NCHRP

RESEARCH REPORT 929

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Unsignalized Full Median Openings in Close Proximity to Signalized Intersections

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Unsignalized Full Median Openings in Close Proximity to Signalized Intersections

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Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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FOREWORD

By Waseem Dekelbab
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This report presents state departments of transportation and other transportation agencies with a quantifiable approach for evaluating the operational and safety performance associated with unsignalized full median openings located near upstream and downstream traffic signals that have at least one turning bay. The report also provides guidelines for evaluating the performance of other median opening configurations. The material in this report will be of immediate interest to traffic engineers and other practitioners responsible for implementing unsignalized median openings to improve operations at a signalized intersection.

Many agencies discourage access within the functional area of a signalized intersection, as recommended in current access management guidelines, which also suggests that unsignalized median openings be bidirectional openings designed for only left turns from the roadway (and possibly U-turns). Closely spaced median openings can result in a complex pattern of overlapping conflicts and a resulting range of safety and operational impacts, while full-access intersections may be unnecessary and result in negative impacts on traffic operations. Managing access is the best solution in most cases; however, there are few guidelines on what parameters an agency should consider when selecting between full- versus restricted-access medians. In addition, removing movements reduces conflict points and, when located and designed correctly, an unsignalized median opening may improve operations at a signalized intersection. There was a need to provide guidelines on the design of median openings to improve the safety and operations of these access points.

Under NCHRP Project 15-64, the Texas A&M Transportation Institute developed guidelines for transportation agencies to evaluate the safety and operational effects of the location and design of unsignalized median openings in close proximity to signalized intersections.

The following appendices are not included in the printed report but are available online by going to www.TRB.org and searching for "NCHRP Research Report 929":

- Appendix A: Individual Site Data
- Appendix B: Field Data Summaries

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction and Overview

Effective access management techniques can improve corridor operations and safety while providing reasonable access to adjacent properties. Raised medians, as an example, provide a strategic access management approach that minimizes the number of left-turn and crossing conflicts and optimizes operations along the roadway corridor. A continuous median between signalized intersections can be expected to provide these benefits, including reducing the number of fatal and injury crashes, but will not provide any mid-block left-turn access. The benefits of this continuous raised median must also be contrasted with the potential disadvantages. For example, a raised median without any mid-block median openings will effectively shift potential left-turning vehicles to the downstream intersection, where drivers must then execute a U-turn or find an alternative route to their destination. Drivers of heavy vehicles find this restrictive median configuration particularly challenging, as U-turns at signalized intersections are often impractical for large trucks. In many cases, business owners perceive that a continuous median will have a negative impact on their business's stability and result in a potential loss of income.

A reasonable compromise to the continuous raised median is to provide a select number of mid-block median openings. This approach will enable metered left-turn or U-turn activity at strategic locations. The median opening could provide full access or could be a directional opening for one or both directions. The proximity of an unsignalized median opening to upstream or downstream signalized intersections can depend on a wide variety of factors, yet little is known about how these individual factors collectively affect the overall operational or safety performance of the corridor upstream and downstream of the median opening. The analysis summarized in this report examines these prospective median openings and ultimately assesses in greater detail the influential factors that should be considered when evaluating full median opening configurations that have at least one turn bay.

This report documents the research efforts conducted as part of NCHRP Project 15-64, "Guidelines for the Design of Unsignalized Median Openings in Close Proximity to Signalized Intersections," to better quantify the operational and safety performance associated with unsignalized full median openings located near upstream and downstream traffic signals that have at least one turning bay. This study also provided general information about common practices for the use of other median opening configurations—namely full median openings (without turn bays) as well as directional median openings. As noted in current access management guidance, many agencies discourage access within the functional area of a signalized intersection (*1, 2*). Much of the current guidance suggests that the configuration of unsignalized median openings be oriented to only provide directional openings designed specifically for left-turn or U-turn maneuvers.

Closely spaced median openings result in a complex pattern of overlapping conflicts and a resulting range of safety and operational impacts. Full-access intersections that do not provide channelized directional movements may be unnecessary and could result in negative impacts on traffic operations. Managing access is the best solution in most cases; however, there is little guidance on what parameters should be considered when selecting between full versus directional access medians, particularly when the median openings are near signalized intersections. In addition, removing movements reduces conflict points. When these openings are located and designed optimally, an unsignalized median opening may potentially improve operations at a downstream or upstream signalized intersection near the median opening.

Research Goal

This research effort focused on the investigation of the operational and safety impacts of unsignalized median openings near signalized intersections. The goal of this effort was to develop guidance to help better quantify the effects of these placement and configuration decisions.

The resulting guidance document (see Appendix C), developed as a concise summary document, can be used by practitioners to better understand the configurations for the various types of unsignalized median openings, including those studied as part of this effort. This research effort, therefore, focused on **quantifying the operational and safety effects of the location and design of these unsignalized full median openings (with at least one turn bay).** This analysis documents the design and implementation factors that influence unsignalized median opening performance, with specific information as to how their design and placement affect site-specific as well as operational and safety performance. The guidance also provides threshold (boundary) conditions for application. This information can help address how these findings can be applied to new construction as well as retrofit construction applications.

For this study, the research team investigated a variety of potential factors that could influence operational and safety performance at these median opening locations (see Table 1). In many cases, these factors were not ultimately determined as influential. Other factors, such as traffic volume, resulted in a significant impact on performance and are explored in greater detail in subsequent chapters of this report.

Table 1. Operational and safety factors considered for analysis.

Operational Characteristics	Design Characteristics	Contextual Influences
• Corridor posted and operating speed • Traffic volume (intersection and median opening) • Heavy vehicle volume • Transit volume and type (where applicable) • Bicycle and pedestrian activity (where applicable) • Intersection functional area • Traffic signal timing • Capacity (level of service) at intersection and median opening • Progression of platoons or availability of gaps • Queuing and proximity to median opening	• Median opening configuration • Distance to adjacent intersections (signalized and unsignalized) • Intersection and driveway configurations in close proximity to median opening • Number and type of access points and associated conflicts • Road characteristics – Lane widths – Number of lanes – Curb or shoulder type – Bicycle lane presence and configuration – Sight distance and/or obstruction – Alignment of opposing turn lanes – Driver expectancy accommodation	• Urban and suburban (rural locations were not identified) • Adjacent land use • User perspectives • Integration of facility into the larger transportation network • Development level of corridor and/or region (new construction, existing construction, etc.)

Report Organization

This report summarizes the findings of this research activity. Chapter 1 introduces the research problem and report organization, and Chapter 2 summarizes the applicable literature associated with this topic. Chapters 3, 4, and 5 address the data collection, operational analysis, and safety analysis, respectively. The body of the report concludes with a summary of findings (Chapter 6), a list of references, and Appendix C, which is a guidance document that can be used for applying the findings of this research effort. Two other appendices provide greater detail about the study sites (Appendix A) and data acquired at these locations (Appendix B); these appendices may be found at www.TRB.org by searching for "*NCHRP Research Report 929*."

CHAPTER 2

Common Practices and Candidate Treatments

Introduction

The published literature related to the placement of unsignalized median openings near signalized intersections is limited; however, past studies have focused on key components that, collectively, may influence how and where these median openings should be constructed. This literature review, therefore, frames the associated median opening information based on four questions:

- What are the advantages and disadvantages of a median opening?
- What types of median openings may be considered?
- What is the appropriate spacing and location for median openings?
- What are the key components or characteristics to consider?

The following summary reviews the published research and highlights the state of practice related to these key questions. The project team identified 19 cities and 10 states with agency access management or design guidelines that included information related to the use of median openings.

The content included in this review is based on the application of physical non-traversable medians and their respective median openings near intersections. The review does not extend to alternative median configurations, such as traversable medians or continuous two-way left-turn lanes. In addition, most locations where median openings occur near signalized intersections are in urban or suburban regions. For this reason, the literature contains minimal information related to the placement of similar openings in rural regions.

Advantages and Disadvantages of Median Openings

The construction of a median opening is typically considered at locations where the benefits associated with the break in the median outweigh the potential drawbacks of introducing this additional mid-block unsignalized intersection. The *Access Management Manual*, *Second Edition* (*1*) and the *Access Management Application Guidelines* (*2*) identify the advantages associated with non-traversable medians and their companion median openings. Common advantages and disadvantages are summarized in Table 2.

The published research related to median openings has generally focused on the following characteristics and their relationship to the median opening:

- The type of median opening
- The spacing and orientation of the median opening related to corridor intersections, driveways, and other median breaks

Table 2. Advantages and disadvantages of median openings.

Advantages	Disadvantages
• The locations where left-turn maneuvers can be accommodated are easily identified by drivers, thereby reducing driver workload. • Median opening separation distances can provide space to accommodate deceleration and vehicle storage. • At opening locations with appropriately designed turn bays and storage, turning vehicles do not block active traffic while waiting to complete turning maneuvers. • Wide medians can provide refuge for vehicles using the median opening. • Corridor access connections can be designed closer together than on roads without this type of median treatment because many of the driveways will function as a right-in/right-out due to the provision of left-turn and through-vehicle maneuvers only at designated locations. • The appropriately designed median opening will help facilitate improved operations, resulting in less overall corridor delay. • A directional median opening will help minimize vehicle conflicts. Similarly, the number of severe crashes at median openings will be reduced, along with the frequency of mid-block crashes.	• Emergency vehicles may have less flexibility to access property adjacent to the opposing direction of travel lanes. • Heavy vehicles may have difficulty using the median openings and could require the construction of additional pavement to help expand the space for turning. • Median type and median opening placement may be controversial to adjacent land owners. • Visibility can be restricted at median openings due to trees planted in the median that impede a driver's view.

Source: Based on Williams et al. (*1*), Dixon et al. (*2*), and Stover and Koepke (*3*).

- Prevailing traffic operations along the corridor
- Safety performance associated with the median opening

Additional factors that should be considered when assessing if a median opening is appropriate include the available sight distance, compatibility for the design vehicle, and how the median will function as a pedestrian refuge location. These additional considerations tend to vary by state.

The following information provides a summary of the published research related to these characteristics. The project team also conducted a state-of-practice review to determine how state and regional agencies apply the research to their jurisdictions. This supplemental state-of-practice information is included where applicable.

Type of Median Openings

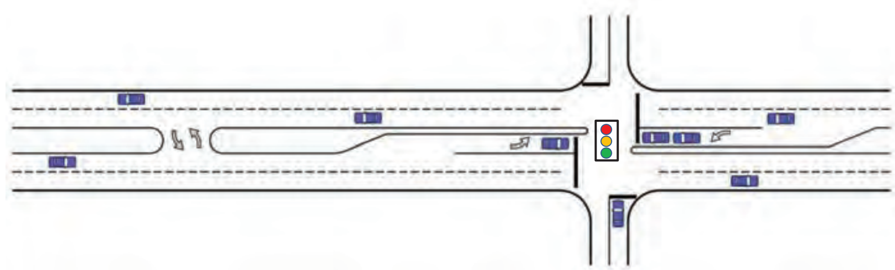
The following information summarizes the published literature related to use of the various median types. In some cases, agencies apply median configurations in a unique manner; therefore, the summary of the published literature is followed by a state-of-practice summary for agencies that stipulate how and when to use the various median configurations.

Research – Type of Median Opening

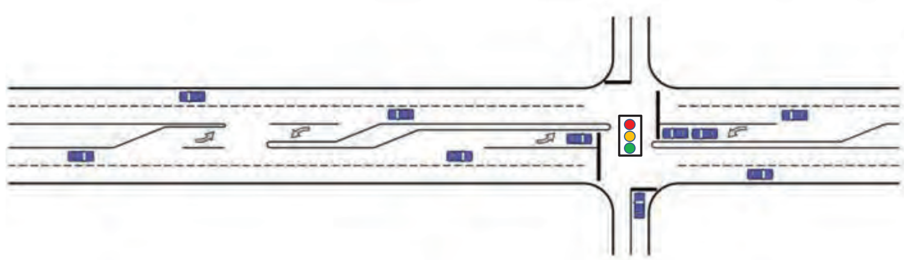
Median openings are often considered when there is a need to provide direct left-turn access to or from a major driveway, accommodate right-turn-then-U-turn maneuvers (sometimes referred to as indirect left turns), or facilitate U-turns at mid-block locations. A secondary benefit resulting from the construction of a median opening is the removal of U-turn maneuvers from proximate signalized intersections. In many cases, these median openings provide unrestricted access and are referred to as a full median opening. Figure 1 demonstrates two examples of full median opening configurations. The opening noted as Type A does not accommodate turn bays and so provides little to no vehicle storage. The Type B median opening includes up to two turn bays so that turning vehicles can shift out of the active travel lanes. Both configurations, however, enable unrestricted maneuvers within the median opening. This introduces the opportunity for conflicts between turning and crossing vehicles. The median configuration schematics are presented to depict general median opening configuration categories. The actual placement of the median opening may be shifted along the corridor. In some cases, this may result in a median opening located within the region of the turn bay for the signalized intersection.

A full median opening functions as an unsignalized intersection; however, at many locations there is a need to limit select movements, such as direct left turns, crossing maneuvers, or U-turns (*3*). One way to minimize or separate the number of conflict points is to construct a directional median opening. Figure 2, Figure 3, and Figure 4 depict examples of dual and single directional median opening configurations. Directional median openings can help improve both safety and operational performance when compared to conventional full median openings. One way directional median openings help improve safety is by preventing or limiting specific turn maneuvers, such as crossing maneuvers or direct left turns (*4, 5, 6, 7*).

A 2013 study by Qi et al. (*4*) evaluated performance issues related to urban directional median openings and recommended that full median openings not be located in the functional area of nearby intersections, as this placement creates operational and safety issues. They further noted that converting the full median opening to a directional median opening can be expected to reduce the number of crossing conflicts significantly, but the conversion will also slightly increase the number of upstream and downstream lane-change conflicts. The authors also noted that directional medians may slightly increase traffic delay for vehicles that exit a driveway and



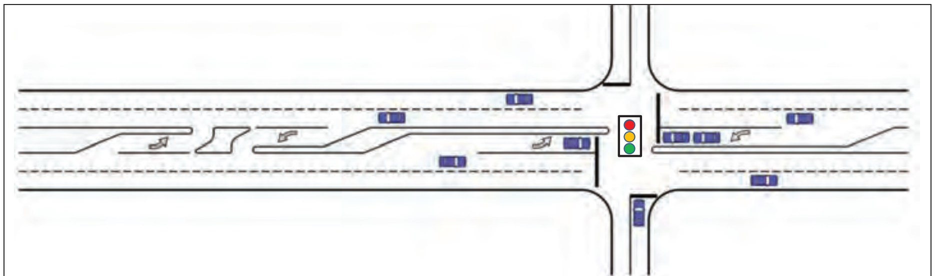
Type A. Full Median Opening without Turn Bays



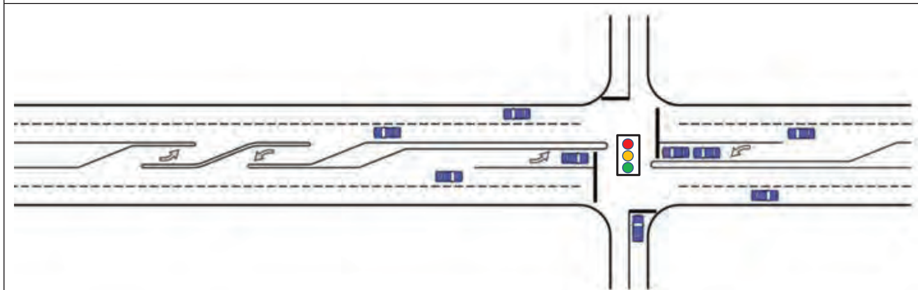
Type B. Full Median Opening with Turn Bays

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity of additional driveways, unless the driveway is essential to the median functionality.

Figure 1. Schematic of full median openings.



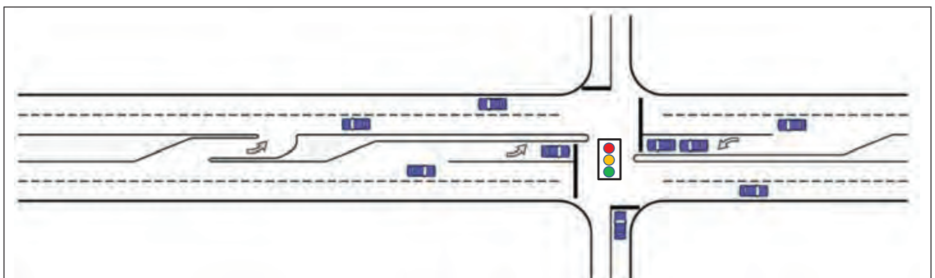
Type C. Dual Directional Median Opening with Island



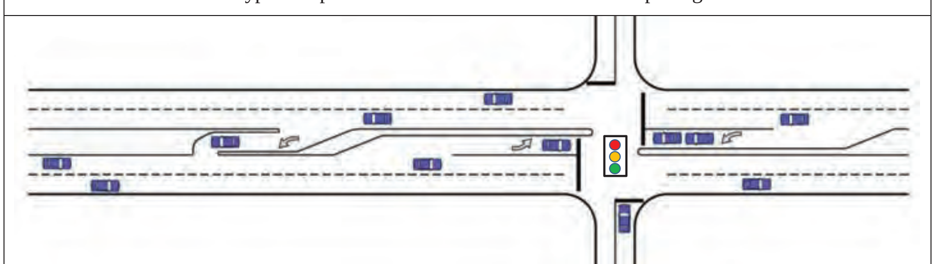
Type D. Dual Directional Median Opening with Separator

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity of additional driveways, unless the driveway is essential to the median functionality.

Figure 2. Schematic of dual directional median openings.



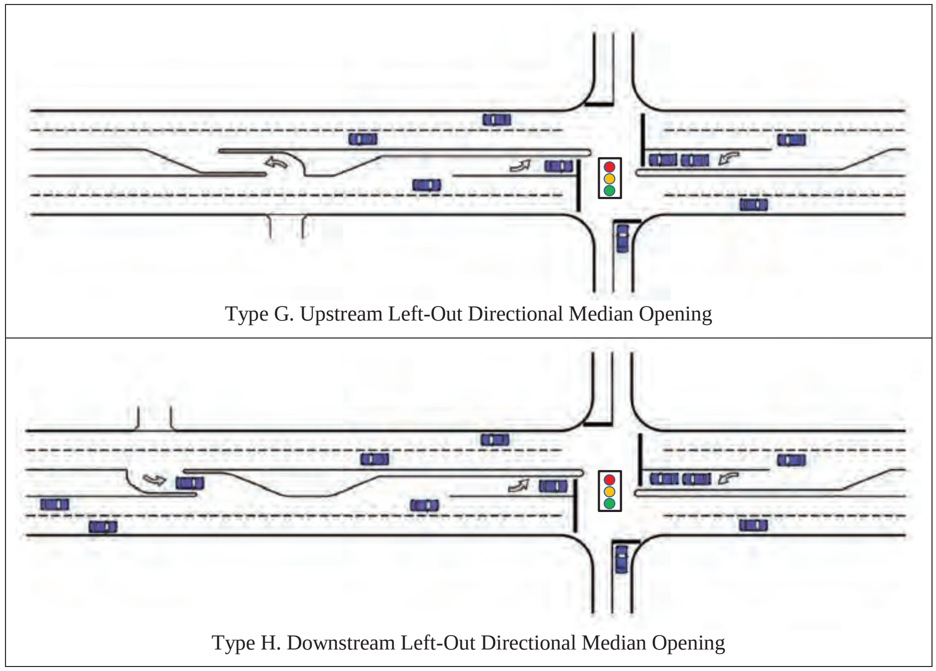
Type E. Upstream Left-In Directional Median Opening



Type F. Downstream Left-In Directional Median Opening

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity of additional driveways, unless the driveway is essential to the median functionality.

Figure 3. Schematics of single left-in directional median openings.



Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity of additional driveways unless the driveway is essential to the median functionality.

Figure 4. Schematics of single left-out directional median openings.

must make an indirect left turn. This re-routing of vehicles can also be expected to contribute to increased congestion levels.

A study by Potts et al. (*5*) examined the safety of U-turns at median openings, and a subsequent paper further determined that directional median openings can reduce crash rates by as much as one-third in some cases (*6*). They also noted that the construction of median openings upstream of a signalized intersection can help reduce concentrated U-turn maneuvers at the intersection. Similarly, median openings located downstream of a signalized intersection can accommodate left-turn and U-turn maneuvers and, in some cases, restrict left-turn maneuvers at the signalized intersection.

A 2013 study by Zhou et al. (*7*) evaluated the performance of a median treatment known as Quick Kurb as an alternative to a permanent concrete median. As part of this assessment, the researchers evaluated the use of these channelization devices for converting a full median opening to a dual directional median opening (similar to Figure 2) and to a left-in-only median opening (see Figure 3). The authors determined, using an Empirical Bayes before-after study, that the left-turn crashes were reduced by approximately 60 percent at dual directional median openings and by 45 percent for the left-in-only median treatment.

Taylor, Lim, and Lighthizer (*8*) evaluated the conversion of 54 full median openings along eight roadway segments in Michigan into dual directional median openings similar to the Type C median opening (see Figure 2). They determined that converting the full median openings reduced the number of crashes, on average, by approximately 30 percent. In particular, the two crash types classified as "rear-end straight" and "angle straight" exhibited the greatest reduction. The researchers hypothesized that this may be due to the lack of storage space and the limited visibility present in the initial full median opening configurations.

Qi et al. (*9*) noted other potential benefits to consider when determining if a median opening should be full or directional, including increased traffic capacity and enhanced operational performance of the facility. They further cautioned that the performance of directional median openings can vary depending on factors such as geometric design, traffic control configuration, environmental conditions, and the type and placement of downstream U-turn facilities. The authors also noted that directional medians can result in increased travel time, increased traffic conflicts where U-turns are accommodated, and resistance from adjacent business owners whose direct access may be affected.

Common Practices – Type of Median

Many of the guidelines related to access management do not provide recommendations about the type of median opening that should be used, but the cities of Houston, TX, and Lee's Summit, MO, as well as the State of Florida, do provide some guidance. Houston recommends that directional median openings be used wherever possible (*10*). Lee's Summit recommends that collector streets that intersect with arterials should use full median openings designed in such a way that, at some future date, they would be suitable for signal installations (*11*). The State of Florida allows the project manager complete flexibility when determining if a directional median is appropriate; however, at a minimum, the median opening must accommodate minimum storage, deceleration, sight distance, and maneuverability based on the prevailing traffic engineering standards (*12*).

Median Opening Spacing and Location

As a transportation designer or planner considers the location of median openings, he or she should weigh factors such as the location of other median openings (i.e., unsignalized intersections), driveways, and signalized intersections located near the potential median opening. The following sections summarize the research and common practices related to median opening spacing and placement decisions.

Spacing Between Median Openings or from Signalized Intersections

The spacing between a median opening and an upstream or downstream unsignalized intersection, driveway, or signalized intersection varies based on several issues, including the median type, the goal of the median opening (direct left turn versus U-turn), and basic corridor land use and operations. The following sections summarize the research and state-of-practice information related to median opening spacing.

Research – Spacing

Research that focuses on the spacing of median openings is generally based on highway design principles that have been adapted for access management applications. As far back as 1962, Moskowitz (*13*) explored how best to accommodate medians in developed areas. This California-based study explored safety and operational performance related to the placement of median openings. Moskowitz recommended that median openings along the mid-block region be based on traffic requirements, with a minimum spacing of approximately 400 ft.

In 1967, Cribbins (*14*) researched how best to locate median openings along higher-speed divided highways. As part of this study, Cribbins noted that the spacing of median openings should be rigidly controlled, with the expectation that someday the opening could be converted to a signalized intersection. Consequently, he advocated that traffic signal spacing standards be applied to median opening spacing as well.

In 1996, Layton and Stover (*15*) developed recommendations for an access management classification system and spacing standards for the Oregon Department of Transportation.

Table 3. Median opening spacing standards for suburban roads.

Functional class of roadway	Full median opening (ft)	Directional median opening (ft)
Strategic arterial	2640	Typically not permitted
Principal arterial	2640	1320
Minor arterial	1320	660

Source: Demosthenes and Elizer (*17*).

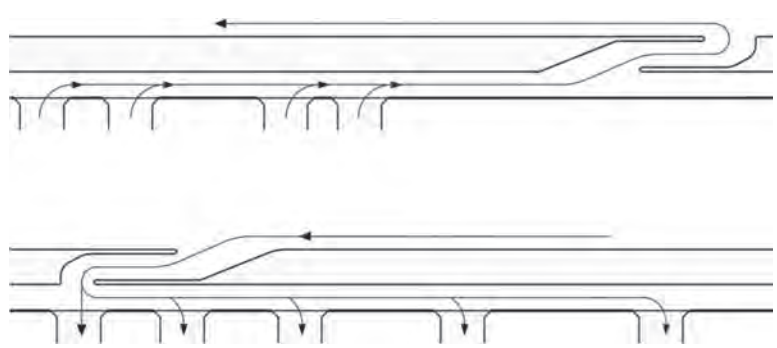
The researchers noted that a minimum spacing criterion should be based on stopping sight distance; however, the basis of this application should consider comfortable deceleration rates in lieu of rapid deceleration rates. Layton and Stover recommended potential spacing criteria for traffic signals, median openings, and driveways. At the same time as the Oregon research, the State of Florida developed a document titled *Median Opening Decision Process* (*16*). As part of this document, Florida established guiding principles for deviating from signal and median opening spacing standards. They indicated that any spacing deviation should directly consider traffic safety, traffic efficiency, and highway functional integrity. The Florida guidance specifically noted that median openings located near signalized intersections need to be positioned outside the boundaries of the intersection functional area and must also allow enough deceleration and storage for the vehicles that will use the median opening.

Demosthenes and Elizer (*17*) developed spacing standards for suburban roads, depicted in Table 3, based on the initial and subsequent recommendations noted by Layton and Stover in Oregon (*15*) as well as by Sokolow in Florida (*16*).

In 1996, a task force for the TRB Standing Committee on Access Management developed *Transportation Research Circular, Number 456*. In the appendix of that document, the task force summarized several state standards that provide additional spacing criteria (*18*). Similar recent state-of-practice information for states and cities, including the more recent Florida spacing standards, is included in the Common Practices – Spacing section.

Stover and Koepke (*3*) further note that a key issue to consider when determining the spacing between median openings is whether U-turns are permitted at the location. Because a directional median can service multiple driveways (see Figure 5), spacing configurations that can accommodate these U-turn maneuvers should be given priority. The design should allow for sufficient storage so that traffic progression along the corridor can proceed without interruption.

Chapter 17 of the *Access Management Manual, Second Edition* (*1*) notes that minimum spacing should be the sum of the turn bays and storage. When considering where to locate an opening



Source: Graphic based on Figure 6-7 of Stover and Koepke (*3*).

Figure 5. Unsignalized directional median opening serving multiple driveways.

near a signalized intersection, the *Manual* further recommends that the turn bays at the signalized intersection should be evaluated to determine if they may need to be lengthened. Priority should be given to the existing signalized intersection over the mid-block opening if optimal spacing cannot be achieved.

Table 4 shows the spacing recommendations presented in the *Access Management Application Guidelines* (*2*). The absolute minimum values are based on the assumption that vehicles will reduce their speed by approximately 10 mph while in the through lane and then decelerate at approximately 8.0 ft/sec^2. The desirable minimum values are then based on no speed reduction in the through lanes and a 6.5 ft/sec^2 deceleration rate.

Common Practices – Spacing

The spacing recommendations incorporated in the guidelines and criteria developed by the various state and local agencies generally address the spacing of median openings as one of seven types (referred to as Option 1 through Option 7 in this summary):

- Option 1: Single value for minimum spacing (Table 5)
- Option 2: Value varies based on primary road function (Table 5)
- Option 3: Value varies based on cross road function (Table 5)
- Option 4: Value based on type of median opening only (Table 6)
- Option 5: Value based on adjacent land use type (Table 6)
- Option 6: Speed-based spacing (Table 7)
- Option 7: Value based on blended conditions, including additional considerations not noted for Options 1 through 6 (Table 8)

For most of the median opening spacing criteria, the state and local agencies permit exceptions to the minimum spacing on a case-by-case basis, with particular consideration for existing sites and retrofit median accommodations. As shown in Table 5, for the Option 1 approach, the agencies typically provide a "one size fits all" minimum spacing value that can range from 400 to 1000 ft. The cities of Houston, TX, Phoenix, AZ, and Orlando, FL, use a one-eighth mile value (i.e., 660 ft).

Option 2 and Option 3 base the minimum median opening spacing on either the primary road type or the type of cross street intersection. These values range from as low as 220 ft (for spacing from other median openings) up to 1320 ft (based on a one-fourth mile value) for full median openings located on major arterials.

Option 4 provides minimum spacing criteria that are based on the type of median opening only. Locations with full median openings, as an example, have larger minimum spacing criteria than directional median openings. The guidelines do typically state that directional median

Table 4. Spacing between unsignalized median openings on divided highways.

Speed (mph)	Spacing Recommendations (ft)*	
	Absolute Minimum	Desirable Minimum
30	190	370
35	240	460
40	300	530
45	360	670
50	430	780
55	510	910

* For each car to be stored, add 25 ft to the spacing shown.
Source: Based on Exhibit 16-4 from Dixon et al. (*2*).

Table 5. State-of-practice median opening spacing – Options 1–3.

State or City	Minimum Median Opening Spacing
Option 1: Single Value for Minimum Spacing	
Indiana (*19*)	400 ft minimum (800 ft desirable) between median openings. If purpose is to accommodate U-turns, spacing should be 1300 to 2500 ft.
Houston, TX (*10*), Phoenix, AZ (*20*), Orlando, FL (*21*)	660 ft or as approved.
Bryan / College Station, TX (*22*)	1000 ft (city can approve at 500 ft if necessary).
Option 2: Value Varies Based on Primary Road Function	
Plano, TX (*23*)	310 ft from the intersection of two major thoroughfares to a street or drive. 260 ft from the intersection of two secondary thoroughfares or a secondary thoroughfare and a major thoroughfare to a residential street or a drive. 220 ft from other median openings.
Scottsdale, AZ (*24*)	1320 ft between full median openings on major arterials and 660 ft on minor arterials. 660 ft between directional median openings (that only permit left turns from street) on the major streets.
Option 3: Value Varies Based on Cross Road Function	
San Diego, CA (*25*)	600 ft for an intersection with a major arterial or collector street. 600 ft from an existing or proposed mid-block median opening. 400 ft for an intersection with a local street.
Reno, NV (*26*)	700 ft from an intersection with an arterial street. 600 ft from the adjacent existing/proposed median opening. 400 ft from an intersection with a local street.

Table 6. State-of-practice median opening spacing – Options 4 and 5.

State or City	Minimum Median Opening Spacing
Option 4: Value Based on Type of Median Opening Only	
Lee's Summit, MO (*11*)	1320 ft for full median openings. 660 ft and 400 ft for directional median openings at major and minor streets.
Mesa, AZ (*27*)	880 ft for full median openings. 660 ft from directional median openings that restrict left turns from a site.
Option 5: Value Based on Adjacent Land Use Type	
McKinney, TX (*28*)	525 ft if retail or commercial land use. 675 ft if residential land use.
Mississippi (*29*)	880 ft in urban areas and 1760 ft in rural areas.
Georgia (*30*)	1000 ft desirable if urban (maximum spacing of 2640 ft), but for low-volume locations the spacing can be reduced to 660 ft. 1320 ft if rural.
Tennessee (*31*)	1320 ft desirable if rural (range from 880 to 1760 ft). 660 ft desirable if urban (range from 440 to 880 ft).

Table 7. State-of-practice median opening spacing – Option 6.

State or City	Minimum Median Opening Spacing		
Option 6: Speed-based Spacing			
Evansville, IN (32)	Speed (mph)	Minimum Spacing (ft)	Desirable Spacing (ft)
	25–30	400	400
	35	400	460
	40	400	530
	45	400	670
	50	430	780
	55	510	910
City of Round Rock, TX (33)	Spacing criteria for directional median openings at major arterials and full median openings at minor arterials:		
	Design Speed (mph)	Nose to Nose Spacing*	
	30	500	
	35	575	
	40	650	
	45	750	
	50	900	
	*Value includes 150 ft minimum storage		

Table 8. State-of-practice median opening spacing – Option 7.

Option 7: Value Based on Blended Conditions				
State or City	**Minimum Median Opening Spacing**			
Sahuarita, AZ (*34*)	**Minimum Spacing (ft)**	**Desirable Spacing (ft)**	**Opening**	**Road Function**
	1,320	2,640	Full	Principal arterial
	660	1,320	Directional	Principal arterial
	660	1,320	Full	Minor arterial
	660	660	Directional	Minor arterial
San Jose, CA (*35*)	1,320 ft (full median opening) and 660 ft (directional median opening) if speed limit ≤45 mph.			
	Median opening should not be placed within 600 ft of a major intersection.			
	Summary of directional median opening minimum spacing thresholds for unsignalized median openings at driveways:			
	Speed Limit (mph)	**Minimum Spacing (ft)**		
	30	370		
	35	460		
	40	530		
	45	660		
	50	780		
	55	910		
Kansas (*36*)	Minimum spacing for divided highways:			
	Area Type	**Full Opening (ft)**	**Directional Opening (ft)**	
	Undeveloped	2,640	1,320	
	Developed (>45 mph)	2,640	660	
	Developed (≤45 mph)	1,320	660	

(continued on next page)

Table 8. (Continued).

<table>
<tr><th colspan="2">Option 7: Value Based on Blended Conditions</th></tr>
<tr><th>State or City</th><th>Minimum Median Opening Spacing</th></tr>
<tr><td>New Mexico (37)</td><td>
- Minimum spacing of 1,320 ft should be provided for full-access unsignalized intersections on urban principal arterials. For urban minor arterials, it is 660 ft for posted speed ranging from 30–50 mph and 1,320 ft for 55 mph.

- Minimum spacing for partial-access unsignalized intersections on urban principal arterials varies by speed as follows:

<table>
<tr><th>Speed (mph)</th><th>Spacing/Principal Arterials(ft)</th><th>Spacing/Minor Arterials (ft)</th></tr>
<tr><td>≤30</td><td>200</td><td>175</td></tr>
<tr><td>35–40</td><td>325</td><td>275</td></tr>
<tr><td>45–50</td><td>450</td><td>400</td></tr>
<tr><td>≥50</td><td>625</td><td>600</td></tr>
</table>
</td></tr>
<tr><td>Florida (12)</td><td>
Median opening spacing as follows:

<table>
<tr><th>Road and Land Use Characteristics</th><th>Full (ft)</th><th>Directional (ft)</th></tr>
<tr><td>High speed, high volume</td><td>2,640</td><td>1,320</td></tr>
<tr><td>Controlled access facilities with sparse land use development</td><td>2,640</td><td>1,320</td></tr>
<tr><td>Extensive land development with little chance for land use change</td><td>2,640 if speed limit > 45 mph, otherwise 1,320</td><td>660</td></tr>
<tr><td>Maximum land development (low speed)</td><td>660</td><td>330</td></tr>
</table>
</td></tr>
<tr><td>Tucson, AZ (38)</td><td>
Minimum desirable spacing based on the functional classification:

<table>
<tr><th colspan="2">Functional Classification</th><th>Spacing (ft)</th></tr>
<tr><td>Arterial</td><td>Urban and Suburban</td><td>660</td></tr>
<tr><td></td><td>Rural</td><td>1,320</td></tr>
<tr><td>Collector</td><td>Urban</td><td>330</td></tr>
<tr><td></td><td>Suburb</td><td>660</td></tr>
<tr><td></td><td>Rural</td><td>1,320</td></tr>
</table>

Minimum desirable spacing between unsignalized median openings:

<table>
<tr><th>Speed Limit (mph)</th><th>Spacing (ft)</th></tr>
<tr><td>30</td><td>370</td></tr>
<tr><td>35</td><td>460</td></tr>
<tr><td>40</td><td>530</td></tr>
<tr><td>45</td><td>670</td></tr>
<tr><td>50</td><td>780</td></tr>
<tr><td>55</td><td>910</td></tr>
</table>
</td></tr>
</table>

openings should include turn bays and storage and that these values need to be considered when selecting the median opening spacing. In some cases where a larger volume is expected, the minimum spacing value between median openings may not be suitable if the turn bay does not accommodate the vehicle storage demand, as this design would result in overflow of queued vehicles into the active through lanes.

The Option 5 spacing criteria bases the placement of median openings on the type of land development in the region. For commercial or retail land use in an urban area, the minimum spacing criteria tend to be smaller than for the higher-speed rural regions and residential locations, though the State of Georgia does permit use of a smaller spacing at low-volume locations even if they have somewhat higher speeds.

As shown in Table 7, the Option 6 spacing criteria use speed as an indicator for median opening spacing, where facilities that either operate or are designed to operate at lower speeds will have shorter minimum spacing values and locations with higher speeds have larger values; however, these values tend to vary between agencies. In some cases, speed is used along with other criteria to determine appropriate spacing. This condition is represented as one of the Option 7 "blended" guidelines. The spacing criterion listed in the Option 7 summary (see Table 8) uses a minimum of two or more criteria to determine the minimum acceptable median opening spacing. As an example, the State of Kansas bases this spacing on the development level of the region as well as the corridor speed.

Though there is considerable variation between agencies in determining how they manage the spacing between median openings, thresholds generally range from as low as 175 ft up to as high as 2640 ft. This large variability in spacing criteria extends to recommendations related to spacing thresholds from signalized intersections. The basis of this criteria should ultimately consider road type (primary and cross street), median type, land use type, corridor speed, traffic volume, queue storage, and proximity to intersection functional areas.

Placement Relative to Driveways

In addition to the spacing of median openings relative to other median openings, unsignalized intersections, and signalized intersections, a common consideration is the distance between median openings and driveways. The published research generally recommends that median openings directly align with a driveway or provide enough distance to prioritize U-turn maneuvers (*3*), but the project team could not identify any explicit research that helped to more clearly define this placement. The state-of-practice review, however, did include select agencies that better defined this orientation for their jurisdictions.

Three of the local jurisdictions the project team studied do provide some guidance. McKinney, TX, requires that median openings be centered on the driveways they service (*28*). Sahuarita, AZ, also recommends that median openings be centered with driveways but notes that if this configuration is not practical for corridor performance, then the median opening should be located at least 100 ft from the driveway (*34*). Finally, Frisco, TX, requires that a driveway must have a left-turn lane if the median opening and the driveway are aligned with each other. If a left-turn lane is not present at the driveway, then a 75 ft separation should be provided from the edge of the driveway to the median opening (*39*).

Key Median Opening Characteristics

The published literature notes several common characteristics that should be considered when developing median openings near signalized intersections. These characteristics can be generally classified as

- intersection functional distance/area,
- sight distance, and
- median opening design and special considerations.

Many of the issues related to these characteristics extend beyond the scope of this research effort. For example, there is extensive available literature on the design of and warrant for auxiliary lanes at signalized and unsignalized intersections. Comprehensive information related to these supplemental topics is available in the following resource documents:

- *NCHRP Report 650: Median Intersection Design for Rural High-Speed Divided Highways* (*40*)
- *NCHRP Report 745: Left-Turn Accommodations at Unsignalized Intersections* (*41*)
- *NCHRP Report 780: Design Guidance for Intersection Auxiliary Lanes* (*42*)
- *NCHRP Report 420: Impacts of Access Management Techniques* (*43*)

Intersection Functional Distance/Area

Content related to functional distance is included in the published literature; however, the greatest variability of this information is linked to the differences in the individual functional distance components for different agencies. The following briefly summarizes the research and state of practice.

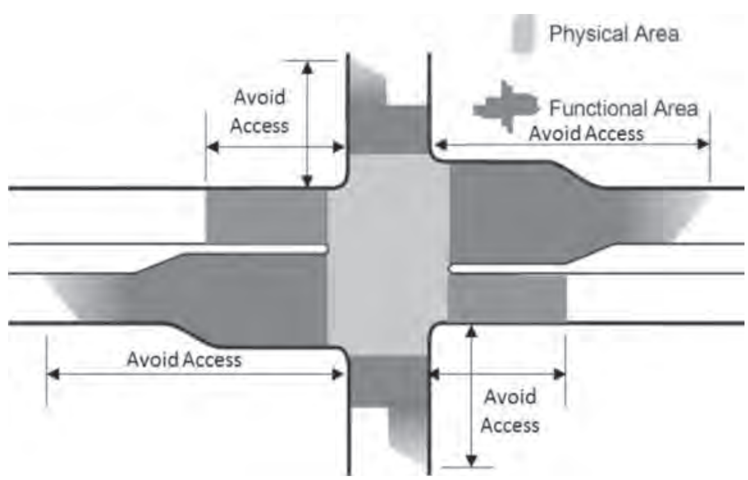
Research – Intersection Functional Distance/Area

A prevailing theme throughout the published research literature is that median openings should not be constructed within any intersection functional areas. In some cases, an additional offset is recommended upstream of the functional area (*1, 2, 3, 12, 15, 18*). Figure 6 depicts the various functional distances for each intersection approach and departure. At locations with left- and right-turn lanes, the functional distance can be different for the left- and right-side approaches on the same intersection leg.

The concept of functional area is widely accepted; however, characteristics that may vary between locations include the length of the deceleration distance, of the taper, and of storage. These vary between agencies and regions (see the following state-of-practice summary) and are generally related to the time of day. An additional concept that should be considered is that of maintaining access windows. Figure 7 depicts the access window concept for a facility without medians. The placement of driveways in this example is based on regions where the intersection functional areas do not overlap. This same concept should be applied to facilities with medians since the unsignalized intersection is also characterized by a unique functional area. The published literature, however, does not explicitly address the parameters associated with access windows at median locations.

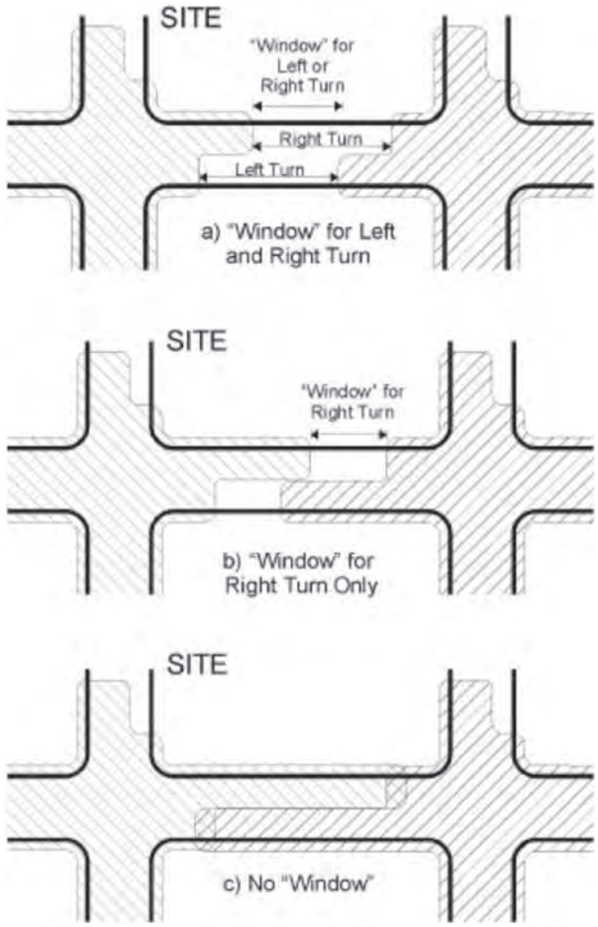
Upstream functional intersection distances will vary depending on corridor speed, queue storage needs, turn-lane taper criteria, and typical deceleration rates. As shown in Table 9, the downstream functional distance is more commonly based simply on the sum of vehicle acceleration distance and taper distance.

The following state-of-practice summary identifies the key information used by agencies when determining their upstream and downstream functional distances.



Source: Exhibit 14-1 of Williams et al. (*1*).

Figure 6. Boundaries of intersection functional area.



Source: Exhibit 14-13 of Williams et al. (*1*).

Figure 7. Access windows concept.

Table 9. Ideal downstream functional distance.

Speed (mph)	Acceleration Distance (ft)	Typical Taper Distance (ft)	Downstream Functional Distance (ft)
20	100	60	160
25	150	80	230
30	220	100	320
35	320	120	440
40	440	140	580
45	580	160	740
50	770	180	950
55	1,000	200	1,200
60	1,300	220	1,520
65	1,750	240	1,990
70	2,320	260	2,580

Source: Exhibit 14-11 of Williams et al. (*1*).

Common Practices – Intersection Functional Distance/Area

For the agencies evaluated as part of the state-of-practice summary, key issues related to intersection functional distance can be categorized as queue or storage assumptions for developing turn-lane criteria and left-turn lane requirements at median openings or adjacent signalized intersections.

Several jurisdictions have specific storage criteria for median opening turn bays and adjacent intersections. Table 10 summarizes the storage requirements for seven jurisdictions. Common storage lengths range from 40 ft up to 200 ft.

In addition, McKinney, TX (*28*) requires that the length of the left-turn lane be based on the storage of the expected queue length during the average peak period. Tucson, AZ (*38*) requires the median opening to be far enough from the signalized intersection to avoid any queue interference. The storage should be designed to accommodate requirements for future demand.

Sight Distance

Sight distance requirements are a fundamental need for all roadway locations. The following section reviews the research and state-of-practice information related to sight distance.

Many of the jurisdictions require the use of left-turn lanes at some or all median opening locations. Table 11 identifies the turn-lane requirements for the agencies included in the state-of-practice assessment.

Research – Sight Distance

As noted previously, researchers have focused primarily on stopping sight distance as a metric for assessing median spacing criteria. AASHTO's *A Policy on Geometric Design of Highways and Streets* (*48*), commonly known as the Green Book, provides recommendations for stopping sight distance, intersection sight distance, and decision sight distance. The published literature has primarily focused on stopping sight distance for median opening considerations.

Table 10. Storage requirements at turn bays/lanes.

Jurisdiction	Storage Requirements
Bryan / College Station, TX (*22*)	50 ft – local 80 ft – collector (rural or minor) 100 ft – collector (other) 200 ft – arterial
Plano, TX (*23*)	Based on function of intersecting roads: 60 ft – major with residential or with private drive 60 ft – secondary with residential or with private drive 100 ft – major with secondary or with private drive 100 ft – secondary with major or with another secondary 150 ft – major with major
Frisco, TX (*39*)	150 to 250 ft
Mesa, AZ (*27*)	Requires storage for both directions (values may vary)
Boonville, MO (*44*)	40 ft for rural median openings 60 ft for urban areas
Raleigh, NC (*45*) Florida (*12*)	Based on actual data, if left-turn volume is minor or unknown, assume: 100 ft (i.e., 4 cars) in urban and suburban areas 50 ft (i.e., 2 cars) in rural areas and small towns

Table 11. Left-turn lane/bay requirements.

Jurisdiction	Left-Turn Lane/Bay Requirements
Bryan / College Station, TX (*22*) Frisco, TX (*39*); Houston, TX (10); McKinney, TX (*28*); Plano, TX (*23*); Lee's Summit, MO (*11*); Georgia (*30*)	Required at all median openings
New Jersey (*46*)	Highly recommended at median openings
Wisconsin (*47*)	• Required at median openings of urban low-speed roads unless daily traffic volume is less than 400 vehicles or left-turn peak is less than 20 vehicles per hour. • At median openings on high-speed divided highways. • At intersections on a two-lane community bypass.

Common Practices – Sight Distance

As previously indicated in the median spacing section, sight distance can be used to define minimum separation thresholds. The State of Florida (*12*) further suggests that locations that must also accommodate U-turn maneuvers should adhere to the speed-based thresholds shown in Table 12.

Boonville, MO (*44*) and Lee's Summit, MO (*11*) are example agencies that explicitly indicate that median openings should not be constructed at locations where the sight distance is not adequate.

In addition to using sight distance to define minimum separation thresholds, the individual design characteristics of a median opening may have sight distance constraints, such as opposing left-turning maneuver obstructions or blockage by another vehicle also positioned in the median area.

Median Opening Design and Special Considerations

The review of the published research and state of practice identified additional recommendations about other median opening considerations. Most often, these additional considerations focused on the design vehicle and accommodation of road users other than motor vehicles.

Design Vehicle

Much of the literature generally states that the median opening should be designed to accommodate the largest design vehicle for the facility (*35, 37*). In many cases, this recommendation

Table 12. Florida sight distance values at locations with U-turns at median openings.

Speed (mph)	Sight Distance (ft)
35	520
40	640
45	830
50	1,040
55	1,250
60	1,540

Source: Florida DOT *2014 Median Handbook* (*12*).

Table 13. Median opening control radii.

Radius	Indiana Vehicle Type	New Jersey Vehicle Type
40	P and SU	P and SU-30
50	SU and WB-40	SU-30, SU-40, Bus, WB-40
75	WB-40 and WB-50	SU-40, WB-40, WB-50, WB-62
130	--	WB-62, WB-67

is supplemented by a recommendation to use turning templates to verify the configuration can handle the design vehicle. Indiana (*19*) and New Jersey (*46*) provide specific guidance about the recommended radii, as shown in Table 13.

Design vehicles should also be extended to emergency vehicle and transit needs in the region.

Pedestrians

The state-of-practice findings noted that a median with a width of 6 ft or more should be maintained at median opening locations so as to provide pedestrian refuge (*22, 46*). At locations with curb, this width extends from the face of curb to the face of curb. Frisco, TX (*39*) further requires that median openings accommodate all crosswalks.

Identified Gaps in Knowledge

During the literature and state-of-practice reviews, the project team noted several potential gaps in knowledge that, collectively, can help better define the operational and safety impacts of placing an unsignalized median opening near a signalized median opening. In many cases, these items were beyond the scope of NCHRP Project 15-64; however, they are documented below so that, where needed, future research can further address each item. The gaps are summarized as follows:

- Functional area/distance of the median opening configurations.
- Minimum spacing between the end of the median opening and the beginning of the signalized intersection left-turn taper, where applicable.
- Influence of left-turn lane changing and weaving on the placement of median openings.
- Influence of right-turn maneuvers at signalized intersections and how associated vehicles may influence unsignalized median opening placement.
- Impact of traffic signal timing and/or corridor progression on the placement of various types of median openings.
- Operational effect of a direct left turn versus a U-turn at the median opening location related to traffic conditions at a nearby signalized intersection.
- Safety effects of median opening spacing.
- Impacts associated with how median openings accommodate ingress versus egress and how that influences operations.
- Acceptable time gaps for vehicles at unsignalized median openings in close proximity to signalized intersections.
- Impacts of decision sight distance and/or intersection sight distance on median opening placement.
- Changes in the access window concept as it applies to median opening placement relative along a corridor.

Chapter 6 provides a summary of the resolution of each gap and how the item, if applicable, was addressed as part of this project.

Chapter Summary Remarks

In the published research, considerable attention has been given to the use of medians and their mid-block openings, but very little consideration has been given to the placement of an unsignalized median opening near a signalized intersection. Though the data that focus on this specific target location may be limited, the published literature and state-of-practice applications provide some guidance as to influential factors that should be considered as part of this research effort.

CHAPTER 3

Data Collection and Reduction

The primary Phase II activities for NCHRP Project 15-64 included the acquisition and analysis of available data to assess the operational and safety performance of unsignalized median openings near signalized intersections. This analysis then informed content included in the companion guideline document specific to this median treatment. This chapter summarizes the data acquired for this research effort.

Data Sampling Plan

The project team initiated preliminary site identification in Arizona, Kansas, Missouri, Pennsylvania, and Texas so that sites from these regions could be included in the study. This effort included oversampling of some of the data so that site selection could then be strategically accomplished based on frequency of median opening configurations as well as median opening location proximate to the signalized intersection. The site selection process excluded locations with recent or active construction. The project team members accomplished this inspection by using archived aerial photographs.

The candidate unsignalized median opening configurations included several potential configurations (as previously noted in the literature review):

- Full median opening with no turn bays (see Figure 1)
- Full median opening with at least one turn bay (see Figure 1)
- Dual directional median opening (see Figure 2)
- Single directional median opening (see Figure 3 and Figure 4)

In some cases, the median opening configuration is unique, as it has been customized to the existing condition. For example, locations with full median openings and at least one turn bay are quite common, but the geometric configuration of the turn bays as well as the distance between the opening and the signalized intersection can vary considerably. Therefore, the research team based the sampling plan and associated sample size on the critical evaluation elements for the median opening treatment. For the purposes of developing the sample size, the analysis used the distance from the median opening to the downstream signalized intersection as a controlling variable for each median treatment type. It is worth noting that a sampling approach could also have focused on the distance from the signalized intersection to the opposing-direction upstream median opening, but since the study corridors were two-way facilities, use of the intersection approach distance similarly captured the majority of the locations for the opposing directions.

Defining the Controlling Variable

The aerial photograph scanning procedure helped the project team define the four primary median opening categories. In addition to this larger scanning effort, the project team extended the scanning activity for the Texas sites by measuring the distance from the median opening (the edge closest to signalized intersection) to the projected curb line for the downstream signalized intersection. This distance represents the primary explanatory variable that is the focus for the sample size analysis. Because the distances between the median opening and the signalized intersection can vary significantly, an upper boundary for this distance was needed prior to initiating the sample size calculation.

The focus of this research effort is an assessment of median openings "near" signalized intersections. The term "near" must therefore be defined. Most of the median opening locations identified during the aerial scanning were in urban or suburban locations. The vehicle operating speeds at these facility types can be expected to range up to 55 mph. For the purposes of defining "near," the project team applied the stopping sight distance for design speeds of 60, 55, 50, 45, and 40 mph to the sampling effort (see Table 14). These distances represent an upper threshold by which the intersection may be expected to function independent of a median opening since drivers would have adequate distance for stopping.

For higher-speed conditions, the standard deviation of the distance between the median opening and the signalized intersection will be greater. This typically results in larger sample size requirements. Alternatively, the use of a very low design speed may not fully capture all of the median openings that do not function independent of the signalized intersection. Therefore, the sample size calculations assumed distances up to each of the design speeds so that it is clear how the increased distances influenced the number of required study sites.

Determining the Sample Size

Based on the aerial photograph scanning activity, the number of sites for each type of median opening varied considerably. The project team members were not able to locate any state or local agency that maintains a database that documents the location and type of median openings, so the ability to develop a random sample from a larger existing database was not available for this effort. Though the sample depicts only the sites that team members could identify using aerial photo scanning techniques, it generally provided a reasonable representation for the distribution of the median types available for review. Table 15 summarizes the types of median openings identified using this scanning technique for all identified sites and for a larger, Texas-specific group of candidate locations. The identification of locations with median openings near signalized intersections occurred primarily at urban locations. The project team was not able to identify similar configurations for rural locations.

Of the 225 sites inspected by the team, 66.6 percent (150 sites) had full median openings with one or more turn bays. In addition, 17.3 percent (39 sites) of the observed sites include single-direction median openings, with 23 of them located downstream of the signalized intersection and 16 of them located upstream. In Table 15, these median types, which make up almost 84 percent of the sites, are shaded for emphasis. It is noteworthy that full median openings without

Table 14. Stopping sight distance for level terrain.

Design Speed (mph)	Stopping Sight Distance (rounded in ft)
60	570
55	495
50	425
45	360
40	305

Source: *A Policy on Geometric Design of Highways and Streets* (*48*)

Table 15. Frequency of each median opening type.

Median Type	Frequency – All Scanned Sites	Percentage – All Scanned Sites (%)	Frequency (Texas Sites)*
Full Median Opening without Turn Bays (Type A)	18	8	12
Full Median Opening with Two Turn Bays (Type B)	86	38.2	31
Full Median Opening with One Turn Bay (Type B)	64	28.4	23
Dual Directional Median Opening with Island (Type C)	13	5.8	10
Dual Directional Median Opening with Separator (Type D)	5	2.2	0
Single Upstream Directional Median Opening (Types E and G)	16	7.1	9
Single Downstream Directional Median Opening (Types F and H)	23	10.2	9
Total	**225**	**100**	**94**

*Used for sample size calculations.

turn bays and dual directional median openings in close proximity to signalized intersections appear to be used at considerably fewer sites, with a total of 16 percent of the studied sites falling within these categories.

Also depicted in Table 15 is a summary of the subset of scanned sites located in Texas. This subset was the basis for the sample size calculations. The project team conducted an expanded assessment for these locations and, using scaled aerial maps, measured the distance from the median opening to the extended curb for the downstream signalized intersections. By calculating the mean and standard deviation for the distance at these locations, team members estimated recommended sample sizes. The sample size activity resulted in a recommended sample size of 25 locations for the Type B median opening configuration. This median type was the most commonly observed type during the scanning activity. Based on feedback from panel members for NCHRP Project 15-64, the project team then proceeded to evaluate Type B median openings for the remainder of this effort.

Site Identification

Identification of candidate study sites can present a challenge when a larger database is not available from which to extract a random sample. For this effort, the project team based the analysis on data collection at 25 sites with the following breakdown:

- Arizona – six sites
- Kansas City (Kansas) – five sites
- Kansas City (Missouri) – two sites
- Pennsylvania – six sites
- Texas – six sites

In addition, the project team was able to acquire detailed crash data for Arizona and Texas. The team supplemented the data for the six Arizona and six Texas study sites with comparison data for an additional 12 Arizona and 12 Texas sites. These additional 24 sites did not have median openings and were located near the primary study sites. The inclusion of these additional comparison sites enabled the research team to further evaluate crashes at locations with and

Table 16. Example stratified site assignment approach.

Geographic Region	Distance from Median Opening to the Projected Curb Line at Intersection (ft)				Regional Total
	0 to 249	250 to 304	305 to 359	360 to 425	
Arizona	1	2	2	1	6
Kansas/Missouri	2	1	2	2	7
Pennsylvania	2	1	1	2	6
Texas	2	2	1	1	6
Total per Distance Threshold	7	6	6	6	25

without medians. The team only used these supplemental data for this crash comparison effort and not for other analyses since these sites did not have median openings.

The five focus states provided geographic representation across the United States and presented the most cost-effective data collection options for the project team, thereby enabling this relatively large number of study sites at minimal cost. Based on the aerial scanning activity previously described and the subsequent state-of-practice assessment for all states, there do not appear to be any significant geographic differences between the common median designs; however, it is feasible that there may be differences in regional driver characteristics.

A common tendency when identifying study locations is to evaluate the sites with the most obvious issues; however, this approach introduces a site selection bias. Therefore, the project team proposed identifying corridors with median openings, compiling a list of median openings based on the use of aerial photograph scanning techniques along the corridor, and then randomly selecting the study samples from this expanded dataset. This approach required a stratified sampling technique, with a number of sites assigned to a geographic location and the assignment of a target distance threshold between the median opening and the signalized intersection at each of these locations. This distance was based on the previously identified stopping sight distance critical variable criteria. For example, for a definition of the median opening distance "near" value of 425 ft (based on the 50 mph design speed stopping sight distance), the site selection process used a matrix format to assign a geographic location and a distance threshold from 360 ft to 425 ft. Table 16 depicts how the sites were then assigned for each geographic region and distance criteria.

Site Data Collection Plan

A critical component to an effective evaluation of the median openings in this study is the identification and collection of contributing site information. The analysis included an operational and safety assessment. For this effort, the project team acquired detailed geometric information for each site, including site-specific dimensions, operational data (volume, travel time, signal timing, etc.), and crash data (where available). Table 17 summarizes the data collection elements that the project team acquired.

The operational data collection activities (shown in the lower portion of Table 17) focused on how traffic operations at the nearby intersection and at the median opening will influence characteristics like queue length, turning and through volumes, and delay. The project team also identified wrong-way maneuvers and the type and frequency of these at-risk activities.

As part of the data collection process, the project team positioned two to four video cameras at each study site during both peak and non-peak traffic volume periods for a total of approximately

Table 17. Data collection elements and potential sources.

Data Measure	Potential Data Collection Method
Physical Site Information (used for Operational and Safety Analysis)	
Intersection geometry (e.g., angle of intersection, distance to nearby intersections, other geometric elements)	Aerial photos and site inspection
Median opening design and configuration (e.g., full access, directional access, offset left turns, geometric characteristics of opening, opposing direction lanes, and access point)	Aerial photos and site measurement
Cross-section geometry (e.g., number, width, configuration of lanes)	Aerial photos or transportation agencies' databases
Horizontal geometry (e.g., left-turn lane length, spacing between movements)	Aerial photos or plan/profile sheets
Available space to facilitate U-turns, such as loons or extra lane width	Aerial photos and site inspection
Traffic control devices (signs, signals markings), including posted speed limit	Aerial photos, Google Street View, or site inspection
Roadside development, including pedestrian and bicycle accommodations and driveways (including operational configuration of the driveways)	Google Street View or site inspection
Presence of bus stops or other transit services	Aerial photos, Google Street View, or site inspection
Operational Data*	
Peak and off-peak traffic volumes	Video, on-site visual data collection
Delay/gap acceptance at median opening	Video, on-site visual data collection
Queue length	Video, on-site visual data collection
Traffic volume by vehicle type	Video, historic permanent loop data
Stops (frequency, length)	Video, on-site visual data collection
Speed limit and other signing and marking configurations	Site inspection, transportation agencies' databases, or Google Street View
Percentage or number of trucks (presence of buses, pedestrians, bicycles, were minimal)	Video, historic permanent loop data
U-turning vehicles or other operations that could affect the above measures	Video
Conflicts (may test gap acceptance to assess conflict likelihood)	Video, on-site data collection

* Video data extended approximately 8 hours per site during daylight conditions.

eight hours of data per study location. Figure 8 depicts an example of a two-camera configuration. This layout is based on a 300 ft radius. At many locations, however, a clear field of view could be obstructed due to road geometry, signage, vegetation, or similar site features. For these locations, up to four cameras were used to facilitate data collection.

Prior to each site visit, the team members used aerial photography tools such as Google Earth to determine preliminary dimension information. Included in this "desk survey" activity was identification of island nose type, a Google Street View inspection of site features such as traffic signs, and an assessment of unique characteristics at the site that could rule it out as representative for that specific median type. The project team also contacted the local jurisdictions and acquired permission to collect data at the study sites.

Appendix A of this report documents in more detail the data collected from each site. As part of data collection, the project team acquired several specific dimensions for each site. Figure 9 shows two examples of the type of information acquired for a Type B median opening (i.e., a full median opening with at least one turn bay). Field operational data are presented in Appendix B.

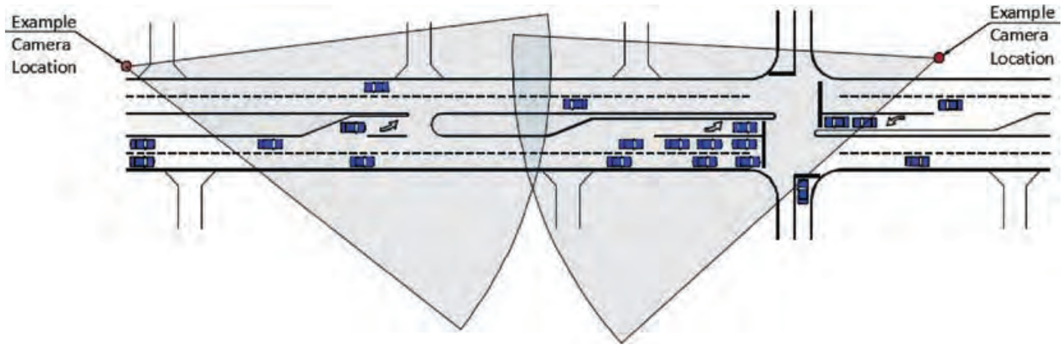
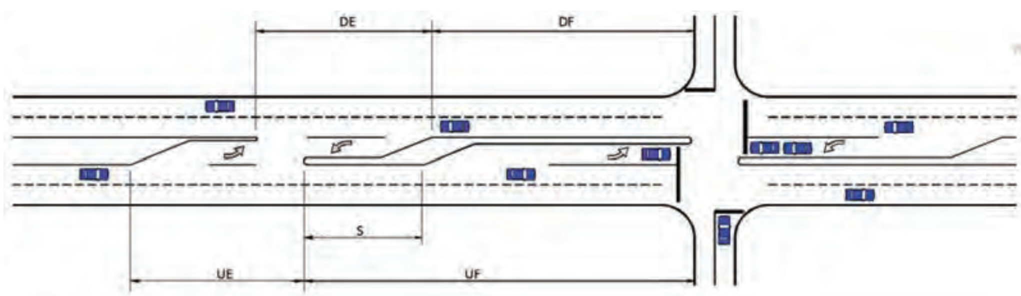
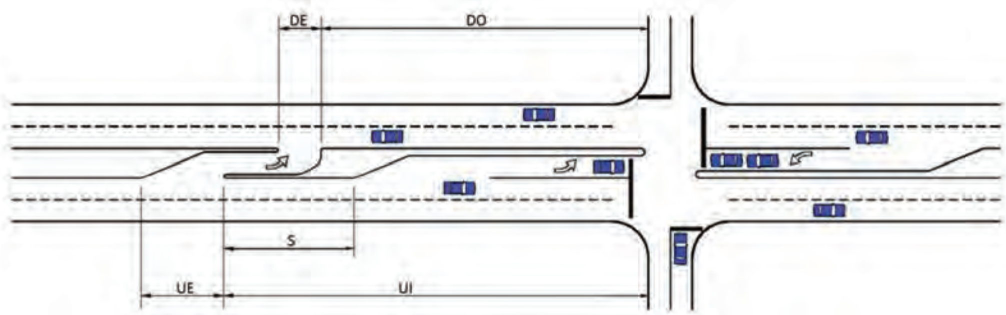


Figure 8. Example two-camera configuration (based on 300 ft radius).



Dimensions for Full Median Opening with Turn Bays



Dimensions for Single Upstream Directional Median Opening

where:

- DE: Downstream Longitudinal Exposure Distance
- DF: Downstream Distance to Full Median Opening
- DO: Distance to Downstream Out
- UE: Upstream Longitudinal Exposure Distance
- UF: Upstream Distance to Full Median Opening
- UI: Distance to Upstream In
- S: Separation from Beginning of Signalized Intersection Taper

Figure 9. Example key dimensions for study sites.

Collection Plan for Crash Data

As part of the overall study, the project team worked with local agencies to acquire crash data for the selected sites. Due to the mixture of sites located on state-maintained facilities versus locally maintained roads, the team determined that it was not feasible to acquire crash data for all 25 sites. Ultimately, team members were successful in acquiring crash data for the study sites in Arizona and Texas and were therefore able to assess crash data from these two states only. Because this assessment included comparison sites without median openings, this corridor approach analysis could not directly assess the influence of crashes in the immediate vicinity of the median opening and could only compare crashes along the intersection approach.

Due to the limited availability of site-specific crash data for all sites, the team also acquired data from the FHWA Highway Safety Information System (HSIS) database to serve as a primary source of information for an expanded analysis of crashes located in the immediate area of the median opening. HSIS intersection, roadway, and crash data are available for several states, but the team selected the California data for the final analysis because inspection of aerial photographs demonstrated that California used similar median openings as the other study sites. The HSIS-based safety analysis required matching the crash data with median opening locations. Chapter 5 provides extended information about the crash data analysis effort for this project.

CHAPTER 4

Operational Analysis

Often, the term "operational analysis" is directly associated with an assessment of corridor speed characteristics; however, for this research effort, the project team focused on facility user interactions. The placement of an unsignalized median opening near a signalized intersection can create overlapping influence zones, resulting in user confusion related to turn-lane entry, intersection encroachment, extended queues, disruption of transit stops, and numerous additional conflicts. The operational analysis focused on these types of roadway activities. The terminology used for the traffic volume data is depicted in Figure 10.

Overview of Potential Variables Used in Statistical Analysis

Traffic Volume

The research team acquired comprehensive traffic volume information that included traffic counts for individual movements (as depicted in Figure 10). These data are included in Appendix B, but Figure 11 provides a depiction of the traffic volume thresholds at each site and throughout the study periods. Similarly, Figure 12 depicts the traffic volume distribution for the turning vehicles that used the median opening during the study period.

Figure 13 further defines the various components for each point on Figure 11 and Figure 12.

Traffic Signal Timing and Progression

The research team acquired the signal timing and type of signal control for the study locations. This detailed information is included in Appendix B. The subsequent operational evaluation focused on how characteristics related to signal timing directly influenced operations. The actual signal timing and traffic control configurations were not determined to be significant, but the evaluation also identified how frequently the queue from downstream intersections blocked the median openings. Though included in the initial statistical models, ultimately this variable was also not determined to be significant.

Though the field data did not provide insightful information to help better understand the influence of traffic signal timing on corridor operations, corridors that have pre-timed traffic signals are candidates for progression. When progression is prioritized along a corridor, traffic will initially travel in a platoon. This behavior provides better opportunities for gaps in traffic, which ultimately helps develop gaps for vehicles exiting median openings.

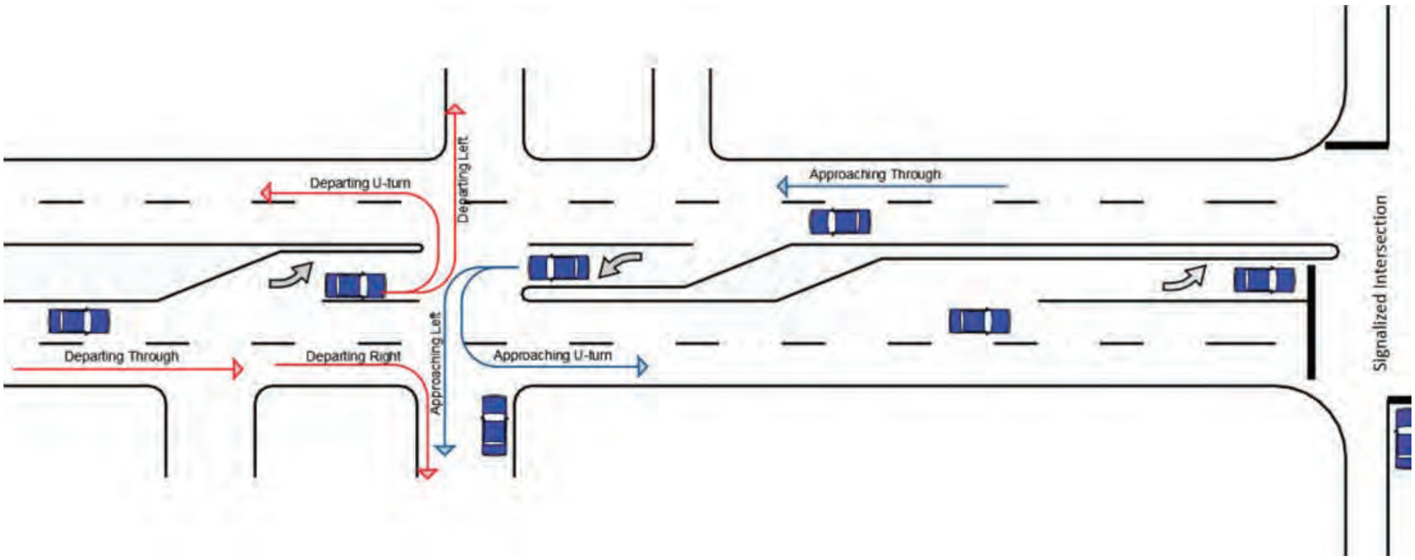


Figure 10. Movement descriptions used in analysis.

Erratic or Wrong-Way Maneuvers

For the purposes of this study, an erratic maneuver is defined as any event that includes braking, changing lane, or weaving to avoid any possible conflict between two or more vehicles or road users. The focus of this is targeted toward vehicles positioned at an unsignalized median opening near a signalized intersection. Figure 14 depicts the region of interest for this assessment.

Often, an erratic maneuver can occur while a vehicle is attempting a legal maneuver. Though this is of interest, this project further focused on illegal maneuvers that, if another vehicle were present, could lead to a crash or, at a minimum, a deterioration of vehicle operations. Figure 15 depicts example illegal maneuvers observed at the study sites.

A total of 20 wrong-way driving maneuvers occurred as the vehicle departed the median opening at the study sites. As noted in Figure 15, these wrong-way maneuvers were typically at

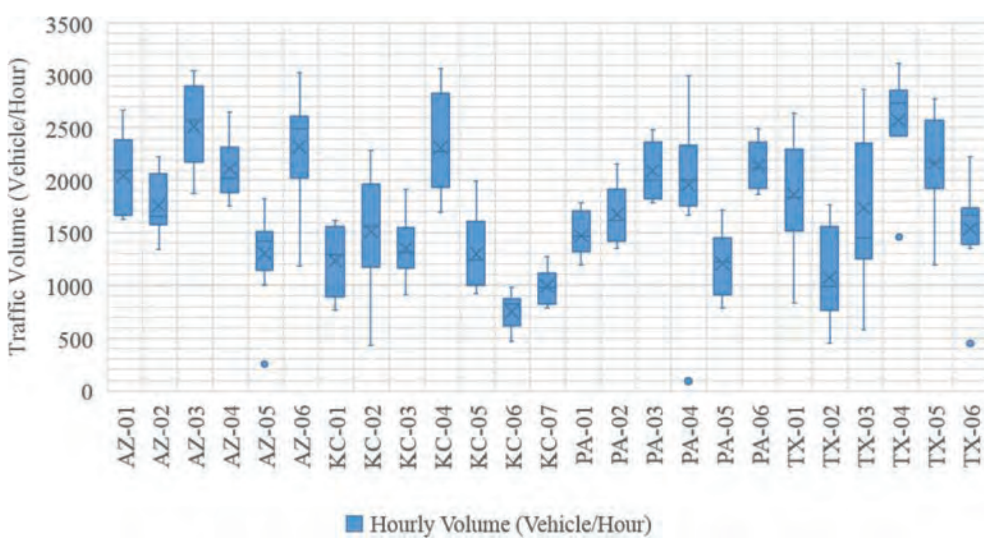


Figure 11. Traffic volume distribution for the study sites.

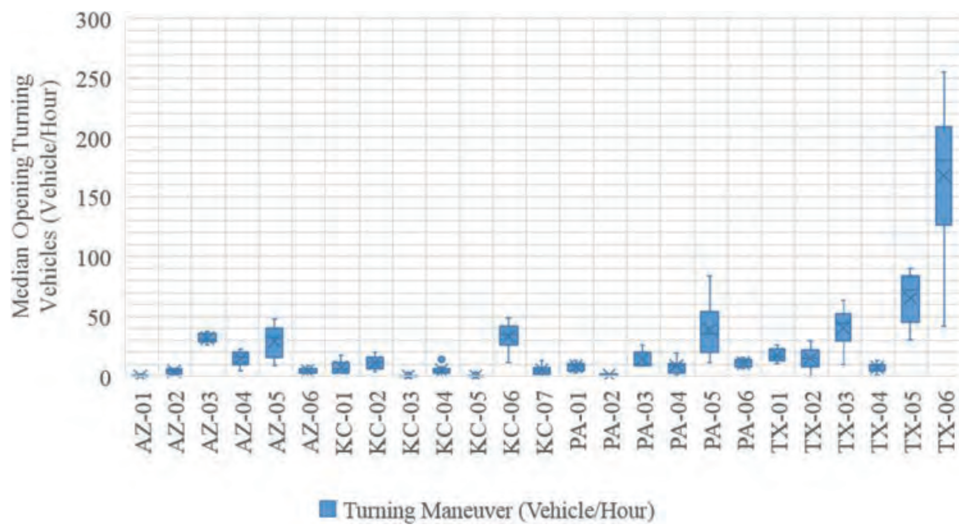


Figure 12. Traffic volume distribution for the median opening turning vehicles.

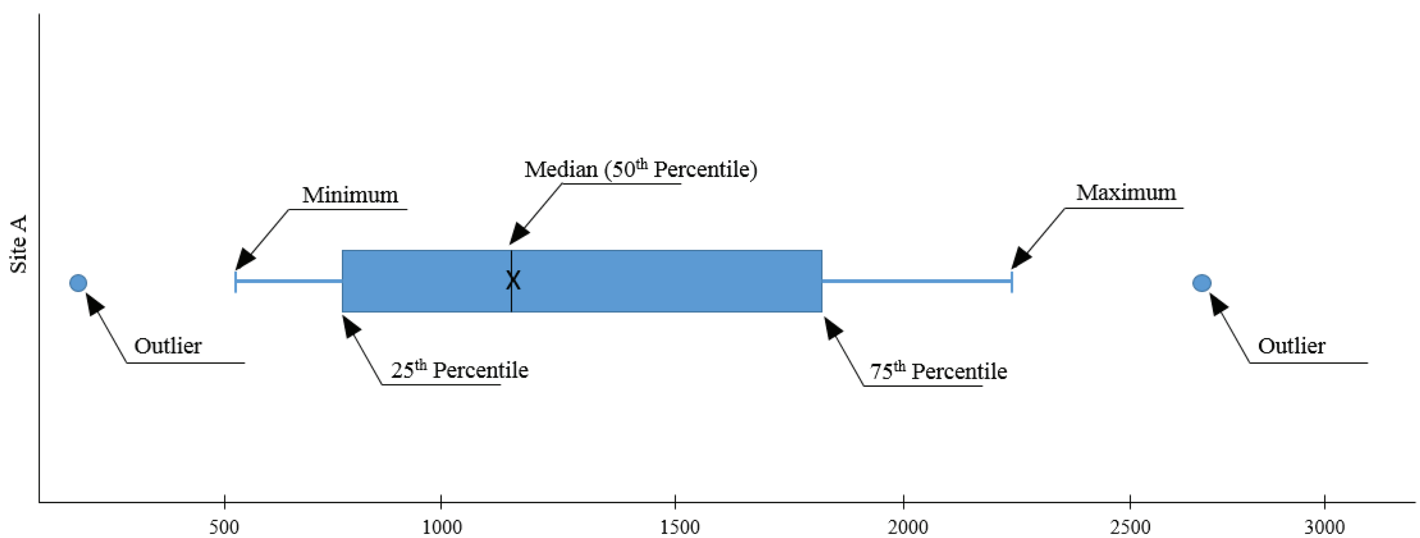


Figure 13. Definition of box plot points.

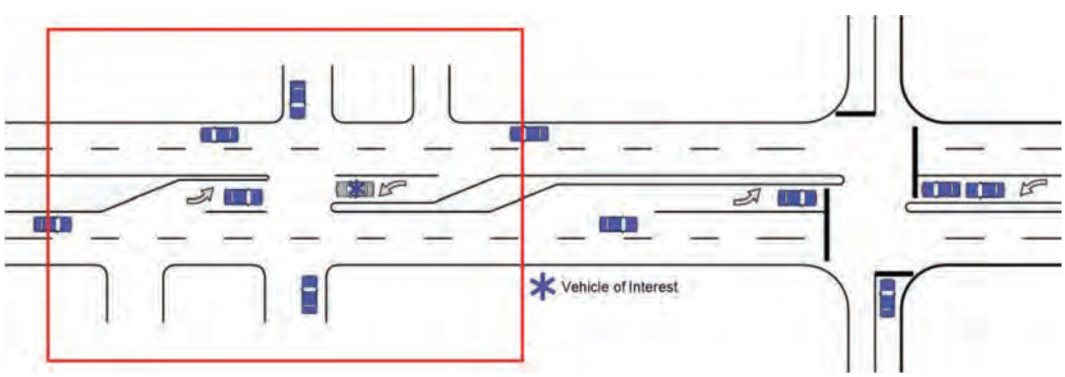
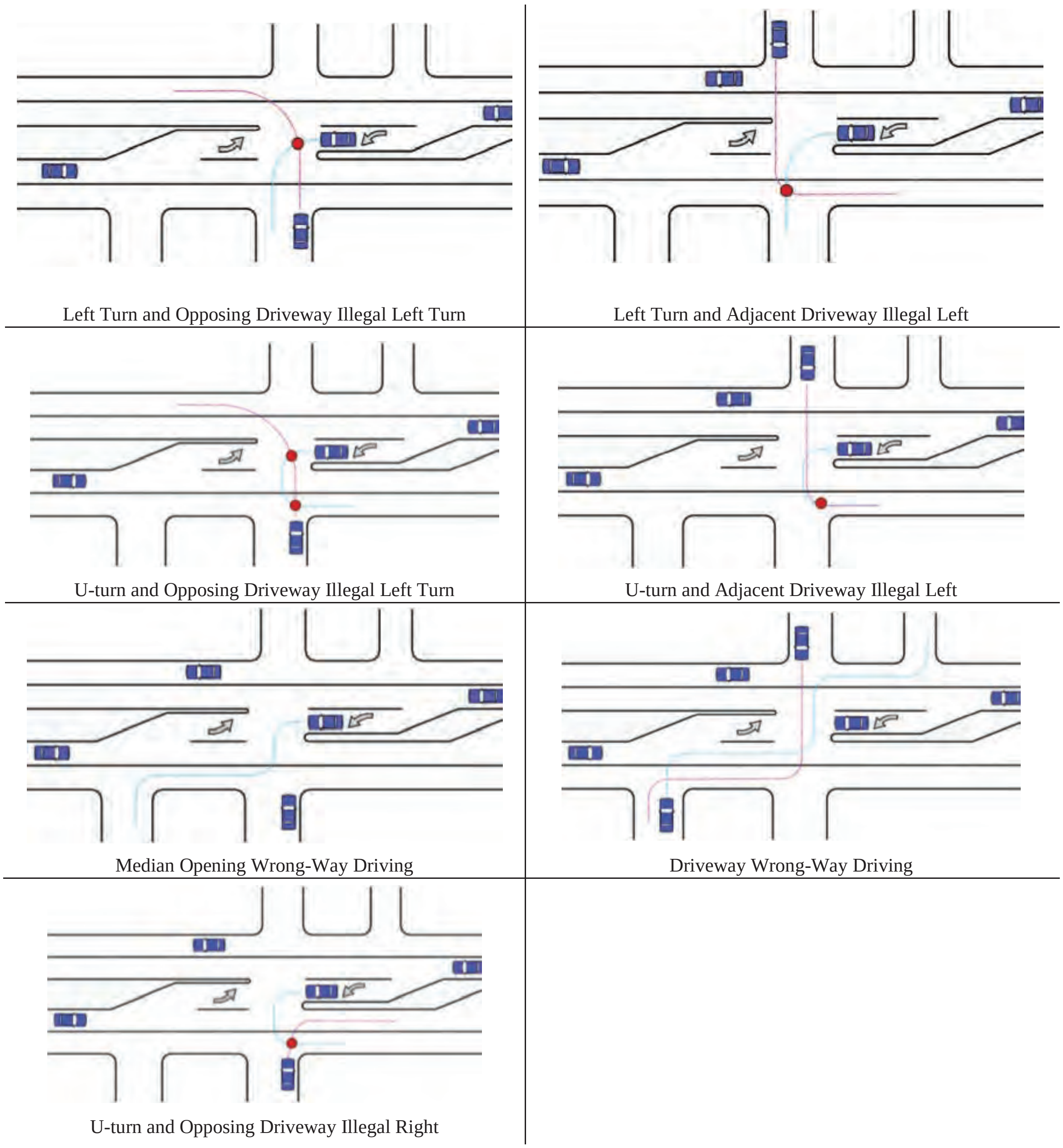


Figure 14. Region of interest for erratic maneuver evaluation.



Note: "Opposing Driveway" refers to the driveway located on the leg receiving the main lane vehicle that is turning at the median opening. "Adjacent Driveway" refers to the driveway on the leg from which the vehicle turning at the median originated.

Figure 15. Example erratic maneuvers observed at study sites.

locations where drivers used the median opening to facilitate access to upstream driveways at opposing lanes. Appendix B further summarizes the observed wrong-way maneuvers that were also identified at driveway locations.

Defining Conflicting Driveways

Figure 16 depicts how the research team documented the number of conflicting driveways. A conflicting driveway can be any driveway where vehicles that are exiting or entering the location may interfere with the operation of vehicles in the median opening and lead to a conflict, as depicted by the red area in the figure. The driveway vehicles may perform either legal or illegal (wrong-way driving) maneuvers. The driveways can be located on either the same direction of travel or at the opposing direction of the median opening vehicles. To determine the definition of the conflicting distance, the research team used the approximate speed of the secondary vehicle that is either entering or exiting the driveway. Vehicles that enter or exit a driveway generally have low primary speeds in the range of 0 mph to 25 mph. The stopping sight distance equation can be used to estimate an approximate limit for influence from a conflicting driveway. This formula is shown as follows:

$$SSD = 1.47Vt + 1.075\left(\frac{v_1^2 - v_2^2}{11.2}\right) \tag{1}$$

where:

SSD = stopping sight distance (ft)
V = design speed (mph)
t = brake reaction time (value up to 2.5 sec)
v_1^2 = speed of vehicle exiting/entering driveway
v_2^2 = speed of approach main lane vehicle

Considering the most dangerous situation, in which the primary speed of the vehicle is 25 mph and the secondary speed is 0, the stopping sight distance (SSD) is approximately 150 ft. Therefore, for this study, a value of 150 ft has been used to identify the influence zone for

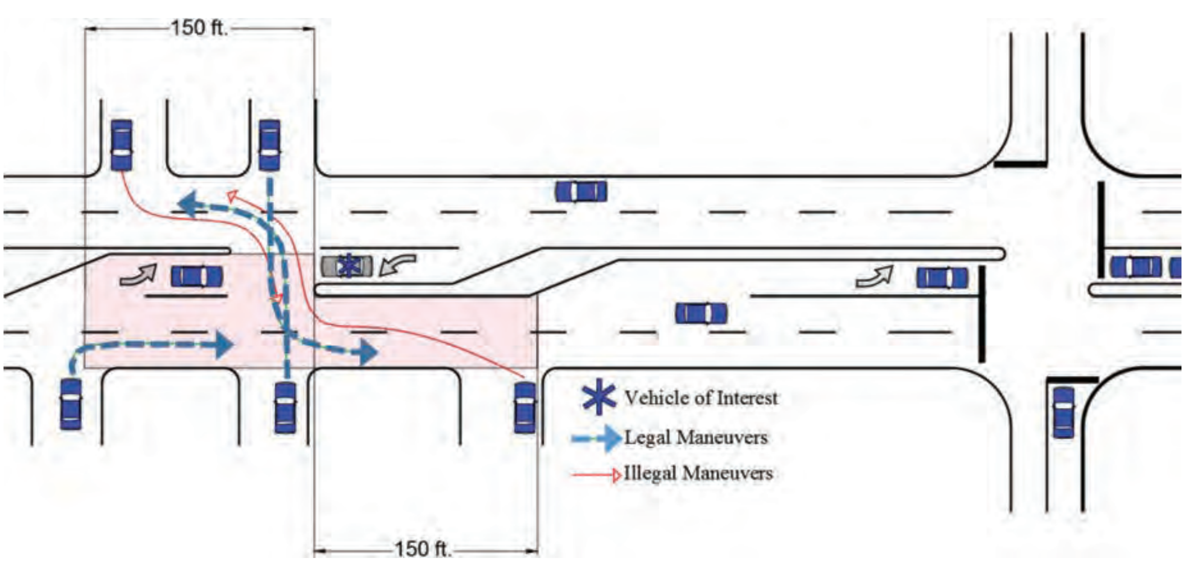


Figure 16. Defining conflicting driveway.

conflicting driveways in both directions of travel. This region for defining conflicting driveways is depicted in Figure 16. The number of conflicting driveways was subsequently used as one possible variable in the statistical analysis presented later in this chapter.

Gap Acceptance

Figure 17 defines the variables used for describing the gap acceptance of median opening vehicles. Specifically, the gap acceptance analysis focused on three key positions:

1. D – Departing from median opening
2. F – Front of queue
3. B – Back of queue

A detailed breakdown for these gaps is included in Appendix B. The analysis evaluated total delay for a vehicle from F to B and from D to F. In addition, the research team documented the number of vehicles, average gap time for a 1-hour period, and vehicle behavior (including stopped or rolling vehicles).

Table 18 shows the average gaps accepted for each site for left turns. Similarly, Table 19 summarizes the gap acceptance for U-turns. The average time for a vehicle leaving the front of the queue and departing the median opening when a vehicle is approaching is approximately 9 seconds. For vehicles classified as stopped but rolling, the time gap extended to approximately 15 seconds. Observed gaps ranged from as little as less than 1 second up to as much as 5 minutes. There were not any clear relationships between the observed gaps and the distance from the median opening to the signalized intersection.

Assessing Influence of Distance from Median Opening to Signalized Intersection

The length of the distance between the median opening and the signalized intersection is the focus of this research and one of the fundamental factors to consider when designing a median opening. Figure 18 depicts this approaching distance.

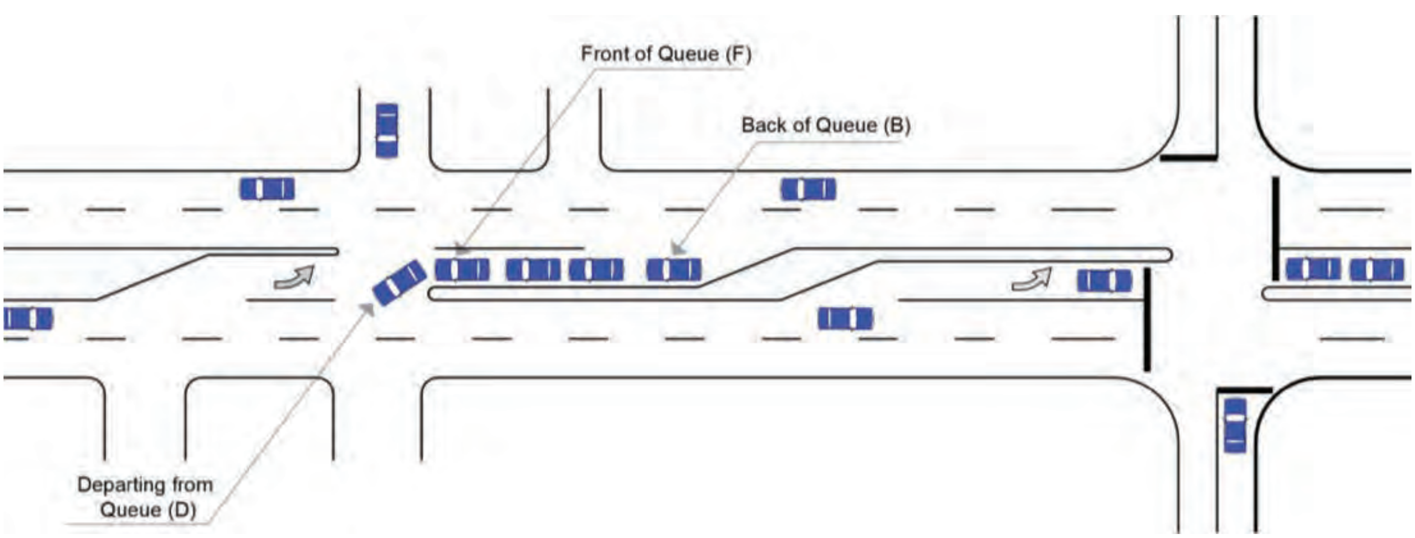


Figure 17. Defining back and front of a queue and departing from a queue.

Table 18. Gap acceptance for median opening left-turning vehicles.

Site	Distance from Median Opening to Intersection (ft)	Average B to F (seconds per vehicle)	Average F to D (seconds per vehicle)	Average F to D for Stopped or Rolling Vehicles (seconds per vehicle)	Critical Gap for Stopped/Rolling Vehicles
AZ-01	107	00:02	00:15	00:42	00:42
AZ-02	267	00:01	00:14	00:17	00:01
AZ-03	277	00:02	00:11	00:18	00:01
AZ-04	344	00:01	00:08	00:14	00:02
AZ-05	331	00:01	00:05	00:09	00:00
AZ-06	369	00:01	00:15	00:21	00:01
KC-01	349	00:01	00:03	00:10	00:00
KC-02	373	00:02	00:08	00:15	00:02
KC-03	355				
KC-04	300	00:01	00:12	00:16	00:01
KC-05	127				
KC-06	177	00:01	00:03	00:08	00:01
KC-07	308	00:01	00:05	00:10	00:02
PA-01	353	00:01	00:06	00:15	00:01
PA-02	400	00:02	00:03	00:09	00:05
PA-03	412	00:01	00:07	00:16	00:02
PA-04	244	00:01	00:11	00:20	00:02
PA-05	288	00:01	00:03	00:08	00:00
PA-06	259	00:02	00:08	00:14	00:00
TX-01	140	00:02	00:11	00:16	00:02
TX-02	265	00:03	00:06	00:10	00:02
TX-03	271	00:04	00:09	00:14	00:01
TX-04	186	00:01	00:25	00:32	00:02
TX-05	320	00:04	00:06	00:13	00:02
TX-06	424	00:08	00:06	00:13	00:00

Note: Shaded fields represent locations where left-turn gap acceptance was not observed.

The heat map shown in Figure 19 depicts the relationship between the approaching distance (on the x-axis), the number of conflicting driveways (on the y-axis), and the average delay of the median opening vehicles (represented by the number of seconds on the color scale). This figure demonstrates that by decreasing the approaching distance, the delay of the median opening vehicles increases. One reason for the negative effect of a shorter approaching distance can be due to signalized intersection queue spillback causing an interruption in the operation of the median opening vehicles.

Before determining the factors that affect the length of the approaching distance, the research team evaluated the key variables to identify potential correlations (see Table 20). The model development process then considered these variables as input for a mixed regression model. The result of the regression model is given in Table 21.

It is notable that the hourly volume was included and evaluated as well. After various iterations, Table 22 presents the results of the final mixed regression model.

Based on the results, the median opening type B1, number of conflicting driveways, and number of lanes for the arterial are the significant variables at a 95 percent confidence interval.

Table 19. Gap acceptance for median opening U-turning vehicles.

Site	Distance from Median Opening to Intersection (ft)	Average B to F (seconds per vehicle)	Average F to D (seconds per vehicle)	Average F to D for Stopped or Rolling Vehicles (seconds per vehicle)	Critical Gap for Stopped/Rolling Vehicles (seconds)
AZ-01	107	00:03	00:02	00:02	00:02
AZ-02	267	00:01	00:10	00:15	00:00
AZ-03	277	00:01	00:11	00:12	00:01
AZ-04	344	00:02	00:12	00:17	00:00
AZ-05	331	00:02	00:08	00:16	00:04
AZ-06	369	00:01	00:21	00:27	00:02
KC-01	349				
KC-02	373	00:01	00:07	00:14	00:02
KC-03	355	00:00	00:01		
KC-04	300	00:01	00:15	00:17	00:02
KC-05	127	00:01	00:00		
KC-06	177	00:01	00:01		
KC-07	308	00:01	00:19	00:23	00:03
PA-01	353	00:01	00:02	00:07	00:07
PA-02	400	00:02	00:06	00:15	00:05
PA-03	412	00:01	00:08	00:19	00:09
PA-04	244	00:04	00:07	00:10	00:01
PA-05	288	00:05	00:03	00:09	00:03
PA-06	259	00:03	00:09	00:11	00:01
TX-01	140	00:02	00:11	00:15	00:00
TX-02	265	00:03	00:08	00:14	00:04
TX-03	271	00:02	00:08	00:15	00:02
TX-04	186	00:04	00:10	00:20	00:02
TX-05	320	00:03	00:07	00:16	00:03
TX-06	424	00:06	00:13	00:19	00:01

Note: Shaded fields represent locations where U-turn gap acceptances were not observed.

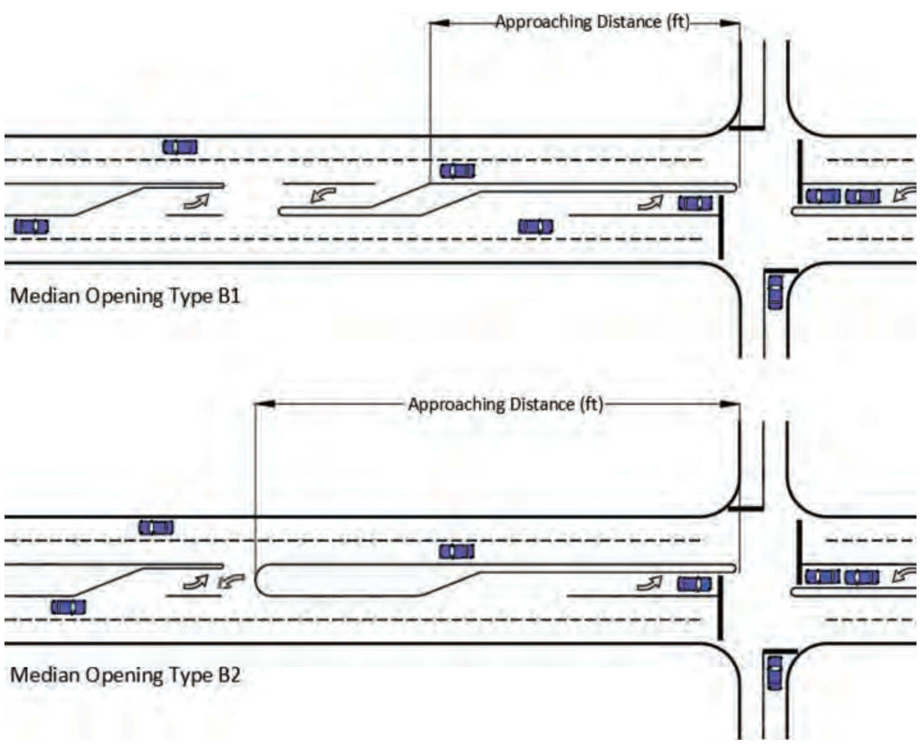


Figure 18. Defining the approaching distance.

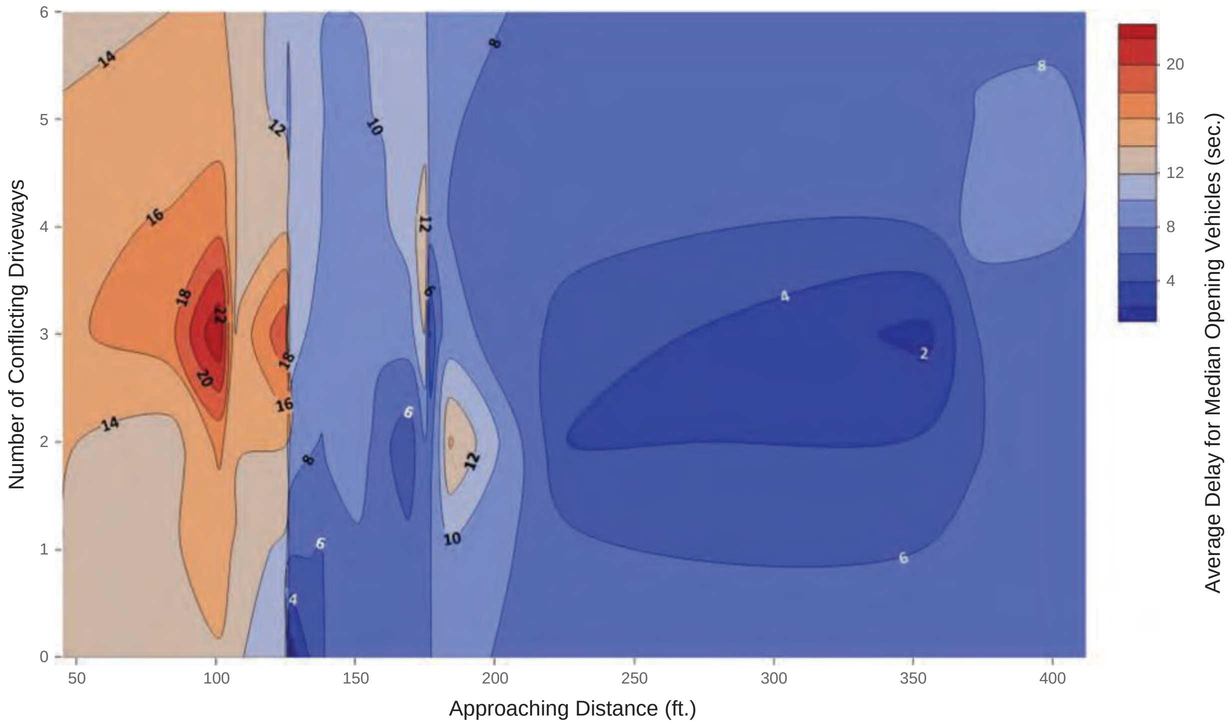


Figure 19. Average delay of the median opening vehicles (sec.) for all the sites.

Table 20. Correlation coefficient test for variables used in the operation model.

Test Variable	Hourly Volume	Departing Through Volume	Median Opening Turning Volume	Percentage of Heavy Vehicle	Number of Conflicting Driveways	Number of Lanes for the Arterial
Hourly Volume	1.0000	0.8588	-0.0941	-0.0494	-0.1984	0.3043
Departing Through Volume	0.8588	1.0000	-0.1417	-0.1047	-0.1427	0.2707
Median Opening Turning Volume	-0.0941	-0.1417	1.0000	0.9493	0.7079	-0.0592
Percentage of Heavy Vehicle	-0.0494	-0.1047	0.9493	1.0000	0.6584	-0.1517
Number of Conflicting Driveways	-0.1984	-0.1427	0.7079	0.6584	1.0000	-0.0465
Number of Lanes for the Arterial	0.3043	0.2707	-0.0592	-0.1517	-0.0465	1.0000

Table 21. Primary regression model for the operation of a median opening.

Term	Estimate	Std Error	t Ratio	Prob>|t|	95% Lower	95% Upper
Departing Through Volume	393.25668	30.726336	12.80	<.0001	332.78438	453.72898
Median Opening Turning Volume	1.809e-9	3.5682e-6	0.00	0.9996	-7.052e-6	7.0559e-6
Percentage of Heavy Vehicle	1.343e-10	6.5284e-5	0.00	1.0000	-0.000129	0.0001291
Number of Conflicting Driveways	6.9104e-8	0.0008348	0.00	0.9999	-0.00165	0.0016505
Median Opening Type B1	-17.77529	6.2587952	-2.84	0.0048	-30.09318	-5.457396
Number of Conflicting Driveways	20.731629	4.0623224	5.10	<.0001	12.736599	28.726659
Signalized Intersection Queue Backs up to the Median Opening [no]	1.3052e-6	0.0013939	0.00	0.9993	-0.002754	0.002757
Number of Lanes for the Arterial	-56.67839	6.5725275	-8.62	<.0001	-69.61373	-43.74304

Table 22. Results of the regression model for the operation of a median opening.

Term	Estimate	Std Error	t Ratio	Prob>|t|	95% Lower	95% Upper
Intercept	393.25663	30.518721	12.89	<.0001	333.19629	453.31697
Median Opening Type B1*	-17.7753	6.2165053	-2.86	0.0045	-30.00928	-5.541316
Number of Conflicting Driveways	20.73163	4.0348741	5.14	<.0001	12.791064	28.672195
Number of Lanes for the Arterial	-56.67838	6.5281177	-8.68	<.0001	-69.5256	-43.83115

*Full median opening with turn bays for both directions.

The number of conflicting driveways has a positive relationship with the length of the approaching distance. Therefore, the approaching distance should be increased if the number of conflicting driveways increases. On the other hand, the Type B1 median and the number of lanes for the arterial have negative impacts on the dependent variable, which is the length of approaching distance. In fact, by implementing a Type B1 median opening, the length of approaching distance can be decreased, as the turn bays provide storage for the median opening vehicles until the vehicles perform their turning maneuvers. Equation 2 is provided to calculate the minimum required approaching distance based on the given variables.

$$\textit{Approaching Distance}\,(\text{ft}) = 393.26 - 17.78\,(\text{Median Opening Type [B1]}) + 20.73\,(\text{Cd}) - 56.68(\text{N}) \quad (2)$$

where:

Median Opening Type [B1] = If there are two turn bays at median opening, assign a value of 1. If there is only one turn bay, assign a value of 0.
Cd = number of conflicting driveways, as defined in Figure 16
N = number of lanes (both directions of travel) for the arterial

To demonstrate how the above equation can be practically applied, the research team developed the following two sample problems.

Sample Problem #1

A transportation agency is considering the installation of a median opening near a signalized intersection on an existing four-lane urban arterial. Due to the high demand of left-turning traffic volume to access adjacent land-uses, the agency plans to provide turn bays for both directions of the median opening (Type B1 median opening). If the number of conflicting driveways near the future median opening is approximately three, what is an appropriate minimum value for the approaching distance?

Solution:

Approaching Distance (*ft*) = 393.26 – 17.78(1) + 20.73(3) – 56.68(4) ≈ 211 ft.

The approaching distance should be at least 211 ft.

Sample Problem #2

The approaching distance of an existing median opening along a six-lane urban arterial is 120 ft. There are currently four conflicting driveways, but adjacent property owners are requesting an additional access point to provide direct access to their proposed new commercial development. The transportation agency would like to evaluate whether adding a new driveway interferes with the operation of the median opening. The current median opening only has one turn bay. Should the agency provide one more access point?

Solution:

Approaching Distance (*ft*) = 393.26 − 17.78(0) + 20.73(5) − 56.68(6) ≈ 157 ft.

This driveway should not be provided because the minimum approaching distance should be 157 ft for five driveways while the available approaching distance is only 120 ft.

Influence of Conflicting Driveways on Approaching Distance

In addition to evaluating median opening performance based on road characteristics, it is also useful to assess how peak hour operations influence median opening operations by estimating the number of conflicts expected at the site.

Figure 20 depicts the relationship between the approaching distance (on the x-axis), the number of conflicting driveways for a site (on the y-axis), and the total number of vehicle

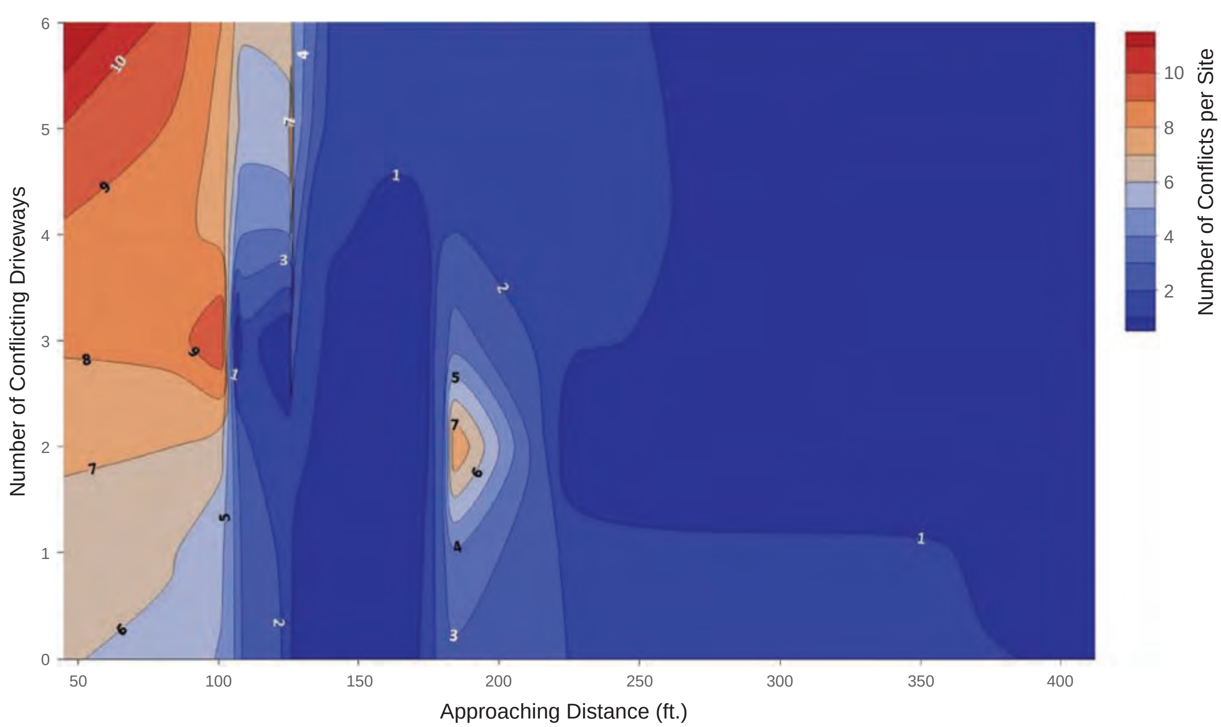


Figure 20. Number of conflicts for all the sites.

conflicts per site (represented by the number of conflicts shown on the color scale). This figure demonstrates that by increasing the number of conflicting driveways and decreasing the approaching distance, the number of expected conflicts increases. By shifting toward larger approaching distances and fewer conflicting driveways, the number of conflicts can be decreased. Table 23 summarizes the correlation test for the number of conflicts.

The distribution of the number of conflicts during the peak hour for the study sites has a structure consistent with that modeled using negative binomial regression. The potential variables used to predict the number of conflicts are shown with their associated Pearson correlation values in Table 23. Table 24 further demonstrates the initial regression modeling effort for the number of conflicts.

After several stepwise iterations, Table 25 presents the final output.

As the results indicate, the number of median opening vehicles and conflicting driveways are statistically significant at a 95 percent confidence interval. Both variables with positive coefficients demonstrate that the number of conflicts increases if the number of median opening vehicles or/and the number of conflicting driveways increases. Equation 3 can be used to predict the number of conflicts based on the given variables.

$$MOC_{PH} = e^{(-6.56+(0.02\times Vmo)+(1.29\times Cd))} \tag{3}$$

where:

MOC_{PH} = number of median opening vehicle conflicts during peak hour
Vmo = median opening turning volume in peak hour
Cd = number of conflicting driveways, as defined in Figure 16

Table 23. Correlation coefficient test for variables used in number of conflicts model for peak hour period.

Variable	Peak Hour Volume	Departing Through Volume	Conflicting Volume	Median Opening Turning Volume	Percent of Heavy Vehicle	Approach-ing Distance	Number of Conflicting Driveways	Number of Lanes for the Arterial
Peak Hour Volume	1.0000	0.8588	-0.0941	-0.0494	-0.1984	-0.1914	0.3043	0.5257
Departing Through Volume	0.8588	1.0000	-0.1417	-0.1047	-0.1427	-0.2321	0.2707	0.4765
Conflicting Volume	-0.0941	-0.1417	1.0000	0.9493	0.7079	-0.0117	-0.0592	-0.0634
Median Opening Turning Volume	-0.0494	-0.1047	0.9493	1.0000	0.6584	-0.0187	-0.1517	-0.1077
Percent of Heavy Vehicle	-0.1984	-0.1427	0.7079	0.6584	1.0000	0.1021	-0.0465	-0.2048
Approaching Distance	-0.1914	-0.2321	-0.0117	-0.0187	0.1021	1.0000	-0.0952	-0.5587
Number of Conflicting Driveways	0.3043	0.2707	-0.0592	-0.1517	-0.0465	-0.0952	1.0000	0.5040
Number of Lanes for the Arterial	0.5257	0.4765	-0.0634	-0.1077	-0.2048	-0.5587	0.5040	1.0000

Table 24. Primary regression model for the number of conflicts at a median opening.

Term	Description	Estimate	Std Error	Wald Chi-square	Prob > Chi-square	Lower 95%	Upper 95%
---	Intercept	-5.109646	7.8037537	0.4287208	0.5126	-20.40472	10.18543
Vd	Departing Through Volume	-0.000746	0.0021293	0.1226786	0.7261	-0.004919	0.0034276
Vc	Conflicting Volume	0.0059419	0.0440871	0.0181649	0.8928	-0.080467	0.0923511
Vmo	Median Opening Turning Volume in Peak Hour	0.0099786	0.0378181	0.0696213	0.7919	-0.064143	0.0841007
P_{HV}	Percent of Heavy Vehicle	-0.194463	1.1606357	0.0280726	0.8669	-2.469267	2.0803409
[B1 – B2]	Median Opening Type	0.8149181	2.1392763	0.145109	0.7033	-3.377986	5.0078226
Da	Approaching Distance	-0.003527	0.0138116	0.065226	0.7984	-0.030598	0.0235429
Cd	Number of Conflicting Driveways	0.5880655	0.5404121	1.1841353	0.2765	-0.471123	1.6472537
Queue	Signalized Intersection Queue Backs up to the Median Opening [No-Yes]	-0.304934	1.4833118	0.0422618	0.8371	-3.212172	2.6023033
N	Number of Lanes for the Arterial	0.478307	1.0334212	0.2142194	0.6435	-1.547161	2.5037753

Table 25. Final regression model results for number of conflicts at median opening.

Term	Description	Estimate	Std Error	Wald Chi-square	Prob > Chi-square	Lower 95%	Upper 95%
---	Intercept	-6.56	1.734	14.31	0.0002	-9.96	-3.16
Vmo	Median Opening Turning Volume in Peak Hour	0.02	0.005	13.52	0.0002	0.01	0.03
Cd	Number of Conflicting Driveways	1.29	0.320	16.34	<.0001	0.67	1.92

Sample Problem #3

A roadway has 85 vehicles at the median opening during the peak hour. This location currently has five conflicting driveways. How many conflicts are expected in the vicinity of the median opening during the peak hour?

Solution:

$MOC_{PH} = e^{(-6.56+(0.02\times 85)+(1.29\times 5))} \approx 5$ conflicts

Five conflicts might be expected during the peak period based on the provided information.

Chapter Summary Remarks

Several road and operational factors can influence operations for an unsignalized median near a signalized intersection. As part of this research effort, the research team acquired a wide variety of geometric and operational information. Ultimately, the most influential factors were as follows:

- For operational evaluation of the distance from median opening to signalized intersection (referred to as "approaching distance" in the report), critical factors include:
  - Number of turn bays (designated as B1 with two bays or B2 with only one turn bay at the median opening)
  - Number of conflicting driveways (within approximately 150 ft of the median opening)
  - Number of arterial through lanes
- For operational evaluation of the estimated number of conflicts that can be expected at the median opening, critical factors include:
  - Turning volume at the median opening
  - Number of conflicting driveways (within approximately 150 ft of the median opening)

CHAPTER 5

Safety Analysis

Quantitative Crash Analysis

Team members conducted an analysis of crashes around unsignalized full median openings with at least one turn bay that were located near a signalized intersection. The goal of this assessment was to investigate the number and severity of crashes that occur at these full median opening locations. An objective of this analysis was to determine whether safety performance functions (SPFs) or crash modification factors (CMFs) could be developed and provide useful results. As reviewed in Chapter 3, the crash analysis included two different evaluations. First, the team evaluated crashes in Arizona and Texas, which included the operational study sites as well as comparison sites (two per operational site). Team members also conducted an analysis for crashes in the immediate vicinity of a median opening. This more localized crash evaluation was based on HSIS crash data from California. Both analyses are documented in the following sections.

Corridor Approach Crash Analysis (Based on Arizona and Texas Data)

To conduct an analysis of the safety performance for the approach corridor, the team evaluated crashes along the length of the approach corridor and contrasted those approaches to similar facilities in Arizona and Texas that did not have median openings but were in the same geographic region with similar traffic volume and land use conditions. The crash data for these locations included 18 Arizona sites as well as 18 Texas sites (six operational sites and 12 comparison sites per state). The following summary contains a review of the approach corridor limits, an overview of the safety analysis methodology, and a discussion of these safety analysis results.

Site Approach Corridor Limits

For this intersection approach crash analysis, the research team used data for the Arizona and Texas study sites. The team subdivided the road network into four segments, as shown in Figure 21. These study segments are defined as follows:

- Segment 1 extended from the signalized intersection to the nose of median opening.
- Segment 2 extended 150 ft from the nose of median opening. This region had been previously defined within the driveway conflict area for the median opening vehicles.
- Segment 3 extended to the left-turn lane for either the next median opening or signalized intersection.
- Segment 4 began at the end of Segment 3 and extended 128 ft (distance derived from the shortest observed length from the end of Segment 3 to the stop bar for the next signalized intersection).

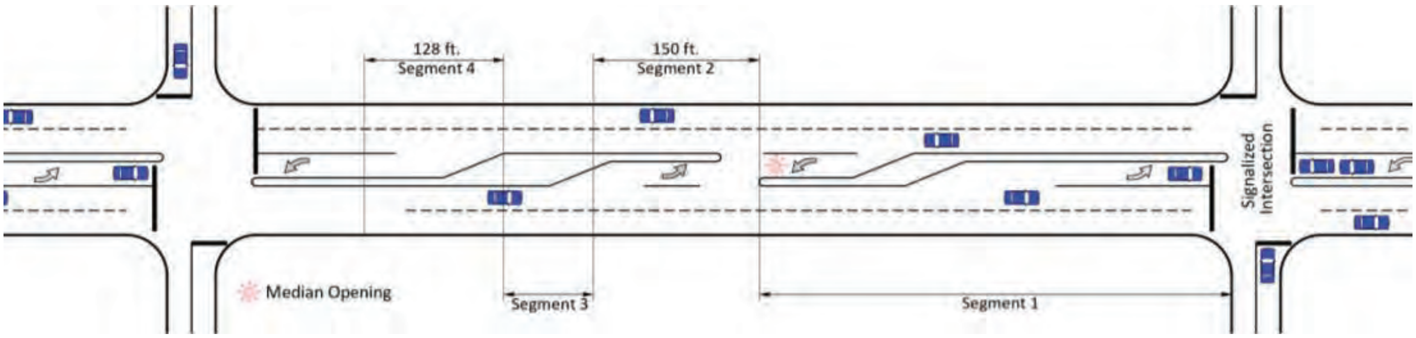


Figure 21. Defined segments for counting the number of crashes along the median opening corridor.

The crash documentation for Arizona and Texas, though generally compatible, did use slightly different crash description codes. Table 26 and Table 27 define the crash manner and crash severity codes, respectively, for the Arizona data. Similarly, Table 28 and Table 29 define the variables for the Texas crash data. Detailed crash data for Arizona and Texas are included in Appendix B. Due to isolated short-term construction during the five-year study period at four of the locations, the analysis excluded five site-specific years of data that extended across four of the analysis sites. The team identified this construction using historic aerial photographs.

Approach Corridor Safety Analysis

In preparation for conducting statistical regression analysis, the team performed a correlation test that resulted in the prospective variables depicted in Table 30. A surprising finding throughout the safety analysis is that the distance from the signalized intersection to the median opening is not significant for any of the crash prediction models. This can be contrasted to the findings from the operational analysis (see Chapter 4), where the placement of the median opening directly influenced vehicle operations and driveway conflicts.

After determining that the numerical variables depicted in Table 30 were not substantially correlated, the team chose to initially include all of these key variables in the total crash and injury crash regression models and then test them for variable significance. The analysts identified the dependent variables as the total number of crashes that occurred at the full median opening sites with a least one turn bay. The other variables included average daily traffic (ADT), median opening type (0 = no median opening, 1 = median opening with one turn bay, 2 = median opening with two turn bays), and the number of arterial through lanes. Due to the presence of several bus stops within the study limits, the analyses also included the presence of bus stops as potential descriptive variable predictors (represented as 0 = no bus stop, 1 = bus stop

Table 26. Arizona crash manner codes.

Code	Definition
1	Single Vehicle
2	Angle (Front To Side)(Other Than Left Turn)
3	Left Turn
4	Rear End
5	Head On
6	Sideswipe Same Direction
7	Sideswipe Opposite Direction
8	Rear to Side
9	Rear to Rear
97	Other

Table 27. Arizona crash severity codes.

Code	Definition
1	No Injury (PDO)
2	Possible Injury (C)
3	Non-Incapacitating Injury (B)
4	Incapacitating Injury (A)
5	Fatal (K)
99	Unknown

Table 28. Texas crash manner codes.

Code	Definition
1	OMV Vehicle Going Straight
2	OMV Vehicle Turning Right
10	Angle - Both Going Straight
13	Angle - One Straight-One Right Turn
14	Angle - One Straight-One Left Turn
15	Angle - Both Right Turn
16	Angle - One Right Turn-One Left Turn
17	Angle - One Right Turn-One Stopped
20	SD Both Going Straight-Rear End
21	SD Both Going Straight-Sideswipe
22	SD One Straight-One Stopped
24	SD One Straight-One Left Turn
29	SD One Left Turn-One Stopped
34	SD One Straight-One Left Turn

Table 29. Texas crash severity codes.

Code	Definition
0	Unknown
1	Incapacitating Injury (A)
2	Non-Incapacitating Injury (B)
3	Possible Injury (C)
4	Killed (K)
5	Not Injured (PDO)
94	Reported Invalid
95	Not Reported

Table 30. Correlation coefficient test.

	Median Opening Type	Number of Through Lanes for the Arterial	ADT
Median Opening Type (0=No Opening, 1=One Turn Bay, 2=Two Turn Bays)	1.0000	0.0348	-0.2714
Number of Through Lanes for the Arterial	0.0348	1.0000	0.2977
Average Daily Traffic (ADT)	-0.2714	0.2977	1.0000

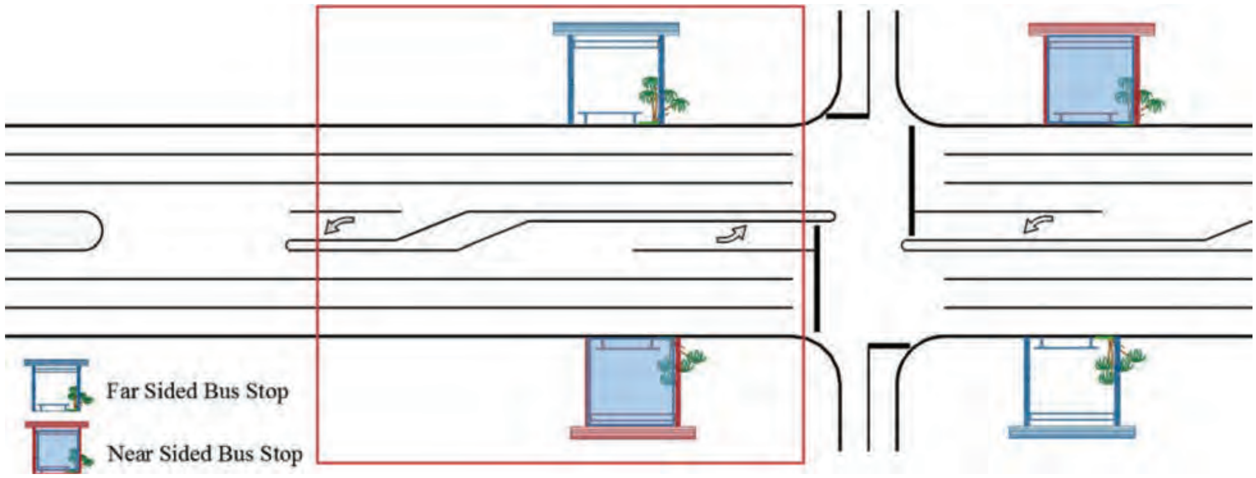


Figure 22. Defining studied bus stops.

on one direction, 2 = bus stop in both directions). Because this analysis focused specifically on the intersection approach with the median opening, the variable for the presence of a bus stop only considered bus stops as depicted in the boxed region shown in Figure 22. These bus stops were both near-side and far-side stops within the study zone.

Arizona Model Development. Initially, the analysis separately considered the Arizona and the Texas sites so that the team could capture heterogeneity, if present. Table 31 presents the full model results for the Arizona sites.

As indicated, all the included variables were significant and influenced the total number of crashes. The median opening and ADT values had a positive impact (i.e., by increasing the value of these variables, the number of crashes also could be expected to increase). The number of arterial through lanes and the presence of bus stop coefficients had a negative value. It is notable that the estimated values of the bus stop variable show that sites with a bus stop in one direction had fewer crashes than the sites with either no bus stop or bus stops in both directions. Also, sites with bus stops present in both directions can be expected to have fewer crashes than sites with no bus stops.

Due to the significance of the number of lanes and bus stops, these sites may benefit from consideration of their associated speed limits in the modeling process. Figure 23 indicates that most of the studied locations with one or two bus stops had a speed limit of 40 mph. The majority of locations without bus stops had speed limits of 35 mph. This observation suggests some additional correlation is introduced with the inclusion of both bus stops and speed limit in the same model.

Table 31. Regression model for the total number of crashes in Arizona sites.

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	4.47	1.84	2.43	0.015
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.83	0.37	2.26	0.024
Number of Arterial Through Lanes	-1.13	0.38	-2.97	0.003
ADT	8.59E-05	4.04E-05	2.13	0.033
Bus Stop, Both Directions	-1.53	0.75	-2.03	0.042
Bus Stop, One Direction	-1.70	0.69	-2.45	0.014

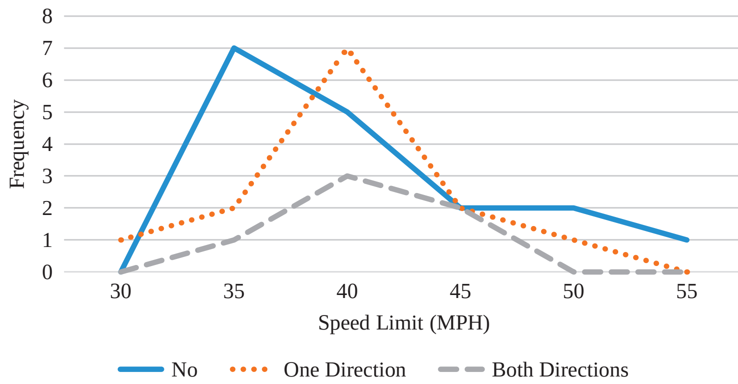


Figure 23. Frequency of bus stops based on speed limit of the roadways.

Texas Model Development. The project team conducted a similar analysis for the Texas sites. As shown in Table 32, the presence of a bus stop in one direction was not determined to be significant.

Following removal of the bus stop variable from the Texas model, the p-values for all of the remaining variables were statistically significant at the 5 percent level when evaluating the impact on the dependent variable (i.e., the total number of crashes). Table 33 presents the results of the final regression model for the Texas sites.

Merged Arizona and Texas Model Development. Next, the research team combined the 18 Arizona sites and 18 Texas sites into a single model. For this analysis, the project team included a categorical variable named "state," where Arizona was assumed the default value and Texas was assigned a value of 1 when applicable. Table 34 depicts the results of this supplemental analysis. As shown, the variable "state" ultimately was not a significant variable for the model. This finding suggests a merged Arizona and Texas model that does not include a "state" variable may be a viable option.

Table 35 depicts the output of the regression model after excluding the variable "state" from the model. The model retained the "bus stop, one direction" variable to balance the companion "bus stop, both directions" variable.

The resulting model indicates that by increasing the ADT and the number of turn bays at a median opening, the number of crashes will increase. However, the number of arterial through lanes and the presence of bus stops appear to be negatively associated with the total number of

Table 32. Primary regression model for the total number of crashes in Texas sites.

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	1.39	0.78	1.78	0.075
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.36	0.13	2.90	0.004
Number of Arterial Through Lanes	-0.35	0.15	-2.36	0.018
ADT	3.77E-05	8.21E-06	4.590342	0.000
Bus Stop, Both Directions	-0.74	0.33	-2.23	0.026
Bus Stop, One Direction	-0.31	0.33	-0.96	0.335

Table 33. Final regression model for the total number of crashes in Texas sites.

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	1.81	0.78	2.33	0.020
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.33	0.11	2.87	0.004
Number of Arterial Through Lanes	-0.45	0.15	-3.06	0.002
ADT	3.87E-05	8.22E-06	4.71	0.000

Table 34. Primary regression model for the total number of crashes (Arizona and Texas).

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	1.86	0.67	2.76	0.006
State: TX	-0.21	0.27	-0.79	0.429
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.46	0.12	3.74	0.000
Number of Arterial Through Lanes	-0.43	0.13	-3.30	0.001
ADT	4.26E-05	8.53E-06	5.00	0.000
Bus Stop, Both Directions	-0.80	0.30	-2.64	0.008
Bus Stop, One Direction	-0.56	0.28	-1.97	0.049

Table 35. Regression model for the total number of crashes in Arizona and Texas sites.

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	1.78	0.67	2.66	0.008
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.45	0.12	3.72	0.000
Number of Arterial Through Lanes	-0.45	0.13	-3.43	0.001
ADT	4.28E-05	8.51E-06	5.02	0.000
Bus Stop, Both Directions	-0.77	0.30	-2.56	0.011
Bus Stop, One Direction	-0.49	0.26	-1.87	0.061

crashes. The estimated values for the bus stop variables show that locations with bus stops on both sides of the road result in fewer crashes than locations with either one or no bus stop. In addition, sites with one bus stop have fewer crashes compared to sites with no bus stop.

As the presence of a bus stop in one direction is not significant at a 95 percent confidence interval, this variable was excluded from the final model. The results are presented in Table 36.

The final model representing the total number of crashes for a site in Arizona or Texas is represented by Equation 4.

$$Total\ number\ of\ crashes = e^{(1.70+(0.40\times MO)-(0.46\times N)+(0.0000415\times ADT))} \tag{4}$$

where:

MO = presence of full median opening and turn bays
N = number of arterial through lanes (both directions total)
ADT = average daily traffic (veh/day), can be used interchangeably with AADT (annual average daily traffic volume)

It is notable that the research team evaluated the variable "median opening" as a categorical variable in the models. This approach assumed a condition with no median opening as the base condition (i.e., the other median opening conditions are then contrasted to this base condition value of 0). Figure 24 and Figure 25 depict this relationship for total crashes.

In addition to total crashes, the research team also used similar statistical techniques to develop an injury-only model for these sites. Table 37 summarizes this injury-related model. This model indicates that the presence of a median opening is associated with the total number of injury crashes. The number of injury crashes also increases with higher ADT values, while a smaller number of arterial through lanes is related to a reduction in injury crashes. These findings are consistent with the total crash model for Arizona and Texas.

The model represented by Equation 5 can be used to predict the total number of injury crashes for the study sites in Arizona and Texas.

$$Injury\ crashes = e^{(0.64+(0.59\times MO)-(1.06\times N)+(0.000047\times ADT))} \tag{5}$$

where:

MO = presence of full median opening and turn bays
N = number of arterial through lanes (both directions total)
ADT = average daily traffic (veh/day), can be used interchangeably with AADT (annual average daily traffic volume)

Table 36. Final regression model for the total number of crashes (Arizona and Texas).

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	1.70	0.70	2.44	0.015
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.40	0.11	3.48	0.001
Number of Arterial Through Lanes	-0.46	0.13	-3.41	0.001
ADT	4.15E-05	8.57E-06	4.84	0.000

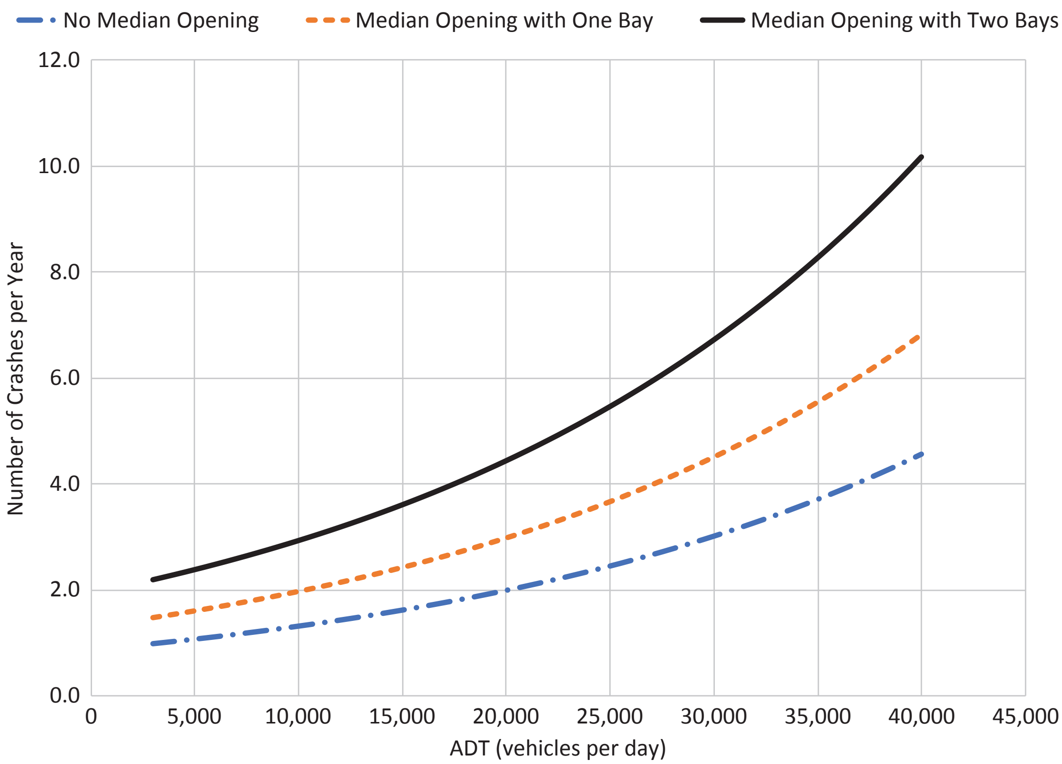


Figure 24. Total crashes for four-lane roadways.

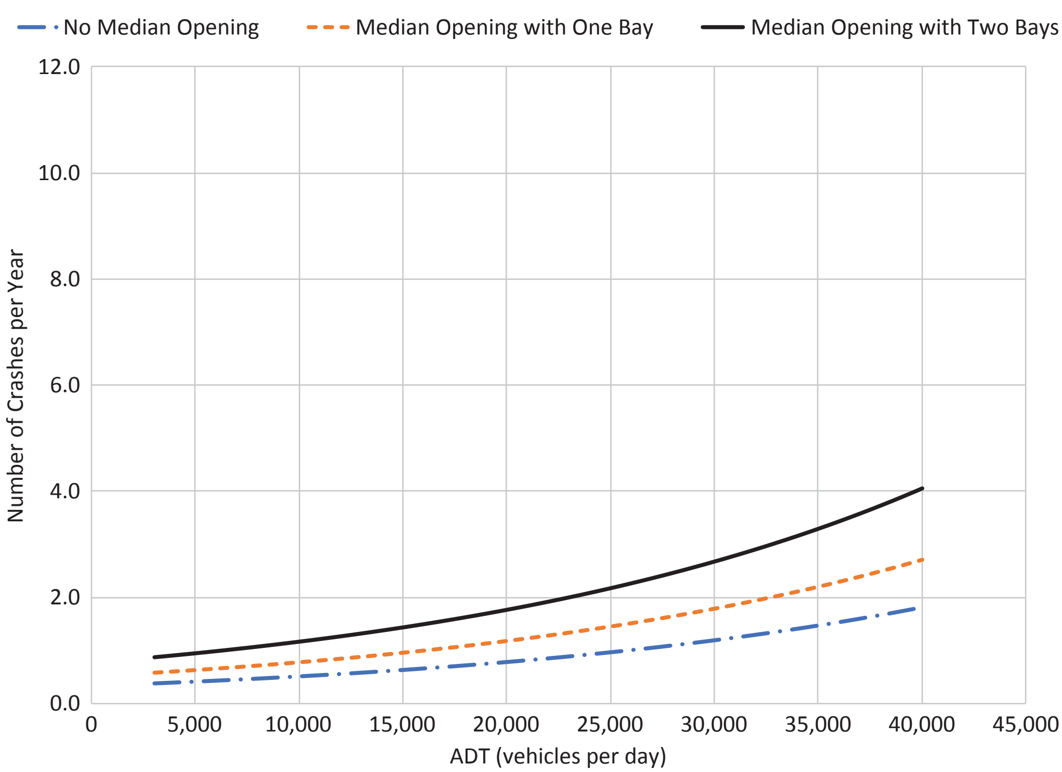


Figure 25. Total crashes for six-lane roadways.

Table 37. Final regression model for the number of injury crashes (Arizona and Texas).

Term	Estimate	Std Error	Z Value	Pr(>|z|)
(Intercept)	0.64	1.24	0.51	0.607
Median Opening (0=No Median Opening, 1=Median Opening with One Turn Bay, 2=Median Opening with Two Turn Bays)	0.59	0.19	3.17	0.002
Number of Arterial Through Lanes	-1.06	0.48	-2.21	0.027
ADT	4.74E-05	1.30E-05	3.63	0.000

The injury crash model is characterized by a low number of injury crashes (typically less than one) for all candidate scenarios. Consequently, the full median configuration does not substantially influence injury crashes for the Arizona and Texas scenarios.

Discussion of Results

Based on the crash analysis for intersection approaches in Arizona and Texas facilities, the resulting models offer the following insights:

- The Arizona-only total crash model resulted in significant variables associated with the type of median opening, the number of adjacent through lanes, the ADT, and the presence of bus stops. The bus stop variable appeared to be strongly correlated to facility speed limit.
- The Texas-only total crash model resulted in significant variables associated with the type of median opening, the number of adjacent through lanes, and the ADT.
- The merged Arizona and Texas crash model included the median opening type, the number of adjacent through lanes, and the ADT. For this model, the coefficient for median type was positive. The ADT variable was also determined to have a positive coefficient, while the number of through lanes variable had a negative value.
- The number of injury crashes at the study sites was very small, and the resulting equations produced a very small number of estimated crashes, likely due to this small sample size.

Sample Problem #4 and Sample Problem #5 depict example applications of these equations resulting from the Arizona and Texas crash analysis.

Sample Problem #4

What is the expected annual number of crashes for a signalized intersection approach that has a full median opening and two turn bays immediately upstream of the intersection? The median opening is on a four-lane arterial, and the predicted average daily traffic for the segment is 25,500 veh/day. Equation 4 can be used to evaluate this scenario.

Solution:

$$\textit{Total annual number of crashes} = e^{(1.70+(0.40\times2)-(0.46\times4)+(0.0000415\times25{,}500))}$$

$$\approx 5.6 \text{ crashes/year (Say 6 crashes/year)}$$

This value can be confirmed by inspection of Figure 24.

Sample Problem #5

Evaluate the feasibility of installing a full median opening on a six-lane arterial near a signalized intersection. The approximate ADT value for the location and study year is 32,000 veh/day. The agency has set a maximum target of no more than three median-related crashes each year. Can this level of crashes be achieved if the full median opening is installed? Will it matter if one or two turn bays are present at the future median opening? Equation 4 can be used to evaluate this scenario.

Solution:

Figure 25 shows that a full median opening with two turn bays is associated with the largest number of predicted crashes for a six-lane arterial. Consequently, an evaluation of a full median opening with two turn bays on a six-lane arterial will provide the most conservative values, as shown below:

$$\textit{Total number of crashes} = e^{(1.70+(0.40\times2)-(0.46\times6)+(0.0000415\times32{,}000))}$$

$$\approx 2.91 \text{ crashes/year (Say 3 crashes/year)}$$

Similarly, the evaluation of the full median opening scenario with one turn bay provides the following results:

$$\textit{Total number of crashes} = e^{(1.70+(0.40\times1)-(0.46\times6)+(0.0000415\times32{,}000))}$$

$$\approx 1.95 \text{ crashes/year (Say 2 crashes/year)}$$

Based on these findings, the target of no more than three median opening-related crashes should be achievable. However, Figure 25 shows that as future ADT values approach 33,000 veh/day, the number of target crashes will soon exceed this value.

Median Opening Localized Crash Analysis (Based on California HSIS Data)

The following section summarizes the HSIS-based crash analysis that focused on crashes that occurred in the immediate vicinity of a median opening. The goal of this effort was to assess crashes that occurred as a direct result of median opening operations. This is in contrast to the corridor approach crash analysis, which included sites without median openings.

Sites Available for Analysis

Inventory data for intersection locations and characteristics are available for the state highway systems of two states in the FHWA Highway Safety Information System (HSIS): California and Washington. Team members reviewed the data for these states and determined that California had many more potential sites than Washington. Therefore, California was selected for the HSIS crash analysis.

Candidate urban arterial road sections on divided non-freeways in California were identified using the HSIS intersection inventory data. Then, these candidate road sections were reviewed using Google Earth and Google Street View to identify suitable unsignalized median openings. For a median opening to be suitable for the crash analysis, the median opening needed to be

- Located on an urban arterial (non-freeway),
- Located on a state highway (so that crash data would be available in HSIS),
- Located on a divided roadway with a raised median,
- Located within 500 ft of a signalized intersection on one of the major-road legs, and
- Unsignalized with stop sign control on the minor-road leg(s) and no control on the major-road legs.

A total of 46 suitable median opening sites were identified. All of the sites had two major-road legs on the state highway, and these were located at the actual median opening. A total of 34 of the 46 sites had one minor-road leg (i.e., the median opening functioned as a three-leg intersection), while the remaining 12 had two minor-road legs (i.e., functioned as a four-leg intersection). At 41 of the 46 median opening sites, at least one of the minor-road legs was a public road; at the remaining five sites, each of the minor-road legs was a driveway (typically leading to and from a shopping center parking lot).

Data Acquisition

Data on the 46 median opening sites were obtained from the HSIS roadway and intersection inventory files and from a review of each location using Google Earth and Google Street View. The site characteristics data obtained for each median opening, where available, included

- Location information (for use in retrieving crash data),
- Annual average daily traffic volume (AADT) for the major road at the median opening (veh/day),
- AADT for the minor road at the median opening (veh/day),
- Number of through travel lanes on the major road (both directions of travel combined),
- Presence of major-road left-turn lanes,
- Presence of major-road right-turn lanes,
- Major-road median width (ft) [measured from the inside edge of the through lane to the inside edge of the opposing through lane],
- Distance from median opening to nearest signalized intersection (always less than 500 ft), and
- Presence of a skewed minor-leg approach (intersection angle of 75 degrees or less).

It should be noted that the AADTs used were for the major and minor roads at the median opening, not for the major and minor roads at the nearby signalized intersection. No traffic movements were restricted at any of the median openings selected. In other words, there were no median openings with traffic movements restricted by median channelization or by turn prohibitions.

Table 38 presents the characteristics of the 46 selected median opening sites. In addition to the site characteristics data, crash history data (including the characteristics of each individual crash for 5 recent years) were obtained from HSIS data files for each median opening. The crash data obtained were limited to crashes that occurred at or within 50 feet of the median opening. Crashes occurring more than 50 ft from the median opening were not used because many such crashes could not be verified as being related to the median opening. A variable in the crash data indicating the distance of a crash from the intersection to which it was related was also used in screening out crashes that were far enough from the median opening that they might not be related to the median opening.

Table 38. Site characteristics for median opening study sites.

Site Number	Public Road (P) / Driveway (D)	AADT (veh/day) for Most Recent Year		Number of Legs	Number of Lanes (Major Road)	Median Width (ft)	Distance from Signal (ft)	Major-Road Turn Lanes?		Skewed Minor Road Leg?
		Major Road	Minor Road					Left	Right	
CA101	P	16,164	800	4	4	21	255	Y	Y	N
CA102	D	--	--	4	4	21	338	Y	Y	N
CA103	P	16,532	900	3	4	20	156	Y	Y	N
CA104	P	44,877	820	4	6	18	394	Y	Y	N
CA105	P	31,182	110	3	6	13	205	Y	N	N
CA106	P	25,263	310	3	4	18	461	Y	N	N
CA107	P	26,293	760	3	4	17	231	Y	N	N
CA108	P	26,388	1,200	3	4	17	273	Y	N	N
CA109	P	34,324	100	3	4	18	396	Y	Y	N
CA110	P	27,150	110	3	4	20	216	Y	N	N
CA111	P	41,553	600	3	6	24	429	Y	N	N
CA112	P	29,609	60	3	4	17	374	Y	N	N
CA113	P	36,125	510	3	6	17	301	Y	N	N
CA114	P	23,087	200	3	4	16	339	N	Y	N
CA115	P	21,812	200	3	4	17	237	N	N	N
CA116	P	19,118	200	3	4	16	196	N	Y	N
CA117	P	19,553	200	3	4	15	297	Y	N	N
CA118	P	20,302	200	3	4	15	332	Y	N	N
CA119	P	21,756	500	3	4	15	265	N	Y	N
CA120	P	21,295	500	3	4	16	150	N	Y	N
CA121	P	20,009	1,300	3	4	16	278	N	N	N
CA122	P	19,182	700	3	4	15	270	N	N	N
CA123	P	14,000	2,300	3	4	22	477	Y	N	N
CA124	P	32,500	17,400	4	6	18	288	Y	Y	N
CA125	P	34,648	1,550	3	6	18	294	Y	N	N
CA126	P	34,412	800	3	4	12	296	Y	N	N
CA127	P	28,168	6,000	3	4	16	272	Y	N	Y
CA128	D	--	--	4	6	19	237	Y	N	N
CA129	P	27,500	600	3	4	18	227	Y	N	N
CA130	D	--	--	3	4	20	202	Y	N	Y
CA131	P	33,500	1,600	4	4	14	338	Y	Y	Y
CA132	P	30,000	200	3	4	20	334	Y	N	N
CA133	P	30,000	200	4	4	16	361	Y	Y	N
CA134	P	39,363	140	3	6	70	325	Y	Y	N
CA135	P	27,615	1,100	3	4	70	414	N	N	N
CA136	P	21,600	300	3	4	16	273	N	N	N
CA137	P	--	--	4	4	24	372	Y	Y	N
CA138	P	12,000	100	4	4	16	348	Y	Y	N
CA139	P	12,000	100	4	4	16	346	Y	N	N
CA140	P	43,559	300	3	6	15	339	Y	N	N
CA141	P	44,873	200	3	4	18	250	Y	N	N
CA142	P	44,106	600	4	4	18	258	Y	Y	N
CA143	P	43,610	2,000	3	4	18	270	Y	N	N
CA144	P	63,710	600	3	6	15	243	N	Y	N
CA145	D	--	--	4	6	20	490	Y	Y	N
CA146	P	45,000	2,000	3	6	15	353	Y	N	N

Table 39. Descriptive statistics for quantitative site characteristics.

Site Characteristic	Minimum	Mean	Maximum
Major-road AADT (veh/day)	12,000	29,375	63,710
Minor-road AADT (veh/day)[a]	60	1,180	17,400
Major-road median width (ft)	12	19.7	70
Distance from median opening to nearest signalized intersection (ft)	150	304.3	490

[a] Minor-road AADT data were available for median openings where at least one minor-road leg was a public road. Minor-road AADT data were not available for median openings for which all minor-road legs were driveways.

Table 40. Distribution of sites by number of legs at median opening intersection.

Number of Legs	Number of Median Openings	Percentage of Median Openings
3	34	73.9
4	12	26.1
Total	46	100.0

Distribution of Site Characteristics

Table 39 summarizes descriptive statistics for the key quantitative site characteristics: major-road AADT, minor-road AADT, major-road median width, and distance to nearest signalized intersection.

Table 40 shows that 34 of the 46 median opening sites (73.9 percent) were at three-leg intersections, while the remaining 12 median openings (26.1 percent) were at four-leg intersections.

Table 41 shows that 34 of the 46 median opening sites (73.9 percent) were on arterials with four lanes, while the remaining 12 median openings (26.1 percent) were on arterials with six lanes.

Table 42 shows that 36 of the 46 median opening sites (78.3 percent) had major-road left-turn lanes on at least one approach, while the remaining 10 median openings (21.7 percent) had no major-road left-turn lanes.

Table 41. Distribution of sites by number of through lanes on the major road.

Number of Through Lanes	Number of Median Openings	Percentage of Median Openings
4	34	73.9
6	12	26.1
Total	46	100.0

Table 42. Distribution of sites by presence of major-road left-turn lanes.

Major-Road Left-Turn Lane(s) Present?	Number of Median Openings	Percentage of Median Openings
Yes	36	78.3
No	10	21.7
Total	46	100.0

Table 43. Distribution of sites by presence of major-road right-turn lanes.

Major-Road Right-Turn Lane(s) Present?	Number of Median Openings	Percentage of Median Openings
Yes	18	39.1
No	28	60.9
Total	46	100.0

Table 43 shows that 18 of the 46 median opening sites (39.1 percent) had major-road right-turn lanes on at least one approach, while the remaining 28 median openings (60.9 percent) had no major-road right-turn lanes.

Table 44 indicates that three of the 46 median opening sites (6.5 percent) had at least one skewed minor-road leg that intersects the major road at an angle of 75 degrees or less. At the remaining 43 median openings (93.5 percent), all minor-road legs intersected the major road at a right angle or within 15 degrees of a right angle.

Crash History Summary

The 46 unsignalized median opening sites experienced a total of 220 crashes in the 5-year study period, or an average of 0.96 crashes per median opening per year. Table 45 shows the distribution of median openings by the total number of crashes experienced in the 5-year period. The distribution shown in Table 45 is typical of crash history data, with a substantial number of sites with no crashes or just a few crashes and relatively few sites with a substantial number of crashes.

Table 46 shows that these crashes included 103 injury crashes of various injury severity levels and 117 crashes only involving property damage. There were no fatalities at any of the median opening sites. The 103 injury crashes included a total of 139 injuries, or an average of 1.35 injuries per crash.

As shown in Table 47, a total of 206 of the 220 median opening crashes involved multi-vehicle collisions. Table 48 shows that the predominant crash types at the median openings of interest were angle/broadside, rear-end, and sideswipe crashes.

Predictive Model Development

Team members developed crash prediction models that could be used as SPFs and, as part of these models, tested the effects of specific site characteristics that might serve as CMFs. The dependent variables selected for modeling were as follows:

- Total crashes per site for all available years combined.
- Injury crashes per site for all available years combined.
- Total crashes per site-year. Treating the crashes in each year of the 5 years at each site as a separate observation increases the sample size of data points by a factor of 5 but reduces the mean crash frequency per observation.
- Injury crashes per site-year. Treating the injury crashes in each year of the 5 years at each site as a separate observation increases the sample size of data points by a factor of 5 but reduces the mean crash frequency per observation.

Table 44. Distribution of sites by presence of at least one skewed minor-road leg.

At Least One Skewed Leg Present on the Minor Road?	Number of Median Openings	Percentage of Median Openings
Yes	3	6.5
No	43	93.5
Total	46	100.0

Table 45. Distribution of median openings by number of crashes in five years.

Number of Crashes per Median Opening	Number of Median Openings	Percentage of Median Openings
0	7	15.2
1	7	15.2
2	4	8.7
3	6	13.0
4	2	4.3
5	4	8.7
6	3	6.5
7	2	4.3
8	3	6.5
9	0	0.0
10	2	4.3
11	0	0.0
12	1	2.2
13	2	4.3
14	1	2.2
15	1	2.2
16	1	2.2

Table 46. Distribution of median opening crashes by crash severity level.

Crash Severity Level (Most Severe Injury)	Number of Crashes	Percentage of Crashes
Fatal	0	0.0
A injury	5	2.3
B injury	31	14.1
C injury	67	30.5
Property damage only	117	53.2
TOTAL	220	100.0

Table 47. Distribution of median opening crashes by number of vehicles involved.

Number of Vehicles Involved	Number of Crashes	Percentage of Crashes
Single vehicle	14	6.4
Multiple vehicle	206	93.6
TOTAL	220	100.0

Table 48. Distribution of median opening crashes by type of collision.

Type of Collision	Number of Crashes	Percentage of Crashes
Head-on	3	1.4
Sideswipe	40	18.2
Rear-end	68	30.9
Broadside	75	34.1
Hit object	15	6.8
Overturned	4	1.8
Pedestrian	10	4.6
Bicycle	0	0.0
Other/unknown	5	2.3
TOTAL	220	100.0

The number of site-years previously noted represents the number of sites times the number of years of crash data available for each site. Since there were 46 sites with 5 years of crash data for each site, that would constitute 230 site-years of data. Regression models developed with all 5 years of data combined for each of the 46 sites were based on a sample size of 46 observations. Where each year of crash data at each site was treated as a separate observation in modeling, the regression models were based on a sample size of 230 observations. The larger sample size obtained by considering each year of crash data separately was worth considering because it may increase the likelihood of obtaining statistically significant models. At the same time, considering each year of crash data separately decreases the average number of crashes per observation and would likely increase the variability of the crash counts. There was no way of knowing before the analysis whether considering all 5 years of crash data together or considering each year separately would produce better models. Therefore, the project team tried both approaches. When each year of crash data was considered separately, a random site effect was used in the regression modeling to account for the presence of repeated measures (i.e., to account for the fact that each of the five observations for a given site were repeated observations of the exact same site.)

In addition, angle/turning crashes (total crashes and injury crashes) were also considered as dependent variables because they related most directly to vehicle-vehicle conflicts in the median opening area. Angle/turning crashes were defined as multi-vehicle crashes involving head-on, sideswipe, broadside, and overturning crashes. Approximately 55.9 percent of all crashes were angle/turning crashes.

Independent variables considered in the modeling included those variables that appeared most likely to be related to crash causation in the median opening area:

- AADT of the major road at the median opening
- AADT of the minor road at the median opening
- Separation distance between the median opening and the nearest signalized intersection
- Major-road median width at the median opening
- Number of intersection legs at the median opening (three or four)
- Number of major-road through lanes (four or six)

The first four independent variables were modeled as continuous variables. The latter two variables were modeled as categorical variables. The base condition for the number of intersection legs was a three-leg intersection. The base condition for the number of major-road through lanes was four lanes.

Left- and right-turn lanes were not used in the models because they seemed unlikely to have much effect on crashes in the median opening area. The skewed intersection indicator was not used in models because of the very small number of skewed intersections (three out of 46).

No minor-road data were available for the five median opening sites at which the minor or side road was a driveway rather than a public road intersection. Thus, 41 of the 46 sites were used in modeling.

Predictive models were developed with negative binomial regression analysis. This approach was used because crash frequency data generally follow a negative binomial distribution. Crash data are known not to follow a normal distribution, which is assumed in ordinary least squares regression. The distribution of crash frequencies illustrated in Table 48 is more akin to a Poisson distribution. However, an assumption of the Poisson distribution is that the mean and variance of the distribution are equal. For crash data, the variance is generally greater than the mean, and such data are said to be overdispersed. Negative binomial regression is the regression technique most suited to overdispersed (or underdispersed) data.

For each dependent variable of interest, preliminary models were developed with negative binomial regression incorporating all six independent variables of interest. These models developed for all years combined at each site have the functional form as shown below (see Equation 6).

$$N_{crashes} = 0.2 \times e^{(a+(b\times MAJAADT)+(c\times MINAADT)+(d\times SEPDIST)+(e\times MEDWIDTH)+(f\times NUMLEGS)+(g\times NUMLANES))} \quad (6)$$

where:

$N_{crashes}$ = number of crashes per year of the target type and severity level
MAJAADT = average daily traffic volume of the major road at the median opening (veh/day) divided by 1,000
MINAADT = average daily traffic volume of the minor road at the median opening (veh/day) divided by 1,000
SEPDIST = separation distance between the median opening and the nearest signalized intersection (ft)
MEDWIDTH = major-road median width (ft) measured from inside edge of through lane to inside edge of through lane
NUMLEGS = variable equal to 1 for four-leg intersections and 0 for three-leg intersections
NUMLANES = variable equal to 1 for six-lane arterials and 0 for four-lane arterials

The models for individual site-years had the following functional form:

$$N_{crashes} = e^{(a+(b\times MAJAADT)+(c\times MINAADT)+(d\times SEPDIST)+(e\times MEDWIDTH)+(f\times NUMLEGS)+(g\times NUMLANES))} \quad (7)$$

where:

$N_{crashes}$ = number of crashes per year of the target type and severity level
MAJAADT = average daily traffic volume of the major road at the median opening (veh/day) divided by 1,000
MINAADT = average daily traffic volume of the minor road at the median opening (veh/day) divided by 1,000
SEPDIST = separation distance between the median opening and the nearest signalized intersection (ft)
MEDWIDTH = major-road median width (ft) measured from inside edge of through lane to inside edge of through lane
NUMLEGS = variable equal to 1 for four-leg intersections and 0 for three-leg intersections
NUMLANES = variable equal to 1 for six-lane arterials and 0 for four-lane arterials

The preliminary models were reviewed and final models were then developed considering only the independent variables that were statistically significant in the preliminary models. The models developed for each dependent variable of interest are presented below.

Models for Total Crashes by Site-Year with a Random Site Effect. Models developed with separate crash counts for each site-year were developed first because this approach provided the largest sample size. With 41 sites and five years of data, there were $41 \times 5 = 205$ observations available for modeling. Since there were multiple observations for each site, a random site effect was included in the modeling.

The tables presenting the predictive models developed have a common format. The model tables each present the following columns:

- Effect – identifies the independent variable of interest.
- Parameter estimate – presents the fitted parameter value for the independent variable of interest.

- Standard error – presents the standard error for the independent variable of interest. Smaller standard errors correspond to smaller confidence limits around the parameter estimate.
- Degrees of freedom – The number of degrees of freedom is a function of the sample size and the number of parameters in the model.
- t is the value of the t-statistic that is used to test the statistical significance of the parameter estimate.
- Pr > |t| is the probability value that results from the test of significance. If the value of Pr > |t| is less than or equal to 0.05, then the parameter estimate is statistically significant at the 5 percent significance level. If the value of Pr > |t| is less than or equal to 0.10 but greater than 0.05, then the parameter estimate is statistically significant at the 10 percent significance level. If the value of Pr > |t| is greater than 0.10, then the parameter estimate is generally considered to be not statistically significant.

Table 49 presents the preliminary model for total crashes by site-year with a random site effect. The "Intercept" row in the table represents a constant term in the regression model. This value is shown in the "Parameter Estimate" column and the "Intercept" row. The results in the table show that the MAJAADT (the average daily traffic volume of the major road) and MINAADT (the average daily traffic volume of the minor road) variables are statistically significant. MAJAADT has a slightly stronger relationship to total crash frequency than MINAADT, but both traffic volume variables are statistically significant at the 10 percent significance level. The other independent variables, SEPDIST (the separation distance between the median opening and the nearest signalized intersection), MEDWIDTH (the major-road median width), NUMLEGS (1 for four-leg intersections and 0 for three-leg intersections), and NUMLANES (1 for six-lane arterials and 0 for four-lane arterials) are not statistically significant. The overdispersion parameter for the model in Table 49, which is needed to use the model with the Empirical Bayes procedure, is 0.1886. The goodness of fit for this model is represented by the value known as −2 Log Likelihood, with a value of 720.06. The smaller this goodness of fit value, the better the model.

It makes logical sense that the two traffic volume variables in Table 49 are statistically significant because traffic volumes usually have the strongest relationship to crash frequency. A final model was developed by dropping the SEPDIST, MEDWIDTH, NUMLEGS, and NUMLANES terms in the model and retaining only the MAJAADT and MINAADT terms. This model is summarized in Table 50. The table shows that both the MAJAADT and MINAADT terms are statistically significant in this model at the 5 percent significance level, a definite improvement over the preliminary model in Table 49. The overdispersion parameter is 0.1937. The −2 Log Likelihood goodness of fit value is 700.75, a slight improvement from the model in Table 49. The goodness of fit value normally preferred for negative binomial regression models, known

Table 49. Preliminary model for total crashes by site-year.

Effect	Parameter Estimate	Std Error	Degrees of Freedom	t	Pr > |t|	Significant?
Intercept	-2.0057	0.7980	35	-2.51	0.0167	SIG @ 5%
MAJAADT	0.0337	0.0174	163	1.93	0.0552	SIG @ 10%
MINAADT	0.0958	0.0512	163	1.87	0.0632	SIG @ 10%
SEPDIST	0.0015	0.0021	163	0.71	0.4793	NS
MEDWIDTH	0.0100	0.0121	163	0.83	0.4100	NS
NUMLEGS	0.1791	0.3842	163	0.47	0.6416	NS
NUMLANES	-0.2565	0.4288	163	-0.60	0.5504	NS

Table 50. Final model for total crashes by site-year.

Effect	Parameter Estimate	Std Error	Degrees of Freedom	t	Pr > |t|	Significant?
Intercept	-1.2146	0.4346	39	-2.78	0.0080	SIG @ 5%
MAJAADT	0.0283	0.0135	163	2.10	0.0373	SIG @ 5%
MINAADT	0.0910	0.0446	163	2.05	0.0429	SIG @ 5%

as the Akaike information criterion (AIC), is not applicable to models that incorporate a random effect and, therefore, was not computed.

Models for Injury Crashes by Site-Year with a Random Site Effect. Crash prediction models for injury crashes are useful because reducing injury crashes is generally considered a higher priority than reducing other crashes. However, in the predictive model for injury crashes shown in Table 51, all six of the independent variables are not statistically significant. The overdispersion parameter for the model presented in Table 51 is 0.2189, and the -2 Log Likelihood value representing goodness of fit is 828.94, representing substantially lower goodness of fit than in the comparable total crash model. Based on these results, it does not appear that a useful injury crash model can be developed. For this reason, no final model was developed for injury crash data using the site-year approach.

Models for Total Crashes by Site for All Years Combined. Models for total crashes for all years combined for each site were developed with negative binomial regression in a manner analogous to the models by site-year. The preliminary model resulting from this effort is shown in Table 52. Like the model for site-years shown in Table 49, only the MAJAADT and MINAADT effects are statistically significant in this model, both at the 10 percent significance level. The overdispersion parameter has a value of 0.4566, and the AIC representing goodness of fit is 222.86.

A final model with just the MAJAADT and MINAADT effects was developed with negative binomial regression. The MAJAADT term was statistically significant at the 10 percent significance level. The MINAADT term was only significant at the 15 percent significance level, which is generally regarded as not statistically significant. The overdispersion parameter has a value of 0.5218, while the AIC goodness of fit value is 217.74, a slight improvement over the model in Table 52.

The total crash model based on data for individual site-years of data shown in Table 50 is based on a larger sample size than the total crash model in Table 53. The model in Table 50 appears preferable to the model in Table 53.

Table 51. Preliminary model for injury crashes by site-year.

Effect	Parameter Estimate	Std Error	Degrees of Freedom	t	Pr > |t|	Significant?
Intercept	-2.1784	0.9135	35	-2.38	0.0226	SIG @ 5%
MAJAADT	0.0251	0.0191	163	1.31	0.1912	NS
MINAADT	0.0708	0.0514	163	1.38	0.1704	NS
SEPDIST	0.0010	0.0023	163	0.45	0.6566	NS
MEDWIDTH	-0.0106	0.0165	163	0.64	0.5214	NS
NUMLEGS	0.6479	0.4003	163	1.62	0.1075	NS
NUMLANES	0.2504	0.4717	163	0.53	0.5962	NS

Table 52. Preliminary model for total crashes by site for all years combined.

Effect	Parameter Estimate	Std Error	Degrees of Freedom	t	Pr > |t|	Significant?
Intercept	-0.3162	0.7658	34	-0.41	0.6823	NS
MAJAADT	0.0335	0.0181	34	1.84	0.0738	SIG @ 10%
MINAADT	0.0878	0.0509	34	1.73	0.0933	SIG @ 10%
SEPDIST	0.0021	0.0019	34	1.09	0.2822	NS
MEDWIDTH	0.0069	0.0112	34	0.61	0.5430	NS
NUMLEGS	0.1734	0.3459	34	0.50	0.6194	NS
NUMLANES	0.3476	0.4024	34	-0.86	0.3937	NS

Models for Injury Crashes by Site for All Years Combined. The injury crash model for all years combined, shown in Table 54, has no statistically significant effects other than the NUMLEGS term, which is statistically significant at the 10 percent significance level. For this model, the overdispersion parameter is 0.3344 and the AIC goodness of fit measure is 166.48.

The statistical significance of the NUMLEGS term for the model in Table 54 does not appear meaningful. The lack of statistical significance for the MAJAADT and MINAADT terms, which would normally be the strongest effects in crash prediction models, suggests that the significance of the NUMLEGS term could be an artifact of a correlation between variables. Based on these results, it does not appear that a useful injury crash model can be developed. For this reason, no final model was developed for injury crash data using the approach with all years of crash data combined for each site. It does not appear that any injury crash models can be successfully developed with the available dataset using either of the approaches that were tried. The reduced crash sample size for injury crashes, less than half of total crashes, appears to impede the development of statistically significant injury crash models.

Models for Total and Injury Angle/Turning Crashes. Models for angle/turning crashes were developed for all four dependent variables used in modeling all crash types combined:

- Total crashes per site for all available years combined
- Injury crashes per site for all available years combined
- Total crashes per site-year
- Injury crashes per site-year

None of these efforts resulted in useful models. The reduced sample size of angle/turning crashes made it difficult to model this set of crashes.

Discussion of Results

Potentially useful crash prediction models were developed for total crashes. The best model, presented in Table 50, can be written as shown in Equation 8.

$$N_{crashes} = e^{(-1.2146+(0.0283\times MAJAADT)+(0.0910\times MINAADT))} \quad (8)$$

Table 53. Final model for total crashes by site for all years combined.

Effect	Parameter Estimate	Std Error	Degrees of Freedom	t	Pr > |t|	Significant?
Intercept	0.5994	0.4558	38	1.32	0.1963	NS
MAJAADT	0.0273	0.0144	38	1.90	0.0648	SIG @ 10%
MINAADT	0.0823	0.0511	38	1.61	0.1159	SIG @ 15%

Table 54. Preliminary model for injury crashes by site for all years combined.

Effect	Parameter Estimate	Std Error	Degrees of Freedom	t	Pr > |t|	Significant?
Intercept	-0.5060	0.8542	34	-0.59	0.5575	NS
MAJAADT	0.0221	0.0184	34	1.20	0.2378	NS
MINAADT	0.0639	0.0502	34	1.27	0.2113	NS
SEPDIST	0.0015	0.0021	34	1.69	0.4920	NS
MEDWIDTH	-0.0112	0.0155	34	-0.72	0.4754	NS
NUMLEGS	0.7078	0.3508	34	2.02	0.0515	SIG @ 10%
NUMLANES	0.2547	0.4259	34	0.60	0.5539	NS

where:

$N_{crashes}$ = number of total crashes per year related to the median opening of interest
MAJAADT = average daily traffic volume on the major road at the median opening (veh/day) divided by 1,000
MINAADT = average daily traffic volume on the minor road at the median opening (veh/day) divided by 1,000

The overdispersion parameter for use with this model is 0.1937. This model could potentially be used as an SPF for unsignalized median openings.

No separate prediction model for injury crashes could be developed. Based on the available crash history data, it can be estimated that 47 percent of the crashes predicted by the model will be injury crashes and 53 percent will be crashes only involving property damage.

No other independent variables showed effects that were sufficiently consistent to serve as a basis for developing CMFs. Most especially, the SEPDIST effect was never statistically significant in any model. Thus, there does not appear to be any evidence for presuming that median openings closer to signalized intersections have more crashes, at least within the range of 150 to 490 ft of separation distance.

Qualitative Crash Analysis

In addition to a statistical analysis of crashes, lessons can be learned by examining site characteristics to determine crash trends at a given site. For this activity, the research team used data for the Arizona and Texas study sites. The data segmentation was previously depicted in Figure 21.

The goal of this qualitative analysis was to identify any over-representation of a particular crash type at the Arizona or Texas study locations. Note that a conflict analysis is included in Chapter 3 that includes all the study sites where the project team collected data. The detailed crash summary information is available in Appendix B; the general observations are summarized in Table 55 (Arizona) and Table 56 (Texas). The evaluation shown in these two tables focused on common crash types that can be expected to be associated with a median opening (namely left-turn crashes, angle crashes, and same-direction sideswipe crashes). These crash types represented 51 percent of all crashes that occurred at the Arizona sites from 2013 to 2017. Similarly, 41 percent of the Texas crashes were associated with these three crash types. An evaluation of the individual segments supports the California statistical findings that there are not any clear trends between crash location/type and the distance from the median opening to the signalized intersection. Because this analysis was limited to crashes in the immediate

Table 55. Summary of crashes at Arizona sites.

Location	Distance from Median Opening to Intersection (ft)	Crash Types Associated with Median Opening Operations				Percentage of Total Related to Median Opening Crash Types
		Left-Turn	Angle	Sideswipe Same Direction	Total All Crashes	
Site AZ-01						
Segment 1	107	0	0	0	0	0
Segment 2		0	0	1	2	50
Segment 3		0	0	0	0	0
Segment 4		0	0	0	0	0
Subtotal		0	0	1	2	50
Site AZ-02						
Segment 1	267	0	2	3	14	36
Segment 2		18	5	3	37	70
Segment 3		0	3	1	10	40
Segment 4		1	2	3	9	67
Subtotal		19	12	10	70	59
Site AZ-03						
Segment 1	277	1	0	1	7	29
Segment 2		2	3	0	6	83
Segment 3		0	1	0	1	50
Segment 4		0	0	0	2	0
Subtotal		3	4	1	16	47
Site AZ-04						
Segment 1	344	0	3	3	21	29
Segment 2		4	0	1	6	83
Segment 3		1	0	0	1	100
Segment 4		0	0	1	2	50
Subtotal		5	3	5	30	43
Site AZ-05						
Segment 1	331	0	2	1	6	50
Segment 2		4	5	2	27	41
Segment 3		n/a	n/a	n/a	n/a	n/a
Segment 4		2	3	1	9	67
Subtotal		6	10	4	42	48
Site AZ-06						
Segment 1	369	0	0	0	0	0
Segment 2		0	0	0	1	0
Segment 3		0	0	0	0	0
Segment 4		0	1	0	1	100
Subtotal		0	1	0	2	40
Total		33	30	21	162	52
Percent of Total		20%	18%	13%	100%	

Table 56. Summary of crashes at Texas sites.

Location	Distance from Median Opening to Intersection (ft)	Crash Types Associated with Median Opening Operations: Left-Turn	Angle	Sideswipe Same Direction	Total All Crashes	Percentage of Total Related to Median Opening Crash Types
Site TX-01						
Segment 1	140	0	2	0	2	100
Segment 2		0	8	0	11	73
Segment 3		0	0	0	0	0
Segment 4		0	3	0	5	60
Subtotal		0	13	0	18	72
Site TX-02						
Segment 1	265	0	0	0	6	0
Segment 2		0	1	0	6	17
Segment 3		n/a	n/a	n/a	n/a	n/a
Segment 4		1	5	1	15	47
Subtotal		1	6	1	27	30
Site TX-03						
Segment 1	271	0	1	0	1	100
Segment 2		0	0	0	2	0
Segment 3		0	1	0	1	100
Segment 4		0	0	0	0	0
Subtotal		0	2	0	4	67
Site TX-04						
Segment 1	186	1	5	4	19	53
Segment 2		0	1	1	5	40
Segment 3		0	0	0	0	0
Segment 4		0	1	0	0	0
Subtotal		1	7	5	24	54
Site TX-05						
Segment 1	320	0	1	2	7	29
Segment 2		0	2	0	2	100
Segment 3		n/a	n/a	n/a	n/a	n/a
Segment 4		0	3	0	7	43
Subtotal		0	6	2	16	50
Site TX-06						
Segment 1	424	0	8	0	11	73
Segment 2		0	2	1	4	75
Segment 3		0	0	0	2	0
Segment 4		0	1	0	1	100
Subtotal		0	11	1	18	67
Total		2	45	9	107	41
Percent of Total		1%	33%	7%	100%	

vicinity of the median opening, it is likely that the absence of a clear trend would suggest that crashes are more likely associated with the adjacent corridor and may not always result in crashes immediately adjacent to the median opening.

Upon inspection of the content of these tables, the following qualitative characteristics are observed:

Arizona Sites

- Arizona sites typically included left-turn crashes and angle crashes as the predominant crashes that occurred near the associated full median openings.
- The distribution of the observed crashes in Arizona did not have any clear pattern, except that sites with a shorter distance between the median opening and the signalized intersection

were often where a larger percentage of total crashes were attributed to median openings. For example, 59 percent of the crashes observed at Site AZ-02, where the distance from the median opening to the intersection was 267 ft, were associated with the median opening. Locations where this distance was 300 ft or greater had between 43 and 52 percent of total crashes attributed to the median opening.

Texas Sites

- Texas sites overwhelmingly featured angle crashes as the crash type most associated with median openings.
- The site with the shortest distance between the median opening and the signalized intersection (Site TX-01, 140 ft) was also the site with the largest percentage of crashes attributed to the median opening (72 percent).

Arizona and Texas Sites

- Across both states, the percentage of total crashes associated with the median opening ranged from a low value of 30 percent (Site TX-02) to a high of 72 percent (Site TX-01).
- As noted in the quantitative safety assessments, the qualitative evaluation also indicated that the relationship of crashes to the distance between the median opening and the signalized intersection does not have a clear trend. It is noteworthy that, generally, the highest percentage of total crashes attributed to the median opening tends to be related to shorter distances between the median opening and the intersection.

Chapter Summary Remarks

This chapter summarized the safety assessment for full median openings with at least one turn bay. The analysis included three targeted evaluations:

- corridor approach crash analysis (Arizona and Texas data)
- median opening localized crash analysis (California HSIS data)
- qualitative crash analysis (Arizona and Texas data)

In general, these collective assessments noted that a small number of crashes do appear to be linked with the presence of this type of median opening; however, the number of injury crashes related to an unsignalized full median opening near a signalized intersection is quite small. For median-related crashes located along a signalized approach, the presence of the full median opening, the number of arterial through lanes (both directions total), and the ADT are influential variables. For crashes immediately adjacent to the median opening, the major and minor AADT at the full median opening are the most influential variables for total crashes. A notable observation is that how far the median openings are located upstream of the signalized intersection is not a significant variable for any of the models.

CHAPTER 6

Findings and Conclusions

The original goal of this research effort was to better understand the implications of constructing a median opening near a signalized intersection. Upon Phase I inspection of candidate median configurations, the research team identified variations of full and directional median openings. Many of these locations included two turn bays for the median opening, but a large number had only one turn bay or no turn bays. Based on representative sample sizes that assessed a variety of geographic locations coupled with varying distances between the median opening and the signalized intersection, the panel directed the project team to limit the subsequent analysis to full median openings with at least one turn bay. The panel selected this median opening configuration based on the configurations most commonly observed during the Phase I sampling efforts. Ultimately, this research evaluated how the placement of an unsignalized full median opening (with at least one turn bay) near a signalized intersection can influence facility operations and safety.

This chapter provides a summary of findings, recommends content for consideration in national technical guidance documents, and then assesses the knowledge gaps (previously identified in Chapter 2) to determine what additional information has been identified that can help address these gaps.

Summary of Findings

The research summarized in this report evaluated several potential factors related to the operational and safety performance of the median opening treatments. Included with these assessments, the team collected extensive data at study locations in Arizona, Kansas, Missouri, Pennsylvania, and Texas. The data included geometric characteristics, operational information, and crash data (where available). The overall analysis included evaluations of the following:

- Operational assessment of distance from median opening to signalized intersection (based on Arizona, Kansas, Missouri, Pennsylvania, and Texas data)
- Assessment of conflicting driveways near the median opening (based on Arizona, Kansas, Missouri, Pennsylvania, and Texas data)
- Quantitative safety assessment for corridor approach (based on Arizona and Texas data)
- Quantitative safety assessment for localized conditions at median opening (based on California data)
- Qualitative evaluation of observed crashes (based on Arizona and Texas data)

The literature review highlighted several factors that were expected to potentially influence vehicle operations and safety. Ultimately, the factors with the greatest operational influence on the distance from median opening to signalized intersection (referred to as "approaching distance" in the report) included:

- Number of turn bays at the median opening (designated as B1 with two bays or B2 with only one turn bay)
- Number of conflicting driveways (within approximately 150 ft of the median opening)
- Number of arterial through lanes

In addition, an assessment of observed conflicts at the study sites determined that the number of conflicting driveways (located within approximately 150 ft of the median opening, for an overall influence length of approximately 300 ft) and the median opening turning volume had the greatest influence on the frequency of vehicle conflicts.

Crash data could not be acquired for all the study sites, but the project team was able to acquire crash data for the Arizona and Texas study and comparison sites. This information enabled the research team to conduct an approach corridor safety assessment for these two states that focused on the section of road just upstream of the median opening and extending to the signalized intersection. The analysis evaluated a total crash and an injury crash model that targeted crashes attributed to the median. As a result of this analysis, the team observed the following:

- The Arizona-only total crash model resulted in significant variables associated with the type of median opening, the number of adjacent through lanes, the ADT, and the presence of bus stops. The bus stop variable appeared to be strongly correlated to facility speed limit.
- The Texas-only total crash model resulted in significant variables associated with the type of median opening, the number of adjacent through lanes, and the ADT.
- The merged Arizona and Texas total crash model included the median opening type, the number of adjacent through lanes, and the ADT. For this model, the coefficient for median type was positive. The ADT variable was also determined to have a positive coefficient, while the number of through lanes variable had a negative value.
- The number of injury crashes at the study sites was very small, and the resulting equations also produced a very small number of estimated crashes, likely due to this small sample size.
- The distance from the median opening to the signalized intersection was not determined to be statistically significant for the approach corridor safety assessment.

A second safety analysis used HSIS data from California to evaluate the localized effect of crashes immediately adjacent to the median opening. This analysis determined that the number of crashes is strongly influenced by the major and minor AADT volume. More specifically, for the studied California locations, the analysis did not find that the distance from the median opening to the signalized intersection substantially influenced the number of crashes along the corridor. This finding should not be interpreted to suggest that median opening characteristics do not influence safety, but rather that the influence of the major and minor traffic volume at the median opening dominates crash prediction at these locations.

A final qualitative analysis of the crash data for Arizona and Texas noted the following:

- Across both states, the percentage of total crashes associated with the median opening ranged from a low value of 30 percent (Site TX-02) to a high of 72 percent (Site TX-01).
- The relationship of crashes to the distance between the median opening and the signalized intersection does not have a clear trend. It is noteworthy that, generally, the highest percentage of total crashes attributed to the median opening tends to be related to shorter distances between the median opening and the intersection.

The sites selected for this analysis had minimal pedestrian or bicycle activity, and so their quantitative effects could not be directly assessed.

Content to Consider for Inclusion in National Technical Publications

The research summarized in this report provides new insights into the performance of full median openings (with at least one turn bay) located in close proximity to signalized intersections. The research team specifically evaluated the following three national documents to assess suitability for inclusion of this content:

- AASHTO *A Policy on Geometric Design of Highways and Streets* (commonly known as the AASHTO Green Book).
- AASHTO *Highway Safety Manual*.
- TRB *Access Management Manual*.

This section of the report, therefore, summarizes recommended content that should be considered for inclusion in these national publications.

A Policy on Geometric Design of Highways and Streets

The AASHTO Green Book (*49*) provides recommendations for the application of geometric elements for use in roadway design. The Green Book covers a variety of road types, including arterial roadways with raised medians. For the research summarized in this report, the research team identified the following recommendations.

Proposed revision #1-Page 7–41, third full paragraph, third sentence:

Original content:

> Spacing between median openings should be adequate to allow for introduction of left-turn lanes and anticipated storage needs of left-turn queues.

Suggested revision:

> Spacing between median openings **or between a median opening and nearby signalized intersection** should be adequate to allow for introduction of left-turn lanes and anticipated storage needs of left-turn queues.

Proposed revision #2-Page 9–118, Section 9.8 (Median Openings), content following the second paragraph:

Add graphics that depict the various types of median openings. These could be adapted from Figures 1, 2, 3, and 4 of this report.

Proposed revision #3-Page 9–118, Section 9.8 (Median Openings), new text at end of section:

> The placement of a median opening near a signalized intersection should be carefully considered. Research has shown that factors influencing the efficient placement of a full median with at least one turn bay include number and types of turn bays, number of through lanes, and conflicting driveways located within 150 feet of the median opening.

Highway Safety Manual

The first edition of the AASHTO *Highway Safety Manual* (HSM) (*50*) was published in 2010 and introduced consistent data-driven assessment techniques that should be considered when evaluating safety performance. Volume 2 of the HSM introduces a predictive method for estimating the number of crashes for a facility with given characteristics. Chapter 12 of the HSM focuses on urban and suburban arterial applications. The first edition of the HSM does not directly address median opening spacing or configuration. The presence and type of a median is included and defined as undivided, divided by raised or depressed median, or divided with a center two-way left-turn lane.

Proposed revision #1-Page 12-15:

Immediately following the third bullet (presence/type of median) and the companion table with rounded median widths, it is recommended that the following note be added:

> The influence of an unsignalized median opening is not directly considered with this model. Full median openings, therefore, should be treated as unsignalized intersections until a median opening variable can be more fully evaluated in future HSM editions.

Access Management Manual

The second edition of the TRB *Access Management Manual* (AMM2) (*1*) is a comprehensive resource for access management principles and applications. The AMM2 already addresses the placement of median openings near driveways or near other median openings, but this content can benefit from the following clarifications, which is based on findings from this research effort.

Proposed revision #1-Page 420, Section 17.4 (Spacing of Median Openings), first paragraph:

Original content:

> In rural areas, median openings commonly permit all movements. However, when a median opening is being provided in the fringe of an urban area, it is important to consider the potential for future signalization. A full median opening that is located where signalization will interfere with efficient traffic progression may need to be closed or reconstructed as a directional opening.

Suggested revision:

> In rural areas, median openings commonly permit all movements. However, when a median opening is being provided in the fringe of an urban area, it is important to consider the potential for future signalization. A full median opening that is located where signalization will interfere with efficient traffic progression may need to be closed or reconstructed as a directional opening. **In some cases, however, the placement of a median opening upstream of a signalized intersection can help facilitate left- or U-turn movements at the signalized intersection by shifting that maneuver out of the intersection. If this application is deployed, turn bays at the median opening should be constructed and overlap with turn bays from the signalized intersection should be avoided.**

Proposed revision #2-Page 424, Section 17.4.2 (Access Connections on Opposite Side of a Full Median Opening), first paragraph:

Original content:

> Access connections are often located directly opposite one another to create a four-way intersection. Some state and local agency regulations require that access connections be located directly opposite one another. This alignment works satisfactorily when volumes are low. When roadway volumes increase to the extent that crossing and left-turn movements cannot be made safely, the median opening needs to be closed.

Suggested revision:

> Access connections are often located directly opposite one another to create a four-way intersection. Some state and local agency regulations require that access connections be located directly opposite one another. This alignment works satisfactorily when volumes are low. **The use of staggered driveways within approximately 150 feet of the median opening, however, can also provide opportunity for accommodation of vehicles attempting to access driveways near the median opening.** When roadway volumes increase to the extent that crossing and left-turn movements cannot be made safely, the median opening needs to be closed.

Resolution of Identified Knowledge Gaps

During the Phase I literature and state-of-practice review, the project team identified several knowledge gaps that were potentially related to this research effort. This section reviews these identified gaps and how, if applicable, they were addressed as part of this research effort.

Median Opening Functional Area/Distance

Intersections generally have well-defined functional areas with associated distances that are based on context, speed, and volume and are blended with engineering concepts such as deceleration. The upstream and downstream boundaries of a functional area aid transportation decision makers in determining appropriate corner clearance (for driveway placement) and expected limits of queuing and deceleration activities.

Median openings have similar influential factors but, to date, a functional area procedure does not exist. This research found that driveways located within approximately 150 ft of the median opening have a significant impact on median opening operations (see Figure 16). This value was determined by considering the most dangerous situation in which the primary speed of the vehicle is 25 mph and the secondary speed is zero. This condition equates to a 150 ft stopping sight distance. Therefore, extending the functional area beyond these boundaries as well as beyond the turn bays for the median opening is advisable. For median types other than full median openings with at least one turn bay (Type B), this finding should be further evaluated.

Minimum Spacing Between Median Opening and Left-Turn Taper

The published literature and state-of-practice review did not provide specific guidance relative to how close the end of a median opening (i.e., the point closest to the downstream intersection) should be located to the beginning of the taper point for a left-turn lane that services the downstream signalized intersection. As part of the operational analysis, the project team reviewed vehicle interactions and/or conflicts for corridor, median opening, and left-turn intersection maneuvers. This spacing between the median opening and the left-turn taper was determined not to be a significant factor. Higher priority should therefore be given to avoiding overlap of the intersection functional area with the physical median opening boundaries.

Impacts of Decision Sight Distance and/or Intersection Sight Distance on Median Opening Placement

The decision sight distance and intersection sight distance are concepts that are comprehensively addressed in the AASHTO Green Book; however, this information has not been explicitly applied to median opening configurations, nor has it been directly addressed in the assessment of median openings for this project. Consequently, the following summary expands on this issue.

Definitions

In roadway design, stopping sight distance (SSD) is to be provided at all locations along a roadway. SSD is the distance traveled during perception-reaction time and maneuver time. Perception-reaction time is the time it takes for a road user to realize that a reaction is needed due to a road condition, decide what maneuver is appropriate (for SSD, stopping the vehicle), and start the maneuver (i.e., move foot from accelerator to brake). Maneuver time is the time it takes to decelerate to a stop. The current AASHTO Green Book includes the following values for consideration with SSD:

- Perception-reaction time = 2.5 sec
- Deceleration rate = 11.2 ft/sec/sec
- Driver's eye height = 3.5 feet
- Object height = 2.0 feet

While the provision of SSD should be sufficient in most cases for a driver to comprehend a possible conflict and react appropriately, there may be a few situations when additional sight distance would permit a driver to have a longer period in which to identify and react to a roadway condition. Decision sight distance (DSD), per the AASHTO Green Book, is "the distance needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered, recognize the condition or its potential threat, select an appropriate speed and path, and initiate and complete complex maneuvers" (*48*). Table 57 provides the sight distance values for SSD and DSD from the AASHTO Green Book.

Literature. Two research efforts have explored the question of SSD and DSD: Barricklow and Jacobson (*51*) and Layton (*52*).

Layton (*52*) noted stopping sight distance is required at all locations along the highway and that DSD may be the control for many access management situations, including the following:

- "Driver workload is heavy, driver expectations vary or drivers are likely to be misled, such as in the vicinity of interchange ramp terminals or where continuous two-way left turn lanes are present.
- Complex operations or design features exist, such as unsignalized intersections, approaches on multilane highways or directional median openings."

Table 57. Stopping and decision sight distance values [AASHTO Green Book (*48*)].

Design Speed (mph)	Stopping Sight Distance (ft)	Decision Sight Distance, Avoidance Maneuver A (ft)	Decision Sight Distance, Avoidance Maneuver B (ft)
15	80	Not provided	Not provided
20	115	Not provided	Not provided
25	155	Not provided	Not provided
30	200	220	490
35	250	275	590
40	305	330	690
45	360	395	800
50	425	465	910
55	495	535	1030
60	570	610	1150
65	645	695	1275
70	730	780	1410
75	820	875	1545
80	910	970	1685
85	1010	1070	1830

Sources: Stopping Sight Distance from 2018 Green Book Table 3-1, assumes brake reaction distance of 2.5 sec, deceleration rate of 11.2 ft/sec/sec.

Decision Sight Distance, Avoidance Maneuver A (ft) is for stop on rural road with pre-maneuver time of 3.0 sec, from 2018 Green Book Table 3-3.

Decision Sight Distance, Avoidance Maneuver B (ft) is for stop on urban road with pre-maneuver time of 9.1 sec, from 2018 Green Book Table 3-3.

He provided the following conditions when DSD may be applied:

- "To control vehicles that must perceive and react with time to stop behind queuing vehicles.
- To assure adequate time for a speed, path or direction change, as would occur where vehicles must weave over to a left turn lane or to an approach on the right.
- To accommodate pedestrians at crossings.
- To deal with bicycles and bicycle lanes at intersections or major driveways.
- To accommodate transit stops in and adjacent to through lanes.
- To mitigate the added difficulties created by through trucks entering, leaving or double parking in through traffic lanes."

Barricklow and Jacobson (*51*) noted that signalized intersections near crest vertical curves could present sufficient complexities to justify using DSD. They state "unexpected or unusual situations that a driver approaching a signalized intersection on the far side of a crest vertical curve may experience include:

- The intersection and traffic signals are not visible; however, the back of the queue from the signalized intersection is reached.
- The intersection and traffic signals are not visible, and the queue on downgrade of the curve not visible.
- The queue on the downgrade of the curve is not visible, but signal head(s) at the downstream intersection is (are) visible; the queue would be especially unexpected if the visible signal head was green."

They note that under normal driving conditions (i.e., in the absence of a vertical curve), objects downstream of the driver are visible and discernable in a sequential manner, which would allow the driver to comprehend and react within the SSD assumption. Because the presence of a crest vertical curve could limit the driver's sight distance, the addition of other elements such as driveways, transit stops, billboards, roadway geometry changes (e.g., left turns), stopped vehicles, and traffic signals could require the driver to process and respond to multiple objects simultaneously. The additional demand placed on the driver would be translated into additional time needed before the appropriate reaction can be made.

Barricklow and Jacobson (*51*) calculated the location of Reduced Decision Zone, which represents the portion along the roadway where high concentrations of visual noise or complex environments, such as a signalized intersection, should not be located.

Discussion. The values in Table 57 illustrate the potentially large differences between using SSD and DSD for an intersection or a median opening. For example, at a 40 mph design speed, SSD and DSD (avoidance maneuver A) only differ by 15 ft (305 ft for SSD and 330 ft for DSD). When a perception-reaction time of 9.1 sec is assumed rather than 2.5 sec, DSD is more than double the SSD (690 ft for DSD versus 305 ft for SSD). Providing that additional distance could require multiple changes to the road design, resulting in the purchase of additional right-of-way and other impacts. That is not to say that DSD should not be considered with respect to median opening; however, the engineer needs to consider whether the conditions at the unsignalized median opening warrant the additional restrictions that would occur with using DSD.

SSD is designed to provide the distance needed to perceive and react to a road condition, such as a stopped vehicle in a downstream queue or to a crossing pedestrian. DSD is for those rare cases when the complexity of the situation requires additional perception-reaction time prior to applying the brakes or changing lanes. The existing guidance as to when DSD should be used rather than SSD is vague and could benefit from additional research.

Changes in the Access Window Concept as it Applies to Median Opening Placement Along a Corridor

The basis of the access window concept is an assessment of how the various intersection functional areas overlap along a corridor. Optimal access point placement occurs at locations without any overlap. The operational analysis developed a method for estimating minimum spacing between the median opening and the signalized intersection. This entire distance should be incorporated into the access window boundaries. It is not clear how these factors may extend to other median opening configurations.

Safety Effects of Median Opening Spacing

One of the objectives of this research project was to determine the safety effects of median openings near signalized intersections. This research did not address the safety effects of spacing distances to other median openings or for median openings that are not located near signalized intersections, as this is beyond the scope of this project. The research team has developed a problem statement for future research related to this issue. This research problem statement is included in the following text box.

Problem Title

Safety Effects of Median Opening Spacing to Other Median Openings

Background

NCHRP Project 15-64 investigated the safety effects of median openings near signalized intersections. Still needed is an investigation of the safety effects of the spacing between median openings or for median openings that are not located near signalized intersections. Because NCHRP Project 15-64 focused on median openings near a signalized intersection, that literature review focused on urban and suburban regions, which is where those types of median openings are typically located. This new research project will also need to consider rural and exurban environments.

Literature Search Summary

NCHRP Project 15-64, "Guidelines for the Design of Unsignalized Median Openings in Close Proximity to Signalized Intersections," provided a literature review on unsignalized median openings in close proximity to signalized intersections. This new project will need to expand upon that review.

Research Objective

The goal of this project is to provide guidance that can be used by agencies to better understand when, where, and how unsignalized median openings can be positioned in proximity to another unsignalized median opening.

The objectives of this research are as follows:

- Conduct a literature search and review of agency practices. Summarize the research.

- Identify how best to select sites and gather appropriate operational and safety data.
- Collect the needed operational and safety data.
- Develop guideline document.

Implementation Planning

State DOTs would use this information to determine the optimal location for median openings. The findings should be able to be integrated with the findings from and guidance document created in NCHRP Project 15-64.

Estimate of Problem Funding and Research Period

Funding requirements would be moderate, approximately $300,000, with a research period of 24 months. The duration is based on spending approximately the first 6 months conducting a literature search and summarizing the research, as well as determining how best to obtain the desired data that will meet the goal of the project. The remaining 18 months would include collecting the data, evaluating the findings, developing the guidelines, and documenting all aspects of the research.

Urgency and Potential Benefits

With the increased use of median U-turns as part of alternative intersection designs, understanding the optimal spacing for median openings is becoming more important.

Person(s) Developing the Problem Statement

Kay Fitzpatrick, Karen Dixon

Nomination for AASHTO Monitor

To be determined.

Potentially Interested AASHTO Councils and/or Committees

To be determined.

Submitted By

To be determined.

Placement of Median Openings due to Left-Turn Lane Changing and Weaving

The operational component of this research effort focused on vehicle interactions in the vicinity of the median opening and adjacent signalized intersection. In this context, the research directly addressed this knowledge gap for the specific median opening configuration. The research determined that the number of conflicting driveways directly influences vehicle operations linked to optimal distances between the median opening and the adjacent signalized intersection. These conflicting driveways are the physically measurable factor that represents lane changing and weaving along the corridor. In the conflict estimation evaluation, conflicting driveways were also statistically significant. Equation 3 depicts this relationship, where the number of conflicts can be directly estimated based on the median opening turning volume during peak hour and the number of conflicting driveways, as depicted in Figure 16. The approaching distance can then be evaluated based on the type of median opening (full median opening with one turn bay or two), the number of conflicting driveways, and the number of lanes for both directions of the arterial (see Equation 2). This research finding is specific to a full median opening with at least one turn bay. It is not clear how this value may differ for other median configurations.

Placement of Median Openings due to Right-Turn Maneuvers at Signalized Intersections

The operational component of this research effort focused on vehicle interactions in the vicinity of the median opening and adjacent signalized intersection. In this context, the research team acquired turning movement data for the signalized intersection, but this information ultimately did not significantly influence corridor operations as they relate to median opening placement or configuration.

Impact of Traffic Signal Timing and/or Corridor Progression on the Placement of the Median Openings

The upstream traffic signal timing plan will directly influence how traffic arrives at the study location. For corridors with progression, vehicles will arrive in platoons, and larger gaps may be provided for mid-block turning maneuvers. For locations that do not have progression, or where the upstream intersection is placed far enough away so that vehicles are no longer traveling in platoons, available time gaps for mid-block turning maneuvers will be limited. For the specific locations studied, the type of signal timing (pre-timed versus actuated) varied, with approximately half of the sites actuated. The influence of signal timing and associated progression for this study did not provide any significant findings. Anecdotally, however, locations where the upstream signalized intersections provide progression for both directions of travel should perform the best when considering median openings near traffic signals. This is because the initial platoon of vehicles released as the traffic signal changes will tend to arrive to the next downstream intersection together (for urban areas like those evaluated). Therefore, the platoon of vehicles released from the nearby intersection and traveling toward the median opening should be beyond this location by the time the opposing platoon arrives. These movements will better facilitate available gaps in traffic, in contrast to actuated signals that do not provide progression.

Effects of a Direct Left-Turn Versus a U-Turn at the Median Opening Location and Relationship to Conditions at Nearby Signalized Intersection

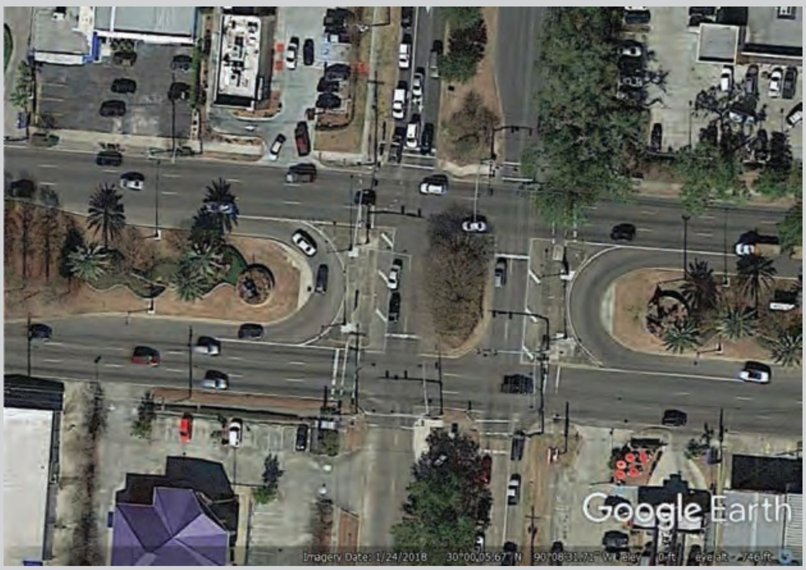
Recent alternative intersection research has explored ways to introduce U-turn maneuvers (typically after the intersection) and remove left turns from the signalized intersection. Some of this information may help address this knowledge gap, but the explicit evaluation of placing a U-turn immediately upstream of a signalized intersection, in lieu of a left turn followed by a U-turn at the intersection, has not been fully addressed. This knowledge gap is beyond the scope of this research project. The project team developed a research problem statement, included in the following text box, for future research related to this issue.

Problem Title

Effects of a direct left turn versus an upstream U-turn and relationship to conditions at nearby signalized intersection

Background

NCHRP Project 15-64 investigated the safety effects of median openings near signalized intersections. A unique type of median opening near a signalized intersection is when the U-turn lane is provided upstream of the signalized intersection rather than downstream. An example of this type of design in Metairie, Louisiana, is shown below. Texas also has several examples of placing a U-turn prior to a signalized intersection.



Removing the left turns from a signalized intersection has shown clear benefits to the operations and safety of the intersection; however, are there unique elements that could offset those benefits when the U-turn is located just prior to the signalized intersection? Examples of potential issues include how the traffic leaving the U-turn merges with the major road traffic and whether driveways should be restricted near the exit of the U-turn.

Literature Search Summary

NCHRP Project 15-64, "Guidelines for the Design of Unsignalized Median Openings in Close Proximity to Signalized Intersections," provided a literature review on unsignalized median openings in close proximity to signalized intersections. A 2017 Texas A&M Transportation Institute study, *Design and Operation of U-Turns at Diamond Interchanges in Texas*, provides insights into the operational and safety effects of these designs in Texas; however, do these results translate to other states?

(continued on next page)

Research Objective

The objectives of this research are as follows:

- Determine the tradeoffs between a direct left turn and an upstream U-turn. Tradeoffs should include consideration of operations and safety.
- Identify and investigate factors affecting U-turn lane use when located upstream of the signalized intersection. Determine optimal geometric design for the upstream U-turn lane.
- Determine the optimal location for the U-turn lane exit with consideration of roadside access. Will drivers attempt to cross multiple lanes to access a driveway? Are supplemental treatments needed to minimize this impact? Should driveways be restricted within a certain range of the U-turn exit?
- Investigate the signing and marking needs for this type of U-turn design.

Implementation Planning

State DOTs would use this information to understand the benefits of locating the U-turn upstream of a signalized intersection. The findings should be able to be integrated with the findings from and guidance document created in NCHRP Project 15-64.

Estimate of Problem Funding and Research Period

Funding requirements would be moderate, approximately $300,000, with a research period of 24 months.

Urgency and Potential Benefits

With the increased use of median U-turns as part of alternative intersection designs, understanding the benefits and optimal design, along with the operational conditions under which a specific design is better, is becoming more important.

Person(s) Developing the Problem Statement

Kay Fitzpatrick, Karen Dixon

Nomination for AASHTO Monitor

To be determined.

Potentially Interested AASHTO Councils and/or Committees

To be determined.

Submitted By

To be determined.

Operational Impacts of How Median Openings Accommodate Ingress Versus Egress

The geometric design of a median opening can influence vehicle positioning with the median opening, driver non-compliance, and similar operational and safety-related issues. The varying physical designs of median opening configurations can be expected to directly influence how vehicles enter and exit the opening and adjacent access points. For this study, the project team evaluated vehicle interactions in the region of the median opening and the adjacent signalized intersection for full median openings with at least one turn bay. For the scenarios and site characteristics studied, this issue has been directly evaluated. Because the number of turn bays was identified as a significant factor in the operational analysis, similar assumptions can be extended to other median opening types with turn bays. These findings, however, do not apply to a full median opening with no turn bays.

Acceptable Time Gaps for Vehicles at Unsignalized Median Openings in Close Proximity to Signalized Intersections

The project team directly measured time gaps at the sites where field observations occurred and found an average time gap of 9 seconds per vehicle. This information should be considered when estimating length for the median opening left-turn bay suitable for peak traffic volume conditions. The time gap for turning vehicles is primarily a factor of driver response to approaching vehicles. It is reasonable to assume this value can be applied to other median openings with turn bays. For configurations without turn bays, the vehicle is exposed to potential rear-end crashes and so can be expected to accept an even shorter time gap.

Concluding Comments

The overall goal of this research effort was to identify ways that practitioners can better understand how the placement of median openings relative to signalized intersections and adjacent driveways can directly affect corridor operational and safety performance. For this study, the research team conducted field observation tests and assessed the influences of various site features. As is common with an observational analysis, it was not feasible to assess all median type configurations or the various nuances for users, such as transit, bicycle, and pedestrian traffic (primarily due to their absence from the sites).

The statistical analysis used to assess significant influential factors for the operational and safety performance of the median helped to identify critical features; however, the lack of statistical significance for some road features should not be interpreted as indicating that they do not influence traffic behavior. As an example, the localized crash analysis did not determine any geometric features were statistically significant but instead found that the major and minor AADT at the signalized intersection significantly influenced the number of crashes. The evaluation of observed vehicle conflicts (as part of the operational evaluation) did highlight that the presence of turn bays and the number of driveways in close proximity to the median opening increased the number of conflicts. This observation suggests that these factors do influence traffic behavior but thankfully do not always result in a crash. A brief companion guidance document accompanies this report (see Appendix C) and highlights the key findings of this research effort.

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Appendices

The following appendices are not included in this report but may be found on the TRB website (www.TRB.org) by searching for "NCHRP Research Report 929":

- Appendix A: Individual Site Data
- Appendix B: Field Data Summaries

Appendix C: Median Opening Guideline Document is included herein. This appendix can be used as needed by transportation professionals responsible for the design of medians and their associate median openings.

APPENDIX C

Median Opening Guideline Document

Scope and Purpose

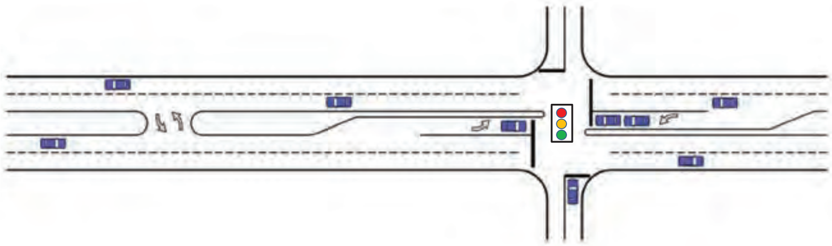
The goal of this guidance document is to provide information that can be used by a practitioner to make informed decisions about how the placement of an unsignalized full median opening near a signalized intersection can influence corridor operational and safety performance. This guidance focuses on full median openings with at least one left-turn bay at the median opening. The following section describes the larger number of potential median openings that could be considered; however, this guidance only includes information related to the full median opening previously identified.

Overview of Potential Median Opening Configurations

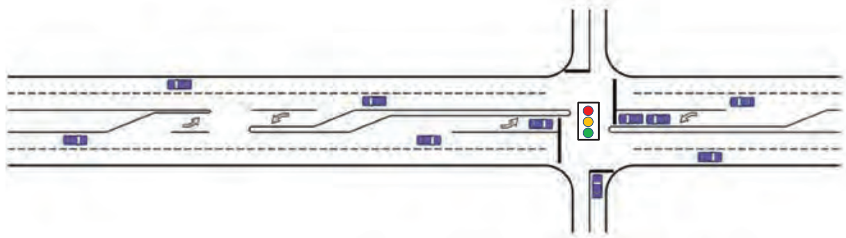
Median openings are often considered when there is a need to provide direct left turn access to or from a major driveway, accommodate right-turn-then-U-turn maneuvers (sometimes referred to as indirect left turns), or facilitate U-turns at mid-block locations. A secondary benefit resulting from the construction of a median opening is the removal of U-turn maneuvers from nearby signalized intersections. In many cases, these median openings provide unrestricted access and are referred to as a full median opening. Figure C-1 demonstrates two example full median opening configurations. The median opening noted as Type A does not accommodate turn bays and so provides little to no vehicle storage. The Type B median opening includes up to two turn bays so that turning vehicles can shift out of the active travel lanes. Both the Type A and Type B full median opening configurations enable unrestricted maneuvers within the median opening. This introduces the opportunity for conflicts between turning vehicles. The median configuration schematics are presented to depict general median opening configuration categories. The placement of the median opening may be shifted longitudinally along the corridor. In some cases, this may result in a median opening located within the region of the turn bay.

A full median opening functions as an unsignalized intersection; however, at many locations there is a need to limit select movements such as direct left turns, crossing maneuvers, or U-turns. One way to minimize or separate the number of conflict points is to construct a directional median opening. Figure C-2, Figure C-3, and Figure C-4 depict example dual and single directional median opening configurations. Directional median openings can help to improve both safety and operational performance when compared to conventional full median openings. One way directional median openings help to improve safety is by preventing or limiting specific turn maneuvers such as crossing or direct left turns.

This guidance document specifically addresses the Type B median opening. This configuration functions as a full median opening but has at least one turn bay that provides storage for turning vehicles. Many of the elements of the Type B median opening also apply to the alternative median configurations, but they are not the focus of this summary guidance document.



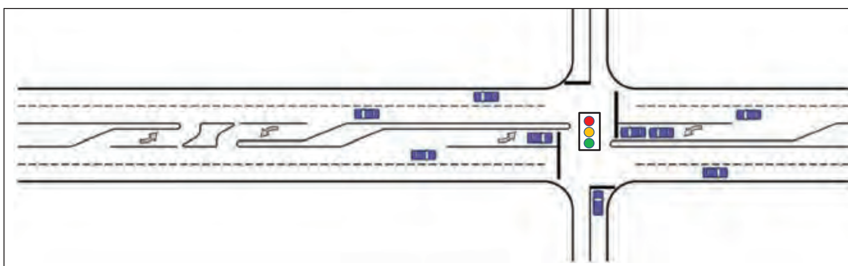
Type A. Full Median Opening without Turn Bays



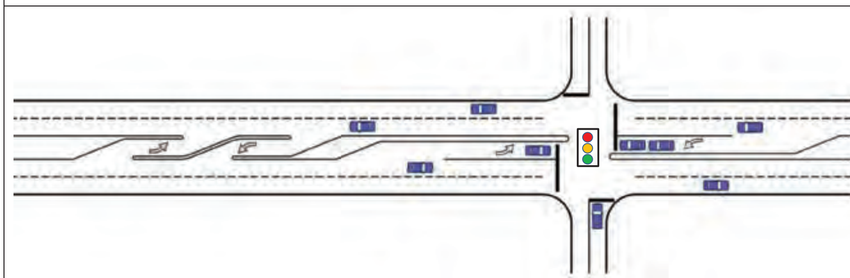
Type B. Full Median Opening with Turn Bays

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity that includes additional driveways unless the driveway is essential to the median functionality.

Figure C-1. Schematic of full median openings.



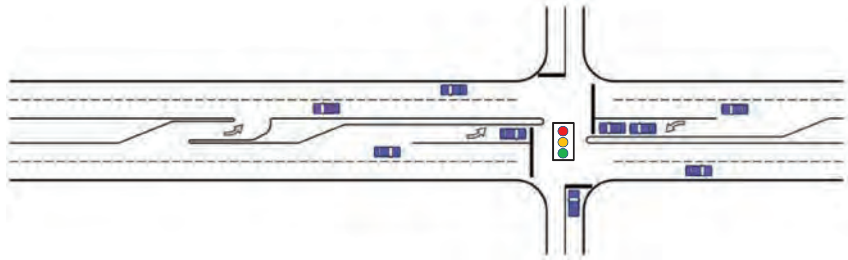
Type C. Dual Directional Median Opening with Island



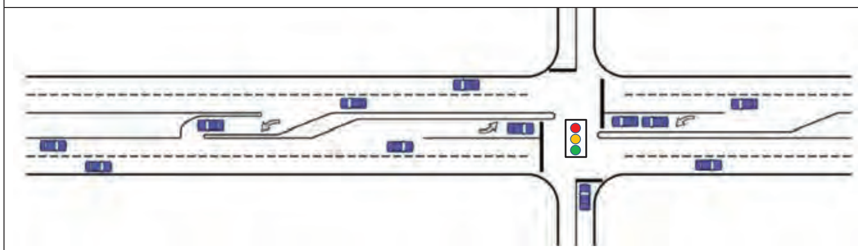
Type D. Dual Directional Median Opening with Separator

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity that includes additional driveways unless the driveway is essential to the median functionality.

Figure C-2. Schematic of dual directional median openings.



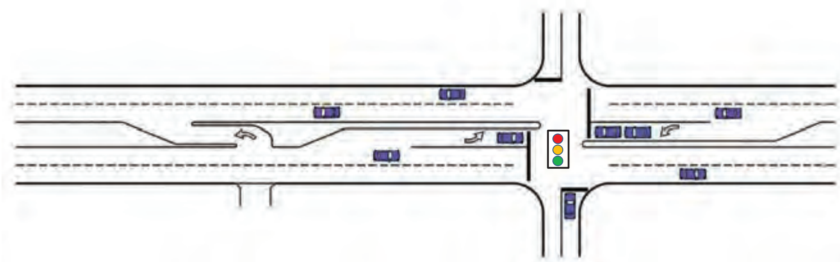
Type E. Upstream Left-In Directional Median Opening



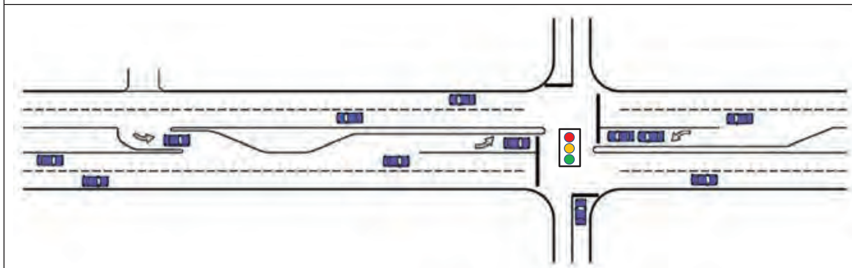
Type F. Downstream Left-In Directional Median Opening

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity that includes additional driveways unless the driveway is essential to the median functionality.

Figure C-3. Schematics of single left-in directional median openings.



Type G. Upstream Left-Out Directional Median Opening



Type H. Downstream Left-Out Directional Median Opening

Note: These schematics are simplified to demonstrate the median opening configuration and do not fully reflect the real-world complexity that includes additional driveways unless the driveway is essential to the median functionality.

Figure C-4. Schematics of single left-out directional median openings.

Table C-1. Data collection elements.

Physical Site Information	Operational Site Characteristics
Intersection geometry and placement	Peak and Off-peak traffic volumes
Median opening design and configuration	Traffic volume by vehicle type AADT and ADT can be used interchangeably
Cross-section geometry	Delay / gap acceptance at median opening
Horizontal geometry (e.g., left-turn lane length, spacing between movements, etc.)	Queue length
Available space to facilitate U-turns such as loons or extra lane width	Speed limit and other signing and marking configurations
Traffic control devices (signs, signals markings) including posted speed limit	Percentage or number of trucks, buses, pedestrians, and bicycles
Roadside development including pedestrian and bicycle accommodations and driveways (including operational configuration of the driveways)	U-turning vehicles and other turning maneuvers
Presence of bus stops or other transit services	Conflicts

Common Site Characteristics to Consider

A comprehensive assessment of a median opening should consider the need for user interactions, safety implications, and other operational impacts. Key median opening characteristics include elements that influence the **optimal placement** of the median opening. This distance from an unsignalized median opening to a nearby signalized intersection is a focus of this guidance document.

A critical component to an effective evaluation of the study median openings is the identification and collection of contributing site information. Table C-1 summarizes example data that can assist with a median opening evaluation. Acquiring this large list of data elements can, however, be expensive. For that reason, this document provides information to estimate three median opening characteristics that collectively can help assess median opening performance – approach distance from median opening to signalized intersection (see distance UF in Figure C-6), number of conflicts, and number of crashes.

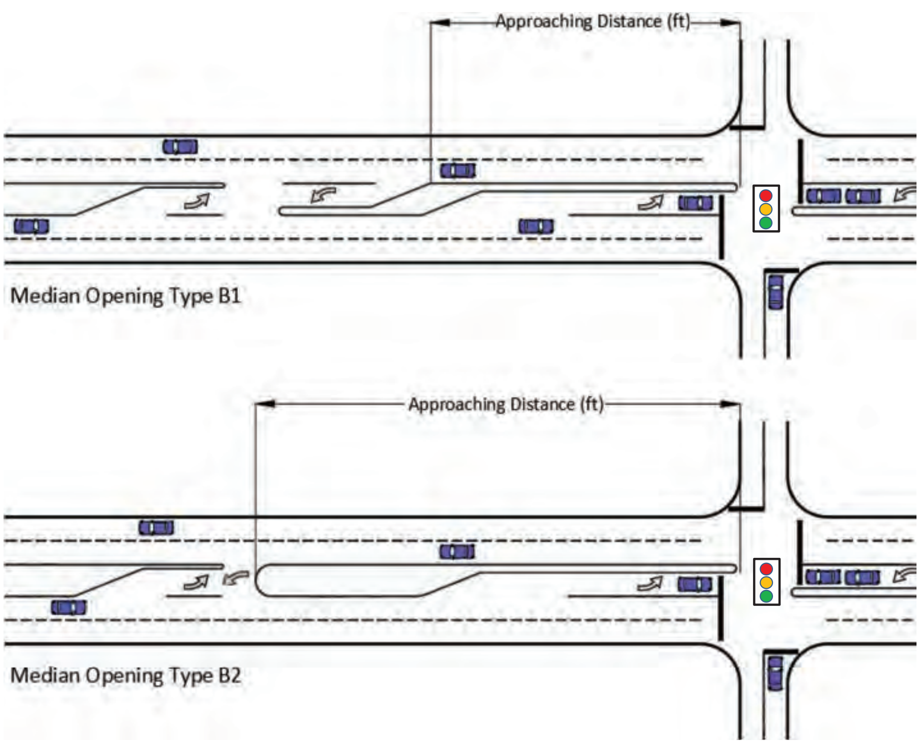
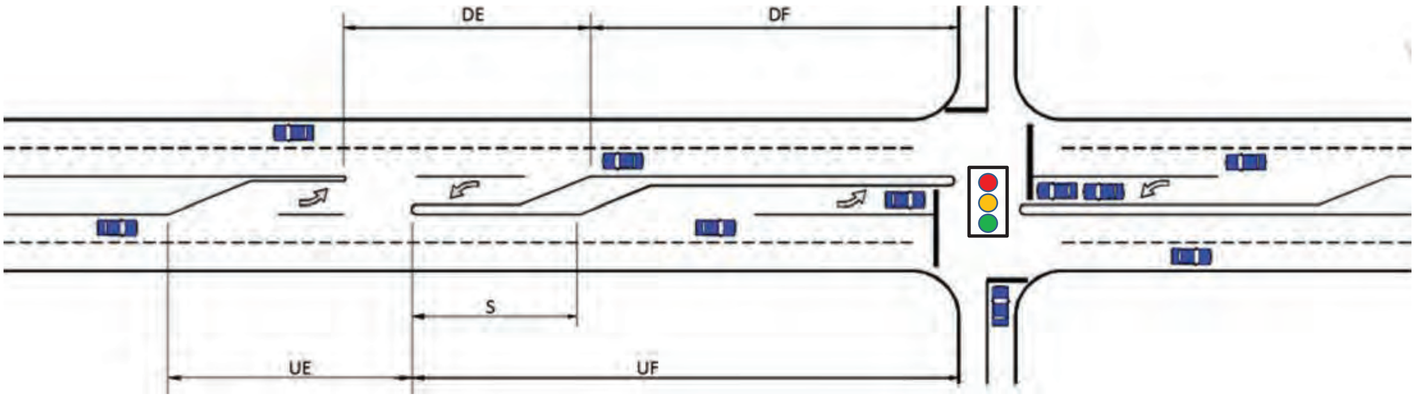


Figure C-5. Defining the approaching distance.



Dimensions for Full Median Opening with Turn Bays

Figure C-6. Key Dimensions at median opening locations.

Minimum Upstream Distance to Full Median Opening

The schematic depicted in Figure C-5 demonstrates the two turn bay full median opening configuration (B1) (recall that "Type B" refers to a full median opening with at least one turn bay) and the one turn bay full median opening (B2). The dimension values shown in the figure represent the approaching distance. This is the longitudinal distance from the full median opening to the projected curb line at the adjacent signalized intersection.

Additional dimensions of reference are shown in Figure C-6 and include the following:

- DE: Downstream Longitudinal Exposure Distance,
- DF: Downstream Distance to Full Median Opening,
- UE: Upstream Longitudinal Exposure Distance,
- UF: Upstream Distance to Full Median Opening, and
- S: Separation from Beginning of Signalized Intersection Taper.

Of interest is the upstream distance to a full median opening (designated as UF). This minimum distance can be calculated based on the number of conflicting driveways, the number of through lanes, and the number of turn bays. The term "conflicting driveways" represents any driveways that are located within 150 ft upstream and 150 ft downstream of the median opening and where vehicle conflicts can be expected. Figure C-7 graphically depicts the region where conflicting driveways can be expected to occur.

Based on these three inputs, the minimum value for the approach distance from full median opening to signalized intersection can be estimated using Equation C-1:

Equation C-1:

Approaching Distance

$$= 393.26 - 17.78(\text{Median Opening Type}[B1]) + 20.73\ (\text{CDwy}) - 56.68(\text{N})$$

where:

Approaching Distance = upstream (approaching) distance to full median opening (feet) [also shown as UF in Figure C-6],

Median opening Type [B1] has a value of one and represents two turn bays. Otherwise this variable would be a Type [B2] and be represented by the value

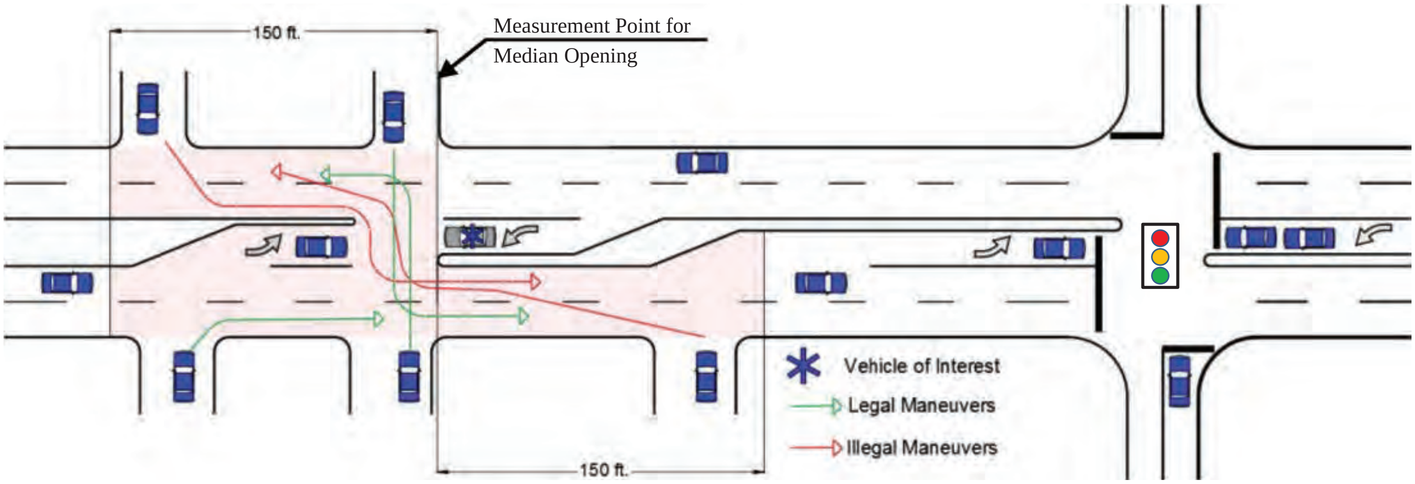


Figure C-7. Defining conflicting driveway.

of zero representing one turn bay. These two median opening configurations are depicted in Figure C-7,

CDwy = number of conflicting driveways in the region of the median opening and as defined in Figure C-7, and

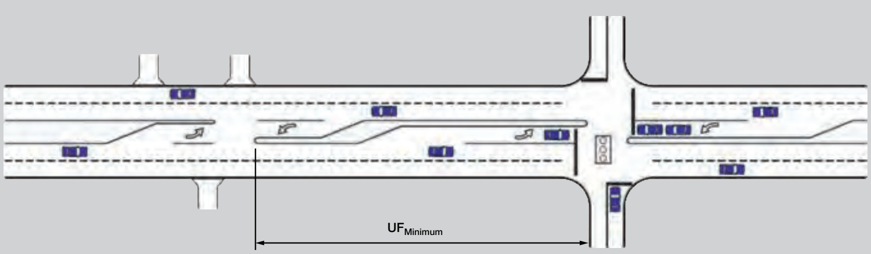
N = number of lanes (both directions of travel) for the arterial.

The following two sample problems demonstrate ways that Equation C-1 can be practically applied.

Sample Problem C-1

A transportation agency is considering the installation of a median opening near a signalized intersection on an existing four-lane urban arterial. Due to the high demand of left-turning traffic volume to access adjacent land-uses, the agency plans to provide turn bays for both directions of the median opening (type B1 median opening). If the number of conflicting driveways near the future median opening is approximately three, what is an appropriate minimum value for the approaching distance ($UF_{Minimum}$)?

Solution:



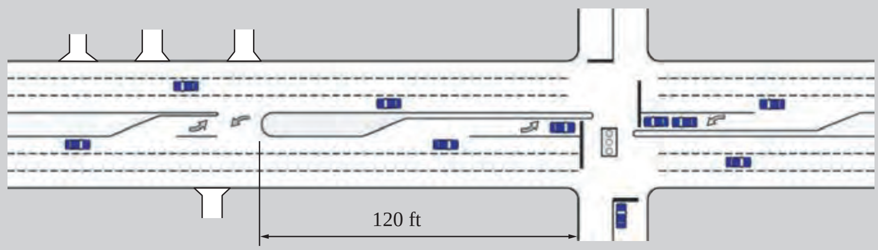
Approaching Distance = 393.26 − 17.78(1) + 20.73(3) − 56.68(4) ≈ 211 ft.

➔ The approaching distance should be at least 211 ft.

Sample Problem C-2

The approaching distance (UF) of an existing median opening along a six-lane urban arterial is 120 ft. There are currently four conflicting driveways, but adjacent property owners are requesting an additional access point to provide direct access to their proposed new commercial development. The transportation agency would like to evaluate if adding a new driveway interferes with the operation of the median opening. The current median opening only has one turn bay. Should the agency provide one more access point?

Solution:



Approaching Distance = 393.26 – 17.78(0) + 20.73(5) – 56.68(6) ≈ 157 ft.

➔ This driveway should not be provided at this location because the minimum approaching distance should be 157 ft for five driveways while the available approaching distance is only 120 ft.

Number of Conflicts at Full Median Opening

The notable influence of conflicting driveways as calculated in the previous examples highlights that the number of conflicts can adversely affect corridor operations. Equation C-2 can be used to estimate the number of conflicts at the median opening during peak hour conditions.

Equation C-2:

$$MOC_{PH} = e^{(-6.56+0.02(MVol)+1.29(CDwy))}$$

where:

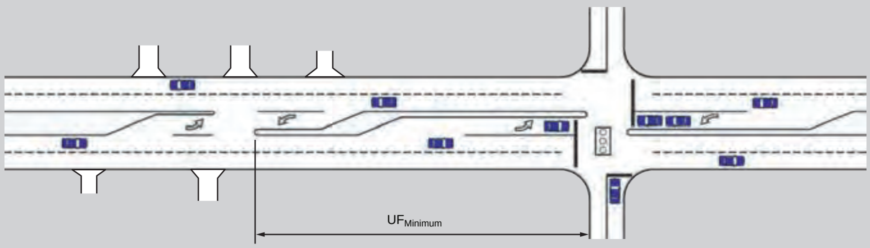
MOC_{PH} = number of median opening vehicle conflicts during the peak hour,
MVol = Median opening turning volume for all directions during the hour (vph), and
CDwy = Number of conflicting driveways in the region of the median opening as defined in Figure C-7.

Sample Problem C-3 demonstrates how Equation C-2 can be used to estimate the number of conflicts at the median opening location.

Sample Problem C-3

A roadway has 85 vehicles at the median opening during the peak hour. This location currently has five conflicting driveways. How many conflicts are expected in the vicinity of the median opening during the peak hour?

Solution:



$MOC_{PH} = e^{(-6.56+(0.02\times85)+(1.29\times5))} \approx 5$ conflicts

➔ Based on the provided information, five conflicts might be expected during the peak period.

Number of Crashes at Full Median Opening if Median Opening AADT Is Known

The number of crashes at the full median opening can be expected to be influenced by a wide variety of site characteristics (i.e., signal timing, queue blockage of the median opening, number and location of conflicting driveways, number of turn bays, and number of through lanes), but the major and minor average daily traffic at the nearby intersection has a dominating influence over the expected number of crashes. This is likely because many of these variables are not independent of the traffic volume and the volume tends to have a stronger influence. Equation C-3 can be used to estimate the expected number of crashes within 50 ft of the median opening if the AADT or ADT is known for the arterial as well as the median opening location.

Equation C-3:

$$N_{crashes} = e^{(-1.21+(0.03\times MAJAADT)+(0.09\times MINAADT))}$$

where:

$N_{crashes}$ = number of total crashes per year related to the median opening of interest,
MAJAADT = major-road average daily traffic volume (veh/day) divided by 1,000, and
MINAADT = minor-road average daily traffic volume (veh/day) divided by 1,000.

Note that heavy vehicle volume is not explicitly considered with this equation. This is due to lack of truck volume data and should not be interpreted as these vehicles having no influence on traffic conditions. In addition, if an agency does not have AADT information, they can use ADT as a reasonable substitute value.

Sample Problem C-4 demonstrates how this equation can be used to estimate the number of crashes adjacent to the median opening.

Sample Problem C-4

An unsignalized median opening is near a signalized intersection. The median opening has a major road ADT value of 48,600 vpd and a minor road ADT value of 18,500 vpd. What is the estimated number of crashes for this median opening location?

Solution:

$N_{crashes} = e^{(-1.21+0.03\times(48,600/1000)+0.09\times(18,500/1000))} = 8$ crashes

➔ Eight crashes can be expected to occur at this median opening location each year.

Number of Crashes at Full Median Opening if Median Opening AADT Is Not Known

Equation C-3 provided an estimate for crashes in the immediate vicinity of the median opening. The equation directly applies to median openings with known AADT or ADT values and focuses on the number of crashes within 50 feet of the median opening. In some cases, the volume of the median opening may not be known. For this instance, it may be helpful to estimate the number of median opening-related crashes along the approach corridor. Figure C-8 and Figure C-9 graphically depict the total number of crashes at the intersection approach

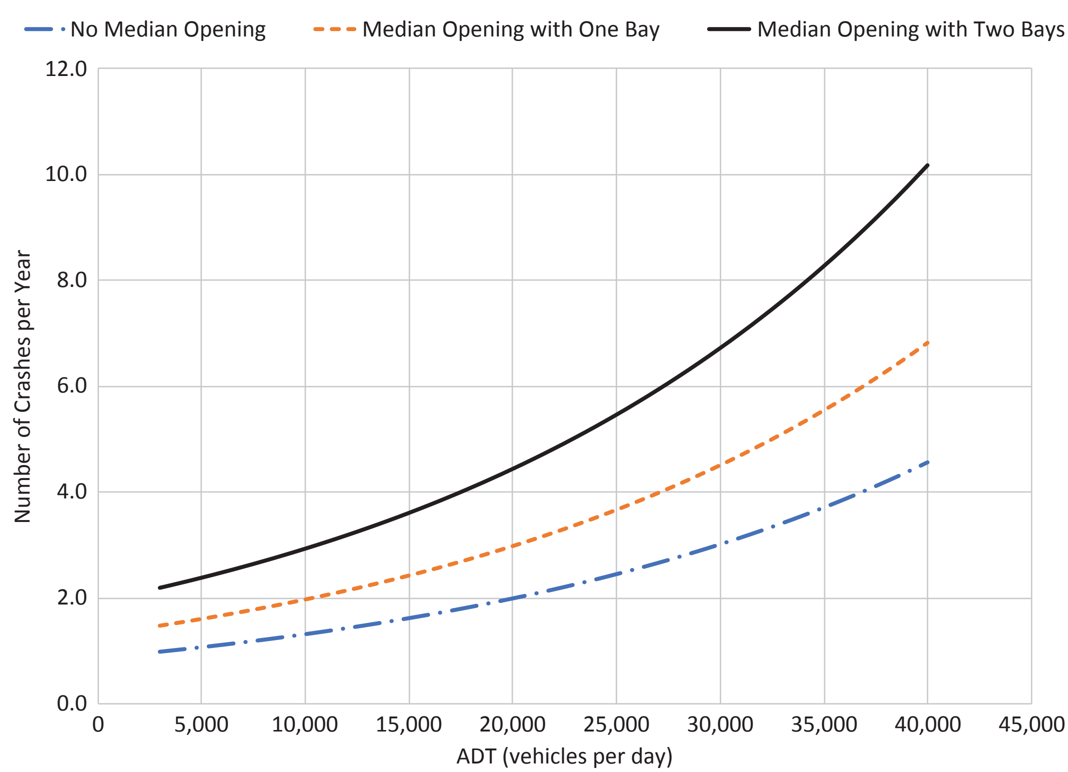


Figure C-8. Total median opening-related crashes for four-lane roadway approaches.

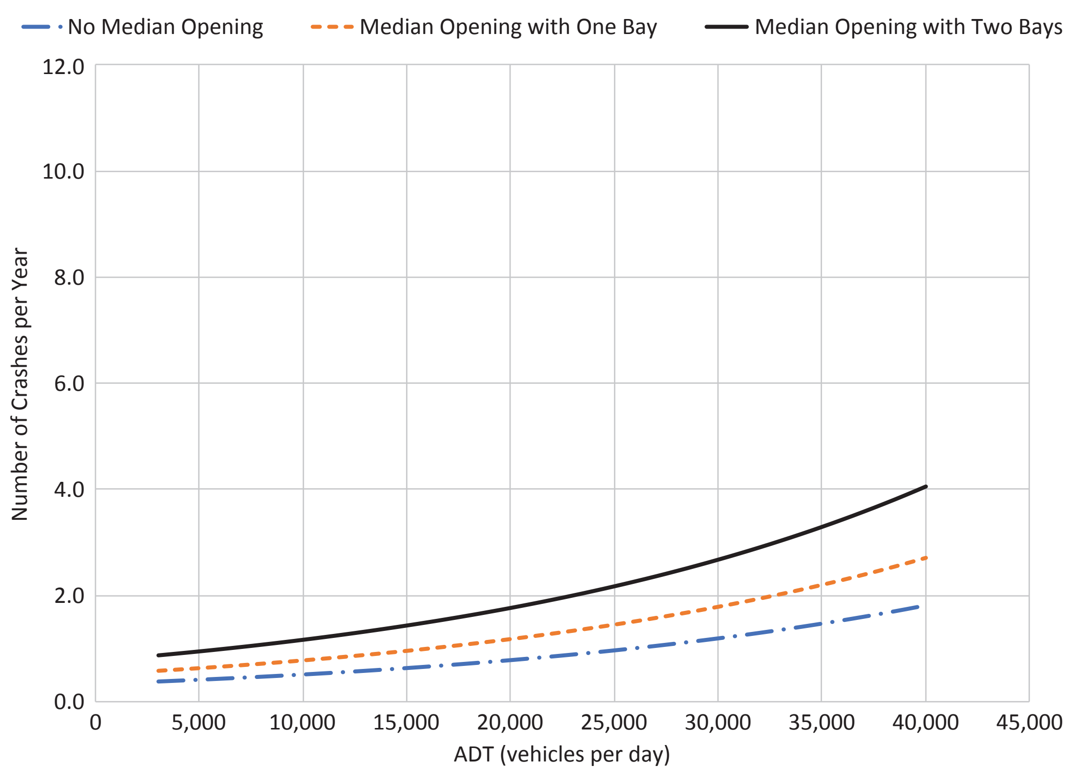


Figure C-9. Total median opening-related crashes for six-lane roadway approaches.

for these locations. In general, the estimated number of crashes at the intersection approach and for which the median opening AADT or ADT is not known are influenced by the type of median opening, major road ADT, and the number of lanes.

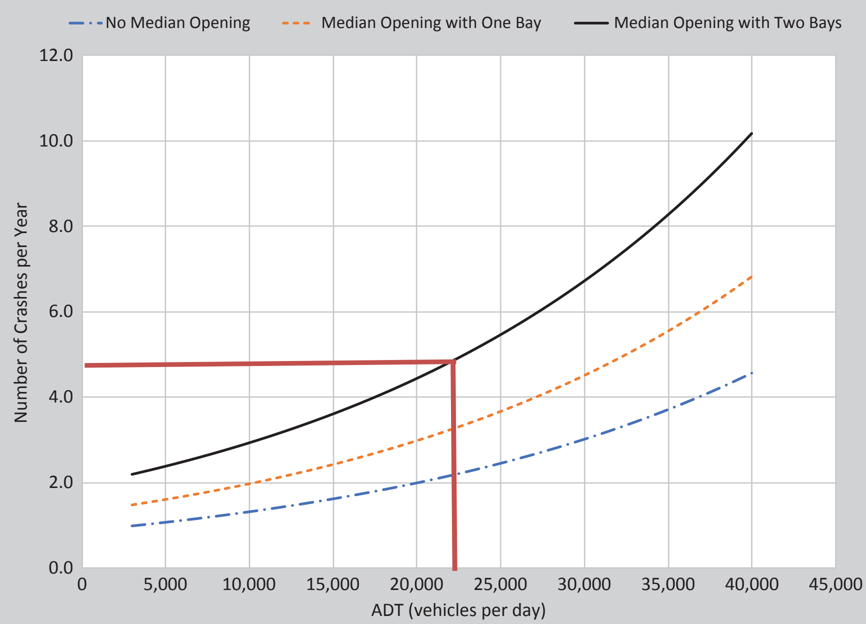
Sample Problem C-5 demonstrates how these figures can be used to estimate the median opening-related crashes at the intersection approach.

Sample Problem C-5

An unsignalized median opening with two turn bays is located on a four-lane arterial near a signalized intersection. The major road ADT has a value of 22,400 vpd and the median opening ADT value is not known. What is the estimated number of crashes for this median opening location?

Solution:

Figure C-8 can be used to estimate the number of median-related crashes at this intersection approach.



➔ Five median-related crashes can be expected to occur at this intersection approach location each year.

Conclusion

There is still much to be learned about how traffic operates at unsignalized median openings near signalized intersections. This document provides some guidance as to the type of median openings that can be expected. It also provides tools to help a practitioner estimate minimum recommended distances from the intersection to the median opening. In addition, this guidance assists analysts with estimating the number of conflicts and crashes that may be expected at a Type B median opening.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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