THE INFLUENCE OF CRASHES ON NETWORK-WIDE FLOW-DENSITY RELATION

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

The Influence of Crashes on Network-wide Flow-Density Relation

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This research compares flow-density relationships of a major urban freeway network in Chicago, Illinois during peak hours with and without reported crashes for the years 2007 – 2010. Currently, there is a long delay in getting information about a crash to drivers approaching a crash site. This leads to congestion as approaching vehicles are unaware of the crash ahead. The correlation between the time or location of a crash on a network and the shape and distribution of the resulting flow-density diagram can be used to understand the areas within the transportation network that will be eventually affected by specific crashes. Once these relationships are defined, then ITS technologies including CV with V2V and V2I communications can be used to send messages to drivers headed in the direction of the crash and alert Emergency Medical Services sooner. This will allow drivers to redirect their routes to avoid the crash site and overall, reduce congestion. Major differences were found in the flow-density diagrams between peak hours with and without reported crashes on the network. This research suggests relationships between the spatial distribution of crashes and the resulting flow-density diagrams. Future work involves obtaining more data to define a more distinct relationship and simulating the same network with CV at different market penetration rates on similar days to study the effects on the resulting flow-density diagrams.

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CHAPTER I

INTRODUCTION

Intelligent Transportation Systems (ITS) provide a highly connected mobile network by setting up communications between various modes of the transportation system. Increasing communication through Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) technologies enables road users to become better aware of their roadway surroundings so that they can make more intelligent driving and navigation decisions. This results in a more efficient and better managed use of the transportation network. One way to provide awareness is to send out information about crashes. Geroliminis and Daganzo noted the importance of using forecasting models "to decrease congestion in large cities and improve urban mobility" by providing valuable information like the existence of a crash on a transportation network (1). A forecasting model can be developed by determining a network-wide relation between flow and density on major arterials in congested cities.

In addition, Connected Vehicles technology, as one of the latest technologies in surface transportation, provides the opportunity to create a connected network of vehicles and infrastructure. In this network, individual vehicles can communicate with each other through V2V communications. Moreover, individual vehicles are connected to infrastructure and the Traffic Management Center (TMC) through V2I communications. The real-time information provided by this technology can improve drivers' operational, tactical, and strategic decisions; thus it can improve operations once a crash has been identified on a freeway. In fact, Connected Vehicles technology is expected to have a significant effect on the characteristics of a network-wide flow-density relation. Less significant hysteresis loops, better recovery, and less grid-lock is expected since Connected Vehicles technology can improve capacity and increase traffic flow stability (2). Connected vehicles (CV) with V2V and V2I capability will be notified quicker in the scenario of a crash on a freeway, and therefore promises a quicker improvement in traffic flow operations. By combining the observed patterns and relationships of flow-density diagrams with CV technologies, a predictive and informative method for crashes can be created which offers the potential for improvements in mobility and safety. This requires an understanding of the effects of crashes at different locations on network flow-density diagrams.

Several studies have suggested that there is a well-defined relationship between flow and density (occupancy in some studies) at the network level (3-8). The pioneer studies that investigated this relationship are the studies by Smeed (9), Thomson (10), Wardrop (11), and Godfrey (12). Later, Herman and Prigogine (13) introduced the two-fluid model to characterize the relationship between average velocity and fraction of moving vehicles. This finding followed by several other studies including Chang and Herman (14), Mahmassani et al. (5), and Williams et al. (6) to investigate the network-level traffic flow characteristics. Recently, Daganzo (15) revisited the network-wide traffic flow relationship and introduced a theory to characterize the flow-density relationship at the network level. He called this relationship “Macroscopic Fundamental Diagram” which is also known as a Network-wide Fundamental Diagram (NFD). This study created a momentum in investigating network-wide traffic flow relationships and resulted in several other studies. Geroliminis and Daganzo (4), Ji et al. (16), Mazloumian et al. (17), Saberi and Mahmassani (18), Saberi and Mahmassani (7), Gayah et al. (19) and several other studies shed light on the properties of the network-wide relationship between flow and density.

Most of the above studies focused on characterizing the observed patterns in network-wide traffic flow relationship based on the current states of transportation systems and were completed over major urban networks. Saberi and Mahmassani (6) collected data from over 100 loop detector stations in Portland, Oregon over a 3-day period to develop a flow-density diagram that observed hysteresis patterns from differences in the distribution of congestion. A correlation between the NFD of a subnetwork to the NFD of the entire freeway network was found (6). Most importantly, quick changes in the distribution of the NFD can provide evidence on the formation of congestion due to high traffic volumes or crashes (6). Saberi and Mahmassani (17) gathered loop detector data from freeway networks in Chicago, Illinois, Portland, Oregon and Irvine, California and compared the NFD of each city. Differences in congestion distribution caused inconsistent hysteresis patterns across time and between networks (17). From the NFDs, two types of hysteresis patterns and capacity drop phenomena observed during the loading and reloading periods of the network were characterized (17). The NFDs of the freeway networks across different days show that the observations are reproducible (17). Geroliminis and Daganzo (4) created a NFD for Yokohama, Japan by collecting data through fixed detectors and floating vehicle probe sensors (GPS equipped taxis). The chaotic pattern observed in flow-density relation from individual patterns disappeared once data from all the detectors were grouped together, suggesting the existence of a NFD for the entire network (3). Geroliminis and Daganzo (1) simulated traffic on a major arterial in Louisiana and a downtown San Francisco network, and the plotted data showed a curvilinear relationship between total distance traveled and number of vehicles and a linear relationship between outflow and total distance traveled.

Crash data was collected from major highways that make up a large network in Chicago, Illinois for the years 2007-2010. The peak hours were chosen as the analysis period since the hysteresis loop is more likely to form during this period. A NFD was plotted for the day with reported crashes in the peak hour and also for a similar day without any reported crashes on the network. The crashes were also plotted on the network to determine whether a relationship existed between the spatial distribution of crashes and its NFD. The two constructed NFDs will help determine if a forecasting model for crashes can be developed by comparing the NFDs.

CHAPTER II

DATA CHARACTERISTICS

Occupancy loop detector information on major highways in Illinois was gathered by submitting a request on the Travel Midwest website (20). This information included the times, volumes, and effective lengths of the detectors. Figure 1 provides an overview of coverage of the occupancy loop detectors used for this study (21).

Figure 1: Snapshot of loop detector coverage: Chicago area (21)

The study network centered on Chicago, Illinois, and its size was limited so that a peak hour without a crash on the network could be identified. In the study network, the loop detectors covered the following major highways in Illinois within Cook County: I-290, I-294, I-355, I-55, I-57, I-80, I-90, I-94, US 41 and IL 53. Figure 2 shows the final network area.

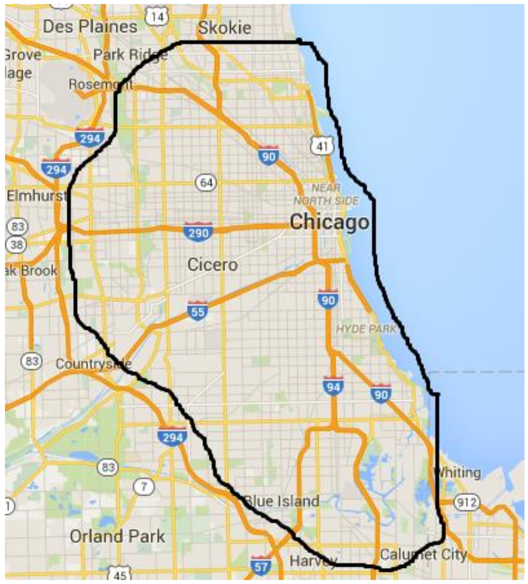


Figure 2: Network study area in Chicago, Illinois

Crash data was collected for the state of Illinois for the years 2007-2010 by submitting a request to the Illinois Department of Transportation (22). In 2007, the state recorded over 107.40 billion vehicle miles traveled (VMT), 422,778 crashes and 1,248 total deaths (22). In 2008, Illinois observed over 105.64 billion VMT, 408,258 crashes and 1,043 total deaths (22). In 2009, the state recorded over 105.73 billion VMT, 292,106 crashes and 911 total deaths (22). In 2010, the state documented over 105.74 billion VMT, 289,260 crashes and 927 deaths (22).

The data was filtered to include crashes that occurred on the major highways of the network on an average weekday (Tuesday - Thursday) with clear weather. Average weekdays have more consistent and predictable traffic patterns. Crashes were separated between those that occurred during the AM peak hour (7 a.m. to 9 a.m.) and the PM peak hour (4 p.m. to 6 p.m.).

The coordinates of each crash were provided in the State Plane Coordinate System. EarthPoint was used to convert the coordinates of each crash into latitude and longitude coordinates by specifying the zone 1202: Illinois West (23). EarthPoint was also used to plot the crashes on Google Earth (23). The crashes that occurred on major state highways within the study area of the network were kept for further analysis.

A code developed in C++ was run in Visual Studio and was used to calculate the needed average flow, speed, occupancy, and length quantities from the loop detectors outputs in the network to plot a NFD for a particular day. Visual Studio code aggregated the data over the network in five minute intervals. The following equations were used to calculate the NFD quantities from the Visual Studio outputs of total flow (F), occupancy (O), speed (S), and length (L) for each five minute interval. This approach was adopted from Saberi and Mahmassani (17).

Normalized F [veh/hr] = (F/L)*12

Normalized O [%] = O/L

NFD plots of normalized flow (veh/hr) vs. normalized occupancy (%) in five minute intervals were plotted in Excel over the peak hours on days with and without reported crashes. The day without reported crashes also occurred on a clear average weekday (Tues – Thurs) and was within at least one week of the day with the reported crash so that the traffic patterns would be similar to make a better comparison.

CHAPTER III

DATA ANALYSIS

This chapter provides the filtered crash results for the AM and PM peak hour with and without crashes for each year and a comparison of the resulting NFDs. The results for the 2008 PM peak hour and 2009 AM peak hour are not shown since an hour without any crashes on the network could not be identified or the loop detector outputs were invalid.

Results

The filtered results use the same headings. The 'location' refers to the highway where the crash occurred. The 'hour' is based on a 24-hour scale and describes the hour in which the crash occurred. The 'injury type' describes the severity of the collision and uses the following injury severity scale: K = fatal, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, PD = property damage only. The 'day without crash' had no reported crashes on the loop detector network during the corresponding AM or PM peak hour. Both peak hours with and without crashes occurred on a clear day in the network. As an example, Table 1 shows the filtered crash results for an AM peak hour in 2007. More crashes occurred on I-294 than on any other highway. All crashes involved only 2 vehicles and were caused by a rear end collision.

Table 1: 2007 AM Peak Hour Results

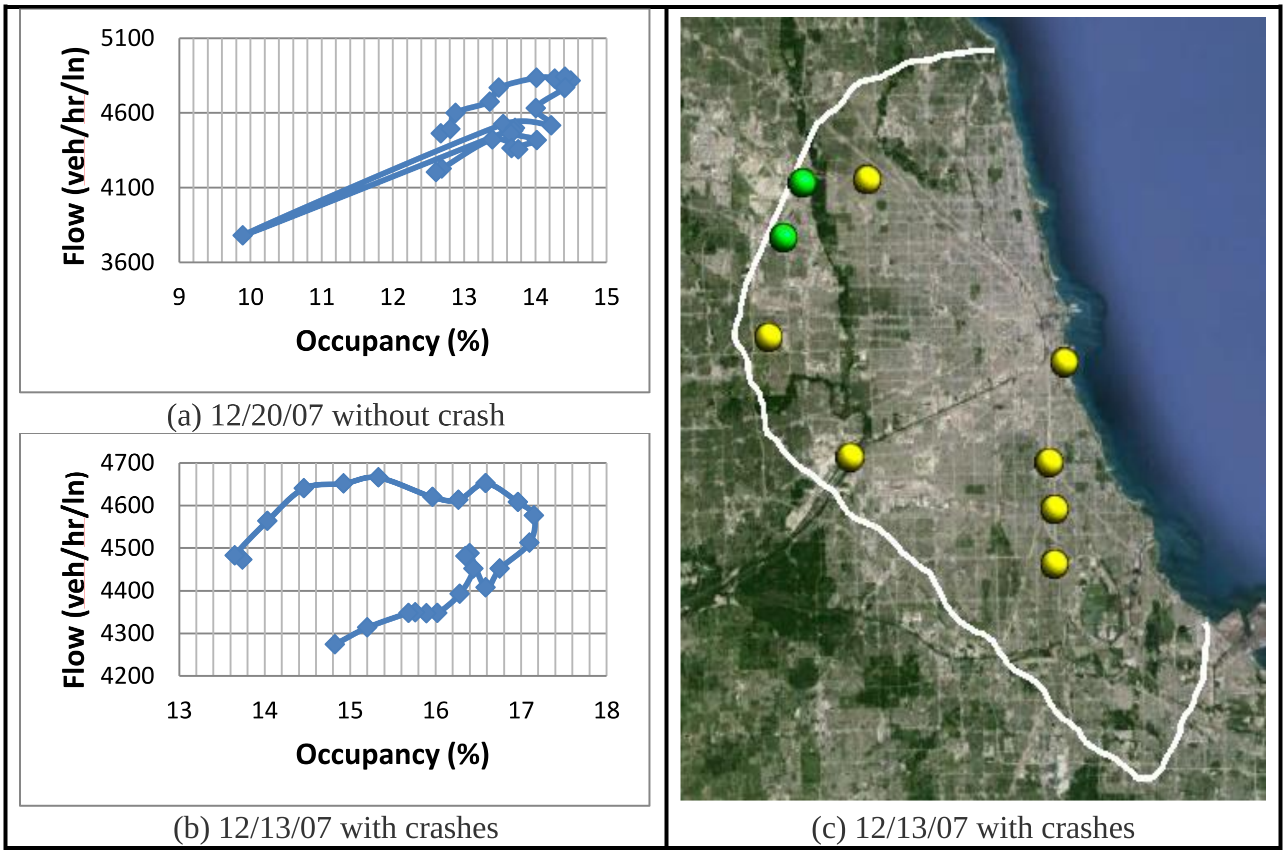
Day with crashes	Location	Hour	Day	Number of Vehicles	Injuries	Collision Type	Injury Type	Day without crash
12/13	I 057	07	Thu	2	0	Rear End	PD	12/20
	I 094	07	Thu	2	0	Rear End	PD	
	I 294	07	Thu	2	1	Rear End	C-Injury	
	US 41	07	Thu	2	0	Rear End	PD	
	I 055	08	Thu	2	0	Rear End	PD	
	I 090	08	Thu	2	0	Rear End	PD	
	I 290	08	Thu	2	0	Rear End	PD	
	I 294	08	Thu	2	1	Rear End	C-Injury	
	I 294	08	Thu	2	0	Rear End	PD	

The crashes were plotted on the network to see whether there was a relationship between the spatial distribution of the crashes and its NFD. Crashes were color-coded according to crash severity. Table 2 shows the color scale used in the plots.

Table 2: Injury Severity Color Scale

Color	Injury Severity
	Fatal
	Incapacitating Injury
	Non-Incapacitating Injury
	Possible Injury
	Property Damage Only

Figure 3 shows plots of the NFDs over the AM peak hour in 2007 on the days with and without reported crashes during the peak hour and the location of crashes on the network. The white line outlines the extent of the network. The crashes resemble a circle near the boundary of the network. These crashes block traffic from flowing smoothly inside the network. During the peak hours, demand usually exceeds capacity. Instead of operating as an over-saturated network, the placement of crashes on the network causes the network to perform similarly to a saturated network since not as much of the demand traffic has access to the network. This can be observed by the smooth curve of the NFD for the hour with crashes on the network versus the rugged pattern of the NFD for the hour without crashes on the network. The peak hour without a crash also reports higher flow rates, indicating that traffic can flow faster when there are no crashes blocking the flow of traffic into the network.



(a) 12/20/07 without crash

(b) 12/13/07 with crashes

(c) 12/13/07 with crashes

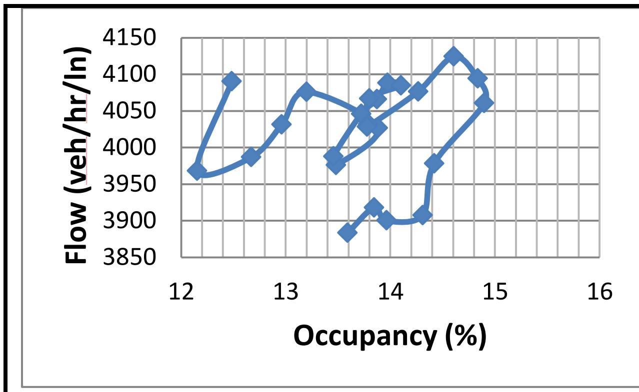
Figure 3: NFD and Location of Crashes for 2007 AM Peak Hour

Table 2 shows the filtered crash results for the PM peak hour in 2007. More crashes occurred on I-290 than any other highway. A few crashes involved 3 vehicles. A majority of the crashes were caused by a rear end collision and occurred during the 5 p.m. – 6 p.m. hour.

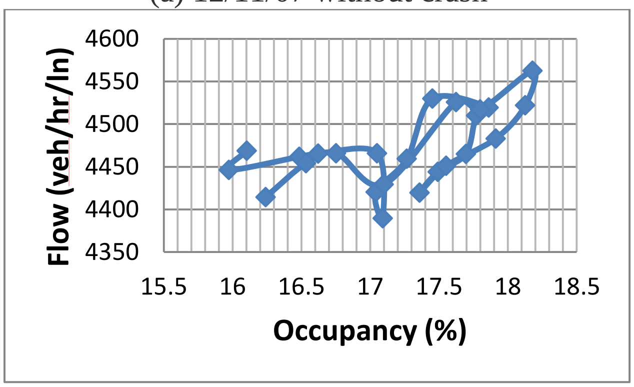
Table 2: 2007 PM Peak Hour Results

Day with crashes	Location	Hour	Day	Number of Vehicles	Injuries	Collision Type	Injury Type	Day without crash
12/19	I 290	16	Wed	2	0	Sideswipe Same Direction	PD	12/11
	I 090	17	Wed	3	1	Rear End	B-Injury	
	I 294	17	Wed	2	0	Rear End	PD	
	I 094	17	Wed	2	0	Sideswipe Same Direction	PD	
	I 290	17	Wed	2	0	Rear End	PD	
	I 055	17	Wed	3	0	Rear End	PD	
	I 290	17	Wed	2	0	Rear End	PD	

Figure 4 shows plots of the NFDs over the PM peak hour in 2007 on the days with and without reported crashes during the peak hour and the location of crashes on the network. The crashes concentrate along a line in the middle of the network. Since traffic is only blocked along the middle part of the network, traffic can move smoother and faster on the rest of the network which is indicated by the higher flow rates for the peak hour with a crash. The NFD for the peak hour without a crash has a much smoother hysteresis loop compared to the day with the crash. This indicates that although the concentration of crashes along the middle of a network may lead to higher average flow rates, the traffic patterns can be less predictable.



(a) 12/11/07 without crash



(b) 12/19/07 with crashes

(c) 12/19/07 with crashes

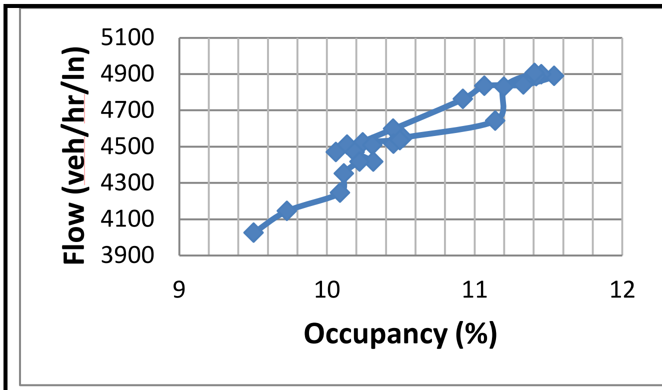
Figure 4: NFD and Location of Crashes for 2007 PM Peak Hour

Table 3 shows the filtered crash results for the AM peak hour in 2008. More crashes occurred on I-90 and I-94. A few crashes involved 3 vehicles. The highest number of vehicles involved in a crash was 5. A majority of the crashes were caused by a rear end collision.

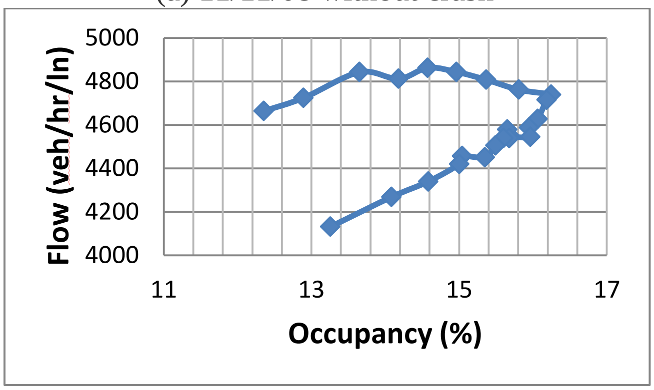
Table 3: 2008 AM Peak Hour Results

Day with crashes	Location	Hour	Day	Number of Vehicles	Injuries	Collision Type	Injury Type	Day without crash
11/18	I 090	07	Tue	2	0	Rear End	PD	11/11
	I 055	07	Tue	3	0	Rear End	PD	
	I 094	07	Tue	2	0	Sideswipe Opposite Direction	PD	
	I 094	07	Tue	2	0	Rear End	PD	
	I 294	07	Tue	2	0	Sideswipe Same Direction	PD	
	I 090	07	Tue	3	0	Rear End	PD	
	I 294	08	Tue	3	0	Rear End	PD	
	I 090	08	Tue	2	0	Sideswipe Same Direction	PD	
	I 094	08	Tue	2	0	Rear End	PD	
	US 41	08	Tue	5	0	Rear End	PD	

Figure 5 shows plots of the NFDs over the AM peak hour in 2008 on the days with and without reported crashes during the peak hour and the location of crashes on the network. Most crashes are concentrated in one location on the upper part of the network. This causes a breakdown in the system since congestion is highly concentrated in one area. The NFDs show that when many crashes are blocking traffic flow in one part of the system, the system appears to act similarly to a saturated network. This can be observed by the difference in formation of the hysteresis loops. The NFD shows a smooth curve for the peak hour with crashes and a less-defined curve for the peak hour without crashes. The flow rates are also lower for the peak hour with crashes.



(a) 11/11/08 without crash



(b) 11/18/08 with crashes

(c) 11/18/08 with crashes

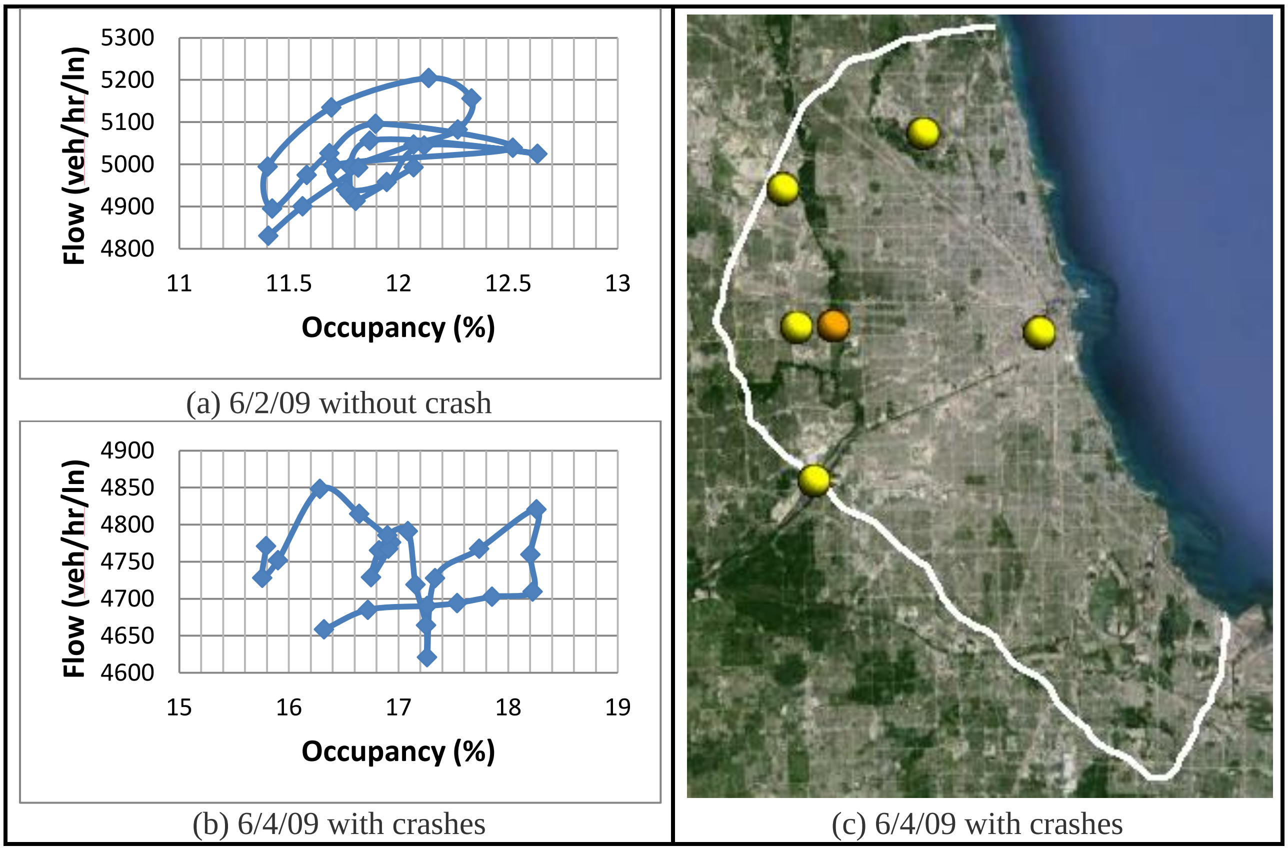
Figure 5: NFD and Location of Crashes for 2008 AM Peak Hour

Table 4 shows the filtered crash results for the PM peak hour in 2009. More crashes occurred on I-94. Only one crash involved 3 vehicles. A majority of the crashes were caused by a rear end collision, and most occurred during the 4 p.m. – 5 p.m. hour.

Table 4: 2009 PM Peak Hour Results

Day with crashes	Location	Hour	Day	Number of Vehicles	Injuries	Collision Type	Injury Type	Day without crash
6/4	I 294	16	Thu	2	0	Rear End	PD	6/2
	I 094	16	Thu	2	0	Rear End	PD	
	I 290	16	Thu	2	0	Sideswipe Same Direction	PD	
	I 094	16	Thu	2	0	Sideswipe Same Direction	PD	
	I 094	17	Thu	2	0	Rear End	PD	
	I 290	17	Thu	3	1	Rear End	B-Injury	

Figure 6 shows plots of the NFDs over the PM peak hour in 2009 on the days with and without reported crashes during the peak hour and the location of crashes on the network. The crashes in this peak hour are mostly concentrated on the outer boundaries of the network in a half-circle. These crashes block traffic flow to the upper part of the network. This is indicated by the drop in traffic flow rates for the hour with crashes versus the hour without any crashes on the network. The declining flow rate for the first half of the NFD for the hour with crashes may be attributed to majority of the crashes occurring during the first hour of the peak hour.



(a) 6/2/09 without crash

(b) 6/4/09 with crashes

(c) 6/4/09 with crashes

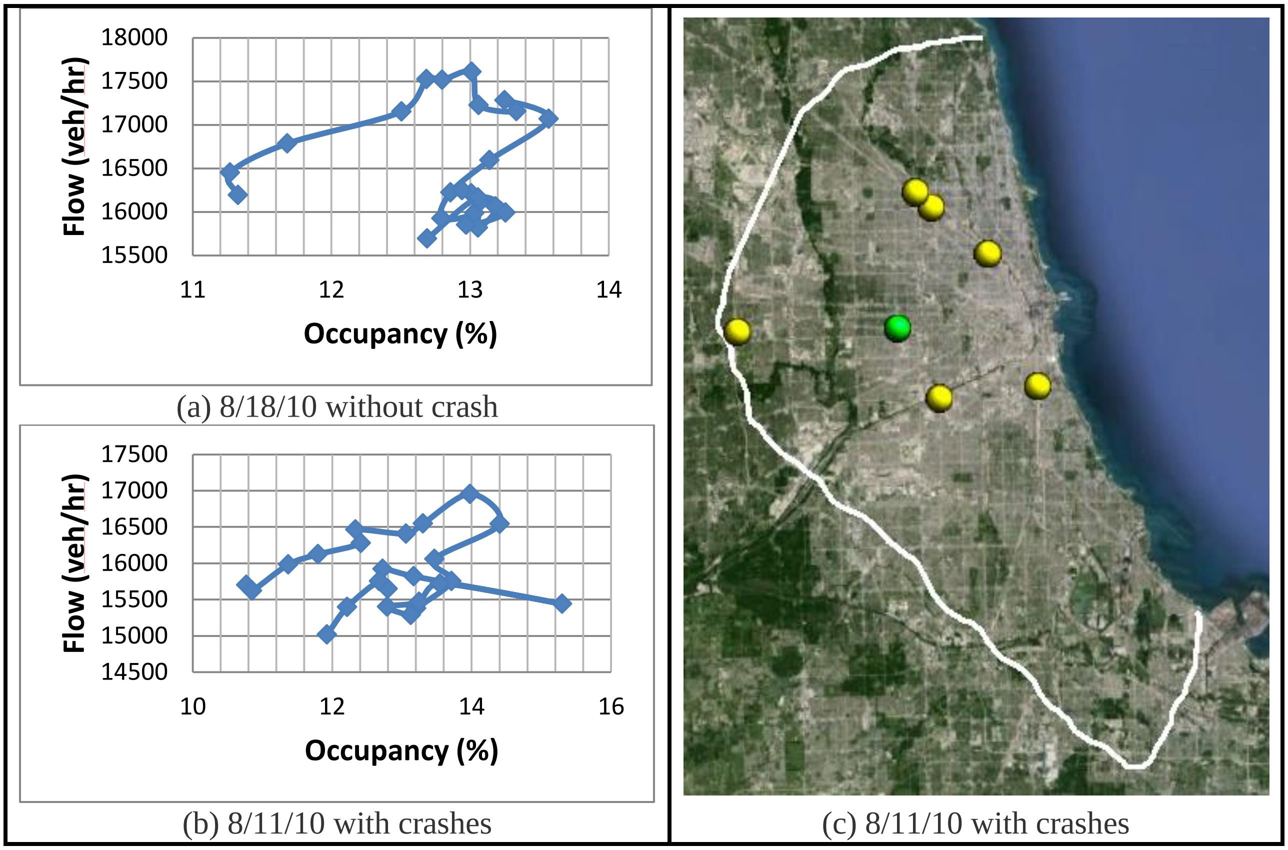
Figure 6: NFD and Location of Crashes for 2009 PM Peak Hour

Table 5 shows the filtered crash results for the AM peak hour in 2010. Most crashes occurred on I-94. One crash involved 7 vehicles. A majority of the crashes were caused by a rear end collision, and most occurred during the 7 a.m. – 8 a.m. hour.

Table 5: 2010 AM Peak Hour Results

Day with crashes	Location	Hour	Day	Number of Vehicles	Injuries	Collision Type	Injury Type	Day without crash
8/11	I 094	07	Wed	2	0	Sideswipe same direction	PD	8/18
	I 294	07	Wed	2	0	Rear end	PD	
	I 094	07	Wed	2	0	Rear end	PD	
	I 094	07	Wed	3	0	Rear end	PD	
	I 290	07	Wed	2	2	Rear end	C-Injury	
	I 055	08	Wed	7	0	Rear end	PD	
	I 094	08	Wed	2	0	Rear end	PD	

Figure 7 shows plots of the NFDs over the AM peak hour in 2010 on the days with and without reported crashes during the peak hour and the location of crashes on the network. The flow rates are much higher than previous analyses because the loop detector units changed from veh/hr/ln to veh/hr. Flow rates are lower for the peak hour with crashes than for the peak hour without crashes. The crashes are located near the border of the network. These crashes prevent the center from overflowing but limits traffic from flowing smoothly throughout the rest of the network.



(a) 8/18/10 without crash

(b) 8/11/10 with crashes

(c) 8/11/10 with crashes

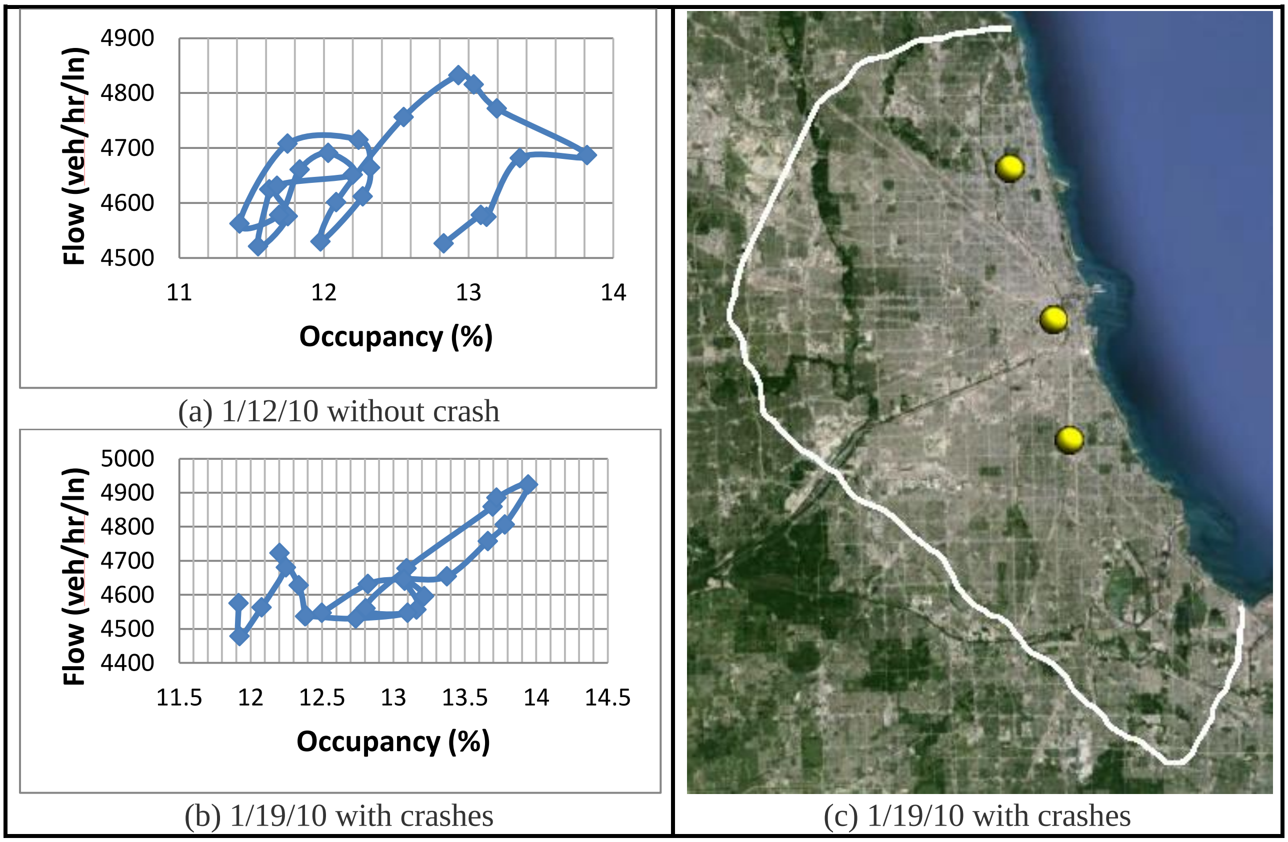
Figure 7: NFD and Location of Crashes for 2010 AM Peak Hour

Table 6 shows the filtered crash results for the PM peak hour in 2010. Most crashes occurred on I-94. All crashes involved two vehicles. A majority of the crashes were caused by sideswipes.

Table 6: 2010 PM Peak Hour Results

Day with crashes	Location	Hour	Day	Number of Vehicles	Injuries	Collision Type	Injury Type	Day without crash
1/19	I 094	16	Tue	2	0	Sideswipe same direction	PD	1/12
	I 094	16	Tue	2	0	Sideswipe same direction	PD	
	US 41	17	Tue	2	0	Rear end	PD	

Figure 8 shows plots of the NFDs over the PM peak hour in 2010 on the days with and without reported crashes during the peak hour and the location of crashes on the network. The majority of the crashes occur along I-94, the major highway in the area. Crashes on this interstate block traffic which appears to have a major effect on operations in the area. The resulting NFD for the peak hour with crashes shows a reverse hysteresis loop going counter-clockwise instead of clockwise. When there are no more crashes on the network, operations improve and the network's NFD operates in the expected clockwise direction. The hysteresis loop is also more pronounced for the peak hour without crashes.



(a) 1/12/10 without crash

(b) 1/19/10 with crashes

(c) 1/19/10 with crashes

Figure 8: NFD and Location of Crashes for 2010 PM Peak Hour

Data Limitations

Although crash information on the network was available, information on construction, lane closures, maintenance, utility work, and special events was not available. All of these can impact traffic patterns significantly and affect the NFD. This research also relied heavily on the crashes reported in the database, but there could have been other accidents that were never reported. This research was also limited to the reliability of police reports for crash information including crash severity. Loop detector data can be unreliable and often resulted in invalid data points. All of these factors impact the results.

CHAPTER IV

CONLUSIONS AND FUTURE WORK

This chapter provides an overview of the conclusions of the data collected in previous chapters and recommendations for future work.

Conclusions

The NFDs plotted in the previous chapter show there is a clear difference between NFDs of peak hours with and without crashes and that different relationships exist between the spatial distribution of crashes and the resulting NFD. The major findings are presented below.

- Peak hours without crashes had more pronounced hysteresis loops
- Crashes located along the outer boundary of the network restrict traffic flow into the network causing the NFD to perform similar to a saturated network
- Crashes concentrated along the middle of the network can cause higher average flow rates for the rest of the network
- Several crashes concentrated in one area may cause the network to act as a saturated network
- Many crashes on the major interstate in a network can significantly impact traffic patterns resulting in a reverse hysteresis loop

Future Work

Future work would involve obtaining data for other large urban networks and looking at data for more years to make more comparisons between the NFDs of peak hours with and without crashes. This will increase the chances of finding peak hours without any crashes on the network which was a limiting factor to the results of this research. To observe the potential benefits of this research, the same network should be simulated with CV at different market penetration rates on similar days to study the effects on the resulting flow-density diagrams. The network can be simulated with CV at different market penetration rates to observe the impact of CV technologies on the formation of the NFD on the same days with and without a reported crash. By comparing the NFDs from various scenarios, the effects of a crash on the flow-density relationship and the effect of CV technologies in similar scenarios on the NFD can be studied. Future studies would help form a more conclusive statement about the effect of crashes on NFDs of large urban networks so that a forecasting model can be created.

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