rate) that occurs during 5-minute time period immediately prior to the breakdown event.” The analysis focused on the occurrence of breakdowns, and the numerical value of breakdown flows. Later, Elefteriadou and Lertworawanich (2003) recommend that the breakdown flow be used regarding the definition and numerical value of capacity based on the research two years ago.
Figure 2. 5 Capacity Definition and Estimation (Lorenz and Elefteriadou (2001))

The literature above have focused on defining and estimating capacity as a fixed value. However, an emerging body of research indicates that the traffic flow rate during the time period preceding observed instances of freeway breakdown (pre-breakdown flow) is better represented as a random variable than a fixed value (Elefteriadou, L., R.P. Roess, W.R. McShane 1995, Minderhoud, M. M., H. Botma, and P. H. L. Bovy 1997, Persaud, B., S. Yagar, and R. Brownlee 1998, Kuehne, R. D., and N. Anstett 1999, Lorenz, M., and Elefteriadou, L. 2000, Okamura, H., S. Watanabe, and T. Watanabe 2000).

Lorenz, M., and Elefteriadou, L. (2000) clearly describe the stochastic freeway capacity concept. Their findings suggest that breakdown is not a deterministic event and that it could occur at any given flow rate with a finite probability. Brilon et al. (2005) developed a methodology to derive roadway pre-breakdown distribution functions for the purpose of
implementing this stochastic capacity concept. Later, Brilon et al. (2007) have suggested the Weibull distribution for characterizing the stochastic capacity on the basis of traffic data from Germany. Based on the probabilistic nature of freeway capacity, Dong and Mahmassani (2009) first illustrated the significant effects of the stochastic concept in a travel time reliability study.

Similar to the traditional definition of capacity in the HCM, the queue discharge flow rate is also typically characterized in a deterministic manner. In other words, after a breakdown occurs, the queue will discharge at a constant flow rate. On the basis of field data, Lorenz, M., and Elefteriadou, L. (2000) clearly demonstrate that the queue discharge flow rate is also stochastic in nature. Most recently, Jia et al. (2010) identified the stochastic nature of freeway bottleneck breakdown and queue discharge by investigating through a comprehensive analysis of sensor data collected at bottleneck sites in the San Francisco Bay Area, California, and San Antonio, Texas. They developed a new method to identify the bottleneck breakdown and queue discharge rate. A method was developed to model stochastic bottleneck breakdown by using an empirically fitted average pre-breakdown headway probability distribution, while a recursive queue discharge model was developed to represents the stochastic, time-correlated nature of freeway bottleneck queue discharge.

In summary, several studies have shown that the pre-breakdown flow (Jiang 1999, Brilon et al. 2005, Brilon et al. 2007, Jia et al. 2010, Bham 2011), breakdown flow (Lorenz, M., and Elefteriadou, L. 2000, Lorenz and Elefteriadou 2001), and queue discharge rate (Jia et al. 2010, Bham 2011) were used in capacity definition and estimation. Specifically, pre-breakdown flow was highly recommended when reasonable and enough flow and speed data from freeway sensors are available.

Furthermore, studies of the stochastic characteristics on capacity definition and estimation are still limited and complicated. In order to simplify the capacity and demand estimation, it was assumed that the capacity and demand during the time period of interest is deterministic and not changed. In this thesis, the assumed deterministic values of downstream capacity and
upstream demand of the objective freeway sites during the time period of interest were estimated based on traffic flow data from Traffic.com sensors.
3. Methodology

In this chapter, the proposed shockwave speed estimation algorithm based on converted speed contour plots are presented. This chapter is organized as follows. Section 3.1 first introduces the field dataset used in the proposed algorithm. Followed with Section 3.1, an effective algorithm was developed in section 3.2.

3.1 Data Source

In this study, speed data were collected from the Regional Integrated Transportation Information System (RITIS), which archives link speeds in 1-min, 5-min, or 15-min aggregation period from the INRIX probe vehicle network as a part of the I-95 Corridor Coalition Vehicle Probe Project (RITIS, 2014). INRIX uses GPS probes to collect speed information on 260,000+ miles of roads across the United States, as shown in Figure 3.1. Traffic data are reported for Traffic Message Channel (TMC) codes defined by TeleAtlas and Navteq. TMC link data are calculated in real time by INRIX and archived by INRIX and RITIS. INRIX reports Speed, Travel Time, Average Speed, Reference Speed, Score and C-Value for each aggregation time period. The interpretation of each archived information are as below.

- **TMC Code:** The code that defines a specific section of road. The attributes of each code are defined by a consortium consisting of TeleAtlas and Navteq (the two major digital map providers) that agree, then publish the location data for each code. INRIX reports at the TMC level, so each TMC code will have a unique speed value.
- **Speed:** The INRIX-reported real time speed on a specific TMC code link.
- **Average Speed:** The average speed expected on a TMC code for a specific hour of day, and day of week.
- **Travel Time:** The travel time, in minutes that it takes to travel the entire link defined by the TMC code based on the current speed.
- **Score:** In many ways, analogous to the C-Value on a tighter range. 30 represents pure real-time data; 20 represents a blend of real-time, predictive and/or historical data; and 10 represents pure historical data.
• **C-value:** A Confidence Value (range 0-100) that will help individual agencies determine whether the INRIX value meets their criteria for real-time data.

![INRIX Probe Network](image.jpg)

**Figure 3.1 INRIX Probe Network**

**TMC Link**

As the queue length is estimated as a function of TMC link lengths in the proposed method, the accuracy of estimated results are critically influenced by TMC link lengths. Thus, it is necessary to clearly understand the interpretation of TMC code link.

The Request for Proposal (RFP) for I-95 project clearly states requirements for defining the roadway segments used for reporting data:

> Segmentation of the road network is the responsibility of the vendor..... Link definition should be based on logical breaks in facilities where one would expect the potential for differing conditions, such as an interchange or major at-grade intersections.

The RFP described anticipated typical segment lengths for freeways (1-3 miles in urban areas; 3-10 miles in rural areas) and arterials (0.5-3 miles in urban areas; 2-5 in rural areas). INRIX’s
architecture meets this requirement utilizing “TMC paths” as the basis of defining road segments.

The TMC code is composed of 9 digits and define a specific link or road. Figure 3.2 decomposed the 9 digits and further explanation follows:

- **Digit 1**: Refers to the country code. Country code is “1” for the United States.
- **Digits 2-3**: Refers to the Location Table Name (see Figure 3.3). North America is covered with 35 distinct tables, allowing the final six digits to be reused as well as allowing the table coverage to grow in density while still maintaining geographic integrity of the coding scheme.
- **Digit 4 (“+” or “-”)**: Refers to both direction of travel and if the TMC path type is “internal” or “external” (as shown in Figure 3.4).
- **Digit 5-9**: Refers to the specific Location ID in the Location table that is tied to a specific interchange, intersection, boundary, or decision point. In most cases there will be 4 distinct TMC paths near one another on the road network that share this same 5 digit Location ID, each preceded by either “+”, “-”, “P” or “N”.

![Figure 3.2 Interpretation of TMC Code](image-url)
TMC location coding describes two types of paths for every location code: “internal path” and “external path”. The internal path refers to the area just past the decision point or intersection at which the TMC code was placed (for example, a freeway off ramp), while the ‘external path’ refers to the section of the road leading up the decision point. In order to maximize possible data precision, INRIX considers the internal path and external path as individual spatial locations; i.e., speed is reported separately for the two paths. Traffic congestion is often caused by traffic exiting at a decision point. Thus, the external and internal path corresponding to that TMC location might have substantially different speed profiles.

Figure 3.4 illustrates the difference between internal (labeled with ‘P’ or ‘N’) and external (labeled with a ‘+’ or ‘-’) TMC points.
Ultimately, daily speed contour plots during a peak period were created based on the speed data, and link information for appropriate study sites which experiencing recurring congestion in a peak period.

3.2 Shockwave Speed Estimation Method

An algorithm was developed to estimate speeds of backward forming shock wave and forward recovery shock wave in a congested regime on recurring congested freeway sites during a peak period based on converted speed contour plots (or speed contour plots).

As described in chapter 1, the backward forming shock wave is propagated during breakdown and forward recovery shock wave is propagate during recovery in general. In the algorithm, two criteria were developed to identify the breakdown and recovery events. Then, it would output the time points, corresponding link numbers and link lengths of all cells which satisfying the criteria by searching the cell in each link and each time interval of converted speed contour plot. The linear regression method was applied to those output points which were plotted at a time vs. distance diagram. The shockwave speed represents the slope of regression line.

The algorithm was implemented in VBA for MS Excel, and Appendix A contains screenshots of the interface. The remainder of this section is the description of the proposed method in detail.
**Speed (or Speed Index) Threshold & Duration of Speed Drop**

Lorenz and Elefteriadou (2001) recommended that breakdown can be defined using a speed threshold, which may be different for different types of freeway segments. In addition to the speed threshold, or speed drop there should be an associated duration of that speed drop to ensure that breakdown has occurred. They defined breakdown occur: “... when the average speed of all lanes on the freeway dropped below 56 mph for a period of at least five minutes.”

Based on the study, the criteria were defined as (i) *Speed (or speed index) below a certain threshold* (ii) *The duration of speed (or speed index) below threshold is 5 minutes* both in breakdown and recovery events in this thesis. The speed (or speed index) threshold is a site specific variable and unique input while implementing proposed algorithm. Therefore, the threshold should be determined for breakdown event and recovery event respectively at a congestion regime during peak period in each freeway facility or site by examining flow and speed data from sensors.

In this thesis, “speed index” were developed to create time space domain contour plots, which refers to a number divide speed by speed limit of a freeway section, when implementing proposed method. In the field study, the speed index threshold were determined by determining speed threshold for objective freeway sites, as shown in Equation 3-1.

\[
\text{Speed Index Threshold} = \frac{\text{Speed Threshold}}{\text{Speed Limit}}
\]

**Equation 3-1**

In a freeway facility or a freeway site, the speed limit may be different. The speed threshold may differ on different speed limit section. Thus, it is effective to develop time space domain speed index contour plot instead of speed contour plot when estimating shockwave speed using proposed method. However, the speed contour can be created in freeway facilities under a fixed speed limit. Figure A.1 shows the screenshot of speed index threshold input.
**Speed Index Contour Plot**

Prior to describing the proposed algorithm, the speed index contour plot was illustrated. Figure 3.5 shows a time space domain speed index contour plot, which was created using link speed data from the Regional Integrated Transportation Information System (RITIS) during a peak period at an interstate I-40 freeway site near Raleigh, North Carolina from a weekday of April, 2014. As shown in figure, first row shows 1 minute aggregation time interval from 6:00am to 10:00am, while y-axle refers to the space in a freeway site and the traffic moving direction is top to bottom. The first column in y-axle represents link numbers, second column represents link names, third column represents link lengths and fourth column represents speed limits at each link. Other cells are speed indexes. Different color of cell represent different speed index range and the red area can be concluded as the congested and queueing area which covered with lower speeds. From the illustrated speed index plot, the backward forming shock wave and forward recovery shockwave can be intuitively identified, even the rear stationary shock wave. But due to the limitation of understanding the process of INRIX speed data reduction, the existence of rear stationary shock wave was not considered in this thesis.

![Speed Index Contour Plot](image)

**Figure 3.5 Illustration of speed index contour plot**
Proposed Algorithm

After the clear definition of two criteria, the proposed algorithm can output time points, corresponding link numbers and link lengths of all cells which satisfying the criteria by searching the cell in each link and each time interval of a speed index contour plot. Below is the algorithm description in detail.

The algorithm is made up of three loops. The first loop changes time. The second loop changes links. The key step of the algorithm is the third loop that identifies all cells which satisfying criteria and output the time points, corresponding link numbers and link lengths. Following are the steps in detail:

Backward Forming Shockwave Speed

Step 1: Input a speed index threshold
Step 2: Start the speed index search for \( n = 1 \) from \( t = 6:00AM \) or \( 3:30PM \), which is start time point in a contour plot, for each time point in increasing order, if speed index \( \leq \) threshold at time point \( t, t+1, t+2, t+3, t+4 \) (5 minutes duration of queue condition), output \( n \) and \( t \) as well as corresponding link length, stop the search.
Step 3: Set \( n = n + 1 \), \( t = \) output \( t \) in step 2, go to step 2.
Step 4: If no speed index \( \leq \) threshold at time point \( t, t+1, t+2, t+3, t+4 \), stop the iteration.

Forward Recovery Shockwave Speed

Step 7: Input a speed index threshold
Step 8: Start the speed index search for \( n = 1 \) from \( t = 10:00AM \) or \( 7:30PM \), which is end time point in a contour plot, for each time point in decreasing order, if speed index \( \leq \) threshold at time point \( t, t-1, t-2, t-3, t-4 \) (5 minutes duration of queue condition), output \( n \) and \( t \) as well as corresponding link length, stop the search.
Step 9: Set \( n = n + 1 \), \( t = \) output \( t \) in step 7, go to step 7.
Step 10: If no speed index $\leq$ threshold at time point $t, t-1, t-2, t-3, t-4$ or $n = n$ in step 4, stop the iteration.

$n$ represent link number,
$t$ represent time point.

Queue length = the cumulative length of all output links.

As shown in Figure 3.6 and 3.7, all time points, link numbers and link lengths that meet the criteria were output during breakdown and recovery as well as cumulative length were developed. Then, the linear regression line was presented based on the output in a time vs. distance diagram. Ultimately, the speeds of backward forming shock wave and forward recovery shock wave were estimated by calculating the values of the slope of linear regression line, as shown in Figure 3.6 and 3.7.
In addition to the speeds of backward forming shock wave and forward recovery shock wave estimation in a speed index contour plot, the corresponding queue length can be estimated easily based on the proposed algorithm. The queue length refers to the maximum queue length in a congested regime during a peak period. In this thesis, two different methods were presented to estimate queue length after shockwave speed estimation. The first method is simply summing up the link lengths of all outputs, while in other method, the queue length was estimated in terms of speeds of backward forming shock wave and forward recovery shock wave as well as start time point of backward forming shock wave and end time point of forward recovery shock wave, as described below.

**Method 1**
Queue length 1 = sum of link lengths of all output links, as shown in Figure 3.8.

**Method 2**
Queue length 2 is equivalent to the distance between frontal point (bottleneck location) to the point of backward forming shock wave ending and forward recovery shock wave starting if assuming no rear stationary shock wave were existed, as shown in Figure 3.8.
Figure 3.8 Illustration of queue lengths estimated from two methods

Figure 3.9 shows the screenshot of queue lengths estimated from the two methods in MS Excel. As the data reduction process of archived vehicle probe data from INRIX is unknown, the queue length 1 may not be the true queue length in field study. Thus, it was assumed that the range of true queue length is between these two values in this thesis, which need further validation.
Figure 3. 9 Screenshot of queue lengths estimated from two method
4. Case Study

This chapter documents estimated speeds of backward forming shock wave and forward recovery shock wave as well as queue lengths based on proposed method; compares the speed results to the shockwave speeds estimated based on shockwave theory associated with HCM 2010 freeway flow-density relationship using assumed deterministic values of freeway downstream capacity and upstream demand.

4.1 Site Description

In this study, the proposed shockwave speed method was implemented in three freeway sites on interstate I-40/I-440 surrounding Raleigh. All three sites experienced recurring congestion in a peak period, making them suitable for shockwave speed analysis. Furthermore, the bottleneck location is at the end of each route (see A below in each figure) during congestion regime. Figure 4.1 through Figure 4.3 show the three routes in a Google Map view, respectively. The red arrow shows the direction of traffic in the analysis period.

- **Route 1**: An approximately 11-mile section from NC 42 (Exit 312) on I-40 to the I-40/I-440 Split (Exit 301), which is a northbound/westbound path along I-40.
- **Route 2**: An approximately 4-mile section from I-40/US 264 Split (Exit 14) on I-440 to Wake Forest Rd (Exit 10) on I-440, which is a westbound path along I-440.
- **Route 3**: An approximately 5-mile section from Capital Blvd (Exit 11) on I-440 to the I-40/I-440 Split (Exit 16), which is an eastbound path along I-440.
Figure 4. 1 Route 1 in Google Map
Figure 4. 2 Route 2 in Google Map

Figure 4. 3 Route 3 in Google Map
Seven speed index contour plots were created for each route based on the speed data from seven different weekdays in April 2014, in which were not influenced by non-recurring factors that affect capacity, including inclement weather, and vehicle incidents. Gaps in the reported data were infrequent. If gaps occurred, linear interpolation for adjacent links and/or time periods was used to fill in the gaps. The speed contours were established in 1-min aggregation period by extracting 1 minute time interval speed data.

The preliminary study on recurring congestion time period has shown that route 1 & 2 experiences recurring congestion during AM peak period, while the recurring congestion occurs at route 3 during PM peak period. Based on such observation, the 1-min interval speed index contour plots for route 1 and route 2 were developed from 6:00AM to 10:00AM, while the speed index contour plots for route 3 were established from 3:30PM to 7:30PM, which are sufficient time period covering congestion regime.

Figure 4.4 indicates a speed index contour plot on route 1 from a weekday. Due to the limited space, the front and rear part were not shown in the figure, which refers to the contour plots from 6:00am to 7:00am and from 8:34am to 10:00am. The speed limit throughout route 1 is 70mph. As shown in the figure, two independent recurring congestions and queues were observed during AM peak period: (i) an approximately 1.5 hours congestion caused by the bottleneck at I-40/I-440 Split (Exit 301), and (ii) a less severe recurring congestion caused by the bottleneck at US 70 BUS (Exit 306). In this thesis, the former recurring congestion was focused for shockwave speeds and queue lengths estimation.

Figure 4.5 and Figure 4.6 shows a speed index contour plots on route 2 and route 3 from a weekday in April, 2014. In the figure, the front and rear part were not show as well. The speed limit on route 2 & 3 are 60 mph and 65 mph, respectively. Appendix B includes the speed index contour plots of remaining days for three routes.
Figure 4. 4 Speed Index Contour Plot on Route 1 - AM Peak
Figure 4.5 Speed Index Contour Plot on Route 2 - AM Peak

<table>
<thead>
<tr>
<th>Time</th>
<th>Forward Recovery Shock wave</th>
<th>Backward Forming Shock wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:00am</td>
<td>Forward Recovery Shock wave</td>
<td></td>
</tr>
<tr>
<td>10:00am</td>
<td>Forward Recovery Shock wave</td>
<td></td>
</tr>
</tbody>
</table>

Speed Index: Green--1.0–0.8; Yellow--0.8–0.4; Red--0.4–0.0
Figure 4. 6 Speed Index Contour Plot on Route 3 - PM Peak
4.2 Speeds of Backward Forming Shock Wave & Forward Recovery Shock Wave

In this section, the speeds of backward forming shock wave and forward recovery shock wave in three objective routes for 7 selected weekdays in April, 2014 were estimated based on both proposed method and traditional shockwave theory method. A comparison of these two results are presented.

The speed index threshold was determined for each route in terms of flow and speed data from sensors located at bottleneck point prior to algorithm implementation in shockwave speed and queue length estimation. The forming and recovery shockwave speeds as well as corresponding queue lengths were estimated.

**Proposed Method**

Prior to the implementation of shockwave speed estimation method based on time space domain speed index contour plot, the speed index threshold was determined for each route in terms of flow and speed data from Traffic.com sensors covered on the three routes.

**Speed Index Threshold**

Traffic.com provides real-time and historic traffic data with sensors covering all of interstate I-440 and the portions of interstate I-40 that surround the Raleigh metropolitan area, as shown in Figure 4.7, and provides 5-min, 15-min, or 1-hour aggregated flow and speed data.
For the purpose of determining speed index thresholds, time series plots of flow and speed of seven weekdays from for each study site were created in terms of the 5-min aggregation flow and speed data collected from appropriate Traffic.com sensors. Then, pre-breakdown speed and post-recovery speed of a congestion and queue condition during the corresponding peak period were collected. *Pre-breakdown speed refers to the speed immediately prior to breakdown; Post-recovery speed refers to the speed immediately after the recovery*, as shown in Figure 4.9. Ultimately, the threshold were determined as the lowest value of pre-breakdown speed (post-recovery speed in recovery event) in seven weekdays. The following has shown the procedure of speed index thresholds determination in detail.

**Route 1**

Figure 4.8 shows the route 1 with covered sensors from Traffic.com. The preliminary study on field site have shown that the sensor 040170 is close to the bottleneck location during congested period (see Figure 4.8).
Figure 4. 8 Route 1 with Covered Sensors (From Traffic.com)

Figure 4.9 illustrates the pre-breakdown speed and post-recovery speed in a single time-series plot (breakdown and recovery event occurred at AM peak period) of flows and speeds at sensor 040170 throughout a weekday.
Table 4.1 shows the pre-breakdown speeds and post-recovery speeds in seven weekdays. As shown in table, the pre-breakdown speeds and post-recovery speeds are almost identical with the speed limit of 70 mph. Thus, the speed index thresholds of backward forming shock wave and forward recovery shock wave estimation are determined as 0.8 and 0.78 respectively, as shown in Table 4.1.
Table 4.1 Pre-breakdown and Post-recovery speeds of seven weekdays on route 1

<table>
<thead>
<tr>
<th>Speed Limit = 70 mph</th>
<th>Pre-Breakdown Speed (mph)</th>
<th>Post-Recovery Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/01/2014</td>
<td>60.11</td>
<td>62.14</td>
</tr>
<tr>
<td>04/02/2014</td>
<td>57.95</td>
<td>59.99</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>57.7</td>
<td>57.75</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>56.79</td>
<td>57.33</td>
</tr>
<tr>
<td>04/11/2014</td>
<td>59.36</td>
<td>58.78</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>58.37</td>
<td>55.72</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>59.57</td>
<td>54.76</td>
</tr>
<tr>
<td>Minimum Speed</td>
<td>56.8</td>
<td>54.8</td>
</tr>
<tr>
<td>Speed Threshold</td>
<td>56.8</td>
<td>54.8</td>
</tr>
<tr>
<td>Speed Index Threshold</td>
<td>0.8</td>
<td>0.78</td>
</tr>
</tbody>
</table>

**Route 2 & 3**

The speed index thresholds on route 2 & 3 were determined using the same procedures. As shown in Figure 4.10 and 4.11, sensor 440140 and 440100 are located close to the bottleneck location of route 2 & 3 under congestion and queue condition during a peak period.

Figure 4.10 Maps of Route 2 with Covered Sensors (From Traffic.com)
Table 4.2 and Table 4.3 shows the pre-breakdown speeds and post-recovery speeds in seven weekdays on route 2 & 3. As shown in Table 4.2, speed index thresholds of backward forming shock wave and forward recovery shock wave estimation were determined as 0.87 and 0.85 on route 2. While, both the values were 0.79 on route 3.

**Table 4.2 Pre-breakdown and Post-recovery speeds of seven weekdays on route 2**

<table>
<thead>
<tr>
<th>Speed Limit = 60 mph</th>
<th>Pre-breakdown Speed (mph)</th>
<th>Post-recovery Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>56.42</td>
<td>57.57</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>58.97</td>
<td>59.22</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>54.31</td>
<td>56.02</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>52.2</td>
<td>55.89</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>55.71</td>
<td>60.58</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>54.12</td>
<td>52.16</td>
</tr>
<tr>
<td>04/28/2014</td>
<td>56.11</td>
<td>51.42</td>
</tr>
<tr>
<td>Minimum Speed</td>
<td>52.2</td>
<td>51.4</td>
</tr>
<tr>
<td>Speed Threshold</td>
<td>52.2</td>
<td>51.4</td>
</tr>
<tr>
<td>Speed Index Threshold</td>
<td>0.87</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Table 4.3 Pre-breakdown and Post-recovery speeds of seven weekdays on route 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre-breakdown Speed (mph)</th>
<th>Post-Recovery Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>58.41</td>
<td>51.58</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>56.38</td>
<td>57.43</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>61.71</td>
<td>59.59</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>65.77</td>
<td>64.78</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>60.76</td>
<td>55.58</td>
</tr>
<tr>
<td>04/22/2014</td>
<td>51.42</td>
<td>57.66</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>56.82</td>
<td>54.21</td>
</tr>
<tr>
<td>Minimum Speed</td>
<td>51.4</td>
<td>51.6</td>
</tr>
<tr>
<td>Speed Threshold</td>
<td>51.4</td>
<td>51.6</td>
</tr>
<tr>
<td>Speed Index Threshold</td>
<td>0.79</td>
<td>0.79</td>
</tr>
</tbody>
</table>

**Shockwave Theory Method**

For the validation purpose, the shockwave speed estimation method based on classical shockwave theory associate with HCM 2010 freeway flow-density relationship using assumed deterministic values of freeway downstream capacity and upstream demand has been explored, as shown in section 2.2. Furthermore, the capacity and demand values were estimated based on Traffic.com sensors flow data.
\[
\nu_{fw} = \frac{q_{arr} - q_c}{k_{arr} - k_c}
\]
Equation 2-1

\[
\nu_{rw} = \frac{q_{arr} - q_c}{k_{arr} - k_c}
\]
Equation 2-2

Where

\( \nu_{fw} \) = propagation speed of forming shockwave (miles/h)

\( \nu_{rw} \) = propagation speed of recovery shockwave (miles/h)

\( q_{arr} \) = demand flow at upstream of proposed route during breakdown period (pc/h/ln)

\( k_{arr} \) = traffic density at upstream of proposed route during breakdown period (pc/mi/ln)

\( q_{arr} \) = demand flow at upstream of proposed route during recovery period (pc/h/ln)

\( k_{arr} \) = traffic density at upstream of proposed route during recovery period (pc/mi/ln)

\( q_c \) = capacity flow at downstream of proposed route during congestion period (pc/h/ln)

\( k_c \) = traffic density at downstream of proposed route during congestion period (pc/mi/ln)

**Capacity Estimation**

Based on the literature review in chapter 2, pre-breakdown flow was highly recommended used in capacity definition and estimation. In this thesis, the pre-breakdown flow was chosen as...
capacity and were estimated at downstream sensors that close to bottleneck location for seven weekdays on each route.

Lorenz and Elefteriadou (2001) defined the pre-breakdown flow as the 5-min flow (for 5-min aggregation intervals) or 15-min flow (for 15-min aggregation intervals) immediately prior to the breakdown. The definition was applied in this thesis to estimate pre-breakdown flow. Figure 4.7 illustrates the pre-breakdown flow in a single time-series plot of flows and speeds from sensor 040170 on route 1.

![Figure 4.7 Illustration of breakdown flow on Time-Series Plot of Flow and Speed (Sensor 040170)](image)

Based on the procedure, the downstream capacities of seven weekdays on each route were estimated from the sensors close to bottleneck location, which were described in section 4.2-speed index threshold determination. Table 4.4 indicates the results for three routes.
Table 4. 4 Capacity at downstream of three study routes in seven weekdays.

(a) Route 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre-Breakdown Flow (vehicle/h)</th>
<th>Pre-breakdown flow (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/01/2014</td>
<td>5196</td>
<td>5508</td>
</tr>
<tr>
<td>04/02/2014</td>
<td>5844</td>
<td>6024</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>5528</td>
<td>5722</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>6108</td>
<td>6360</td>
</tr>
<tr>
<td>04/11/2014</td>
<td>5244</td>
<td>5490</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>5640</td>
<td>5856</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>5694</td>
<td>5892</td>
</tr>
<tr>
<td><strong>Average Capacity</strong></td>
<td><strong>5603</strong></td>
<td><strong>5836</strong></td>
</tr>
</tbody>
</table>

(b) Route 2

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre-breakdown flow (vehicle/h)</th>
<th>Pre-breakdown flow (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>7500</td>
<td>7824</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>7066</td>
<td>7349</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>7044</td>
<td>7230</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>7188</td>
<td>7446</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>7152</td>
<td>7440</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>7104</td>
<td>7638</td>
</tr>
<tr>
<td>04/28/2014</td>
<td>6864</td>
<td>7284</td>
</tr>
<tr>
<td><strong>Average Capacity</strong></td>
<td><strong>7131</strong></td>
<td><strong>7459</strong></td>
</tr>
</tbody>
</table>

(c) Route 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre-breakdown flow (vehicle/h)</th>
<th>Pre-breakdown flow (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>4980</td>
<td>5268</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>4968</td>
<td>5190</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>4836</td>
<td>5172</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>5160</td>
<td>5288</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>4596</td>
<td>4884</td>
</tr>
<tr>
<td>04/22/2014</td>
<td>4500</td>
<td>5028</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>4880</td>
<td>4974</td>
</tr>
<tr>
<td><strong>Average Capacity</strong></td>
<td><strong>4734</strong></td>
<td><strong>5046</strong></td>
</tr>
</tbody>
</table>

**Demand Estimation**

Upstream demands on each route were simply estimated by averaging 5-min flow rate from sensors at far upstream of the route during the time period of interest. The backward forming shock wave propagation time period and recovery shock wave propagation time period can be
easily identified from time-space domain speed index contour plots. Table 4.5 shows the results of each route in seven different weekdays.

Table 4. 5 Demand at upstream of three study routes in seven weekdays.

(d) **Route 1**

<table>
<thead>
<tr>
<th>Date</th>
<th>Route 1 Demand (vehicle/h)</th>
<th>Route 1 Demand (pc/h)</th>
<th>Route 1 Demand (vehicle/h)</th>
<th>Route 1 Demand (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/01/2014</td>
<td>6315</td>
<td>6543</td>
<td>4248</td>
<td>4486</td>
</tr>
<tr>
<td>04/02/2014</td>
<td>6202</td>
<td>6573</td>
<td>6619</td>
<td>7088</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>5922</td>
<td>6359</td>
<td>2121</td>
<td>2469</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>6164</td>
<td>6489</td>
<td>4440</td>
<td>4696</td>
</tr>
<tr>
<td>04/11/2014</td>
<td>5832</td>
<td>6203</td>
<td>4217</td>
<td>4541</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>6178</td>
<td>6611</td>
<td>4329</td>
<td>4976</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>5972</td>
<td>6332</td>
<td>4590</td>
<td>5039</td>
</tr>
<tr>
<td><strong>Average Demand</strong></td>
<td><strong>6084</strong></td>
<td><strong>6458</strong></td>
<td><strong>4366</strong></td>
<td><strong>4756</strong></td>
</tr>
</tbody>
</table>

(e) **Route 2**

<table>
<thead>
<tr>
<th>Date</th>
<th>Route 2 Demand (vehicle/h)</th>
<th>Route 2 Demand (pc/h)</th>
<th>Route 2 Demand (vehicle/h)</th>
<th>Route 2 Demand (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>7655</td>
<td>8264</td>
<td>6037</td>
<td>6244</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>8555</td>
<td>8984</td>
<td>3078</td>
<td>5272</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>7631</td>
<td>7992</td>
<td>5905</td>
<td>6203</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>8655</td>
<td>8959</td>
<td>6035</td>
<td>6205</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>8292</td>
<td>8586</td>
<td>5583</td>
<td>5842</td>
</tr>
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<td>04/24/2014</td>
<td>8612</td>
<td>8984</td>
<td>5593</td>
<td>5873</td>
</tr>
<tr>
<td>04/28/2014</td>
<td>7956</td>
<td>8220</td>
<td>5407</td>
<td>5599</td>
</tr>
<tr>
<td><strong>Average Demand</strong></td>
<td><strong>8222</strong></td>
<td><strong>8570</strong></td>
<td><strong>5663</strong></td>
<td><strong>5891</strong></td>
</tr>
</tbody>
</table>

(f) **Route 3**

<table>
<thead>
<tr>
<th>Date</th>
<th>Route 3 Demand (vehicle/h)</th>
<th>Route 3 Demand (pc/h)</th>
<th>Route 3 Demand (vehicle/h)</th>
<th>Route 3 Demand (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
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<td>5759</td>
<td>4128</td>
<td>4167</td>
</tr>
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<td>04/03/2014</td>
<td>5852</td>
<td>5914</td>
<td>3813</td>
<td>3858</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>5956</td>
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<td>4268</td>
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<td>5728</td>
<td>3602</td>
<td>3643</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>5443</td>
<td>5501</td>
<td>3794</td>
<td>3838</td>
</tr>
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<td>04/22/2014</td>
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<td>5536</td>
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<td>4295</td>
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<td>04/24/2014</td>
<td>5581</td>
<td>5543</td>
<td>3881</td>
<td>3926</td>
</tr>
<tr>
<td><strong>Average Demand</strong></td>
<td><strong>5543</strong></td>
<td><strong>5602</strong></td>
<td><strong>3880</strong></td>
<td><strong>3925</strong></td>
</tr>
</tbody>
</table>
Results

Shockwave speed results estimated from proposed method based on time-space domain speed index contour plot are presented in this section. Then compared to the results from classical shockwave theory method to examine the validation.

Estimated speeds of backward forming shock wave and forward recovery shock wave based on proposed method and shockwave theory method on each route are shown in Table 4.6, Table 4.7, and Table 4.8. Intuitively, the higher of R Square, the more accurate and reliable of estimated shockwave speeds.

As shown in Table 4.6, average R Squares of backward forming and forward recovery shockwave speeds are 0.72 and 0.78, respectively. Compared to the results from shockwave theory method, average percentage of differences of backward forming shock wave speed is 26.73%, while the value of forming recovery shockwave speed is approximately 45%, which is almost two times larger than former one.

Specifically, significant differences of forward recovery shockwave speeds occurred in April 3 and 11, 2014. The further observation on these two particular days has indicated that both the durations of congestion and queue condition are significantly shorter and experienced short queue lengths. Furthermore, the magnitudes of backward forming shockwave speeds are less than those of forward recovery shock wave at most of days in both methods.
Table 4. 6 Speeds of Shock waves of Route 1

<table>
<thead>
<tr>
<th></th>
<th>Proposed Method</th>
<th>Shockwave Theory Method</th>
<th>Percentage of Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forming Shockwave</td>
<td>Recovery Shockwave</td>
<td>Forming Shockwave</td>
</tr>
<tr>
<td>Speed (mph)</td>
<td>Speed (mph)</td>
<td>Speed (mph)</td>
<td>Speed (mph)</td>
</tr>
<tr>
<td>04/01/2014</td>
<td>-14.32</td>
<td>6.89</td>
<td>22.01</td>
</tr>
<tr>
<td>04/02/2014</td>
<td>-5.68</td>
<td>0.89</td>
<td>5.45</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>-13.37</td>
<td>6.74</td>
<td>26.74</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>-6.01</td>
<td>0.57</td>
<td>22.10</td>
</tr>
<tr>
<td>04/11/2014</td>
<td>-9.40</td>
<td>0.76</td>
<td>4.65</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>-9.17</td>
<td>0.53</td>
<td>17.06</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>-5.82</td>
<td>0.66</td>
<td>13.06</td>
</tr>
<tr>
<td>Average</td>
<td>-9.54</td>
<td>0.72</td>
<td>15.95</td>
</tr>
</tbody>
</table>

Table 4.7 shows the results on route 2. On route 2, average R Squares of backward forming and forward recovery shockwave speeds are also significantly high, of which values are 0.74 and 0.88, respectively. The numerical value of average forming shockwave speed is 6.51 mph and lower than average recovery shockwave speed (10.73 mph). The average percentages of difference are 28.45% and 13.99%, respectively, which indicated that the speeds estimated from both methods are close to each other.

Table 4. 7 Speeds of Shock waves of Route 2

<table>
<thead>
<tr>
<th></th>
<th>Proposed Method</th>
<th>Shockwave Theory Method</th>
<th>Percentage of Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forming Shockwave</td>
<td>Recovery Shockwave</td>
<td>Forming Shockwave</td>
</tr>
<tr>
<td>Speed (mph)</td>
<td>Speed (mph)</td>
<td>Speed (mph)</td>
<td>Speed (mph)</td>
</tr>
<tr>
<td>04/01/2014</td>
<td>-4.23</td>
<td>0.64</td>
<td>7.81</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>-10.63</td>
<td>0.75</td>
<td>4.96</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>-2.76</td>
<td>0.88</td>
<td>4.28</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>-8.82</td>
<td>0.75</td>
<td>8.95</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>-1.95</td>
<td>0.35</td>
<td>19.81</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>-7.17</td>
<td>0.95</td>
<td>21.34</td>
</tr>
<tr>
<td>04/28/2014</td>
<td>-7.90</td>
<td>0.83</td>
<td>8.46</td>
</tr>
<tr>
<td>Average</td>
<td>-5.31</td>
<td>0.74</td>
<td>10.75</td>
</tr>
</tbody>
</table>

Figure 4.8 shows that the speeds of backward forming shock wave and forward recovery shock wave on route 3 is much lower than those on other two routes, due to lower downstream capacity and lower upstream demand as well as the impact of geometric characteristics. And the forward recovery shock wave propagated faster than backward forming shock wave in both methods. The average percentages of difference is 18% and 21.37%, respectively.
Table 4. 8 Speeds of Shock waves of Route 3

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>-1.91</td>
<td>0.79</td>
<td>-1.47</td>
<td>3.03</td>
<td>23.15%</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>-2.01</td>
<td>0.45</td>
<td>-2.16</td>
<td>3.56</td>
<td>7.49%</td>
</tr>
<tr>
<td>04/04/2014</td>
<td>-1.56</td>
<td>2.14</td>
<td>-1.74</td>
<td>2.46</td>
<td>9.90%</td>
</tr>
<tr>
<td>04/05/2014</td>
<td>-2.25</td>
<td>0.88</td>
<td>-1.29</td>
<td>4.45</td>
<td>42.61%</td>
</tr>
<tr>
<td>04/06/2014</td>
<td>-2.06</td>
<td>0.88</td>
<td>-1.70</td>
<td>2.66</td>
<td>17.42%</td>
</tr>
<tr>
<td>04/07/2014</td>
<td>-1.83</td>
<td>0.72</td>
<td>-1.64</td>
<td>1.93</td>
<td>8.50%</td>
</tr>
<tr>
<td>Average</td>
<td>-1.82</td>
<td>0.70</td>
<td>-1.67</td>
<td>2.89</td>
<td>18.00%</td>
</tr>
</tbody>
</table>

Overall, the average R Squares of both backward forming shockwave speed and forward recovery shockwave speed are significantly high and the average percentages of difference for both shockwave speeds are lower enough on three routes. Thus, it can be concluded that the results estimated from proposed method are effective and reasonable. Furthermore, the shockwave speeds estimated from proposed method are slightly higher than those estimated from shockwave theory method in most of cases.

The average speed of backward forming shock wave is much lower than the speed of forward recovery shock wave on three routes, which indicated that the breakdown event last longer than recovery event in a congested regime.

Note that, significant differences of estimated forward recovery shockwave speeds between two methods were observed in some particular days on route 1, such as April 3 and 11, 2014. Further examine has been done on those days by scrutinize the speed index contours. It was indicated that, the durations of congestion regime are significantly short with drastic recovery, while the queue lengths are short as well. Thus, an assumption can be presented that, the more severe the congestion is, and the larger queue length is, the more accurate and effective the estimated shockwave speeds from proposed method are.
4.3 Queue Length

In this section, queue lengths were estimated in two different methods described in chapter 3 based on the estimated shockwave speeds from proposed method. Note that, the queue length 1 refers to the maximum queue length estimated based on method 1, while the queue length 2 represents the maximum queue length estimated using method 2.

Results

The queue lengths estimated from two different methods as well as percentage of difference for route 1 are shown in Table 4.9. The average queue lengths from method 1 and 2 are 6.49 and 7.39 miles, respectively, which indicated that the true average queue length is between 6.49 and 7.39 mile. The percentage of difference of two queue lengths is 17.58%.

Table 4.9 Queue Lengths on Route 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Queue Length 1 (mile)</th>
<th>Queue Length 2 (mile)</th>
<th>Percentage of Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/01/2014</td>
<td>8.79</td>
<td>10.99</td>
<td>25.01%</td>
</tr>
<tr>
<td>04/02/2014</td>
<td>4.56</td>
<td>4.13</td>
<td>9.37%</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>8.79</td>
<td>10.85</td>
<td>23.41%</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>2.22</td>
<td>3.00</td>
<td>35.10%</td>
</tr>
<tr>
<td>04/11/2014</td>
<td>3.48</td>
<td>4.10</td>
<td>17.69%</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>8.79</td>
<td>9.66</td>
<td>9.90%</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>8.79</td>
<td>9.01</td>
<td>2.55%</td>
</tr>
<tr>
<td>Average</td>
<td>6.49</td>
<td>7.39</td>
<td>17.58%</td>
</tr>
</tbody>
</table>
The queue lengths estimated from two different methods as well as percentage of difference for route 2 are shown in Table 4.10. The average queue lengths from method 1 and 2 are 2.75 and 3.02 miles, respectively, which indicated that the true average queue length is between 2.75 and 3.02 mile. The percentage of difference of two queue lengths is 24.72%.

### Table 4.10 Queue Lengths on Route 2

<table>
<thead>
<tr>
<th>Date</th>
<th>Queue Length 1 (mile)</th>
<th>Queue Length 2 (mile)</th>
<th>Percentage of Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>1.71</td>
<td>1.88</td>
<td>9.91%</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>2.79</td>
<td>2.22</td>
<td>20.40%</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>3.18</td>
<td>3.10</td>
<td>2.48%</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>2.79</td>
<td>2.22</td>
<td>20.40%</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>2.79</td>
<td>3.57</td>
<td>28.01%</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>2.79</td>
<td>5.19</td>
<td>86.04%</td>
</tr>
<tr>
<td>04/28/2014</td>
<td>3.18</td>
<td>3.00</td>
<td>5.81%</td>
</tr>
<tr>
<td>Average</td>
<td>2.75</td>
<td>3.02</td>
<td>24.72%</td>
</tr>
</tbody>
</table>

The queue lengths estimated from two different methods as well as percentage of difference for route 3 are shown in Table 4.11. The average queue lengths from method 1 and 2 are 4.77 and 3.11 miles, respectively, which indicated that the true average queue length is between 3.11 and 4.77 mile. The percentage of difference of two queue lengths is 35.25%.

### Table 4.11 Queue Lengths on Route 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Queue Length 1 (mile)</th>
<th>Queue Length 2 (mile)</th>
<th>Percentage of Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/02/2014</td>
<td>5.49</td>
<td>3.40</td>
<td>38.08%</td>
</tr>
<tr>
<td>04/03/2014</td>
<td>3.57</td>
<td>2.44</td>
<td>31.58%</td>
</tr>
<tr>
<td>04/08/2014</td>
<td>5.49</td>
<td>3.29</td>
<td>39.98%</td>
</tr>
<tr>
<td>04/14/2014</td>
<td>5.49</td>
<td>4.12</td>
<td>25.03%</td>
</tr>
<tr>
<td>04/17/2014</td>
<td>5.14</td>
<td>3.74</td>
<td>27.26%</td>
</tr>
<tr>
<td>04/22/2014</td>
<td>3.57</td>
<td>1.81</td>
<td>49.29%</td>
</tr>
<tr>
<td>04/24/2014</td>
<td>4.64</td>
<td>2.99</td>
<td>35.51%</td>
</tr>
<tr>
<td>Average</td>
<td>4.77</td>
<td>3.11</td>
<td>35.25%</td>
</tr>
</tbody>
</table>
In general, the queue lengths estimated from both methods are slightly different on all routes. The average queue length 1 is lower than average queue length 2 on route 1 and 2, which is adverse on route 3. Furthermore, the average duration of congestion and queue condition can be easily evaluated for each route in terms of the average shockwave speeds and average queue length 2. The congestion regime on route 3 during peak period sustained approximately 2.5 hours and much longer than the durations on route 1 and 2. The average duration of congestion and queue condition on route 1 and 2 are approximately 1.2 hours and 1 hour, respectively.
5. Conclusions and Recommendations

This chapter concludes the proposed methodology and meaningful findings in this study. This chapter also documents discussions and recommendations about data collection, methodology for further research.

5.1 Conclusions

This study developed a methodology to estimate speeds of backward forming shock wave and forward recovery shock wave as well as queue length based on time-space domain speed index contour plots. The speed data were collected and reduced from Regional Integrated Transportation Information System (RITIS), which archives one-minute aggregation link speed from the INRIX probe vehicle network as a part of the I-95 Corridor Coalition Vehicle Probe Project. Additionally, traffic demands and capacities were estimated from point sensor data provided by Traffic.com. The shockwave speed estimation method using shockwave theory associated with HCM 2010 flow-density relationship was explored to examine the validation of proposed method. It compared the results from three different routes on interstates I-40/I-440 freeway facilities, which experience recurring congestion during a peak period.

**Speeds of Backward Forming Shock Wave & Forward Recovery Shock Wave**

As shown in Table 5.1, it can be concluded that the shockwave speeds estimated from proposed method are effective and reasonable, as the average R Squares are significantly high and the average percentages of difference for shockwave speeds from both methods are significantly low on each route. Besides, several findings are concluded as follows:

- The shockwave speeds estimated from proposed method are slightly **higher than** those estimated from associated with HCM 2010 flow-density relationship using assumed deterministic values of freeway downstream capacity and upstream demand.
- The average speed of backward forming shock wave is significantly **lower than** the average speed of forward recovery shock wave on each route. It possibly due to the drastic demand
reduction at upstream during recovery compared to the progressive demand increasing at upstream when backward forming shock wave propagating.

Table 5. 1 Summary of Shockwave Speeds

<table>
<thead>
<tr>
<th>Route</th>
<th>Average Speed of Backward Forming Shock wave (mph)</th>
<th>Average Speed of Forward Recovery Shock wave (mph)</th>
<th>Average Percentage of Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1</td>
<td>-9.54</td>
<td>-6.71</td>
<td>13.06</td>
</tr>
<tr>
<td>Route 2</td>
<td>-6.51</td>
<td>-7.23</td>
<td>10.72</td>
</tr>
<tr>
<td>Route 3</td>
<td>-1.82</td>
<td>-1.67</td>
<td>3.81</td>
</tr>
</tbody>
</table>

**Queue Length**

From the results, the queue lengths estimated from two proposed methods are slightly different on each route, while the average percentages of difference are 17.58%, 24.72%, and 35.25%, respectively. The average queue length 1 is lower than queue length on route 1 and 2, while the results are adverse on route 3. On route 1, the estimated queue lengths based on proposed method vary from day to day. Specifically, the queue lengths vary from 2.22 to 8.79 mile. Under congestion and queue condition, the true steady state queue length on route 2 was between 2.75 and 3.02 mile, while between 3.11 and 4.77 mile on route 3.

Furthermore, the durations of congestion regime were evaluated for each route. The congestion regime on route 3 during peak period sustained approximately 2.5 hours and the duration is much longer than those on route 1 and 2, which is approximately 1.2 hours and 1 hour, respectively.
5.2 Discussions and Recommendations

**Speed Index Threshold & Duration of Speed Drop**

Speed index threshold is a key parameter and a unique input when implementing proposed algorithm to estimate speeds of backward forming shock wave and forward recovery shock wave in a time space domain contour plot. It is important to determine appropriate threshold to define breakdown and recovery event, as the minor variation of threshold may lead different results. The threshold may be different for different types of freeway segments, and be determined as a function of geometric characteristics and free flow speed or speed limit at the site. Furthermore, sensitivity analysis is highly recommended by testing different speed index threshold to find out the most appropriate speed index threshold.

In addition to the speed index threshold, there should be an appropriate duration of speed drop to ensure breakdown event. In the proposed methodology, duration of 5-minutes was developed to identify breakdown and recovery. However, 5 minutes may not long enough in the freeway facilities located at other states or other sites. Consistent with previous research (Lorenz and Elefteriadou 2001), duration of 15-minutes are recommended while the results from 5-minutes duration are not precise and reasonable.

**Proposed Method**

In this thesis, the shockwave theory method associated with HCM 2010 flow-density relationship using assumed deterministic values of freeway downstream capacity and upstream demand was explored for validation. However, the assumed deterministic values of capacities and demands may reduce the accuracy of the results. It recommended that the capacity and demand can be estimated more precisely when fully considering the stochastic characteristics of freeway capacity, although the process is more complicated.
Furthermore, other method, such as HCM simulation model using FREEVAL (a macroscopic analysis tool) will be applied to estimate shockwave speeds for the purpose of comprehensive validation of proposed methodology in future research.
REFERENCES


11. Regional Integrated Transportation Information System (RITIS),2014 vpp.ritis.org


27. Dong, J., and H. S. Mahmassani, “Flow Breakdown and Travel Time Reliability”, In Transportation Research Record: Journal of the Transportation Research Board, No. 2124,


31. Regional Integrated Transportation Information System (RITIS), 2014 vpp.ritis.org


Appendix A: Screenshots of the interface and output of VBA coded MS Excel.

Figure A. 1 Input Screenshot

Figure A. 2 Screenshot of backward forming shockwave speed estimation
Figure A. 3 Screenshot of forward recovery shockwave speed estimation

Figure A. 4 Screenshot of shockwave speeds estimated from shockwave theory & queue lengths estimated from two methods
Appendix B: Time-Space Domain Speed Index Contour Plots

(a) Speed Index Contour Plot (April 1, 2014)
(b) Speed Index Contour Plot (April 2, 2014)
(c) Speed Index Contour Plot (April 3, 2014)
(d) Speed Index Contour Plot (April 8, 2014)
(e) Speed Index Contour Plot (April 11, 2014)
(f) Speed Index Contour Plot (April 14, 2014)
(g) Speed Index Contour Plot (April 24, 2014)

Figure B. 1 Route 1 - AM Peak
(a) Speed Index Contour Plot (April 2, 2014)

(b) Speed Index Contour Plot (April 3, 2014)

(c) Speed Index Contour Plot (April 8, 2014)
(g) Speed Index Contour Plot (April 28, 2014)

Figure B. 2 Route 2 - AM Peak
(a) Speed Index Contour Plot (April 2, 2014)
(b) Speed Index Contour Plot (April 3, 2014)
(a) Speed Index Contour Plot (April 8, 2014)
(b) Speed Index Contour Plot (April 14, 2014)
(c) Speed Index Contour Plot (April 17, 2014)
(d) Speed Index Contour Plot (April 22, 2014)
(e) Speed Index Contour Plot (April 24, 2014)

Figure B. 3 Route 3 - PM Peak