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Analysis and evaluation of safety impacts of median types and midblock left turn treatments for urban arterials

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ANALYSIS AND EVALUATION OF SAFETY IMPACTS OF MEDIAN TYPES AND MIDBLOCK LEFT TURN TREATMENTS FOR URBAN ARTERIALS

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ABSTRACT

Analysis and Evaluation of Safety Impacts of Median Types and Midblock Left Turn Treatments for Urban Arterials

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Urban growth leads to new land-uses abutting arterials requiring driveways for their accessibility. Uncontrolled number and locations of such access points causes safety, mobility and accessibility problems. The solution to these problems is access management (AM) which controls the number and location of the access points. AM techniques are normally documented in the form of guidelines for engineers and planners to follow when implementing the techniques. However, AM guidelines may not cover every technique due to the fact that AM is still growing. For example, the current AM guideline prepared by The Nevada Department of Transportation addresses many AM techniques. The guideline, however, addresses the design of lengths and ends of median openings but not spacing and type of the openings in segments with raised median (RM).

Spacing, location, and types of median openings have impacts on safety of midblock sections of arterials. Short spacing of median openings results in overlapping functional areas and consequently high number of traffic conflicts and crashes. Long spacing of median openings results in few median openings in a given segment length hence concentrating turning traffic at those few median openings. Concentrating turning traffic at the openings increases potential conflicts, impedance to through traffic, and accessibility problems. This study evaluates the impacts of median type, density, spacing,

location, and type of median openings and proposes optimal spacings that minimize number of crashes.

This study deviates from past studies that evaluated safety impacts of an aggregate number of median openings using crash data collected over shorter periods of one to three years. The studies reported mixed results, making it difficult to transfer findings across geographical locations. Aggregating the impacts might have concealed the impacts of individual spacing between median openings.

Statistical models were calibrated for median openings in RM segments at aggregate and disaggregate levels of analysis. Other variables such as signal spacing, number of driveways, land-use, AADT, and speed limits were included.

Results of the analyses reveal that density, spacing, location and type of median openings do have significant impacts on midblock crashes. The results show that one median opening in a mile corresponds to 5.7% and 5.3% total and injury crash rates, respectively. Optimal spacing of the median openings is found in the range of 340 feet to 730 feet based on types of crashes and speed limits. Median openings located adjacent to signalized intersection have up to 30% more crashes than intermediate openings.

The results of this research are expected to assist transportation agencies in prioritizing retrofit projects, updating existing, and developing new AM strategies related to spacing between median openings.

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DEDICATION

To my wife Nyembezi, our wonderful children Fatima and Habib, and my caring parents Amina and Ibrahim Mauga.

TABLE OF CONTENTS

ABSTRACT iii

ACKNOWLEDGEMENTS v

DEDICATION vi

LIST OF TABLES x

LIST OF FIGURES xi

CHAPTER 1 INTRODUCTION 1
1.1. Background 1
1.2. Statement of the Problem 3
1.3. Research Hypotheses 6
1.4. Objectives 8
1.5. Study Contributions 9
1.6. Organization of the Report 10

CHAPTER 2 LITERATURE REVIEW 10
2.1 Types of Medians 10
2.2 Median Openings and Their Types 12
2.3 Determination of Spacing between Median Openings 14
2.4 Guidelines on Spacing of Median Openings 17
2.5 Density or Number of Driveways 18
2.6 Summary 19

CHAPTER 3 METHODOLOGY 23
3.1 Introduction 23
3.2 Definition of Terms 23
3.2.1 Median 23
3.2.2 Median openings 24
3.2.3 Midblock segment 26
3.3 Levels of Analyses 28
3.3.1 Aggregate Analysis 28
3.3.2 Disaggregate Analysis 28
3.4 Data Collection 29
3.4.1 Data for Aggregate Analysis 29
3.4.2 Data for Disaggregate Analysis 31
3.5 Statistical Modeling 35
3.6 Model Selection 36
3.6.1 Generalized Linear Models 36
3.6.2 Non-linear Least Squares (NLS) 39
3.7 Evaluation of Marginal Impacts 40
3.7.1 Case I: $\lambda = 0$ 41

3.7.2 Case II: $\lambda = 1$ 43
3.7.3 Case III: $\lambda \neq 0$ and $\lambda \neq 1$ 44
3.8 Calibration of Models..... 45

CHAPTER 4 DATA SUMMARY..... 47
4.1 Data for Aggregate Analysis..... 47
4.1.1 Access Management Data 47
4.1.2 Crash Data 47
4.2 Data for Disaggregate Analysis..... 51
4.2.1 Access Management Data 51
4.2.2 Crash Data 52

CHAPTER 5 CALIBRATION OF MODELS..... 55
5.1 Introduction..... 55
5.2 Model Selection for the Aggregate Analysis 55
5.2.1 Calibration of the Aggregate models..... 55
5.2.2 Selected Model 58
5.3 Model Selection for the Disaggregate Analysis..... 59
5.3.1 Functional Form 60
5.3.2 Calibration of the Disaggregate model..... 61
5.3.3 Selected Model 63

CHAPTER 6 RESULTS OF AGGREGATE ANALYSIS..... 65
6.1 Introduction..... 65
6.2 Summary of Results for Total Crash Models..... 65
6.3 Summary of Results for Crash Types Models 68
6.4 Summary of Results for Models of Crashes by Severity 72
6.5 Evaluation of Marginal Impacts on Midblock Crashes..... 72
6.5.1 Raised medians..... 73
6.5.2 Density of median openings 75
6.5.3 Density of driveways..... 76
6.5.4 Density of unsignalized public approaches 77
6.5.5 Signal spacing..... 78
6.6 Implications of the Results on the Effectiveness of AM Techniques 79

CHAPTER 7 RESULTS OF DISAGGREGATE ANALYSIS 82
7.1 Introduction..... 82
7.2 Summary of results for Total Crash Models..... 82
7.3 Summary of Results for Crash Types Models 85
7.4 Summary of Results for Models by Severity of Crashes 89
7.5 Evaluation of Marginal Impacts..... 92
7.5.1 Marginal Impacts of Spacing between Median Openings..... 92
7.5.2 Marginal Impacts of Types of Median Openings..... 96
7.5.3 Marginal Impacts of Adjacency of Median Openings to Signals..... 98

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS..... 100

8.1 Conclusions 100
8.2 Recommendations for Implementation of AM Techniques 104
8.3 Recommendations for Future Research 105

REFERENCES 106

APPENDIX SUPPLEMENTAL RESULTS 111

VITA 115

LIST OF TABLES

Table 2-1. Recommended Minimum Separation Distances 16
Table 2-2. Recommended Separation Distance Values 16
Table 2-3. Spacing Criteria between Median Openings 17
Table 2-4. Impacts of AM features in studies for segments with RM 21
Table 2-5. Impacts of AM features in studies for segments with TWLTL 22
Table 3-1. Common values of θ_1 and θ_2 for the Two Variance Formulations 38
Table 4-1. Descriptive Statistics of AM and Traffic Characteristics 48
Table 4-2. Descriptive Statistics of Crashes by Type and Severity 49
Table 4-3. Descriptive Statistics of Crash Rates by Type and Severity 50
Table 4-4. Descriptive Statistics of Variables by Location of Median opening 52
Table 4-5. Crashes per Median opening by Type and Location of Median Opening 53
Table 5-1. Parameters for Selecting an Appropriate Aggregate Model 57
Table 5-2. Parameters for Selecting Appropriate Aggregate Model 62
Table 6-1. Model Results for the Impacts on Total Crash Rates 66
Table 6-2. Model Results for Angle and Rear-end Crash Rates 69
Table 6-3. Results for Sideswipe, Head-on and Single Vehicle Crashes 71
Table 6-4. Model Results for Injury and PDO Crash Rates 73
Table 7-1. Model Results for Total Crashes 83
Table 7-2. Model Results for Angel and Rear-end Crashes 87
Table 7-3. Model Results for Sideswipe and Single Vehicle Crashes 88
Table 7-4. Model Results for Injury and PDO Crashes 90
Table 7-5. Optimal Spacing of Median Openings based on Crashes 94
Table 7-6. Percentage Difference in Crashes between Full and other Types 97
Table A-1. Model Results for Total Crashes 111
Table A-2. Model Results for Angel and Rear-end Crashes 112
Table A-3. Model Results for Side Swipe and Single Vehicle Crashes 113
Table A-4. Model Results for Injury and PDO Crashes 114

LIST OF FIGURES

Figure 1-1. Variation of functional forms across studies. 6
Figure 3-1. Common types of medians. 24
Figure 3-2. Types of median openings. 25
Figure 3-3. Midblock and intersection areas. 26
Figure 3-4. A driveway connecting a land-use to an arterial road. 27
Figure 3-5. Spatial distribution of crashes along segments. 30
Figure 3-6. Functional area of a median opening. 33
Figure 3-7. Distance measurements for median openings. 34
Figure 3-8. The procedure for selecting appropriate models 40
Figure 3-9. Process of calibration of models 46
Figure 5-1. Distribution of crash rates in midblock segments. 56
Figure 5-2. Scatter plot of residual versus observation number. 59
Figure 5-3. Distribution of number of crashes in median openings 60
Figure 5-5. Relationship between crashes and spacing 61
Figure 5-5. Scatter plot of residual versus observation number. 64
Figure 6-1. Comparison between RM and driveway consolidation 81
Figure 7-1. Sensitivity analysis for optimal spacing under model for injury crashes....... 95

CHAPTER 1

INTRODUCTION

1.1. Background

Urban growth leads to new land-uses abutting arterials requiring driveways for their accessibility. Uncontrolled number and locations of such access points has been reported to cause safety, mobility and accessibility problems (TRB, 2003). The solution to these problems is access management (AM). Access management (AM) is defined as the systematic control of location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway (TRB, 2003). The purpose of AM is to improve safety and mobility by controlling the number and location of accessing points while balancing the need for accessibility.

Several studies have reported various benefits of carrying out AM programs. As an example of the effectiveness of AM programs, before and after studies have reported reduction in crashes by an average of 40%, increase in level of service during peak period (Maze and Plazak, 1997; Plazak *et al*., 1998; Maze *et al*., 2000), and positive economic impacts (Maze and Plazak, 1997; Frawley and Eisele, 1998; Maze *et al*., 2000) on corridors where AM programs were carried out.

One AM technique is that of designing roads with medians to facilitate land-use accessibility for left turning traffic. Several divided arterials built in growing areas consist of two-way-left-turn lanes (TWLTL) in their medians. The TWLTL provides a continuous space for left-turning traffic into or out of land-uses abutting the arterials. With TWLTL, left turning traffic can access any adjacent land-use directly. In other words, TWLTL provides uncontrolled or unrestricted accessibility for the left turning

traffic. As land-use activities increase, midblock left turning traffic increases and so do crashes. Controlling median access through raised medians (RM) is usually a means for improving arterial safety and mobility. However, these RM reduce direct accessibility of the adjacent land-uses in midblock sections. The reduction in direct accessibility depends on the extent of control of access. Fully controlled access converts all midblock left turning traffic into U turning traffic at signalized intersections.

The extent of access control in RM can be quantified by the number of median openings and their types. These median openings are used to facilitate land-use accessibility for crossing, left and U-turning traffic. The presence of median openings relieve signalized intersections of huge loads of U-turning traffic and also eliminate extra travel distances and travel times that motorists would have to incur to access land-uses adjacent to roads without median openings. The median openings, however, are conflict zones that cause safety and congestion problems.

Safety at the median openings is usually improved by controlling the number of movements that use the openings. For example Florida—as reported by Liu (2006) and Pirinccioglu (2007)— has a policy of restricting vehicles out of land-uses from executing direct left turns onto arterials. Instead, vehicles have to make right turns followed by U turns at downstream median openings. Restricting direct left turning traffic out of land-uses has shown success in terms of reducing number of crashes and at the same time reducing delay especially during peak periods. A combination of the use of number of median openings and proper control of movement type can result in safety improvements in the long run of arterials. Although the initial costs may be huge, the benefits may outweigh the costs.

1.2. Statement of the Problem

Spacing, location and types of median openings (like other conflict points on highways) have impact on safety of midblock sections of arterials. Short spacing of median openings (implies high density) results in overlapping their functional areas and hence high number of traffic conflicts and crashes. Long spacing of median openings results in few median openings in a given segment length hence concentrating turning traffic at those few median openings. Concentration of turning traffic at the openings increases potential for conflicts for turning and through traffic. Turning traffic over-spilling turning bays usually impede mobility of through traffic hence leading to safety and congestion problems. Congestion problems also have negative impacts on accessibility of land-uses especially when median openings are blocked and turn bays oversaturated.

Adjacency of median openings to signalized intersections has adverse impacts on safety due to overlapping their functional areas. Overlapping the functional areas of median openings and intersections results in increased number of crashes at both the intersections and median openings. However, no research has been published on safety problems of individual spacing between median openings and between a median opening and a signalized intersection. Only three studies (Cribbins *et al*. 1967, Squires and Parsonson 1989, and Xu 2010) were found to have evaluated safety impacts of an aggregate number of median openings in a given length of arterial segments.

Cribbins *et al.* (1967) conducted a study consisting of 92 rural and urban highway sections, each longer than half a mile. The study used multiple regression techniques with accidents per equivalent mile as the dependent variable. The study found that generally

the density of median openings has impact on safety only where the openings do not have turn lanes. In another article published by Cribbins *et al.* (1967), it was found that median openings are not accident prone under conditions of low volume, wide medians, and light roadside development. At high values of the mentioned conditions, crash rates were high.

Squires and Parsonson (1989) conducted a regression analysis to compare safety performances of RM and TWLTL median treatments. The study used arterial sections longer than 0.75 mi. The regression analysis of total arterial crash rates resulted in insignificant coefficient for the density of median openings. However, regression analysis of arterial mid-block crash rates resulted in negative coefficient for the density of median openings. The negative coefficient might imply that the median openings improve safety while they are conflict points.

Xu (2010) conducted a regression analysis to evaluate the safety and mobility impacts of AM in the Las Vegas Valley. Xu focused on developing simultaneous models of safety and mobility both being dependent on AM features. Panel data was used to develop the models where arterials were considered as panels and segments within those arterials as repetition of observations. Crash data used was for the year 2003. The data included RM and TWLTL segments. A dummy variable was used to estimate safety impacts of median type while density of median openings was used to estimate impacts of the openings on crashes. The density of one-directional median openings was found to have adverse impact on safety. However, the densities of full and two-directional median openings (which have more number of conflicts than one-directional ones) were not found to have significant impact on safety.

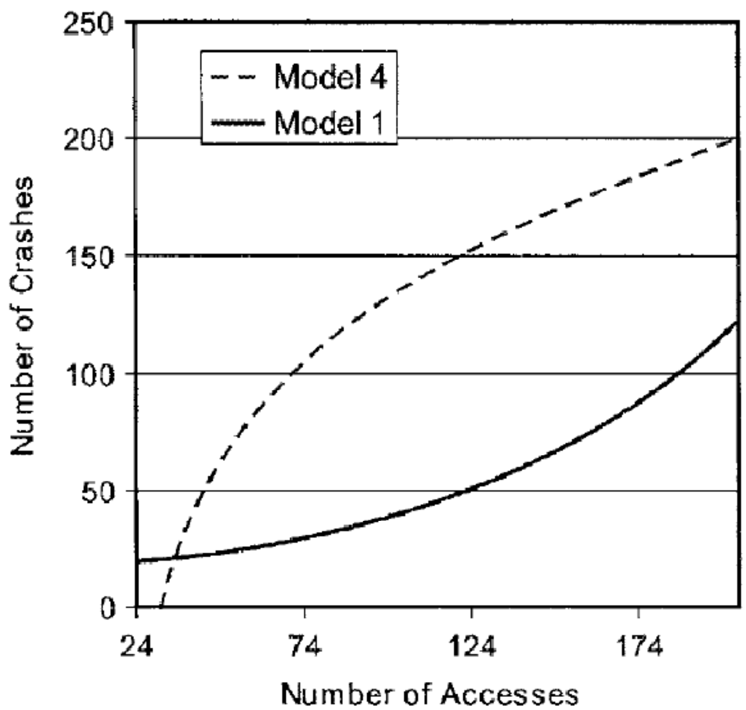
All the three studies (i.e. Cribbins *et al*. 1967, Squires and Parsonson 1989, and Xu 2010) evaluated safety impacts of an aggregate number of median openings. The results from the studies are mixed and it is difficult to draw a conclusion whether or not median openings pose safety threats. The use of density of median openings might have concealed the impacts of individual spacing between median openings on crashes. Had the studies focused on evaluating the impacts of individual spacing between median openings the results could have been different. Moreover, the studies used crash data collected over short periods of time i.e. 21 months, 3 years, and 1 year, respectively.

The problem of mixed results has been observed for other AM features also. For example, Gluck *et al*. (1999) summarized findings of 16 studies revealing safety improvements of RM as ranging from -15 to 57 percent. This range of effectiveness of using RM makes it difficult to judge whether or not installing RM results in safety improvement.

The combination of mixed results and different functional forms of models relating crashes to AM features pose a problem of transferability of findings across geographical regions. Miller *et al*. (2001) studied transferability of five models relating crashes to AM features. Figure 1-1 (extracted from Miller *et al*., 2001) shows two models out of five models they studied, one with exponential like and another with logarithmic like forms. Similar figure is also presented by Gluck *et al*. (1999) for nine studies. From the figures, it is difficult to pick the right form for transferring and applying the findings in other locations without doing some research.

Miller *et al*. (2001) also reported that transferability of models across geographical regions without site-specific adjustments may lead to erroneous predictions and/or

estimation of the safety impacts. Miller found that the errors can be as high as a few hundred percent when models developed in one location are used to estimate impacts in other locations. However, such errors can be reduced to as low as 27% if site-specific adjustments are made. The error of 27% is significant enough to justify motivation for conducting a local study with local data.



Source: Miller *et al*. (2001), pp. 19, Figure 3.

Figure 1-1. Variation of functional forms across studies.

1.3. Research Hypotheses

In this study it is presupposed that:

1. Both very short and very long spacings between median openings in RM segments lead to high number of crashes. Very short spacings imply that many median openings are within a given segment while very long spacings imply few

median openings. Very short spacings degrade safety due to overlapping of functional areas of the openings and that U-turn traffic does not have enough space to weave especially during peak periods. Vehicles have to either wait for large simultaneous gaps to occur in all directional lanes or merge into mainstreams and look for gaps in individual lanes and making lane changes in succession. Aggressively looking for individual gaps under heavy traffic and short spacings might cause safety and congestion problems. Less aggressive drivers might travel past at least one median opening before they reach a point of performing U-turns.

Very long spacings cause traffic to concentrate at few available median openings or at signalized intersections. Concentration of these movements at few median openings increases potential for more traffic conflicts and crashes. Also U-turning vehicles have to travel long distances hence incurring additional travel time. If capacity of the few available median openings is less than demand, the turning traffic might impede through traffic and cause safety, congestion, and accessibility problems. Therefore, for any given segment there is an optimal number of median openings (hence optimal spacing between the openings) that will minimize crashes.

2. Median openings that are located adjacent to signalized intersections are likely to have higher crash rates than those located elsewhere. The reason might be that of interaction with queuing vehicles and traffic activities at the intersections. Where spacing between median openings and signalized intersections is very short, the median openings are likely to be blocked by queues generated by through traffic.

If turning traffic is subjected to long delays due to blockage of the openings, drivers might become impatient and attempt to accept short time gaps in through traffic which might result in crashes.

1.4. Objectives

This research has four objectives:

1. To evaluate the impacts of median openings at aggregate and disaggregate levels on safety. At both levels of analysis, the safety impacts are evaluated by total, type and severity of crashes. At the aggregate level, midblock crashes are related to the density of median openings. Other variables included are AADT, speed limit, number of lanes, land-use characteristics, and other AM features. Other AM features considered in the study are signal spacing, densities of unsignalized public approaches and driveways.

   At the disaggregate level, crashes occurring in median openings are related to individual spacing, type, and location of median openings. Similar to the aggregate analysis, other variables are also considered. The variables include AADT, speed limit, land-use characteristics, and number of driveways within functional areas of the median openings. Results obtained from the disaggregate analysis will lead to determination of optimal spacing between median openings based on crashes.

2. To evaluate the impacts of type and location of median openings on safety. Location of a median opening refers to its adjacency to a signalized intersection. Only two categories of location are considered: adjacent to signalized

intersections and intermediate. Type of median openings refers to the number of left turning movements permitted by geometric channelization of the openings.

3. To evaluate the safety impacts of AM features in midblock TWLTL segments and compare with those in RM segments (under objective number 1). The common AM features are signal spacing, densities of unsignalized public approaches, and driveways. Also, AADT, speed limit, number of lanes and land-use characteristics are included in the analysis.

   Along with evaluating median specific impacts of AM features, models including both types of medians are calibrated for the purpose of evaluating advantages of RM over TWLTL. The density of median openings is not included in these models because it is not a common denominator.

1.5. Study Contributions

This study evaluates the impacts of individual spacing between median openings and estimates marginal impacts of types of median openings by location. The study proposes optimal spacings between median openings and between median openings and signalized intersections for different posted speed limits. The results of the study may be used by local transportation agencies in updating existing or developing new AM guidelines. The new guidelines include spacing between median openings, proximity of the median openings to signalized intersections, restriction of turning movements at median openings, and installation of auxiliary signals at median openings.

The results obtained from evaluating the safety impacts of AM features in RM and TWLTL segments may be used to develop median specific crash modification factors

(CMFs) for the features. These CMFs can be used in prioritizing and decision making when evaluating AM programs. The CMFs are simple numbers whose implications are easy to understand by the general public as well as leaders who make decisions on their behalf.

The CMFs may also be used by local transportation agencies in updating existing land-use guidelines and policies. For example, there are arterials that were once residential but they have changed to commercial land-uses nowadays. These arterials have high posted speed limits and still have driveway spacings that don’t meet the existing AM guidelines. The guidelines can be updated through merging transportation and land-use planning such that future policies on frontages of parcels are in agreement with minimum spacing requirements for driveways.

1.6. Organization of the Report

This dissertation consists of eight chapters. Chapter 1 presents the introduction, statement of the problem, hypotheses and objectives. Chapter 2 presents the review of relevant literature on the topic in focus. Chapter 3 documents in detail the methodology used to accomplish the mentioned objectives. Chapter 4 to 7 presents data analyses, results and their discussions. Chapter 8 consists of conclusions and recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Types of Medians

Medians are continuous spaces, landscapes, slabs, or barriers installed in the middle of a roadway for the purpose of separating opposing traffic. Most new projects that incorporate AM aspects in their planning and designs have medians. Old roads that did not consider AM in their designs are subject to retrofit programs in order to improve their service to the community. One of the most common AM feature considered in retrofit projects is the median. It can be traversable (two way left turn lane—TWLTL) or non-traversable (also known as raised medians—RM). TWLTL are used when upgrading 2-lane or undivided multilane highways with average daily traffic less than 24000 vehicles per day in developing areas (TRB, 2003). Raised medians are used where traffic is higher than 24000 vehicles per day and TWLTL roads need safety improvement.

Raised medians may consist of physical barriers, walls, or curbed slabs (usually six inches high from pavement surface) that are installed between opposing traffic directions for the purpose of reducing conflict points. The related traffic conflicts usually result from left turning maneuvers across a length of an undivided road or TWLTL. In short, raised medians limit left turning and crossing traffic to a few locations known as median openings. Therefore, raised medians reduce many conflict points caused by jogging (overlapping left turns to-and-from offset driveways) and crossing (for aligned driveways) movements in TWLTL segments.

For street segments with RM, median openings and signalized intersections are used to provide access for vehicles to turn left into and out of the adjacent land-uses and

unsignalized public approaches. The unsignalized public approaches are access roads of low functional classification that are designed to serve more for accessibility than mobility and connect other land-uses to major roads.

As far as safety of medians is concerned, Maze and Plazak (1997) reported a decrease in crash rates by 36.5% and 41.7% in the cities of Ankeny and Clive in Iowa, respectively, after installing RM. Gluck *et al*. (1999) summarized finding of 16 studies comparing crash rates by median type. Some of the studies were before-and-after and others were cross sectional. The safety improvement reported ranges from -15% to 57% with an average of 27% reduction in crash rates. Also, the authors reported six studies that had a decrease in side-swipe, angle, and head-on crashes averaging 31%, 40%, and 54%, respectively. The percent decrease in rear-end crashes ranged from -15% to 50% with an average of 27%. The implication from the literature is that the RM has mixed impacts and the real marginal effect is either not known or varies from a location to another.

Parsonson *et al*. (2000) reported two studies comparing TWLTL with RM in the State of Georgia. The authors reported that segments with RM on the two sites had lower total crash rates by 36% and 45%, and injury crash rates by 38% and 48%. Eisele and Frawley (2005) reported a decrease of 17% and 58% in crash rates on two sites in Texas after RM replaced TWLTL on selected streets. Schultz *et al*. (2007) conducted before and after analysis to evaluate the safety effectiveness of RM over TWLTL. The authors concluded that the RM did not reduce the total crash rates but improved safety in terms of reducing high severity crashes, namely, angle, fatal and injury crashes.

2.2 Median Openings and Their Types

Bonneson and McCoy (1997) built analytical models to evaluate the operational impacts of midblock left-turn treatments on through and left turn traffic. The models were used for evaluating alternatives for midblock left turn treatments (in other words: evaluating alternative median types). Their model for raised curb median assumed presence of median openings at all active access points (those with volume of at least 10 vph). The authors pointed out that the models fit situations of low density of active access points. On purpose, the study did not vary the number/spacing of median openings due to the difficulty of accounting for effects of closure of openings on route choices without considering the surrounding street network. Delay was found to be about the same for raised curb and TWLTL medians. However, delay was slightly more for raised curb than TWLTL median at high traffic and frequency of bay overflow. The results showing TWLTL being better than RM were also documented as reviewed literature in their report.

Analysis of traffic conflicts reported by Gluck *et al*. (1999) in the NCHRP 420 reveals that full median openings comprise of 18 major and 20 minor conflicts whereas directional median openings have only 4 major and 2 minor conflicts. Driveways that are not aligned to median openings have only 2 conflict points. Gluck *et al*. listed studies and findings regarding types of median openings. The studies indicated that replacing direct left turns from driveways with indirect left turns reduces crash rates by 22%. Among the listed studies is a Michigan based study that reported an increase in crash rate by 14% on directional median crossovers where highways were not signalized. Signalized highways

with directional crossovers had lower crash rates in the rage of 35% to 50%. Summarized were also studies reporting improvement in capacity by 18% to 50%.

Brown *et al*. (1998) developed a model to predict crushes on multilane highways by total and severity of crashes. The study found that presence of medians improves safety and that RM sections with no median openings between signalized intersections are safer than those with the openings. However, evaluation of benefits of RM without median openings should consider crashes in both midblock sections and their respective signalized intersections. Migration of crashes to signalized intersections might still be present in sections where median openings are closed but the migrated crashes might probably not outweigh the total safety benefits.

Jagannathan (2007) reported that, in Michigan, there is a significant number of signalized intersections which prohibit U and left turning traffic at the intersection. Instead, the turning traffic has to cross the intersections and perform U turns at downstream median openings followed by right turns. Jagannathan reported that the use of the crossovers improves safety by 20% to 50%. Capacity improvements are also in the same range. An earlier study reported a reduction of total and injury crashes by an average of 30% after directional crossovers replace non-directional ones (Taylor *et al*. 2001).

Potts *et al*. (2004) conducted a study on the safety of unsignalized median openings in seven states. The study found that average crash rates for directional three-leg median openings are 48% lower than that of full three-leg median openings. The average crash rates for directional four-leg median openings are 15% lower than that of four-leg intersections. In addition, Potts reported that overall, there was no indication that U-turns

constituted major safety concern although they make 58% of the turning movements at median openings. Potts also concluded that there was no indication that safety problems resulted from occasional use of short spacings in the range of 300 to 500 ft.

2.3 Determination of Spacing between Median Openings

Yang (2001) evaluated operational performance of direct left turns versus right-plus U-turns from driveways. The study focused on figuring out traffic conditions under which it is worthy replacing direct left turns with right plus U-turns. Yang found that at 200 vph of traffic left turning from major streets, delay for direct left turns is always bigger than that of right-plus U turns for all through traffic conditions. For volumes of left turns from major streets lower than 200 vph, direct left turns always have bigger delay for left turn volumes of 150 from driveways. Holding constant the traffic left turning from main street, the cut point of through traffic at which the delay for right-plus U-turns is smaller than that of direct left turns increases with decrease in left turn volume from driveways. Also, the study reported that when weaving distances are very long (700 feet and over) there may be no benefits of the right-plus U-turns. When through traffic is between 6,000 and 7,000 vph, the direct left turns fail to operate and only right-plus U-turns are recommended.

Zhou *et al.* (2003) conducted a study on location of median openings for U-turning traffic downstream of directional median openings. Zhou stated the problem as unavailability of procedure or guidelines for determining optimal location of U-turn median openings. They added that if spacing is long, travel time for diverted left turning traffic increases and if short there may be safety problems.

In determining optimal location, they considered vehicles leaving driveways would join tails of platoons in one direction. On arrival at downstream U-turn median openings, the vehicles would join the tails of other platoons in the opposite direction. The model used signal offset as the main input and hence appropriate where signal timings are likely to last long unchanged. The model is also appropriate when the subject driveways (and their directional median openings) are halfway from both signalized intersections otherwise problems of asymmetry design may arise. Symmetry may be important if traffic reversal may demand reversal of signal offsets. Restricting vehicles from directly turning left onto major roads was reported to reduce delay of diverted traffic and to improve safety by 68%.

Liu (2006) stated similar problem of lacking regulations or guidelines for minimum and optimal separations between upstream driveways and downstream U-turn median openings. Liu used the 50^{Th} percentile crash rate to determine the minimum separations. On 4 lane roads, the study recommended 350 feet and 500 feet for U-turn locations in midblock and at signalized intersections, respectively. For 6-8 lane roads, the study recommended 450 and 750 feet for U-turning traffic in midblock and at signalized intersections, respectively. The numbers imply that 1,320 feet segments might have one median opening while 2,640 feet segments might have 3 median openings (if the middle median opening is 570 feet from the two). Table 2-1 summarizes the recommended spacings.

Although Liu (2006) demonstrated that the separation between upstream driveways and downstream U-turn median openings affects both safety and operations, in the end recommended that only safety criteria should be used in determining the separation. Liu

Table 2-1. Recommended Minimum Separation Distances

Number of Lanes	Location of U-turn Bay	Critical Separation Distance (feet)	Recommended distances (feet)
4	Median Opening	341	350
4	Signalized Intersection	508	500
6 to 8	Median Opening	457	450
6 to 8	Signalized Intersection	774	750

Source: Liu (2006), pp. 94, Table 6-4

did not clarify why the 50th percentile was taken as the threshold value instead of lower percentiles which correspond to lower crash rash rates.

A study similar to Liu's (2006) study was conducted to determine minimum separation of upstream driveways and downstream U-turn median openings (Pirinccioglu, 2007). The study used rates of conflicts (evasive actions for crash avoidance) as surrogate for safety. The separation of the median openings was determined at the 50th percentile conflict rates. The study yielded results similar to those presented by Liu (2006) but a little longer spacings (Table 2-2). The separation of 1,000 feet between a signal and an upstream driveway (or directional median opening) looks big for land-use accessibility. The implications are that segments 1,320 feet long won't have a median opening and those 2,640 feet will only have two.

Table 2-2. Recommended Separation Distance Values

Location of U-turn Bay	Number of Lanes	Critical Separation Distance	Recommended Separation Distance
Median Opening	4	419	400
Median Opening	6 to 8	687	700
Signalized Intersection	4	614	600
Signalized Intersection	6 to 8	1005	1000

Source: Pirinccioglu (2007), pp. 90, Table 6-3

2.4 Guidelines on Spacing of Median Openings

Koepke and Levinson (1992) reported that several states had criteria for spacing between median openings for suburban and rural areas. The criteria corresponded to spacing ranging from 300 feet to 2,640 feet. The study also reported guidelines from another study (NCHRP 93) which used arterial speed for specifying minimum spacing (Table 2-3). Generally, the guideline specifies a spacing of 660 feet for urban roads on principal and minor arterials, and 300 feet for collectors. The guideline also recommends spacing of 1,320 feet for rural highways.

Table 2-3. Spacing Criteria between Median Openings

Speed (mph)	Spacing Recommendations (feet) Desirable Minimum
30	370
35	460
40	530
45	670
50	780
55	910

Source: Koepke and Levinson (1992), pp. 63, Table 7-8

Harwood *et al.* (1995), in the NCHRP 375, reported that very few state highway agencies had design policies with provisions for spacing between median openings. The study reported one anonymous state that didn’t have specific minimum spacing for unsignalized median openings but required spacings that accommodate left turn lanes with proper taper and storage length. The state, however, recommended the minimum spacing of 1600 feet for openings that might potentially be signalized in the future.

Harwood *et al.* also reported spacings ranging from 0.25 to 1 mile being recommended for rural areas in another state.

The Transportation Research Circular number 456 (1996) recommends that median openings should relate to block spacing. The circular adds that full median openings should be consistent with signal spacing criteria or be susceptible to closure. It is not clear whether or not the circular refers to signalized median openings only.

Potts *et al*. (2004) reported that 50% of state and local highway agencies had guidelines on minimum spacing between median openings. The author reported that some states had guidelines that included several variables in determining the minimum spacing. Those guidelines with one variable had minimum values ranging from 500 to 2,460 feet for rural areas and 300 to 2,460 feet for urban roads. The report also listed the state of Nevada having a guideline specifying the minimum spacing of 660 feet for rural areas and nothing for urban areas. Henderson, a city in the Las Vegas Valley, was listed having a guideline specifying the minimum spacing of 660 feet for urban highways and nothing for rural. Potts concluded that there was no indication that safety problems result from occasional use of short spacings in the range of 300 to 500 feet.

2.5 Density or Number of Driveways

With respect to driveways, Maze and Plazak (1997) reported a decrease of 33.3% in crash rates in the City of Fair Field, Iowa, resulting from closing eight driveways in a 0.6 mile section along with adding signals and improving side streets. Gluck *et al*. (1999) reported that addition of a driveway in a mile increases crash rates by 4%. The data in their report shows that driveways on roadways having RM had lower impact on crashes

than those having TWLTL. The authors also reported data showing adverse safety impacts of driveways in segments with high signal density. Eisele and Frawley (2005) reported that driveways on roads with TWLTL have bigger impact on crashes than driveways on roadways with RM.

Bonneson and McCoy (1997) conducted median specific regression analyses and found that increasing the density of driveways and unsignalized public approaches increases the number of crashes. The authors also found that the driveways and unsignalized public approaches had the same safety impacts for different median types.

In another literature, Bonnesson & McCoy (1997) summarized a number of previous studies that reported safety impacts of driveway density by type of median. Tables 2-4 and 2-5 below (reproduced from Bonnesson & McCoy, 1997) show variation of the safety impacts of driveway density across studies. Several studies found driveway density to have no significant impact on safety. Studies which found driveways having significant impacts on safety reported mixed results in terms of signs and magnitudes of the impacts. Some indicated that increasing driveway density improves safety while some report the opposite. The marginal impacts of driveway density might be varying by geographical location.

2.6 Summary

In summary, major studies which evaluated safety of arterials with RM did not consider the density of median openings as a safety factor (see Table 2-4 below). Moreover, several guidelines reported in the literature do not provide background studies and information used in developing the guidelines. Therefore, it is not known how safety

influenced the making of the guidelines. The guidelines also vary between jurisdictions and settings, for example in urban areas, Potts *et al*. (2004) reported that New Mexico State requires the minimum spacing of 300 feet while Arizona requires 660 feet. This variation of spacing requirements adds to the problem of transferability of guidelines across geographical regions. The problem of transferability of the guidelines partly justifies motivation for conducting a local study with local data.

Table 2-4. Impacts of AM features in studies for segments with RM

Component	Parameter		Accidents/mile				Accidents/MVM	
	Var	Name	Parker (1983)	Squires (1989)	Parker (1991)	Chatterjee (1991)[1]	Harwood (1986)	Squires (1989)
Exposure (non-linear)	β_0	Intercept	1	1	1	1	1	1
	β_1	Traffic (ADT)	0	0	0	0	1	1
	β_2	Segment length	1	1	1	1	1	1
Explanatory (linear)	C_0	Intercept	-12.7	-14.8	-12.6	11.0	2.55	1.92
	C_1	Traffic (ADT)	0.0015	0.00192	0.00137	0.0035	0	0
	C_2	Population	-0.0000093	--	--	--	--	--
	C_3	Driveway density	-0.00228	0[2]	0[2]	0[2]	0.013	0[2]
	C_4	Signal density	8.04	16.1	8.3	0	--	2.72
	C_5	Unsig. approach density	--	0	--	0	0.127	0
	C_6	Public St. approach density	0	--	0	--	--	--
	C_7	Truck percentage	--	--	--	--	-0.111	--
	C_8	Left-turn volume	--	--	--	--	0	--
	C_9	Development type	--	--	--	--	3.51	--
Database		Years of accident data	3	3	3	3-4	5	3
		Number of sections	19	15	3	11	44	15
		Total section length (mi)	28.2	24.7	NA[3]	19.9	21.8	24.7
		R^2	0.73	0.77	0.84	0.65	NA[3]	0.80
		Through lanes	4	4	4	4	4	4

Source: Bonnesson & McCoy (1997), pp. 98, Table 4-4

Dashes indicate the factor is not specifically included in the model

1. Commercial only
2. The factor was considered but not found to be statistically significant
3. NA=Not available

Table 2-5. Impacts of AM features in studies for segments with TWLTL

Component	Parameter Var	Parameter Name	Accidents/mile: Walton (1979)	Parker (1983)	Mcoy (1986)	Squires (1989)	Parker (1991)	Chatterjee (1991)[1]	Accidents/MVM: Harwood (1986)	Squires (1989)
Exposure (non-linear)	β_0	Intercept	1	1	1	1	1	1	1	1
	β_1	Traffic (ADT)	0	0	0	0	0	0	1	1
	β_2	Segment length	1	1	1	1	1	1	1	1
Explanatory (linear)	C_0	Intercept	-43.5	-28.8	9.44	-21.7	-22.3	19.7	16.9	4.01
	C_1	Traffic (ADT)	0.00203	0.00173	0.00214	0.00388	0.00153	0.0035	0	0
	C_2	Population	0.000175	-0.0000058	--	--	--	--	--	--
	C_3	Driveway density	0.491	0[2]	0[2]	0[2]	0[2]	0[2]	0.013	0[2]
	C_4	Signal density	9.20	5.43	0	22.7	5.6	0	--	2.29
	C_5	Unsig. approach density	--	--	0	-8.85	--	0	0.127	0
	C_6	Public St. approach density	--	2.16	--	--	1.94	--	--	--
	C_7	Truck percentage	--	--	--	--	--	--	-0.111	--
	C_8	Left-turn volume	--	--	--	--	--	--	0	--
	C_9	Development type	--	--	--	--	--	--	2.56	--
Database	Years of accident data			3	4	3	3	3-4	5	3
	Number of sections			17	4	42	5	12	135	42
	Total section length (mi)			12.2	4.35	62.5	NA[3]	19.7	91.2	62.5
	R^2		0.75	0.71	0.84	0.60	0.73	0.65	NA[3]	0.44
	Through lanes		4	4	4	4	4	4	4	4

Source: Bonnesson & McCoy (1997), pp. 97, Table 4-3
Dashes indicate the factor is not specifically included in the model
1. Commercial only
2. The factor was considered but not found to be statistically significant
3. NA=Not available

CHAPTER 3

METHODOLOGY

3.1 Introduction

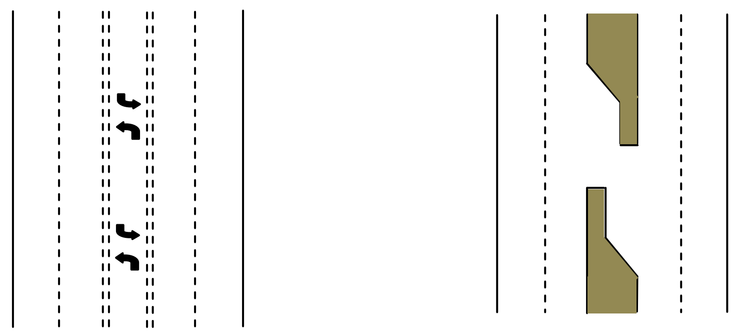
This chapter describes the methodology for analysis of safety impacts of median openings and other AM features in midblock segments of urban arterials. A midblock segment is defined as a roadway section that is bounded by two consecutive signalized intersections and without any control device such as stop or yield signs for through traffic. The methodology is divided into two levels of analyses. The first level involves evaluating the safety impacts of median types and density of median openings at an aggregate level. The second level involves evaluating the safety impacts of median openings at a disaggregate level. The level focuses on the impacts of types, location and spacing between median openings on crashes in functional areas of median openings. Before discussing in detail the two levels of analyses, a description of the terms used in the analyses is presented below.

3.2 Definition of Terms

3.2.1 Median

Medians are continuous spaces, landscapes, or concrete structures installed in the middle of a roadway for the purpose of separating opposing traffic. Medians are categorized as traversable or non-traversable. Traversable medians are middle lanes mostly known as two-way-left-turn lanes (TWLTL) that are used by left turning traffic to access land-uses. Non-traversable medians are landscapes, slabs, short concrete walls, or barriers intended to prevent left turning traffic from directly accessing land-uses. Curbed

concrete or asphalt slabs are the most common types of non-traversable medians on urban arterials and they are known as raised medians (RM). The RM are usually used in access management programs to replace TWLTL for the purpose of improving safety and mobility. Figure 3-1 presents sketches for the TWLTL and RM medians.

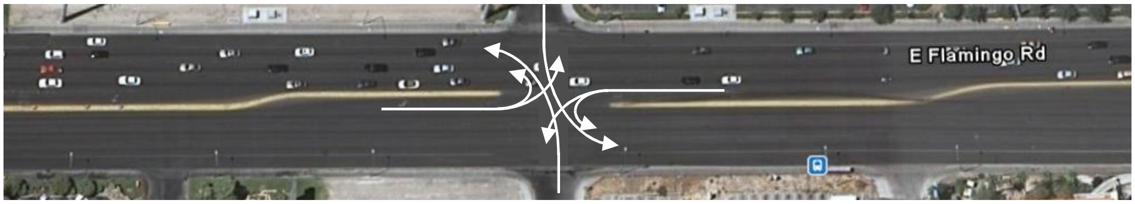


TWLTL median RM median

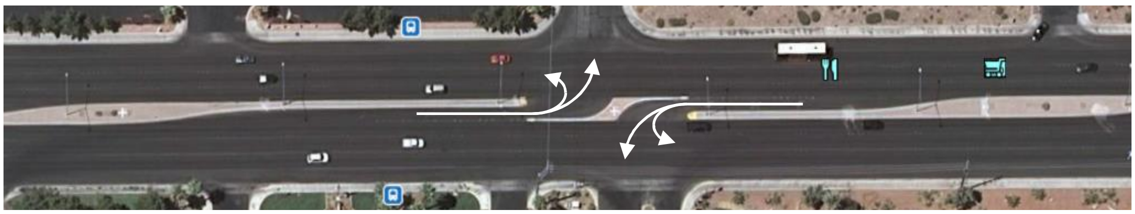
Figure 3-1. Common types of medians.

3.2.2 Median openings

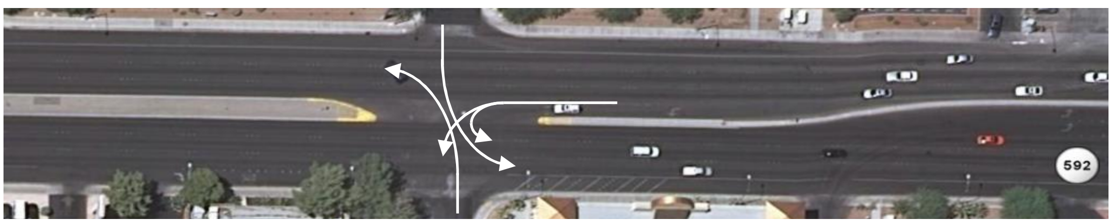
Median openings are spaces in RM used to provide access for vehicles to turn left into and out of land-uses adjacent to arterials. There are four types of median openings, namely, full, directional, semi-full, and unidirectional median openings. The classification of each is based on the number and type of left turning movements permitted by the opening. Figure 3-2 presents snapshots of the types of median openings with the accommodated number of left turning movements. A full median opening allows all left turning movements at the opening while a directional opening allows only traffic turning left into land-uses. On the other hand a unidirectional opening allows only traffic into land-uses in only one of the two arterial directions. Lastly, a semi-full median



(a) Full median opening.



(b) Directional median opening.



(c) Semi-full median opening.

(d) Unidirectional median opening.

Figure 3-2. Types of median openings.

opening allows full access from the land-uses but only unidirectional access from the arterial streets. It is expected that the smaller the number of turning movement at a median opening the fewer the number of crashes due to smaller number of conflict

points. Note that the words semi-full and unidirectional have been used in this study for ease of differentiation but may not be found in the literature.

3.2.3 Midblock segment

A midblock segment is a section of a road bounded by two consecutive signalized intersections excluding physical areas of the intersections. These segments do not have any traffic control device to through traffic along them. Figure 3-3 shows a midblock segment and its bounding physical areas of signalized intersections. The physical areas of signalized intersections range from 200 to 250 feet from centers of the intersections (Brown *et al.* 1998, Vogt and Bared 1998, Harwood *et al.* 2003, Lyon *et al.* 2003, Lewis 2006, and Bindra *et al.* 2009).

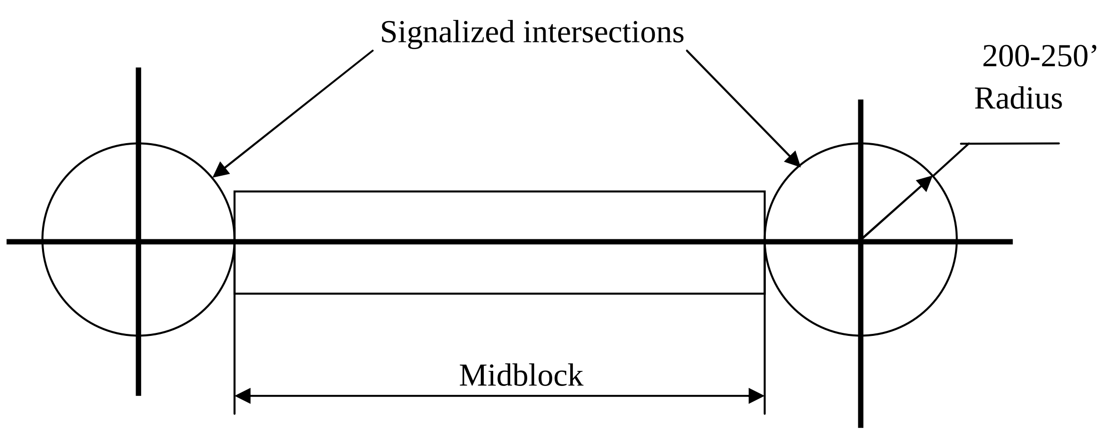


Figure 3-3. Midblock and intersection areas.

Reasons for differentiating between intersections and midblocks in this study are that:

- Only midblock crashes are assumed to be associated with midblock AM features such as median types, driveways and median openings,

- Intersections have more crashes than midblocks hence combining the crashes together might lead to intersection crashes overwhelming midblock crashes, and
- It is difficult to account for cross traffic in modeling (in calculating crash rates and determining impacts of cross traffic). Although some studies (especially those which considered signal density as one of the variables) have calculated crash rates for whole arterials using only traffic along the arterials, the resulting rates inaccurately estimate safety on those sites.

3.2.4 Driveways

Driveways are features that provide connection between arterials and land-uses for the purpose of providing access. The driveways are considered as stop controlled intersections and contribute to safety and mobility problems of midblocks due to the conflicting movements they generate. Access management programs may involve separating the conflict points by increasing spacing between driveways or controlling the number of movements that use the driveways. Figure 3-4 presents a sketch of a typical driveway.

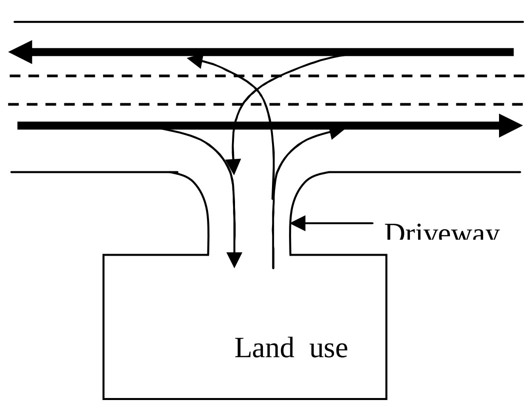


Figure 3-4. A driveway connecting a land-use to an arterial road.

3.2.5 Unsignalized public approaches

Unsignalized public approaches are local roads of low functional classification that are designed to serve more for accessibility than mobility and connect other land-uses to major roads. These local roads, like driveways, are usually stop-controlled at points where they meet major roads. The major difference between an unsignalized public approach and a driveway at junctions with major roads is that a driveway carries less turning traffic and directly links one land-use to an adjacent major road while an unsignalized public approach links several land-uses to major roads.

3.3 Levels of Analyses

3.3.1 Aggregate Analysis

This level of analysis evaluates the impacts of density of median openings and other AM features on crashes that occur in the midblock segments of arterials. Each midblock segment is considered as one data point. Other AM features considered are the types of median, signal spacing, density of unsignalized public approaches, density of driveways, and land-uses abutting the segments. Additional variables considered include the number of through lanes, the average annual daily traffic (AADT), and posted speed limit.

3.3.2 Disaggregate Analysis

This level of analysis evaluates the impacts of types, location, and individual spacing between median openings on crashes that occur in the functional areas of the openings. Each median opening is considered as one data point. Other AM features considered are the number of driveways and the land-uses served by the openings. Like the aggregate

analysis, this analysis also includes the number of through lanes, the average annual daily traffic, and posted speed limit.

3.4 Data Collection

3.4.1 Data for Aggregate Analysis

The aggregate analysis needs crash data that occurred only in midblock sections of arterials excluding crashes that occurred at intersections. To obtain such data, the influence area of an intersection has to be determined before data are collected. In this study, the influence area of an intersection is defined as the distance from the center of the intersection to a point where spatial distribution of crashes begins to level off.

A pre-sample consisting of six approaches to signalized intersections was collected in order to determine the physical area of an intersection. These approaches did not have driveways, unsignalized public approaches, or median openings within the functional areas of the intersections. Crash data from the approaches were summarized by distance of occurrence at intervals of 50 feet. Figure 3-5 presents the spatial distribution of crash rates up to 600 feet from the center of the intersections down the approaches. It is apparent that beyond a distance of 100-200 feet the distribution of crashes practically levels off. Therefore, all crashes that occurred within 200 feet of signalized intersections were considered intersection crashes and all crashes outside this range were categorized as midblock crashes. The midblock crashes also included those that occurred within 100 feet of arterial center line (Figure 3-3).

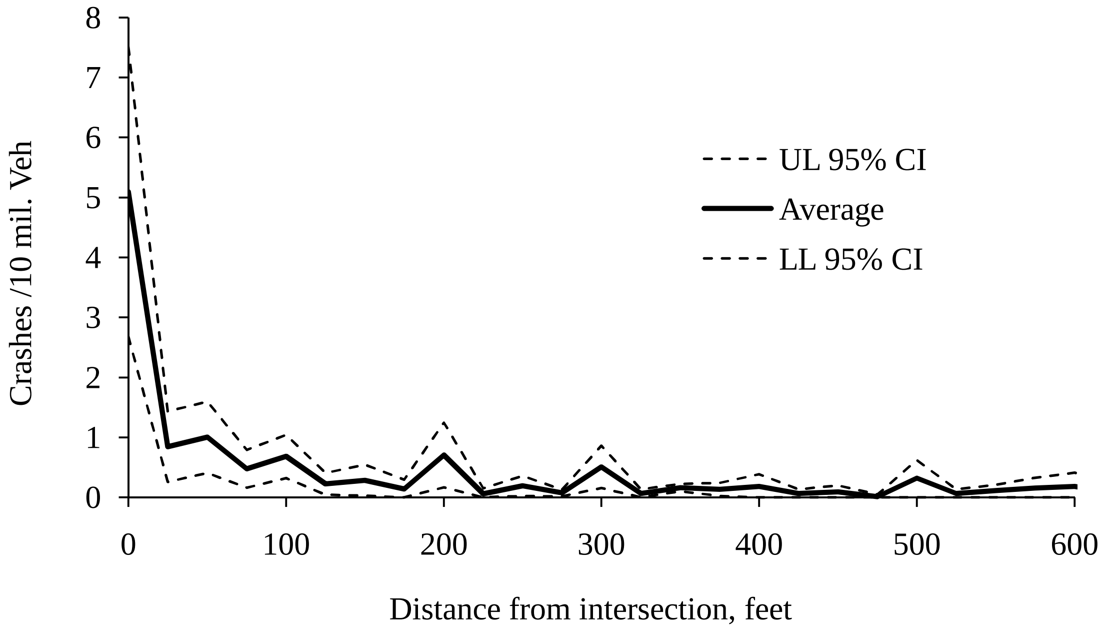


Figure 3-5. Spatial distribution of crashes along segments.

After determining the radius of intersection areas, a total of 319 representative samples of midblock segments were selected from the Las Vegas Valley. The selection was based on the requirement to obtain a sample of segments covering a variety of traffic, geometric, and land-use characteristics. Crash data for the segments were then extracted from a GIS (Geographic Information Systems) database maintained by NDOT. The database had five years worth of data: from 2002 to 2006. The crashes were summarized by total, type and severity of crashes. Although having the data by type of movement before impact would be more useful for the analysis, the data available for this study did not consistently provide information on types of movement.

An inventory of existing AM and geometric features was conducted in the laboratory using satellite imagery from Google Earth and a GIS street network database provided by the Regional Transportation Commission (RTC) of Southern Nevada. Significant effort

was put to ensure that the observed AM features in the study segments had not changed over the period of analysis. This was achieved by using a recent tool in the Google Earth imagery that shows history of image acquisition. Whenever necessary, site visits were conducted to supplement the laboratory inventory for the sake of correcting misinterpretation of aerial photos in cases they were not clear. The AM and geometric features that were collected for each segment are:

- Signal spacing
- Number of median openings
- Type of median openings
- Number of driveways
- Proportion of the driveways serving residential land-uses
- Number of unsignalized public approaches
- Number of through lanes

In addition, the following variables were collected from the NDOT:

- Average annual daily traffic (AADT)
- posted speed limit

3.4.2 Data for Disaggregate Analysis

The disaggregate analysis involves evaluating the impacts of spacing, type and location of median openings on crashes. For this analysis, representative median openings were selected from the midblock segments already selected in Section 3.4.1. Only arterial crashes within functional areas of median openings were considered in the

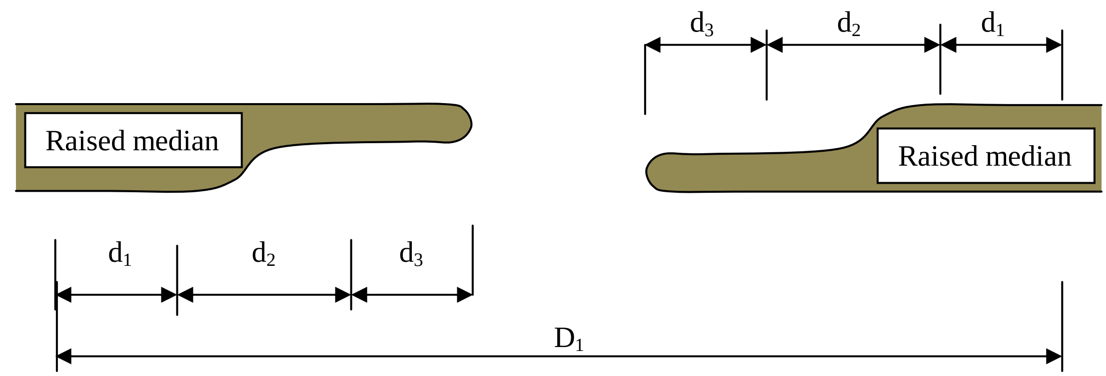
analysis. Also crashes within 50 feet of driveway approaches were considered in order include driveway crashes related to median openings.

The functional area of a median opening was defined as the zone covering three distances: perception reaction distance (d_1), maneuver distance (d_2), and storage distance (d_3) (TRB 2003, AASHTO 2004). Drivers' reaction time was assumed to be one second. Since crashes were not classified by direction of traffic, this study could not differentiate near and far functional areas at median openings. Figure 3-6 illustrates the dimensions of the functional area of a median opening. The figure shows the total functional length D_1 for full and directional median openings and D_2 for semi-full and unidirectional.

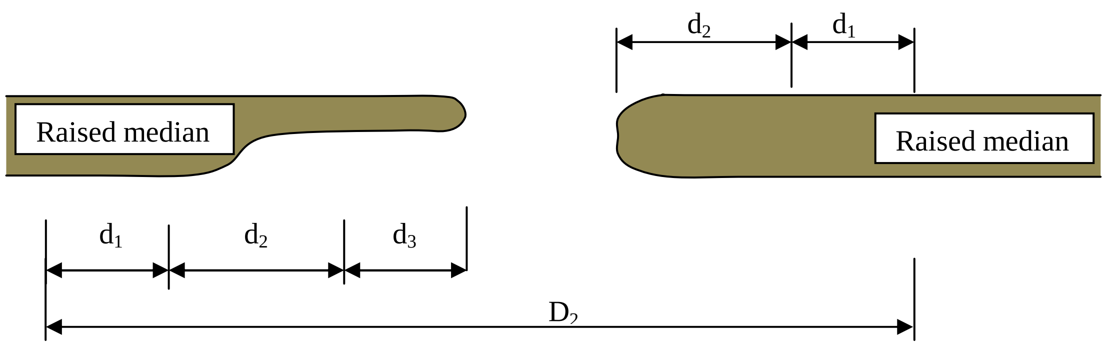
For segments having median openings with overlapping functional areas, lengths of turn pockets were taken as their functional areas in order to avoid having two median openings in one functional area or double counting their crashes. Crashes in the functional areas were then summarized by total, type and severity of crashes.

The AM and geometric features that were collected for each median opening are:

- Location of a median opening
- Distance to the nearer median opening
- Distance to the farther median opening
- Distance to the nearer signalized intersection (for median openings adjacent to intersections)
- Alignment of driveways to the median opening (3-legs or 4-legs)
- Number of driveways served by the median opening
- Proportion of the driveways serving residential land-uses and
- Total number of through lanes



(a) Functional areas of full and directional median openings.



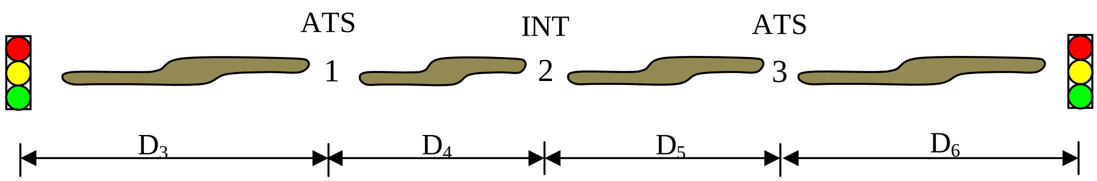
(b) Functional areas of semi-full and unidirectional median openings.

where
d_1 = perception reaction distance
d_2 = maneuver distance (braking and lane changing)
d_3 = storage length
D_1 = functional distance for full and directional median opening
D_2 = functional distance for semi-full and unidirectional median opening

Figure 3-6. The functional area of a median opening.

Location of a median opening refers to whether it is bounded by another median opening and a signalized intersection, by two signalized intersections, or by two other median openings. Median openings that are bounded by at least one signalized intersection are referred to 'adjacent to signalized intersection (ATS).' Those bounded by

two median openings are referred to as ‘intermediate.’ Figure 3-7 shows the difference between median openings by location.



where

ATS = median opening adjacent to signalized intersection
INT = intermediate median opening
D_3 = the distance from median opening number 1 to the adjacent intersection
D_4 = the shorter distance for median opening number 2
D_5 = the longer distance for median opening number 2
D_6 = the distance from median opening number 3 to the adjacent intersection

Figure 3-7. Distance measurements for median openings.

Distance to signalized intersection for ATS median openings is the center-to-center distance from the subject median opening to the nearer signalized intersection. In Figure 3-7, D_3 is the distance to the signalized intersection for median opening number 1. Also, D_6 is the distance to the signalized intersection for median opening number 3.

Distance to the nearer median opening is the center-to-center distance from the subject median opening to a median opening closer to it. In Figure 3-7, for example, D_4 is the distance from median opening number 2 to the nearer median opening number 1. Also, D_4 is the distance from median opening number 2 to the farther median opening number 3.

3.5 Statistical Modeling

For both aggregate and disaggregate analyses, multivariate regression analysis was used to develop relationships between crashes and AM explanatory variables. The relationships between crashes and the variables are important in evaluating the impacts of each AM variable on safety of midblock and median openings.

Theoretically, the number of crashes per time in a midblock segment or median opening is considered to follow Poisson distribution. Eq. (3.1) presents the structure of Poisson distribution as the probability of a number of crashes Y in a given time interval. In the equation, μ is a positive real number equal to the expected number of crashes in that time interval.

$$p(Y;\mu) = \frac{\mu^{y} e^{-\mu}}{y!}; \quad y = 0, 1, 2, \dots \tag{3.1}$$

where

y is the number of crashes observed per time

μ is the expected number of crashes per time

In this study, the observed number of crashes (outcomes) Y is used to estimate the impacts of AM variables on the unobserved Poisson parameters μ. If the parameters μ are Gamma distributed, based on empirical Bayesian setting, Negative Binomial (NB) regression model is used to estimate coefficients of explanatory variables (Berger, 1980; Hauer et al., 1988; Hauer, 1997) because the NB is known to be the continuous mixture of Gamma and Poisson distributions. However, if the Poisson parameters are not Gamma distributed, the relationship might be unknown and using the NB regression may yield incorrect results. Moreover, it is difficult to preliminarily determine the distribution of the Poisson parameters due to the fact that midblock segments or median openings do not

have identical variables. Hence, an appropriate model is empirically searched or selected from a number of models using statistical methods and measures of goodness of fit such as adjusted R^2, and Akaike Information Criterion (AIC) (Faraway, 2005). The process of searching for the appropriate model is presented in the following section.

3.6 Model Selection

This section presents the process of obtaining appropriate regression models for the aggregate and the disaggregate analyses of median openings. Two general models are tested for suitability. The first model is the Generalized Linear Model (GLM), and the second is Non-linear Least Square (NLS) model. The following subsections describe the two mentioned models.

3.6.1 Generalized Linear Models

These are models which relate the mean of a dependent variable to a linear combination of explanatory variables while allowing for non-constant variance. The non-constant variance is allowed for by specifying the probability distribution that relates variance to the expected value of the data. For example, for Gamma distribution variance is related to the square of the mean. Eq. (3.2) and (3.3) show the setting of the GLM model.

$$\mu^{\lambda} = \beta_0 + \sum_{i}^{N} \beta_i X_i \tag{3.2}$$

$$V = f(\mu) \tag{3.3}$$

where β_0 is the constant term
β_i is the coefficient for an explanatory variable *i*
X_i is the explanatory variables *i*
V is variance of a probability distribution

The ancillary parameter λ is used to characterize the functional form of the model. For example, if λ = 1 and variance is constant then the model takes a linear form (Eq. 3.4), on the other hand if λ = 0 the model take a logarithmic (or exponential) form (Eq. 3.5).

$$\mu = \beta_0 + \sum_i^N \beta_i X_i \tag{3.4}$$

$$log(\mu) = \beta_0 + \sum_i^N \beta_i X_i \tag{3.5}$$

The GLM models are associated with a problem of selecting a probability distribution and a functional form (value of λ) prior to calibration. Selecting an appropriate distribution and functional form may involve a tedious process of calibrating models for several different distributions and values of λ. The best model is chosen from a list of calibrated models based on measures of goodness of fit. The chosen model is only the best from the list and may not be that which fits the data best.

A method proposed by Basu (2005) may be used to avoid the need for calibrating several models. The method uses explanatory variables to determine characteristics of the distribution of a dependent variable. The method estimates variable coefficients, the ancillary parameter for the model (i.e. λ), and two additional ancillary parameters (i.e. θ_1 and θ_2) for variance functions of the underlying probability distribution of the dependent variable (Table 3-1). Only two variance functions are considered, namely, power (PV) and quadratic (QV) functions as seen in Eq. (3.6) and (3.7).

$$V = \theta_1 \mu^{\theta_2} \tag{3.6}$$

$$V = \theta_1 \mu + \theta_2 \mu^2 \tag{3.7}$$

Table 3-1 presents values of the ancillary parameters for common probability distributions. For example, a power variance-mean relationship (PV) reporting θ_1 and θ_2 with values close to one (1) each implies Poisson distribution. For Exponential models, θ_1 and θ_2 are reported with values close to one (1) and two (2), respectively. If quadratic variance-mean relationship (QV) is used, θ_1 and θ_2 are reported with values close to one (1) and zero (0), respectively, for Poisson distribution. For Exponential model, θ_1 and θ_2 are reported with values 0 and 1, respectively. Values of the parameters close to those belonging to negative binomial may validate the assumption in section 3.4 that crash counts are Poisson distributed and that the Poisson parameters μ are Gamma distributed. The dashes in Table 3-1 indicate that the underlying probability distribution does not have the form of the variance functions under consideration.

Table 3-1. Common values of θ_1 and θ_2 for the Two Variance Formulations

Variance Formulations				
Power Variance		Quadratic Variance		
θ_1	θ_2	θ_1	θ_2	Distributions
1	1	1	0	Poisson
> 0	2	0	> 0	Gamma
> 0	3	--	--	Inverse Gaussian
--	--	1	> 0	Negative Binomial

Source: Basu (2005), pp. 504, Table 1

The variable coefficients estimated using the Basu's (2005) method are then used to estimate marginal impacts of explanatory variables. Estimation of the marginal impact is simple and independent of the values of the variables for $\lambda = 1$ or $\lambda = 0$. For other values of λ, the marginal impacts may be estimated at specified values of the explanatory variables. For the purpose of meeting the objectives of this research, the estimates of

variable coefficients are used to estimate safety impacts for cases $\lambda = 1$ or $\lambda = 0$. For other cases, a GLM model is calibrated for $\lambda = 1$(if variance function does not exist) or for $\lambda = 0$ with a probability distribution close to that suggested by the values of θ_1 and θ_2. In the case the values of θ_1 and θ_2 do not suggest any distribution, an NLS model is resorted to.

3.6.2 Non-linear Least Squares (NLS)

The functional forms of these models may be determined based on data trends and prior expectation. For example, variables in this study have wide range of values from zero (0) to big positive values; also models calibrated in this research must predict a wide range of positive values from small to big ones. The appropriate functional forms for such data may be of power or exponential nature. Since some of variables are dummy, only exponential form is considered in this study as shown in Eq. (3.8).

$$\mu = e^{\beta_0 + \sum_i^N \beta_i X_i} \tag{3.8}$$

where β_0 is the constant term
β_i is the coefficient for explanatory variable *i*
X_i is the explanatory variable *j*
N is the number of explanatory variables

Coefficients of variables in nonlinear models are estimated by nonlinearly minimizing the sum of square errors. The errors may not be normally distributed nor may they have zero mean (Pindyck and Rubinfeld, 1998).

The process of selecting the appropriate model is presented in Figure 3-8. The calibration of the models is presented later in Section 3.8 and Figure 3-9.

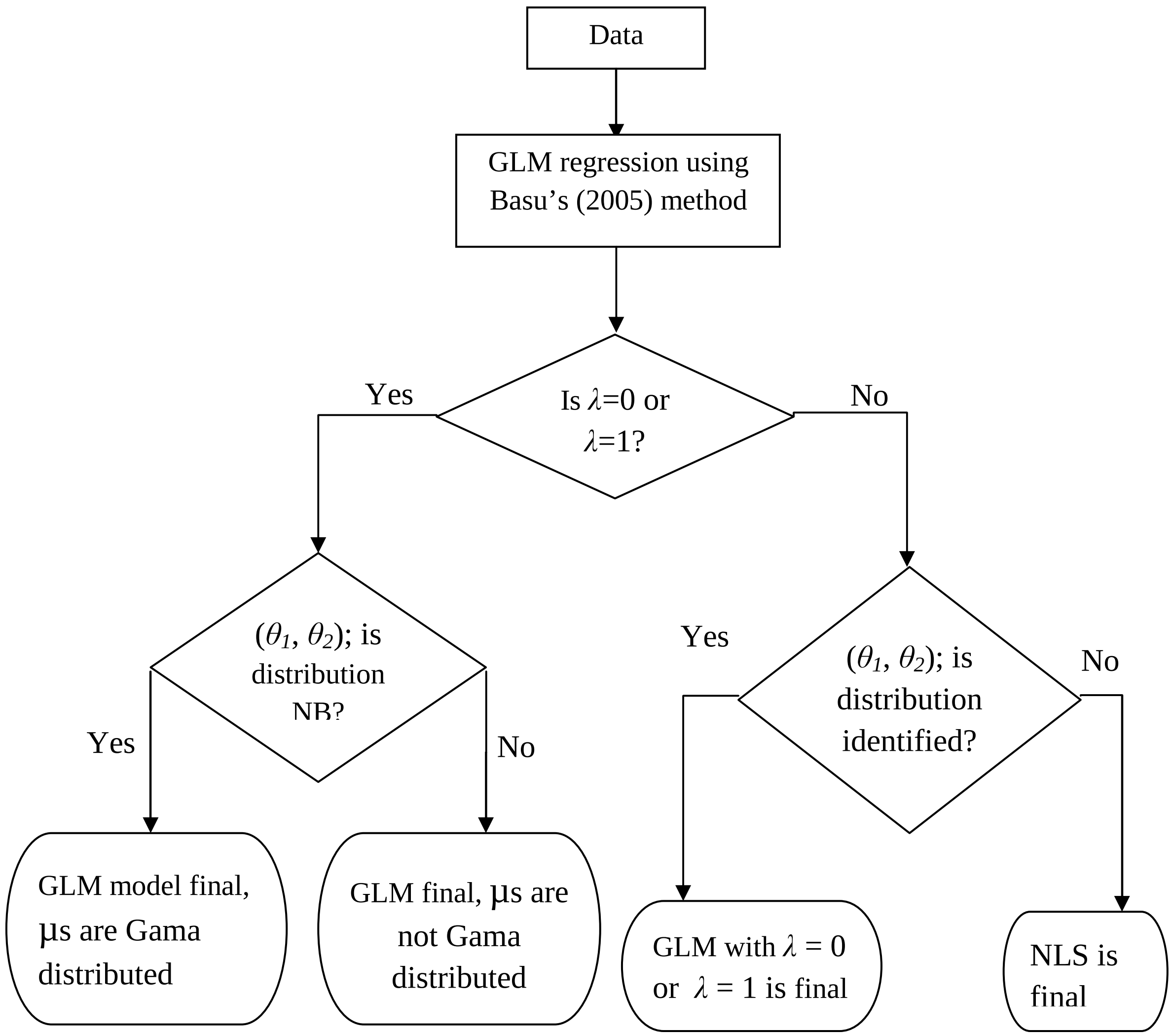


Figure 3-8. The procedure for selecting appropriate models

3.7 Evaluation of Marginal Impacts

Coefficients estimated in both GLM and NLS models are used to estimate marginal impacts of AM variables on safety. The ease of estimation of the impacts depends on the complexity of a model. The complexity of a model in this case is expressed by values of

the ancillary parameter λ in Eq. (3.2). Simple models are those with λ values of zero (0) and one (1). Below is a description of how coefficients are used in the evaluation of the marginal impacts.

3.7.1 Case I: $\lambda = 0$

GLM models with $\lambda = 0$ are equivalent to models with exponential functional form. In this case the GLM (Eq. 3.5) will have the same functional form as the NLS (Eq. 3.8). For marginal analysis, models of exponential form are known as 'semi-elastic' or 'constant percentage' models (Wooldridge, 2006). Their coefficients are used to estimate constant percentage change or incident rate ratios (irr) of crashes due to an absolute change in value of an explanatory variable. Below is the description of the two evaluations:

1. Constant percentage: Let μ_1 and μ_2 be the expected values of the dependent variable corresponding to two values X_j and $(X_j + \Delta X_j)$ of variable j, respectively. It follows that:

$$\mu_1 = e^{\beta_0 + \sum_i^N \beta_i X_i + \beta_j X_j} \quad (3.9)$$

$$\mu_2 = e^{\beta_0 + \sum_i^N \beta_i X_i + \beta_j (X_j + \Delta X_j)} \quad (3.10)$$

$$\mu_2 = e^{\beta_0 + \sum_i^N \beta_i X_i + \beta_j X_j + \beta_j \Delta X_j} \quad (3.11)$$

Simplifying Eq. (3.11)

$$\mu_2 = \mu_1 e^{\beta_j \Delta X_j} \quad (3.12)$$

The difference between μ_1 and μ_2 is given as

$$\Delta\mu = \mu_1 e^{\beta_j \Delta X_j} - \mu_1 \quad (3.13)$$

$$\Delta\mu = \mu_1 (e^{\beta_j \Delta X_j} - 1) \quad (3.14)$$

$$100 \times \frac{\Delta\mu}{\mu_1} = 100 \times \frac{\mu_1(e^{\beta_j \Delta X_j} - 1)}{\mu_1} \qquad (3.15)$$

The percentage change in the expected number of crashes is given by

$$\%\Delta\mu = 100(e^{\beta_j \Delta X_j} - 1) \qquad (3.16)$$

where ΔX_j is the change in value of the explanatory variable j
$\%\Delta\, \mu$ is the percentage change in the dependent variable

Removal of 100 from Eq. (3.16) will estimate the fractional change of previous value of the dependent variable. The fractional change is related to 'crash reduction factor (CRF)' as applied in traffic safety.

2. Incident rate ratio (*irr*): this is a ratio of two values of the dependent variable due to change of value an explanatory variable by one. Using Eq. (3.9) to (3.11) and letting the change in the value for variable j (i.e. ΔX_j) be one unit, the *irr* is derived as follows:

$$irr = \frac{\mu_2}{\mu_1} = \frac{\mu_1 e^{\beta_j \Delta X_j}}{\mu_1} \qquad (3.17)$$

$$irr = e^{\beta} \qquad (3.18)$$

If evaluation is done on a change in value other than one (1) for variable j, the *irr* raised to the amount of change gives the overall change ratio in the dependent variable (Eq. 3.19).

$$irr^{\Delta X} = e^{\beta \Delta X} \qquad (3.19)$$

The *irr* is related to what is known in traffic safety as the crash modification factor (CMF). The CMF is a factor by which the expected safety of a roadway entity after the geometry of the entity or control is improved, is related to the initial expected safety before improvement. CMFs are also used in the forthcoming Highway Safety Manual (HSM) to express effectiveness of safety programs. The sum of CRF and CMF is 1 (Bonneson and Zimmerman, 2006).

3.7.2 Case II: $\lambda = 1$

In this case the GLM model has a linear form (Eq. 3.4) and coefficients are directly read as marginal impacts. The value of a coefficient is the amount of change in the average value of a dependent variable due to unit change in an explanatory variable. Letting μ_1 and μ_2 be the expected values of the dependent variable corresponding to two values X_j and ($X_j + \Delta X_j$) of variable j, respectively. It follows that:

$$\mu_1 = \beta_0 + \sum_i^N \beta_i X_i + \beta_j X_j \quad (3.20)$$

$$\mu_2 = \beta_0 + \sum_i^N \beta_i X_i + \beta_j (X_j + \Delta X_j) \quad (3.21)$$

$$\mu_2 = \beta_0 + \sum_i^N \beta_i X_i + \beta_j X_j + \beta_j \Delta X_j \quad (3.22)$$

Simplifying Eq. (3.22)

$$\mu_2 = \mu_1 + \beta_j \Delta X_j \quad (3.23)$$

The difference between μ_1 and μ_2 is given as Eq. (3.24)

$$\Delta\mu = \mu_1 + \beta_j \Delta X_j - \mu_1 \quad (3.24)$$

The marginal impact is given as Eq. (3.25)

$$\Delta\mu = \beta_j \Delta X_j \tag{3.25}$$

where β_j is the regression coefficient for an explanatory variable j
ΔX_j is the change in the value of the explanatory variable j
$\Delta\,\mu$ is the change in the dependent variable

3.7.3 Case III: $\lambda \neq 0$ and $\lambda \neq 1$

Letting μ_1 and μ_2 be the expected values of the dependent variable corresponding to two values X_j and $(X_j + \Delta X_j)$ of variable j, respectively. Using Eq. (3.2), it follows that:

$$\mu_1 = [\beta_0 + \textstyle\sum_i^N \beta_i X_i + \beta_j X_j]^{\frac{1}{\lambda}} \tag{3.26}$$

$$\mu_2 = [\beta_0 + \textstyle\sum_i^N \beta_i X_i + \beta_j (X_j + \Delta X_j)]^{\frac{1}{\lambda}} \tag{3.27}$$

$$\mu_2 = (\beta_0 + \textstyle\sum_i^N \beta_i X_i + \beta_j X_j + \beta_j \Delta X_j)^{\frac{1}{\lambda}} \tag{3.28}$$

Simplifying Eq. (3.28)

$$\mu_2 = (\mu_1^\lambda + \beta_j \Delta X_j)^{\frac{1}{\lambda}} \tag{3.29}$$

Taking the ratio of μ_2 to μ_1

$$\frac{\mu_2}{\mu_1} = \frac{(\mu_1^\lambda + \beta_j \Delta X_j)^{\frac{1}{\lambda}}}{\mu_1} \tag{3.30}$$

Simplifying further, Eq. (3.31) is arrived at

$$\frac{\mu_2}{\mu_1} = \left(1 + \frac{\beta_j \Delta X_j}{\mu_1^\lambda}\right)^{\frac{1}{\lambda}} \tag{3.31}$$

Eq. (3.28) estimates the *irr* as a function of change in the value ΔX of an explanatory variable Xj. As it is seen, to estimate the *irr* the value of the explanatory variable, the change in the value of the explanatory variable, and values of the rest of the variables in

the model must be specified. Therefore, it is difficult to estimate marginal impacts using only changes in values of an explanatory variable as in cases 3.7.1 and 3.7.2.

3.8 Calibration of Models

In this study, Stata statistical software (Baum 2006) was used to estimate variable coefficients of the GLM and the NLS models. The software provides an advantage for solving GLM problems mentioned earlier. The models described in Figure 3-8 were first calibrated with all AM, geometric, and traffic related variables. Coefficients of the variables were then examined. Variables whose coefficients were insignificant were systematically removed from the model through stepwise procedure. Statistical significance was evaluated at a p-value of 10%. After systematically removing all insignificant variables, a residual analysis was conducted. Figure 3-9 presents the flow diagram of the calibration process undertaken in this study.

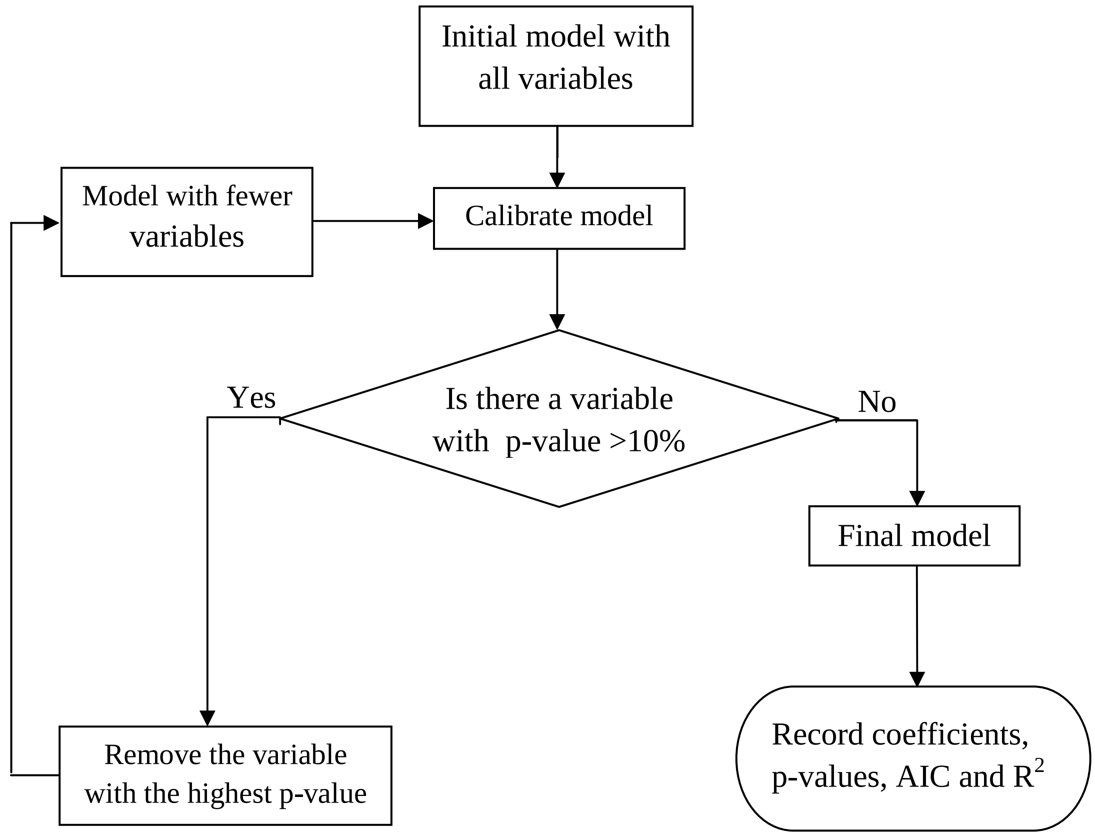


Figure 3-9. Process of calibration of models

CHAPTER 4

DATA SUMMARY

4.1 Data for Aggregate Analysis

Twenty five urban roads classified in the Nevada Department of Transportation (NDOT) AM guidelines (1999) as principal arterials, minor arterials, and collectors in the Las Vegas valley were selected. The selection was based on the requirement to obtain a sample of street segments covering a variety of traffic, geometric, and land-use characteristics. From these roadways, 319 midbblock segments were selected for the study. Since the Las Vegas urban area has only a few signalized undivided roadways, only street segments with RM and/or TWLTL were included in the study. Of the 319 study segments, 134 had RM and 185 had TWLTL.

4.1.1 Access Management Data

Table 4-1 presents a summary of the descriptive statistics of the AM features and traffic characteristics for the segments used in this study. The table shows, for example, that the average of signal spacings for the segments is 2,171 feet with the shortest segment being 621.2 feet and the longest one being 7,091 feet. Also, the average of signal spacings for TWLTL segments is larger than that of RM segments.

4.1.2 Crash Data

The study dataset was divided into two subsets, one for segments having RM and the other for segment with TWLTL. The RM dataset was used to evaluate safety impacts of median openings. The TWLTL datasets was used to evaluate safety impacts of other AM features for the purpose of comparing with those under the RM case. Table 4-2

summarizes the descriptive statistics of crashes by type of segment and also by total crashes, type and severity of crashes.

Table 4-1. Descriptive Statistics of AM and Traffic Characteristics

Variable	Dataset	Minimum	Average	Maximum	Standard deviation
Signal spacing (feet)	All	621.2	2,171	7,091	1,029
	RM	621.2	1,955	5,345	842
	TWLTL	646.5	2,331	7,091	1,124
Density of median openings (per mile)	All				
	RM	0	5.00	10.80	2.48
	TWLTL				
Density of public approaches (per mile)	All	0	4.89	28.88	5.39
	RM	0	4.42	28.88	5.91
	TWLTL	0	5.24	24.01	4.95
Density of driveways (per mile)	All	0	41.32	104.52	20.94
	RM	0	41.06	94.45	20.37
	TWLTL	0	41.51	104.52	21.40
AADT	All	4,883	37,865	96,080	15,037
	RM	29,320	47,566	96,080	12,383
	TWLTL	4,883	30,681	71,280	12,616
Speed limit (mph)	All	30	41.68	45	5.13
	RM	30	43.54	45	3.70
	TWLTL	30	40.30	45	5.59

The table also shows, for example, that the average number of crashes per segment is 77.61 for all segments combined. However, for TWLTL segments, the average number of crashes is 71.22 which is smaller than 86.18 for the RM segments. Preliminarily, it is unexpectedly observed that RM segments have more crashes by an average of 14.96 (or 21.0%) than TWLTL segments. Also, RM segments are observed to have bigger average number of fatal and injury crashes than TWLTL segments by 19.2% and 25.4%,

respectively. Overall, the table shows that the average number of crashes for all types of crashes except head-on, are higher for RM segments than for TWLTL segments.

Table 4-2. Descriptive Statistics of Crashes by Type and Severity

Crashes per segment	Dataset	Minimum	Average	Standard deviation	Maximum
Total	All	0	77.61	67.19	457
	RM	0	86.18	79.00	457
	TWLTL	2	71.22	56.71	273
By Crash Type					
Angle	All	0	33.90	33.32	185
	RM	0	35.05	37.75	185
	TWLTL	0	33.17	29.78	164
Rear-end	All	0	28.90	28.11	188
	RM	0	36.42	34.38	188
	TWLTL	0	23.03	20.38	109
Sideswipe	All	0	5.37	5.20	35
	RM	0	6.08	5.54	35
	TWLTL	0	4.86	4.91	28
Head-on	All	0	0.52	0.83	5
	RM	0	0.44	0.84	5
	TWLTL	0	0.59	0.82	4
Single Vehicle	All	0	4.59	4.38	27
	RM	0	4.73	4.39	27
	TWLTL	0	4.47	4.40	22
By Crash Severity					
Fatal	All	0	0.28	0.65	4
	RM	0	0.31	0.59	2
	TWLTL	0	0.26	0.69	4
Injury	All	0	32.87	29.92	231
	RM	0	37.14	35.57	231
	TWLTL	1	29.62	24.62	118
Property Damage Only (PDO)	All	0	44.38	38.04	224
	RM	0	49.35	43.93	224
	TWLTL	1	40.56	32.69	166

Since Table 4-1 shows that RM segments have higher AADT than the TWLTL segments, it is better to compare the two types of segments based on crash rates (per MVMT). It is observed in Table 4-3 that the average crash rate is higher for the TWLTL segments than for the RM segments. The numbers indicate that segments with RM have lower crash rates by 11.48% than TWLTL ones. Also, RM segments are observed to have smaller fatal and injury crash rates than TWLT segments by 22% and 7.8% respectively.

Table 4-3. Descriptive Statistics of Crash Rates by Type and Severity

Crash rate (per MVMT)	Dataset	Minimum	Average	Standard deviation	Maximum
Total	All	0	3.93	2.68	16.01
	RM	0	3.66	2.40	11.09
	TWLTL	0.31	4.13	2.87	16.01
By Crash Type					
Angle	All	0	1.70	1.48	10.57
	RM	0	1.41	1.33	6.32
	TWLTL	0	1.91	1.55	10.57
Rear-end	All	0	1.48	1.18	7.15
	RM	0	1.61	1.14	7.15
	TWLTL	0	1.38	1.21	6.90
Sideswipe	All	0	0.27	0.21	1.30
	RM	0	0.28	0.21	1.30
	TWLTL	0	0.26	0.22	1.17
Head-on	All	0	0.03	0.05	0.30
	RM	0	0.02	0.03	0.16
	TWLTL	0	0.04	0.06	0.30
Single Vehicle	All	0	0.22	0.17	1.29
	RM	0	0.20	0.17	1.29
	TWLTL	0	0.24	0.18	0.74
By Crash Severity					
Fatal	All	0	0.01	0.04	0.43
	RM	0	0.01	0.02	0.11
	TWLTL	0	0.02	0.05	0.43
Injury	All	0	1.64	1.17	7.47
	RM	0	1.57	1.09	5.11
	TWLTL	0.09	1.70	1.23	7.47
Property Damage Only (PDO)	All	0	2.27	1.60	8.70
	RM	0	2.10	1.39	6.91
	TWLTL	0.16	2.40	1.73	8.70

4.2 Data for Disaggregate Analysis

4.2.1 Access Management Data

The study selected 112 median openings from 11 arterials. Only six-lane arterials were considered for this study because most four-lane arterials in Las Vegas have TWLTL medians. Out of the 112 median openings, 76 were full, 16 directional, 12 semi-full, and 8 unidirectional. Partitioning the dataset by adjacency to signalized intersections, 74 of the 112 openings were adjacent to signals (ATS) while 38 openings were intermediate median openings. Of the 74 openings, 48 were full, 13 directional, 7 semi-full and 6 unidirectional. Of the 38 intermediate openings, 28 were full, 3 directional, 5 semi-full and 2 unidirectional. Center-to-center distances to the nearer and the farther median openings were extracted from the GIS database for each opening. Distances to adjacent signalized intersections were also recorded for median openings adjacent to signals.

Data on AM features, traffic characteristics, geometric characteristics, and land-use characteristics were collected from functional areas of median openings. Table 4-4 presents a summary of the descriptive statistics of spacing, driveways, fraction of driveways serving residential land-uses, speed limits, and traffic (AADT). For median openings adjacent to signalized intersections (ATS), it is observed that spacing to their nearer openings ranges from approximately 250 to 1025 feet with an average of 580 feet. For intermediate median openings, the range of spacing is narrower and the average spacing is smaller. The distance between the ATS median openings and signalized intersections has the range of 250 to 1025 feet with an average of approximately 630 feet, which is the longest of the averages of distances collected.

Table 4-4. Descriptive Statistics of Variables by Location of Median opening

Data element	Min	Mean	Std.Dev.	Max
Distance (feet) to the nearest MO[1]				
ATS[2]	248	582.4	162.1	1,025
Intermediate	248	544.9	180.4	850
Spacing from signal (feet)				
ATS	255	629.3	156.7	1,025
Driveways (number)				
ATS	1	7.9	5.2	25
Intermediate	1	8.9	5.0	19
Land-use proportion				
ATS	0	0.11	0.21	1.00
Intermediate	0	0.11	0.24	0.83
Speed limit (mph)				
ATS	35	43.9	3.2	45
Intermediate	35	43.38	3.74	45
Average AADT				
ATS	29,740	47,043	11,546	91,200
Intermediate	29,740	43,555	9,884	65,500

1. MO = Median opening
2. ATS= Adjacent to signalized intersection

4.2.2 Crash Data

Crash data within the functional areas of the median openings were summarized by median type and by type and severity of crashes. Table 4-5 shows descriptive statistics of the number of crashes by total and severity of crashes for each type and location of median openings. Generally, the average of total crashes per median opening is highest for “full” ATS median openings, while it is highest for “directional” intermediate openings. The same general trend is observed for most of the crash types and crashes by severity. This is surprising finding as it was expected that the full median openings would have the highest number of crashes for both ATS and intermediate median openings since they allow the most turning movements.

Table 4-5. Crashes per Median opening by Type and Location of Median Opening

Crash type	Opening type	Combined	ATS[1]	Intermediate
Total crashes	Full	36.29	40.30	28.74
	Directional	36.63	36.54	37.00
	Semi-full	16.58	20.29	11.40
	Unidirectional	13.88	17.17	4.00
Fatal crashes	Full	0.21	0.18	0.26
	Directional	0.19	0.00	1.00
	Semi-full	0.17	0.29	0.00
	Unidirectional	0.00	0.00	0.00
Injury crashes	Full	16.25	18.12	12.78
	Directional	17.88	18.31	16.00
	Semi-full	7.42	9.00	5.20
	Unidirectional	4.88	6.50	0.00
PDO crashes	Full	19.83	22.00	15.70
	Directional	18.56	18.23	20.00
	Semi-full	9.00	11.00	6.20
	Unidirectional	9.00	10.67	4.00
Angle crashes	Full	16.64	18.48	13.37
	Directional	17.81	18.62	14.33
	Semi-full	5.17	6.57	3.20
	Unidirectional	4.75	6.17	0.50
Rear-end crashes	Full	13.14	15.00	9.44
	Directional	12.5	12.15	14.00
	Semi-full	7.17	8.14	5.80
	Unidirectional	7.13	8.67	2.50
Sideswipe crashes	Full	2.21	2.40	1.93
	Directional	2.56	2.38	3.33
	Semi-full	1.25	2.00	0.20
	Unidirectional	1.50	1.83	0.50
Head-on crashes	Full	0.22	0.26	0.15
	Directional	0.19	0.23	0.00
	Semi-full	0.00	0.00	0.00
	Unidirectional	0.00	0.00	0.00
Single Vehicle crashes	Full	2.34	2.36	2.30
	Directional	2.31	2.08	3.33
	Semi-full	1.50	1.57	1.40
	Unidirectional	0.38	0.33	0.50

1. ATS= Adjacent to signalized intersection

Table 4-5 also indicates that the semi-full median openings have higher number of crashes than unidirectional ones. This preliminary result was also expected because semi-full openings allow all traffic movements out of land-uses while unidirectional openings allow none. All the unidirectional openings included in the study did not have high severity crashes such as fatal and head-on crashes. Although preliminarily the openings seem the safest, vehicles that are deviated from them might be involved in crashes somewhere else downstream. Analyses of crash migration and land-use accessibility might be important in evaluating overall benefits of the unidirectional median openings.

CHAPTER 5

CALIBRATION OF MODELS

5.1 Introduction

This chapter presents the implementation of the procedure for model selection and calibration as was introduced in Chapter 3. For the aggregate analysis, models for total crash rates (crashes per million vehicle-miles) were calibrated. For the disaggregate analysis, models for total crashes per median opening were calibrated. The calibrated models in the two analyses were used for identifying the appropriate models for further evaluating the impacts of median types, median openings, and other AM features on types and severity of crashes. Below is the description of the implementation process.

5.2 Model Selection for the Aggregate Analysis

Initially, histograms were constructed for the purpose of understanding the distribution of crash rates. The crash rates in midblock segments appear to have a distribution close to Gamma (Figure 5-1). The parameters of the fitted Gamma distribution are $\alpha = 2.1496$ and $\beta = 1.8281$. The Chi-square statistic for the goodness of fit is 7.3097 and its p-value is 0.50362. The values imply that the data are Gamma distributed hence a model with linear form is not appropriate for the regression analysis of the data. The values also imply that Gamma distribution may be specified in calibrating a GLM model.

5.2.1 Calibration of the Aggregate models

The approach proposed by Basu (2005) was used to calibrate the models relating crash rates to AM and other variables. The variables included in the model are:

- Median type (dummy variable = 1 for RM and 0 for TWLTL;

- Density of median openings per mile in RM segments;
- Signal spacing in 1000's of feet;
- Density of driveways per mile;
- Density of unsignalized public approaches;
- AADT in 1000's of vehicles;
- Speed limit in mph;
- Number of through lanes; and
- Types of adjacent land-uses, measured as the proportion of driveways serving residential land-uses. The variable takes values between zero and one. If all the driveways serve residential land-uses, the value of the variable is 1. Otherwise, if they all serve commercial land-uses, the value is zero.

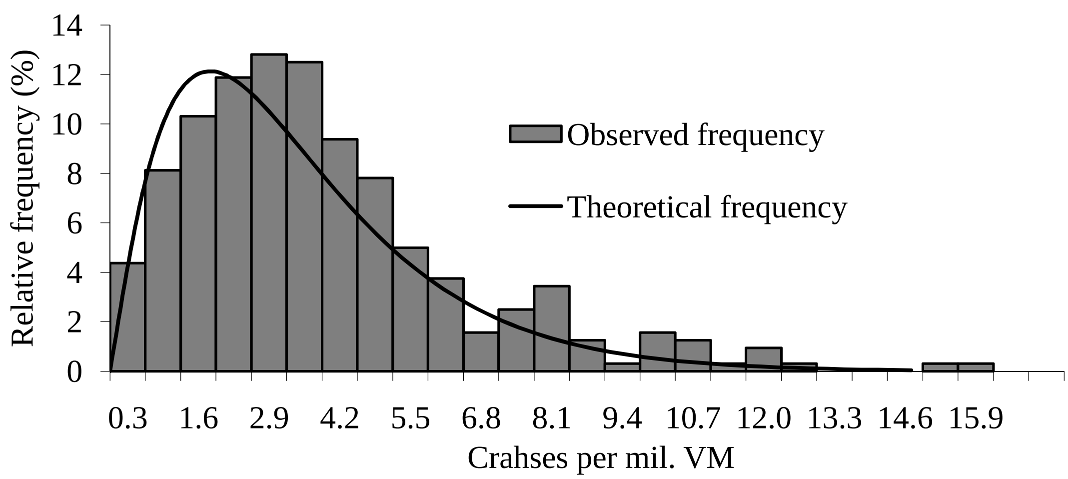


Figure 5-1. Distribution of crash rates in midblock segments.

Both power and quadratic variance relationships (Eq. 3.6 and Eq. 3.7) were evaluated for the underlying distribution of the crash rates. Table 5-1 presents the estimated values of the ancillary parameters, λ for the functional forms, and θ_1 and θ_2 for the variance functions of the underlying distribution of the data. The numbers in brackets are the p-values for the values of the parameters.

Table 5-1. Parameters for Selecting an Appropriate Aggregate Model

Model	Variance function	Parameter	Total crash rates
Basu (2005) method	Power	λ	1.3645 (0.000)
		θ_1	0.6953 (0.001)
		θ_2	1.5419 (0.000)
	Quadratic	λ	1.3779 (0.000)
		θ_1	0.6158 (0.048)
		θ_2	0.2102 (0.015)
GLM (Gamma)		AIC	1501.282
		BIC	1531.428
NLS		AIC	1482.367
		BIC	1516.281

From Table 5-1, based on Figure 3-8 presented in chapter 3, the values of the ancillary parameter λ for the functional forms are different than 0 and 1 therefore variable coefficients should be estimated with either the NLS or GLM (with λ = 1). The values of the distributional parameters (θ_1 and θ_2) for the power variance functions (Eq. 5.1 and 5.2) do not clearly suggest a known distribution as per Table 3-1. However, the histogram

in Figures 5-1 suggests specifying Gamma distribution for the GLM model. Although the quadratic variance function is close to that of negative binomial, as per Table 3-1, the underlying distribution is unknown.

$$V = 1.2128\mu^{1.7455} \quad (5.1)$$

$$V = 0.6953\mu^{1.5419} \quad (5.2)$$

The measures of goodness of fit (AIC and BIC) for the NLS model are smaller than those of the GLM model indicating that the NLS model is better than the GLM model. Therefore, The NLS model is selected for calibrating models for crash rates by types and severity of crashes. The functional form of the NLS model for the crashes by type and severity is presented in the next subsection.

5.2.2 Selected Model

The NLS model with crash rates as dependent variable is selected for calibration of models for crash type and severity of crashes. Eq. (5.3) presents the functional form of the model.

$$\mu = e^{\beta_0 + \sum_i^N \beta_i X_i} \quad (5.3)$$

where μ is the expected crash rate for a segment
β_0 is the constant term
β_i is the coefficient for explanatory AM or other variable *i*
X_i is the explanatory AM or other variable *j*
N is the number of explanatory variables

Residual analysis was also conducted to determine presence of outliers. From Figure 5-2, the scatter diagram of residuals shows absence of outliers.

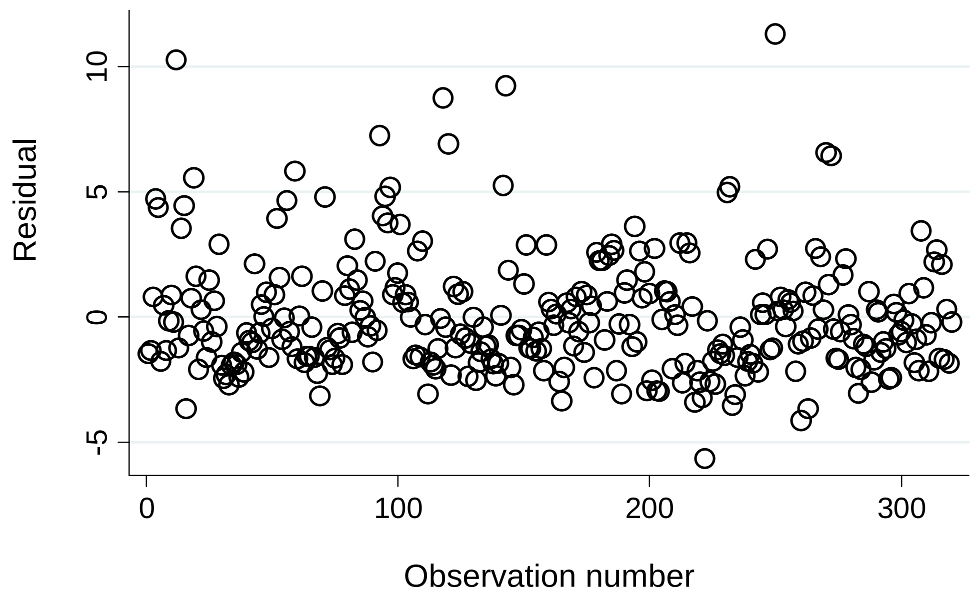


Figure 5-2. Scatter plot of residual versus observation number.

5.3 Model Selection for the Disaggregate Analysis

A histogram was constructed for the number of crashes occurring in the functional areas of median openings. Gamma distribution with parameters α = 2.008 and β = 16.2480 appear to fit well to the histogram (Figure 5-3). The Chi-square statistic for goodness of fit is 1.6504 and its p-value is 0.9489. The values imply that the data are Gamma distributed hence a model with linear form is not appropriate for the regression analysis of the data. The values also imply that Gamma distribution may be specified in calibrating a GLM model.

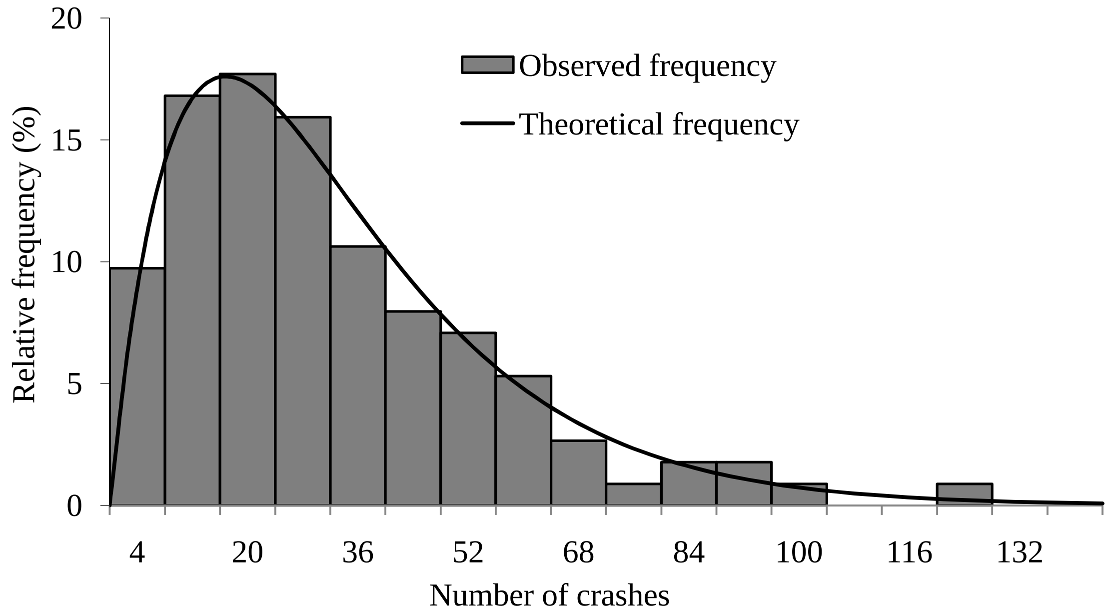


Figure 5-3. Distribution of number of crashes in median openings

5.3.1 Functional Form

The hypothesis put forth in this study considers a convex relationship between spacing of median openings and crashes occurring in the functional areas of the openings. Figure 5-4 shows the convex-like form determined from preliminary analysis of the data. The average crashes on the vertical axis are scaled by lengths of functional areas (i.e. crashes per 100 feet of functional area of a median opening). Note also that the average number of crashes is computed over a varying number of explanatory variables other than spacing, hence the averages are not marginal values. From Figure 5-4, the functional form for regression analyses have to include quadratic terms for the variable for spacing.

Additionally, most decisions made in access management are based on functional classification of roads. In this study, therefore, optimal spacing between median openings

is determined for different classes of roadways. Speed limit of a road is used as a proxy for the functional class of the roadway. In order to yield optimal spacing that is based on functional classification of roadways, spacing variable is interacted with speed limit.

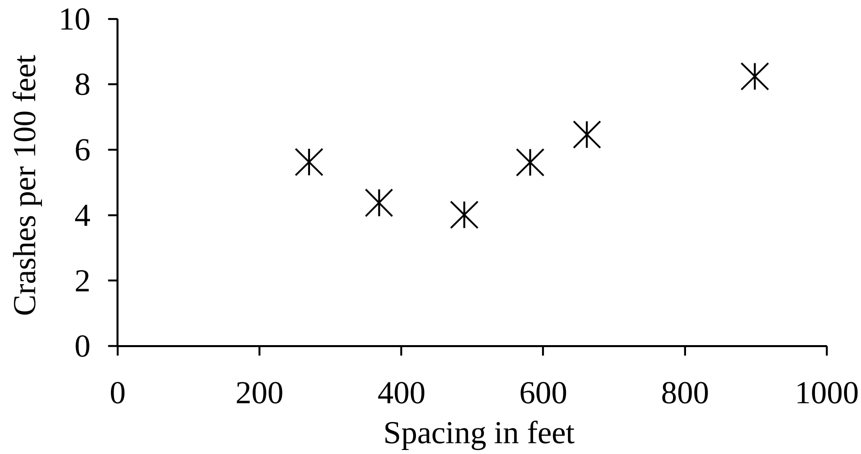


Figure 5-4. Relationship between crashes and spacing

5.3.2 Calibration of the Disaggregate model

The approach proposed by Basu (2005) was used to calibrate the model relating crashes to median opening variables. The variables included in the model are:

- Spacing between median openings (in 100's of feet) ;
- Type of median opening, a dummy: full(default), directional, semi-directional, and unidirectional;
- Proximity to signals (dummy: 1 yes, 0 no);
- Alignment of driveways (dummy: 1 for T or 3-way, 0 for 4-way);
- Speed limit (mph);
- AADT in 1000's of vehicles;

- Number of driveways;
- Land-use as a proportion of driveways serving residential land-uses within the service areas of the median openings. The variable takes values between zero and one. If all the driveways serve residential land-uses, the value of the variable is 1. Otherwise, if they all serve commercial land-uses, the value is zero.

Both power and quadratic variance relationships (Eq. 3.6 and Eq. 3.7) were evaluated for the underlying distribution of the data. Table 5-2 presents the estimated values of the ancillary parameter, λ for the functional forms, and parameters θ_1 and θ_2 for variance functions of the distribution of the data. The numbers in brackets are p-values for the values of the parameters.

Table 5-2. Parameters for Selecting Appropriate Aggregate Model

Model	Variance function	Parameter	Total Crashes
Basu (2005) method	Power	λ	0.4836 (0.004)
		θ_1	0.3240 (0.295)
		θ_2	1.9967 (0.000)
	Quadratic	λ	0.6189 (0.007)
		θ_1	0.1893 (0.788)
		θ_2	0.2478 (0.000)
GLM (Gamma)		AIC	1148.761
		BIC	1177.282
NLS		AIC	970.849
		BIC	998.123

From Table 5-2, based on Figure 3-8 presented in chapter 3, the values of the ancillary parameter λ for the functional forms are different than 0 and 1 therefore variable coefficients should be estimated with either the NLS or GLM (with λ = 0). The values of the distributional parameters (θ_1 and θ_2) for the variance functions do not clearly suggest a known distribution as per Table 3-1. However, the values of the distributional parameters (Eq. 5.4) of the quadratic variance function and the histogram in Figure 5-3 suggest specifying Gamma distribution for the GLM models.

$$V = 0.2478\mu^2 \tag{5.4}$$

5.3.3 Selected Model

Based on the fact that the AIC and BIC values (Table 5-2) for the NLS model are smaller than those of the GLM model, the NLS model is selected for calibrating models for crashes by type and severity. Equation 5.4 presents the functional form of the NLS model.

$$\mu = e^{\beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + \sum_i^N \beta_i X_i} \tag{5.4}$$

where β_0 is the constant term
β_1 is the coefficient for the linear term of spacing variable
X_1 is the spacing variable
β_2 is the coefficient for the quadratic term of spacing variable
β_i is the coefficient for explanatory variable *i*
X_i is the explanatory variable *i*
N is the number of explanatory variables

The functional form for the models in which spacing variable is interacted with speed limit is also shown in Eq. (5.5).

$$\mu = e^{\beta_0 + \beta_1 X_1 V + \beta_2 X_1^2 + \sum_i^N \beta_i X_i} \tag{5.5}$$

where β_0 is the constant term
β_1 is the coefficient for the linear term of spacing variable
X_1 is the spacing variable
V is the variable for speed limit
β_2 is the coefficient for the quadratic term of spacing variable
β_i is the coefficient for explanatory variable i
X_i is the explanatory variable i
N is the number of explanatory variables

Residual analysis was also conducted to determine presence of outliers. From Figure 5-5, the scatter diagram of residuals shows absence of outliers.

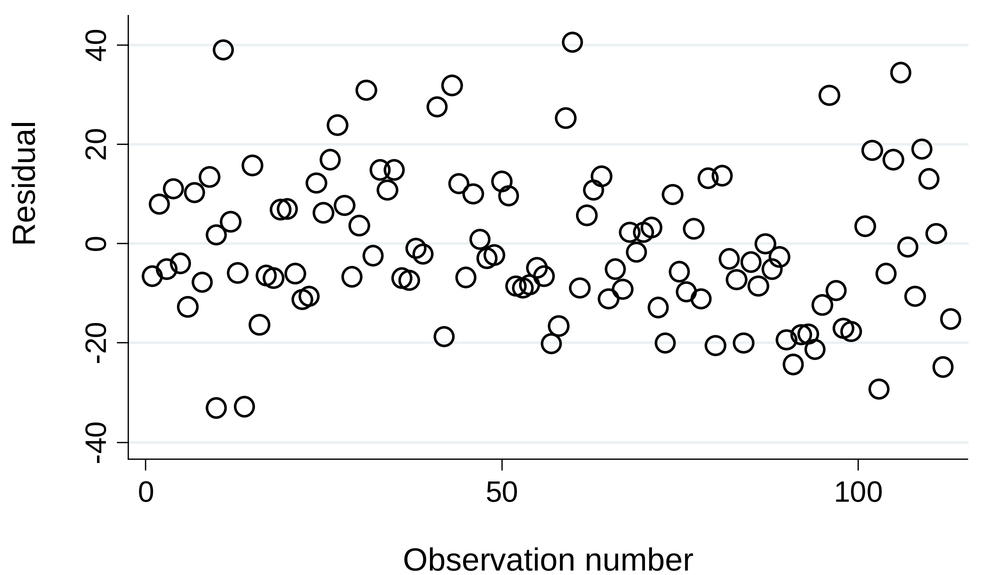


Figure 5-5. Scatter plot of residual versus observation number.

CHAPTER 6

RESULTS OF AGGREGATE ANALYSIS

6.1 Introduction

Three groups of models, one for all segments combined, one for the RM subset, and the third for the TWLTL subset were calibrated to obtain the nonlinear multivariate regression coefficients for the explanatory variables. For each group, separate models were calibrated for total crashes, crash types, and crashes by severity. The model combining RM and TWLTL medians was calibrated for the purpose of estimating the marginal impacts of using RM versus TWLTL. Analyzing the median-specific datasets jointly assumed that the marginal impacts of other AM features were the same regardless of type of median. The following sections provide summaries and discussions of results of the models calibrated.

6.2 Summary of Results for Total Crash Models

Table 6-1 summarizes the regression results for the three models with total crashes per MVMT as the dependent variable. The table shows the resulting regression coefficients for the explanatory variables with their corresponding p-values reported in brackets. Negative signs to the coefficients indicate improvement in safety as the value of a variable increases. Values of these coefficients are used to quantify marginal impacts of the variables on crash rates.

Results for the combined model (the model with the two types of medians, presented in the second column of Table 6-1) show that median type has statistically significant impact on crash rates. The other three AM features, namely, signal spacing, densities of

unsignalized public approaches and driveways have significant impact on safety. Land-use type is also a very significant factor. Commercial driveways have higher crash rates because traffic accessing commercial land-uses is heavy and spread throughout the day causing many potential conflicts while traffic accessing residential land-uses is low and peaks in the morning and evening.

Table 6-1. Model Results for the Impacts on Total Crash Rates

Variable	All Segments	RM Segments	TWLTL Segments
Signal spacing (1000's feet)	-0.0752 (0.054)	-0.1256 (0.037)	-0.1028 (0.021)
Density of public approaches	0.0241 (0.000)	0.0161 (0.043)	0.0311 (0.001)
Density of driveways	0.0050 (0.000)	0.0027 (0.118)	0.0074 (0.000)
Median type (1 RM, 0 TWLTL)	-0.3778 (0.000)	NA	NA
Density of median openings	NA[1]	0.0557 (0.001)	NA
Traffic per lane (1000's of vehicles)	0.0432 (0.000)	0.1453 (0.000)	
Speed Limit (mph)	-0.0160 (0.029)		
Number of through lanes	0.0853 (0.071)		
Land-use proportion	-0.3547 (0.024)	-1.1561 (0.046)	-0.4803 (0.001)
Constant	1.4584 (0.000)	-0.0573 (0.866)	1.3056 (0.000)
Sample size	319	134	185
Adjusted R^2	0.7402	0.7895	0.7471

1. NA= Not Applicable

The results further show that the longer the signal spacing, the lower the crash rates, meaning that longer segments are "safer" than shorter ones. Long signal spacings provide

enough room for traffic to move in platoons, enough room for weaving traffic to make lane changes, and time to react to downstream signals. In addition, the results show that the higher the density of driveways, the higher the number of conflict points and hence higher crash rates.

However, the biggest impact on crash rates is median type, with the model showing that RM segments have significantly lower total crash rates compared to TWLTL segments. Given the value -0.3778 for the coefficient for median type, the total crash rate after installing RM would be 31.5% lower than previous crash rate (Eq. 6.1). This improvement in safety is very significant and indicates that raised medians are very effective safety counter measures.

$$\%\Delta Y = 100 * (e^{(-0.3778)(1)} - 1) = 31.5\% \qquad (6.1)$$

Similarly, the calibration results for the model for RM segments (column 3 of Table 6-1) show that the density of median openings has statistically significant impact on the crash rates. The other three AM features, namely, signal spacing, the density of unsignalized public approaches, and the density of driveways also have statistically significant impact on the crash rates. The trends for the impacts are as expected, with signal spacing being negatively correlated to crash rate, meaning that longer segments have lower crash rates. On the other hand, the densities of median openings, unsignalized public approaches, and driveways are positively correlated to crash rate, meaning that the higher the densities, the higher the number of conflicts and hence higher crash rates.

For the TWLTL model, all the three relevant AM parameters are statistically significant. Signal spacing, the density of unsignalized public approaches, and the density of driveways have trends similar to those under RM segments in their impacts on crash

rates. The results also show that coefficients with positive signs in the RM model have smaller magnitudes than those in the TWLTL model. Similarly, negative coefficients in the RM model have bigger magnitudes than those in the TWLTL model. The constant term in the RM model is not significant while that in the TWLTL model is positive and significant. All these observations indicate that raised medians not only reduce the crash rates but also improve safety of other AM features. For land-use variable, RM segments in residential areas have low crash rates compared to those in the commercial ones.

6.3 Summary of Results for Crash Types Models

Table 6-2 and Table 6-3 summarize the results of the calibrated models for crash rates by type of crash for the RM segments, the TWLTL and for all the segments combined. The results are based on a total of 11,510 angle, 9,885 rear-end, 1,850 side-swipe, 185 head-on, and 1,526 single vehicle crashes. The single vehicle crashes include non-collision and fixed-object crashes. Crashes recorded in the database as other or unknown were not included in the study.

With respect to angle crashes, the model results show that the type of median and the density of median openings are significant factors. The densities of driveways and unsignalized approaches are also statistically significant factors for both RM and TWLTL segments. The higher the driveway densities, the higher the angle crash rates. However, as observed in the models for total crash rates, the magnitudes of the coefficients for the densities are greater in TWLTL segments than in RM segments. Signal spacing does not appear to be a factor for angle crashes.

For rear-end crashes, median type is a significant factor but the density of median openings in RM segments is not. Signal spacing and driveway density are significant

factors for both RM and TWLTL segments. The magnitudes of the coefficients for the densities are greater in TWLTL segments than in RM segments. In addition, the density of public approaches is a significant factor with TWLTL segments but not with RM segments.

Table 6-2. Model Results for Angle and Rear-end Crash Rates

	Angle			Rear-end		
Variable	All	RM	TWLTL	All	RM	TWLTL
Signal spacing (1000's feet)				-0.1528 (0.002)	-0.1509 (0.075)	-0.2305 (0.000)
Density of public approaches	0.0291 (0.000)	0.0193 (0.094)	0.0271 (0.023)			0.0340 (0.005)
Density of driveways	0.0050 (0.004)	0.0042 (0.152)	0.0067 (0.001)	0.0057 (0.000)	0.0035 (0.101)	0.0091 (0.000)
Median type (1 RM, 0 TWLTL)	-0.4654 (0.000)	NA	NA	-0.2071 (0.049)	NA	NA
Density of median openings	NA	0.0761 (0.001)	NA	NA		NA
Traffic per lane (1000's of vehicles)		0.1699 (0.004)		0.0852 (0.004)	0.1269 (0.000)	
Speed Limit (mph)	-0.0140 (0.097)		-0.0210 (0.028)	-0.0201 (0.045)	-0.0298 (0.105)	
Number of through lanes				0.1248 (0.052)		
Land-use proportion	-0.6146 (0.000)	-1.9096 (0.013)	-0.5966 (0.001)	-0.4590 (0.038)		-0.7242 (0.000)
Constant	1.0368 (0.006)	-1.6114 (0.006)	1.2296 (0.004)	0.1523 (0.774)	0.8533 (0.350)	0.4234 (0.035)
Sample size	319	134	185	319	134	185
Adjusted R^2	0.6339	0.6444	0.6666	0.7047	0.7358	0.6966

For sideswipe crash rates, the models show that only the density of median openings and signal spacing affect the crash rates for RM segments, while for TWLTL segments, it

is the densities of public approaches and driveways that have impact on the sideswipe crash rates. The trends of the impacts are similar to other crash types previously discussed.

For head-on crashes, RM is the only AM factor that has impact on crash rates. This might be due to the fact that vehicles can use the TWLTL for left-turns and U-turns at several locations on a street segment, unlike for RM segments, where turns are typically restricted to only few median opening locations.

For single vehicle crashes, the AM variables that have significant impact are signal spacing and the densities of median openings and public approaches for RM segments while signal spacing and the density of driveways are significant for TWLTL segments. As opposed to all the other crash types, for single vehicle crashes, the model for TWLTL segments indicates that the longer the signal spacing the higher the crash rates. This could be due the fact that vehicles can be able to attain higher speeds, and hence a higher potential for loss of vehicle control resulting in higher crash rates. Although the signal spacing seems to have negative impacts with respect to this crash type, the reductions in other types of crashes such as rear-end and side swipe far outweigh the increase in single vehicle crashes because there are more rear-end crashes than single vehicle ones and that the absolute marginal impact of signal spacing on rear-end crash rate is bigger than that on single vehicle crash rate.

The results of the models further show that land-use type has impacts on crashes by type of crashes. The negative coefficients in the models for angle and rear-end crashes imply that everything else being equal, segments with driveways serving residential land-uses have lower crash rates compared to driveways serving commercial land-uses.

Table 6-3. Results for Sideswipe, Head-on and Single Vehicle Crashes

Variable	Sideswipe All	Sideswipe RM	Sideswipe TWLTL	Head-on All	Head-on RM	Head-on TWLTL	Single Vehicle All	Single Vehicle RM	Single Vehicle TWLTL
Signal spacing (1000's feet)		-0.3834 (0.000)						-0.1178 (0.092)	0.0868 (0.056)
Density of public approaches	0.0181 (0.048)		0.0288 (0.050)				0.0427 (0.000)	0.0586 (0.014)	
Density of driveways	0.0062 (0.004)		0.0087 (0.001)						0.0042 (0.046)
Median type (1 RM, 0 TWLTL)	-0.2446 (0.034)	NA	NA	-0.5036 (0.033)	NA	NA		NA	NA
Density of median openings	NA	0.0591 (0.015)	NA	NA		NA	NA	0.0424 (0.000)	NA
Traffic per lane (1000's of vehicles)	0.0892 (0.000)	0.1132 (0.037)	0.0663 (0.031)	-0.1483 (0.045)		-0.1658 (0.044)	-0.0925 (0.000)		-0.0959 (0.000)
Speed Limit (mph)	-0.0387 (0.000)		-0.0400 (0.001)					0.0414 (0.040)	
Number of through lanes	0.2131 (0.000)		0.2554 (0.001)						
Land-use proportion					1.2887 (0.000)			0.5330 (0.093)	
Constant	-1.7852 (0.000)	-1.8256 (0.003)	-2.0056 (0.000)	-2.5249 (0.000)	-4.2103 (0.000)	-2.4455 (0.000)	-1.1065 (0.000)	-3.7934 (0.000)	-1.2683 (0.000)
Sample size	319	134	185	319	134	185	319	134	185
Adjusted R^2	0.6883	0.7131	0.6841	0.3019	0.2471	0.3215	0.6943	0.7945	0.6892

However, for head-on and single-vehicles crashes, segments with driveways serving residential land-use have higher crash rates on RM segments than on TWLTL segments.

6.4 Summary of Results for Models of Crashes by Severity

Table 6-4 summarizes the calibration results for crash severity models. The results are based on a total of 92 fatal crashes, 11,172 injuries and 15,057 property damage only (PDO). The variable coefficients are not presented for the model for fatal crashes because they were all insignificant.

Based on the combined model, the results show that, overall, injury crash rates are lower in RM segments than in TWLTL segments. The value -0.2700 for the coefficient for median type means that, everything else being equal, RM segments have lower injury crash rates by 23.7%. The results further show that the density of median openings is a factor to injury crash rates. The density of driveways is the only significant AM factor in both types of medians. The TWLTL segments also have the density of public approaches as a significant factor.

With regard to PDO crash rates, all AM factors are statistically significant in the three models. The coefficients for the variables are larger in the model for segments having TWLTL than for those with RM as expected. The density of median openings has almost the same impact on both injury and PDO crashes. Residential areas have less PDO crashes compared to commercial ones on roads with either type of median.

6.5 Evaluation of Marginal Impacts on Midblock Crashes

This section evaluates and summarizes the marginal impacts of median type, the density of median openings, and other AM features on crashes in midblock sections. The

marginal impacts are then discussed in the context of improving safety as would be applied in retrofit projects. The impacts are further compared to the findings of past studies reviewed in this research.

Table 6-4. Model Results for Injury and PDO Crash Rates

	Injury Crashes			Property damage only		
Variable	All	RM	TWLTL	All	RM	TWLTL
Signal spacing (1000's feet)	-0.0857 (0.026)	-0.1242 (0.068)		-0.0941 (0.025)	-0.1406 (0.017)	-0.1281 (0.009)
Density of public approaches	0.0246 (0.000)	0.0133 (0.114)	0.0330 (0.001)	0.0240 (0.000)	0.0180 (0.024)	0.0284 (0.003)
Density of driveways (per mile)	0.0043 (0.006)		0.0083 (0.000)	0.0054 (0.000)	0.0034 (0.053)	0.0077 (0.000)
Median type (1 RM, 0 TWLTL)	-0.2700 (0.002)	NA	NA	-0.4073 (0.000)	NA	NA
Median openings (per mile)	NA	0.0519 (0.010)	NA	NA	0.0563 (0.001)	NA
Traffic per lane (1000's)		0.1326 (0.001)		0.0470 (0.067)	0.1509 (0.000)	
Speed Limit				-0.0176 (0.024)		
Number of through lanes				0.0940 (0.048)		
Land-use proportion	-0.4489 (0.005)	-1.1373 (0.047)	-0.5353 (0.003)	-0.3966 (0.016)	-0.9371 (0.091)	-0.5331 (0.001)
Constant	0.5609 (0.000)	-0.6400 (0.136)	0.1559 (0.151)	0.7823 (0.052)	-0.6943 (0.047)	0.8197 (0.000)
Sample size	319	134	185	319	134	185
Adjusted R^2	0.7084	0.7281	0.7198	0.7391	0.7853	0.7387

6.5.1 Raised medians

The single most effective way of reducing crashes, as observed in this study, is to convert a TWLTL segment to an RM segment. The value -0.3778 (in Table 6-1) of the

coefficient for the median type dummy variable in the total crash rates indicates that, everything else being equal, an RM segment has 31.5% lower total crash rates than a TWLTL segment. This improvement in safety is within the range of 3% to 57% reported in the 15 of 16 studies reviewed by Gluck *et al.* (1999).

The results from this study further indicate that the crash reductions come from all crash types except single vehicle crashes. For example, the segments with RM have lower rear-end and sideswipe crash rates by 18.7% and 21.7%, respectively. The percentage reductions in these rear-end and sideswipe rates are smaller than those reported by Gluck *et al.* (1999). The reductions in high dangerous crashes such as angle and head-on are larger compared to rear-end and sideswipe; segments with RM have lower rates by 37.2% and 39.6%, respectively, compared to segments with TWLTL. The percentage reduction in angle crashes is comparable to the values reported by Gluck *et al.* (1999) while the reduction in head-on rate is smaller. Regarding crash severity, segments with RM have 23.7% and 33.5% lower injury and PDO crash rates than those with TWLTL.

The raised medians reduce the crash rates by modifying the operations of other AM features and hence their marginal impacts. Generally, the coefficients of the densities of driveways and unsignalized public approaches in the TWLTL models are two to three times bigger than those in the RM models. For injury crash rates, driveway density is not significant for the RM segments and has a positive coefficient for TWLTL segments, indicating the effectiveness of the raised medians in reducing driveway related high severity crashes. The low marginal impacts for driveway densities on the RM segments come from limiting crossing and left turning traffic to a few median openings. Limiting

crossing and left turning traffic to the median openings reduces conflict points hence low crash rates.

6.5.2 Density of median openings

Density of median openings is the AM feature that is in RM segments only. Generally, the RM models show that the lower the density of median openings, the lower the crash rates. For the total crash rates, the coefficient for the density of median openings is 0.0557, which means that a reduction of one median opening per mile would result in 5.4% reduction in the total crash rate (Eq. 6.2).

$$\%\Delta Y = 100^* (e^{(0.0557)(-1)} - 1) = 5.4\% \tag{6.2}$$

For the sake of illustration, assuming an RM segment is 2,640 feet long and has four median openings. If there is a desire to reduce and reconfigure the median openings from four to three, it translates to a reduction in the density of median openings by about 2 per equivalent mile (i.e. 8 openings/mi to 6 openings/mi). Using Eq. (3.16), the reduction in the density would result in a reduction of about 10.5% in total crash rate. The corresponding reductions in angle, sideswipe, and single-vehicle crash rates are 14.1%, 11.2% and 8.1%, respectively. These reductions are further disaggregated to 9.9% reduction in injury crashes and 10.7% in property damage only crashes.

In retrofit projects where reduction of number of median openings is likely to be the case, it is noteworthy that although reducing the number of median openings implies safety benefits, it also might result in other demerits, such as reduced land-use accessibility and hence increased travel times for accessing traffic.

6.5.3 Density of driveways

From the results of the models for total crash rates as summarized in Table 6-1, the impacts of reducing the density of driveways is quantified using Eq. (3.16). For example, for a segment with TWLTL, the coefficient for driveway density is 0.0074, reducing the density by 1 driveway per mile reduces the total crash rate by 0.74%. Although this improvement appears negligible, it can be significant when driveway consolidation is evaluated over the entire retrofit program.

Table 4-1 in Chapter 4 shows that a typical TWLTL segment used in this study has a driveway density of about 41 driveways per mile (for all driveways on both sides of the roadway), the density translates into an average driveway spacing of approximately 5280/(0.5*41) = 258 feet. If a decision were made to increase the driveway spacing to 400 feet, it would reduce the driveway density to 26.4 per mile, a reduction of about 14.6 driveways per mile. In this case the model predicts an average reduction in crash rates of 10.2%. This is a significant improvement in safety. On RM roads, however, the reduction is 3.9%.

With respect to crash types, the density of driveways is the only AM feature that is significant in almost all crash types. However, quantitatively, its impacts are more significant on angle and rear-end crashes for both RM and TWLTL segments. For sideswipe and single-vehicle crashes, driveways have significant impacts in TWLTL segments only. Based on the example on total crashes above, the reduction of 14.6 driveways per mile would result in reductions in angle and rear-end crash rates of 9.3% and 12.4%, respectively for TWLTL. The impacts on the sideswipe and single-vehicle crashes for a similar reduction in driveway density would be 11.9% and 5.9%,

respectively. The percentage reductions in crash rates for TWLTL segments are two to three times bigger than those for RM segments.

With regard to severity, consolidating driveways by 14.6 per mile reduces injury crash rates by 11.4% for TWLTL. For property damage only crashes, the reductions in crash rates corresponding to driveway consolidation would be 4.8% and 10.6% for RM and TWLTL segments, respectively.

Some studies which found significant driveway impacts have reported somewhat larger marginal effects. Gluck *et al.* (1999) generalized an impact of 4% for every new driveway in a mile, almost five times bigger than the values reported in this research. Gluck *et al*. also reported an increase of 0.09 to 0.13 in crash rates (crashes per million vehicle miles) on roads having TWLTL or RM in urban and suburban areas. Eisele and Frawley (2005) used a univariate linear model and reported coefficients of access density as 0.0618 and 0.1225 for segments with RM and TWLTL, respectively. However, their sample size was only 23. These results indicate that increasing the access density by eight (two driveways in a 0.25 mile segment with TWLTL) would increase the crash rate by one per million vehicle miles. The size of the marginal impacts might have been caused by inclusion of intersection crashes in the analyses. Overall, these models indicate that significant reductions in crash rates can be achieved by reducing the density of driveways.

6.5.4 Density of unsignalized public approaches

Results of this study show that the density of public approaches has impacts on total crash rates on RM as well as TWLTL segments. The coefficient of 0.0311 in the model for TWLT segments indicates that a reduction of one unsignalized public approach per

mile would result in a reduction of 3.1% in total crash rates, not a very significant impact quantitatively. If retrofit programs target reducing 2 approaches (i.e. from 6 to 4) from a main arterial in a half mile segment, the change in density is 4 approaches per mile. The reduction in total crash rate would be 11.7%, also very significant. The reduction is 6.2% for segments with RM, almost half of that for segments with TWLTL.

For crash types, public approaches have impacts on angle crashes for TWLTL and RM segments. The reductions in angle crash rates due to reducing 4 approaches per mile are 10.3% and 7.4% for TWLTL and RM segments, respectively. For rear-end, sideswipe and single vehicle crashes, the impacts of public approaches can be estimated for TWLTL segments only. The corresponding reductions in crash rates are 12.7%, 10.9%, and 20.9% respectively.

With respect to crash severity, the models show that the density of public approaches has significant impacts on crashes for both TWLTL and RM segments. Closing 4 public approaches per mile would reduce injury crash rates by about 12.4% and 5.2% for TWLTL and RM segments, respectively. With respect to property-damage-only crashes, consolidating public approaches would reduce crash rates by 10.7% and 6.9% for TWLTL and RM segments respectively. Again, the impacts are more for TWLTL than for RM segments.

6.5.5 Signal spacing

Results show that the longer a segment is for both types of medians, the lower the crash rates. The values -0.1256 and -0.1028 for the coefficients obtained for RM and TWLTL segments, respectively, are comparable. Comparing improvement in safety for half-mile versus quarter-mile segments, RM and TWLTL half-mile segments have 15.3%

and 12.7% lower crash rates than their respective quarter-mile segments. The improvement is larger for RM than TWLTL segments.

For crash types, the models show that signal spacing has impacts on rear-end and single-vehicle crash rates for both TWLTL and RM. For the rear-end crashes, half-mile segments have 22.2% and 18.1% lower crash rates than quarter-mile segments for TWLTL and RM medians, respectively. For the single-vehicle crashes, half-mile segments have 12.1% higher crash rates for TWLTL median while and 14.4% lower crash rates for RM medians than quarter-mile segments. However, it should be noted that the proportion of single vehicle crashes in the database was relatively low. Hence, the increase in crash rates due to increase in length of TWLTL segments would be outweighed by the reduction in rear-end crashes and hence a positive overall reduction in crash rates. For sideswipe crashes, half-mile segments have lower crash rates than quarter-mile ones by 39.7% on TWLTL medians.

With respect to crash severity, signal spacing has impact on injury crash rates on RM segments only. Half-mile segments have lower injury crash rates by 15.1% than quarter-mile segments. For property-damage-only crashes, half-mile segments have 15. 6% and 16.9% lower crash rates than quarter-mile segments for TWLTL and RM medians, respectively.

6.6 Implications of the Results on the Effectiveness of AM Techniques

This study has demonstrated the importance of the five important AM policies, namely, choice of median type (RM vs. TWLTL), density or average spacing between median openings, densities of driveways and unsignalized public approaches, and signal

spacing. This study has quantified the safety advantages of RM versus TWLTL medians, lower versus higher densities of median openings, driveways and unsignalized public approaches, and longer versus shorter signal spacings.

For retrofit projects, the single most effective strategy is converting a TWLTL segment into an RM segment. Though it may be costly, its safety benefits over the lifetime of a facility may far outweigh those initial costs. The study results have shown that the fewer the number of median openings in the RM segments the lower are total crash rates and rates of crash types and severities. Also, consolidating driveways hence reducing conflict points can have very significant improvement in the safety of a roadway, though not as effective as RM.

For example, consider a six-lane half-mile segment with 8 unsignalized public approaches/mile, 48000 vehicles per day, equal number of commercial and residential driveways, and 3 median openings (for an RM segment). Predicting crash rates for RM and TWLTL segments from 0 to 100 driveways per mile simplifies the comparison of RM installation versus driveway consolidation. Figure 6-1 shows midblock crash rates as a function of driveway density for the two median types.

In Figure 6-1, the gap between RM and TWLTL crash rates widens as driveway density increases. Widening of the gap between the two curves is due to the differences in magnitudes for the coefficients of driveway density in the RM and TWLTL models. That means, improvement in safety is more when RM medians are installed on TWLTL segments with higher driveway densities. The reduction in crash rates comes from reducing conflict points at driveways. From Figure 6-1, it is apparent that the safety improvement achieved by installing RM medians cannot be attained by just consolidating

driveways. It is thus recommended that RM be given priority in retrofit AM programs before other AM techniques are considered.

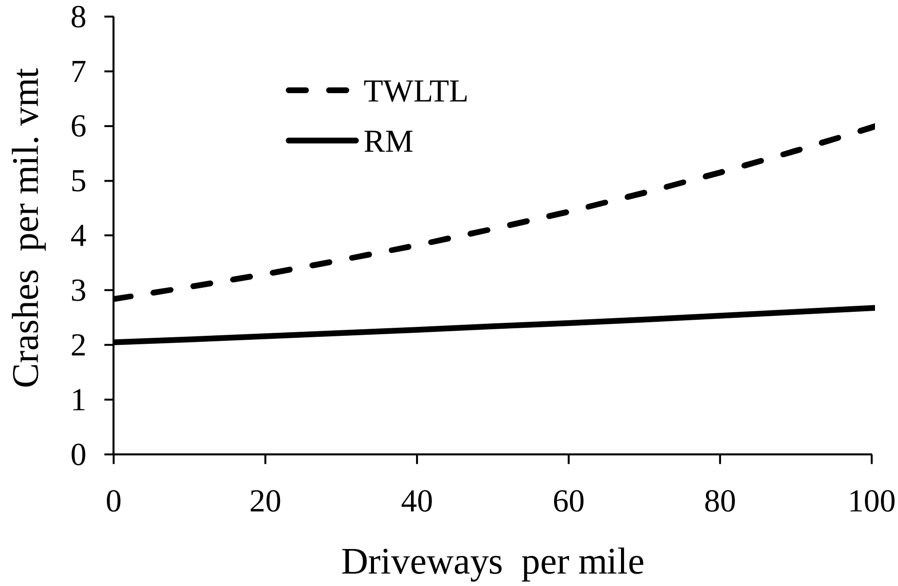


Figure 6-1. Comparison between RM and driveway consolidation

The AM feature that needs proper planning is the density or spacing of unsignalized public approaches that collect traffic and feed it onto major roads. These approaches most of the time are aligned with median openings and might actually be signalized in the future upon meeting appropriate signal warrants. The implications of the potential future growth of these approaches on AM have to be carefully considered.

CHAPTER 7

RESULTS OF DISAGGREGATE ANALYSIS

7.1 Introduction

Two groups of disaggregate models were calibrated, one with spacing variable alone and the other with the interaction of spacing and speed limit. For each of the two groups of models three models were calibrated, one for all median openings combined, one for median openings adjacent to signalized intersections, and the other for intermediate median openings. For each case, separate models were calibrated for total crashes, crash types, and crashes by severity. Models combining location specific median openings were calibrated for the purpose of estimating the impacts of proximity of median openings to signalized intersections. The following sections provide summaries and discussions of results of the models calibrated.

7.2 Summary of results for Total Crash Models

Table 7-1 summarizes the regression results for the three models with total crashes as the dependent variable. The table presents the resulting regression coefficients for the explanatory variables with their corresponding p-values reported in brackets. The empty cells in the table imply that variables were not significant and hence removed from the model. The analysis was based on 112 median openings from which 3,687 crashes were collected. Results for models for total crashes with spacing variable interacted with speed limit are presented in the appendix, Table A-1.

Table 7-1. Model Results for Total Crashes

Variable	Combined MO[1]	ATS[2] MO	Intermediate MO
Directional MO	-0.4577 (0.027)	-0.4905 (0.046)	-0.6505 (0.002)
Semi-Full MO	-0.4641 (0.001)	-0.5678 (0.001)	
Unidirectional MO	-0.5547 (0.014)	-0.4697 (0.027)	-1.0099 (0.000)
Spacing, 100's of feet	-0.2267 (0.038)	-0.4098 (0.023)	
Square of spacing, 10,000's of feet squared	0.0214 (0.006)	0.0327 (0.008)	
Adjacency to signal	0.2406 (0.058)	NA[3]	NA
Alignment, 1for 3 way, 0 for 4 ways	-0.3463 (0.004)	-0.3216 (0.026)	
Speed limit	0.0441 (0.027)	0.0661 (0.036)	
Traffic, in 1000's of vehicles	0.0294 (0.000)	0.0276 (0.000)	0.0545 (0.000)
Driveways			0.0328 (0.077)
Land-use proportion		-1.0731 (0.009)	0.6142 (0.016)
Constant	0.7204 (0.320)	0.7601 (0.451)	0.5917 (0.243)
Samples size	112	74	38
Adjusted R^2	0.8166	0.7947	0.8490

1. MO= Median opening, 2. ATS=Adjacent to signalized intersection,
3. NA= Not applicable

The combined model shows that coefficients for the three types of median openings are statistically significant and have negative signs meaning that directional, semi-full, and unidirectional median openings have significantly lower number of conflict points and hence crashes than full median openings. Spacing between median openings has

significant impact on the number of crashes at median openings. The negative coefficient for the linear term of spacing means that for short spacings between median openings, the shorter the spacing the higher the number of crashes. On the other hand, the positive coefficient for the quadratic term implies that at long spacings, the longer the spacing the higher the number of crashes per median opening. These last two observations show that there is an optimal length of spacing that minimizes the number of crashes, supporting the hypothesis put forth in this study. Also, as expected, 3-way median openings have smaller number of crashes than 4-way median openings. The coefficient for the variable “adjacency to signal” is positive and significant, meaning that median openings adjacent to signalized intersections have higher number of crashes than intermediate median openings.

For the model for median openings adjacent to signalized intersections, the results are similar in sign only but different in magnitudes than those in the combined model. In the model, the proportion of driveways serving residential land-uses is also a significant factor. The significance of the variable is due to the fact that traffic accessing residential driveways tends to be low and peaky while traffic accessing commercial driveways is heavier and distributed throughout the day. Therefore, residential driveways have fewer potential traffic conflicts than commercial ones.

For the model for intermediate median openings, only directional and unidirectional median openings are significantly different than full ones. The insignificance of semi-full median openings might be due to the fact that they allow crossing traffic just like full median openings. Another observation is that the spacing variables are insignificant. Also, contrary to the combined and ATS models, increase in the number of driveways

increases the number of crashes in the functional areas of the intermediate median openings. The larger values of the proportion of residential driveways seem to correspond to larger number of crashes than commercial ones.

The results for models for total crashes with spacing variable interacted with speed limit (Table A-1 in the appendix) also have similar trends as the models presented in Table 7-1 above. Holding speed limit constant, the spacing variables agree with the hypothesized convex relationship between crashes and spacing between median openings.

7.3 Summary of Results for Crash Types Models

Tables 7-2 and 7-3 summarize the results of impacts of type, location, and spacing between median openings on crashes by type of crash. The results are based on a total of 1,670 angle, 1348 rear-end, 240 side-swipe, 20 head-on, and 238 single vehicle crashes. The single vehicle crashes include run-off the road and fixed-object crashes. Crashes recorded in the database as other or unknown totaled to 171 and were not included in the analyses. Coefficients for the models for head-on crashes are not presented because they all were statistically insignificant. It is observed in the tables that the three types of median openings are simultaneously significant only in the model for angle crashes.

For the models for angle crashes, the results for the combined model show that the three types of median openings, namely, directional, semi-full, and unidirectional have smaller average number of crashes than full ones. Spacing variables do not support the supposed quadratic form. However, the linear term for spacing variable is significant; longer spacing corresponds to higher number of angle crashes at median openings. Longer spacing between median openings cause concentration of turning traffic at the

openings hence increasing potential for crashes. Moreover, adjacency of median openings to signalized intersections and having T or 3 approaches do not significantly impact the number of angle crashes at median openings. The results are similar in sign for the model for median openings adjacent to signalized intersection. Also, the model for intermediate median openings has similar results except that spacing variables are insignificant.

For the combined model for rear-end crashes, only directional median openings seem to have smaller number of rear-end crashes per median opening than full ones. The semi-full and unidirectional median openings do not show significant difference from full ones. The reason is probably the smaller number of semi-full and unidirectional openings in the dataset. The spacing variables, however, keep the quadratic form like in the models for total crashes. For the model for median openings adjacent to signalized intersections, the coefficients have trend similar to those in the combined model except that the coefficient for semi-full openings is significant.

For sideswipe crashes, the models do not show correlation of type of median openings with crashes. The reason might be the fact that sideswipe crashes occur between vehicles travelling in the same direction (most probably through traffic) hence unaffected by channelization of median openings. The spacing variable is significant only in the linear term. The longer the spacing the higher the average number of sideswipe crashes. Increase in the number of vehicles weaving into or out of the median openings might be the reason for increasing potential conflicts. The models for median openings adjacent to signalized intersections and intermediate openings have results similar to the combined model except that all spacing variables are insignificant in the model for openings adjacent to signalized intersections.

Table 7-2. Model Results for Angel and Rear-end Crashes

Variable	Angle			Rear-end		
	Combined MO	ATS MO	Intermediate MO	Combined MO	ATS MO	Intermediate MO
Directional MO	-0.5483 (0.007)	-0.5918 (0.006)	-0.5770 (0.101)	-0.7867 (0.001)	-0.8917 (0.001)	
Semi-full MO	-0.8544 (0.000)	-0.7415 (0.001)	-1.2150 (0.001)		-0.6563 (0.023)	
Unidirectional MO	-0.7332 (0.013)	-0.6757 (0.032)	-2.8310 (0.001)			
Spacing, 100's of feet	0.1049 (0.005)	0.1511 (0.000)		-0.2946 (0.026)	-0.7525 (0.003)	
Square of spacing, 10,000's of feet squared				0.0268 (0.005)	0.0527 (0.001)	
Alignment 1for 3 way, 0 for 4 ways				-0.5522 (0.001)	-0.5910 (0.002)	
Speed limit				0.0637 (0.019)	0.1105 (0.015)	
Traffic, in 1000's of vehicles	0.0332 (0.000)	0.0284 (0.000)	0.0370 (0.001)	0.0433 (0.000)	0.0399 (0.000)	0.0441 (0.000)
Land-use proportion		-1.3981 (0.096)			-1.1121 (0.083)	
Constant	0.5546 (0.051)	0.5052 (0.131)	1.0140 (0.049)	-1.4497 (0.131)	-1.3835 (0.246)	0.1349 (0.773)
Samples size	112	74	38	112	74	38
Adjusted R^2	0.7386	0.7323	0.7653	0.7712	0.7999	0.7459

Table 7-3. Model Results for Sideswipe and Single Vehicle Crashes

	Side Swipe			Single-vehicle		
Variable	Combined MO	ATS MO	Intermediate MO	Combined MO	ATS MO	Intermediate MO
Directional MO						
Semi-Full MO					-0.4754 (0.019)	
Unidirectional MO				-1.6293 (0.021)	-1.7306 (0.078)	
Spacing, 100's of feet	0.1212 (0.008)		0.3453 (0.108)	-0.3072 (0.088)	-0.7190 (0.000)	-1.8621 (0.048)
Square of spacing, 10,000's of feet squared				0.0316 (0.030)	0.0598 (0.000)	0.1908 (0.022)
Alignment 1for 3 way, 0 for 4 ways	-0.4061 (0.016)	-0.3220 (0.102)	-1.0725 (0.000)			
Traffic, in 1000's of vehicles	0.0200 (0.002)	0.0181 (0.007)	0.0350 (0.035)	0.0117 (0.054)	0.0111 (0.009)	0.0364 (0.097)
Driveways						0.0647 (0.003)
Constant	-0.8233 (0.024)	0.0385 (0.900)	-3.0351 (0.081)	0.8702 (0.109)	2.2389 (0.000)	2.6239 (0.144)
Samples size	112	74	38	112	74	38
Adjusted R^2	0.6615	0.6414	0.6415	0.6605	0.7644	0.6665

For single-vehicle crashes, the combined model results show that only the unidirectional median openings have smaller average number of crashes than full ones. The fact that directional median openings do not show reduction in average number of single-vehicle crashes over full openings might lead to suspecting that traffic crossing at full median openings is less probably involved in single vehicle crashes. Spacing variables retain the quadratic form as models for total and rear-end crashes. The model on median openings adjacent to signalized intersections has results similar to those of the combined model except that semi-full median openings are significant. Also the model for intermediate median openings has results similar to those of the two models except that all types of median openings are insignificant.

Results for models for types of crashes with spacing variable interacted with speed limit are presented in the appendix, Tables A-2 and A-3. The results have similar trends as the models presented in Table 7-2 and 7-3 above.

7.4 Summary of Results for Models by Severity of Crashes

Table 7-4 summarizes the calibration results for crash severity models. The results are based on a total of 21 fatal crashes, 1,665 injury crashes and 2,001 property damage only (PDO) crashes. Coefficients for the models for fatal crashes are not presented because they all were statistically insignificant. It is observed in the table that the three types of median openings are simultaneously significant only in the combined model for injury crashes.

For the combined model of injury crashes, the results show that there are fewer injury crashes at directional, semi-full and unidirectional median openings than at full openings. Spacing between median openings is also a significant factor for injury crashes and

retains the supposed quadratic form. As observed earlier, median openings adjacent to signalized intersections have higher number of crashes than intermediate median openings. T-junctioned or 3-way median openings have smaller number of injury crashes than those with 4-leg approaches. Other factors such as speed limit and traffic have significant impact on injury crashes as expected.

Table 7-4. Model Results for Injury and PDO Crashes

	Injury			PDO		
Variable	Combined MO	ATS MO	INT MO	Combined MO	ATS MO	INT MO
Directional MO	-0.4001 (0.077)		-0.6398 (0.014)	-0.5017 (0.011)	-0.5731 (0.016)	-0.7108 (0.002)
Semi-Full MO	-0.5763 (0.000)	-1.0925 (0.000)				-0.3894 (0.117)
Unidirectional MO	-0.7476 (0.004)	-0.8187 (0.008)	-19.2055 (0.000)			
Spacing, 100's of feet	-0.3497 (0.004)	-0.8315 (0.000)		0.1164 (0.001)	0.1288 (0.001)	
Square of spacing	0.0288 (0.001)	0.0609 (0.000)				
Adjacency	0.2622 (0.062)	NA	NA	0.2275 (0.066)	NA	NA
Alignment, 1for 3 way, 0 for 4 ways	-0.2794 (0.040)			-0.4249 (0.001)	-0.4535 (0.002)	
Speed limit	0.0693 (0.007)	0.1345 (0.000)				
Traffic, in 1000's of vehicles	0.0308 (0.000)	0.0178 (0.000)	0.0536 (0.000)	0.0298 (0.000)	0.0289 (0.000)	0.0570 (0.000)
Driveways			0.0380 (0.065)			0.0288 (0.106)
Land-use prop.		-1.2870 (0.008)	0.6739 (0.020)		-0.9716 (0.031)	0.5612 (0.012)
Constant	-0.8343 (0.389)	-1.9904 (0.064)	-0.2210 (0.727)	0.7704 (0.001)	0.9239 (0.001)	-0.0913 (0.845)
Samples size	112	74	38	112	74	38
Adjusted R^2	0.7836	0.7647	0.5129	0.8116	0.7879	0.8560

For the model for median openings adjacent to signalized intersection, variable coefficients have signs similar to those in the combined model except that directional median openings are not significant. The variable coefficients for the model for intermediate median openings also have signs similar to those in the combined model except that spacing variables are insignificant. The number of driveways and proportion of residential driveways have significant contribution to crashes occurring at intermediate median openings.

For the combined model for PDO crashes, only directional median openings have significantly smaller number of crashes than full median openings. The insignificance of the semi-full and unidirectional median openings is suspected to be due to their small number in the dataset. Spacing is only significant in its linear term. The longer the spacing the more the turning traffic at median openings and the more are the corresponding total number of traffic conflicts. The T-junctioned openings have smaller number of crashes than 4-leg-junctioned openings.

The model for median openings adjacent to signalized intersections has results similar to those for the combined model. The model for intermediate openings also has results similar to those of the two models except that spacing is insignificant and coefficients for driveways and proportion of residential driveways have positive signs.

Results for models for crashes by severity with spacing variable interacted with speed limit are presented in the appendix, Table A-4. The results have similar trends as the models presented in Table 7-4 above. For the combined and ATS models for injury crashes, holding speed limit constant, the spacing variables agree with the hypothesized convex relationship between crashes and spacing between median openings.

7.5 Evaluation of Marginal Impacts

This section presents a detailed analysis of the marginal impacts of type, location and spacing between median openings on crashes by type and severity of crashes. The impacts are calculated using Eq. (3.16) derived in chapter 3. The variable coefficients in the models with spacing-speed interaction terms (Tables A-1 to A-4 in the appendix) are used as opposed to those presented in Tables 7-1 to 7-4. The coefficients of spacing variables in Tables 7-1 to 7-4 show only the general relationship between crashes and spacing between median openings but cannot be used to estimate optimal spacing for different speed limits. Therefore, the evaluation of the impacts of type, location and spacing between median openings is conducted using the coefficients in the models with spacing-speed interaction terms. The impacts are then discussed in the context of improving safety as would be applied in retrofit projects.

7.5.1 Marginal Impacts of Spacing between Median Openings

The marginal impacts of spacing between median openings are evaluated based on the speed limit of a roadway. Speed limit is used as a proxy for the functional class of the roadway.

From Tables A-1 to A-4, differences in coefficients for spacing variables are observed across models of severity of crashes and types of crashes. That is, the coefficients of spacing in the injury models are different than those in PDO, rear-end and single-vehicle models. Thus, the differences in the coefficients lead to determination of crash-specific optimal spacing between median openings based on types and severity of crashes. The equation for crash specific optimal spacing is derived below by

differentiating Eq. (3.8) with respect to the spacing variable X_1. The terms β_1 and β_2 are coefficients to the interaction and quadratic terms of the spacing variable.

$$\mu = e^{\beta_0+\beta_1 X_1 V+\beta_2 X_1^2+\sum_i^N \beta_i X_i}\ ; \qquad i=2, 3, \ldots, N \tag{7.1}$$

where β_0 is the constant term
β_1 is the coefficient for the linear term of spacing variable
X_1 is the spacing variable
V is the variable for speed limit
β_2 is the coefficient for the quadratic term of spacing variable
β_i is the coefficient for explanatory variable i
X_i is the explanatory variable i
N is the number of explanatory variables

Differentiating Eq. (7.1) with respect to X_1

$$\frac{d\mu}{dX_1} = (\beta_1 V + 2\beta_2 X_1)e^{\beta_0+\beta_1 X_1 V+\beta_2 X_1^2+\sum_i^N \beta_i X_i} \tag{7.2}$$

Equating the right hand side to zero, Eq. (7.3) is arrived at

$$X_1^* = \frac{-\beta_1 V}{2\beta_2} \tag{7.3}$$

where X_1^* is the optimal spacing

Taking the second derivative of Eq. (7.1) with respect to X_1

$$\frac{d^2\mu}{dX^2} = [(\beta_1 V + 2\beta_2 X_1)^2 + 2\beta_2]e^{\beta_0+\beta_1 X_1 V+\beta_2 X_1^2+\sum_i^N \beta_i X_i} \tag{7.4}$$

Since β_2 is positive, the right hand side of Eq. (7.4) is also positive implying that the optimal spacing corresponds to the minimum number of crashes. Table 7-5 below presents the coefficients of the spacing variables and estimated optimal spacings for models whose quadratic terms were significant. The optimal spacings are estimated for

speed limits 35 mph to 45 mph. Generally, models for median openings adjacent to signalized intersections yield longer optimal spacings than the combined models. Also models for injury and rear-end crashes result in longer optimal spacings than other models. Since different models result in different optimal spacings, selection of the optimal spacing for design should probably be based on spacings that minimize injury crashes.

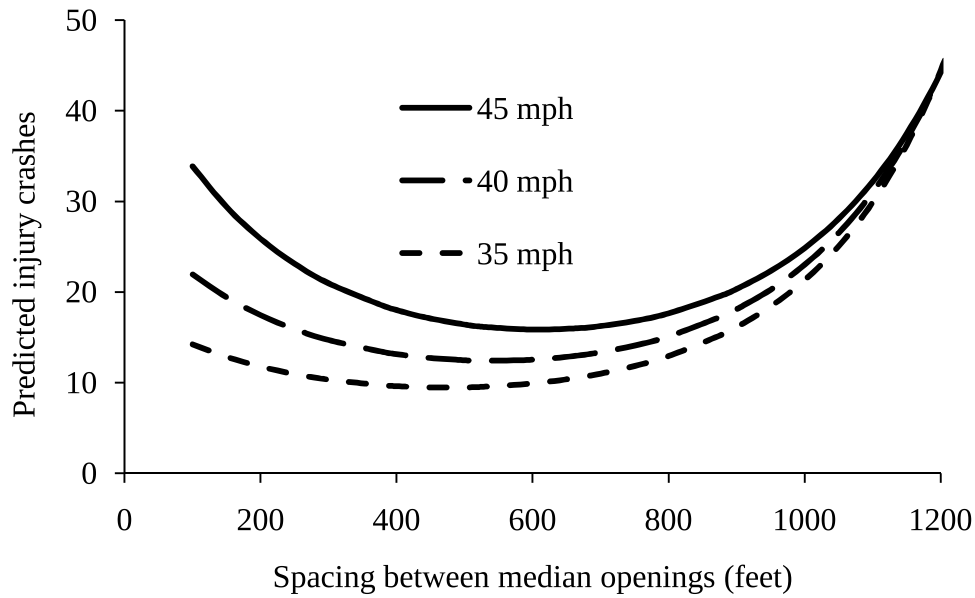
For example, given a typical 45 mph half mile segment subtended by two consecutive traffic signals, three median openings would be provided with two openings located 730 feet from the signals and one intermediate opening 590 feet from each of the two openings. Segments quarter mile in length with 45 mph speed limit would have only one median opening and segments shorter than quarter mile would have no opening.

Table 7-5. Optimal Spacing of Median Openings based on Crashes

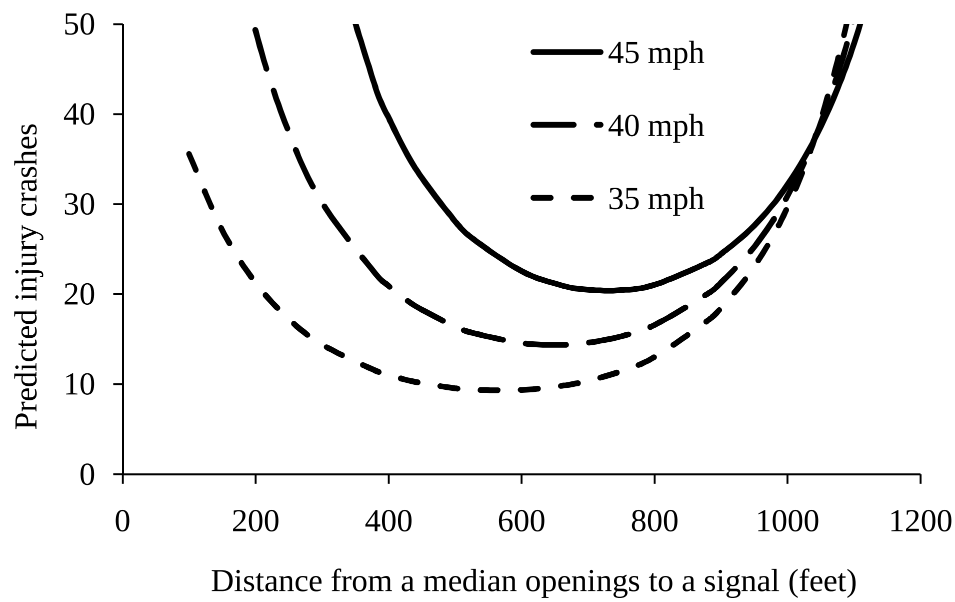
Dataset	Model	β_1	β_2	Optimal spacing (feet)		
				35mph	40mph	45mph
Total	Combined	-0.0053	0.0222	418	477	537
	ATS	-0.0116	0.0392	518	592	666
Injury	Combined	-0.0079	0.0294	470	537	605
	ATS	-0.0200	0.0617	567	648	729
Rear-end	Combined	-0.0066	0.0269	429	491	552
	ATS	-0.0157	0.0493	557	637	717
Single Vehicle	Combined	-0.0054	0.0276	342	391	440
	ATS	-0.0174	0.0632	482	551	620
	Intermediate	-0.0320	0.1633	343	392	441

Figure 7-1 presents the predicted number of injury crashes in functional areas using the combined and ATS models for speed limits between 35 mph and 45 mph, an AADT

of 50,000 vehicles per day, and commercial land-use.



(a) Predicted injury crashes for the combined model.



(b) Predicted injury crashes for the model for openings adjacent to signals.

Figure 7-1. Sensitivity analysis for optimal spacing under model for injury crashes.

It is observed that the higher the speed limit the longer the optimal spacing and the bigger the number of injury crashes in the functional areas. Also the higher the speed limit the more sensitive to spacing is the number of injury crashes, suggesting stricter adherence to optimal values for roads higher in the functional classification of roadways.

For both locations of median openings, the number of injury crashes does not increase significantly from the minimum values if median openings are located within ±100 feet of optimal values for 35 mph speed limit. However, locating a median opening within ±200 feet of optimal spacing would result in high number of injury crashes.

7.5.2 Marginal Impacts of Types of Median Openings

The results of regression analysis have shown that, generally, median openings with restricted number of left turning movements have smaller number of crashes in their functional areas. Based on the calibrated model coefficients, approximate percentage difference in number of crashes between full median openings and other types are estimated using Eq. (3.16). The value -0.4571 for the coefficient for directional median openings in the combined model for total crashes (Table A-1), implies that directional openings have 36.7% less crashes than full openings as shown in Eq. (7.4).

$$\%\Delta Y = 100 * (e^{(-0.4571)(1)} - 1) = -36.7\% \tag{7.4}$$

Table 7-6 summarizes percent defferences in average number crashes between full median openings and other types. It is apparent that the figures under semi-full and unidirectional median openings are bigger than those under directional openings. Negative signs indicate that the openings have fewer crashes than full ones.

Table 7-6. Percentage Difference in Crashes between Full and other Types

Crash type	Model	Type of median opening: Directional	Semi-full	Unidirectional
Total	Combined	-36.7	-37.4	-42.6
	ATS	-38.3	-38.6	-39.1
	Intermediate	-51.3		-60.8
Injury	Combined	-32.9	-44.0	-52.6
	ATS	-32.5	-53.8	-49.7
	Intermediate	-51.9		
PDO	Combined	-39.6		
	ATS	-44.2		
	Intermediate	-53.4		
Angle	Combined	-42.2	-57.7	-52.2
	ATS	-46.3	-54.6	-51.3
	Intermediate	-43.8	-70.3	-94.1
Rear-end	Combined	-54.5		
	ATS	-59.8	-41.6	
	Intermediate	-75.3		
Single Vehicle	Combined			-80.0
	ATS		-42.7	-83.2

The reduction in total number of crashes by directional median openings over full ones is in agreement with the range of 20-50% reported in other literature (Gluck *et al.* 1999, Taylor *et al.* 2001, Zhou *et al.* 2003, Potts *et al.* 2004, and Jagannathan 2007). This reduction in crashes is due to restricting crossing traffic as well as traffic wishing to turn left onto arterials. These diverted traffic movements normally have to make right turns followed by U-turns at downstream median openings or signalized intersections. Hence, converting median openings from full to directional might cause some increase in crashes at downstream openings or signalized intersections. However, a before-and-after study by Taylor *et al*. (2001) reported a decrease in crashes on subject median openings, adjacent median openings, and adjacent signalized intersections. Another before-and-after study

conducted by Zhou *et al.* (2003) reported a 68% reduction in crashes at a subject directional median opening and downstream U-turn median opening.

In retrofit projects where converting full to unidirectional median openings is likely to be the case, it is noteworthy that although reducing the number of left turning movements implies safety benefits, it also might result in other problems. Diversion of the left turning traffic might lead to poor land-use accessibility, even higher travel times, and in turn more crashes. Therefore, selection of type of median opening should consider both safety and accessibility needs.

7.5.3 Marginal Impacts of Adjacency of Median Openings to Signals

From the Tables A-1 to A-4 in the appendix, it is observed that the combined models for total crashes as well as for crashes by severity have significant coefficients for the variable for adjacency of median openings to signalized intersections. Moreover, the coefficients of the spacing-speed interaction and quadratic variables in the combined models as well as models for ATS openings are not the same, implying that location of a median opening also does have influence on spacing between median openings (as presented above in Table 7-5 and Figure 7-1).

Using Eq. (3.16) to quantify the marginal impacts of proximity of median openings to signals, Eq. (7.5) shows that median openings adjacent to signalized intersections have 27.1 % more total crashes than intermediate median openings.

$$\%\Delta Y = 100 * (e^{(0.2401)(1)} - 1) = 27.1\% \quad (7.5)$$

These median openings also have higher injury and PDO crashes by 29.9% and 25.7% respectively, than intermediate median openings. A combination of optimal spacing and the use of directional channelizations can help reduce the high number of

crashes at these median openings. Also, during peak periods, these openings may often be blocked by spill-over queues, naturally restricting crossing traffic and traffic turning left onto arterial. Therefore, installing directional channelizations at the openings may already support what drivers experience during peak periods.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This study calibrated statistical models that relate median type, density, and individual spacing between median openings to midblock crashes in the Las Vegas Valley. Other AM features considered include signal spacing and the densities of driveways and unsignalized public approaches. The main objective of the study was to evaluate the impacts of density, type, location and spacing between median openings and other AM features on traffic crashes. The additional objective was to evaluate the impacts of signal spacing, the densities of driveways, and the density of unsignalized public approaches on the midblock crashes of segments with TWLTL and compare with the impacts of the same features in segments with raised medians.

The study deviates from past studies that evaluated safety impacts of an aggregate number of median openings using crash data collected over shorter periods of one to three years. The studies reported mixed results, making it difficult to transfer findings across geographical locations. Aggregating the impacts might have concealed the impacts of individual spacings between median openings.

Twenty five representative urban roads classified in the Nevada's Department of Transportation (NDOT) guidelines as principal, minor, and collector arterials in the Las Vegas valley were selected. The selection was based on the requirement to obtain a sample of street segments covering a variety of traffic, geometric, and land-use characteristics. Out of the 25 arterials, 319 midblock segments were identified. Of the 319 segments 134 had raised medians and the rest had TWLTL. A mid-block segment

was defined as a portion of an arterial bounded by two consecutive signalized intersections.

An inventory of existing AM features for the selected study segments was conducted in the laboratory using satellite imagery from Google Earth and a GIS street network database provided by the Regional Transportation Commission (RTC) of Southern Nevada. Significant effort was put to ensure that the observed AM features in the study segments had not changed significantly over the period of analysis. This was achieved by selecting street segments from locations that were already developed and also by utilizing a recent tool in the Google Earth imagery that shows image acquisition dates.

Crash data recorded over a period of five years, from 2002 to 2006, were obtained from a GIS database maintained by NDOT. The crashes were summarized by type and severity. The data were partitioned into midblock and intersection crashes. A radius of 200 feet around intersections was used to isolate intersection crashes from mid-block crashes. All crashes that occurred with the 200 feet radius were considered intersection crashes and hence were not used in the analysis of mid-blocks. Traffic and speed limit data were obtained from NDOT annual traffic reports.

Two levels of analyses were conducted, namely, aggregate and disaggregate analyses. The aggregate analysis involved evaluating the safety impacts of median type, density of median openings, and other AM features. In this analysis, each midblock segment was considered as one data point. The disaggregate analysis involved evaluating the safety impacts of type, location, and individual spacing between median openings. Each median opening was considered as one data point. In both levels of analysis, other variables such as through lanes, AADT, and speed limit were included.

For the aggregate analysis, different models were calibrated by type of median (i.e. RM, TWLTL, and a combination of the two types of medians). For each case, models were calibrated by total crashes, crash types, crashes by severity. Crash types included angle, rear-end, sideswipe, head-on, and single-vehicle crashes. Crashes coded as other or unknown in the database were not used to calibrate their own models. Two levels of severity of crashes, namely, injury and PDO, were used. For fatal crashes, the AM and other variables were all insignificant.

For the disaggregate analysis, 112 representative median openings were selected from the 134 midblock RM segments already selected in the aggregate analysis. Crash data within functional areas of these median openings were used for evaluating the safety impacts of spacing between the openings. The functional areas were defined as zones covering three distances as described in the green book (AASHTO, 2004): perception reaction distance, maneuver distance and storage distance. Drivers' reaction time was assumed to be one second. Four types of median openings were analyzed: full, directional, semi-full and unidirectional median openings.

For the disaggregate analysis, different models were calibrated by location of median opening (i.e. adjacent to signals, intermediate, and a combination of the two). For each group, models were calibrated by total crashes, crash types, crashes by severity. Crash types included angle, rear-end, sideswipe, and single-vehicle crashes. Severity of crashes included injury and PDO crashes only. For fatal and head-on crashes, the AM and other variables were all insignificant.

Results of the aggregate analysis revealed that everything else being equal, road segments with raised medians have lower crash rates than segments with TWLTL. The

reduction in crash rates comes from restricting left-turning traffic in midblock to few locations known as median openings. By so doing the number of conflict points is reduced and so are crash rates.

In the segments with raised medians, the results indicate that crash rates increase with increase in density of the median openings for total, types, and severity of crashes. Therefore, reducing the density of median openings by 1 per mile would reduce total and injury crash rates by 5.4% and 5.1%, respectively.

Other AM features also have significant correlations with crash rates. Increase in the densities of driveways and unsignalized public approaches increases crash rates. Also, long segments have lower crash rates than short ones. The results also show that the impacts of the AM features on crash rates are higher on roadways with TWLTL than those with raised medians due to the role of the raised medians in reducing conflicts.

Results of the disaggregate analysis reveal that spacing between median openings does have impacts on total, types, and severity of crashes. The results are in agreement with the hypothesis put forth that both very short spacing and very long spacing result in high number of crashes per median opening. Therefore, there is an optimal spacing which minimizes traffic conflicts and crashes. The optimal spacing varies from 340 feet to 730 feet depending on types of crashes and speed limits. The speed limit variable was used as a proxy for functional class of a roadway. It is suggested that optimal spacings for design should be based on the more critical crashes which are injury crashes.

For types of median openings; directional, semi-full, and unidirectional median openings have significantly smaller number of crashes than full openings. The differences in number of crashes are due to the smaller number of conflicting movements at the non-

full openings. Directional median openings, being the most common non-full openings, are found to have 35.5% and 31.5% lower average number of total and injury crashes than full ones.

Median openings that are adjacent to signalized intersections are found to have 27.1% more total crashes than intermediate openings. As for crash severity, median openings adjacent to signalized intersections have 29.9% and 25.7% less injury and PDO crashes, respectively, than intermediate openings.

8.2 Recommendations for Implementation of AM Techniques

Similar to other studies, this study has demonstrated that raised medians are the most effective AM features due to the significant safety advantage they have over TWLTL. The safety improvement achieved by converting TWLTL to raised medians may not be achieved even by aggressively consolidating driveways. It is recommended that raised medians be given priority in new and retrofit projects before other AM techniques are considered.

In order to minimize the number of injury crashes per median opening, optimal spacings derived from models for injury crashes range from 470 feet to 730 feet depending on speed limit and location of a median opening. The optimal spacings suggest that segments that are half-mile long should have three (3) median openings for roads with speed limits 40 mph and 45 mph. For lower speed limits, not more than four (4) openings may be installed. Segments quarter-mile in length should not have more than one (1) median opening for speed limits 35 mph to 45 mph.

Median openings adjacent to signalized intersections have been found to have higher number of crashes than intermediate ones. Therefore, openings adjacent to signalized intersections should be designed with directional channelization in order to minimize the number of crashes. Intermediate median openings that are not expected to be signalized in the future may also be directional.

8.3 Recommendations for Future Research

The following are recommendations for future research related to this study:

1. Research should be conducted to evaluate the impacts of number and types of median openings on crashes occurring at signalized intersections. The analysis would lead to determination of optimal number of median openings (hence optimal spacing) that minimizes the number of crashes for entire arterials.
2. In this study, the impacts of spacing between median openings have been evaluated with driveways and proportions of driveways serving residential land-uses as proxies for traffic accessing adjacent land-uses. To be more accurate, future studies should consider collecting turning movement data at median openings.
3. Crash data used in this study did not have enough information for classifying crashes by movement type and direction of traffic. Such data, if available, can provide more detailed direction-specific analysis.
4. Finally, future studies should consider larger sample sizes and data from different areas in order to validate the results obtained in this study and evaluate their transferability to other geographical locations.

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APPENDIX

SUPPLIMENTAL RESULTS

Table A-1. Model Results for Total Crashes

Variable	Combined MO[1]	ATS[2] MO	Intermediate MO
Directional MO	-0.4571 (0.027)	-0.4834 (0.046)	-0.7193 (0.000)
Semi-Full MO	-0.4691 (0.000)	-0.4877 (0.007)	
Unidirectional MO	-0.5549 (0.014)	-0.4958 (0.022)	-0.9360 (0.002)
Speed limit	0.0624 (0.009)	0.1192 (0.018)	
Spacing * speed (spacing in 100's of feet)	-0.0053 (0.027)	-0.0116 (0.027)	
Square of spacing	0.0222 (0.005)	0.0392 (0.010)	
Adjacency to signals	0.2401 (0.058)	NA	NA
Alignment 1for 3 way, 0 for 4 ways	-0.3474 (0.004)	-0.3487 (0.009)	
Traffic, in 1000's of vehicles	0.0294 (0.000)	0.0299 (0.000)	0.0578 (0.000)
Driveways			0.0329 (0.081)
Land-use proportion		-0.6176 (0.093)	0.5884 (0.014)
Constant	-0.0564 (0.943)	-1.2698 (0.378)	0.4136 (0.446)
Samples size	112	74	38
Adjusted R^2	0.8169	0.7915	0.8505

1. MO = Median opening
2. ATS = adjacent to signalized intersections

Table A-2. Model Results for Angel and Rear-end Crashes

Variable	Angle			Rear-end		
	Combined MO	ATS MO	Intermediate MO	Combined MO	ATS MO	Intermediate MO
Directional MO	-0.5490 (0.007)	-0.6225 (0.004)	-0.5770 (0.101)	-0.7867 (0.001)	-0.9111 (0.001)	-1.3977 (0.000)
Semi-full MO	-0.8598 (0.000)	-0.7905 (0.001)	-1.2150 (0.001)		-0.5385 (0.099)	
Unidirectional MO	-0.7390 (0.012)	-0.7196 (0.035)	-2.8309 (0.001)			
Speed limit				0.0862 (0.009)	0.1491 (0.013)	
Spacing * speed (spacing in 100's of feet)	0.0022 (0.007)	0.0031 (0.001)		-0.0066 (0.028)	-0.0157 (0.010)	-0.0067 (0.005)
Square of spacing				0.0269 (0.005)	0.0493 (0.005)	
Alignment 1for 3 way, 0 for 4 ways				-0.5518 (0.001)	-0.6845 (0.001)	
Traffic, in 1000's of vehicles	0.0329 (0.000)	0.0310 (0.000)	0.0370 (0.001)	0.0432 (0.000)	0.0432 (0.000)	0.1304 (0.000)
Land-use proportion					-1.1121 (0.083)	
Constant	0.5991 (0.036)	0.4171 (0.180)	1.0140 (0.049)	-2.4588 (0.026)	-3.4796 (0.033)	-2.1471 (0.000)
Samples size	112	74	38	112	74	38
Adjusted R^2	0.7303	0.7219	0.7653	0.7711	0.7932	0.7836

Table A-3. Model Results for Side Swipe and Single Vehicle Crashes

Variable	Side Swipe			Single Vehicles		
	Combined MO	ATS MO	Intermediate MO	Combined MO	ATS MO	Intermediate MO
Directional MO						
Semi-full MO					-0.5564 (0.012)	
Unidirectional MO				-1.6096 (0.024)	-1.7815 (0.074)	
Speed limit					0.0820 (0.032)	
Spacing * speed (spacing in 100's of feet)	0.0026 (0.015)		0.0067 (0.105)	-0.0054 (0.094)	-0.0174 (0.000)	-0.0320 (0.071)
Square of spacing				0.0276 (0.026)	0.0632 (0.000)	0.1633 (0.042)
Alignment 1for 3 way, 0 for 4 ways			-1.1219 (0.000)			0.7120 (0.067)
Traffic, in 1000's of vehicles	0.1381 (0.004)	0.1322 (0.006)	0.2100 (0.044)	0.0126 (0.043)	0.0101 (0.024)	0.0505 (0.092)
Land-use proportion						
Constant	-1.0312 (0.010)	-0.2353 (0.537)	-2.6366 (0.080)	0.5920 (0.139)	-1.1301 (0.374)	0.7131 (0.312)
Samples size	112	74	38	112	74	38
Adjusted R^2	0.6074	0.5886	0.6385	0.6599	0.7538	0.6561

Table A-4. Model Results for Injury and PDO Crashes

Variable	Injury			PDO		
	Combined MO	ATS MO	Intermediate MO	Combined MO	ATS MO	Intermediate MO
Directional MO	-0.3996 (0.077)	-0.3936 (0.117)	-0.7325 (0.006)	-0.5041 (0.011)	-0.5837 (0.015)	-0.7639 (0.000)
Semi-full MO	-0.5791 (0.000)	-0.7721 (0.001)				
Unidirectional MO	-0.7471 (0.004)	-0.6865 (0.002)	-19.3994 (0.000)			
Speed limit	0.0948 (0.002)	0.2076 (0.000)				
Spacing * speed (spacing in 100's of feet)	-0.0079 (0.004)	-0.0200 (0.000)		0.0025 (0.001)	0.0025 (0.005)	
Square of spacing	0.0294 (0.001)	0.0617 (0.000)				
Adjacency to signals	0.2614 (0.063)	NA		0.2285 (0.066)	NA	
Alignment 1for 3 way, 0 for 4 ways	-0.2797 (0.040)	-0.2916 (0.068)		-0.4300 (0.001)	-0.5075 (0.001)	
Traffic, in 1000's of vehicles	0.0308 (0.000)	0.0313 (0.000)	0.0578 (0.000)	0.0296 (0.000)	0.0311 (0.000)	0.0601 (0.000)
Driveways			0.0373 (0.073)			0.0303 (0.087)
Land-use proportion		-0.8117 (0.048)	0.6172 (0.027)			0.5636 (0.011)
Constant	-1.9572 (0.062)	-4.6226 (0.008)	-0.4313 (0.534)	0.8133 (0.000)	0.9038 (0.003)	-0.2803 (0.537)
Samples size	112	74	38	112	74	38
Adjusted R^2	0.7839	0.7787	0.5088	0.8112	0.7879	0.8633

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