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Evaluation of safety impact of access management in urban areas

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EVALUATION OF THE SAFETY IMPACT OF ACCESS MANAGEMENT IN
URBAN AREAS

by

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ABSTRACT

Evaluation of the Safety Impact of Access Management in Urban Areas

by

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The access provided by streets and highways to adjacent lands are managed by controlling the spacings between the access points including signals, driveways, and media openings on mid-block segments, and setting the limit on the corner clearances around intersections. There have been studies on evaluating the impact of access management techniques on safety and mobility in urban areas. Samples of mid-block segments and intersections can be collected from selected arterials. Because the mid-block segments or intersections in the same arterials share the same missing information, safety and mobility on them show unique features that should be taken into account when modeling.

In this study panel data models were proposed for safety analysis on mid-block segments and intersections. A virtual “mid-block” segment was assumed to exist for each arterial. The observations of the mid-block segments on this arterial were viewed as repeated observations for the virtual “mid-block” segment. This perspective of the mid-block segments or intersections over space made it feasible for the panel data model to evaluate the impact of access management techniques on safety. In addition, this study also recognized that interdependency existed between safety and mobility for a mid-block segment or an intersection. Therefore, for mid-block segments, simultaneous equation

models were adopted by integrating with the panel data modeling structure. For intersections, the interdependence between safety and mobility wasn't considered due to the lack of data, and only count data models combining with the panel data structure was developed.

Data were collected from different sources for the urban areas of Southern Nevada. The results from the models for mid-block segments indicate that there is a strong interdependency between safety and mobility. The length of mid-block segments, driveway density, and median opening density are very significant factors that influence crash rate on mid-block segments. From the results of the models for intersections, it was found that corner clearance significantly influenced the number of crashes occurred at intersections. Other factors also influence the occurrence of crashes at intersections that include land use, traffic flow, number of lanes, and posted speed limit.

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CHAPTER 1

INTRODUCTION

1.1 Background

Access management is a way to control the access to adjacent lands along streets and highways so that vehicles can reach their destinations smoothly while safety and mobility of the transportation system are maintained. The lands are used for various purposes including commercial, residential, and public services, and are clustered along streets and highways in different patterns. Furthermore, the access to them from streets and highways vary and can have different impact on traffic. The typical techniques for organizing the access are to control the spacing, location, design, and operation of signals, driveways, median alternatives, median openings, left-turn lanes, and interchanges on urban streets and highways.

Although many of these techniques existed in the Las Vegas area, this study focused on the spacings of signals, driveways, median openings, and selected use of median alternatives on mid-block segments, while at intersections the corner clearance was emphasized.

Traffic Signal Spacing

Appropriate spacing between signalized intersections can improve through traffic movements. Figure 1-1 shows the uniform and irregular spacing patterns between signals. When drivers start their trips from one signalized intersection, they follow a process of acceleration, running at stable travel speed, and deceleration. When the spacing between two signals is long and uniform, drivers can have enough time to accelerate and decelerate; they can drive to certain travel speeds before reaching to another signalized

intersection. When the spacing between two signalized intersections is too close or irregular, drivers may not have enough time to reach certain travel speeds before they have to stop at the next intersection. The resultant stops would produce unnecessary delays, and this kind of premature travel pattern could possibly lead to crashes.

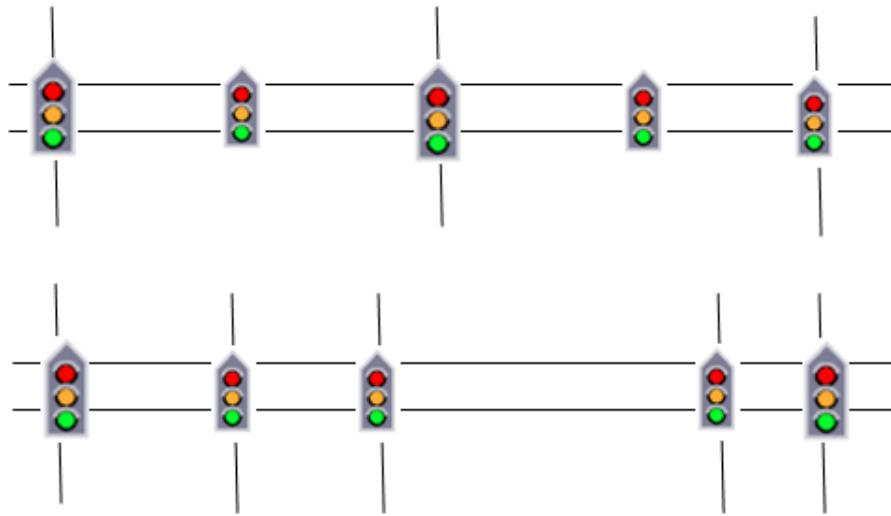


Figure 1-1 Different Traffic Signal Spacing Patterns

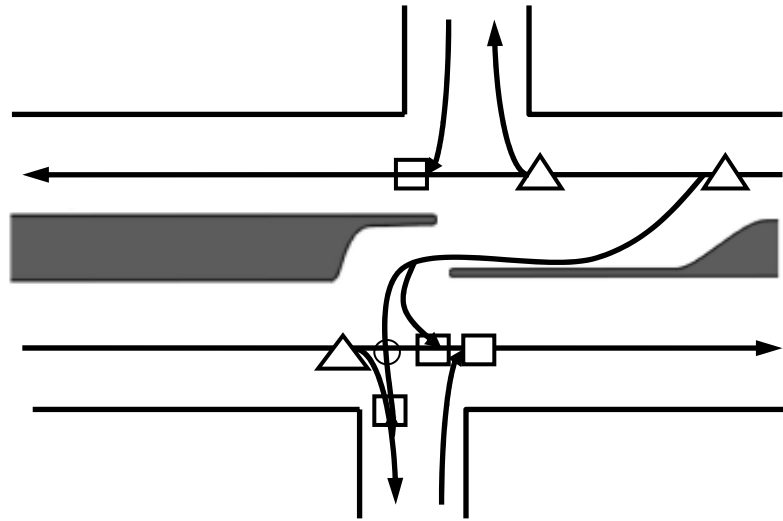
Studies conducted on the impact of signal spacing on safety and mobility indicated that higher traffic signal density (number of signals per mile) leads to higher crash rate (crashes per year, or crashes per million vehicle miles travelled). For instance, if the number of traffic signals per mile increases from two to four, the crashes increase about 40 percent along highways in Georgia and about 150 percent along US 41 in Lee County, Florida (ACM 2003). If one additional traffic signal per mile is added to a roadway, travel speed will be reduced by 2 to 3 mph (ACM 2003).

Unsignalized Access Spacing

Unsignalized access includes driveways and median openings. When vehicles make turns at driveways and median openings, some conflicts, such as crossing, diverging, merging, etc., would be produced, which may lead to potential crashes. Figure 1-2 shows the conflict points on driveways and median openings on a mid-block roadway segment. There is one crossing conflict point shown as “○” between the left turn and through traffic when vehicles turn left at median opening. Three diverging conflict points occur between the through traffic and turning lanes (two right turns, one left turn shown as “Δ”) and four merging conflict points presented as “□” when the turning vehicles (three right turns and one U-turn) merge into the through traffic. Thus, controlling the number of driveways and median openings on mid-block segments can reduce potential crashes.

It is stated in AASHTO (2001) that more crashes happen at driveways than at intersections. Thus, the design and location of driveways need to be considered specifically. It is gradually recognized that the spacing of driveways should follow the requirements for traffic signal design and compensate for shortcomings of signalized intersections to make the traffic move efficiently.

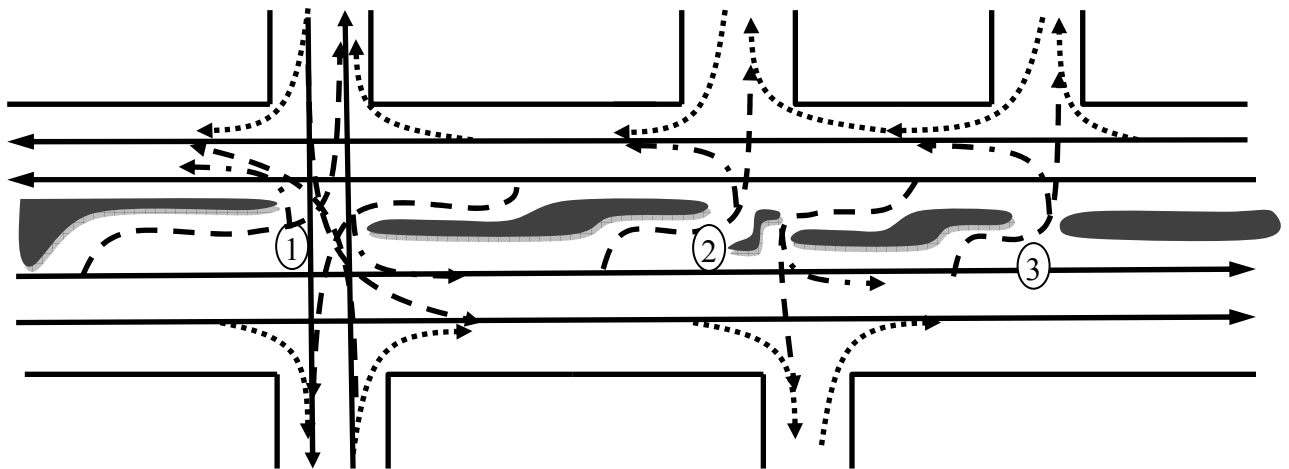
Many studies have shown that crash rate increase as the number of driveways increases. When one additional driveway is added, the conflict points are increased and the chances of potential crashes are raised.



○ 1 Crossing △ 3 Diverging □ 4 Merging

Figure 1-2 Conflict Points for Mid-block Roadway Segments

Source: Access Management Manual 2003



————→ Traffic flow - - - - -> Left turns > Right turns - . - . - .> U turns

Figure 1-3 Conflicts from Driveways and Median Openings

Figure 1-3 shows the conflicts from driveways and median openings, which include all the diverging, merging and crossing. Compared to the two driveways on east bound direction, the conflicts for one additional driveway on west bound direction are higher, which is expected to increase the chances to cause crashes. When vehicles merge into or drive out of driveways, there is risk for running into the turning and through traffic, which might lead to side-wipe, angular or left-turn crashes.

There are three types of median openings in this figure: “1” for full access median opening, “2” for the two-directional median opening, and number “3” for the one-directional median opening. At a full access median opening, vehicles can make left-turns, U-turns, or crossings from two directions. At a two-directional median opening, vehicles can make left-turns and U-turns from two directions. This type of median opening can significantly reduce the conflicts between vehicles making turns, but it still presents the potential risk between the turning and through traffic for producing head-on, angular, or rear-end crashes. The one-directional median opening type can only allow the vehicles to make left-turns and U-turns in one direction.

Some studies used access density to represent the spacing between access points. Their results indicated that crash rate increased with increasing access density. When access density reached certain value, the relationship may not hold. It has also been noted that the interrelationship between driveway, median opening, and land use were not considered in previous studies.

Median Alternatives

There are three alternatives for medians: undivided roadway, Two-Way-Left-Turn-Lane (TWLTL) and raised median as shown in Figure 1-4. The undivided median

cannot prevent vehicles from turning or crossing over it. Thus, it is not effective as an access-management measure. The TWLTLs and raised medians are safer than the undivided roadways because the left turns are removed from the through traffic lanes. TWLTLs can provide a refuge area for vehicles to turn left from both directions and thus improve the operational flexibility. Raised medians separate traffic flow in opposite directions, limit access and reduce conflict points.

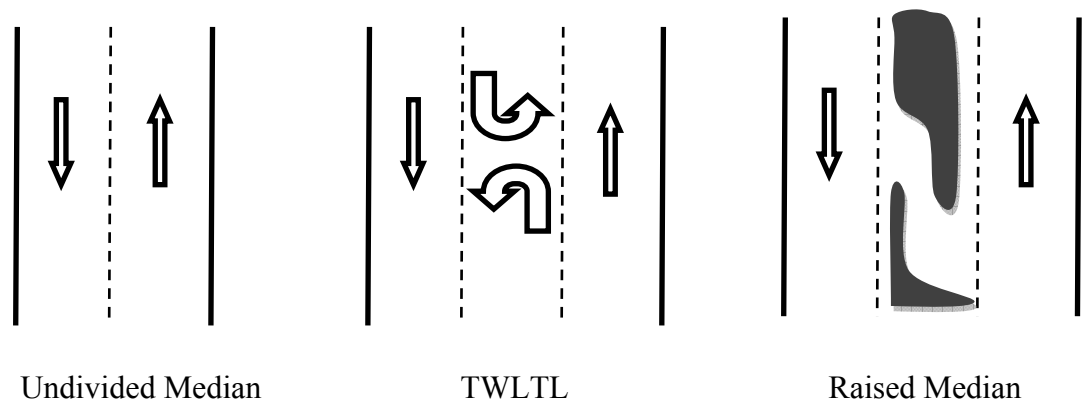


Figure 1-4 Median Alternatives

Since drivers on undivided roadways and TWLTLs can make left turns at any point on a roadway, most of the crashes for these two median types are related to left turns. Directional raised medians are used to control left-turn movements. They specify the location for switching from one side of major roadways to the other. Directional raised medians are installed to replace the undivided roadways and TWLTLs because raised medians utilize separate left-turn lanes to limit the locations for making left turns and then reduce the traffic conflicts.

Many studies have proved that fewer crashes occurred on the roadways with TWLTLs than those on undivided roadways. When traffic volume reached certain limits, roadways with TWLTLs became less safe. Some studies have evaluated the impact of replacing TWLTLs with raised medians. It was found that crashes on roadways with raised medians were fewer than those with TWLTLs.

Corner Clearance

A signalized intersection is the area where drivers go through or complete the turning by responding to traffic signals. Too much access around intersections can cause traffic conflicts and produce many crashes. Figure 1-5 presents the conflict points at intersections when vehicles travel east with only one corner to pass through. At this corner, there are four crossing points (two on through lanes, two on left turns); three diverging points (one left turn and two right turns); and four merging points (two driveways, one right turn and one left lane). More conflict points would be shown if the four corners are considered at the same time. As such, more crashes would be produced.

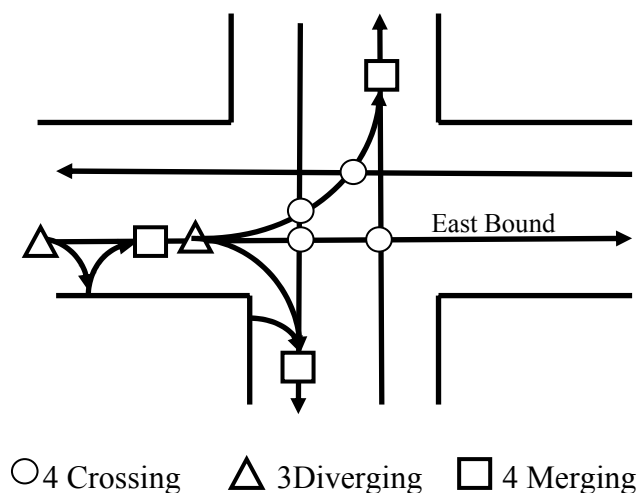


Figure 1-5 Conflict Points at the Intersections

Corner clearance is defined as the distance between an intersection and the first driveway along connecting streets, which is presented in Figure 1-6. The symbols “A” and “B” represent the upstream and downstream corner clearances, respectively, for the major roadway, while “C” and “D” correspond to those on a minor roadway.

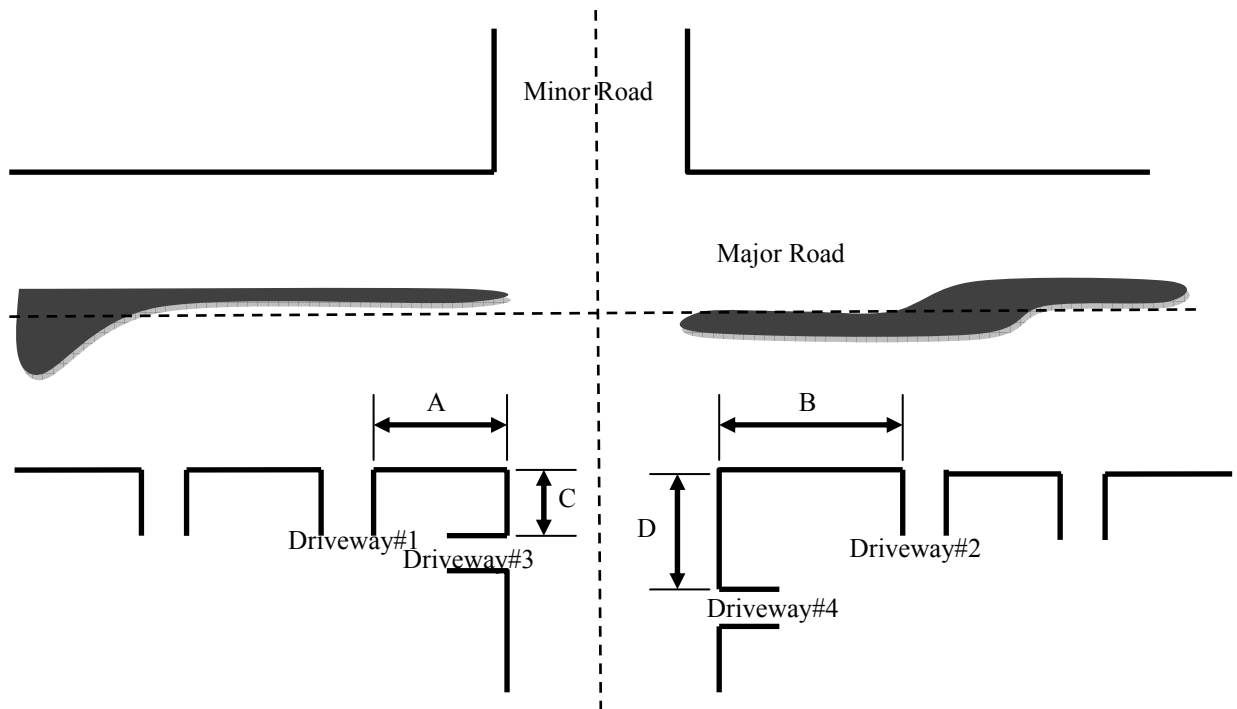


Figure 1-6 Intersection Corner Clearances

It is important to provide enough distance between the corners and the first driveways before the corners to separate conflict points effectively. It would give drivers enough time to make safe maneuvers. When corners are not adequately cleared, the conflicts between the turning and through traffic would be produced, which would cause more crashes and longer delay.

Most of the studies on corner clearance have focused on how to specify the corner clearance criteria. Some studies considered the perception-reaction time when defining minimum corner clearance, while others examined the impact of corner clearance on safety at intersections. The factors that influenced the safety varied significantly. Some studies included the number of driveways in the defined range of intersections as a factor while only a few of them considered the types of land use around the intersections.

Different land uses along roadways may be associated with different number of access to the adjacent properties. Residential streets provide fewer driveways and would reduce the risk of crashes, while commercial areas with more driveways would bring more conflicts to arterial roadways, thereby causing safety and mobility problems. Therefore, access for residential and commercial land should be balanced without obstructing traffic to adjacent properties.

1.2 Problem Statement

Two major issues exist in evaluating the impact of access management on safety in the urban area: heterogeneity (uniqueness) and endogeneity (interdependency). Heterogeneity refers to the issues raised for observations that share common missing information. In urban streets, the roadway segments sampled for analysis would be from the same arterials. The safety and mobility data for these segments from the same arterials would show similar patterns that are unique to the arterials from which their data are collected. If this issue is not addressed appropriately, the impact of the safety and mobility would not be estimated accurately. This issue may not be obvious in previous studies where the sampled roadways were from different jurisdictions such as cities or

counties. It becomes noticeable when investigation of the safety and mobility issues related to access management is for a single constrained area, like the Las Vegas area.

Endogeneity refers to the interdependence between dependent and independent variables in regression models. In the past, the measures for safety, such as crash rate, were used as the only dependent variable. The measures for mobility, such as travel speed, were used as independent variables by which only the dependence of safety on mobility was addressed. In reality, mobility is also influenced by safety. By including mobility, like travel speed, only as independent variable, researchers failed to address the dependency of mobility on safety. Both safety and mobility are the measures for roadway performance. They share common influences such as roadway characteristics, traffic flow, and access management.

Figueroa (2005) developed simultaneous equation models to address the interrelationship between safety and mobility. The models consisted of two equations, one for the safety related to mobility and other factors, and the other for mobility related to safety. These two equations were estimated together, employing sequential or joint estimation techniques. The issue with this study was that free-flow speeds were adopted as a measure for mobility. Free-flow speeds only occur in uncongested time periods in a day, while crash frequency used in Figueroa (2005) to measure safety included crashes that happened in any time period during a day. The mismatch between the performance measures for safety and mobility made the results from their study questionable.

Jointly considering the interdependency between safety and mobility at intersection is more difficult because there is usually no mobility data, such as travel speed, travel time and delay for intersections. Thus, investigating the impact of access

management on safety at intersection was restricted in this study to the one-way relationship only.

1.3 Research Objectives

The objective of this study is to evaluate the impact of access management techniques on safety in urban areas by developing advanced regression models based on data collected from an identified urban area: the metropolitan area of Southern Nevada. Since the study focuses on urban areas, it is necessary to address the heterogeneity issue in the regression models. The interdependency of safety and mobility influenced by common factors such as roadway characteristics, traffic flow, and access management techniques, need to be considered because the endogeneity is a fundamental issue regardless of urban or rural areas in which the study was conducted. Due to the limitation of the data for mobility at intersections, the interdependency of safety and mobility is incorporated in the regression models only for mid-block roadway segments, not for intersections. For clarification, the major modeling issues addressed in the regression of this study are listed in Table 1-1.

Table 1-1 Main Objectives

	Model for Mid-block Segment	Model for Intersection
Heterogeneity	Yes	Yes
Endogeneity	Yes	No

The regression models should include performance measures for safety and mobility. Other factors like access management, roadway characteristics, and traffic flow should be included. The proposed model should be calibrated and justified with appropriate statistical tests. Reasonable interpretations of the results from the models should be provided. Recommendations regarding the practice of access management should then be proposed. In addition, the future study should also be indicated based on the research in the end.

1.4 Research Methodology

The investigation on the safety impact of access management was conducted for mid-block segments and intersections separately in this study. Figure 1-7 shows the mid-block segments that are defined in the study. The safety and mobility in the mid-block segments are influenced by access management techniques, roadway characteristics, traffic flow, and land use. In addition, safety and mobility interact with each other. Some previous studies about safety impact selected roadway segments within some corridors that consisted of several mid-block segments (see Figure 1-8). Since the driving behaviors on mid-block segments and intersections are different, the safety impact cannot be evaluated reliably if the data from mid-block segments and intersections are mixed together.

For mid-block segments, panel data simultaneous equation models were developed. Among the panel data models, this study chose the random coefficient model. In this model, it was assumed that the impact of factors on safety vary over different arterials, each following a certain probability distribution. This panel data was

incorporated into the simultaneous equation models by which both the heterogeneity and endogeneity issues were addressed.

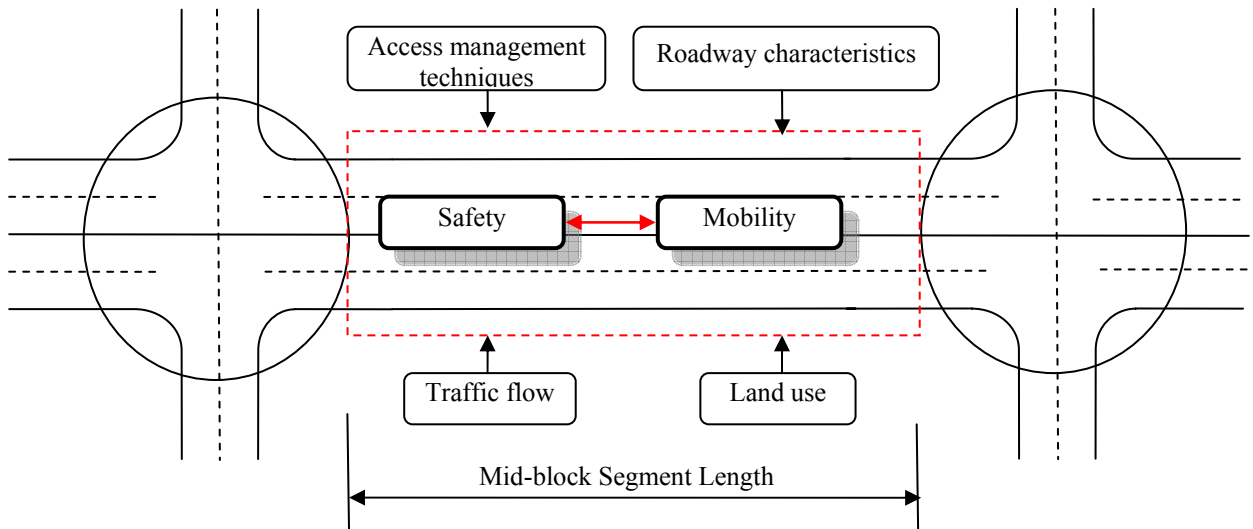


Figure 1-7 Roadway Segment Structure

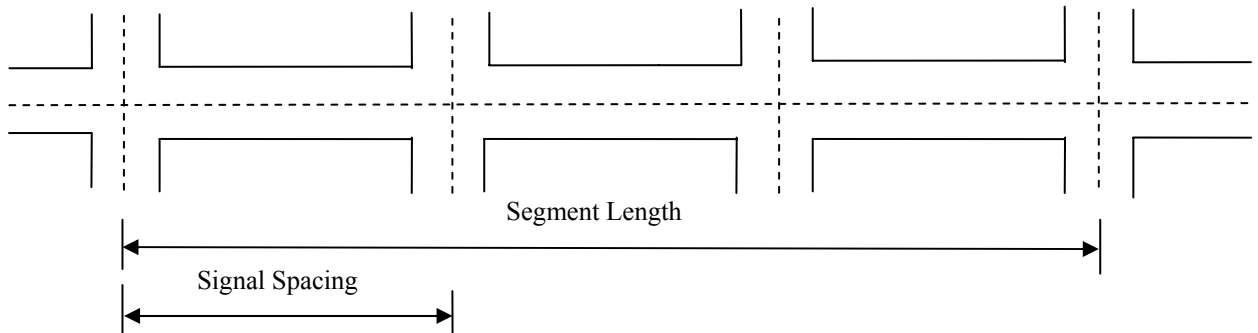


Figure 1-8 Corridor Structure

For intersections, count data models incorporated with panel data models were developed in this study. Among the panel data model, the random-effects model was chosen for this study. Because of the flexibility of dealing with dispersion of count data, negative binomial count data model was selected in which panel data structure was integrated.

To develop the models for mid-block segments, data were collected from arterials in the Las Vegas area. These data included crash, travel speed, roadway characteristics, and access management techniques, and were obtained from different sources. Significant efforts were made in extracting the access management and roadway characteristics data from Google Earth. The same set of arterials for mid-block segments was used to collect data for intersections. The same efforts were made in extracting corner clearance data from Google Earth.

With these data collected, the panel data simultaneous equation model and the panel data negative binomial model were calibrated. A popular statistical software STATA 9.0 was used in calibrating the models. The results from these models were interpreted with the consideration of the situations in the Las Vegas area and the results in previous studies. Conclusions were made based on the results.

This dissertation made significant contributions in the following areas. First, it proposed the panel data modeling approach to address the heterogeneity issue that existed uniquely in urban areas. Replacing cross-section and time series data with the cross-section and spatial data is innovative. The results from the investigation indicate that such a modeling approach is effective, and the results produced are meaningful. Second, this research used a performance measure for mobility that matched with the safety

measurement. By this, the gap in a previous study that took the simultaneous equation modeling approach was filled. Third, this study included more influencing factors on safety that involved access management, land use, roadway characteristics, and traffic flow. In previous studies, the number of factors used in the models was fewer than that in this study. Fourth, this is the first study that investigates the impact of corner clearance on safety based on the regression model that can incorporate more relevant factors. In previous studies, the corner clearance was not included as an influencing factor on the safety at intersection.

1.5 Dissertation Organization

Chapter 1 introduces the background of access management, problem statement, the objectives of the study, and the methodology proposed in this study.

In Chapter 2, relevant literature was reviewed for the studies on safety in arterials that are related to develop regression models for mid-block segments. Literature on safety at intersection was also reviewed to develop models for intersections.

Details of the methodology are presented in Chapter 3. Formulations for the proposed regression models are described. In addition, the statistical tests for calibrating the models are also included in this chapter. Chapter 4 describes the efforts made in collecting the data from different sources related to the Las Vegas area.

In Chapter 5, the calibration of the random coefficient simultaneous equations model is presented. In the calibration of the model, the descriptive results are introduced first, followed by the model testing and interpreting the results from the calibrated models.

Chapter 6 provides the model development for intersection, following the same fashion as for the model at mid-block segments.

In Chapter 7, conclusions are made for this study on the impact of access management in urban areas. The issues to be addressed in future are also discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Access Management Techniques for Mid-Block Segments

Head (1959) developed multiple linear regression models to predict crashes on the state highway system in Oregon. Among the factors considered in this study, those related to access management are spacings between driveways, signalized and non-signalized intersections. Other factors were AADT, speed limits, pavement width, effective lane width, and the numbers of lanes. A total of 426 roadway segments were chosen from roads that had a total length of 186.4 miles. It was found that crash rate increased with the increase of the number of commercial units adjacent to roadway segments, the number of traffic signals and the number of intersections on selected roadway segments.

Cribbins (1967) investigated the effects of selected access management techniques -- signal spacing and median openings on crash rate for multilane divided highways in North Carolina by developing statistical model. In addition to considering signal spacing and median openings, the model also included level of service as an influencing factor. The study selected 92 sites on multilane highways and these sites were selected as homogenous as possible. Note that the selected highways included both signalized and unsignalized intersections. Multiple regression models were developed, which can be utilized to predicate crash rate at different roadway locations. Crash data were collected on each of the multilane highways during 21-months. The results showed that the crash rate considering all types of crashes and crash rate that considered injury

only increased as the number of signals per mile and traffic volume increased. The frequency of median openings did have a significant effect on occurring crashes.

Squires and Parsonson (1989) compared crashes occurred on four- and six-lane roads in Georgia where two different median types, raised medians and continuous TWLTLs were used. The influencing factors included average daily traffic (ADT), signals per mile, the number of driveways per mile and the number of openings per mile. The linear regression models were developed to forecast the crash rate separately for four- and six-lane roadways. Note that the mid-block segments were not defined clearly in this study. For both the four- and six-lane roadway sections, the crash rate of raised medians was found to be lower than that of TWLTLs.

Brown et al. (1998) developed multivariate regression model to predict crash rate on multi-lane arterial segments with the consideration of geometric and access control characteristics. Different models were developed for the total number of crashes, property-damage-only crashes, and fatal/injury crashes, separately, but all had the same model structures. The influencing factors included segment length, AADT, number of years, access density, proportion of signalized spacing, presence of an outside shoulder, presence of TWLTLs, and presence of a median with no openings between signalized intersections. The results showed the number of crashes of different severity types increased as the access density and proportion of signalized spacing increased.

Davis, Parsonson and Leonard (2000) evaluated the crashes on twelve multi-lane arterial roadways that were selected from areas of four states. An integrated database was constructed to include data of traffic volume, land use, signal spacing, and those related to roadway safety. Linear regression analysis was used to predict crash rate on roadway

segments. Note that the roadway segments in this study included the signalized intersections in the middle. The analysis looked into the crashes on 4/6 lane roadways with raised medians and TWLTLs, separately. It was found that traffic signal density of roadways with raised medians was significant statistically.

Sawalha et al. (2000) developed crash prediction models to estimate the safety based on 58 urban arterials in the cities of Vancouver and Richmond in Canada. Crash data from 1994 to 1996 were collected from these cities. Crashes that occurred at signalized intersections were not included as part of the data used to develop the models. From these 58 arterials, 392 arterial sections were chosen to develop the safety prediction model. The independent variables investigated were: section length, traffic volume, number of lanes between signals, number of unsignalized intersections, the total number of driveways, total number of bus stops on two sides of roadways, number of cross-walks, type of median, type of land use, and percentage of arterial section in length along which parking was allowed. The generalized linear regression approach was employed to develop the models for crash occurrence. In addition to segment length, AADT, and unsignalized intersection density, the model identified the number of cross-walks, number of lanes, driveway density, median type and land use as influencing factors on crash occurrence.

Parsonson et al. (2000) studied the impact of raised medians on crash rate based on data for all the divided highways in Georgia. By comparing the crash rate, before and after installing the raised medians it was found that raised medians were associated with a 45 percent lower crash rate than TWLTLs both on mid-block segments and at

intersections. There was 43 percent crash rate reduction for injury and 4 percent crash rate reduction for fatality.

In Miller et al. (2001), several existing mathematical models were presented that predicted the number of crashes as a function of signal spacing, median alternatives, and unsignalized driveways. They were compared based on a 10-years geometric, operational and crash data that were collected for three corridors. The exponential regression model was developed and the results indicated that crash rate increased exponentially with all the variables involved.

Mayora and Rubio (2003) developed a multivariate regression model to predict crashes on two-lane rural roads in Spain. The roadway sections selected in this study had signalized intersections included in the middle, and AADT on these sections were less than 20,000 vehicles per day. Crash data were obtained for two periods: 1993-1997 and 1998-1999, each for model calibration and assessment, respectively. Crash rate for personal injury was used as the dependent variable, while access density, average sight distance, average speed limit and the proportion of no-passing zones were the independent variables. Access density is the variable that influences the rate of head-on and lateral collisions the most, and has a negative effect on safety.

In the study by Eisele et al. (2004) the safety impact of access management techniques was investigated based on crash data collected from ten selected corridors in Texas and Oklahoma. The crash data from January 1993 to June 2000 were obtained from the Accident Records Bureau (ARB) of the Texas Department of Public Safety (DPS) in Austin, Texas. The access management techniques considered in the study included access points per mile and median types. The linear regression model based on

the crash and access management data showed an upward relationship in the crash rate as the number of access points per mile increased.

The safety performance of rural and suburban four-lane highways in Arkansas was studied by Gattis et al. (2005). The influencing factors included access density, median alternatives, traffic volume, lane width, and median width. The data for these factors were collected on 111 roadway segments, each with signalized intersections included in the middle. The negative binomial regression model was developed, which showed that for the volumes ranging from 1,800 to 25,667 vehicles per day, as the traffic volume increased, the crash rate gradually increased. The analysis found that the relationship between the crash rate and each variable was significant statistically. Moreover, for the roadways with lower access density (<20 access points per mile), roadways containing depressed medians had the best safety record, and narrow medians had the better safety record than TWLTLs on the roadways with medium access density (20-40 access points per mile).

Welch (2005) evaluated the safety effects of reducing a four-lane urban roadway to two travel lanes with a center TWLTL. Two years' data, including median types and traffic volume, were collected on urban corridors. The data for before and after the conversion from four-lane to two lanes with TWLTLs were compared. It was found that urban corridors with less than 20,000 vehicles per day improved traffic safety when four lanes were reduced to three lanes.

Eisele and Frawley (2005) compared the safety performance for 11 corridors in Texas before and after the installation of access management techniques. The data collected in the study included crash rate, access density, traffic volume as well as the presence of

raised medians or TWLTLs. It was found that safety improvement was demonstrated on all the corridors after the installation of raised median.

In the study by Lewis (2006), the safety impact of access management techniques in several corridors in Utah were evaluated. Linear regression models were developed for the cases before and after the implementation of selected access management techniques. The influencing factors included in this study were access density, AADT, and land use. Although the R-squared value of the regression models for the case after the installation of the access management techniques has increased, when compared to the before case, it is still relatively low. The results indicated that other factors not included in the study, such as land use, geographic location, and geometric features may influence the performance of the model.

Gattis et al. (2007) investigated the safety performance of access on urban multilane roadways in Arkansas State. The following data were collected: number of through-traffic lanes, posted speed limit, volume of vehicles, roadway cross-section width, presence of on-street parking or bicycle lanes, median type, number and location of traffic signals, and the number, location and type of access points. These data were collected on 326 segments, some of which have signalized intersections included in the middle. Negative binomial regression models were developed for the groups of roadway segments that had different medians installed. The results indicated that the expected number of crashes increased with the increasing of the number of signals per mile, traffic volume, and access density for each group of segments with different median types.

Schultz et al. (2008) investigated the safety impact of access management techniques on roadway segments selected from some arterials in Utah, based on

developing stepwise linear regression models. There were 175 segments that were chosen from 49 different state routes of six counties in Utah. Independent variables collected in this database included segment length, access categories, number of travel lanes, median type, posted speed limit, orientation (e.g., north/south vs. east/west), adjacent land use (e.g., commercial, residential, industrial, or agricultural), access density, signals per mile, AADT for all travelling lanes, and AADT per lane. The dependent variables obtained included the number of crashes that aggregated all severity and collision types over the three-year period from 2002 to 2004. The results showed statistically significant correlations between crash rate and signal spacing, adjacent land use, speed limit, and median type.

Figueroa (2005) developed simultaneous equations models to investigate the safety performance with the consideration of typical access management technique, such as driveway density. Recognizing that the factor travel speed was a contributor to safety as well as a measure that was influenced by safety on a road, simultaneous equations models were developed, one equation for safety and the other for free-flow travel speed, a measure for mobility of the same road for which the safety was evaluated. The variables selected for the models included access management techniques, roadway characteristics, and geometric features. The roadway segments for which crashes were counted for modeling included more than one mid-block segment. The results indicated that higher free-flow speed caused crash rate, and that higher crash rate can change travel speed.

In summary, it can be found from these studies that some used corridors or arterials as units of modeling in which signalized intersections were included in the middle, while some separated mid-block segments from the signalized intersections. The

popular research approaches are before and after study and multiple linear regressions. In the multiple linear regression models, the dependent variable is either the number of crashes, or crash rate (the number of crashes per million vehicles miles travelled). The number of access management techniques included in these studies varies. Some studies dealt with only one access management technique, while some of the others include more than one access management technique. In addition to access management techniques, other influencing factors are also included in these studies, depending upon the availability of the data. All these studies have found that access management techniques have important influences on roadway safety.

Among all the research results, as for the impact of signal spacing or signal density, all studies concluded that signal spacing or signal density had significant impact on roadway safety, longer signal spacing increased safety. As for impact of driveways or access density, all the studies reached the conclusions that higher driveways or access density produced more crashes. As for the impact of median types, most studies found out that roadways with TWLTLs were safer than undivided ones, while roadways with raised medians were safer than those with TWLTLs. In addition, with the traffic volume increasing, roadways with raised medians tend to replace those with TWLTLs in order to increase safety.

The literature reveals that among all the studies few of them have considered the interaction between safety and mobility on the same roadway segment. These two performance aspects have to be considered in an appropriate way so that the impact on each of them can be better estimated. Studies by Head (1959) and Drummond et al.

(2002) considered roadway mobility such as Level of Service (LOS), but developed the model for safety only, and the influence of safety on mobility was not considered.

The work by Figueroa (2005) attempted to establish the interrelationship between safety and mobility using simultaneous equations models. However, the following issues presented in their approach were worth for further discussion. First, the study used the free-flow speed to represent the mobility in the roadway segments. In general, free flow traffic conditions only occur in very limited time period during a day. Thus, it may not be appropriate to use mobility as a measure for the roadway conditions that vary over a day and include both free-flow conditions and constrained travel conditions. If free-flow speed as the measure for mobility is used, the crash rate used for safety has to be developed based on the crash data on the same time period, during which free-flow speed data are collected. In other words, the measures for safety and mobility for the same road have to be matched for the time periods they are representative for. The inconsistency between the measures for safety and mobility would bring errors in models estimation. Second, some roadway segments for which safety and mobility data were collected may be on the same roads, which is very likely in the studies for urban areas. Some data on these roadway segments may not be collected in their study, in which the safety and mobility data from the same roads share the same unobserved characteristics. This issue is usually called heterogeneity. It may not be a serious problem when the data are collected for roadway segments that are spread out in a large area such as counties in a state, but it would be a noticeable issue when the large number of samples of roadway segments is distributed in a relative small area like the Las Vegas area in this study. Thus, panel data approach was proposed to address this issue.

2.2 Access Management Technique for Intersections

There have been many studies on the safety performance at intersections; however, few of them have explored the impact of corner clearances on intersections. McCoy and Heimann (1994) evaluated the effects of driveway traffic on saturation flow rates at signalized intersections at two locations in Lincoln, Nebraska. The influencing factors in the study were the traffic flow, corner clearance, and driveways. More than 400 pairs of departure and prevailing headways in curb lanes were collected and analyzed. The research found that driveway traffic can reduce the saturation flow rate on signalized intersection approaches, and the amount of reduction depended on the corner clearance of driveways and the proportions of curb-lane volume that entered and exited driveways.

Long and Cheng-Tin (1993) developed an analytical model for estimating the required corner clearances at intersections. Separate minimum corner clearance distances were derived for saturated and unsaturated conditions. The model is expressed as: $MCC_i = IMCC_i * If_i$ where MCC_i stands for corner clearance for traffic conditions, $IMCC_i$ is the initial minimum corner clearance, and If_i is for the product of individual adjustment factors for facility type, median type, driveway channelization, driveway width, driveway volumes (daily and peak hours), coincidence of driveway and arterial peak period volumes, driveway corner turning speed, and curb-lane widths.

Kaub (1994) presented an access spacing model based upon driver perception-response times and vehicle dynamics, which reflected driver perception-reaction times, acceleration rates and braking rates for both through and turning vehicles. When the driveway is located on the “far” side of an intersection, allowance is made for accelerating right-turn vehicles at the street intersections.

In *NCHRP 420 Report* by Gluck et al. (1999), corner clearance criteria were assembled for selected cities, counties and states. These criteria, summarized in Table 2-1, illustrate a wide range from 16 ft (urban area in Iowa) to more than 300 ft (Colorado), many of which fall within 100- to 200-ft range.

Table 2-1 Summaries of Corner Clearance Criteria

Government Unit	Criteria
Collier County, FL	With Median: 75 to 115ft upstream, 100 to 230 ft downstream
	Without Median: 100 to 230ft upstream, 100 to 230 ft downstream
Colorado DOT	325 ft from intersection for 40mph
Florida DOT	75 to 115ft upstream, 100 to 230 ft downstream
Ingham County, MI	125ft from intersection
Iowa DOT	16ft from intersection in urban area
Maine DOT	Suggested spacing in urban area:
	Signalized intersections: 115 to 230ft
	Unsignalized intersections: 85 to 115ft
	Suggested spacing in rural area is doubling the above
New York State DOT	Approximately 35 to 75 ft from intersections
North Dakota DOT	Signalized Intersections: Local-50ft, Collector-85 to 175ft, Arterial 115 to 230ft
	Unsignalized intersections: Local-50ft, Collector-75 to 85 ft, Arterials -85 to 115ft
New Jersey	50ft unsignalized/100ft signalized
Pennsylvania DOT	Follows AASHTO criteria
Texas DOT	Follow "AASHTO green book for corner clearances without medians"
Virginia DOT	50 desirable, 25ft minimum from intersections
Washington State DOT	Varies depending on classification of road

Different from the studies above where safety at intersections were not considered, Oh et al. (2004) developed crash prediction models for three-legged and four-legged stop controlled and signalized intersections. Various models were calibrated for total crash counts and injury crashes for Georgia, separately. Poisson and negative binomial regression models were chosen for the model development. The data were

obtained for crashes occurred in Georgia, California and Michigan. In addition, traffic volume for major and minor roadways, intersection geometric design factors, speed limits for the approaches at each intersection and lighting conditions were also considered. It was found from the study that traffic volumes at intersection approaches were always positively correlated and had the highest impact on crash occurrence. On the other hand, lighting conditions had the strongest impact in reducing both the total and injury crashes at signalized intersections. Among other factors more numbers of commercial driveways within 250 ft of intersections and higher approach speed for major roads caused more total intersection crashes.

From the literature review on the studies related to corner clearance at intersections, it can be found that corner clearance have not been specifically studied with the relation to safety. Oh et al. (2004) was the one in which safety at intersections was studied. Even though driveways at intersection were considered in this study, only the number of driveways at intersections was included, not the corner clearance. In concept, an intersection approach may have more than one driveway. However, the corner clearance could vary significantly given a fixed number of driveways on approach. Thus, it is necessary to consider corner clearance directly in the evaluation of intersection safety in addition to other factors, such as traffic flow and roadway function classifications that have been included in the study by Oh et al. (2004). It was also found that the study by Oh et al. (2004) was for intersections in the rural area. The corner clearance requirements in urban areas would be different from the rural areas.

The study presented in this dissertation is to evaluate the safety impact of corner clearance at intersections by developing count data regression models. In urban areas, the

same samples of intersections are usually located at the same arterials. The safety performance of these intersections on the same arterials may be highly correlated due to the missing information to the arterials, which is usually called heterogeneity problem. To address this problem, this study incorporated the panel data feature into the count data models for traffic safety at intersections.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research Approach

The literature review in Chapter 2 indicates that typical studies on investigating the safety performance of access management are to develop statistical models to establish the relationship between roadway safety and access management techniques with the consideration of other related roadway characteristics. For studies related to safety in urban areas, roadway segments sampled would highly likely come from the same arterials. These sampled roadway segments within the same arterial possess unique characteristics, such as driver population, that are related to the arterials studied. When these unique characteristics are not included in the modeling, the heterogeneity issue arises. In previous studies only one study where the interrelationship, also called endogeneity, between safety and mobility was addressed, and the performance measures for safety and mobility for a roadway segment do not match from the perspective of time periods they cover.

In this study, panel data simultaneous equation models were developed, where the panel data feature in the model was to mitigate the heterogeneity issue while simultaneous equations model was to address the endogeneity issue. Different from approaches where roadway segments with signalized intersections in the middle were used as modeling units, this study divided such long segments into mid-block segments and signalized intersections. These mid-block segments did not contain any signalized intersections in the middle. The safety and mobility performance of these mid-block segments in the same arterials are highly correlated, so the panel data model was

developed in this study. For the selected mid-block segments, both safety and mobility data was made available to this study. Thus, simultaneous equations models integrated with panel data model were developed to consider the impact of safety and mobility at the same time. However, the data that popularly measured the mobility at intersections, such as traffic delay, were not made available to this study and thus simultaneous equation models were not developed. For intersections, only single equation models for safety measured in terms of the number of crashes were developed in which the panel data feature was considered. Figure 3-1 shows the framework followed to accomplish the objectives established for this dissertation.

To develop the panel data simultaneous equation models for mid-block segments, arterial streets were selected in the Las Vegas area. From these selected arterials, mid-block segments and signalized intersections were chosen to collect relevant data.

For each mid-block segment, the data collected for this study included: the total number of crashes, travel speed, access management techniques, traffic volume, land use and relevant roadway characteristics, such as the length of roadway segments and the number of lanes.

With the data collected, panel data simultaneous equation models were developed. Among many different modeling approaches to considering the panel data feature, the random coefficient models were developed and compared with random-effects models in this study. The endogeneity that was expected to exist between safety (e.g., crash rate) and mobility (e.g., travel speed) was evaluated by conducting endogeneity test.

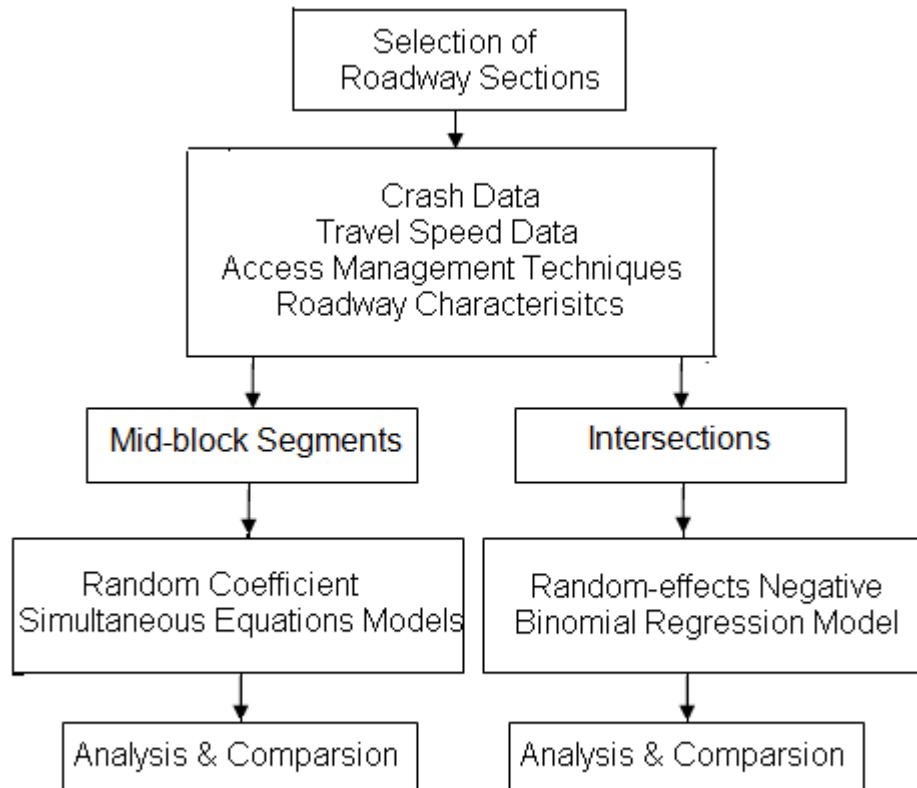


Figure 3-1 Research Methodology

To develop panel data based count data models for the safety at intersections, the arterials chosen for mid-block segments were used for data collection. The data collected at each intersection included the number of crashes, corner clearance, number of driveways, traffic volume, and land use. Instead of using crash rate to measure safety that was suitable for mid-block segments, the number of crashes was used to evaluate the safety at intersections. To handle the number of crashes, which was count data in nature, count data models were developed with the consideration of panel data features. Among the count data models, negative binomial regression models were developed in this study because of its capability to accommodate wide variations in count data. Random-effects

features were incorporated into the negative binomial models to reflect heterogeneity issue in this study. The random-effects negative binomial model was then compared with the negative binomial regression model where the heterogeneity issue was not considered. In the following sections, the panel data simultaneous equation models and the count data models with panel data features are described.

3.2 Model Development for Mid-Block Segments

3.2.1 Crash Rate Model

Most of the existing crash rate models have the following linear form:

$$CR_i = \sum_k b_k X_{ik} + \varepsilon_i \quad (3-1)$$

where CR_i represents the crash rate at segment i , X_{ik} is the value of the k -th independent variables at segment i , b_k denotes the regression coefficient for variable k , and ε_i is the normally distributed disturbance term, which is generally assumed to have zero mean and constant variance σ^2 .

There are some assumptions that make the linear regression model valid, including (1) the relationship between dependent variable and independent variables is linear; (2) the independent variables are either deterministic or random; (3) the error terms are normally distributed with an expected value zero and a constant variance, and these errors are independent of independent variables and uncorrelated among themselves. When any of the model assumptions are not met, some transformation or remedial actions are imperative.

To make sure that the estimated crash rate from the linear model above is positive, the dependent variable is usually taken using the logarithmic form: $\ln(\text{crash rate})$. The

independent variables include travel speed, access management techniques selected in this study, land use, roadway conditions, and traffic flow. With only this single equation developed, the endogeneity between crash rate and travel speeds cannot be addressed

3.2.2 Travel Speed Model

The travel speeds on a roadway segment were influenced by many factors, which include: roadway, driver and vehicle characteristics, environmental conditions, traffic conditions, posted speed limit, and enforcement level.

The models for travel speed can be expressed as the followings:

$$V_i = \sum_k b_k X_{ik} + \varepsilon_i \quad (3-2)$$

where V_i is the average speed or a specific percentile speed on segment i , X_{ik} denotes the value of the k -th independent variable at segment i , b_k represents the corresponding regression coefficient, and ε_i is the normally distributed disturbance term with zero mean and constant variance σ^2 . Similar to the crash rate model, some transformation or remedial actions are necessary to run this model if some assumptions for this model are not valid.

3.2.3 Panel Data Simultaneous Equations Models

In general, the interdependency between safety Y_i and mobility X_i can be addressed by developing the following simultaneous equations model:

$$Y_i = \alpha_1 + \alpha_2 X_i + \alpha_3 Z_i + \varepsilon_i \quad (3-3)$$

$$X_i = \beta_1 + \beta_2 Y_i + \beta_3 Z_i + \gamma_i \quad (3-4)$$

where Z represents the influencing factors such as access management techniques and roadway characteristics, and ε_i and γ_i denote the error terms.

Considered the fact that more than one mid-block segment was selected from an arterial, Equations (3-3) and (3-4) can be written as follows:

$$Y_{ij} = \alpha_1 + \alpha_2 X_{ij} + \alpha_3 Z_{ij} + \varepsilon_{ij} \quad (3-5)$$

$$X_{ij} = \beta_1 + \beta_2 Y_{ij} + \beta_3 Z_{ij} + \gamma_{ij} \quad (3-6)$$

where subscribes i and j represent an observation from j -th mid-block segments on i -th arterial. This data structure is the same as the time and space structure possessed for panel data. A mid-block segment can be “imagined” for each arterial i for which the repeated “time series” observations are those for the mid-blocks sequentially laid out on an arterial.

To deal with the information that is not observed for specific arterials, fixed-effects model can be developed for which Equations (3-5) and (3-6) can be written as:

$$Y_{ij} = \alpha_i + \alpha_2 X_{ij} + \alpha_3 Z_{ij} + \varepsilon_{ij} \quad (3-7)$$

$$X_{ij} = \beta_i + \beta_2 Y_{ij} + \beta_3 Z_{ij} + \gamma_{ij} \quad (3-8)$$

where the constants α_1 and β_1 in Equations (3-5) and (3-6) become α_i and β_i , each is specific to different arterials. In other words, there would be more coefficients to be estimated for Equations (3-7) and (3-8) comparing with those for Equations (3-5) and (3-6).

Another approach to dealing with the unobserved information is random-effects model, in which the missing information associated with the individual arterials is not identifiable to their specific arterials, but an assumption is made that the missing

information is distributed probabilistically over the population of arterials that include both sampled and not sampled. For such an assumption, Equations (3-7) and (3-8) can be written as:

$$Y_{ij} = \alpha_i + \alpha_2 X_{ij} + \alpha_3 Z_{ij} + u_i + \varepsilon_{ij} \quad (3-9)$$

$$X_{ij} = \beta_i + \beta_2 Y_{ij} + \beta_3 Z_{ij} + v_i + \gamma_{ij} \quad (3-10)$$

where u_i and v_i are parts of the errors that follows certain distributions over the whole population of arterials in the Las Vegas area. The means of these two errors would become constants that can be estimated for Equations (3-9) and (3-10), respectively.

The coefficients in Equations (3-5) and (3-6) are assumed to be uniform over different arterials. By Equations (3-5) and (3-6), the amount of influencing factors on safety are the same among different arterials. This assumption may not be true in reality. Thus, these coefficients for a variable over different arterials can be assumed to follow a certain distribution. With this assumption, Equations (3-5) and (3-6) can be written as:

$$Y_{ij} = \alpha_1 + \alpha_2 X_{ij} + (\alpha_3 + w_{3i}) Z_{ij} + \varepsilon_{ij} \quad (3-11)$$

$$X_{ij} = \beta_1 + \beta_2 Y_{ij} + (\beta_3 + s_{3i}) Z_{ij} + \gamma_{ij} \quad (3-12)$$

where the coefficients of Z_{ij} variables include two parts, fixed parts α_3 and β_3 , and random parts w_{3i} and s_{3i} which are independently identically distributed. The model to estimate Equations (3-11) and (3-12) is referred to as random coefficient models.

The fixed-effects model can be applied to this study if the arterials are viewed as the true population of arterials, which was not the case in this study and not included in the model development. The random-effects model can be applied to this study as well because the arterials for which data were collected can be viewed as random samples

from the whole populations of arterials in the Las Vegas area. The random coefficient model is applicable in this study because it can be suitable to the cases where the samples can be viewed as either from a subset of population or the entire population itself. However, the estimation of the fixed effects model involves many arterial specific coefficients. The application of the model to arterials not included in the sampled arterials would be a problem.

For this study, Equations (3-5) and (3-6) can be further written as:

$$Ln(CR) = \beta_{C_0} + \beta_{C_1} \cdot (AM)_C + \beta_{C_2} (RC)_C + \beta_C \cdot V + \varepsilon_C \quad (3-13)$$

$$V = \beta_{V_0} + \beta_{V_1} \cdot (AM)_V + \beta_{V_2} \cdot (RC)_V + \beta_V \cdot (Ln(CR)) + \varepsilon_V \quad (3-14)$$

where $Ln(CR)$ and V are endogenous variables for crash rate and travel speed respectively, β_{C_0} and β_{V_0} are constants, AM and RC represent the vector of the exogenous variables for access management techniques and roadway characteristics, β_{C_1} , β_{C_2} , β_{V_1} , and β_{V_2} are the vectors of estimable parameters for access management techniques and roadway characteristics correspondingly, β_C and β_V stand for the vectors of estimable parameters for crash rate and travel speed, and ε_C and ε_V represent error terms for crash rate and travel speed, respectively.

The estimation of the simultaneous equations model was performed using the two-stage least squares (2SLS) method that was provided in the statistical software STATA. The 2SLS estimation method is an extension of instrumental variables because it finds the best instrument for endogenous variables in the equation system (Washington et al., 2003). The first stage regresses each endogenous variable on all exogenous variables. In the second stage the estimated values from the first stage are used as

instruments and the equations are estimated using ordinary least square (OLS) with the instruments as independent variables. The estimates of the parameters obtained with the instrumental variables are consistent because they are uncorrelated with the disturbance terms ε_C and ε_V .

3.2.4 Endogeneity Test

A general approach used to test for endogeneity is the Durbin-Wu-Hausman (DWH) test. The test is based on the difference between parameters estimates with and without controlling for potential endogeneity. The null hypothesis is that parameters estimated without controlling for endogeneity are consistent, while the alternative hypothesis is that parameters estimated without controlling for endogeneity are inconsistent, which implies endogeneity of the explanatory variables (Kim, 2006).

The DWH test statistic can be expressed as the following equation:

$$H = (\hat{\theta}_S - \hat{\theta}_L) [Var(\hat{\theta}_S) - Var(\hat{\theta}_L)]^{-1} (\hat{\theta}_S - \hat{\theta}_L) \quad (3-15)$$

where $\hat{\theta}_S$ is the vector of estimated parameters obtained from single equation estimation without controlling for endogeneity, and $\hat{\theta}_L$ is the vector of estimated parameters using maximum likelihood estimation with controlling for endogeneity. Under the null hypothesis, the test statistic is asymptotically distributed as $\chi^2(k)$, where k is the number of positive elements in the diagonal of $Var(\hat{\theta}_S) - Var(\hat{\theta}_L)$.

3.3 Model Development for Intersections

For intersections, panel data based count models were developed to relate corner clearance features, land use types, number of driveways, and traffic flow to the number of crashes occurred at intersections. Different from the crash rate measuring the safety on

mid-block roadway segments for which vehicle miles travelled (VMT) are meaningfully available, crash counts are used for evaluating the safety condition at intersections since VMT is not a popular measure available for intersections. Crash counts are non-negative integer values that are better modeled using discrete variable models such as Poisson and Negative Binomial regression models.

Panel models are cross-sectional time series models in which different identities are observed over different time periods. In this study, the crash data collected for different intersections on the same arterials have the nature of time series data since the intersections at one arterial are located next to each other spatially, and share some unobservable factors related to specific arterials. A unique intersection can be imagined for an arterial, and the observations for the intersections on the same arterials are viewed as repeated observations for the “imaged” unique intersection. With this approach, the unobserved factors for each unique arterial can be better taken into account using panel data model.

3.3.1 Cross-sectional Count Data Models

The process of crash occurrence at an intersection can be viewed as a Bernoulli trial, each with unequal probabilities of independent events. A Bernoulli trial has two potential outcomes: one is considered as a “success” (i.e., a crash) and the other is “failure” (i.e., no crash). The number of trials with “success” in a certain time period follows binomial distribution. With the large number of trials, the binomial distribution can be approximated with a Poisson distribution. According to Poisson distribution, the probability $P(y_i)$ of intersection i having y_i crashes in a time period can be written as:

$$P(y_i) = \frac{e^{-\lambda} \cdot \lambda^{y_i}}{y_i!} \quad (3-16)$$

where λ_i denotes the Poisson parameter for intersection i . By definition, λ_i is equal to the expected number of crashes in a time period for intersection i .

Poisson regression models applied to this study to relate the expected number of occurrences λ , crashes in this study, to explanatory variables, which according to Washington et al. (2003) can be expressed as:

$$\lambda_i = \exp(\beta \cdot X_i) \quad (3-17)$$

where X_i is a vector of explanatory variables and β represents a vector of estimable parameters.

By the virtue of Poisson distribution, the mean and variance of crashes occurring at an intersection in a year are equal (i.e. $E[y_i] = Var[y_i]$). To handle the cases where the mean and variance of crashes are not equal, Equation (3-15) is modified as follows:

$$\ln(\lambda_i) = \beta \cdot X_i + \varepsilon_i \quad (3-18)$$

where X_i is a vector of explanatory variables, β is a vector of estimable parameters, and $\exp(\varepsilon_i)$ is a gamma-distributed error term with mean one and variance α^2 . With such a modification, the mean λ_i becomes a variable that follows binomial distribution. The mean-variance relationship becomes:

$$Var[y_i] = E(y_i) \cdot [1 + \alpha E(y_i)] = E[y_i] + \alpha E(y_i)^2 \quad (3-19)$$

If α is significantly different from zero, the crash data are over-dispersed or under-dispersed. If α is equal to zero, the negative binomial distribution reduces to Poisson distribution. The resulting negative binomial probability distribution is:

$$P(y_i) = \frac{\Gamma\left(\left(\frac{1}{\alpha}\right) + y_i\right)}{\Gamma\left(\frac{1}{\alpha}\right) y_i!} \left(\frac{\frac{1}{\alpha}}{\left(\frac{1}{\alpha}\right) + \lambda_i}\right)^{\frac{1}{\alpha}} \left(\frac{\lambda_i}{\left(\frac{1}{\alpha}\right) + \lambda_i}\right)^{y_i} \quad (3-20)$$

where $\Gamma(x)$ is a value of the gamma function, y_i is the number of crashes for intersection i and α is an over-dispersion parameter .

3.3.2 Panel Data Negative Binomial Models

Considering that intersections on the same arterials share the missing information that is unique to the arterials, Equation (3-18) can be written as:

$$\ln(\lambda_{ik}) = \beta \cdot X_{ik} + \varepsilon_{ik} \quad (3-21)$$

where X_{ik} represents a vector of explanatory variables for the k -th intersection on arterial i , β is a corresponding vector of estimable parameters, and $\exp(\varepsilon_{ik})$ denote a gamma-distributed error term with mean one and variance α^2 . Assuming that there is unobserved information that unique to different arterials, Equation (3-18) can be written as:

$$\ln(\lambda_{ik}) = \beta_i + \beta x_{ik} + \delta_{ik} \quad (3-22)$$

where β_i is the constant related to arterial i , and k stands for the k -th intersection on arterial i . Then the fixed-effects NB with this assumption can be resulted, for which probability function for crashes can be expressed as:

$$f(y_{ik}; x_{ik} \beta) = \prod_{t=1}^{n_i} \left(\frac{\Gamma(\lambda_{ik} + y_{ik})}{\Gamma(\lambda_{ik}) y_{ik}!} \right) \left(\frac{\Gamma\left(\sum_{t=1}^{n_i} \lambda_{ik}\right) \Gamma\left(\sum_{t=1}^{n_i} y_{ik} + 1\right)}{\Gamma\left(\sum_{t=1}^{n_i} \lambda_{ik} + \sum_{t=1}^{n_i} y_{ik}\right)} \right) \quad (3-23)$$

Assuming that there is missing information that is distributed over arterials with a probability distribution, Equation (3-18) can be written as

$$\ln(\lambda_{ik}) = \beta x_{ik} + v_i + \varepsilon_{ik} \quad (3-24)$$

with v_i follows a probability distribution over arterials, and ε_{ik} is the error term for the intersection k on arterial i . For the random effects, the beta distribution is selected, which is the conjugate prior of the negative binomial. With inverse dispersion following a Beta distribution like $v_i / (1 + v_i) \sim \text{Beta}(a, b)$ (a and b are distributional parameters for v_i), which integrates the random panel effect into the negative binomial model, the probability of occurring y_i crashes can be written as:

$$\Pr(y_{ik}; x_{ik}, \beta, a, b) = \frac{\Gamma(a+b) \Gamma(a + \sum_k \exp(\beta x_{ik})) \Gamma(b + \sum_k y_{ik})}{\Gamma(a) \Gamma(b) \Gamma(a+b + \sum_k \exp(\beta x_{ik}) + \sum_k y_{ik})} \prod \frac{\Gamma(\exp(\beta x_{ik}) + y_{ik})}{\Gamma(\exp(\beta x_{ik})) \Gamma(y_{ik} + 1)} \quad (3-25)$$

where the terms prior to the product is the probability of Beta distribution and the terms from the product sign to the right provide the Poisson probability function. The details of the fixed-effects and random-effects negative binomial models can be referred to Greene (2006) and Hibe (2007).

In this study whether the fixed-effects or random-effects negative binomial regression models are suitable to estimate the impact of corner clearance on safety is determined based on the dispersion factor α . To evaluate if the model results are fit, log-likelihood ratio is adopted, given by $\rho^2 = 1 - \frac{l(\beta)}{l(0)}$ where $l(\beta)$ is the log-likelihood value of the fitted model and $l(0)$ is the log-likelihood value of the model with no variables included.

CHAPTER 4

DATA COLLECTION

4.1 Data Collection for Mid-block Segments

A set of arterials were randomly selected for data collection in order to develop the regression models for mid-block segments and intersections. These arterials were distributed in the Las Vegas Metropolitan area including Clark County, City of Las Vegas, City of North Las Vegas and City of Henderson. In addition, they were divided four-lane and six-lane types on which raised median and TWLTL are highly likely installed. As a result, 27 major and minor arterials were chosen, which are listed in Table 4-1.

On each arterial, not all the mid-block segments were collected for data. Some roadway segments had significant design change during the study period. There might be significant difference in geometrics such as number of lanes within a mid-block segment. Considering these factors, 395 mid-block segments are eligible for data collection. In Table 4.1, the number of mid-block segments for which data were collected for model development is listed.

The average length of the selected mid-block segments was 0.42 miles. The selected segments and the arterials are shown in GIS map in Figure 4-1. It can be observed from Figure 4-1 that there are not many mid-block segments sampled from northwest and southwest areas. It was because at the time when the study was conducted the two areas were under developing and there were many vacant lands, which led to incomplete data for collection.

Table 4-1 Study Sample

No	Arterial	Section		No. of Segments	
		From	To	Raised Median	TWLTL
1	Ann Rd.	N. Rainbow Blvd.	N. Simmons St.	5	0
2	Bonanza Rd.	N. Maryland Pkwy.	N. Hollywood Blvd.	0	10
3	Buffalo Dr.	W. Charleston Blvd.	W. Sahara Ave.	5	0
4	Charleston Blvd.	Pavilion Center Dr.	Tree Line Dr.	15	16
5	Cheyenne Ave.	N. Hualapai Way	N. Rancho Dr.	8	4
6	Craig Rd.	N. Buffalo Dr.	Las Vegas Blvd.	20	0
7	Decatur Blvd.	Meadow Ln.	W. Hacienda Ave.	8	7
8	Dessert Inn Rd.	S. Rainbow Blvd.	S. Sandhill Rd.	0	16
9	Eastern Ave.	E. Pebble Rd.	E. Owens Ave.	4	17
10	Flamingo Rd.	S. Fort Apache Rd.	S. Sandhill Rd.	22	4
11	Jones Blvd.	W. Oakey Blvd.	Foothill Blvd.	4	6
12	Lake mead Blvd.	N. Rainbow Blvd.	N. Hollywood Blvd.	3	14
13	Lamb Blvd.	E. Lake Mead Blvd.	E. Charleston Blvd.	0	6
14	Martin L King Blvd.	W. Craig Rd	W. Lake Mead Blvd.	5	0
15	Maryland Pkwy.	Franklin Ave.	E. Russell Rd.	3	10
16	Nellis Blvd.	E. Lake Mead Blvd.	E. Hacienda Ave.	12	4
17	Owens Ave.	Main St.	N. Hollywood Blvd.	3	8
18	Pecos Rd.	E. Flamingo Rd.	Pebbles Rd.	4	8
19	Rainbow Blvd.	Westcliff Dr.	W. Hacienda Ave.	11	1
20	Sahara Ave.	Blue Willow Ln.	S. Mojave Rd.	29	0
21	Spring Mountain Rd.	Rainbow Blvd.	Valley View Blvd.	0	7
22	Stephanie St.	Galleria Dr.	American Pacific Dr.	5	0
23	Sunset Rd.	S. Eastern Ave.	Mountain Vista St.	7	0
24	Tropicana Ave.	S. Durango Dr.	Andover Dr.	14	12
25	Valley View Blvd.	Meadows Ln.	W. Flamingo Rd.	0	12
26	Warm Spring Rd.	S. Eastern Ave.	N. Stephanie St.	4	0
27	Washington Ave.	N. Durango Dr.	N. Hollywood Blvd.	6	17
Subtotal				197	179
Total				395	

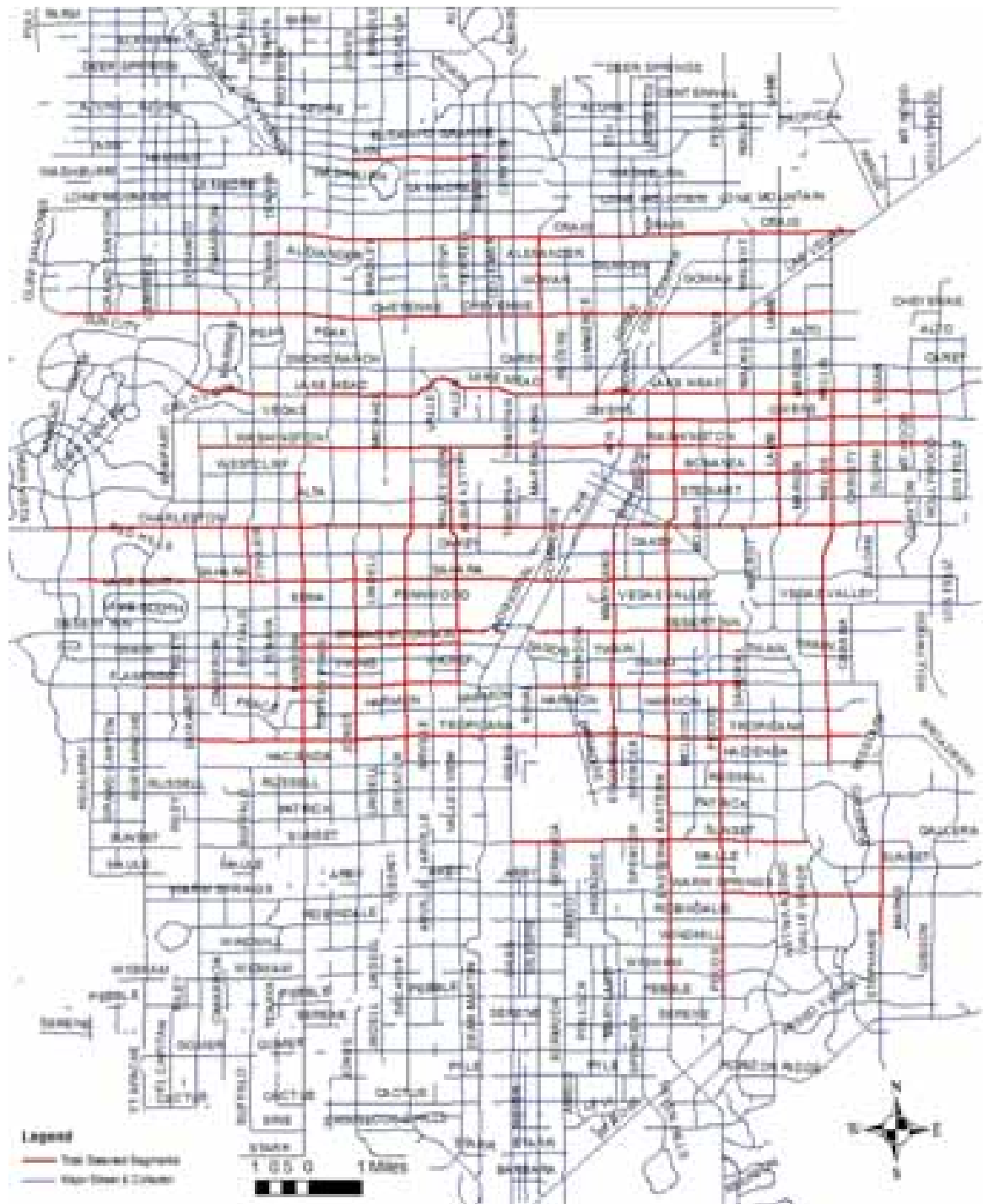


Figure 4-1 Selected Segments and Arterials Marked as Red in Las Vegas

4.1.1 Crash Data

The data of crashes that happened in 2003 were obtained from Nevada Department of Transportation (NDOT), and the data are managed using the Arc GIS system. The attributes in the database for each crash include the crash date, the crash location (primary road and secondary road), crash severity, crash type, and vehicle conditions. Table 4-2 shows a snapshot of the database in Microsoft Excel format. Because there was geo-location information for each crash, the crashes can be displayed on a GIS map as shown in Figure 4-2.

The crash data used in this study was extracted from the GIS database by using a 100 ft buffering area along each of the selected mid-block segments. The crashes occurred within the buffering area along the segment was summed up to give the total number of crashes on the segment. With the total number of crashes counted for each mid-block segment, crash rate was calculated given the segment length and traffic volume obtained for the segment.

Table 4-2 Attribute Table of Crash Data

FID	Shape	AccidentID	County	CollisionID	PrimaryRoa	SecondaryR	Severity	CRCrashTyp	Month	WeekDay	Day	Year
8	Multipoint	0212292086	CLARK	12/29/2003	NELLIS BOULEVARD	CINCINNATI AVENUE	PDO	Other	12	2	29	2003
1	Multipoint	0301011096	CLARK	1/1/2003	MAIN STREET	WYOMING AVENUE	PDO	Other	1	4	1	2003
2	Multipoint	0301060404	CLARK	1/6/2003	SAHARA AVENUE	DECATUR BOULEVARD	PDO	Other	1	2	6	2003
3	Multipoint	0302041686	CLARK	2/4/2003	SPENCER STREET	ST ROSE PARKWAY (N)	Injury	Other	2	3	4	2003
4	Multipoint	030214060	CLARK	2/14/2003	TROPICANA	EDMOND	PDO	Sideswipe Overtaking	2	6	14	2003
5	Multipoint	030214061	CLARK	2/14/2003	BOULDER	TROPICANA	Injury	Rear End	2	6	14	2003
6	Multipoint	0302151199	CLARK	2/15/2003	MESQUITE AVENUE	RANCHO DRIVE	Injury	Other	2	7	15	2003
7	Multipoint	0302151262	CLARK	4/10/2003	RAINBOW BOULEVARD	LAKE MEAD BOULEVARD	Injury	Other	4	5	10	2003
8	Multipoint	0302291028	CLARK	3/29/2003	CHARLESTON BOULEVARD	13TH STREET	Other	Other	3	3	29	2003
9	Multipoint	030302049	CLARK	3/2/2003	FREMONT	LAS VEGAS	Injury	Pedestrian	3	1	2	2003
10	Multipoint	0303021872	CLARK	3/2/2003	US 95 NORTH	FLAMINGO ROAD	PDO	Other	3	1	2	2003
11	Multipoint	030306171	CLARK	3/6/2003	DESERT INN	PARADISE	PDO	Rear End	3	5	6	2003
12	Multipoint	0303141531	CLARK	3/14/2003	RAINBOW BOULEVARD	WESTCLIFF DRIVE	Injury	Other	3	6	14	2003
13	Multipoint	030316	CLARK	3/16/2003	CARSON	9TH	PDO	Angle	3	1	16	2003
14	Multipoint	0303222962	CLARK	3/22/2003	SPEEDWAY BOULEVARD	HOLLYWOOD BOULEVARD	PDO	Other	3	7	22	2003
15	Multipoint	030324230	CLARK	3/24/2003	WASHINGTON	MAGNOLIA	Injury	Angle	3	2	24	2003
16	Multipoint	0303280172	CLARK	4/9/2003	ANN ROAD	MUSTANG STREET	Injury	Other	4	4	9	2003
17	Multipoint	03032821279	CLARK	3/28/2003	MARYLAND	DAKEY	PDO	Sideswipe Overtaking	3	6	28	2003
18	Multipoint	0304100048	CLARK	4/10/2003	FARM ROAD	NO VISTA STREET	Injury	Other	4	5	10	2003
19	Multipoint	0304152349	CLARK	4/22/2003	FLAMINGO ROAD	EASTERN AVENUE	Injury	Other	4	3	22	2003
20	Multipoint	0304250408	CLARK	4/25/2003	FREMONT STREET	15TH STREET	Fatal	Other	4	6	25	2003
21	Multipoint	0304270608	CLARK	4/27/2003	BOULDER HIGHWAY	LAKE MEAD DRIVE	Injury	Other	4	1	27	2003
22	Multipoint	03050810044	CLARK	5/8/2003	BOULDER	MARTIN L KING	Injury	Angle	5	6	8	2003
23	Multipoint	0305081008	CLARK	5/28/2003	CHARLESTON BOULEVARD	VALLEY VIEW BOULEVARD	Injury	Other	5	2	28	2003
24	Multipoint	0306031914	CLARK	6/3/2003	INDUSTRIAL ROAD	OGUENDO ROAD	Injury	Other	6	3	3	2003
25	Multipoint	0306150111	CLARK	6/15/2003	LAS VEGAS BOULEVARD	MANDALAY BAY ROAD	Injury	Pedestrian	6	1	15	2003
26	Multipoint	03062100297	CLARK	6/21/2003	TEE	SAHARA	PDO	Angle	6	7	21	2003
27	Multipoint	030623033	CLARK	6/23/2003	6TH	FRANKLIN	Injury	Angle	6	2	23	2003

In this study, crash rate was used to measure the roadway safety. It is defined as the number of crashes per million vehicles miles travelled (MVMT), and calculated using the formula in Equation (4-1).

$$CR_{seg} = \frac{N}{V_{seg} \times 365 \times L} \times 10^6 \quad (4-1)$$

where: CR_{seg} = crash rate for a mid-block segment (in crashes per MVMT),

N = number of crashes occurred on the segment specific during a time period, a year adopted in this study,

V_{seg} = AADT passing through the mid-block segment, and

L = length of the mid-block segment (in miles).

Because crash rate incorporates the effect of volume and segment length, it is more adequate to measure the crash risk exposed to and perceived by individual drivers than crash frequency which is highly related to the traffic volume (Schultz et al., 2008).

Two approaches can be used to determine the roadway segments to be used as the base to count crashes and derive other data: fixed length or homogeneous segments. By fixed length it implies that the selected roadway segments all have the same length. For the homogenous segment approach, the roadway segments have varied lengths, however the characteristics describing a segment is homogenous. Thus, the use of homogeneous segments may result in very short segments when numerous curves and grades show up on the roadway. Shankar (1997) indicated that using homogeneous segments might also lead to a loss in estimation efficiency due to the potential for heteroscedasticity caused by the selection of segments based on the independent variables in regression models. In contrast, the use of fixed-length segments might result in segments with diverse roadway

characteristics that might require careful consideration during modeling process. In this study the way in which the mid-block segments were chosen is the homogenous segment approaches since the mid-block segments didn't have signalized intersections included in the middle. Two signalized intersections, one at each end, defined a mid-block segment. Thus, the lengths of the segments were not fixed to a same value. Caution was taken in selecting the mid-block segments such that the basic characteristics for a segment were uniform.

4.1.2 Traffic Flow and Travel Speed

The traffic flow and travel speed data in 2003 were obtained from the Regional Transportation Commission (RTC) of Southern Nevada. These data were also in GIS format. Table 4-3 presents a snapshot of this database. The data items included in this database are the segment identification (ID), street name, functional class, segment length, the number of lanes in each direction, posted speed limit, AADT, and travel speed. Note that the segments defined in this database were different from those for this study. They were even shorter than mid-block segments because non-signalized intersections were also used to define segments and were aggregated to mid-block segments defined in this study. Figure 4-3 displays traffic flow data of 2003 with a GIS map.

The travel speed data provided by the RTC were the speed at which a probe vehicle traveled with the traffic on a roadway segment. The probe vehicles traveled along arterials several runs during different time periods. For each run, the travel speed was recorded and the average travel speeds within the segments were then obtained. In this case the travel speeds measured using probe vehicles for different time periods are much

closer to the actual speeds of all the vehicles operating over a roadway segment, and can be better to represent the mobility for this segment. Therefore, it was used in developing the simultaneous equations models in this study. Because the travel speeds within some segments defined in the RTC database were not located between two signalized intersections, the weighted average travel speeds between two signalized intersections were calculated by using segment lengths and travel speeds.

Table 4-3 Attribute Table of Traffic Flow

FID	Shape	ID *	STNAME	FUNCTIONAL	LENGTH	AB_LANES	BA_LANES	AB_POSTEDS	BA_POSTEDS	AB_DAY_FLO	BA_DAY_FLO	TOT_DAY_FI	GR
0	Polyline	23975	FLAMINGO	Minor Arterial	0.37	2	2	35	35	2320.71	2690.93	5011.64	
1	Polyline	20091	SUMMERLIN	Collector	0.02	1	1	55	55	269.81	277.71	547.52	
2	Polyline	23694	CHARLESTON	Major Arterial	0.09	3	3	60	60	1704.06	3037.04	4741.1	
3	Polyline	15179	CHARLESTON	Major Arterial	1.22	2	2	60	60	2125.71	2125.71	4251.43	
4	Polyline	15181	CHARLESTON	Minor Arterial	0.47	1	1	60	60	2125.71	2125.71	4251.43	
5	Polyline	15182	CHARLESTON	Major Arterial	0.2	1	1	60	60	2125.71	2125.71	4251.43	
6	Polyline	6636	CHARLESTON	Major Arterial	0.12	2	2	60	60	2577.93	2566.9	5144.83	
7	Polyline	15176	CHARLESTON	Major Arterial	0.51	2	2	60	60	2566.9	2577.93	5144.83	
8	Polyline	6635	CHARLESTON	Major Arterial	0.06	2	2	60	60	2566.9	2577.93	5144.83	
9	Polyline	6609	CHARLESTON	Major Arterial	0.21	3	3	60	60	1445.97	1744.81	3190.77	
10	Polyline	6608	CHARLESTON	Major Arterial	0.32	2	2	60	60	2566.9	2577.93	5144.83	
11	Polyline	10116	CHARLESTON	Major Arterial	0.08	2	2	60	60	2577.93	2566.9	5144.83	
12	Polyline	6610	CHARLESTON	Major Arterial	0.22	3	3	60	60	1744.81	1445.97	3190.77	
13	Polyline	20092	SUMMERLIN	Collector	0.35	1	1	35	35	269.81	277.71	547.52	
14	Polyline	5485	BUFFALO	Major Arterial	0.17	3	3	45	45	20154.51	25174.11	45328.62	
15	Polyline	5491	LAMB	Major Arterial	0.26	3	3	45	45	25648.16	24270.92	49920.08	
16	Polyline	5497	TORREY PINES	Minor Arterial	0.52	2	2	25	25	12451.29	10775.21	23226.5	
17	Polyline	5537	RAINFALL	Major Arterial	0.14	3	3	45	45	31356.04	34436.47	65793.31	
18	Polyline	5538	MAIN	Minor Arterial	0.16	2	2	30	30	13593	13589.72	27182.73	
19	Polyline	5546	VALLEY VIEW	Minor Arterial	0.12	2	2	35	35	15473.16	13359.24	28832.4	
20	Polyline	5559	BOHANNAN	Minor Arterial	0.09	2	2	35	35	11308.59	9436.31	20744.89	
21	Polyline	5569	RAINBOW	Major Arterial	0.07	3	3	35	35	18601.54	27455.16	46056.69	

Given the travel speed from probe vehicles, the travel speed data that represented mobility for each mid-block segment can be derived from equation (4-2):

$$v = \frac{\sum_{i=1}^n L_i}{\sum_{i=1}^n (L_i / \bar{v}_i)} \quad (4-2)$$

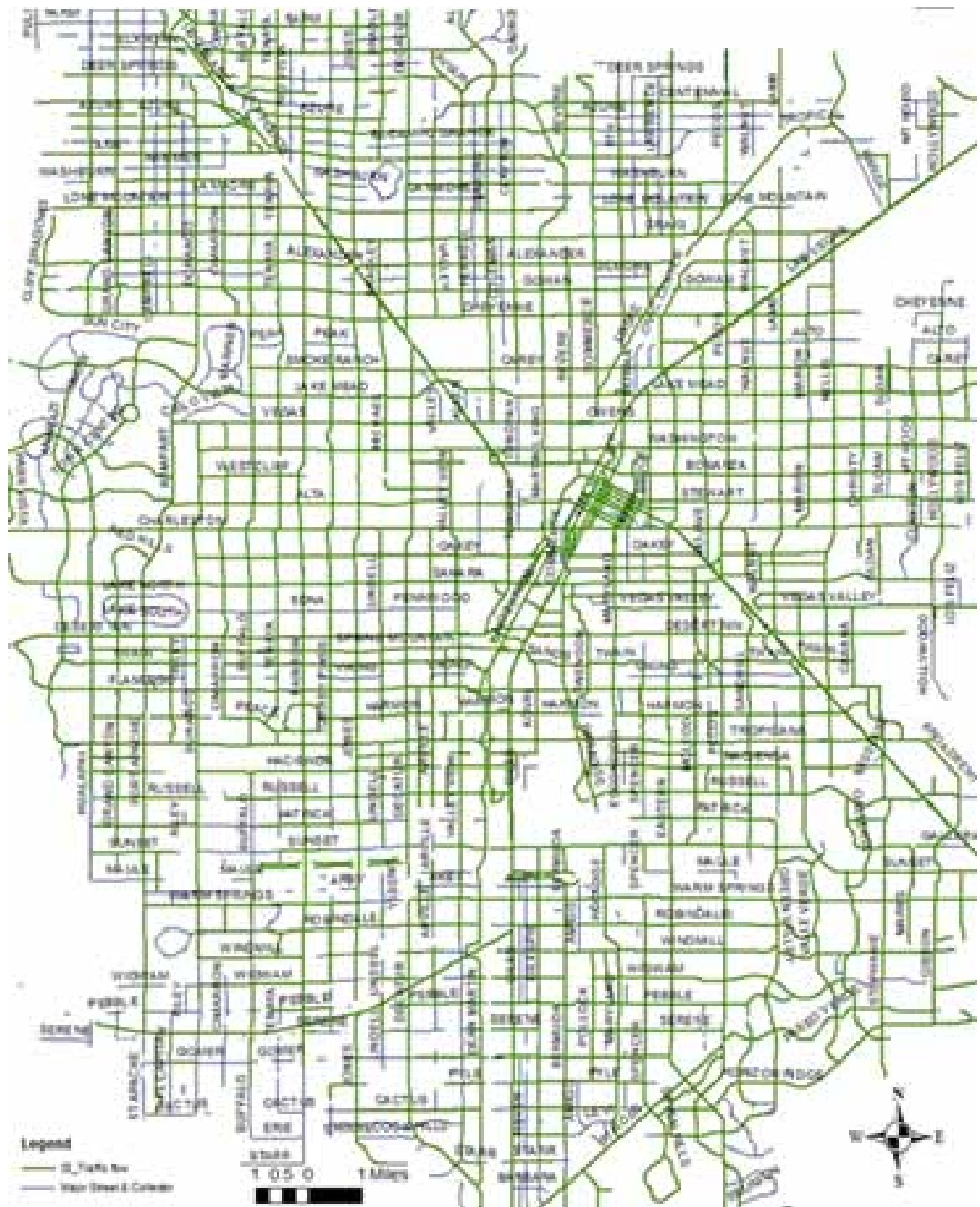


Figure 4-3 Traffic Flow in 2003

where L_i refers to the length of a mid-block segment i and \bar{v}_i denotes the corresponding average speed. The average speed \bar{v}_i for the mid-block segment can be derived from the formula below:

$$\bar{v}_i = \frac{v_i^1 + v_i^2 + \cdots + v_i^n}{n} \quad (4-3)$$

where v_i^n represents the speed measured at different time periods. For different mid-block segments, the number of speed available in the database is different. In theory, the average speed of vehicles for a road segment can be derived by using the following formula:

$$\bar{v}_i = \frac{q_1 v_1 + q_2 v_2 + \cdots + q_n v_n}{q_1 + q_2 + \cdots + q_n} \quad (4-4)$$

where travel speeds are weighted by traffic volumes q_i running through a road segment in different time periods. Because the traffic volume data corresponding to the travel speed in different time periods was not available to this study, the simplified average speeds for a road segment with a road segment as shown in Equation (4-3) was used in this study. In general, the speed of vehicles running through a road segment during peak period is low, while the volume is high. Reflected in Equation (4-4), this situation would cause a low speed highly weighed. Comparing with Equation (4-3) where the speeds in different time periods are equally weighed, the resulting average speeds from Equation (4-4) would be lower than the actual average speeds.

4.1.3 Access Management Features

Field data related to access management techniques along mid-block segments were collected primarily by using Google Earth and certain verification by field observations.

Signal Spacing

Access management related to signal is usually measured using signal density and signal spacing. Signal density is more appropriate to the studies where the basic roadway segments are long and include signalized intersections in between, while signal spacing can be used for both cases where either the roadway segments include signalized intersections or not. Because this study used mid-block segment (no signalized intersection in between) as the base for the evaluation of safety and mobility, segment length was chosen as the measure for access management techniques related to signal spacing. Figure 4-4 shows that segment length is equal to the signal spacing excluding the “400 ft buffering area” that is defined for the effect area of signalized intersections.

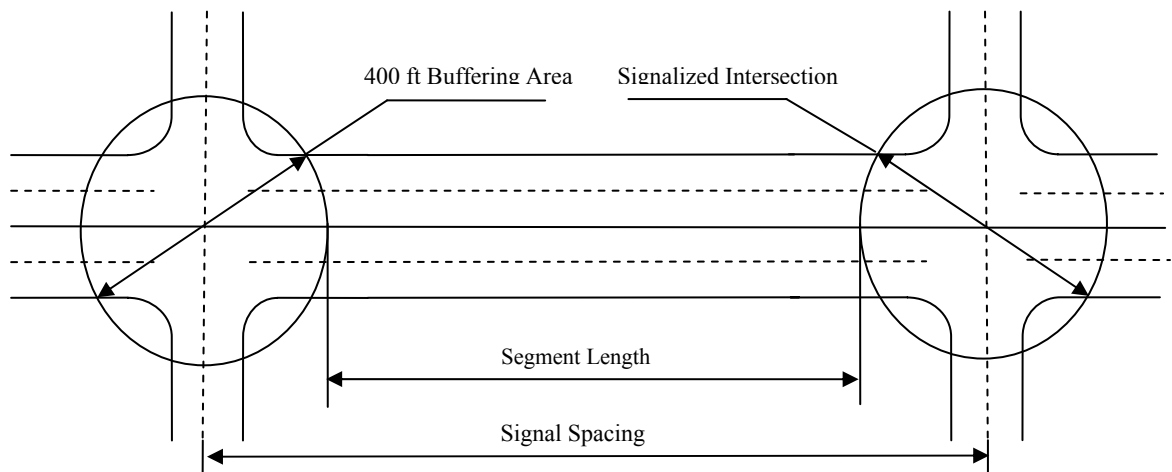


Figure 4-4 Illustration of Segment and Intersection

Unsignalized Access Spacing

The measures for access management techniques related to unsignalized access are access spacing and density. The spacing between access points are the distance between access points, while the density is the number of access point over a distance. The latter one was adopted in this study because the spacing may be hard to derive when there is no or only one driveway on a mid-block segment. To derive the density, the number of driveways and unsignalized median openings on a mid-block segment were counted from Google Earth. Any crossing road on a mid-block segment showing a stop sign or stop bar was counted as an unsignalized intersection; otherwise, it was considered as a driveway. Driveways were counted separately for each direction. Any left-turns to either direction on roadway segment with raised medians were counted as unsignalized median openings. There are cases that raised median is discontinued and TWLTL is used as a replacement within a mid-block segment. Such TWLTL was also counted as unsignalized opening. Given the extracted number of driveway and median opening, their density was derived by dividing them using the corresponding mid-block segment length.

Figure 4-5 shows the driveways and unsignalized median openings on a mid-block segment on West Flamingo Road in Las Vegas, NV. The two circles in the figure stand for the buffering areas around the two intersections. There are four and five driveways in west bound and east bound, respectively. The length of the segment is 0.20 mile. So the driveway density for this mid-block segment is calculated as $4/0.20 = 20$ per mile and $5/0.20 = 25$ per mile correspondingly.

On this segment, it can be seen that the median alternative is raised median, and there is one median opening between the two signals. Thus, the median opening density

is calculated as $1/0.20 = 5$ per mile. Because vehicles can make left turns to either sides from the median, it is counted as two-directional median opening. If vehicles can turn left in only one direction, the median opening is considered as one-directional median opening.



Figure 4-5 Illustration of Driveways and Median Opening

Median Alternatives

Two types of median alternatives were considered in this study: TWLTL and raised medians. When a mid-block segment was selected, the portion of TWLTL and raised medians between two signalized intersections were counted from Google Earth. If only one type of median existed on the segment, the median type for the segment is determined simply as either of the two types that extended through over the entire length.

If both the two median types exist on a mid-block segment, the type that accounts for most part is designated as the median type for the segment.

4.1.4 Data for Roadway Characteristics

In addition to the access management data, the data on roadway functional classification, number of lane, and posted speed limit were collected from the GIS database provided by the RTC.

The data on the land use types (residential, commercial) along the mid-block segments were read from Google Earth based on visual observations and judgments. The number of residential and commercial lands on both sides of a mid-block segment was counted from Google Earth, which was then divided by the segment length to derive the density for these two types of land use for this segment. The size of the land uses was not considered in this study.

4.2 Data Collection for Intersections

In this study, 300 signalized intersections were selected for evaluating the safety performance with regard to corner clearance at intersections. These intersections are actually those at the two ends of mid-block segments for which data were collected for safety analysis in this study. Figure 4-6 displays the locations of these intersections.

Instead of using crash rate data for mid-block segments, crash count data were collected for the identified intersections. Similar to collecting data crash data for mid-block segment where a rectangular buffering zone along the mid-block segments was used, a circular area centered at the middle of an intersection was used as a buffer. All the types of crashes falling in the buffering zone are viewed as those happened at the intersection. The radius of the circle is 400 ft, the longest corner clearance used in the

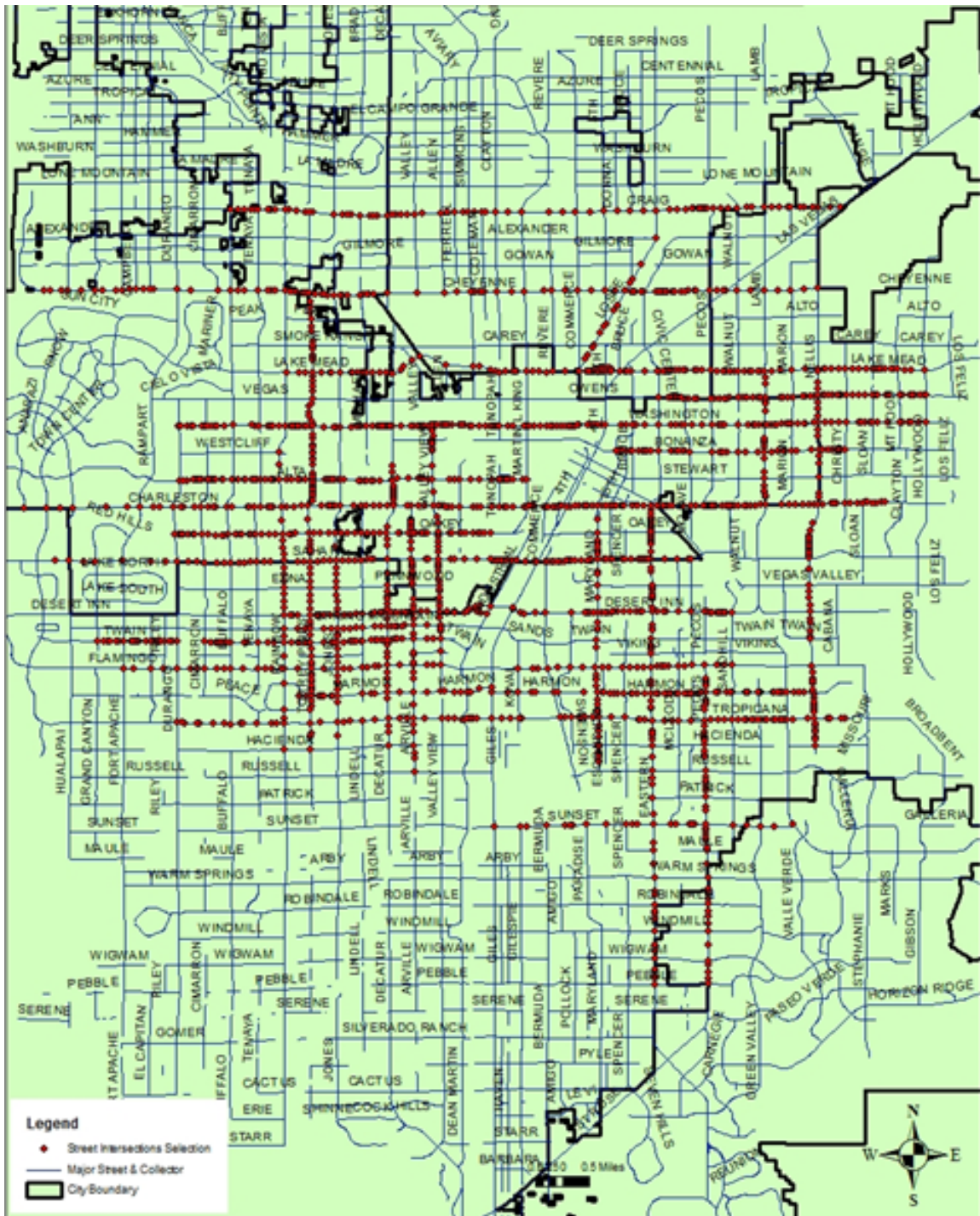


Figure 4-6 Selected Intersections in Las Vegas Area

2003 Access Management Manual. There is a tradeoff about choosing the radius of the circle. If it is too short, the clearance longer than it would not be accurately presented in

the data. Otherwise, crashes happened on the roads in the adjacent lands would be included in the crash counts, which would then produce errors in the analysis. Figure 4-7 shows the circular buffering zone drawn for the intersection on Flamingo Road at Swenson Street. There were 114 crashes in total at this intersection.

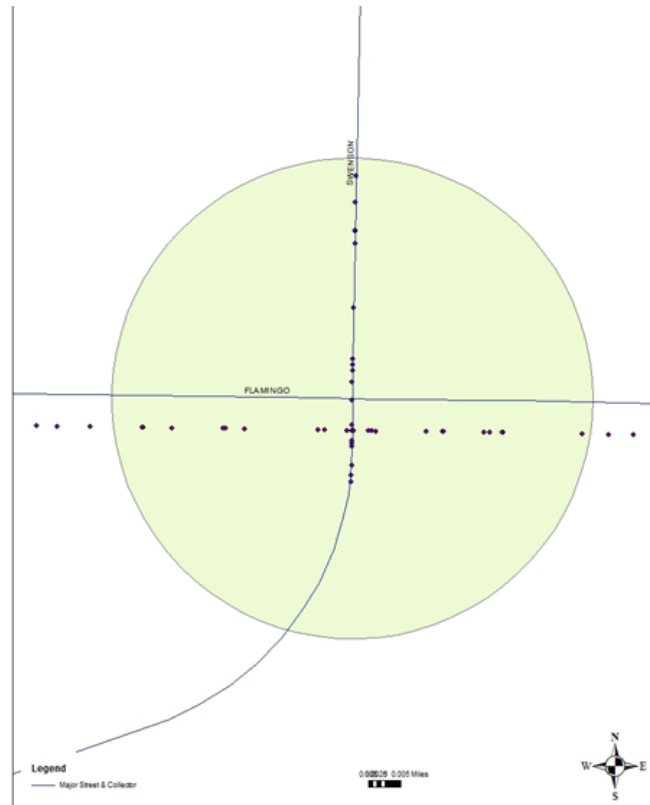


Figure 4-7 Intersection Sample Flamingo Rd. & Swenson

The lengths of corner clearances on each approach at an intersection were measured using Google Earth. Generally if the land use type is commercial around one intersection, more traffic volume could be attracted and more approaches would have driveways. In addition, the lengths of corner clearance for the commercials are shorter than those for the residential areas.

As shown in Figure 4-8 where the signalized intersection at Tropicana Avenue and Rainbow Blvd. is presented, four corner clearance data were collected: one on east bound approach with the length 134.40 ft, one on west bound approach with 86.50 ft long, one on southbound approach with the length of 90.35 ft and the last one on north bound approach with 105.84 ft, so the average length is 104.27 ft. It can be read from the map that there were eight lanes on east-west bound and south-north bound approaches, including the left and right turn lanes.



Figure 4-8 Corner Clearances for Commercial and Residential Land

Similar to the data collection for mid-block segments, land use type data were also collected for the lands adjacent to the corners at intersection. Usually four pieces of lands are divided into by an intersection. Land use type is 1 if all the four parts are commercial and the type is 0 if all the four parts are residential. All the other conditions for the land use value would result in being equal to a number between 0 and 1.

In Figure 4-8, two corners are adjacent with lands of residential nature and the other two are commercial. Then the value for land use is 0.5. It can also be seen that the clearances of corners with commercial land are shorter, while those with residential were longer.

The AADT data collected for the approaches at intersection were specified about their directions: west and east flow for east-west bound, north and south flow for north-east bound.

For each approach, functional classification data were obtained from the GIS database provided by RTC. From the same database, the number of lanes on both directions and the posted speed limit were also extracted. Between the two intersecting roads, which road was the primary and which was the secondary were determined based on the AADT volumes on the roads.

CHAPTER 5

MODEL DEVELOPMENT FOR MID-BLOCK SEGMENTS

5.1 Descriptive Statistics

Descriptive statistics were produced for 395 mid-block segments using the statistical software STATA 9.0. These descriptive statistics are presented below.

1) Crash Rate

Figure 5-1 shows the histogram of crash rate for the mid-block segments. It is calculated that the mean of the crash rate is 24.36, the standard deviation is 16.72, the minimum value is 0.79, and the maximum is 112.1. Note that all the mid-block segments randomly selected all have crashes in this study. Thus, the shape of the histogram looks like a bell shape truncated at the minimum value.

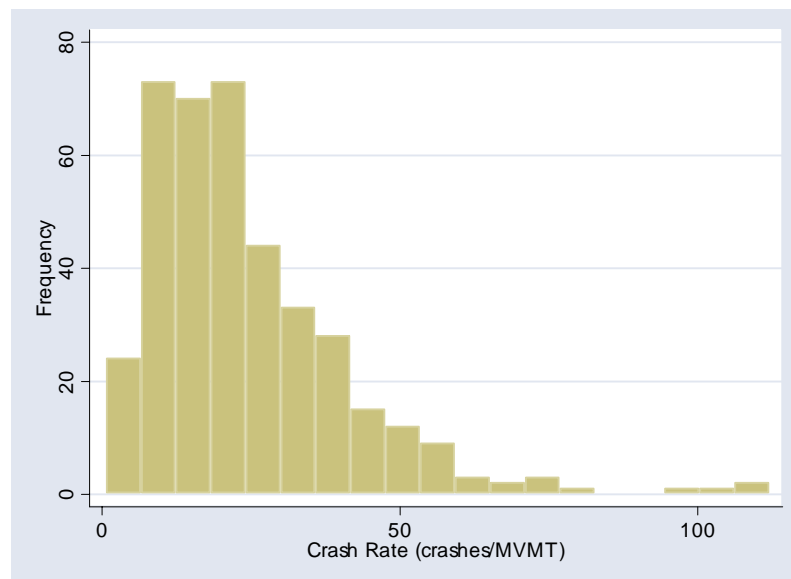


Figure 5-1 Histogram of Crash Rate

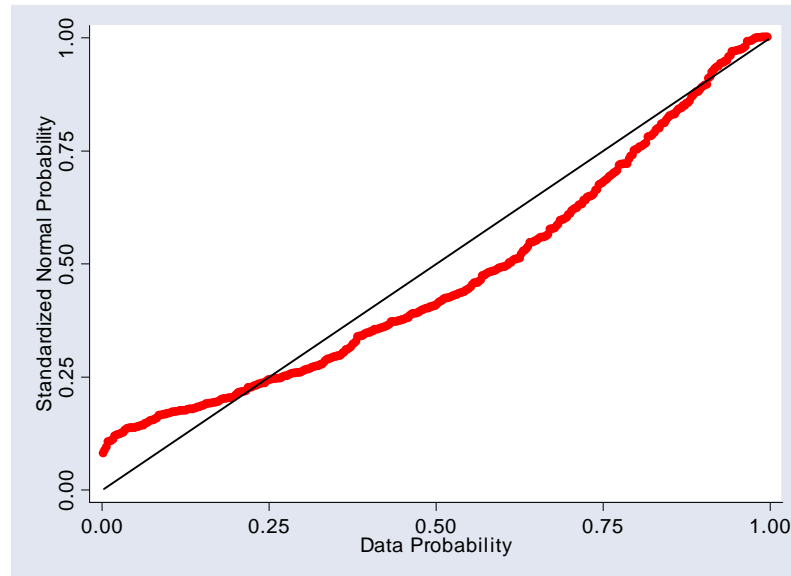


Figure 5-2 Normal Probability Plot of Crash Rate

To test whether the calculated crash rate in Figure 5-1 follows Normal distribution, the plot of data probability against standardized normal probability is shown in Figure 5-2. In this method, the crash data are ordered from the smallest to the largest. If the ordered number for a crash rate is i and the total observation number is N , the probability for the crash rate is calculated as $i / (N+1)$, which enters the x-axis in Figure 5-2; For the same crash rate within a mid-block segment, its z-score is computed as $(\text{crash rate} - \text{mean}) / \text{standard deviation}$, where the mean and standard deviation are derived from the same set of crash rate data. With the z-score calculated, the standardized normal probability can be derived from the z-score table for the crash rate data, which stands for y-axis.

If the crash rate follows Normal distribution, the data points in the figure should be close to the 45-degree straight line. However, the crash rate data show higher

probability before the data probability of 0.25 and lower probability after 0.25, which implies that crash rate is not normally distributed.

In order to make the crash rate follow Normal distribution, the transformation $\ln(\text{crash rate})$ is used to normalize crash rate. As shown in Figure 5-3, the data points with the transformation are very close to the 45-degree straight line, which implies the $\ln(\text{crash rate})$ is normally distributed.

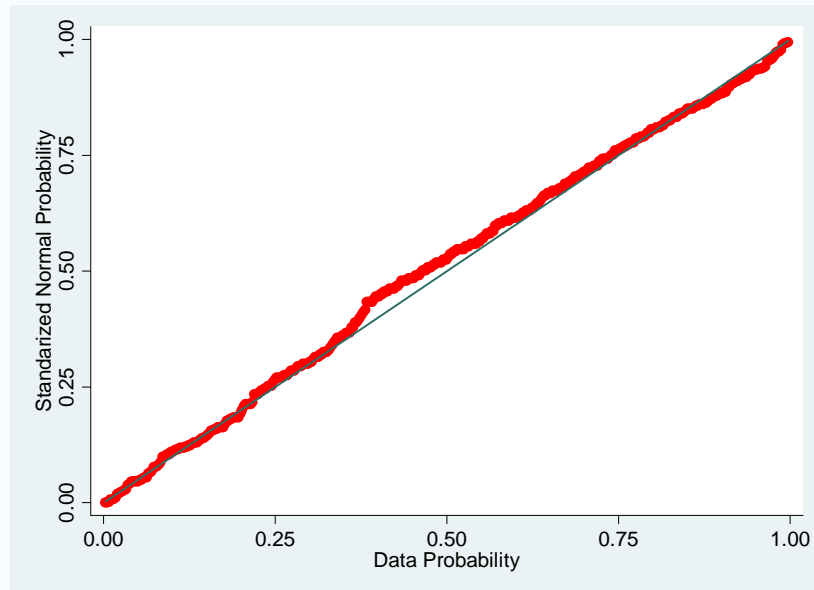


Figure 5-3 Normal Probability Plot of $\ln(\text{Crash Rate})$

2) Travel Speed

A histogram for the average speeds from the same set of mid-block segments as for crash rate is shown in Figure 5-4. The mean of the average speeds is equal to 38.41 mph, and the standard deviation is 4.37. The minimum average speed is 20.36 mph while

the maximum is 43 mph. Figure 5-4 indicates that most of the roadway segments have average speeds over 30 mph. The histogram of the average speeds seems not following Normal distribution, which is further validated from the Normal probability plot in Figure 5-5. It seems reasonable for average speeds to have this frequency distribution and the reasons are as follows. The average travel speeds for each mid-block segment is the average of the speeds that were collected during several time periods on the segment. These speeds representing different time periods may not follow normal distribution. In addition, these speeds may include the travel in the effective area of a boundary intersection that is not part of the mid-block segment as defined in this study. Thus, these speeds may contain errors compared with the speed defined for this study. Furthermore, the histogram includes the average speeds from all the segments which have different posted speed limits. The distribution of these posted speed limits are not supposed to follow the Normal distribution.

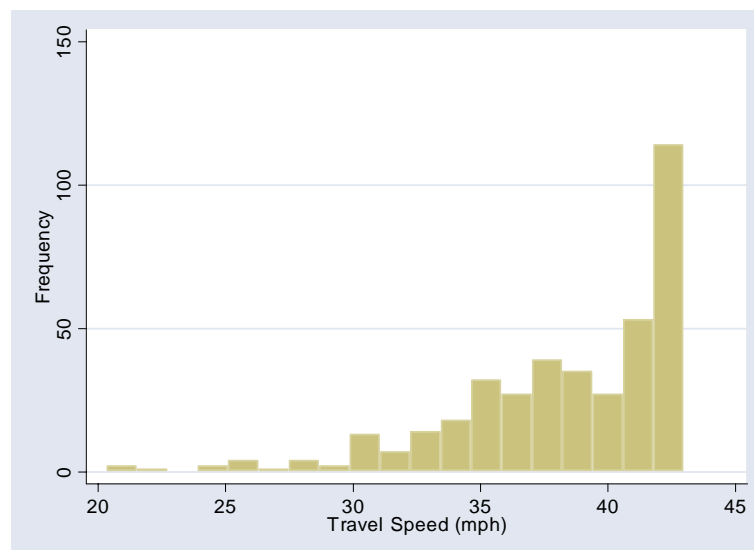


Figure 5-4 Distribution Histogram of Travel Speed

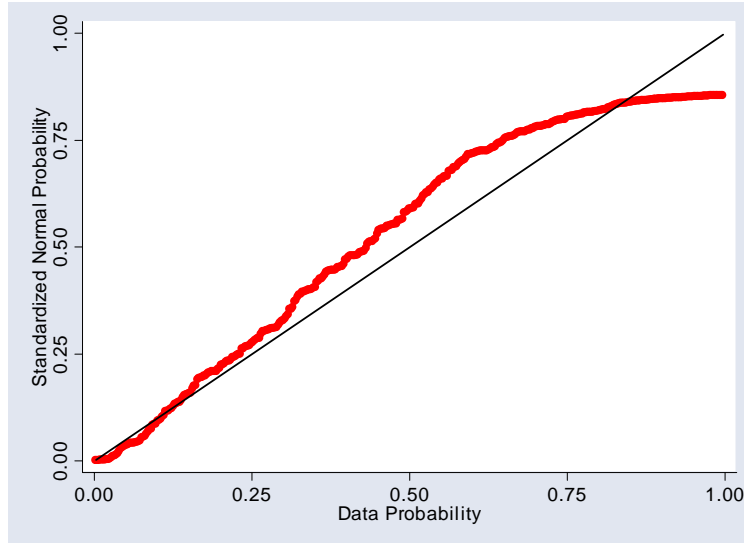


Figure 5-5 Normal Probability Plot of Travel Speed

In order to make the travel speed follow Normal distribution, the transformation formula $|x - \bar{x}| / \sigma$ is used to normalize travel speed, in which x is travel speed, \bar{x} is the mean of the average speeds and σ is the variance of average speeds. As shown in Figure 5-6, most of the data points are close to the 45-degree straight line after the transformation, which implies the transformed travel speed is close to the Normal distribution.

3) Access Management Techniques and Roadway Characteristics

The number of mid-block segments with posted speed limits by median type is shown in Table 5-1. There are 224 and 171 mid-block segments with raised median and TWLTL, respectively. Most of the mid-block segments with raised medians have speed limits of 45 mph, and a significant number of roadway segments with TWLTLs has speed limit of 35 mph. It was calculated that the average speed limits were 42 mph and 30 mph

for mid-block segments with raised median and TWLTL, respectively. The observation is consistent with the application requirements of these two median types.

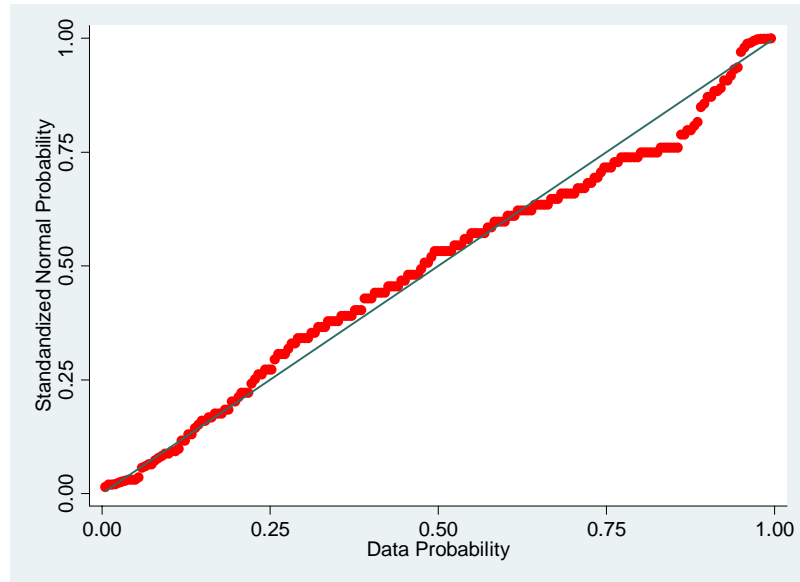


Figure 5-6 Normal Probability Plot of Transformed Travel Speed

Table 5-1 Frequency of Posted Speed Limit by Median Type

Posted Speed (mph)	Raised Median		TWLTL		All
	Number	Percentage	Number	Percentage	
30	3	1.34	7	4.09	10
35	40	17.86	70	40.94	110
40	4	1.79	2	1.17	6
45	177	79.02	92	53.80	269
Total	224	100	171	100	395

The range of those variables describing the segments by median type is shown in Table 5-2. It can be seen that AADT on the roadway with raised medians is higher than those with TWLTLs and the average length of mid-block segments and driveway density for both raised medians and TWLTLs are close.

Table 5-2 Range of Continuous Variables by Median Type

Items	Value	Raised Median	TWLTL	All
N		224	171	395
AADT	Minimum	7,936	494	494
	Average	46,883	35,858	41,370
	Maximum	89,041	73,936	89,041
Mid-block Segment Length (ft)	Minimum	338.21	369.60	316.80
	Average	2164.80	2323.20	2244.00
	Maximum	5544.00	5385.60	5544.00
	Std. Dev.	1007.95	1014.15	102.71
Driveway Density (number of driveways per segment, both sides)	Minimum	0.00	0.00	0.00
	Average	34.80	34.42	34.61
	Maximum	95.78	95.07	95.78
	Std. Dev.	19.69	18.56	1.94
Median Opening Density(number of median openings per segment)	Minimum	0.00	-	-
	Average	5.22	-	-
	Maximum	13.89	-	-
	Std. Dev	2.91	-	-
Full-access Median Opening Density (number of full-access median openings per segment)	Average	5.73	-	-
Two-directional Median Opening Density (number of two-directional median openings per segment)	Average	2.91	-	-
One-directional Median Opening Density (number of one-directional median openings per segment)	Average	1.81	-	-
Commercial Land Density (number of patches of commercial lands per segment, both sides)	Minimum	0.00	0.00	0.00
	Average	27.20	20.89	24.04
	Maximum	71.83	87.22	87.22
	Std. Dev	16.33	16.01	

Among the 395 mid-block segments sampled in this study, there were 241 that contained the raised medians and 171 that were TWLTLs. AADT on the roadway with raised medians was higher than those with TWLTLs. The average lengths of these two types of roadway segments with raised median and TWLTLs were 2,164 and 2,323 ft, respectively. Their average lengths seemed very close.

From Table 5-2, it can also be seen that the driveway density on these roadway segments with raised medians and TWLTLs are also similar: 34.80 and 34.42 per mile.

On average, there are about five median openings on the roadway segments with raised median. At maximum, there were about 14 median openings per mile on a mid-block segment, which is quite significant. Median openings were classified into full access, two-directional, and one-directional. The average densities for the three types were 5.73, 2.91 and 1.81, respectively, which showed that there were more full access median openings than the other two types. However, which type of median opening density is significant to influence the crash occurrence needs to be investigated.

The average commercial land density with raised medians was a little higher than with TWLTLs, although TWLTLs had the maximum value. Table 5-2 also indicated that the land along the sampled mid-block segments with raised median was more likely to be commercial than residential.

5.2 Relations between Crash Rate and Related Variables

Analysis of total crash rate and crash rate by median type for the identified access management techniques in this study are described below.

1) Crash Rate vs. Mid-block Segment Length

Plot of crash rate by median type versus distance between two signalized intersections that are at the two ends of a mid-block segment is shown in Figure 5-7. It can be distinctly observed that there are two clusters of the mid-block segments that have lengths around 1,500 and 2,500, respectively. This pattern might be consistent with the design of old and new urban areas. The mid-block segments in the old urban areas were

shorter than those in the new areas. The selected arterials run through these two typical areas. It can be seen from Figure 5-7 that when the longer the mid-block segments, the fewer crashes would occur. The crash rate is at two different levels for the distances longer or shorter than 3,000 ft. The crash rate for the mid-block segments with TWLTL seems higher than those with raised medians.

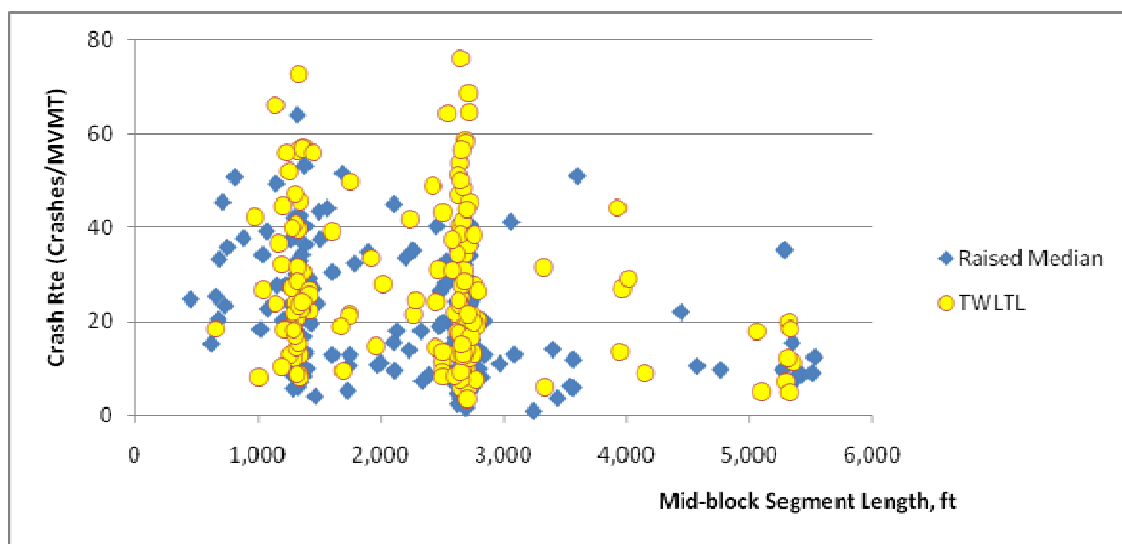


Figure 5-7 Plot for Crash Rate vs. Mid-block Segment Length

2) Crash Rate vs. Driveway Density

The relationship between crash rate and driveway density is presented in Figure 5-8. It can be seen that as the driveway density increased, the crash rate for two median types increased correspondingly, but the crash rate on mid-block segments with TWLTLs were higher than those with raised medians when the density was above 60 driveways per

mile. In addition, there were some mid-block segments where there were no driveways on either side of the road, for which the driveway density was defined as zero.

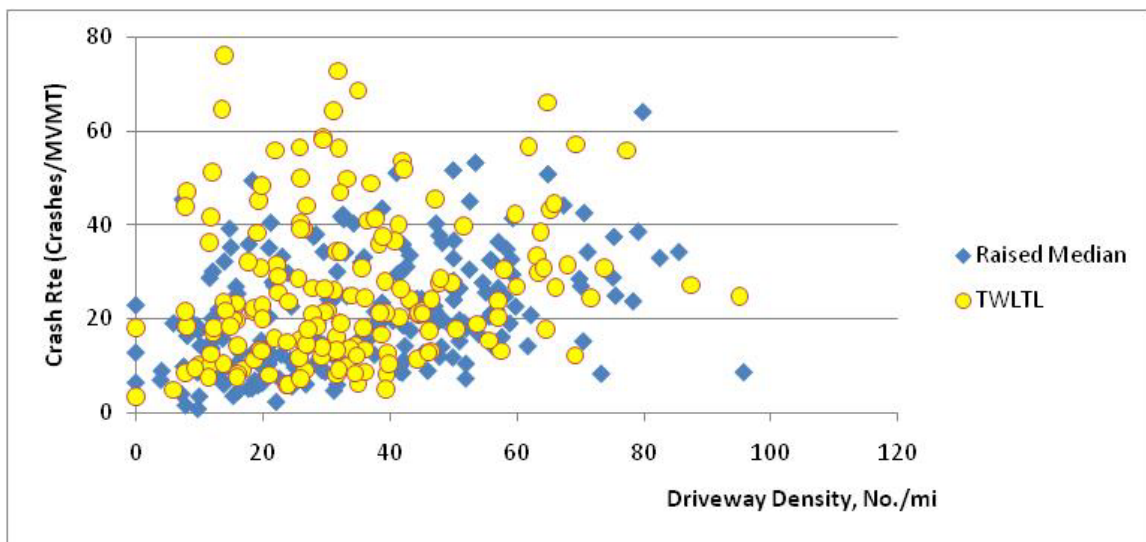


Figure 5-8 Scatter Plot for Crash Rate vs. Driveway Density

3) Crash Rate vs. Median Opening Density

Figure 5-9 presents the rate of crashes versus the density of median openings. Note that the median openings only exist on segments with raised medians. The mid-block segments with TWLTLs can be assumed to have “zero” or “infinite” number of median openings. It can be found from Figure 5-9 that most of mid-block segments had less than eight median openings, for which their crash rate seemed to be at the same level. The crash rate seemed lower for the segments that had more than eight openings.

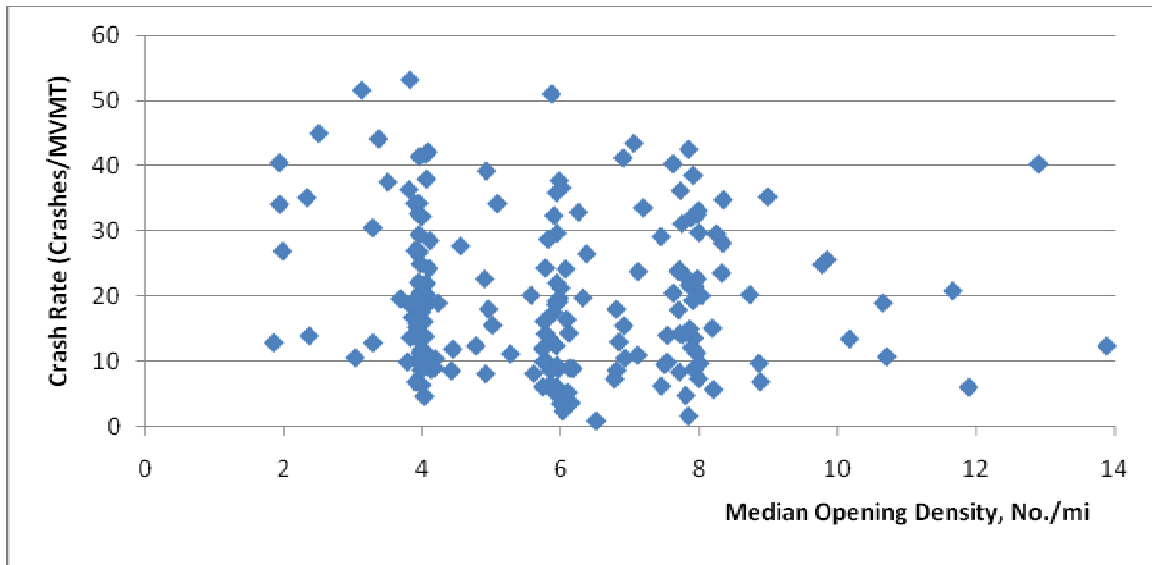


Figure 5-9 Scatter Plot for Crash Rate vs. Median Opening Density

4) Crash Rate vs. Commercial Land Density

To observe the relationship between crash rate and land use along the mid-blocks segments, the crash rate versus commercial land density are plotted in two different ways with distinction of median type, and each is shown in Figure 5-10 and Figure 5-11, respectively. Figure 5-10 indicates that the crash rate generally increased with more portions of lands was used for commercial purposes on a mid-block segment. From Figure 5-11 it can be further identified that crash rate was relatively higher for mid-block segments with TWLTL as a median when the commercial land use density was small. When the commercial land use density was large, there seemed to be no distinction regarding these two types of mid-block segments with either raised medians or TWLTLs.

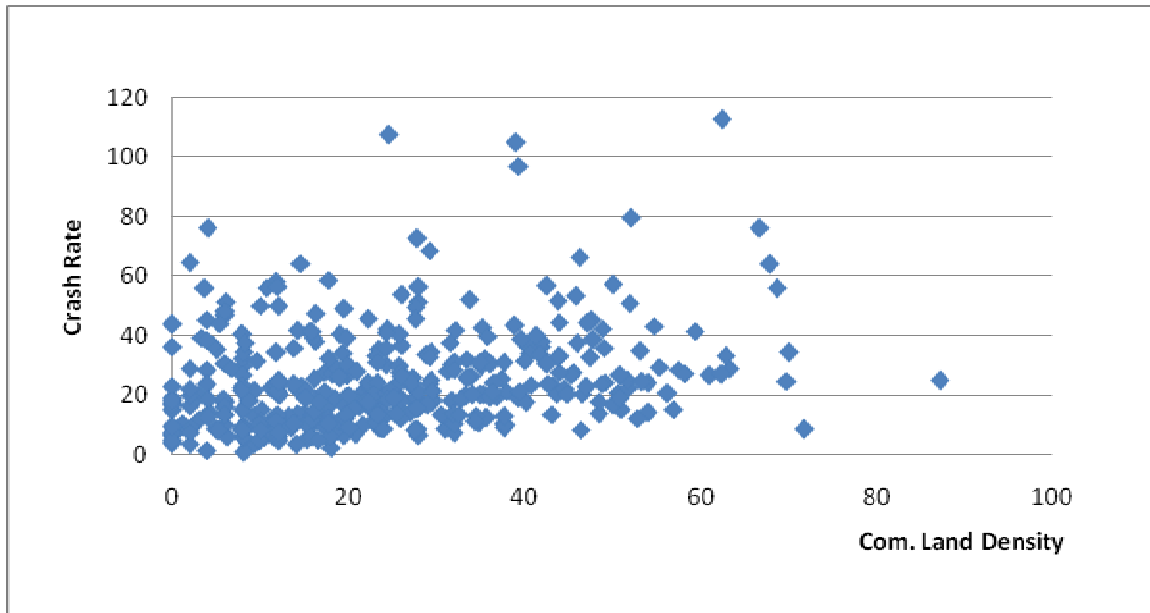


Figure 5-10 Scatter Plot for Total Crash Rate vs. Commercial Land Density

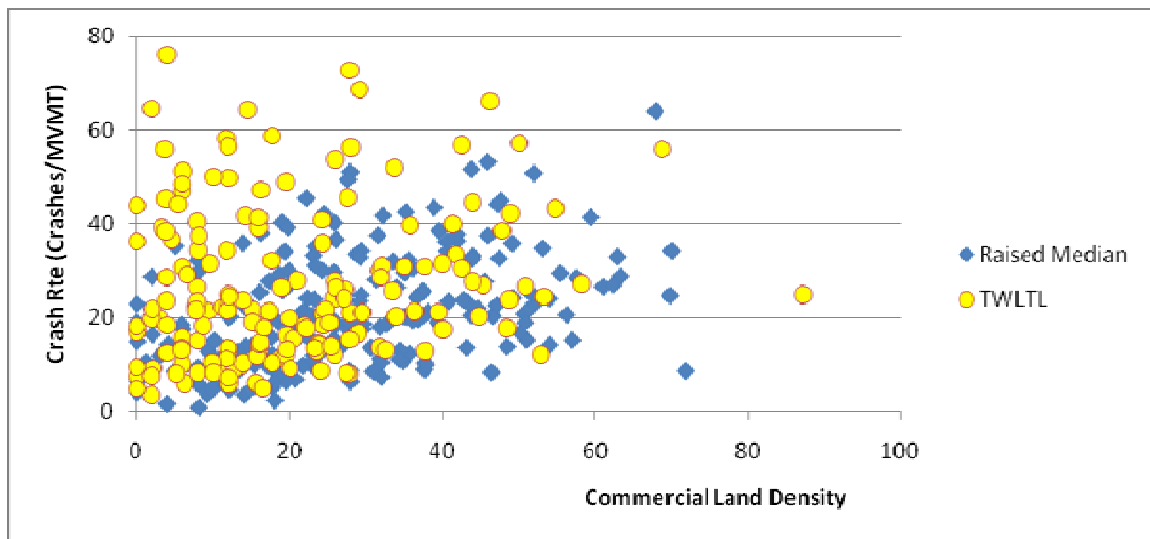


Figure 5-11 Scatter Plot for Crash Rate and Commercial Land Density by Median Type

5) AADT

Because raised medians and TWLTLs are recommended for different types of mid-block segments with different roadway classifications, the AADT on the roadway segments of two median types are plotted in Figure 5-12. It can be seen that AADTs

spread in different ranges for the two median types. For raised medians, AADT was averaged at 46,883, while for TWLTLs it is averaged around 35,858.

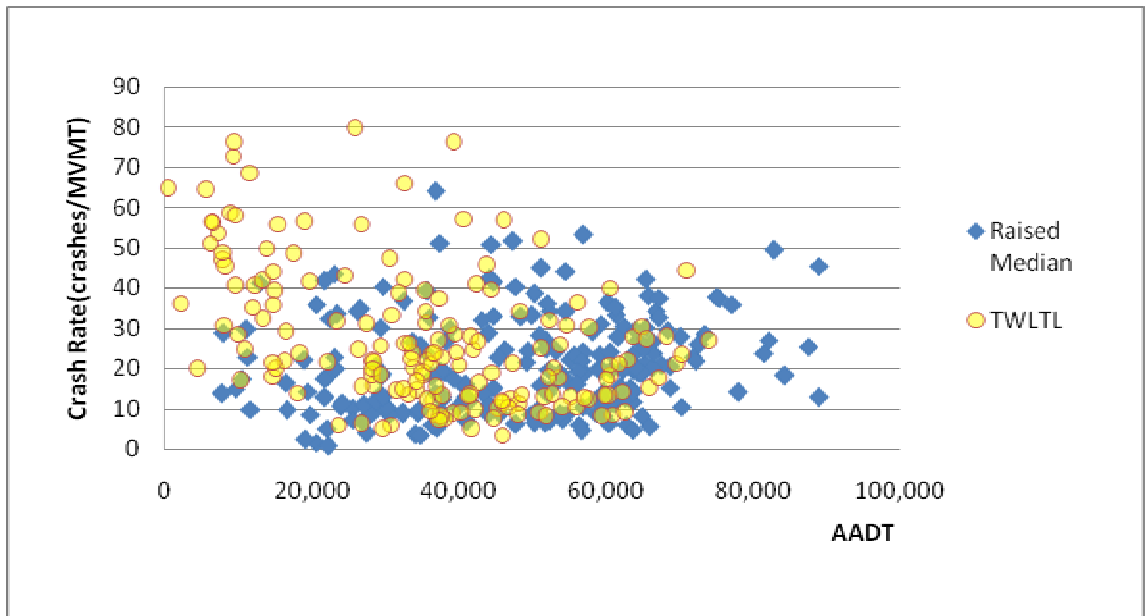


Figure 5-12 Scatter Plot for Crash Rate and AADT by Median Type

The relationship between the crash rate data and AADT data is also presented in Figure 5-13. It can be seen that there is a turning point around 30,000 vehicles, which is consistent with the studies before, i.e., when AADT reaches some point, TWLTL is replaced with raised median.

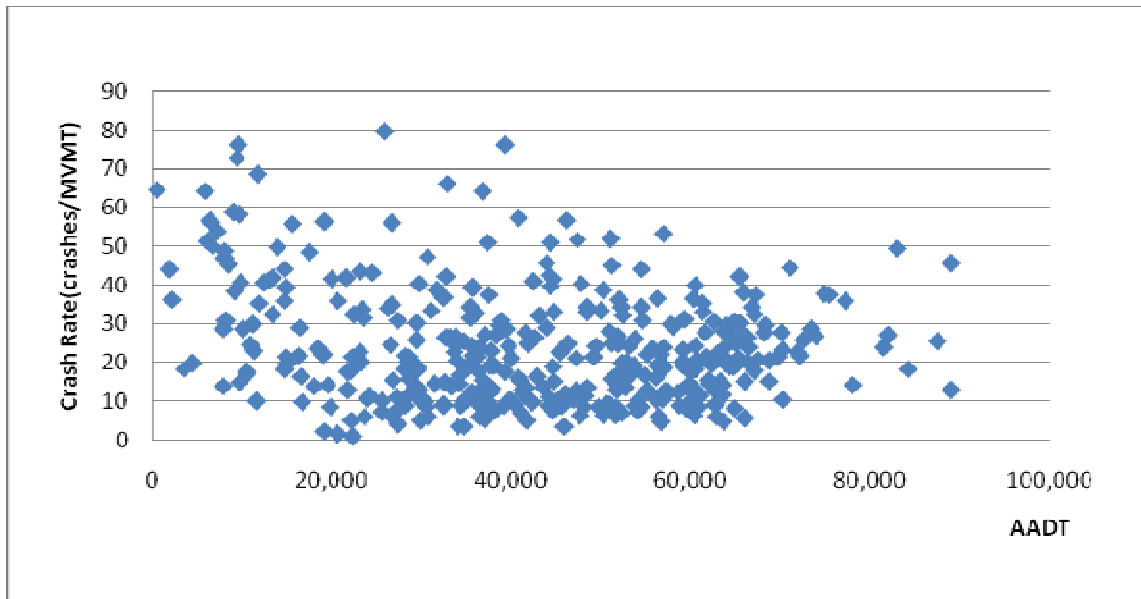


Figure 5-13 Scatter Plot for Crash Rate and AADT

5.3 Relations between Travel Speed and Related Variables

1) Travel Speed vs. Distance between Signalized Intersections

The data of travel speed versus the distance between signalized intersections are plotted, as shown in Figure 5-14. It can be observed that most of the mid-block segments were shorter than 3,000 ft and their travel speeds were above 25 mph. Two clusters of mid-block segments are shown in this figure, one for old urban areas with short segments, and the other for the new area toward the outskirts of urban areas with long segments. There were no obviously different speed patterns between mid-block segments with raised medians and TWLTLs.

2) Travel Speed vs. Driveway Density

The relationship between travel speed and driveway density by median type is shown in Figure 5-15. It can be seen from the figure that the travel speed was mainly

located between 20 to 60 driveways per mile. As the driveway density increased, the travel speed reduced a little. The trend of change is not obvious.

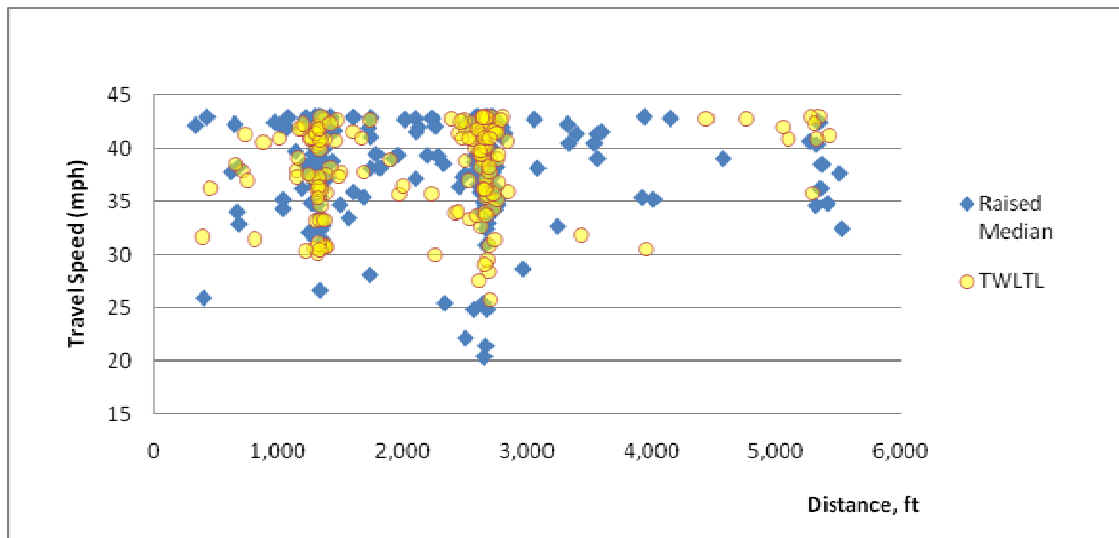


Figure 5-14 Scatter Plot for Travel Speed with Mid-block Segment Distance

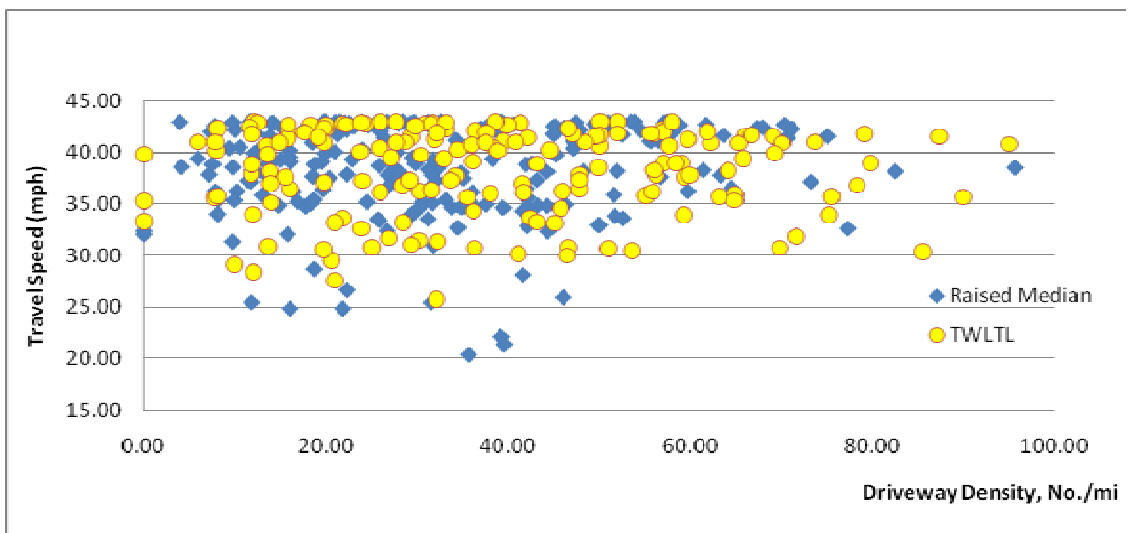


Figure 5-15 Scatter Plot for Travel Speed with Driveway Density

3) Travel Speed vs. Median Opening Density

Figure 5-16 shows the distribution of travel speed with median opening density. The travel speed mainly focused on four, six and eight median openings per mile. These median openings included all three types. No clear pattern between travel speed and median opening density is observed.

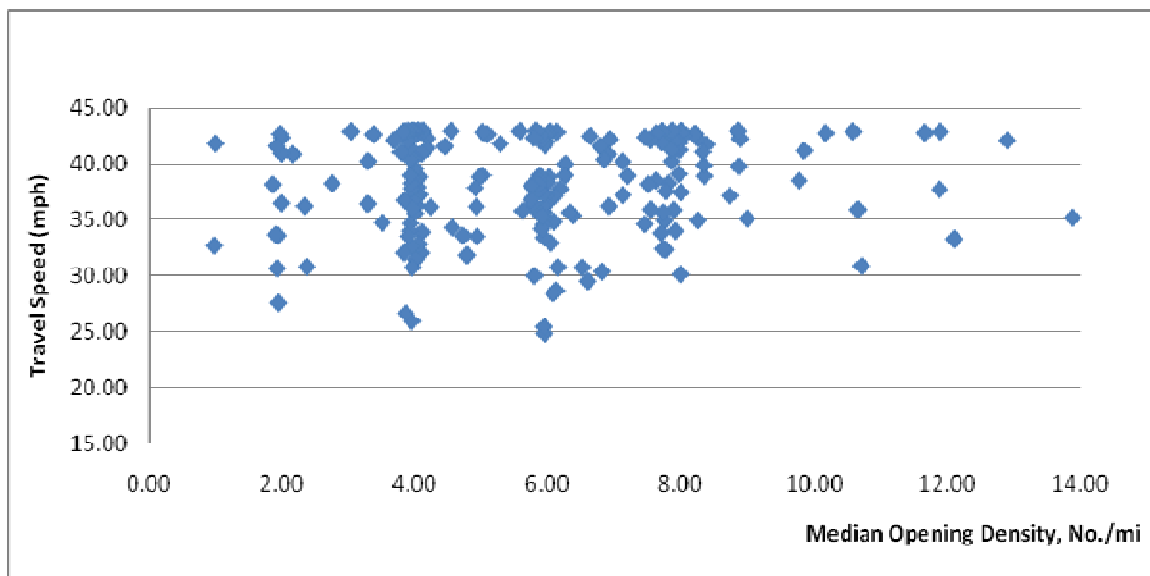


Figure 5-16 Scatter Plot for Travel Speed with Median Opening Density

4) Travel Speed vs. Commercial Land Density

Relationship between travel speeds with commercial land density by median type is shown in Figure 5-17. The trend shows that as the commercial land density increased, the travel speeds reduced. The travel speeds on TWLTLs reduced more than those on raised medians.

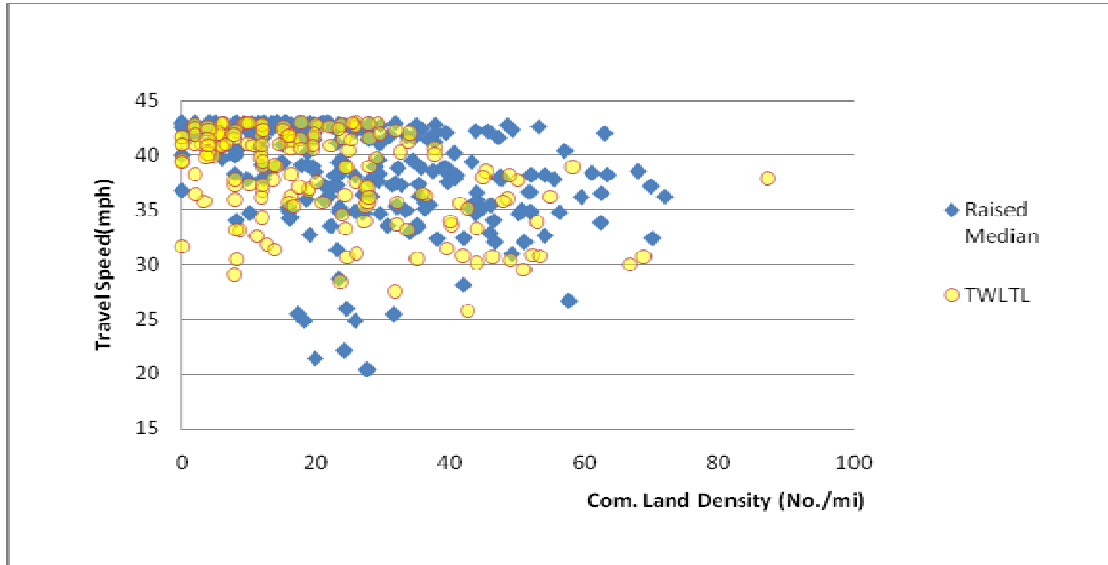


Figure 5-17 Scatter Plot for Travel Speed with Commercial Land Density

5.4 Panel Data Simultaneous Equations Models

5.4.1 Variables Selection

Simultaneous equations models include two equations: one for crash rate, and the other for travel speed. Crash rate and travel speed are endogenous variables. The variables that represent the access management techniques for mid-block segments are mid-block segment length (equivalent to the distance between signalized intersections), driveway density, median type, and median openings density. In addition, land use, AADT and roadway characteristics were included as exogenous variables in these two equations.

In this study, the length of mid-block segments is the distance between two consecutive signalized intersections excluding the short part that defines the effective area of intersections. Previous studies indicated that shorter length of segments tended to

increase crash occurrence. Thus, segment length was included as one of the exogenous variables.

Driveway density measured as the number of driveways per mile was included as one of exogenous variables since previous studies showed that more driveways within a fixed distance of roadway would lead to more conflicts between the turning and through vehicles.

Between the two median types, raised medians and TWLTLs, previous studies indicated that road segments with raised medians were associated with fewer crashes. Thus, a variable with value “1” for raised median and “0” for TWLTL was included as one of exogenous variables.

Median opening density was also included in the model for representing the spaces between median openings. This variable was only applied to the roadway segments that were raised medians. Previous studies indicated that more crashes would occur on roadways with more median openings because more conflicts between traffic either in one direction or from two directions were generated. Moreover, the types of median openings determine the amount and nature of conflicts. Different median opening types of one-directional, two-directional or full access produce different conflicting points, and lead to varying impact on safety and mobility.

Traffic volume is a measure of exposure to roadway crashes. Intuitively, more crashes tend to occur when more traffic is on the roads. Thus, as many previous studies included this variable for analysis, it was also considered in this study.

The safety impact of access management techniques vary with the types of land use on sides of mid-block segments. Commercial lands attract traffic with drivers of

different familiarity to the adjacent areas. The traffic composition attracted to commercial lands may be more diverse than that to residential areas. The traffic to these two types of lands may have different peaks. As a result, given a fixed number of access, these land use types may show different influences on safety.

The posted speed limit is typically associated with many of the roadway characteristics and geometric design. Correlation between access management techniques and the posted speed limit is expected due to the application of design standards and guidelines.

One of the roadway characteristics is number of lanes, which is critical to the safety. The more the number of lanes, the more traffic flow, leading to more crashes.

Table 5-3 provides the description of these variables used in the modeling. The correlation coefficients of these variables are listed in Table 5-4.

Table 5-3 Variable Description

Abbreviation	Variable Description
LNCR	Ln (crashes per million vehicles miles travelled)
AVGSP	Average travel speed, mph
SEGLN	Mid-block segment length, mi
DWDEN	Driveway density, number of driveways per mile
MEDTYP	1 is for raised median dominating in a mid-block segment, otherwise 0
FULACEDEN	Full access median opening density, number of full access median openings per mile
TWODIRDEN	Two-directional median opening density, number of two-directional median openings per mile
ONEDIRDEN	One-directional median opening density, number of one-directional median openings per mile
RESDEN	Residential land density, number of residential lands per mile
COMDEN	Commercial land density, number of commercial lands per mile
POSTSP	Posted speed limit, mph
AADT	Annual Average Daily Traffic
NOLN	Number of lanes on a mid-block segment

Table 5-4 Correlation Matrix of the Variables

	CR	AVGSP	SEGLN	DWDEN	MEDTYP	FULACEDE N	TWODIRDE N	ONEDIRDE N	RESDEN	COMDEN	POSTSP	AADT	NOLN
CR	1.000												
AVGSP	-0.200	1.000											
SEGLN	-0.295	0.405	1.000										
DWDEN	0.275	-0.356	-0.290	1.000									
MEDTYP	-0.171	0.013	-0.067	0.010	1.000								
FULACEDEN	-0.167	0.045	0.111	0.092	0.390	1.000							
TWODIRDEN	-0.189	0.143	0.178	0.002	0.469	-0.005	1.000						
ONEDIRDEN	-0.007	0.060	-0.045	0.011	0.423	-0.027	-0.029	1.000					
RESDEN	-0.035	0.133	0.200	-0.098	-0.349	-0.026	-0.102	-0.128	1.000				
COMDEN	0.272	-0.369	-0.436	0.831	0.190	0.095	-0.030	0.117	-0.463	1.000			
POSTSP	-0.191	0.108	0.089	0.021	0.275	0.119	0.127	0.075	-0.091	0.072	1.000		
AADT	-0.215	-0.584	-0.304	0.298	0.287	0.120	0.034	0.111	-0.269	0.380	0.242	1.000	
NOLN	-0.070	-0.220	-0.177	0.231	0.311	0.120	0.070	0.124	-0.275	0.348	0.406	0.635	1.000

5.4.2 Model Results

The random coefficient simultaneous equations models were developed using the statistical software STATA. At first, full models that included all the variables listed in Table 5-3 were developed. Table 5-5 displays the results of the full model. By removing those variables that were not significant statistically, the models were finalized with the results listed in Table 5-6.

The DWH test was applied to examine the endogeneity between crash rate and travel speed. For the DWH test, the null hypothesis is that parameters estimated without controlling for endogeneity are consistent. Table 5-7 shows the results for the endogeneity test. For the crash rate model, because the DWH test statistic (15.65) is greater than the critical value (12.6, d.f.=8, $p=0.05$), the null hypothesis is rejected at the 95% significance level. Therefore, it is concluded that parameters estimated without controlling for endogeneity are inconsistent, implying that independent variables are endogenous. Similarly, the test result for the travel speed model also shows that independent variables are endogenous since the test statistic (84.16) is much greater than the critical value (9.49, d.f.=5, $p=0.05$).

With the model developed, the assumptions made for the simultaneous equations models were evaluated. For the crash rate model, residuals and the predicted value of logarithmic transformation $\text{Ln}(\text{crash rate})$ were calculated and plotted in Figure 5-18. It can be seen from the figure that the residuals are randomly distributed around the zero value along the axis for the predicted crash rate. This pattern indicates that there is no heteroscedasticity in the assumed error terms.

Table 5-5 Results for the Models with All Variables Included

Variables	Estimated Coefficient	Std. Error	z- statistic
Crash Rate Model			
AVGSP	0.042	0.009	4.410
SEGLN	-0.648	0.163	-3.980
DWDEN	0.007	0.003	2.150
MEDTYP	-0.113	0.094	-1.210
FULACEDEN	-0.022	0.023	-0.950
TWODIRDEN	-0.037	0.020	-1.810
ONEDIRDEN	0.017	0.012	1.360
RESDEN	0.000	0.005	-0.050
COMDEN	0.006	0.004	1.430
POSTSP	0.000	0.008	0.040
AADT	-0.018	0.003	-6.300
NOLN	0.214	0.042	5.060
CONST	4.100	0.464	8.830
Number of Observations	395		
Number of groups	27		
Chi square (7)	192.63		
R square	0.344		
Travel Speed Model			
LNCR	-1.144	0.265	-4.320
SEGLN	0.272	0.878	0.310
DWDEN	-0.005	0.017	-0.270
MEDTYP	-0.684	0.494	-1.380
FULACEDEN	0.238	0.120	1.980
TWODIRDEN	0.243	0.107	2.260
ONEDIRDEN	0.190	0.065	2.920
RESDEN	-0.019	0.029	-0.650
COMDEN	-0.014	0.024	-0.580
POSTSP	0.234	0.041	5.710
AADT	-0.175	0.014	-12.980
NOLN	0.763	0.229	3.330
CONST	35.567	2.017	17.630
Number of Observations	395		
Number of groups	27		
Chi square (5)	336.40		
R square	0.536		

Table 5-6 Random Coefficient Simultaneous Equations Model Results

Variables	Estimated Coefficient	Std. Error	z- statistic
Crash Rate Model			
AVGSP	0.042	0.009	4.72
SEGLN	-0.714	0.152	-4.68
DWDEN	0.005	0.003	2.16
MEDTYP	-0.216	0.068	-3.16
ONEDIRDEN	0.027	0.011	2.44
COMDEN	0.008	0.003	2.43
AADT	0.018	0.003	6.20
NOLN	0.224	0.416	5.39
CONST	4.109	0.429	9.59
Number of Observations	395		
Number of groups	27		
Chi square (8)	187.37		
R square	0.329		
Travel Speed Model			
LNCR	-1.456	0.231	-6.31
ONEDIRDEN	-0.120	0.055	-2.21
POSTSP	0.234	0.039	5.89
AADT	-0.184	0.012	-14.85
NOLN	0.775	0.227	3.41
CONST	36.386	1.922	18.93
Number of Observations	395		
Number of groups	27		
Chi square (5)	327.45		
R square	0.520		

Table 5-7 Results for Endogeneity Test

Endogeneity Test		
H ₀ : Parameters estimated without controlling for endogeneity are consistent.		
H ₁ : Parameters estimated without controlling for endogeneity are inconsistent.		
	DWH Test Statistic	Critical Value
Crash Rate Model	15.65	12.6 (d.f.=8, p=0.05)
Travel Speed Model	84.16	9.49 (d.f.=6, p=0.05)

Note: Crash rate model is used to test for the endogeneity of travel speed, while travel speed model is used to test for the endogeneity of crash rate.

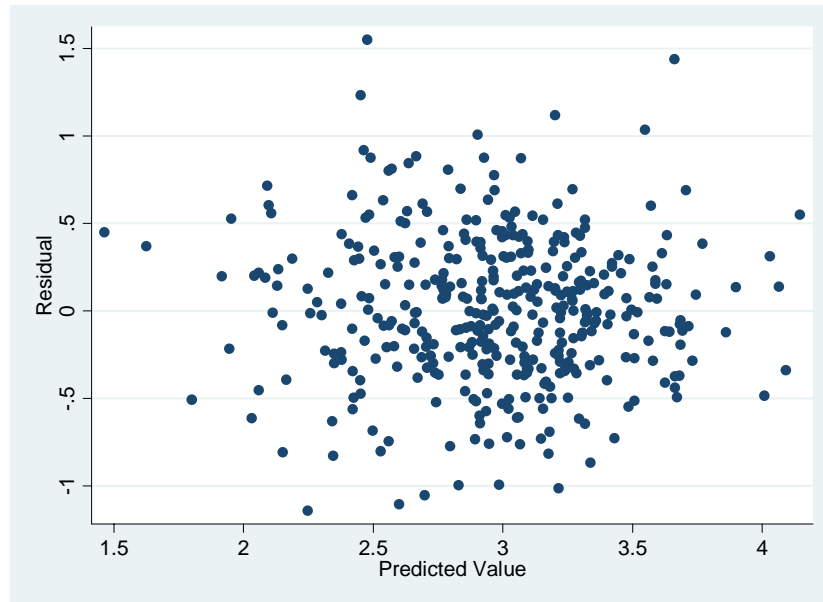


Figure 5-18 Residual Plot of the Ln (crash rate)

The normal probability graph for the estimated versus observed crash rate was developed and displayed in Figure 5-19. It can be found from the figure that although there are several outliers, most of the data are distributed along the 45-degree line evenly, which implies that the residuals follow normal distributions.

To verify whether there is linear relationship between the dependent and independent variables, plots showing the relationships between the residuals and each of the independent variables were developed in this study and presented in Figures 5-20 to 5-26. From these figures, no nonlinear relationship was found for the relationships between the independent and dependent variables. Given the pattern shown in Figure 5-18 and the observations from Figures 5-20 to 5-26, it is concluded that there is no nonlinear relationship between the crash rate and the independent variables.

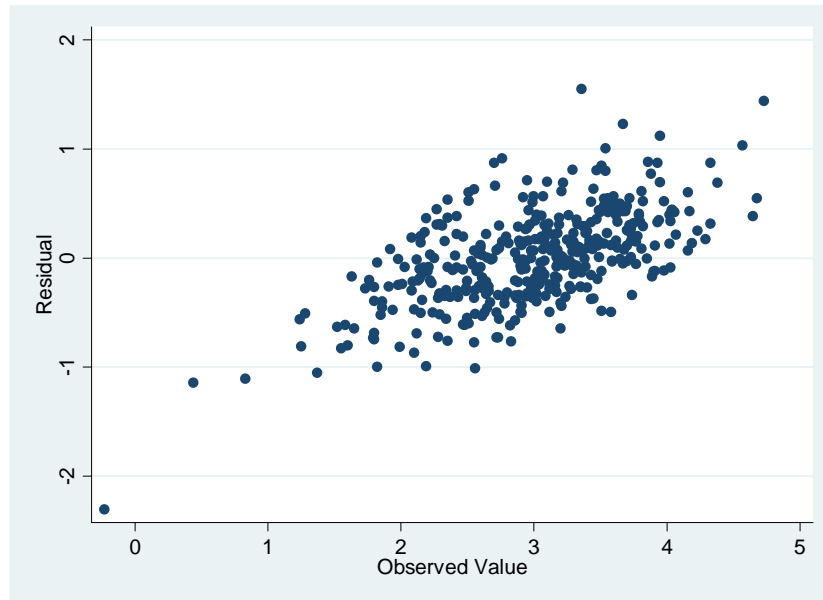


Figure 5-19 Performance of Crash Rate Estimates

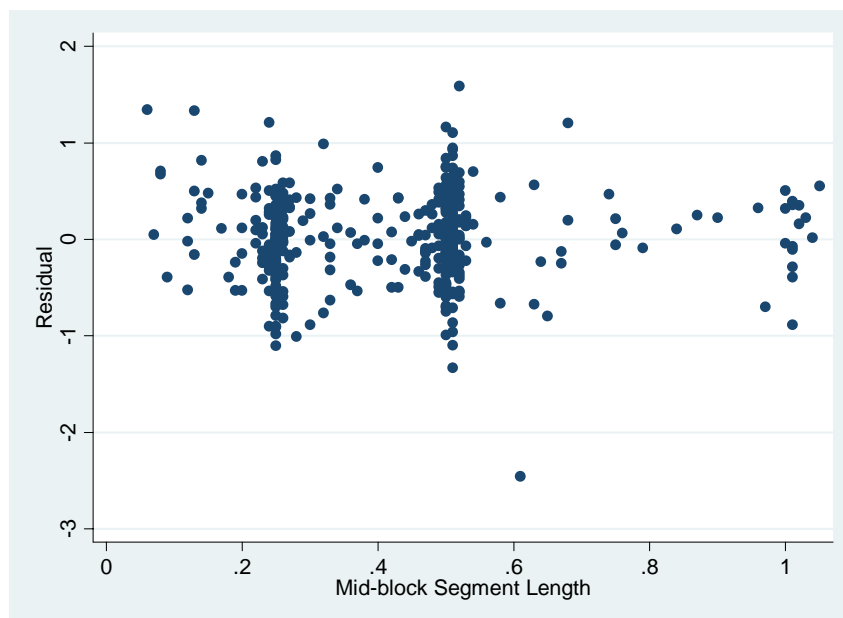


Figure 5-20 Relations between Residuals and Mid-block Segment Length

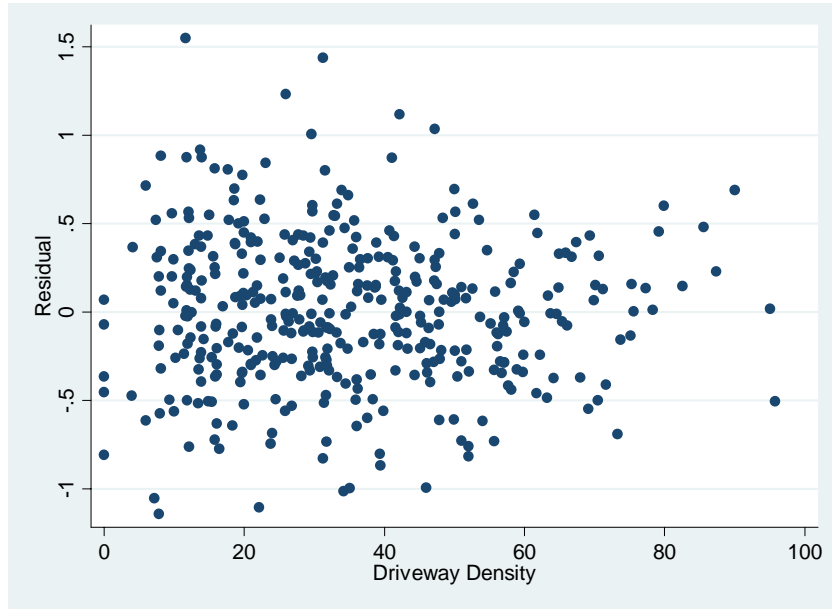


Figure 5-21 Relations between Residuals and Driveway Density

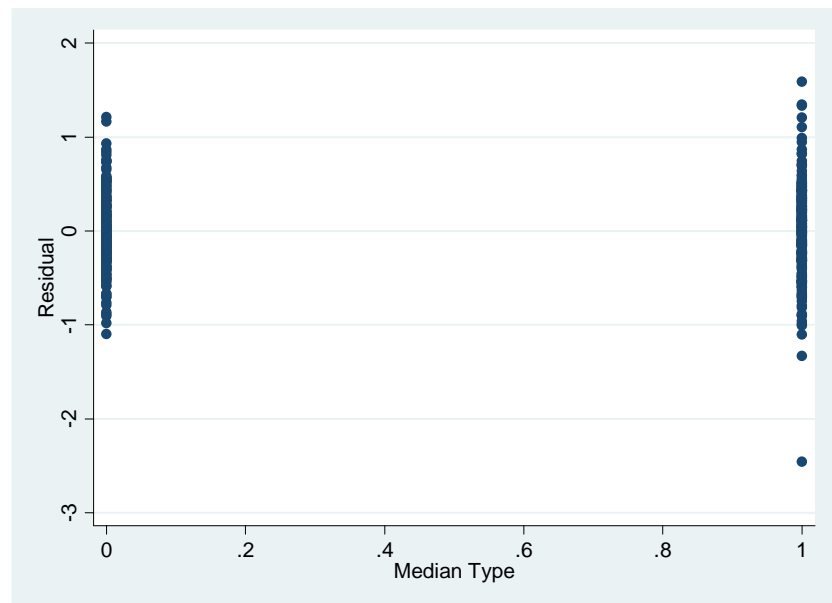


Figure 5-22 Plot of Residuals and Median Type

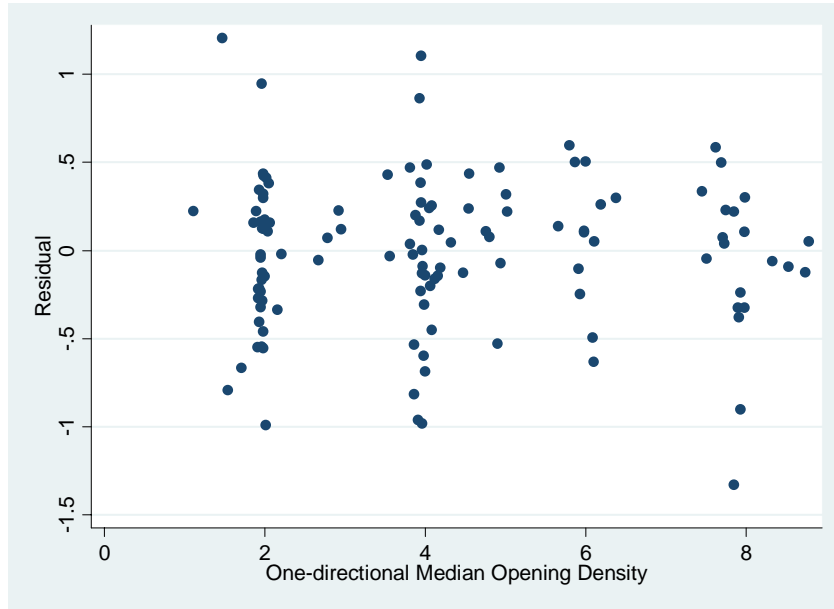


Figure 5-23 Plot of Residuals and One-directional Median Opening Density

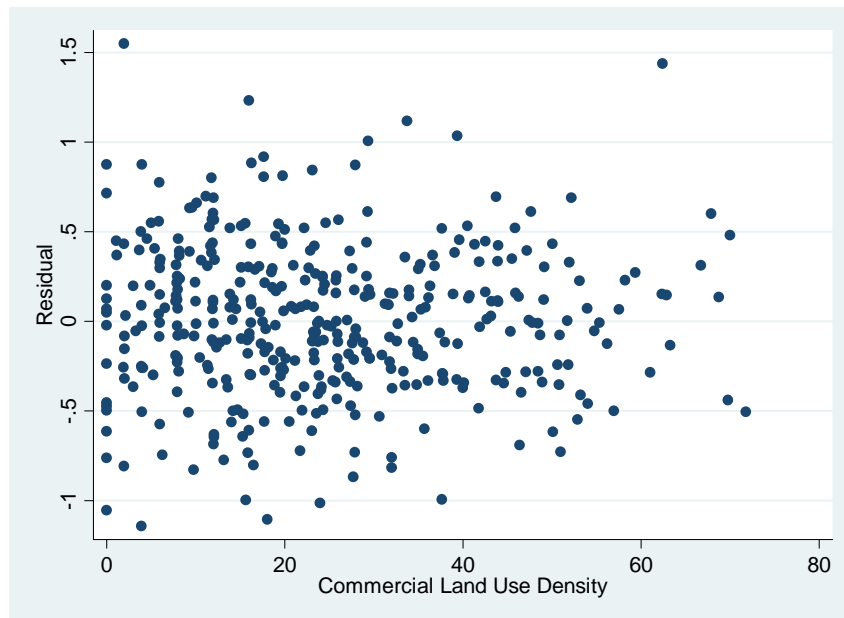


Figure 5-24 Plot of Residuals and Commercial Land Use Density

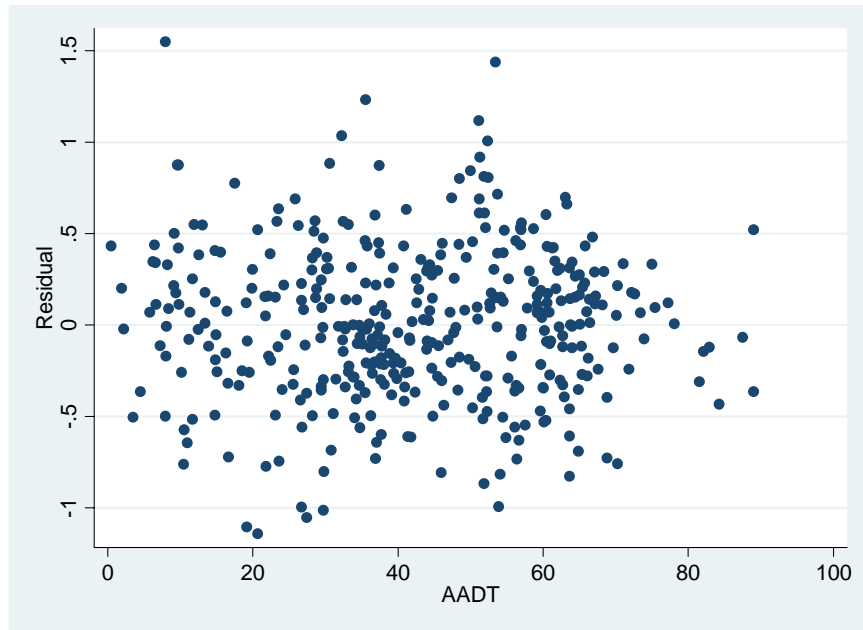


Figure 5-25 Plot of Residuals and AADT

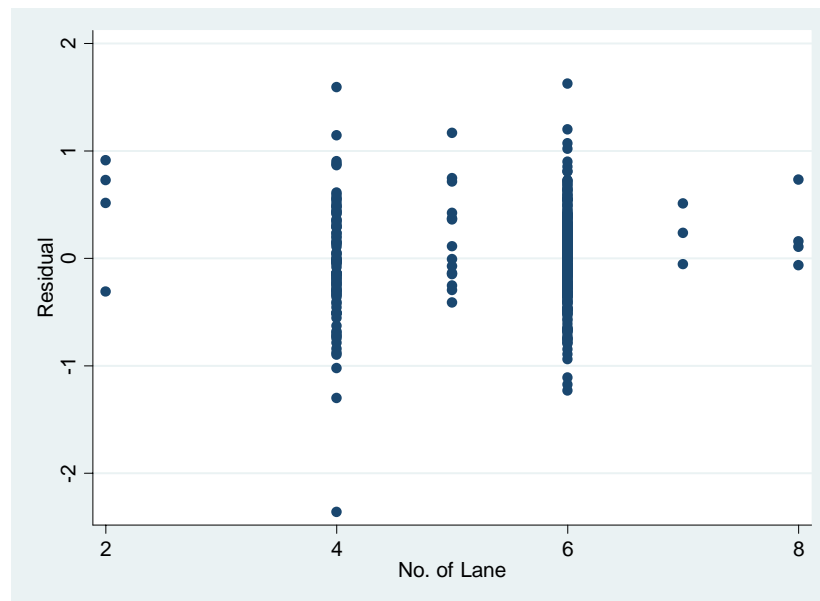


Figure 5-26 Plot of Residuals and Number of Lane

Similar checks on the validity of the assumptions for the travel speed model were performed and no violations were found.

In order to test the zero mean of the residual assumption, the performance of the travel speed model was evaluated graphically. Figure 5-27 shows the estimated travel speed against the residuals. Most of the residuals are randomly scattered along the zero line except on the right end like a funnel. The frequency of residuals in Figure 5-28 shows that the residuals are distributed normally.

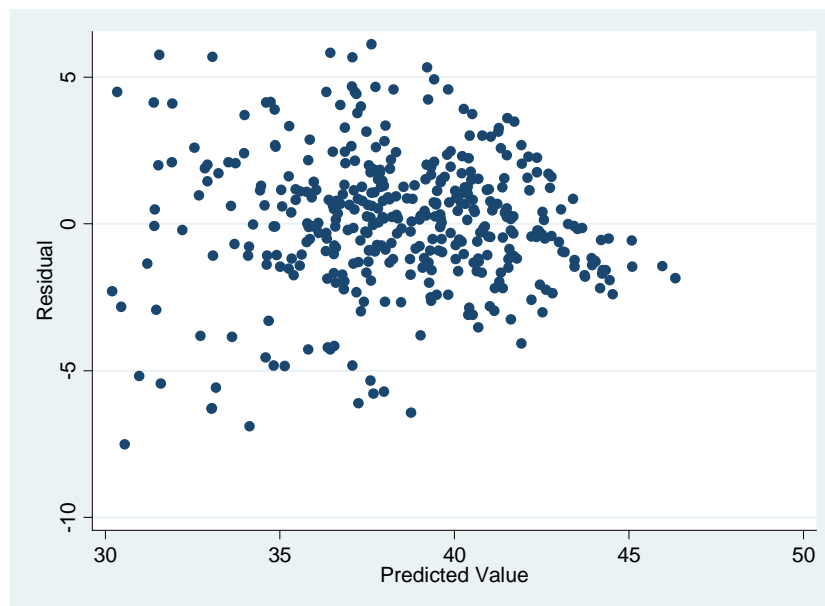


Figure 5-27 Relations between Predicted Travel Speed and Residuals

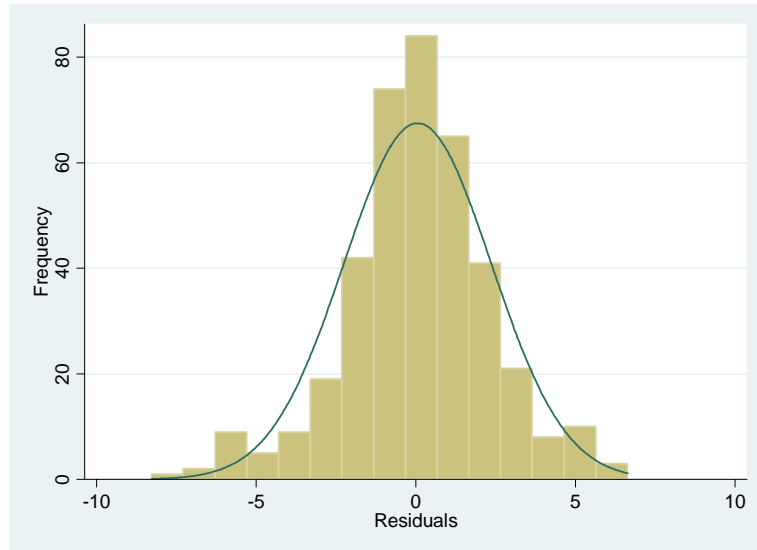


Figure 5-28 Histogram of Travel Speed Residuals Frequency

In addition, the normality graph between the estimated and observed crash rate in Figure 5-29 displays that although there are several outliers, most of the data are distributed along the 45-degree diagonal line evenly.

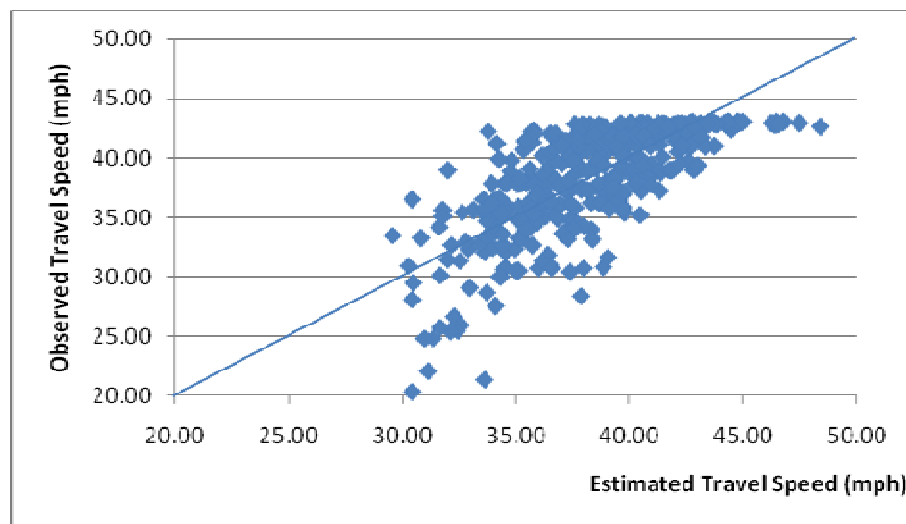


Figure 5-29 Performance of Travel Speed Estimates

In order to test the homoscedasticity of the residuals, the relationships between the independent variables and the residuals were examined. After going through the plots between independent variables and the residuals shown in Figures 5-30 to 5-33, it can be concluded that there is no apparent heteroscedasticity existing for the residuals.

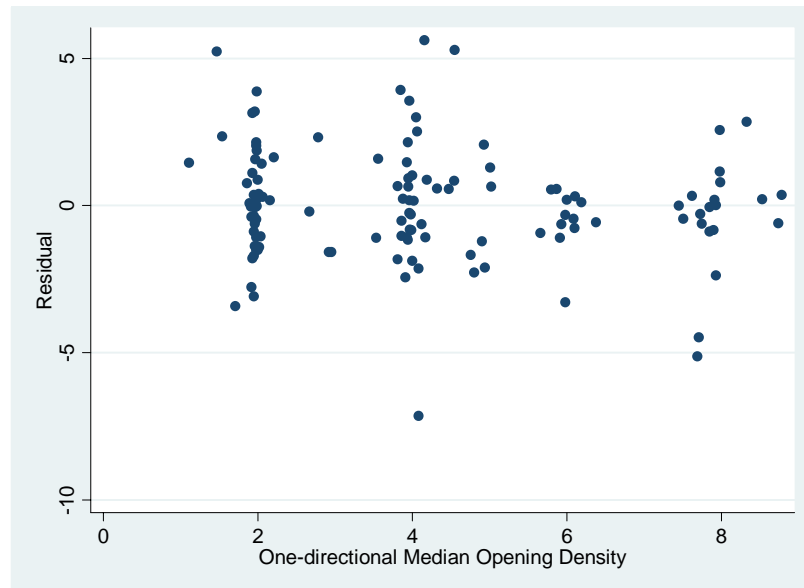


Figure 5-30 Relation between Residuals and One-directional Median Opening Density

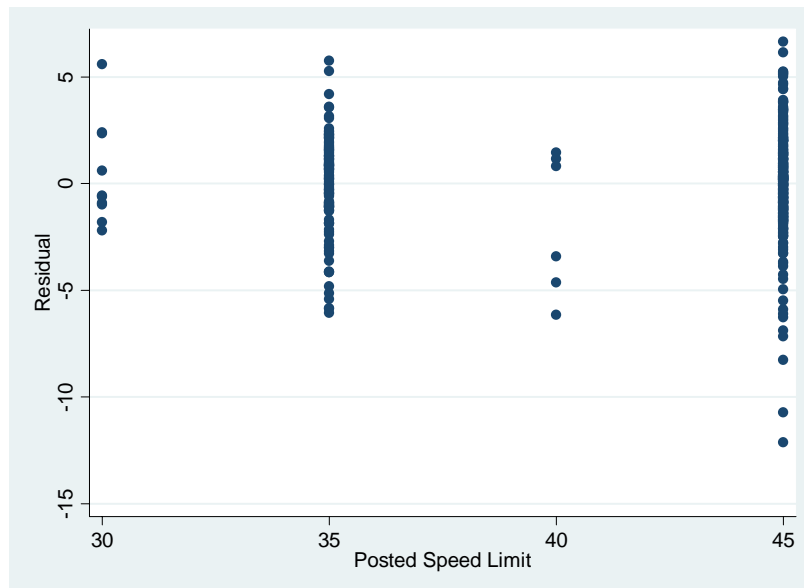


Figure 5-31 Plot of Residuals and Posted Speed Limit

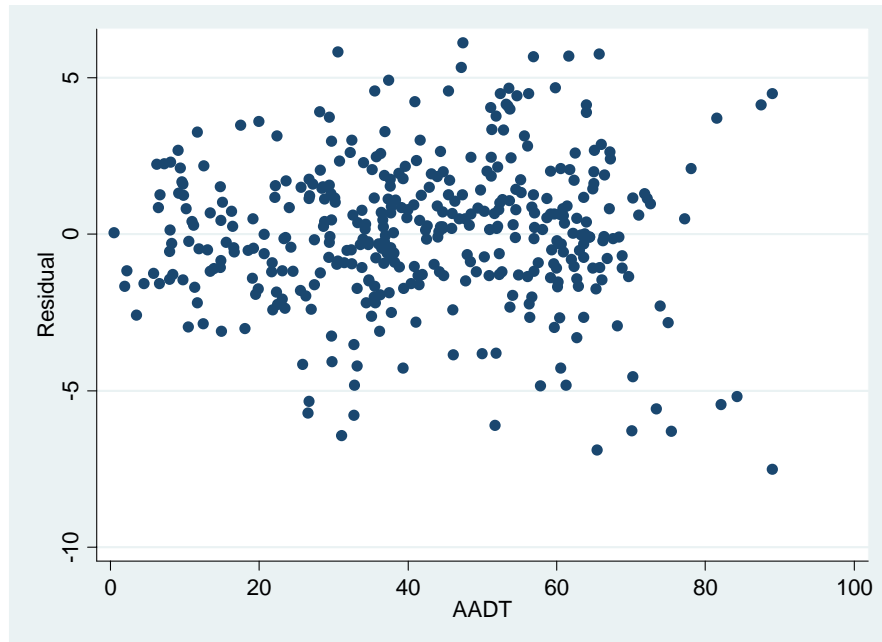


Figure 5-32 Residuals vs. AADT

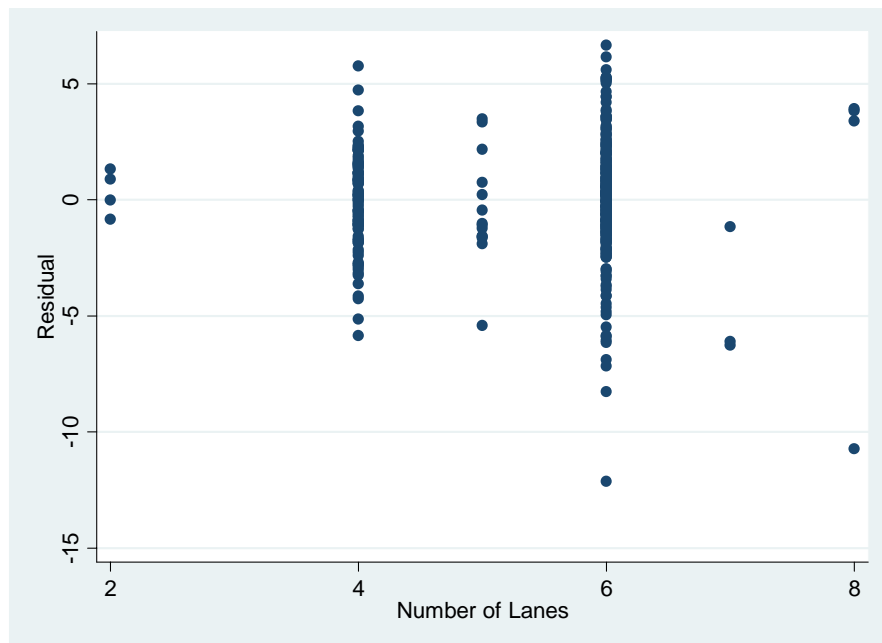


Figure 5-33 Residuals vs. Number of Lanes

Given the validation of the results for the random coefficient simultaneous equations model, the interpretations of the results are presented below.

The crash rate equation shows that the coefficient for average speed is positive that implies that higher rate of crashes was resulted for a mid-block segment when the traffic on the segment is operated at higher speed on average. This implication is consistent with our intuitive because vehicles running at higher speed need to have longer distance either to stop or slow down to a lower speed when they perceive a vehicle at their front for making any interfering maneuvers, such as making a turn to adjacent lands.

The coefficient for mid-block segment length is negative, which indicates that the longer a segment is, the lower the crash rate is. This result seems reasonable as well.

The coefficient for driveway density is positive, which implies that more crashes occur on a mid-block segment with more driveways in it. This result makes sense because more driveways create more opportunities of conflicts, and thus tend to cause more crashes.

The variable for median type has a negative coefficient. In this study, median type is defined as “1” if a mid-block segment has longer portion of raised medians than TWLTLs, otherwise, this variable takes value of “0”. Thus, the result implies that fewer numbers of crashes occurred on mid-block segments with raised medians than those with TWLTLs. This observation is consistent with most of the results in previous studies.

The coefficient for the density of one-directional median opening is positive, while the coefficients for the densities of other median openings are not significant statistically, which implies that more crashes occurred on mid-block segments that had more one-directional median openings. In addition, the result indicates that the other two types of median opening did not show significant impact on crashes, which deserves further investigation.

The coefficient for the density of commercial land use along mid-block segments is positive. It implies that relatively more crashes occurred on mid-block segments comparing with those that had adjacent lands for residential use. It is perceivable that the drivers attracted to such lands may not be as familiar to the roads as the drivers accessing residential areas, which posts higher crash potential.

The variable AADT that represents the amount of exposure along mid-block segments on each lane has a positive coefficient, which implies that more crashes occurred on mid-block segments with more traffic volume. This is consistent with the intuitive.

The variable number of lane has a positive coefficient, which implies that the mid-block segments with more number of lanes had more crashes occurred. It is possible that vehicles tend to run at higher speeds at mid-block segments with more lanes. In addition, more lane changing opportunities may exist on such mid-block segments. These factors may have contributed to having more crashes occurred on them.

As for the travel speed equation, the results in Table 5-6 indicate that crash rate is negatively related to travel speed. Traffic on mid-block segments is operated slower when more crashes occur on the segments. This might be caused by either the response of the drivers to the higher risk of crashes on the segments or the congestions created by the crashes. Sometimes, minor crashes such as property damage only may cause severe congestion during peak periods. If the frequency of crashes is high, drivers on the road may have the impression of higher potential of crashes, and thus tend to drive slower than they would on other roads with fewer crashes.

The coefficients of the variable one-directional median opening density is negative, which implies that vehicles run on mid-block segments at relatively lower speeds when there are more one-directional median openings on the segment. The coefficients for other median opening types are zero statistically, which indicates that they don't have significant impact on the mobility of traffic on the segments, which may also deserve further investigation in future.

The variable posted speed limit has a positive coefficient, implying that vehicles on mid-blocks with higher speed limits tend to drive at higher speeds, which is consistent with the intuitive.

The variable for traffic flow AADT has a negative coefficient, which indicates that when there is more traffic on mid-block segments, the vehicles on the segments tend to run at lower speed. More vehicles on roads implies smaller chance for vehicles to find gaps to change lanes, which would force them to follow the slow moving vehicles in front of them, thus resulting in slower travel speed as a whole.

The coefficient for the variable number of lane is positive. It indicates that vehicles on mid-block segments with more lanes run at higher speed on average. This is reasonable.

With the interpretation of the results from the random coefficient simultaneous equations models, it can be found that there is a strong endogenous relationship between safety and mobility. To confirm this observation, random-effects simultaneous equations model was developed. The results from these two models were listed in Tables 5-8. It can be seen from the table that a negative relation between travel speed and crash rate is identified from the models, which is not consistent with the intuitive. This finding

indicates that random coefficient simultaneous equations model is superior to the random-effects model.

Table 5-8 Random-effects Simultaneous Equations Model Results

Variables	Estimated Coefficient	z- statistic	P> z
Crash Rate Model			
AVGSP	-0.036	0.009	-3.90
SEGLN	-0.638	0.151	-4.22
MEDTYP	-0.210	0.070	-2.98
ONEDIRDEN	0.028	0.011	2.53
COMDEN	0.013	0.002	6.57
AADT	-0.015	0.003	-4.70
NOLN	0.236	0.044	5.39
CONST	3.753	0.456	8.22
Number of Observations	395		
Number of groups	27		
Chi square (7)	15442.06		
R square	0.279		
Travel Speed Model			
LNCR	-1.217	0.244	-5.00
ONEDIRDEN	0.102	0.055	1.84
POSTSP	0.252	0.043	5.80
AADT	-0.191	0.014	-13.76
NOLN	0.715	0.239	2.99
CONST	35.510	2.135	16.63
Number of Observations	395		
Number of groups	27		
Chi square (5)	90509.9		
R square	0.509		

CHAPTER 6

MODEL DEVELOPMENT FOR INTERSECTIONS

6.1 Descriptive Statistics

Given the collected data for intersections as described before, descriptive statistics were developed using statistical software STATA 9.0 and they are presented below.

Table 6-1 Statistics Summary

Variable	Observation	Mean	Std. Dev.	Min	Max
Crash count	285	57.589	50.569	2	261
Average corner clearance	285	165.807	61.127	43.63	369.61
No. of corner clearance	285	5.950	1.893	1	8
No. of lanes on main street	285	7.253	1.210	3	10
No. of lanes on minor street	285	5.4	1.699	2	9
Speed limit on main street	285	41.698	5.340	25	45
Speed limit on minor street	285	31.968	7.713	13	45
Land use types	285	0.765	0.332	0	1
Total traffic flow	285	114704.7	52,161.06	20,391	269,076

From Table 6-1 it can be seen that about 58 crashes happened on average at an intersection in 2003. Figure 6-1 shows the distribution of crash counts at these selected intersections. Note that this distribution only applies to the set of intersections selected in this study, where the locations were determined by the adjacent mid-block segments on which crashes occurred in 2003. If the intersections associated with mid-block segments included no crashes, this distribution would be changed toward having zero crash frequency in the histogram.

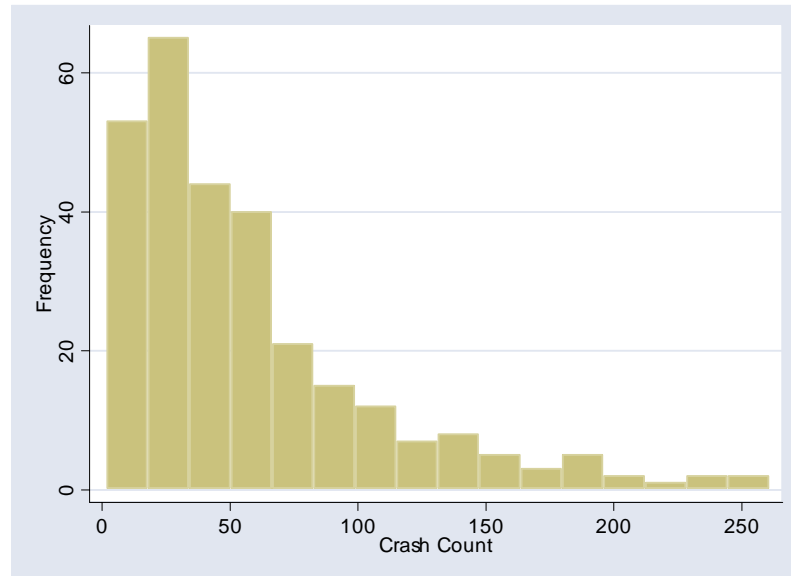


Figure 6-1 Distribution of Crash Count Frequency

The average number of corner sides with driveways is 5.95. The maximum number of corner sides is 8, which most likely is the case when there is one driveway within the 400 ft range on each side of a corner at a four-leg intersection. The minimum number of corner sides is 1, which is the case when there is only one driveway within the specific range at an intersection. Figure 6.2 shows the distribution of the number of corner sides with driveways. It can be observed that significant number of intersections has eight corner sides with driveways.

The average corner clearance is 165.8 ft. The minimum is 43.6 ft, very short compared with the value recommended in the Access Management Manual (2003). The distribution of the clearances seems to have a bell shape, with the median or mean at the average value of 165.8 ft. The average length of corner clearance is very close to normal distribution, as displayed in Figure 6-3.

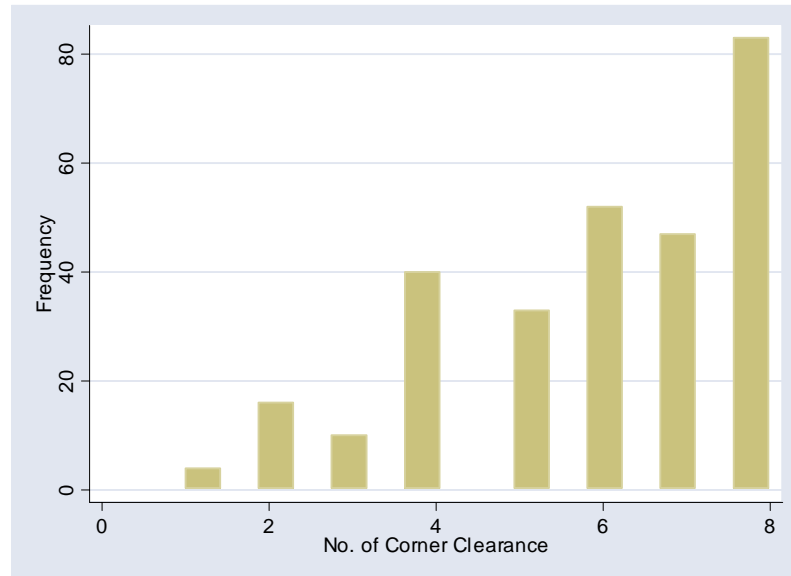


Figure 6-2 Distribution of Number of Corner Sides with Driveways

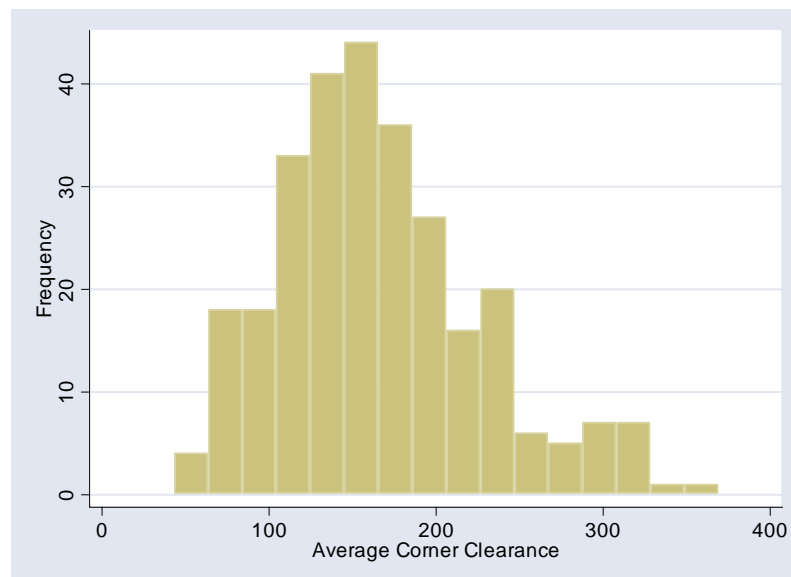


Figure 6-3 Distribution of Average Corner Clearance

The numbers of lanes on major and minor streets are 7.4 and 5.4 on average, respectively. The maximum numbers of lanes on major and minor streets are ten and five, respectively, equivalent to five and four lanes in each direction. These numbers are

correct because left or right turn lanes were also counted as a traveling lane in this study. The posted speed limits on major and minor streets are 41.6 and 31.9 mph on average. The index for land use at an intersection is 0.76 on average.

According to the definition for land use at intersections in the data collection, if the land use types around an intersection are all commercials, the land use index is “1”, and if the land use types are all residentials, it is considered as “0”. The average of the index is about 0.7, which implies that there is more commercial use than residential use for the land around intersections.

6.2 Relations between Crash Count and Related Variables

Figures 6-4 to 6-9 display the relationship between crash counts and the relevant factors influencing the occurrence of crash at intersections. Figure 6-4 shows that the more the number of the corner sides with driveways within the effective area of an intersection (also called the number of corner clearance), the higher the probability to have crashes occurred at the intersection. Most of the data followed the trend except several outliers at intersections that had four corner sides with driveways.

Figure 6-5 indicates that more crashes occurred at intersections that had shorter average corner clearance. This negative relationship seems not linear.

Figure 6-6 presents that more crashes occurred at intersections that had more commercial lands in their adjacent areas. Note that there were significant numbers of intersections that had commercial land use at all of their corner areas. The number of crashes occurred at these intersections were significantly high.

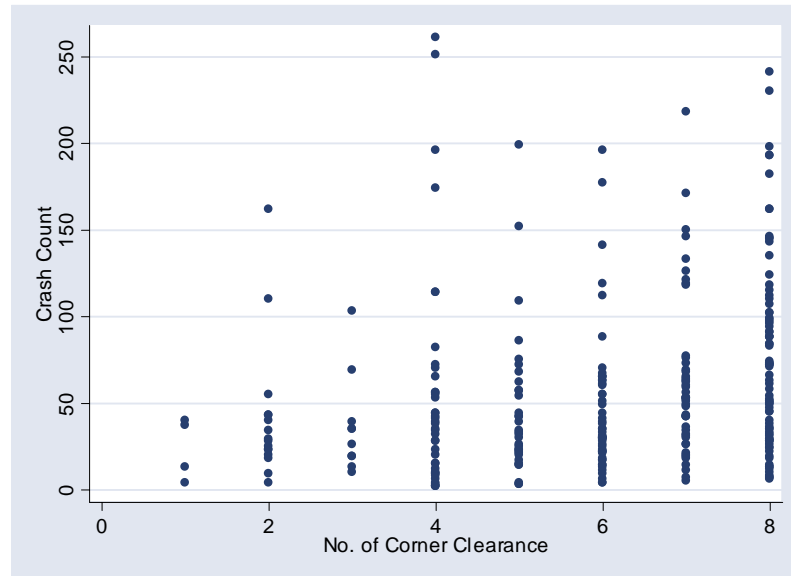


Figure 6-4 Scatter Plot of Crash Count and No. of Corner Side

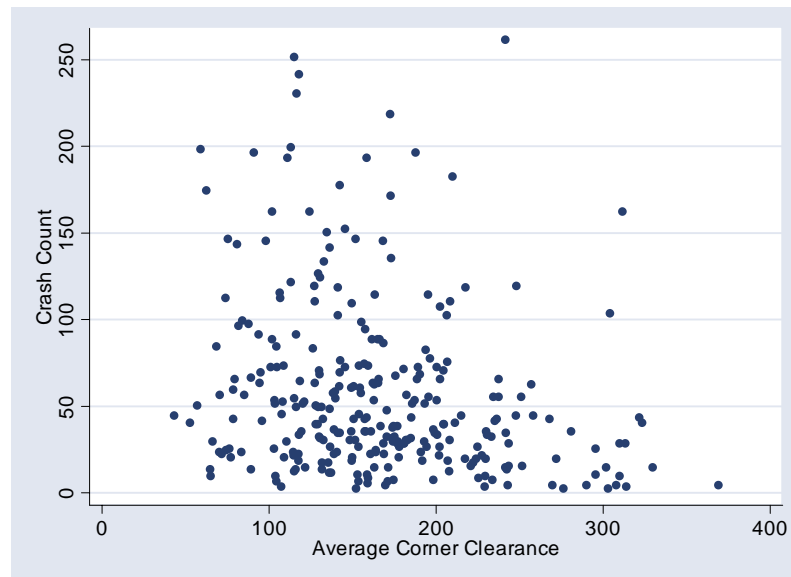


Figure 6-5 Scatter Plot of Crash Count and Average Corner Clearance

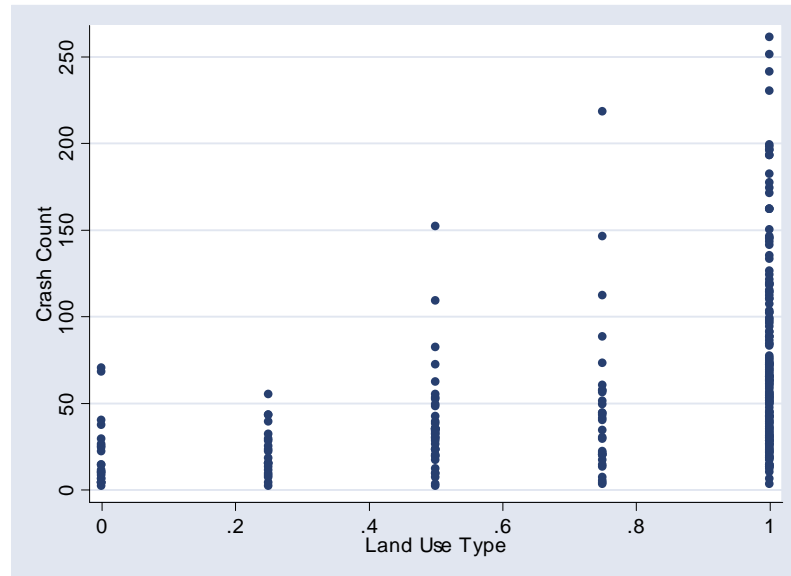


Figure 6-6 Scatter Plot of Crash Count and Land Use Type

Figure 6-7 indicates that more crashes occurred at intersections with streets that had more lanes, regardless of whether the streets were main or minor streets.

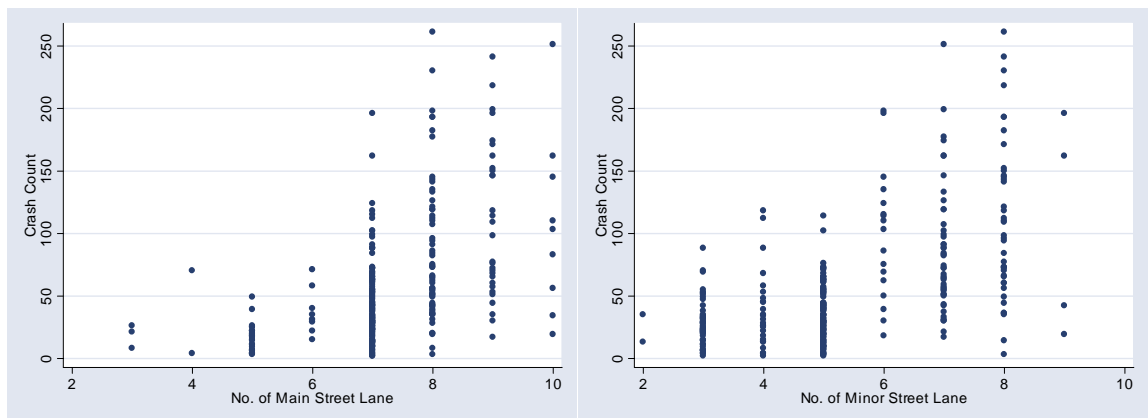


Figure 6-7 Scatter Plot of Crash Count and No. of Main & Minor Street Lanes

Figure 6-8 presents the relationship between the numbers of crashes occurred at intersections and the posted speed limits on the main and minor streets. It can be seen that higher speed limits tended to be associated with more crashes, for both the main and minor streets.

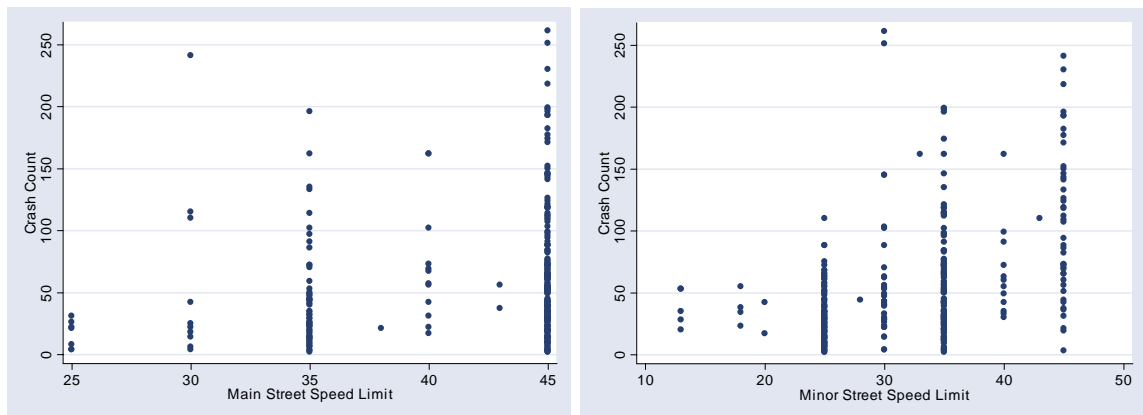


Figure 6-8 Scatter Plot of Crash Count and Main & Minor Street Speed Limits

Figure 6-9 shows the trend of crashes versus the total traffic flow that run through intersections. A clear pattern can be observed that higher traffic flow was related to high crashes. Note that the relationship between crashes and the possible influencing factors presented above may become weak when these factors are considered together in a regression model.

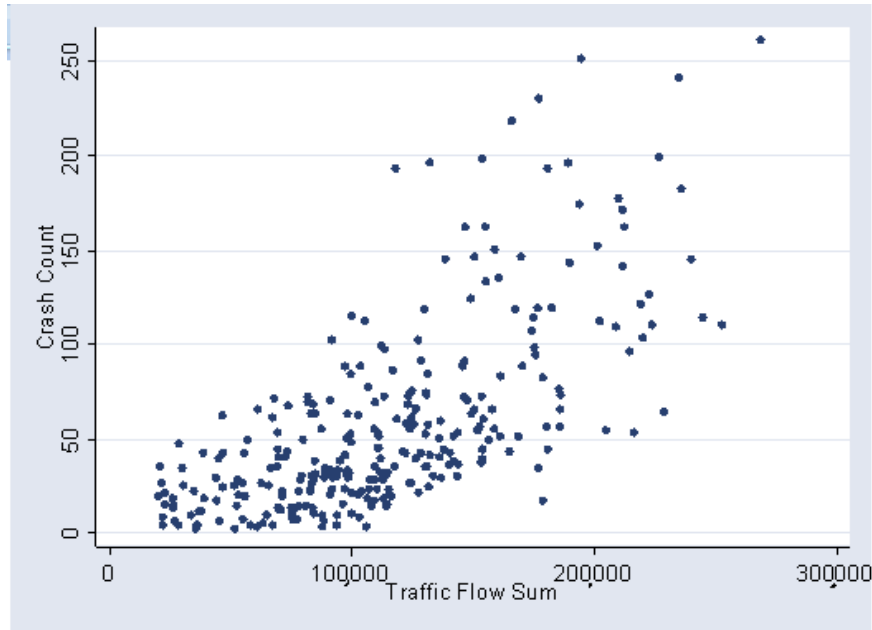


Figure 6-9 Scatter Plot of Crash Count and Traffic Flow Sum

6.3 Count Models for Intersections

6.3.1 Variables Selection

Because the objective of this study was to investigate the impact of corner clearance on safety at intersections, the corner clearance and the number of corner sides with driveways (number of corner clearances) were considered as influencing factors. The shorter the corner clearances are and the more driveways at intersections, the higher chances conflicts occur between turning and through traffic.

The safety impact of corner clearance varies with the types of land use at intersections. Commercial lands usually provide shorter corner clearance and more driveways to make customers to access business efficiently. However, they may generate traffic or cause crashes in intersection areas. Residential lands attract the residents only who live there, and thus provide fewer driveways, the traffic flow for the residential land

is very limited, and risks to run into crashes are low. As a result, the two types of land use may show different influence on safety. In this study if all the lands at an intersection are commercials, the land use index is expressed as “1”. If all the lands are residential, “0” is used for land use index. If there exists both commercials and residentials, the land use index takes a value between 0 and 1.

Another influencing factor considered in this study is the number of lanes. At each approach of an intersection the left and right-turn lanes were also counted as part of the number of lanes. The more lanes on an approach, the more conflicts among diverging, merging and crossing, and chances to run into crashes are expected to increase. Main streets usually have different number of lanes from minor streets. Whether the number of lanes on main streets or minor streets has influence on the safety at intersections needs to be determined.

In previous studies, traffic flow is an important measure for crashes at intersections. The higher traffic flow at intersections, the more conflicts are produced and the more crashes tend to occur. Thus, traffic flow is also considered in this study.

Posted speed limits at intersections influence the speeds of vehicles arriving at intersections. Generally, higher speed limits cause higher speeds of vehicles approaching intersections, which may lead to higher probability for crashes. Thus, speed limits on main streets and minor streets should be considered for safety at intersections.

Random-effects negative binomial regression model was developed using STATA. The variables included in the model are listed in Table 6-2. The correlation matrix of these variables is provided in Table 6-3.

Table 6-2 Variables Considered in the Random-effects Negative Binomial Regression Model

Abbreviation	Variable Description
Crash Count	Number of crashes at intersections
AVGCC	Average corner clearance
NOCC	Number of corner sides with driveways
LANDUSE	Land use type, 1 is for commercial, 0 is for residential, the mixed is in between
MAINLN	Number of lanes on main streets
MINORLN	Number of lanes on minor streets
TOTFL	Total of traffic flow in all directions of intersections
MAINSR	Posted speed limit on main streets
MINORSR	Posted speed limit on minor streets

Table 6-3 Correlation Matrix of Variables

	COUNT	AVGCC	NOCC	LANDUSE	MAINLN	MINORLN	TOTFL	MAINSR	MINORSR
COUNT	1.000								
AVGCC	-0.234	1.000							
NOCC	0.226	-0.383	1.000						
LANDUSE	0.409	-0.297	0.457	1.000					
MAINLN	0.505	-0.088	0.055	0.403	1.000				
MINORLN	0.574	-0.075	0.184	0.295	0.514	1.000			
TOTFL	0.683	-0.141	0.054	0.361	0.656	0.586	1.000		
MAINSR	0.169	-0.021	0.020	0.284	0.534	0.173	0.347	1.000	
MINORSR	0.154	-0.010	0.009	0.086	0.220	0.205	0.196	0.179	1.000

6.3.2 Model Results

A full model was developed first in which all the variables listed in Table 6-2 were considered. The results from this full model are listed in Table 6-4. After removing the variables that are not significant, the random-effects negative binomial regression model is finalized, the results of which are given in Table 6-5.

The dispersion parameter α listed in Table 6-6 is 0.287 with z-statistic 2.16. This result indicates that the crash data are significantly dispersed for which Poisson regression model is not an appropriate choice. It implies that negative binomial regression model is a better approach.

Table 6-4 Full Model for Random-effects Negative Binomial Regression

Variables	Estimated Coefficient	Std. Error	z- statistic
AVGCC	-0.013	0.005	-2.600
NOCC	0.032	0.020	1.620
LANDUSE	0.417	0.136	3.060
MAINLN	0.046	0.041	1.120
MINORLN	0.100	0.023	4.380
TOTFL	0.007	0.001	8.450
MAINSR	-0.006	0.007	-0.980
MINORSR	-0.002	0.007	-0.220
CONST	-0.217	0.361	-0.600
Parameter, a	21.60		
Parameter, b	203.73		
Number of Observations	300		
Number of groups	27		
Log likelihood at convergence, $l(\beta)$	-1264.39		
Log likelihood at zero, $l(0)$	-1689.81		
Ratio of log-likelihood index, ρ^2	0.252		
Chi square (8)	435.77		

To see whether the random-effects model is improved by comparing with the model that does not consider the panel data structure, a negative binomial regression model was developed where the data were not grouped based on arterials. The results of this model are listed in Table 6-6. The Chi square from this model is smaller than the one obtained from the random-effects model. This is a strong validation for developing the random-effects model.

From Table 6-5 it can also be seen that the coefficient for average length of corner clearance is negative, which implies that the longer driveways were from a corner, the fewer crashes happened at intersections in 2003. With longer corner clearance, the drivers of through traffic could perceive and respond more quickly to the maneuvers by traffic into the adjacent lands, by which the chance to occur crashes were reduced.

Table 6-5 Random-effects Negative Binomial Regression Model

Variables	Estimated Coefficient	Std. Error	z- statistic
AVGCC	-0.017	0.005	-3.540
LANDUSE	0.485	0.120	4.030
MINORLN	0.619	0.027	2.280
TOTFL	0.007	0.001	9.840
MINORSP	0.014	0.005	2.680
CONST	-0.213	0.183	-0.370
Parameter, a	19.98		
Parameter, b	189.70		
Number of Observations	300		
Number of groups	27		
Log likelihood at convergence, $l(\beta)$	-1266.54		
Log likelihood at zero, $l(0)$	-1697.96		
Ratio of log-likelihood index, ρ^2	0.254		
Chi square (5)	422.80		

Table 6-6 Negative Binomial Regression Model without Panel Data Structure

Variables	Estimated Coefficient	Std. Error	z- statistic
AVGCC	-0.020	0.006	-3.240
LANDUSE	0.659	0.117	5.630
MINORSP	0.019	0.005	4.130
TOTFL	0.008	0.001	11.56
CONST	2.055	0.198	10.38
Dispersion parameter, α	0.287	0.026	2.16
Number of Observations	300		
Number of groups	27		
Log likelihood at convergence, $l(\beta)$	-1286.65		
Log likelihood at zero, $l(0)$	-1335.69		
Ratio of log-likelihood index, ρ^2	0.037		
Chi square (4)	254.71		

As shown in Table 6-5, the coefficient of land use type is positive. This result shows that more crashes were caused when there were more commercials at the corners, which is consistent with the intuitive.

The variable for the number of lanes on minor streets has positive coefficient. It implies that there were more crashes at intersections that had fewer numbers of lanes on the intersecting streets. This is understandable because fewer lanes including left or right

turn lanes are usually associated with more potential conflicts with vehicles, which tends to cause more crashes at intersections.

The coefficient for the variable of total traffic flow is positive. This result implies that more crashes occur at intersections that have more traffic running through them. This is consistent with the intuitive since more interactions between vehicles together with many potential conflicts at intersections tend to cause more crashes.

The variable for posted speed limit on minor streets has a positive coefficient. It is reasonable because higher speed limit on streets is associated with higher running speeds, which usually contributes significantly to the occurrence of crashes.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

This research was originally started based on the study on evaluating the safety impact of selected access management techniques in the Las Vegas area and was sponsored by the University Transportation Center at University of Nevada, Las Vegas. Although many studies have been conducted on this topic, their methodologies cannot be adopted to the case in the urban areas immediately due to the data issue. Specifically, in the urban areas some roadway segments or intersections for which safety and other relevant data are collected are likely located on the same arterials. These segments on the same arterials would share commonly unobserved information that is unique to the arterials. Thus, this data issue, heterogeneity, calls for a special modeling approach. In addition, interdependence or endogeneity exists between safety and mobility for mid-block segments and intersections. A previous study developed simultaneous equation models in which two different equations were included, one for safety and the other for mobility. The calibration of such simultaneous equation models took into account the interdependence between safety and mobility. However, there was an issue about choosing appropriate performance measure for mobility.

In this study, different regression models were developed for mid-block segments and intersections, separately, where these two issues – heterogeneity and endogeneity, were treated in different ways. For the models dealing with the safety on mid-block segments, random coefficient simultaneous equations models were developed. The panel data structure of the model addressed the heterogeneity issue, while the simultaneous

equation models treated the endogeneity issue between safety and mobility. In the simultaneous equations model, a more comprehensive variable - average travel speed was used to represent mobility. For intersections, the random-effects negative binomial model was developed by which the heterogeneity issue was addressed. The issue of interdependence between safety and mobility was not taken in account because of the lack of data for mobility at intersections.

The data on safety, mobility and relevant information in the Las Vegas Metropolitan area were collected in this study. These data with various formats were obtained from different sources. Major efforts were also made in extracting data using Google Earth.

Based on the developed random coefficient simultaneous equation model, it can be concluded that the access management techniques, mid-block segment length, driveway density, median type, and median opening spacing are significant factors that influence the safety on mid-block segments. The longer distance between signals, driveways and median openings, the fewer crashes are caused. Raised medians are associated with fewer crashes than TWLTLs. In addition to these access management techniques, there are other factors that influence safety on mid-block segments as well, which include land use, traffic flow and number of lanes. From the random-effects negative binomial regression model developed in this study, it can be concluded that corner clearance is significant in influencing the safety at intersections. The longer the clearance is, the fewer crashes occur. In addition, the more corners that have driveways, the more crashes happen. Other factors identified to influence the safety at intersections are land use type, traffic flow, speed limits, and number of lanes.

7.2 Recommendations and Future Study

The research presented in this dissertation evaluated the impact of some selected access management techniques on safety in urban areas by developing advanced statistical regression models.

Based on the results, it is recommended that mid-block segments be built longer, which is very important to urban areas, like Las Vegas, where there are spaces available for future development. The number of driveways on mid-block segments should be controlled, probably by providing with better circulation systems in the adjacent lands. If possible, raised medians should be installed. TWLTLs should be restricted to the roads with lower speeds. At intersections, driveways should be built with an appropriate distance maintained to corners. In addition, the number of driveways at intersections should also be minimized.

For mid-block segments, random coefficient simultaneous equation models were developed by which the unobserved missing information that was commonly shared by the mid-block segments in the same arterials and the interdependency between safety and mobility on mid-block segments were addressed. For intersections, panel data based count data models were developed by which the unobserved missing information on intersections on the same arterials was taken into account. The results can be reasonably interpreted. Thus, these modeling approaches are highly recommended for applications in future.

Based on the study, the following needs are recommended for future work.

- 1) Include more relevant information about mid-block segments and intersections in modeling the safety impact of access management techniques. In this study, some

data were not collected due to the limitation of time frame. Such missing data included those related to geometric designs (horizontal, vertical curves, sidewalk, pedestrians), weather conditions (sun glare, rain, snow), light conditions (light pole density, light intensity), driver conditions (age, gender, drinking, fatigue), vehicle types (cars, motorcycles, pickups, trucks), etc. All the information may have influence on roadway safety and mobility. By having them included in the modeling, the accuracy of the models can be improved.

- 2) Incorporate the interdependence between safety and mobility into the regression models for evaluating the safety impact at intersections. In this study, the interdependence between safety and mobility was incorporated in the model for mid-block segments only. It was not considered for the model at intersections due to the lack of mobility data. Efforts could be made in future to make such mobility data available, so that a similar modeling approach to mid-block segments can be taken for intersections.

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