System-wide Safety Analysis of a Complex Transportation Facility: Urban Freeway Off-ramps

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Abstract

Highway safety has been a priority for many years now. A system-wide crash analysis is a practical solution when only a limited budget is available for improving safety of highways. A systematic approach, in contrast to a hotspot analysis, allows for a widespread installation of lower-cost countermeasures across the highway network. This study focuses on the safety evaluation of a particular facility type, urban freeway off-ramps, in terms of its geometric and traffic characteristics. 144 off-ramp segments in Richmond, VA were evaluated based on the crash data available from 2011 to 2015. A statistical model was developed that relates crashes to the geometric and traffic characteristics of each off-ramp segment. A test for independence was performed to identify if a statistically significant difference existed between type of collision and severity of crashes with respect to ramp geometry and traffic control. Significant geometric and traffic variables were then identified from the model and independence test to assist in the selection of low-cost countermeasures.

AADTs of both freeways and off-ramps were found to be the most statistically significant variables. Installation of advance warning signs for better traffic management near the freeway diverge area and clearing roadsides of fixed objects to reduce rear-end collisions are low-cost solutions for crashes on urban off-ramps in the study area. The results of this study demonstrate an approach to safety evaluations that could support transportation planners and agencies in identifying system-wide locations to install or apply appropriate low-cost countermeasures.

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General Audience Abstract

Efforts to improve highway safety has been a priority for many years now. An approach that considers all the locations in the network as opposed to considering only high crash locations helps in identifying low-cost countermeasures that can be installed across the highway network. This study focusses on the safety evaluation of urban freeway off-ramps. 144 off-ramp segments in Richmond, VA were evaluated based on the crashes that occurred on them from 2011 to 2015. The results from the safety evaluation identified geometric and traffic characteristics that led to a crash on the off-ramp segments. It was also determined whether type of collision and severity of crashes varied with geometry and traffic control. The results from the study assisted in selecting low-cost countermeasures that can be implemented across the highway network.

Traffic volume of both freeways and off-ramps were found to be a significant cause for crashes. Installation of advance warning signs where off-ramp segments leave the freeways and clearing roadsides of fixed objects are some of the low-cost solutions to reduce off-ramp crashes. This study demonstrated an approach to safety evaluation that could help transportation planners and agencies in identifying locations across the highway network to install or apply low-cost countermeasures.

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Dedications

I would like to dedicate this work to my family, especially my parents, without whom this would not have been possible. It is their persistent encouragement and love that kept me moving forward.

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CHAPTER 1: INTRODUCTION

Highway Safety has been a priority for many years. Every year, vehicle crashes result in major loss of life and property. The level of safety depends on the road user, vehicle and road characteristics and their mutual interactions. In particular, road environment can influence the driver in making better decisions.

A common approach to evaluate the safety of highways is to identify high crash locations and implement countermeasures. In such hotspot analyses, the locations with high crashes are selected to find the crash patterns. The significant factors that led to a crash are identified to select countermeasures that can yield maximum benefits. Funds are allocated based on the priority of sites identified from the analysis. Focusing the analysis to improve safety of high crash locations can be expensive.

A new approach, known as a systematic approach, is adopted by agencies to compliment hotspot analysis when there is a limited availability of funds. In this approach, low-cost countermeasures are implemented near a particular facility type across the highway network. One such approach uses Safety Performance Functions (SPFs). They are regression models used to estimate the crash frequency on a continuous highway facility type such as rural two-lane roads, rural multi-lane highways and urban and suburban arterials with specified base conditions (AASHTO 2010).

A system-wide safety evaluation of a particular complex facility type, urban freeway off-ramps, is performed in this study to demonstrate the efficacy of a new systematic approach. The safety of freeway off-ramps is evaluated in terms of geometric and traffic characteristics that led to a crash. The results identify possible low-cost countermeasures that can be implemented at multiple locations across the highway network. Unlike SPFs, this study focusses on the detailed characteristics of a specific complex transportation facility for the safety evaluation.

1.1. BACKGROUND

Roadways in the United States (US) are grouped into classes based on geometric and traffic characteristics and the level of access. The three roadway functional classifications are arterial, collector and local roads (FHWA 2013). Arterials provide the greatest speed for the longest uninterrupted distance.

Local roads have the lowest mobility but they provide a high level of land access. The speed and accessibility provided by the collectors fall between arterials and local roads. Freeways belong to the highest category, designed to carry vehicles at the highest speeds, and typically have directional travel lanes separated by a physical barrier. The location where a freeway crosses another freeway or surface roadway is a freeway interchange or junction. Interchanges, unlike intersections, are grade separated and allow the traffic to flow through freeway junctions without directly crossing another traffic stream thus reducing number of conflicting points and thereby increasing the safety and capacity of the system.

Interchanges consist of different geometric layouts including cloverleaf, partial cloverleaf, full diamond and turbine interchanges. The actual pattern of an interchange is determined by several factors including the volume of traffic that makes specific turning movements, local terrain, availability of land, and alignment of roadways being connected among others. (Bauer and Harwood 1998).

Freeway interchanges in urban areas are potentially more problematic because of higher traffic volumes, directional changes, larger speed changes and increased lane change maneuvers. Because of these conditions, the driver is presented with complex and multiple decision points which can increase the potential for a crash (Geedipally et al. 2014). Understanding how these complexities impact safety can provide important information about recommendations for improving urban ramp characteristics, control strategies and driver information.

1.2. PROBLEM STATEMENT

A traditional approach to identify problems related to highway safety is to focus the analysis near locations with higher than expected numbers of crashes and then select appropriate countermeasures. This approach can be expensive when the agencies have limited funds to allocate for improving safety. An alternate approach is to focus on facilities with similar characteristics across the highway network where installation of low-cost countermeasures is effective. This type of systematic approach has used Safety Performance Functions (SPFs) for the safety evaluation of continuous facilities. SPFs are statistical regression models developed using historical crash data, and are typically based on traffic volume and length of the road segment (AASHTO 2010). The extension of this approach to more complex discrete facilities may be problematic as they have varying geometric characteristics. This research focusses on a system-wide safety evaluation of a specific facility type, urban freeway off-ramps, to identify design and traffic variables that led to a crash, and select possible low-cost countermeasures.

The ramp that leaves the freeway is known as a freeway exit ramp or off-ramp. The ramp that joins the freeway is known as a freeway entrance ramp or on-ramp (Michigan Roadway Design Manual 2014). The traffic operations of on-ramps and off-ramps are different mainly due to the speed with which the vehicles move on these sections of road and their acceleration characteristics. Vehicles entering off-ramps travel faster than those on on-ramps, as they come from freeways and tend to enter the ramps at freeway speed resulting in high-speed vehicles adjusting to a lower speed traffic stream. Bauer and Harwood (1998) and Geedipally et al. (2014) concluded that off-ramps tend to experience more ramp crashes compared to other ramp types (Bauer and Harwood 1998, Geedipally et al. 2014) while Bauer and Harwood (1998) identified that ramps in urban areas are more crash-prone than those in rural areas, in spite of having similar ramp configurations.

Because of access to detailed crash and roadway data, Virginia was used to demonstrate the approach used in this research. The Commonwealth of Virginia has 1,118 miles of four-to-ten lane freeways that connect states and major cities. On average, 5% of all crashes that occur in Virginia are ramp-related with 70% of these occurring in urban areas (DMV 2015). The three largest urban centers in Virginia are northern Virginia which is part of the Greater Washington DC urban area, the Virginia Beach urban area and the city of Richmond urban area (Census 2010). For this study, Richmond area was selected because it is totally within the Commonwealth and the highway system is not constrained by the coastal and peninsular structure of the Virginia Beach region thus providing a more representative analysis area.

1.3. OBJECTIVES

Studies in the past have focused on the analysis of all crashes that occurred on a particular type of interchange or interchanges where high crash frequencies were experienced. This study focusses on a system-wide safety evaluation of a particular facility type, urban freeway off-ramps, to select low-cost countermeasures that can be installed on facilities across the highway network.

The objectives of this study include:

(1) Demonstrate a systematic approach for safety evaluation of a particular highway facility type by applying it on urban freeway off-ramps.

(2) Select appropriate low-cost countermeasures that can be installed across the highway network based on the results from the system-wide analysis.

1.4. THESIS CONTRIBUTION

The results of a system-wide crash analysis can be used by transportation planners and agencies to identify low-cost countermeasures to be installed near a facility type across the highway network. The system-wide crash analysis identifies significant geometric and traffic characteristics of the road segment that led to a crash. This research focuses on all the locations of a facility type in the highway network as opposed to a traditional hot spot analysis that focusses on locations experiencing higher than expected number of crashes. The research analyzes a specific facility type, urban freeway off-ramps, with varying geometric characteristics.

1.5. THESIS ORGANIZATION

This thesis follows the manuscript format for theses/dissertations and is organized into four chapters. Chapter 1 presents a brief background, problem statement, research objectives and thesis contribution. Chapter 2 is a review of relevant literature. Chapter 3 is the manuscript presenting the research performed by me based on a system-wide crash analysis that is applied to a specific facility type where installation of low-cost countermeasures across the highway network will be effective. The research work presented in this chapter was reviewed and edited by Dr. Kathleen L. Hancock. Chapter 4 presents the discussion, conclusion and suggestions for extending this research in future. Appendix A consists of four subsections that gives additional information about the research.

Appendix A.1 provides a sample of information related to off-ramp segments collected from road centerline data, ortho-imagery, Google Street View and traffic data. The information in the road centerline data such as number of lanes on freeway and length of off-ramp segment were available as attributes in the road centerline data and could be readily used in the analysis. Other geometric characteristics related to the 144 off-ramp segments in the study area were identified by manual inspection of state ortho-imagery. Traffic control characteristics of the off-ramp segment were identified from Google Street View. The information related to traffic volume of both freeways and off-ramps was obtained from traffic data.

Appendix A.2 provides a sample of data used in this study to identify frequency and characteristics of crashes that occurred on 144 off-ramp segments in the study area. Information related to type of collision, number of vehicles involved in the crash and severity of crashes were used in the analysis. There were 704 crashes that occurred on the off-ramp segments over a 5-year analysis period. Each crash is geo-located and are associated with the off-ramp segment where they occurred.

A statistical model that relates crashes to the geometric and traffic characteristics of the off-ramp segment was developed in R; a programming language and software environment for statistical computing. A pseudo code to develop this statistical model is provided in Appendix A.3.

The complete results from the stepwise regression analysis while developing the statistical model reported in Chapter 3 is given in Appendix A.4. Eight continuous variables and five categorical variables were used as the explanatory variables in the initial model. After each step, those variables that were found to be insignificant at 95% confidence level were removed from the model. This process is repeated until all the variables in the model were found to be significant at 95% confidence level. The intermediate and final models are given in detail in Appendix A.4.

This research work was performed under the guidance of Dr. Kathleen L. Hancock, Dr. Samuel Tignor and Dr. Kevin Heaslip.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), 2010. Highway Safety Manual. Washington, DC.

Bauer, K.M., Harwood, D.W., 1998. Statistical models of accidents on interchange ramps and speed-change lanes. FHWA-RD-97-106.

Census. (2010). 2010 Census of Population and Housing. . https://www.census.gov/prod/cen2010/cph-2-48.pdf

Chen, H., 2010. Comparison of safety performance by design types at freeway diverge areas and exit ramp section. Graduate Theses and Dissertations, University of South Florida, Tampa, Florida.

Federal Highway Administration (FHWA), 2013. Highway functional classification concepts, criteria and procedures.

Federal Highway Administration (FHWA), 2008. Toolbox of Countermeasures and their effectiveness for Roadway Departure Crashes. U.S. Department of Transportation. Washington,DC. http://safety.fhwa.dot.gov/tools/crf/resources/briefs/rdwydepartissue.cfm

Geedipally, S., Bonneson, J., Pratt, M., & Lord, D. (2014). Analysis of Injury Severity in Crashes on Ramps and at Crossroad Ramp Terminals. Transportation Research Record: Journal of the Transportation Research Board, 2435, 37-44. doi:10.3141/2435-05

Michigan Road Design Manual, 2014. Chapter 3: Alignment and Geometrics, Michigan Department of Transportation. http://mdotcf.state.mi.us/public/design/englishroadmanual/

National Highway Traffic Safety Administration (NHTSA), 2013a . Fatality Analysis Reporting System. Washington, DC. http://www.nhtsa.gov/FARS

National Highway Traffic Safety Administration (NHTSA), 2013b. Traffic safety facts. U.S. Department of Transportation, Washington, DC. http://www-nrd.nhtsa.dot.gov/Pubs/812139.pdf

U.S. Department of Commerce, 2010. Census of Population and Housing, Economics and Statistics Administration, U.S. Census Bureau, https://www.census.gov/prod/cen2010/cph-2-48.pdf

Virginia Department of Motor Vehicles (DMV), 2015. TREDS - Traffic Records Electronic Data System. https://www.treds.virginia.gov/

CHAPTER 2: LITERATURE REVIEW

A system wide crash analysis is a complementary approach to the traditional hot spot analysis. The analysis identifies the design and traffic characteristics that led to crashes at specific types of facilities and helps transportation planners and agencies to select low-cost countermeasures that can be installed at these locations. SPFs are regression models, developed for the systematic safety evaluation of continuous facilities and may be problematic when extended to localized facilities with complex geometric characteristics (AASHTO 2010).

Interchanges improve the safety and capacity of the system by reducing the number of conflicting movements. Although interchanges are considered to be safer because of the reduced conflicting movements, 5% of fatal crashes that occurred in the US are interchange-related (NHTSA, 2013a) and an estimated 3% of all the crashes that occurred in the US were on interchange ramps (NHTSA, 2013b). Freeway off-ramps are locations of interest in highway safety studies due to the high occurrence of crashes in these segments (Chen 2010). McCartt et al. (2004) reported that two-thirds of 1,150 crashes that occurred at 33 interchanges in Northern Virginia, were on ramps. A review of previous studies about system wide crash analysis for a particular facility is provided, studies on ramp safety is briefed followed by a summary of statistical analyses performed on crash data. Different methods for the statistical modelling of crashes and the techniques to estimate the parameters in the model are also summarized, as are appropriate countermeasures for effectively reducing the severity and frequency of crashes.

2.1. SYSTEMATIC CRASH DATA ANALYSIS

A systematic approach for the safety evaluation considers all the locations of a facility type in the study area. The facility is evaluated to identify possible design and traffic characteristics that will lead to a crash, and selecting low-cost countermeasures for its widespread implementation. SPFs use regression models to estimate the average crash frequency with specified base conditions of a continuous facility type. It is typically a function of Annual Average Daily Traffic (AADT), and for roadway segments, the length of the segment (AASHTO 2010). The SPFs in the Highway Safety Manuals are developed for three continuous facility types; rural two-lane two-way roads, rural multilane highways and urban and suburban arterials.

2.2. RAMP CRASHES

Drivers have a higher crash risk when traveling along interchanges compared to other sections of freeways because they are presented with complex conditions and multiple decisions. Ramps are critical sections of interchanges because drivers are required to navigate onto the ramp, decelerate from the mainline and/or accommodate to existing ramp traffic and merge from ramps into traffic on the surface street (McCartt et al. 2004). The extent of this change in driver behavior depends on ramp configuration, geometry, horizontal and vertical alignment, design speed and traffic composition (Geedipally et al. 2014)

2.3. OFF-RAMP SAFETY

Ramps that are part of interchanges, can further be classified as on-ramps and off-ramps based on the direction of movement of traffic. Previous studies have reported that off-ramps are more crash-prone than on-ramps. Analysis of crashes on urban and rural freeway ramps in California indicate that off-ramps experienced high crash-frequency and crash-rates compared to on-ramps (Khorashadi 1998). Geedipally et al. (2014) reported that exit ramps have about 42% more crashes than the entrance ramps, given the same traffic volume and configuration (Geedipally et al. 2014). Bauer and Harwood (1998) also reported a similar finding based on their research in Washington State (Bauer and Harwood 1998).

McCartt et al. (2004) classified crashes that occurred on ramps based on the design characteristics of the interchange (McCartt et al. 2004). They categorized the interchange types to straight, cloverleaf, partial loop, short curve and long curve. They identified that short curve ramps were more hazardous compared to other categories of ramps, although they represented less than one third of all ramp design types. Twomey et al. (1992) reported that curved ramps have 14% more crashes than straight ramps (Twomey et al. 1992).

Geometric cross-sectional features of off-ramps also affect safety. Bauer and Harwood (1998) examined the effect of ramp lane width on the frequency of crashes. They found that wider lanes were associated with fewer number of crashes (Bauer and Harwood 1998). Chen et al. (2009) found that one-lane exits with a taper are safer in terms of crash frequency and crash rates (Chen et al. 2009). They classified crashes on freeway exit ramps in Florida into four types: Single lane exit ramp with a tapered design was classified as Type I, single lane exit ramp with the outer lane that becomes a drop lane as Type II, two-lane exit ramp with an optional lane as Type III and two lane exit-ramps with the outer lane dropped at the exit gore as Type IV. Cross-sectional comparisons were conducted between these to find their safety performance. The authors emphasized the importance of lane-balance (*number of approach lanes on freeway near exit must equal number of lanes beyond the exit plus number of lanes on the exit minus one (AASHTO 2001)*) that supersedes the influence of width on the safety of exit ramp sections. Categorizing ramp crashes based on ramp configuration and cross-sectional features help identify proper countermeasures (Retting et al., 1995).

Type of crash is also important to identify proper countermeasures. McCartt et al. (2004) reported that for crashes that occurred on the interchanges of Northern Virginia during 1993-1998, 48% were rear-end and 36% were run-off road crashes (McCartt et al. 2004). They also identified that run-off road crashes were more prominent for those who were exiting the freeway. On analyzing the travel direction and ramp design type together, they identified that drivers exiting short curve ramps were the most crash prone. McCartt et al. (2004) noted traffic congestion and speed as the significant causes for 90% of rear-end crashes on ramps (McCartt et al. 2004).

2.4. MODELLING METHODS FOR CRASH DATA

A statistical model of crashes is a mathematical relation between frequency of crashes and road geometry, traffic and crash characteristics. These models are used to identify significant design factors that led to a crash at the locations of interest as well as to predict future crashes.

Poisson Regression is applied to a wide range of transportation data and has served as a starting point for crash frequency analysis for decades (Lord and Mannering 2010). Jones et al. (1991) developed six Poisson regression models (for each of the six zones under consideration in Seattle) to estimate crash frequency and its influencing factors (Jones et al. 1991). Month and day-of-the-week indicator variables in these models were able to predict the frequency of crashes on a particular day. This helped in resource allocation as to when and where the detection and response should be enhanced. Chen et al. (2011) developed Poisson regression model to quantify the safety impacts of left-side and right-side off-ramps (Chen et al. 2011). They used a scaled deviance to find the goodness of fit and found that the data adequately fits Poisson regression model.

Although Poisson Regression can be successfully applied, it is not appropriate for data that is over- or under-dispersed. The NB model or Poisson-gamma model is an extension of Poisson model that can handle over- or under-dispersion of data (Lord and Mannering 2010). This approach has traditionally included development and use of Safety Performance Functions (SPFs) which consist of developing NB regression models for estimating crashes occurring on a roadway facility with specified base conditions. SPFs are typically a function of a few variables, typically traffic volume and length of the road segment, which are used to estimate average crash frequency to aid the transportation planner in identifying potential crash locations (AASHTO 2010).

Li et al. (2015) estimated an NB model to find the significant factors that cause crashes of various collision types (rear-end, sideswipe and angle collisions) in freeway diverge areas (Li et al. 2015) The dispersion parameters of the model were found to be larger than zero indicating that NB models can fit the data better than the Poisson model. Chen et al. (2009) arrived at a similar finding for the freeway exit ramps in Florida by using an NB model (Chen et al. 2009). The value of scaled deviance and Pearson's χ^2 statistic were used to find the goodness of fit for the model.

2.5. TEST FOR STATISTICAL INDEPENDENCE

A contingency table is a useful tool to determine a statistical independence between two categorical variables (Washington et al. 2010). It is tested with the null hypothesis that the variables under consideration are statistically independent of each other. McCartt et al. (2004) used a chi-squared test to identify travel direction (exit/enter), roadway location (ramp, margin or access/road) or ramp characteristic design (cloverleaf, short curve, long curve, partial loop etc.) as significantly affecting the occurrence of different types of crashes (run-off road, rear-end or side-swipe) (McCartt et al. 2004). Their results showed that exit ramps experienced a high frequency of run-off road and rear-end crashes. Chen et al. (2011) conducted t-tests, as the sample sizes were small, to find if crash frequency and crash rate between different types of exit ramps were independent of each other (Chen et al. 2011). Ramps with similar geometric characteristics and control factors were paired and compared to each other. The results showed crash frequency and crash rates are independent of each other at 10% significance level.

2.6. PARAMETER ESTIMATION METHODS

Maximum likelihood estimation (MLE) and Bayesian methods are the two most common methods used for crash-frequency models (Lord and Mannering 2010). Wan et al. (2014) used Generalized Estimating Equations (GEE) to deal with the issue of small sample sizes that cause temporal correlation during the crash analysis (Wan et al. 2014). A GEE model was estimated by using a four-year crash data at exit ramps on a freeway in China. The exit ramp section included two sub-segments that is located in the upstream and downstream of the painted nose. In this case, GEE is an extension of Generalized Linear Model (GLM) to estimate the temporally correlated data. Independent, Exchangeable, Autoregressive and unstructured are the four types of correlation structures that were explored in this modeling process. The study found that the coefficients and standard errors for explanatory variables are consistent between models with different correlation structures. The GLM with the GEE led to more accurate estimation of the explanatory variables in the model. In their dataset, few of the explanatory variables that were found insignificant in the traditional models, were found to be significant after accounting for the temporal correlation.

Research related to ramp safety focused on the analysis of either all crashes on all types of interchange ramps or a particular type of crash on all interchange ramps. The ramps that were considered for the analysis connected a freeway to another. Few of the studies considered only a particular segment of an off-ramp. This study focusses on the safety of entire urban freeway off-ramp segment that connects freeway to a surface road.

This section summarized the highway safety studies performed for ramps in general and off-ramps in particular. Statistical tests used for finding the independence of categorical variables are also summarized. Statistical modelling of crashes to identify significant design factors that led to a crash at the locations of interest and their estimation methods are summarized. Identifying these variables will assist in finding appropriate countermeasures.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), 2001. A Policy on Geometric Design of Highways and Streets, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), 2010. Highway Safety Manual. Washington, DC.

Bauer, K.M., Harwood, D.W., 1998. Statistical models of accidents on interchange ramps and speed-change lanes. FHWA-RD-97-106.

Chen, H., 2010. Comparison of safety performance by design types at freeway diverge areas and exit ramp section. Graduate Theses and Dissertations, University of South Florida, Tampa, Florida.

Chen, H., Liu, P., Lu, J.J., Behzadi, B., 2009. Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps. Accident Analysis & Prevention 41 (3), 543-551.

Geedipally, S., Bonneson, J., Pratt, M., & Lord, D. (2014). Analysis of Injury Severity in Crashes on Ramps and at Crossroad Ramp Terminals. Transportation Research Record: Journal of the Transportation Research Board, 2435, 37-44. doi:10.3141/2435-05.

Jones, B., Janssen, L., and Mannering, F., 1991. Analysis of the frequency and duration of freeway accidents in Seattle, Accident Analysis & Prevention, Vol. 23 (239-255).

Khorashadi, A., 1998. Effect of ramp type and geometry on accidents. FHWA/CA/TE-98/13, California Department of Transportation.

Lord, D., Mannering, F., 2010. The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice 44 (5), 291-305.

Mccartt, A.T., Northrup, V.S., Retting, R.A., 2004. Types and characteristics of ramp-related motor vehicle crashes on urban interstate roadways in northern virginia. Journal of Safety Research 35 (1), 107-114.

Retting, R.A., Williams, A.F., Preusser, D.F., Weinstein, H.B., 1995. Classifying urban crashes for countermeasure development. Accident Analysis & Prevention 27 (3), 283-294.

Twomey, J., Heckman, M., Hayward, J., 1992. Safety effectiveness of highway design features. Volume iv: Interchanges. FHWA-RD-91-047. FHWA, U.S. Department of Transportation, 1992.

Washington, Simon P., Karlaftis, Matthew G. and Mannering, Fred, L., 2003. Statistical and Econometric Methods for Transportation Data Analysis, CRC Press Company, Washington, DC.

Yang, Zhang, Zhibin, L. I, Pan, L. I. U and Liteng, Z. H. A., 2011. Exploring contributing factors to crash injury severity at freeway diverge areas using ordered probit model, Procedia Engineering, Vol. 21 (178-185).

CHAPTER 3: MANUSCRIPT

A SYTEM-WIDE SAFETY EVALUATION OF A COMPLEX TRANSPORTATION FACILITY: URBAN FREEWAY OFF-RAMPS

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Abstract

The United States faces a continuing challenge of improving safety on its highways with ever reducing resources. As a result, developing more systematic approaches to identifying and mitigating hazards associated with transportation facilities is crucial. With increasing availability of the locations of all crashes on all facilities along with the necessary underlying infrastructure information, system-wide analyses are more practical and can provide a supplemental approach for identifying and implementing lower cost countermeasures across the transportation network, thus maximizing available resources. This study evaluated the crashes related to geometric and traffic characteristics associated with 144 urban off-ramp segments in Richmond, VA, over a 5-year period from 2011 to 2015. Crashes that occurred on each segment were statistically modelled assuming a negative binomial distribution. A chi-squared test for independence was performed to identify if a statistically significant difference exists between type of collision and severity of crashes with respect to ramp geometry and traffic control.

AADTs of both freeways and off-ramps were determined to be the most statistically significant variable. Rear-end collisions were the most common type of crash with shorter curve ramps experiencing nearly half of these collisions. The combination of rear-end crashes and the significance of mainline and ramp AADTs indicates the use of improved traffic management approaching freeway diverge areas. A low cost method could be the installation of signage with appropriate warnings. It was also observed that 38% of higher severity crashes occurred on off-ramp segments that are part of partial clover leaf interchanges. A decrease in speed differential between the freeway and ramps and clearing roadsides of fixed objects are possible low-cost countermeasures to reduce the frequency or severity of rear-end and fixed object crashes on these segments. The results of this study identified significant geometric and traffic factors associated with the occurrence and severity of crashes for a specific type of transportation facility, urban off-ramps, across the roadway system allowing decision makers to identify locations to install appropriate low-cost countermeasures.

Keywords: Highway safety, Freeway off-ramps, Ramp geometry, Statistical modelling, Negative binomial distribution

Highlights

- Safety of urban freeway off-ramps is evaluated
- Significant off-ramp design and traffic characteristics are identified
- Possible low-cost countermeasures are identified

3.1. Introduction

Every year, vehicle crashes result in major loss of life and property. A common approach to addressing crash reduction is to identify locations with the highest number of crashes, research the corresponding causal factors and implement appropriate countermeasures. This can be expensive, resulting in apportioning a large part of an agency's safety resources to a relatively small number of safety improvements. A complimentary approach is to consider types of facilities which have similar characteristics where low-cost countermeasures can be implemented across the highway system. This approach has traditionally included development and use of Safety Performance Functions (SPFs) which consist of developing regression models for estimating crashes occurring on a roadway facility with specified base conditions. SPFs are usually a function of a few variables, typically traffic volume and length of the road segment, which are used to estimate average crash frequency to aid the transportation planner in identifying potential crash locations (AASHTO 2010). This approach works well for continuous facilities such as rural two-lane roads but is problematic when considering specific facilities with varying geometric characteristics.

This paper presents the results of a study that evaluated facility and crash characteristics for a specific type of facility, urban freeway off-ramps, to identify possible causal factors across all off-ramps in an urban area, and to identify possible appropriate countermeasures. Unlike SPFs, the approach presented in this paper incorporates detailed characteristics associated with a more complex road facility by evaluating all sites in the study area.

Interchanges connect freeways to surface streets and consist of multiple transition zones including weave segments at the freeway diverge location, the ramp(s) between the freeway and surface-street, and weave segments at the surface street merge location resulting in the potential for increased risk to drivers as they maneuver from a freeway segment to the local street. Understanding the characteristics associated with the physical infrastructure and associated traffic as it relates to crashes helps to inform low-cost strategies that could improve driver understanding and behavior thus reducing crashes. When applied on a system wide basis, this could result in increased benefits.

This research evaluates the safety of urban freeway off-ramps through the statistical modelling of crash data which identifies the mathematical relationship between frequency of crashes and design, traffic and environmental variables associated with these facilities. The statistically significant variables in the model assist in identifying appropriate low-cost countermeasures across the highway network based on this system-wide crash analysis.

3.2. BACKGROUND

Freeway interchanges improve the safety and capacity of the system by reducing the number of conflicting movements. However, 5% of fatal crashes that occurred in the United States (US) in 2013 are interchange-related (NHTSA 2013a). An estimated 3% of all crashes that occurred in 2013 were on interchange ramps (NHTSA 2013b). Freeway interchanges in urban areas are potentially more problematic when compared to rural areas because of higher traffic volumes, directional changes, larger changes on speed and increased lane change maneuvers(McCartt *et al.* 2004). McCartt *et al*. (2004) reported that two-thirds of 1,150 crashes that occurred at 33 interchanges in Northern Virginia, were on interchange ramps (McCartt *et al.* 2004).

Vehicles entering off-ramps travel faster than those on on-ramps, because they come from freeways and tend to enter ramps at freeway speeds resulting in high-speed vehicles adjusting to a lower speed facility and traffic stream. This in turn results in the potential for higher number of crashes on off-ramps than on other types of ramps (Bauer and Harwood 1998, Khorashadi 1998, Chen 2010, Geedipally *et al.* 2014). As a result, this study focused specifically on freeway off-ramps.

Chen *et al.* 2009 evaluated the safety of off-ramp segments in terms of their design features and the types of crashes that occurred on these segments, including factors such as number of lanes, average annual daily traffic (AADT) and acceleration/deceleration lane length. Similarly, geometric cross-sectional features of off-ramps have been shown to influence traffic safety (Twomey *et al.* 1992, Bauer and Harwood 1998, McCartt *et al.* 2004). Chen *et al* (2009) found that off-ramp segments with fewer lanes and those that taper from the freeway have fewer crashes (Chen *et al.* 2009). They also emphasized the importance of lane-balance in reducing crashes on off-ramps. Retting *et al.* (1995) indicated that categorizing ramp crashes based on ramp configuration and cross-sectional features helped in identifying proper countermeasures (Retting *et al.* 1995).

Type of crash is also important when considering appropriate countermeasures. McCartt *et al.* (2004) reported that for crashes that occurred on Northern Virginia interchanges during 1993-1998, run-off road crashes were more common for those who were exiting the freeway (McCartt *et al*. 2004). When analyzing travel direction and ramp design type together, they identified that drivers on curve ramps were the most crash prone.

Statistical modelling of crashes relates frequency of crashes to road geometry, traffic, and crash characteristics. These models are used to identify significant design factors that lead to a crash at the locations of interest as well as to predict future crashes (Chen *et al.* 2009). Countermeasures for these locations are selected after identifying significant crash causal factors. The Negative Binomial (NB) model or Poisson-gamma model, which is an extension of the Poisson model, is used in highway safety studies to model over– or under-dispersed crash data (Chen *et al.* 2009, Lord and Mannering 2010, Li *et al.* 2015). Chen *et al.*, (2009) assumed a negative binomial distribution for the crashes that occurred at freeway diverge areas to identify significant traffic and geometric characteristics that had an influence on crashes. The dispersion parameters of these models were found to be greater than zero indicating that NB models fit the crash data better than the Poisson model. The value of scaled deviance and Pearson's χ^2 statistic confirmed over-dispersion and goodness of fit of the data.

Maximum Likelihood Estimation (MLE) and Bayesian methods are used for estimating the parameters in the statistical modelling of crashes. The method of maximum likelihood selects the model parameters that maximize a likelihood function. Since a closed-form function exists for most probability distributions, maximum likelihood estimation is commonly used for the parameter estimation (Lord and Mannering 2010). A similar approach was used in this study to identify ramp characteristics that led to a crash.

The significant characteristics that led to a crash at the locations of interest may also significantly affect the severity of crashes or type of collision. A Chi-square test is a non-parametric test to identify if two samples are significantly associated with each other. McCartt *et al*. (2004) used a chi squared test to identify a significant difference between type of crashes and roadway location. The results identified that type of crash was significantly associated with the roadway location (McCartt *et al.* 2004).

3.3. CASE STUDY

To demonstrate the methodology used in this research, an urban location was selected for analysis as discussed in the following sections.

3.3.1. Study area

Virginia has 1,118 miles of four-to-ten lane freeways that carry traffic across the Commonwealth and connect its major cities. Approximately, 5% of all crashes that occur in Virginia are ramp-related with 70% of these occurring in urban areas (DMV 2015).

The three largest urban centers in Virginia are northern Virginia which is part of the Greater Washington DC urban area, the Virginia Beach urban area and the city of Richmond urban area (Census 2010). For this study, the urban area around Richmond was selected because it is totally within the Commonwealth and the highway system is not constrained by the coastal and peninsular structure of the Virginia Beach region, thus providing a more

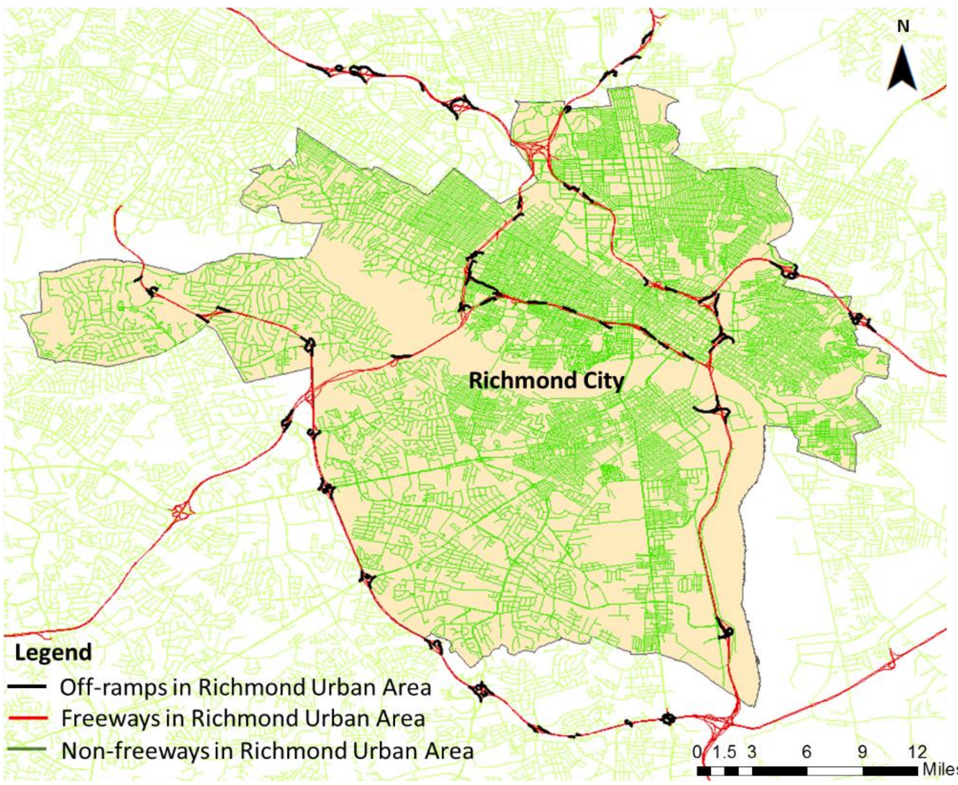


Figure 1: Richmond Urban Area

representative analysis area. Figure 1 highlights the 6 freeways, 40 interchanges and the 144 off-ramps that were included in the study. High speed freeway to freeway ramps were excluded from the analysis.

3.3.2. Data

Two types of information were used in this research, off-ramp characteristics and crash characteristics. Figure 2 shows the steps used to select off-ramps and the crashes that occurred on them.

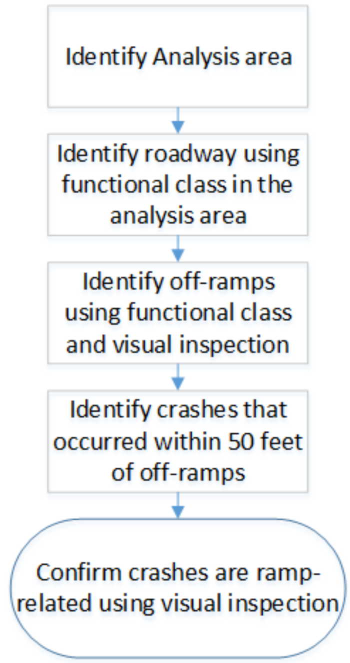


Figure 2: Steps to identify freeway off-ramps and crashes

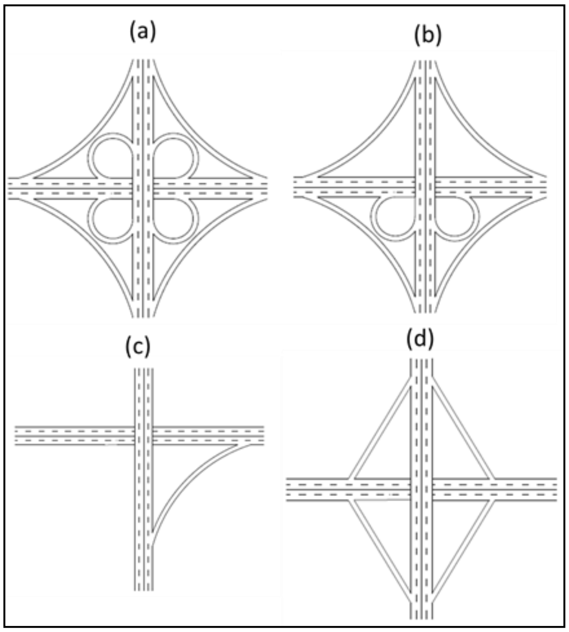
3.3.2.1. Ramp characteristics

Information associated with off-ramps as outlined in Table 1 was obtained from the Virginia Department of Transportation (VDOT) using their road centerline geodatabase (VITA 2015b) and their AADT layer (VDOT 2013). Characteristics that were not available from these sources were identified using manual inspection of state ortho-imagery available through an ArcGIS web service published by Virginia Information Technologies Agency (VITA 2015a) and Google Street View (Google, 2015). Figure 3 provides diagrams of interchange and ramp categories that are referenced in Table 1.

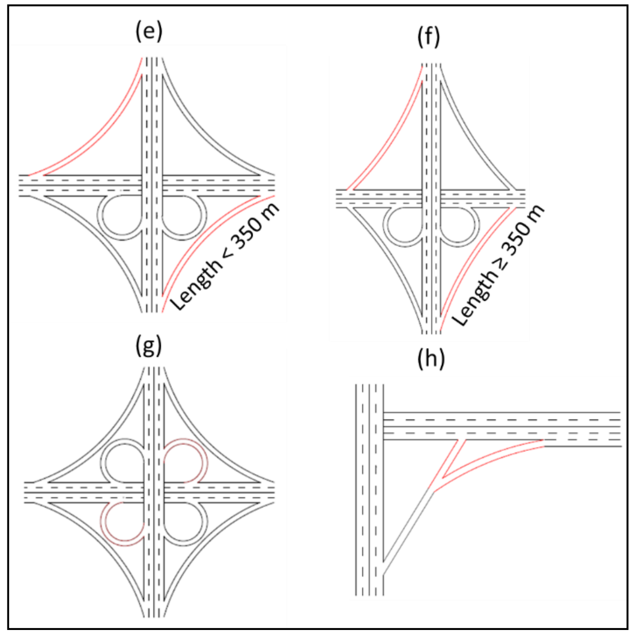
Of the 144 off-ramp segments in the study area, 50 did not include AADT data. For these segments, traffic data was approximated based on adjoining freeway and surface streets (Florida DOT, 2014). Seven segments did not have AADT for the adjoining surface streets and, after a review of the land-use at these interchanges, these were assigned a value of 500 vehicles/day. Length of the deceleration lane from freeway to off-ramp was measured along the road centerline from the beginning of the diverge area as identified from the lane markings, to the beginning of the gore area. Length of the acceleration lane from off-ramp to surface-street was measured as the length from the gore area to the end of the solid line (AASHTO 2010).

Table 1: Ramp characteristics

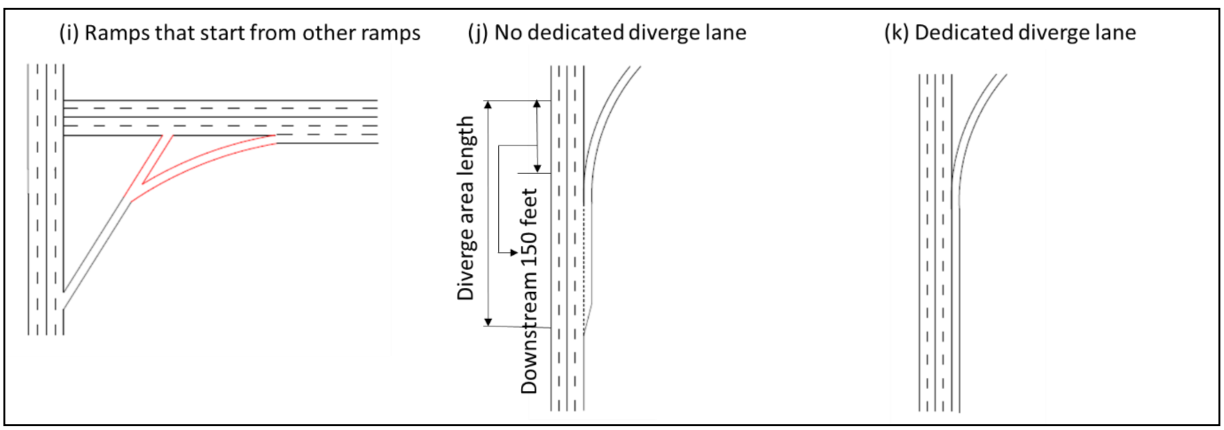
Characteristics	Purpose	Source (reference)
Functional Classification of freeways	Ramp selection	Road Centerline, VDOT
Street Name	Ramp selection and reference	Road Centerline, VDOT
AADT	Analysis variable	Traffic Data, VDOT
Number of lanes (Freeway)	Analysis variable	Road Centerline, VDOT
Number of lanes (off-ramp) No. of lanes near the diverge area No. of lanes on off-ramp curve No. of lanes near the merge area	Analysis variable	Imagery, VITA
• Speed Limit (Freeway)	Analysis variable	Google Street View
• Speed Limit (Off-ramp)	Analysis variable	Imagery, VITA
• Length of deceleration lane (to off-ramp)	Analysis variable	Imagery, VITA
• Length of acceleration lane (from off-ramp)	Analysis variable	Imagery, VITA
Type of interchange	Analysis variable	Imagery, VITA (Figure 3 (1))
Type of ramp	Analysis variable	Imagery, VITA (Figure 3 (2))
Type of Diverge Area	Analysis variable	Imagery, VITA (Figure 3 (3))
Type of Merge Area	Analysis variable	Imagery, VITA (Figure 3 (4))
Type of traffic control at Merge Area No control Stop control Yield control Signal control Ramps ending at other ramps	Analysis variable	Imagery, VITA



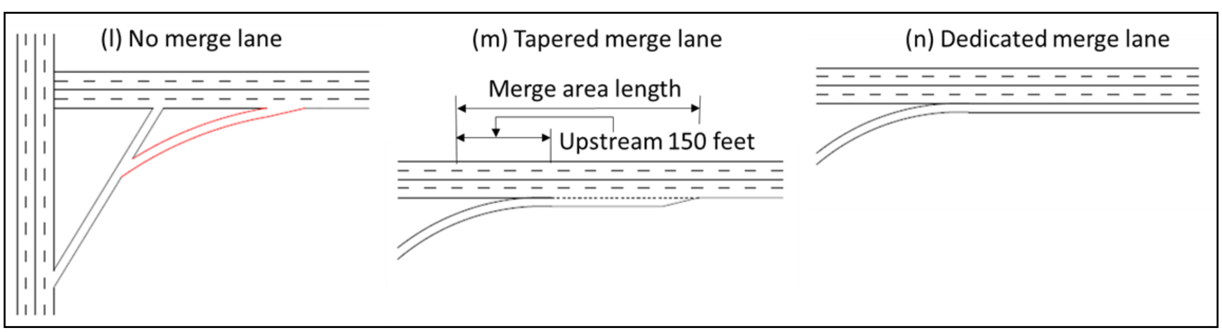
(a) Type of interchange



(b) Type of ramp



(c) Type of diverge area



(d) Type of merge area

Figure 3: Interchange and ramp characteristics

Table 2 summarizes the characteristics of off-ramps in the study area.

Table 2: Summary of study area off-ramp segment characteristics

Characteristic	Minimum	Maximum
Number of Lanes - Mainline	2	5
Number of Lanes – Off ramp	1	2
Number of Lanes in the Diverge Area	1	2
Number of Lanes in the Merge Area	1	3
Lane length to merge with the surface street (feet)	0	500
Lane Length to diverge from freeway (feet)	0	1300
Speed Limit - Main Line (mph)	55	65
Speed Limit - Off Ramp (mph)	15	45
AADT – Mainline	28000	142000
AADT – Off ramp	500	27000
Length of off-ramp segment (miles)	0.012	0.444

3.3.2.2. Crash data

Crash data for 2011 through 2015 was obtained from Virginia Department of Motor Vehicles (DMV 2015). All police reported crashes on all roads were located by Virginia Tech using state ortho-imagery, geospatial layers and all applicable information provided by law enforcement (Schutt *et al.* 2013), resulting in detailed crash locations as shown in Figure 4.

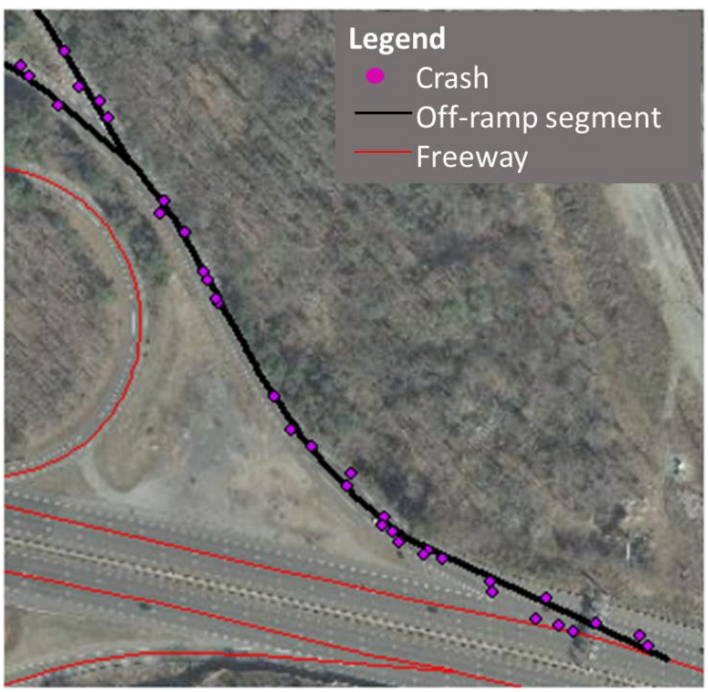


Figure 4: Crash locations (Imagery: VITA 2015a)

Table 3 summarizes the number of crashes from 2011 to 2015 that occurred on these ramps as well as in the Commonwealth, putting the numbers in context.

Table 3: Highway crashes

	2011	**2012**	**2013**	**2014**	**2015**
Off-ramp crashes in Richmond	111	175	146	132	140
All freeway ramp crashes in Richmond	520	498	517	418	489
All crashes on urban freeway ramps	4,500	4,407	4,481	4,266	4,487
All crashes on freeway ramps	5,394	5,266	5,437	5,067	5,404
All crashes in Virginia	120,513	123,579	121,763	120,282	125,800

Figure 5 provides a histogram of the 704 off-ramp crashes that were reported during the analysis period. The mean number of crashes per segment was 4.92 with a variance of 25.38. As shown, crashes range from 0 to 28 per ramp segment with 75% of segments experiencing less than 7 crashes. The ramp with the highest number occurred just outside of northern Richmond.

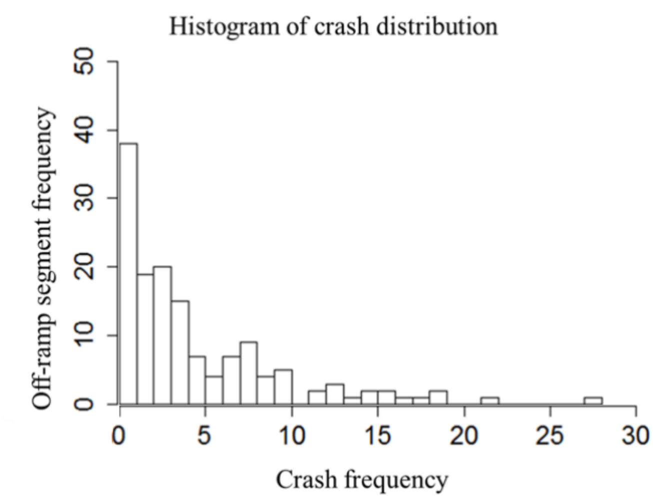


Figure 5: Histogram of crashes on off-ramp segments

Table 4 **Error! Reference source not found.**summarizes crashes by ramp characteristics while Table 5 provides the frequency of crashes by severity and crash type. The most common type of collision in the study area was rear-end collision which was double the next most common type, off-road into a fixed object.

Table 4: Summary of off-ramp segments with corresponding number of crashes

Interchange Type (Figure 3 (1))	**No. of segments**	**% of total segments**	**Crashes**	**% of total crashes**
Type a	25	17.36%	132	18.75%
Type b	42	29.17%	258	36.65%
Type c	75	52.08%	296	42.05%
Type d	2	1.39%	18	2.56%
Total	**144**	**100.00%**	**704**	**100.00%**
Ramp Type (Figure 3 (2))				
Type e	65	45.14%	322	45.74%
Type f	22	15.28%	167	23.72%
Type g	24	16.67%	105	14.91%
Type h	33	22.92%	110	15.63%
Total	**144**	**100.00%**	**704**	**100.00%**
Diverge Area Type (Figure 3 (3))				
Ramps start from others	30	20.83%	116	16.48%
No dedicated lane	51	35.42%	280	39.77%
Dedicated Lane	63	43.75%	308	43.75%
Total	**144**	**100.00%**	**704**	**100.00%**
Merge Area Type (Figure 3 (4))				
No Merge Lane	73	50.69%	339	48.15%
Tapered Merge Lane	7	4.86%	44	6.25%
Dedicated Merge Lane	29	20.14%	142	20.17%
Ramps that end at others	35	24.31%	179	25.43%
Total	**144**	**100.00%**	**704**	**1.00%**
Traffic Control at the Merge Area				
No control	26	18.06%	158	22.44%
Stop control	19	13.19%	48	6.82%
Yield control	37	25.69%	223	31.68%
Signal control	33	22.92%	155	22.02%
Ramps that end at others	29	20.14%	120	17.05%
Total	**144**	**100.00%**	**704**	**100.00%**

Table 5: Crashes by type and severity

Crash Severity	Number of crashes
Fatal Crash	3
Serious Injury Crash	23
Major Injury Crash	120
Minor Injury Crash	57
Property Damage Crash	501
Type of Collision	
Rear-end	308
Fixed Object – Off-road	152
Angle	101
Side swipe – Same direction	78
Head – On	17
Non-collision	15
Fixed Object in Road	12
Others	21

3.4. METHODOLOGY

The approach for this research is to evaluate the facility type under consideration, in this case urban off-ramps, using a statistical model to relate crashes to the characteristics associated with these facilities, determining the facility features that most affect both the type of collision and severity of crash, and identifying possible countermeasures that would address the identified characteristics and features. Figure 6 outlines this process.

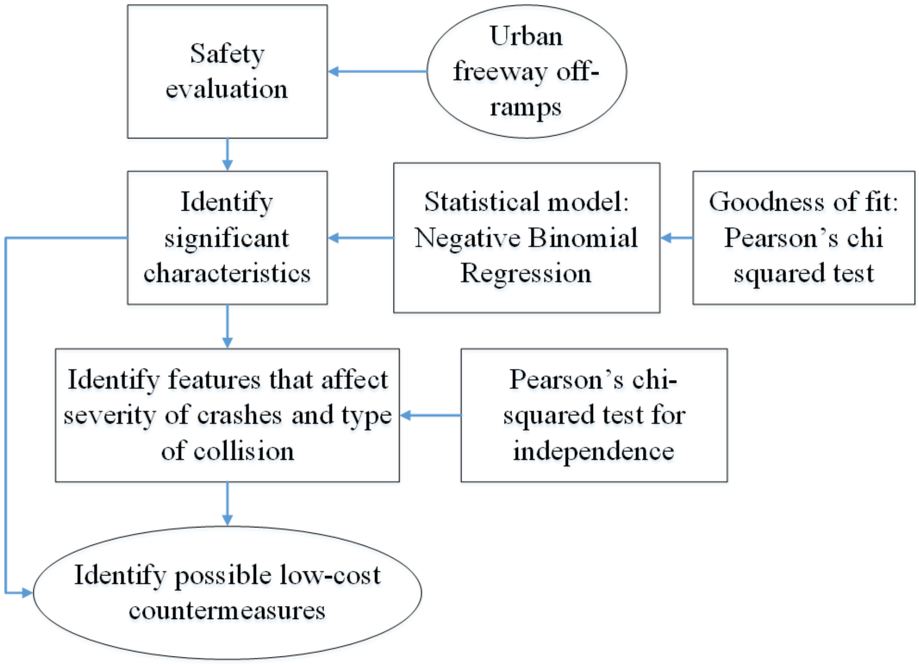


Figure 6: Analysis approach

3.4.1. Relating facility characteristics to crashes

Statistical modelling relates the frequency of crashes to road geometry, traffic, and crash characteristics. These models identify significant variables that contribute to a crash at the locations of interest (Chen *et al.* 2009). In this study, because the variance of crashes that occurred on off-ramp segments is much higher than the mean, a Negative Binomial (NB) model was selected, which addresses the observed over-dispersion in the data. The dependent variable is assumed to be Poisson-gamma distributed and the probability density function is defined as:

$$p(Y = y_i) = p(y_i) = \frac{\Gamma(y_i + \Theta)}{y_i!\,\Gamma\Theta}\left(\frac{\lambda_i \Theta^{-1}}{1 + \lambda_i \Theta^{-1}}\right)^{y_i} \left(\frac{1}{1 + \lambda_i \Theta^{-1}}\right)^{\Theta} \quad (1)$$

Where,

y_i − *frequency of crashes on off − ramp i*
$p(Y = y_i)$ − *probability of having* y_i *crashes on off − ramp i*
λ_i − *Poisson parameter, expected number of crashes on segment i*
Θ − *overdispersion parameter of the negative binomial distribution*

In addition to the Poisson parameter, λ, from the Poisson model, the NB model has one other parameter Θ, the overdispersion parameter, to adjust the variance independent of the mean. A log linear link function connects the Poisson parameter to the covariates using equation 2. The error term accounts for the unobserved heterogeneity in the model.

$$\log_e \lambda_i = \beta X_i \;+\; \varepsilon_i \qquad (2)$$

Where,

X_i – *vector of explanatory variables*
ε_i – *gamma – distributed error term with mean* 1 *and variance* Θ^{-1}

Table 6 lists the explanatory variables used in the model.

Table 6: Explanatory variables, X_i

Variable	Modelling type of the variable
Number of Lanes – Freeway	Continuous
Number of Lanes – Off ramp	Continuous
Number of Lanes in the Diverge Area	Continuous
Number of Lanes in the Merge Area	Continuous
Log (length of deceleration lane (feet))	Continuous
Log (length acceleration lane (feet))	Continuous
Type of Interchange	Categorical - Nominal
Type of Ramp	Categorical - Nominal
Type of Diverge Area	Categorical - Nominal
Type of Merge Area	Categorical - Nominal
Log (AADT – Freeway)	Continuous
Log (AADT – Off-ramp)	Continuous
Log (Length of off-ramp segment (feet))	Continuous
Difference in Speed Limit (mph)	Continuous
Type of Traffic Control at Merge Area	Categorical - Nominal

Scaled deviance (SD) and Pearson's χ^2 test statistics are used to find the goodness of fit of a generalized linear model (Chen *et al.* 2009). SD is defined as twice the difference between the log-likelihoods under the reduced model and the maximum model is shown as equation 3.

$$SD = -2(log(L_\beta) - log(L_s)) \qquad (3)$$

Where,

L_β – *likelihood under the reduced model*
L_s – *likelihood under the maximum model*

Pearson's χ^2 statistic is calculated as:

$$Pearson's\ \chi^2 = \sum_{i=1}^{n} \left(\frac{y_i - \lambda_i}{\sigma_i}\right)^2 \tag{4}$$

Where,

y_i	$-$ *crashes on off $-$ ramp segment* i
λ_i	$-$ *expected number of crashes on segment* i
σ_i	$-$ *estimation error for segment* i

The closer that SD and the Pearson's χ^2statistic are to the difference between the number of observations and number of parameters in the model, the better the distribution represents the data.

3.4.2. Identifying facility features most affected by type of collision and severity of crash

The Chi-squared test of independence is used to identify whether a statistically significant difference exists between two groups. The χ^2 test statistic is given by:

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c} \frac{\left(O_{i,j} - E_{i,j}\right)^2}{E_{i,j}} \tag{5}$$

Where,

$$E_{i,j} = N \sum_{j=1}^{c} \frac{O_{i,j}}{N} \sum_{i=1}^{r} \frac{O_{i,j}}{N} \tag{6}$$

Where,

$O_{i,j}$	$-$ *Observed frequency*
$E_{i,j}$	$-$ *Expected frequency*
N	$-$ *Total number of observations*
r, c	$-$ *number of categories in each group*

And

$$Degrees\ of\ freedom = (r - 1)(c - 1)$$

For this research, the test is applied to facility characteristics as they relate to both type of collision and severity of crash. Table 7 shows the cross-tabulation between the four types of facility characteristics and eight types of collisions. Similarly, Table 8 is a cross-tabulation between the same types of facility characteristics and three crash severity groupings. Crash severities were grouped because of the very small number of fatal crashes and the increasing emphasis on serious injury crashes. If the calculated chi-square value is greater than the chi-square critical value at a 0.05 level of significance for the group's degrees of freedom, then the two categories under consideration are dependent on each other. Thus, if the type of collision or severity of crashes is dependent on a particular facility characteristic, priority should be given to improve that particular facility characteristic while considering low-cost countermeasures.

Table 7: Number of crashes by type of collision by off-ramp geometry and traffic control type

Interchange Type (Figure 3 (1))	**Rear end**	**Fixed Object - Off road**	**Angle**	**Sideswipe - Same Direction**	**Head On**	**Non-collision**	**Fixed Object In Road**	**Others**	**Total**
Type a	61	29	16	9	3	7	1	6	132
Type b	106	62	40	29	7	5	2	7	258
Type c	131	58	41	40	7	3	9	7	296
Type d	10	3	4	0	0	0	0	1	18
Ramp Type (Figure 3 (2))									
Type e	135	78	46	36	6	4	7	10	322
Type f	78	37	11	27	4	5	3	2	167
Type g	38	31	12	8	5	6	1	4	105
Type h	57	6	32	7	2	0	1	5	110
Traffic Control at the Merge Area									
No control	60	37	23	24	5	4	3	2	158
Stop Control	25	6	10	4	0	0	2	1	48
Yield Control	102	48	25	24	5	9	3	7	223
Signal Control	68	31	27	16	2	1	2	8	155
Off-ramps ending at other ramps	53	30	16	10	5	1	2	3	120
Total Crashes	308	152	101	78	17	15	12	21	704

Table 8: Number of crashes by crash severity

Interchange Type (Figure 3 (1))	**Fatal and Serious Injury Crashes**	**Injury and Minor Injury Crashes**	**Property Damage Only Crashes**
Type a	5	33	94
Type b	10	69	179
Type c	9	65	222
Type d	2	10	6
Ramp Type (Figure 3 (2))			
Type e	15	70	237
Type f	6	41	120
Type g	2	34	69
Type h	3	32	75
Traffic Control at the Merge Area			
No control	7	36	115
Stop Control	0	7	41
Yield Control	9	53	161
Signal Control	7	48	100
Off-ramps ending at other ramps	3	33	84

3.5. RESULTS AND DISCUSSION

This section summarizes results from the analysis of crashes on urban off-ramps.

3.5.1. Off-ramp and traffic characteristics

For each off-ramp segment, average crashes per year from five years of data was used as the response variable with off-ramp traffic and geometric characteristics from Table 1 as the explanatory variables. Number of lanes near the off-ramp diverge area, on the off-ramp curve and near the off-ramp merge area were highly correlated (correlation coefficient = 0.86), resulting in including only number of lanes on the off-ramp curve in the model. This resulted in the original model including 13 explanatory variables, 8 of which were continuous and 5 were nominal. A step-wise regression was performed to find the explanatory variables that are significant at 95% confidence level which are listed in Table 9. Although not required for identifying the most significant characteristics, the final model is shown as equation 7.

Table 9: Results from the statistical modelling of crash data on off-ramps

	Estimate	Std. Error	Z value	Pr(>|Z|)
(Intercept)	-11.34	1.86	-6.1	0
Number of lanes - Freeway	-0.35	0.12	-2.95	0
Log(Length of off-ramp segment)	0.44	0.08	5.40	0
Log (length of deceleration lane (feet))	-0.05	0.02	-2.27	0.02
Log(AADT – Freeway)	0.7	0.16	4.26	0
Log(AADT - Off-ramp)	0.23	0.09	2.54	0.01
Difference in Speed Limit (mph)	0.02	0.01	2.06	0.04
Interchange Type-Type c (Figure 3(1))	-0.48	0.15	-3.22	0
Ramp Type- Type e (Figure 3(2))	-0.65	0.2	-3.30	0
Traffic Control at Merge Area - Stop Control	-0.58	0.23	-2.51	0.01
Traffic Control at Merge Area - Off-ramps that join other ramps	-0.36	0.17	-2.18	0.03

$$\begin{aligned} &crash\ frequency \\ &= AADT_{freeway}^{0.7} AADT_{ramp}^{0.23} Length_{ramp}^{0.44} Length_{dec}^{-0.05} \exp\Big(-11.35 \\ &- 0.35(number\ of\ lanes - freeway) + 0.02(speed\ differential) \\ &- 0.48(Interchange_{exit-ramp}) - 0.65(Ramp_{cloverleaf}) \\ &- 0.58(Traffic_{stop-control}) - 0.36(Traffic_{off-ramps\ joining\ others})\Big) \end{aligned} \tag{7}$$

The dispersion parameter for the model was calculated to be 3.06 which is significantly different from zero, thus supporting the use of a negative binomial distribution. The model's degrees of freedom is 133, which give a ratio of SD to degrees of freedom as 1.19 and a ratio between Pearson's χ^2 statistic to degrees of freedom as 1.20. Because both of these are close to 1, the data is well represented by the model at 95% confidence level. Another evaluation of the model is the residual plot (Figure 7) which shows the relationship between the residuals and predicted values from the model. An appropriate graphical way to assess model adequacy is to plot the deviance residuals to predicted outcome values known as the residual plot (Cameron & Trivedi 1998). The lowess (locally weighted scatterplot smoothing) line fits a low-degree

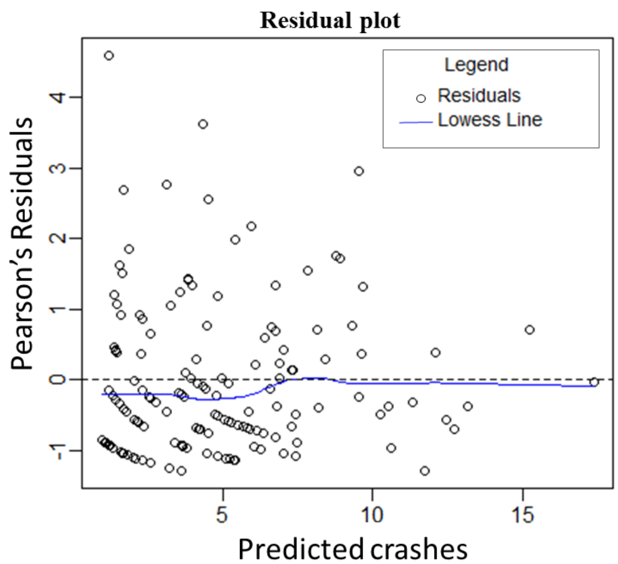


Figure 7: Residual plot

polynomial to data in the residual plot using weighted least squares. The lowess line in Figure 7, shown in blue which is very close to zero, is the best non-parametric fit of the relationship between Pearson's residuals and predicted crashes, and indicates that no specific pattern is observed (Coxe *et al.* 2009). Moreover, 96% of the residual values are between ±2 indicating that this model is a good representation of data.

From**Error! Reference source not found.**, AADT of freeways is the most significant factor and the positive coefficient indicates that it is responsible for an increase in the likelihood of a crash. Number of lanes on the freeway is negative indicating that fewer number of lanes on the freeway cause a higher frequency of crashes on the off-ramp segment. As the length of deceleration lane increases, crashes on those segments tend to decrease. Crashes increase with increase in length of off-ramp segment. An increase in speed difference between the speed limits of freeway and off-ramps indicates a higher frequency of crashes.

The ramps that are part of interchange type c as shown in Figure 3(1), experience fewer crashes compared to ramp type a as shown in Figure 3(1) which experiences less crashes than ramp type e as shown in Figure 3(2). Ramps having a stop control at their ends and those that end at other ramps tend to be safer than those that end where there is no traffic control. The intercept, which is approximately 0 ($exp(-11.34)$), is significant at 95% confidence level and represents the estimate of the regression model when all explanatory variables are zero. So for this model, crash frequency per year would be approximately zero when all the explanatory variables are zero.

3.5.2. Ramp features

Based on the chi-squared test for independence, the types of collision and severities of crashes were evaluated for each of three ramp features; ramp type, interchange type and type of traffic control at the off-ramp merge. To do this, the Pearson's chi-squared test statistic was compared to the critical value at 5% significance level, $\chi^2_{critical}$ and the corresponding degrees of freedom for each feature. Table 10 summarizes the results from the test for independence.

Table 10: Results of Pearson's chi-squared test for independence

	Type of collision			Severity of crashes		
	χ^2	degrees of freedom	$\chi^2_{critical}$	χ^2	degrees of freedom	$\chi^2_{critical}$
Type of interchange	29.2	21	32.67	15.48	6	12.59
Type of ramp	70.06	21	32.67	7.24	6	12.59
Traffic control at off-ramp merge	30.51	28	41.34	10.27	8	15.51

Because χ^2 is less than the corresponding critical χ^2 between type of collision and type of interchange and between type of traffic control and type of collision, these features are not significant to type of collision. The χ^2 value between type of ramp and type of collision is over double the value of critical χ^2 indicating that ramp geometry is significantly associated with the type of collision. As seen in Table 7, type e ramps (Figure 3 (2)) experienced the highest number of crashes indicating that priority should be given to considering countermeasures on this ramp type when compared to other ramp types for this type of crash.

The chi-squared test was also applied to off-ramp features and crash severity. As seen in Table 8, χ^2 between severity of crashes and type of interchange is greater than the corresponding critical χ^2 value indicating that severity of crashes varies with geometry of the interchange. From Table 8, it is seen that type b interchanges (Figure 3 (1)) tend to experience more severe crashes than other interchange types. This shows that priority should be given to type b interchanges (Figure 3 (1)) over other interchange types. The χ^2 value between ramp type and severity, and type of traffic control and severity, are less than the corresponding critical χ^2 indicating that ramp type and traffic control are not significantly associated with severity of crashes.

3.5.3. Countermeasures

Table 11 lists a subset of the Federal Highway Administration's recommended countermeasures that are appropriate for improving off-ramp safety (FHWA 2008). When compared to redesign and construction, these are relatively lower cost and can be applied more readily to multiple facilities.

Table 11: Low-cost countermeasures (FHWA 2008)

Countermeasures	Expected crash reduction (%)	Relative Cost
Lane markings - Increase the length of deceleration lanes	All crashes: 26	Low
Install curve advance warning signs (advisory speed)	All crashes: 29 Injury: 13 PDO: 29	Low
Implement sign corrections to MUTCD* standard	Injury: 15 PDO: 7	Low
Install variable queue warning signs	PDO: 16	Low
Improve pavement friction (grooving)	All crashes: 20	Medium
Improve guard rails	All crashes: 18	Low
Improve Lighting	Fatal: 73 Injury: 27 PDO: 32	Medium

**MUTCD – Manual on Uniform Traffic Control Devices*

From the results of the statistical modelling, ramp design and traffic characteristics that indicated an increase in the occurrence of crashes included higher traffic volumes on the freeways and off-ramps, length of ramp, and speed differential between freeway and off-ramp. Ramp type (as defined in Figure 3(2)) was significant for crash type with the highest numbers of crashes occurring on type e (Figure 3 (2)), followed by type f (Figure 3 (2)), then type g (Figure 3 (2)), and type h (Figure 3 (2)). Rear-end crashes were the most prevalent for all ramp types with 33% of them occurring at yield control involving two vehicles. Rear-end crashes are more likely to cause low-severity crashes as 70% of these caused only property damage. Interchange type was significant for crash severity with the most fatal and serious injury crashes occurring on type b ((Figure 3 (1))) and type c (Figure 3 (1)). Once these have been identified, a review of the crashes associated with them (tables 7 and 8) can provide guidance on selecting the appropriate countermeasure.

Considering this information with respect to possible countermeasures, improved traffic management including advance warning signs and variable queue warning signs, could be implemented near the off-ramp diverge and merge locations on ramps with higher traffic volumes. The speed differential could be addressed through traffic management at the diverge area by modifying markings to increase the deceleration lane length to at least 800 feet (AASHTO 2001, HFG 2012), if possible, or by implementing advance traffic signs that gives the driver enough time to react to conditions ahead.

As indicated earlier, rear-end collisions were the most frequent with short curve ramps experiencing 44% of total collisions indicating that emphasis should be placed on identifying countermeasures for type e ramps (Figure 3 (2)). Because traffic congestion has been associated with rear-end collisions (McCartt *et al.* 2004), variable queue warning signs or a surveillance system that detects congestion ahead can be considered for ramps with higher traffic volumes. The cost of queue warning systems depends on the existing infrastructure and is estimated to have a return on investment (ROI) within three years of implementation (TTI 2010). Improving pavement friction at merges can reduce rear-end collisions. Pavement grooves or high friction surfaces increase skid resistance by creating a rougher pavement.

Because of the material, equipment and labor involved, this is considered a moderate-cost countermeasure (FHWA 2006). However, it could be incorporated into normal resurfacing schedules, thus minimizing the costs.

Off-ramps that are part of type b interchanges (Figure 3 (1)) experienced 38% of higher severity crashes with 34% of rear-end and 40% of the fixed object (off-ramps) collisions. Clearing roadsides of fixed objects and ensuring that guardrails on the inside curves have proper end treatments are some of the effective low-cost countermeasures for these segments. Providing adequate lighting on off-ramp curves could also provide a low-cost solution if the power infrastructure is available.

3.6. CONCLUSIONS

A system-level approach to evaluate the safety associated with a complex transportation facility, urban freeway off-ramps, was demonstrated by relating crash history to geometric and traffic characteristics associated with all instances of that facility across the highway system. The results of the statistical modeling identified significant causal factors that could be associated with low-cost countermeasures while the results of the independence test identified specific features of these facilities that were targets for application of those countermeasures. The focus of this study was to demonstrate the efficacy of this approach using a study area that consisted of 144 facilities. To validate the approach, a before and after study would be necessary, which was beyond the scope of this research. Additional research would also be necessary to determine how to aggregate facilities to be analyzed. This study selected urban as opposed to rural facilities and considered off-ramps instead of on-ramps. Whether these distinctions are necessary would require a more comprehensive study.

This analysis had detailed location of every police reported crash on every road which allowed them to be associated with specific features. Similarly, it used information that was either included as attributes of a geospatial (GIS) road centerline layer maintained by the state transportation agency as described in section 3 or that was easily observable from imagery, making a system-wide analysis possible without doing site visits to obtain detailed information at each site. Some design characteristics were not included because they were not yet readily available, such as super-elevation and horizontal and vertical curvatures, which would potentially be important indicators. As agencies add attributes to their road centerline layers and Highway Performance Monitoring Systems, these types of characteristics will become available for expanded analysis and should be included in further research.

The methodology used in this research is readily extensible to other transportation facilities such as on-ramps, complex weaving sections, signalized or un-signalized intersections, or any group of facilities that require more than SPF factors to identify high-risk characteristics or elements for countermeasures. This, in turn, can assist agencies with incorporating a more systematic approach to allocating resources for reducing crashes.

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), 2001. A Policy on Geometric Design of Highways and Streets, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO), 2010. Highway Safety Manual. Washington, DC.

Bauer, K.M., Harwood, D.W., 1998. Statistical models of accidents on interchange ramps and speed-change lanes. FHWA-RD-97-106.

Cameron, A. C., Trivedi, P. K., 1998. Regression analysis of count data. Cambridge University Press, New York.

Chen, H., 2010. Comparison of safety performance by design types at freeway diverge areas and exit ramp section. Graduate Theses and Dissertations, University of South Florida, Tampa, Florida.

Chen, H., Liu, P., Lu, J.J., Behzadi, B., 2009. Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps. Accident Analysis & Prevention 41 (3), 543-551.

Coxe, S., West, S.G., Aiken, L.S., 2009. The analysis of count data: A gentle introduction to poisson regression and its alternatives. Journal of Personality Assessment 91 (2), 121-136.

Federal Highway Administration (FHWA), 2008. Toolbox of Countermeasures and their effectiveness for Roadway Departure Crashes. U.S. Department of Transportation. Washington, DC. http://safety.fhwa.dot.gov/tools/crf/resources/briefs/rdwydepartissue.cfm

Federal Highway Administration (FHWA), 2006. Low-Cost Treatments for Horizontal Curve Safety. U.S. Department of Transportation. Washington, DC. http://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa07002/fhwasa07002.pdf

Florida Department of Transportation, 2014. Project Traffic Forecasting Handbook, U.S. Department of Transportation. Washington, DC. http://www.dot.state.fl.us/planning/statistics/trafficdata/ptf.pdf

Geedipally, S., Bonneson, J., Pratt, M., Lord, D., 2014. Analysis of injury severity in crashes on ramps and at crossroad ramp terminals. Transportation Research Record: Journal of the Transportation Research Board 2435, 37-44.

Google Street View, 2015. Google Inc. Panoramic view of streets. https://www.google.com/intl/en_ALL/maps/streetview/

Human Factor Guidelines for Road Systems, 2012. National Cooperative Highway Research Program. Report 600. Transportation Research Board, Washington, DC. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_600Second.pdf

Khorashadi, A., 1998. Effect of ramp type and geometry on accidents. FHWA/CA/TE-98/13, California Department of Transportation.

Li, Z., Wang, W., Liu, P., Bai, L., Du, M., 2015. Analysis of crash risks by collision type at freeway diverge area using multivariate modeling technique. Journal of Transportation Engineering 141 (6), 04015002.

Lord, D., Mannering, F., 2010. The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice 44 (5), 291-305.

Mccartt, A.T., Northrup, V.S., Retting, R.A., 2004. Types and characteristics of ramp-related motor vehicle crashes on urban interstate roadways in northern virginia. Journal of Safety Research 35 (1), 107-114.

National Highway Traffic Safety Administration (NHTSA), 2013a . Fatality Analysis Reporting System. Washington, DC. http://www.nhtsa.gov/FARS

National Highway Traffic Safety Administration (NHTSA), 2013b. Traffic safety facts. U.S. Department of Transportation, Washington, DC. http://www-nrd.nhtsa.dot.gov/Pubs/812139.pdf

Retting, R.A., Williams, A.F., Preusser, D.F., Weinstein, H.B., 1995. Classifying urban crashes for countermeasure development. Accident Analysis & Prevention 27 (3), 283-294.

Schutt, K., Newman, J., Hancock, K., Sforza, P., Year. Carl: Crash attribute and reference locator. In: Proceedings of the Computing for Geospatial Research and Application (COM. Geo), 2013 Fourth International Conference on, pp. 116-121.

Texas A&M Transportation Institute (TTI), 2010. Urban Mobility Information: Queue Warning, http://mobility.tamu.edu/mip/strategies-pdfs/active-traffic/executive-summary/queue-warning-1-pg.pdf

Twomey, J., Heckman, M., Hayward, J., 1992. Safety effectiveness of highway design features. Volume iv: Interchanges. FHWA-RD-91-047. FHWA, U.S. Department of Transportation,.

U.S. Department of Commerce, 2010. Census of Population and Housing, Economics and Statistics Administration, U.S. Census Bureau, https://www.census.gov/prod/cen2010/cph-2-48.pdf

Virginia Department of Motor Vehicles (DMV), 2015. TREDS - Traffic Records Electronic Data System. https://www.treds.virginia.gov/

Virginia Department of Transportation (VDOT), 2015. Annual Average Daily Traffic, http://www.arcgis.com/home/item.html?id=cd4d084cccc84cea9e77a08e3de20fa2

Virginia Information Technologies Agency (VITA), 2015a. Commonwealth of Virginia state ortho-imagery. https://www.vita.virginia.gov/

Virginia Information Technologies Agency (VITA), 2015b. Virginia Road Centerline https://ftp.vgingis.com/Download/Historical_RCL/

CHAPTER 4: DISCUSSION AND CONCLUSION

4.1. DISCUSSION

A system-wide crash data analysis was performed to evaluate a complex facility type. The systematic approach is different from the traditional hot spot analysis as it takes all the locations of a facility type in the study area into consideration. The analysis identified significant geometric and traffic characteristics that led to a crash. These results can potentially assist transportation planners and agencies in selecting low-cost countermeasures for implementation across the highway network.

Urban freeway off-ramps were selected to demonstrate this systematic approach. The selected urban area consisted of 144 freeway off-ramp segments that were categorized based on their geometry and traffic control characteristics and associated with crash frequency and characteristics.

From the results of the statistical modeling of crashes, AADT of freeways was found to be one of the most significant factors that causes a crash. As AADT on freeways increases, crashes on off-ramps also increases. As the length of deceleration lane length increases, crashes on off-ramp segments tend to decrease. These results indicate the importance of a better traffic management near the diverge area. Increasing the deceleration lane length by changing the existing lane markings is one of the low-cost solutions that can be implemented. As the deceleration lane length increases, the driver will get enough time to react to the situation ahead. A variable queue warning sign alerts the driver about a possible stop-and-go traffic in the off-ramp curve using flashing beacons or warning signs. The cost of implementing these warning signs for a better traffic management near diverge area depends on the existing infrastructure (TTI 2010). The warning signs inform the driver about a congestion ahead thus reducing collision related to unexpected braking.

The results from the statistical independence test identified that type of collision is significantly associated with the geometry of ramps. Rear-end collisions were found to be the most frequent in the study area. Improving skid resistance near the end of off-ramps using high friction surfaces or pavement grooves reduce the frequency of rear-end crashes. Fixed-object crashes were the second most frequent in the study area. Guard rails protect the vehicle occupants from roadside hazards where vehicles might experience fixed object crashes. The results from the statistical independence test also identified that severity of crashes is significantly associated with the geometry type of interchange. Guard rails with proper end-treatment reduce the frequency and severity of crashes that occur on the sides of road. Removing obstacles to improve sight distance and clearing roadsides of fixed objects are some of the low-cost solutions that improve safety of vehicles travelling on off-ramps.

4.2. CONCLUSION

This project demonstrated that a system wide approach could effectively be used to identify low-cost safety improvements related to a specific facility type. The crash histories for every instance of a facility within the study area were associated with its individual geometric and traffic characteristics which resulted in the ability to identify significant factors that could be addressed at multiple facilities. A test for statistical independence was performed to identify with geometry and traffic characteristics of the off-ramp segment were associated with type of collision and severity of crashes. The results from this test identified locations of a particular geometry or traffic characteristic that should be given priority when installing low-cost solutions to reduce frequency or severity of crashes.

The detailed location information of each crash in the study area that was available for this research allowed it to be spatially associated with the appropriate ramp features which supported the ability to identify critical factors and ramp features. If crash locations had only been snapped to the road centerlines, this would not have been possible. Similarly, having a mature geospatial road centerline file and access to high resolution imagery supported the population of comprehensive ramp characteristics and features for all facilities in the study area without having to do site visits or manually extract information from design or construction drawings.

The ability to classify specific characteristics of complex facilities, such as ramp type and merge type, allows these characteristics to be included in a system wide analysis which then supports the ability to identify critical factors across multiple facilities instead of having to evaluate them one at a time. Although high crash locations should still be evaluated in more detail, the ability to identify and improve several facilities that have fewer crashes can be an effective complimentary approach to helping transportation agencies meet their safety goals.

4.3. FUTURE WORK

The effectiveness of a countermeasure can be measured in terms of the reduction in crashes after its installation. Observational before-after studies are the most common approach performed for safety effectiveness evaluation (AASHTO 2010). The crash and traffic data before and after the implementation of countermeasure are used for observational before-after studies. An empirical Bayes (EB) method is commonly used in observational before-after studies when a non-treatment group is included in the analysis. EB method also takes care of the regression-to-the-mean (RTM) bias when treatment sites were selected because of higher than expected crashes on these sites. An observational before-after study to evaluate the effectiveness of the selected low-cost countermeasures was not included in this research. An extension to this research to evaluate the effectiveness of a countermeasure will validate the results of the research and the agencies can select low-cost countermeasures with maximum benefits.

Extending the model could potentially improve the understanding related to crash causation at specific facility types. Additional variables such as super-elevation and horizontal and vertical curvature could improve the model fit to the data. As the data for these variables were not readily available they could not be included and can be considered for a follow-up research. The statistical model was developed based on crashes per year on each off-ramp segment over a 5-year analysis period. Averaging the crashes that occurred in five years on an off-ramp segment may ignore variations within the 5-year analysis period (Lord and Mannering 2010). The statistical model can be extended to incorporate the temporal correlation in the observation of crashes over the analysis period as many of the unobserved effects associated with a road segment may remain the same over years. Also, accounting for the temporal correlation can improve the efficiency of estimation of parameters in the model.

This study focused on urban freeway off-ramps that are functionally similar with similar types of geometric characteristics. The systematic approach for the safety evaluation may be extended to other facilities such as on-ramps, complex weaving sections, signalized and un-signalized intersections or group of facilities. Similarly, grouping facilities and evaluating their safety at a system level will be an extension to this study. In doing so, spatial correlation has to be taken into consideration as roadway entities in close proximity may share unobserved effects (Lord and Mannering 2010).

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), 2010. Highway Safety Manual. Washington, DC.

Lord, D., Mannering, F., 2010. The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice 44 (5), 291-305.

Texas A&M Transportation Institute (TTI), 2010. Urban Mobility Information: Queue Warning, http://mobility.tamu.edu/mip/strategies-pdfs/active-traffic/executive-summary/queue-warning-1-pg.pdf

APPENDIX A

Appendix A consists of four sub-sections that give an overview of the data used in the study to identify the off-ramp segment characteristics and crash characteristics that occurred on off-ramps, the pseudo code to develop a statistical model that relates crashes to off-ramp characteristics and the detailed results from the statistical modeling after each step of the regression.

A.1. SAMPLE OF OFF-RAMP SEGMENT DATA

The data used in the analysis to identify characteristics of off-ramp segments in the study area is provided in this section. This data provides information related to geometric and traffic characteristics associated with 144 off-ramp segments in the study area. The data is collected from multiple data sources. The information related to number of lanes on freeway and length of off-ramp segment was available as attributes in the road centerline data and could be readily used in the analysis. Other geometric characteristics were observed from state ortho-imagery. The traffic control characteristics were observed from Google Street View and traffic volume information was obtained from traffic data. The data for 10 off-ramp segments is provided in the following table as a sample.

Table A 1: Off-ramp characteristics

Object ID	Number of freeway lanes	Number of off-ramp lanes	Number of lanes in diverge	Number of lanes in off-ramp merge	Acceleration Length	Deceleration Length	Freeway Speed limit	Off-ramp Speed limit	Freeway AADT	Off-ramp AADT
1	3	1	1	1	0	0	55	25	91000	2300
2	3	2	2	2	0	0	55	25	91000	4400
3	3	2	2	3	0	1300	55	15	123000	8600
4	3	2	2	3	0	0	55	35	142000	12000
5	3	2	2	3	0	0	55	35	142000	12000
6	3	1	1	1	0	600	55	25	123000	4100
7	3	1	1	1	0	0	55	25	123000	2100
8	3	1	1	1	0	0	55	25	123000	2000
9	4	1	1	1	0	0	55	25	137000	9300
10	4	1	1	1	0	0	55	25	137000	9300

Table A 1: Off-ramp characteristics (contd.)

Object ID	Interchange Type	Ramp Type	Traffic signal type at the merge area	Number of end ramps	Merge area type	Diverge area type	Length of the off-ramp segment (Miles)	Number of crashes
1	2	2	2	2	1	1	0.37	17
2	2	4	4	0	1	1	0.02	5
3	3	1	3	0	1	1	0.15	18
4	3	1	3	0	1	2	0.02	1
5	3	1	4	2	3	2	0.14	12
6	3	1	1	2	3	1	0.13	8
7	3	4	2	0	1	1	0.07	2
8	3	4	4	0	1	1	0.04	6
9	3	4	3	0	1	2	0.02	2
10	3	2	4	2	3	2	0.23	16

A.2. Sample of crash data

The characteristics of crashes that occurred on off-ramp segments in the study area is obtained from the crash database. The data provides information related to type of collision, severity of crashes and type of collision that occurred on off-ramp segments. Furthermore, each of the geo-located crash are spatially related to the off-ramp segment where they occurred.

Table A 2: Crash characteristics

Object ID	Latitude	Longitude	Street name	Year	Type of crash	Type of collision	Number of vehicles involved	Type of injury
1	37.5547	-77.411096	I 64	2013	Injury Crash	1	2	4
2	37.55583	-77.411934	I 64	2011	Property Damage Crash	1	2	9
3	37.55692	-77.412437	I 64	2012	Property Damage Crash	1	2	9
4	37.55715	-77.412865	I 64	2013	Property Damage Crash	1	2	9
5	37.55725	-77.41303	I 64	2014	Injury Crash	1	2	4
6	37.55735	-77.41322	I 64	2014	Property Damage Crash	1	3	9
7	37.55743	-77.413222	I 64	2012	Property Damage Crash	1	4	9
8	37.55788	-77.414208	I 64	2012	Property Damage Crash	9	1	9
9	37.55794	-77.414248	I 64	2012	Property Damage Crash	1	2	9
10	37.55809	-77.41452	I 64	2014	Property Damage Crash	2	2	9
11	37.55809	-77.4146	I 64	2013	Property Damage Crash	9	1	9
12	37.55812	-77.41448	I 64	2014	Injury Crash	1	2	3
13	37.55826	-77.414828	I 64	2013	Property Damage Crash	9	1	9
14	37.55826	-77.414766	I 64	2013	Property Damage Crash	4	2	9
15	37.55748	-77.4089	I 64	2014	Injury Crash	4	2	3
16	37.55758	-77.408928	I 64	2011	Property Damage Crash	2	2	9
17	37.55758	-77.40892	I 64	2014	Injury Crash	2	2	3
18	37.55758	-77.408873	I 64	2012	Injury Crash	2	2	3
19	37.55767	-77.408847	I 64	2012	Fatal Crash	2	2	1
20	37.5526	-77.445869	I 95 / I 64	2012	Property Damage Crash	4	2	9

A.3. R pseudo code

A statistical model was developed in R; a programming language and software environment for statistical computing. This section provides the pseudo code to develop the statistical model that relates crashes to off-ramp segment characteristics.

Package used: MASS (Modern Applied Statistics with S)

```
function NBModel (OfframpSegmentData)
{
#Import k variables for analysis for each of the 144 off-ramp segment in the study area

#factorize the categorical variables into binary
        for i =1 to k #iterate through k variables
                {if OfframpSegmentData (variable[k]) is categorical then
                        factorize (OfframpSegmentData (variable[k]))
                end if
                }
        end for

#Generalized Linear Model – Negative Binomial Regression
        fit ← glm.nb (response_variable ~ OfframpSegmentData (variable[1]) +
                    OfframpSegmentData (variable[2])+…
                    OfframpSegmentData (variable[k]), link = "log")

#Print results
        summary (fit)

#Histogram of crash distribution
        hist(response_variable)

#Plot the residuals
        pearsonresiduals ← residuals(fit, "pearson")
        plot (fit$fitted.values, pearsonresiduals)
        lines(lowess(fit$fitted.values,residuals(fit,"pearson")),col = "blue")

end function
}
```

A.4. Step-wise regression

A statistical model was developed to identify significant geometric and traffic characteristics of the off-ramp segment that led to a crash. With crashes as response variables and off-ramp characteristics as the explanatory variables, a statistical model was developed. Eight continuous variables and five categorical variables were used in the initial model. For the interchange type categorical variable, interchange type a (Figure 3 (1)) was taken as the base case against which other interchange types were compared. Similarly, ramp type e (Figure 3 (2)), diverge area type i (Figure 3 (3)), merge area type l (Figure 3 (4)) and ramps that have no traffic control at their ends were taken as the base cases against which other types in ramp type, diverge area type, merge area type and traffic control at the off-ramp merge area type categorical variables were compared respectively. The base cases were not included for developing the model. A step-wise regression was performed and those variables that were not found to be statistically significant at 95% confidence level were removed, and the model is rerun with only the significant variables. Model 1 and Model 2 are the intermediate models before identifying Model 3, which has all its variables that are statistically significant at 95% confidence level.

Table A 3: Model 1

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-12.48	1.97	-6.35	2E-10
Number of lanes - Freeway	-0.37	0.12	-3.00	3E-03
Number of lanes - Off-ramp*	0.05	0.16	0.29	8E-01
Log(Length of off-ramp segment)	0.57	0.12	4.69	3E-06
Log(AADT - Freeway)	0.75	0.17	4.49	7E-06
Log(AADT - Off-ramp)	0.24	0.09	2.61	9E-03
Difference in Speed Limit (mph)	0.02	0.01	2.26	2E-02
Log (length of acceleration lane)*	0.01	0.04	0.18	9E-01
Log (length of deceleration lane)	-0.06	0.04	-1.62	1E-01
Interchange Type - Type b (Figure 3(1))	-0.43	0.21	-2.03	4E-02
Interchange Type - Type c (Figure 3(1))	-0.75	0.23	-3.35	8E-04
Interchange Type - Type d (Figure 3(1))*	0.07	0.52	0.13	9E-01
Ramp Type - Type f (Figure 3(2))*	-0.12	0.20	-0.59	6E-01
Ramp Type - Type g (Figure 3(2))	-0.60	0.22	-2.75	6E-03
Ramp Type - Type h (Figure 3(2))*	0.29	0.27	1.07	3E-01
Diverge Area - Type j (Figure 3(3))*	0.00	0.26	0.02	1E+00
Diverge Area - Type k (Figure 3(3))*	-0.13	0.23	-0.58	6E-01
Merge area - Type m (Figure 3(4))*	-0.33	0.34	-0.95	3E-01
Merge area - Type n (Figure 3(4))*	-0.36	0.22	-1.64	1E-01
Traffic control at merge area - Stop control	-0.74	0.29	-2.50	1E-02
Traffic control at merge area - Yield control	-0.02	0.21	-0.12	9E-01
Traffic control at merge area - Signal control*	-0.17	0.25	-0.68	5E-01
Traffic control at merge area - Ramps ending at other ramps	-0.73	0.31	-2.36	2E-02

* Variables removed from the model as they are found to be insignificant at 95% confidence level

(Dispersion parameter for Negative Binomial (3.6196) family taken to be 1)

Null deviance: 292.26 on 143 degrees of freedom
Residual deviance: 159.49 on 120 degrees of freedom
AIC: 730.59
Number of Fisher Scoring iterations: 1
Theta: 3.620
Std. Err.: 0.835
2 x log-likelihood: -680.588

Table A 4: Model 2

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-11.61	1.86	-6.23	0.00
Number of lanes - Freeway	-0.35	0.12	-3.00	0.00
Log(Length of off-ramp segment)	0.45	0.08	5.38	0.00
Log(AADT - Freeway)	0.74	0.17	4.42	0.00
Log(AADT - Off-ramp)	0.22	0.09	2.47	0.01
Difference in Speed Limit (mph)	0.02	0.01	2.02	0.04
Log (length of deceleration lane)	-0.06	0.02	-2.37	0.02
Interchange Type - Type b (Figure 3(1))*	-0.23	0.19	-1.18	0.24
Interchange Type - Type c (Figure 3(1))	-0.63	0.20	-3.08	0.00
Ramp Type - Type g (Figure 3(2))	-0.70	0.20	-3.51	0.00
Traffic control at merge area - Stop control	-0.56	0.24	-2.37	0.02
Traffic control at merge area - Yield control*	0.05	0.16	0.28	0.78
Traffic control at merge area - Ramps ending at other ramps	-0.34	0.18	-1.95	0.05

* Variables removed from the model as they are found to be insignificant at 95% confidence level

(Dispersion parameter for Negative Binomial (3.106) family taken to be 1)

Null deviance: 270.45 on 143 degrees of freedom
Residual deviance: 158.21 on 131 degrees of freedom
AIC: 718.34
Number of Fisher Scoring iterations: 1
Theta: 3.106
Std. Err.: 0.663
2 x log-likelihood: -690.343

Table A 5: Model 3 (Final model)

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-11.34	1.86	-6.10	0.00
Number of lanes - Freeway	-0.35	0.12	-2.95	0.00
Log(Length of off-ramp segment)	0.44	0.08	5.40	0.00
Log(AADT - Freeway)	0.70	0.16	4.26	0.00
Log(AADT - Off-ramp)	0.23	0.09	2.54	0.01
Difference in Speed Limit (mph)	0.02	0.01	2.06	0.04
Log (length of deceleration lane)	-0.05	0.02	-2.27	0.02
Interchange Type - Type c (Figure 3(1))	-0.48	0.15	-3.22	0.00
Ramp Type - Type g (Figure 3(2))	-0.65	0.20	-3.30	0.00
Traffic control at merge area - Stop control	-0.58	0.23	-2.51	0.01
Traffic control at merge area - Ramps ending at other ramps	-0.36	0.17	-2.18	0.03

(Dispersion parameter for Negative Binomial (3.0614) family taken to be 1)

Null deviance: 268.41 on 143 degrees of freedom
Residual deviance: 158.78 on 133 degrees of freedom
AIC: 715.99
Number of Fisher Scoring iterations: 1
Theta: 3.061
Std. Err.: 0.652
2 x log-likelihood: -691.994