SAFETY IMPACTS OF DESIGN EXCEPTIONS IN UTAH

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ABSTRACT

The objective of this research was to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed. Data were collected for design exceptions in Utah in the years 2001 through 2006. Design exception request and approval forms, Google Earth, Google Street View, UDOT functional classification maps, and UDOT traffic volume data were used to identify and define road segments with and without design exceptions. Ultimately, a total of 48 segments with design exceptions and 132 segments without design exceptions were used for modeling. Propensity scores were applied in this study to assess the comparison sites (i.e., sites without design exceptions). The relationship between design exception presence and crash frequency was explored using a negative binomial regression modeling approach. The relationship between design exception presence and crash severity was explored in three ways: 1) computing severity distributions at locations with and without design exceptions, 2) estimating separate negative binomial regression models by severity level, and 3) estimating multinomial logit models. Design exception presence was represented in the regression models by an indicator variable (1 = one or more design exceptions; 0 = no design exceptions). Crash data from the years 2006 through 2008 were used for model estimation. Road segments with one or more design exceptions had the same expected frequencies of total crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes as road segments without design exceptions. There were no detectable differences in the severity distributions of crashes occurring on roads with one or more design exceptions when compared to crashes occurring on roads without any design exceptions.

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LIST OF ACRONYMS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CMF	Crash Modification Factor
DOT	Department of Transportation
FHWA	Federal Highway Administration
NHS	National Highway System
PDBS	Project Development Business System
RE	Resident Engineer
SPF	Safety Performance Function
STRAHNET	Strategic Highway Network
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

State Departments of Transportation (DOTs) develop designs and prepare plans for road construction. Designers are guided by a set of state-adopted standards and policies that include design criteria. There are cases where meeting all design criteria would result in significant environmental impacts, community impacts, and/or construction costs. When this occurs, a design exception may be explored as an alternative. The potential safety implications of design exceptions are a central issue in design exception review and approval, but documentation of the process by which safety is considered varies from state to state. A survey of state DOTs indicated that safety analysis methods also varied. A literature review conducted as part of this project showed that attempts to revisit locations with approved and constructed design exceptions and analyze their safety performance were limited.

The objective of this research was to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed. The project used data from the State of Utah. Data were collected for design exceptions granted in Utah in the years 2001 through 2006. Design exception request and approval forms, Google Earth, Google Street View, Utah Department of Transportation (UDOT) functional classification maps, and UDOT traffic volume data were used to identify and define road segments with and without design exceptions. Ultimately, a total of 48 segments with design exceptions and 132 segments without design exceptions were used for modeling. Propensity scores were used in this study to assess the selection of comparison sites (i.e., sites without design exceptions).

Design exception effects on expected crash frequency were quantified using a negative binomial regression modeling approach. Road segments with one or more design exceptions had the same expected frequencies of total crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes as road segments without design exceptions. This finding was based on parameters for the negative binomial regression models estimated using data from both freeways and non-freeways with variables and interactions that captured the expected differences in safety performance between these facility types.

Design exception effects on expected crash severity were quantified using two approaches: 1) computing severity distributions at locations with and without design exceptions and 2) estimating separate negative binomial regression models by severity level. There were no detectable differences in the severity distributions of crashes occurring on roads with one or more design exceptions when compared to crashes occurring on roads without design exceptions. This finding is based on parameter estimates for the series of negative binomial regression models separated by severity level. The results of this study showed that the UDOT design exception review and approval process, as implemented in years 2001 through 2006, was effective from a safety perspective. Findings are not intended to support approving a greater number of design exceptions or fewer design exceptions.

1. INTRODUCTION

1.1 Problem Statement

Designs and plans for construction and reconstruction projects on state facilities are created using state-agency adopted geometric design criteria. UDOT has adopted A Policy on Geometric Design of Highways and Streets (Green Book) as its standard for roadway design with some differences noted in the UDOT Roadway Design Manual of Instruction (AASHTO 2004, UDOT 2007). Meeting established design criteria is not always practical or cost-effective. Deviating from design criteria requires documentation and approval. This generally occurs at two levels within UDOT: design exceptions and design waivers. Design exceptions are the focus of this research.

Design exceptions are prepared when a road design deviates from one or more of the FHWA 13 controlling design criteria. Formal review and approval is required for design exceptions on an NHS or STRAHNET construction or reconstruction project. Project costs with the design exception(s) are estimated and compared to project costs if the 13 controlling criteria are met (UDOT 2009). The FHWA, *Federal-Aid Policy Guide* states that an "exception should not be approved if the exception would result in degrading the relative safety of the roadway" (FHWA 1997). Predicting the potential safety consequences of design exceptions is challenging, and only two studies were identified where an attempt was made to "track" safety of road segments where design exceptions had been approved (Stamatiadis et al. 2005, Malyshkina & Mannering 2010).

A recent survey of transportation agencies revealed that design exception procedures for most states included safety assessments of the proposed exceptions; the types of safety analyses varied substantially between states and relatively little was known about actual, quantitative safety impacts of design exceptions (Mason & Mahoney 2003). The AASHTO *Highway Safety Manual* was intended to fill this void, but a significant amount of safety information related to the controlling criteria was not included in the first edition (AASHTO 2010). Research to assess the safety impacts of design exceptions in Utah was needed. Research results will provide insights into the effectiveness of the current UDOT design exception preparation and approval process. Results also create additional documentation that includes an evaluation of designs resulting from design exceptions.

1.2 Objectives

The objective of this research was to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed.

1.3 Scope

The research objectives were met by accomplishing eight research tasks. Road segments where design exceptions were approved and the resulting design constructed were identified and defined in Task 1. Traffic, geometric, and other key characteristics for these road segments were then collected (Task 2). The number and severity of crashes occurring on the road segments defined in the first two tasks were determined in Task 3. Crash data spanning the years 2006 through 2008 were used for analysis, as these were the only recent years updated to UDOT's current linear referencing system at the time of the research project. Therefore, the road segments defined in Task 1 had projects that ended prior to 2006. Similar road segments to those defined in Task 1, but without design exceptions, were defined in Task 4. These segments made up the comparison group. The adequacy of the comparison group was assessed using propensity scores. Traffic, geometric, and other key characteristics for these comparison road segments were then collected (Task 5) and the number and severity of crashes occurring on these road segments were defined (Task 6). Expected crash frequency and severity on roads segments where design exceptions were approved were compared to expected crash frequency and severity on similar road segments where no design exceptions were approved in Task 7. The entire study was documented in a final report (Task 8).

The study looked at the safety effects of design exceptions at an aggregate level. The safety effects of exceptions to individual design criteria or specific combinations of design criteria were not explored in detail due to limited sample sizes. The analysis focused on all crash types by severity level. Specific crash types (e.g., single-vehicle, run-off-road; same-direction-sideswipe) were not explored. The study was not intended to recommend any new additions or modifications to the UDOT design exception policy. It was intended to provide insights into the effectiveness of the current design exception preparation and approval process from a safety perspective.

1.4 Outline of Report

The report is organized into six sections and two appendices:

- A general introduction is provided in Section 1. The need for this research is outlined in the form of a problem statement. Research objectives and the research scope are also described.
- Background information and a literature review on the safety effects of design exceptions and other safety information related to FHWA's 13 controlling design criteria are provided in Section 2.
- Research methods used to study the effects of design exceptions on crash frequency and crash severity are presented in Section 3.
- Data collection efforts, including data sources, protocol, and quality control steps, are described in Section 4.
- Modeling results and interpretations related to the safety impacts of design exceptions are provided in Section 5.
- Key findings, research conclusions, challenges, and limitations of the research are identified in Section 6.
- Recommendations for future work and an implementation plan are included in Section 7.
- Crash frequency and severity model estimation results, disaggregated by facility type, are presented in Appendix A.

2. BACKGROUND

2.1 Overview

State DOTs develop designs and prepare plans for road construction. Designers are guided by a set of state-adopted standards and policies that include design criteria. Design criteria are based on research and practice, and are generally expressed as minimums, maximums, or ranges of values for design elements (e.g., minimum horizontal curve radius, maximum grade). Individual state DOTs, as well as AASHTO, consider factors such as safety, efficiency, driver comfort, aesthetics, construction cost, and future maintenance activities when adopting or recommending design criteria.

Meeting all design criteria is not always possible or practical. There are cases where meeting all design criteria would result in significant environmental impacts, community impacts, and/or construction costs. When this occurs, a design exception may be explored as an alternative. A design exception is the process and resulting documentation associated with a geometric feature created or perpetuated by a highway construction project that does not conform to the criteria set forth in design standards or policies (Mason & Mahoney 2003). The term design exception is sometimes used only when referring to one or more of FHWA's following controlling criteria:

1. Design speed
2. Lane width
3. Shoulder width
4. Bridge width
5. Horizontal alignment
6. Superelevation
7. Vertical alignment
8. Grade
9. Stopping sight distance
10. Cross slope
11. Vertical clearance
12. Lateral offset to obstruction
13. Structural capacity

Terms such as "design variance" or "design waiver" are sometimes used when referring to other design criteria. A design exception requires formal review and approval if the construction project is on the NHS and the design criterion (or criteria) is among the 13 controlling criteria.

The controlling criteria are identified in the *Federal-Aid Policy Guide* (FHWA 1997) and described in *Mitigation Strategies for Design Exceptions* (Stein & Neuman 2007). State-adopted design criteria for NHS construction or reconstruction projects must be at least "as great as" values in AASHTO's Green Book and AASHTO's *A Policy on Design Standards – Interstate System* for these elements (AASHTO 2004, AASHTO 2005). UDOT has adopted the Green Book along with other relevant AASHTO guides as its standard for roadway design with some differences noted in the UDOT *Roadway Design Manual of Instruction* (UDOT 2007).

Some states have identified additional controlling or critical criteria, considered equal in importance to the 13 identified above. State DOTs also prepare design exceptions for other design criteria. These supplemental criteria that are currently used by more than one state DOT include cut/fill slopes, roadside features (including culverts), median width, guardrail, design level of service, median opening spacing, intersection sight distance, and ramp acceleration and deceleration lane lengths (Mason & Mahoney 2003).

A recent survey of state DOTs identified benefits, problems, and potential improvements associated with design exceptions (Mason & Mahoney 2003). Almost all DOTs surveyed viewed design exceptions, and the resulting documentation of the associated decision process, as valuable. Reported difficulties included lack of supporting quantitative information, inadequate guidance on controlling criteria definitions and applications, and resource requirements (e.g., agency personnel, funds, and time). The potential safety implications of design exceptions are a central issue to design exception review and approval, but documentation of the process by which safety is considered varied from state to state (Mason & Mahoney 2003). Documentation on the selection and effectiveness of safety mitigation measures, sometimes implemented with a design exception, also varies (Mason & Mahoney 2003). Several design exception related research topics were identified, including (Mason & Mahoney, 2003):

- Actual benefits – evaluate the benefits of preparing design exceptions;
- Tort liability – evaluate the magnitude of claims, plaintiff and defendant legal doctrines, awards and settlement amounts, and agency risk factors;
- Analytic techniques – develop practitioner guidance for evaluating the safety implications of design exceptions; and
- Mitigation – provide guidance on mitigation measures for various design criteria.

Tort liability, as discussed by Martin (1994), is a legal issue for state DOTs that do not have sovereign immunity from being sued for civil wrong or injury to person or property due to negligence. Negligence in design is often considered to have occurred when design standards are not met, the design is considered to be flawed, or the road segment in question is known to have had safety issues for which nothing has been done to correct the issues. In the case of design exceptions, jurors in a court will likely view the existence of a design exception as negligence on the part of the DOT unless it can be shown that the existence of a design exception does not, by virtue of its existence, mean that the road segment in question will be less safe than if the minimum design standards are met.

The objective of this research is to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed. The project will use data from the State of Utah. A study that looks at the safety effects of design exceptions in this way would have the following expected benefits that overlap each of the research needs identified above:

- Provide insights into the effectiveness of UDOT's current design exception preparation and approval process;
- Create additional documentation, as recommended by Martin (1994) and outlined by Mason & Mahoney (2003), that includes an evaluation of the designs resulting from the design exceptions; and
- Outline a methodology for other states to reference when conducting similar safety evaluations of design exceptions.

2.2 Literature Review

Little is known about the safety impacts of design exceptions. Stamatiadis et al. (2005) gathered data for 562 design exceptions on 319 projects in Kentucky completed between 1993 and 2000 (average 1.8 design exceptions per project). The majority of projects were bridge replacements (57%), followed by roadway widening (13%), and turning lane additions (9%). The data included exceptions to the 13 controlling criteria as well as to several supplemental criteria used in Kentucky (e.g., ditch width, number of lanes, access spacing, guardrail end treatment). The most frequent exception was for using a design speed that was lower than the posted speed limit (34%), followed by exceptions to minimum sight distance (12%), minimum curve radius (12%), and shoulder width (11%).

A safety analysis was conducted using data from 86 of the 319 sites. Two types of study designs were used to investigate the safety effects of design exceptions: 1) a naive before-after study design where safety "after" the project with one or more design exceptions was compared to safety "before" the project;

and 2) a cross-sectional study design where safety “after” the project with one or more design exceptions was compared to the statewide “average safety” for similar facility types.

A comparison of crash rates was the only analysis method used in both the before-after and cross sectional studies. The conclusions indicated that the use of design exceptions in Kentucky did not result in a higher crash rate than the statewide average for similar facility types and that projects constructed with design exceptions resulted in an improvement over the “before” condition at those locations. The study design and the use of crash rates were the most significant analytical limitations of the study. The naive before-after study assumed that nothing changed from “before” to “after” periods other than traffic volumes and the implementation of a design exception. The cross-sectional evaluation assumed nothing was different between locations with and without design exceptions other than traffic volume and the design exception. Finally, the use of crash rates can lead to incorrect conclusions about safety. Crash rates assume a linear relationship between traffic volumes and crashes. This is often not the case; Hauer (1997) provides additional detail.

Malyshkina & Mannering (2010) assessed the impacts of design exceptions on both the frequency and severity of vehicle crashes using data from Indiana. They collected data at 48 locations with exceptions to “level-one” design criteria (35 on bridges and 13 on road segments) and at 98 similar locations without design exceptions. Standard multinomial logit models and mixed multinomial logit models were used to analyze crash severity. Standard negative binomial models and a random parameter negative binomial model were used to analyze crash frequency. Five years of crash data were used for model estimation. Parameter significance in the logit models, in addition to the results of a likelihood ratio test of models estimated at design-exception sites and non-design-exception sites, suggested that design exceptions do not have a statistically significant impact on crash severity. Parameter significance in the negative binomial models suggested that design exceptions do not have an effect on expected crash frequency. However, a likelihood ratio test of models estimated at design-exception sites and non-design-exception sites indicated a different crash generating process. The need for more data to explore this finding in greater detail was noted.

The results of this study indicated that the current design exception process in Indiana was adequate to avoid adverse safety impacts resulting from design exceptions. Model results showed that design exceptions granted in Indiana between 1998 and 2003 had no adverse effect on safety. The authors recognized that the number of design exceptions used in their study was too small to make broad generalizations about design exception policy. The study served as a key reference to the study design and analysis approach described in this report.

There is a large body of research on the relationships between road geometric design and safety that have resulted in CMFs for geometric features. A review of these studies was conducted to determine what was known about the relationships between the 13 controlling criteria and safety. Four resources were used: the AASHTO *Highway Safety Manual* (AASHTO 2010), *Roadway Safety Design Synthesis* (Bonneson et al. 2005), *Roadway Safety Design Workbook* (Bonneson & Pratt 2009), and FHWA’s *Crash Modification Factors Clearinghouse* (FHWA, www.cmfclearinghouse.org). Findings of this review are summarized in Table 2.1. The table illustrates whether or not there are documented relationships between the 13 controlling criteria and crash frequency, crash severity, and crash type. Findings are disaggregated by area type and facility type.

Some researchers have suggested that results of studies such as those behind Table 2.1, with corresponding CMFs, can be used to assess the safety effects of design exceptions (Lord & Bonneson 2006). However, the studies leading to these CMFs tend to use data from a broad sample of road segments that may or may not have design exceptions and that are intended to be a randomly selected sample of the road segment population. Estimating the safety effects of design exceptions from these models may be misleading, as locations with design exceptions are likely to have systematic differences from locations without design exceptions. In other words, “roadway segments that are granted design exceptions are likely to be a non-random sample of the roadway segment population…” (Malyshkina & Mannering 2010). This study is intended to address this limitation by directly estimating the difference between the safety of a location with one or more design exceptions and the predicted safety of that same location without a design exception.

Table 2.1 Controlling Criteria Safety References

No.	Design Criteria	Safety Information				
		Rural			Urban	
		Freeways	Multilane highways	Two-lane highways	Freeways	Arterials
1	Design speed [a]	FR[1,2]; SV[2]	FR[1,4]	FR[1,4]; SV[1]	FR[1,2]; SV[1,2]	FR[1,4]
2	Horizontal alignment	FR[1]; FR[2]	FR[1,2]; SV[2]	FR[1,2,3]; SV[2]	FR[1,2]	FR[2];SV[2]
3	Superelevation		FR[1]	FR[1,2,3]; SV[2]		
4	Grade	FR[1,2]; SV[2]	FR[1,2]; SV[2]	FR[1,2,3]; SV[2]	FR[1,2]; SV[2]	FR[1]
5	Vertical clearance					
6	Vertical alignment	FR[4]; SV[4]	FR[4]; SV[4]	FR[4]; SV[4]	FR[4]; SV[4]	FR[4]; SV[4]
7	Stopping sight distance					
8	Travel lane width	FR[1,2], SV[1,2]; TY[1]	FR[1,2,3]; TY[1,3]; SV[2]	FR[1,2,3]; TY[1,3]; SV[1,2]	FR[1,2,3], TY[1]; SV[2,3]	FR[2,3]; SV[2]
9	Cross slope					
10	Shoulder width	FR[1,2,4]; SV[1,2]; TY[1]	FR[1,2,3,4]; TY[1,3]; SV[2]	FR[1,2,3,4]; SV[1,2]; TY[1,3];	FR[1,2,4]; SV[1,2]; TY[1]	FR[2,4]; SV[2]
11	Horizontal clearance to obstructions	FR[1,2,3]; TY[1]; SV[2]	FR[1,2]; TY[1]; SV[2]	FR[1,2,3];TY[1]; SV[2]	FR[1,2]; TY[1]; SV[2]	FR[2,3]; SV[2]; TY[3]
12	Bridge width	FR[4]	FR[1,4]; TY[1]	FR[1,4]; TY[1]	FR[4]	FR[4]
13	Structural capacity					

[a] Posted speed is used as a surrogate for design speed in the cited models. Actual operating speeds likely differ from both design speed and posted speed.
FR[i, j, k] = documented effect between design criteria and crash frequency in references i, j, and k
SV[i, j, k] = documented effect between design criteria and crash severity in references i, j, and k
TY[i, j, k] = documented effect between design criteria and crash type in references i, j, and k
References: 1 = *Road Safety Design Synthesis* (Bonneson et al., 2005); 2 = *Road Safety Design Workbook* (Bonneson & Pratt, 2009); 3 = *Highway Safety Manual* (AASHTO, 2010); 4 = CMF Clearinghouse (FHWA, www.cmfclearinghouse.org)

3. RESEARCH METHODS

3.1 Overview

The objective of this research is to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed. This chapter includes a description of the methods used to achieve the research objective. The approach used, which compares expected crash frequency on road segments with and without design exceptions, is described in Section 3.2. Three different methodological alternatives used to compare expected crash severity on road segments with and without design exceptions are included in Section 3.3.

3.2 Design Exception Effects on Expected Crash Frequency

The relationship between design exception presence and crash frequency was explored in this study using a negative binomial regression modeling approach. The use of Poisson regression to model the relationships between crash frequency, traffic volumes, and weather conditions was introduced by Jovanis & Chang (1986). Negative binomial regression, a more general form of Poisson regression, was later used to explore the relationship between crash frequencies, daily traffic, and highway geometric design variables (Miaou 1994). In the negative binomial model, the expected number of crashes of type *i* on segment *j* is expressed as:

$$\mu_{ij} = E(Y_{ij}) = \exp(X_j\beta + \ln L_j)$$

where:

$\mu_{ij} = E(Y_{ij})$ = the expected number of crashes of type *i* on segment *j*;

X_j = a set of traffic and geometric variables characterizing segment *j*;

β= regression coefficients estimated with maximum likelihood that quantify the relationship between $E(Y_{ij})$ and variables in X;

L_j = length of segment *j*; and,

$\ln L_j$ = the natural logarithm of segment length.

The mean-variance relationship of the negative binomial regression model is expressed as:

$$VAR(Y_{ij}) = E(Y_{ij}) + \alpha[E(Y_{ij})]^2$$

where:

$E(Y_{ij})$ = the expected number of crashes of type *i* on segment *j*;

$VAR(Y_{ij})$ = variance of of crashes of type *i* on segment *j*; and

α = overdispersion parameter.

The data are over-dispersed if α is greater than zero and under-dispersed if α is less than zero. The negative binomial model reduces to the Poisson model if α equals zero.

The presence of one or more design exceptions, coded as an indicator variable (1 = one or more design exceptions; 0 = no design exceptions), was the primary variable of interest in the matrix of explanatory variables, X_j. However, a number of other traffic and geometric variables were included in model specifications to decrease unexplained variation in expected crash frequency and to try and minimize omitted variable bias. Omitted variable bias would result in the model over- or under-estimating the safety effects of design exceptions due to other variables that influence crash frequency and are correlated with design exception presence, but are excluded from the model.

Segment length, L, was included in the models as an offset variable (i.e., the regression coefficient for the natural logarithm of segment length was constrained to 1.0), and captures the linear increase in expected crash frequency with an increase in segment length due to increased exposure. Model fit was evaluated using the McFadden Pseudo R-Squared. The McFadden Pseudo R-Squared (ρ^2) is analogous to the R-squared value used to express the goodness of fit of a standard, ordinary least squares regression model. It is expressed as:

$$\rho^2 = 1 - \frac{L(full)}{L(0)}$$

where:

ρ^2 = McFadden Pseudo R-Squared;

L(*full*) = log-likelihood of the model with explanatory variables; and,

L(0) = log-likelihood of the intercept-only model.

The McFadden Pseudo R-Squared may take a value between 0 and 1; the value moves closer to 1 as model fit improves. Negative binomial regression models were estimated separately for “total” crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes.

3.3 Design Exception Effects on Expected Crash Severity

The relationship between design exception presence and crash severity was explored in three ways: 1) computing severity distributions at locations with and without design exceptions, 2) estimating separate negative binomial regression models by severity level, and 3) estimating multinomial logit models. The first two approaches are currently used in the predictive methods of the *Highway Safety Manual* (AASHTO 2010). “Default” severity distributions (i.e., alternative method 1 above) are applied to the total crash prediction in Chapter 10 of the *Highway Safety Manual* (rural, two-lane). Chapter 11 of the *Highway Safety Manual* (rural, multilane) includes separate regression equations to independently predict the average crash frequency for total (KABCO) crashes, fatal-plus-injury (KABC) crashes, and fatal-plus-injury-without-possible-injury (KAB) crashes (i.e., alternative method 2 above). The *Highway Safety Manual*, Chapter 11 method itself does not predict PDO crashes.

The predictive method in Chapter 12 of the *Highway Safety Manual* (urban/suburban) requires that three SPFs be applied independently to predict average crash frequencies for total (KABCO), fatal-plus-injury (KABC), and property damage only (O) crashes. The sum of fatal-plus-injury crashes and property-damage-only crashes do not add up to equal the total crashes since the SPFs were independently estimated, so the following adjustments are made to the fatal-plus-injury and property-damage-only predictions:

$$KABC(new) = KABCO\left(\frac{KABC}{KABC+O}\right)$$

$$O(new) = KABCO - KABC(new)$$

Modeling crash severity is important to understanding the safety effects of design exceptions. Severity distributions may change significantly with traffic volume. Design decisions may also influence severity distributions, through a resulting increase or decrease in operating speeds (e.g., an increase or decrease in lane and shoulder widths). Severity distributions are likely to vary differently with traffic volumes and design decisions. Computing "default" severity distributions with and without design exceptions may not capture these complexities. Estimating separate negative binomial regression models by severity level may also have limitations. Milton et al. (2008) suggested that a series of crash frequency models, developed for each level of severity, "can introduce significant estimation errors in that it implicitly assumes that the factors generating the occurrence of an accident are independent across severity outcomes."

Estimating a "severity distribution function" using logit models is one possible alternative to address these issues. The logit models produce the probabilities (or proportions) of crash severity outcomes as a function of traffic volume, geometry, and other road characteristics, including the presence of one or more design exceptions. The multinomial logit (Shankar & Mannering 1996), nested logit (Shankar et al. 1996), and ordered outcome models (Khattak et al. 1998) are possible model alternatives. The databases used to estimate the severity models consist of the same crashes and road segments as the frequency model databases, but are restructured so that the basic observation unit (i.e., database row) is the crash instead of the road segment. A body of published research exists on the application of discrete choice models to explore crash severity, but their application in applied safety research and in practice (e.g., the *Highway Safety Manual*) is relatively limited.

The multinomial logit model is a widely used discrete choice model. It was used as the third alternative in this research to model crash severity, resulting in a severity distribution function. The presence of one or more design exceptions was again coded as an indicator variable (1 = one or more design exceptions; 0 = no design exceptions) in the utility function for each severity category. This alternative addressed the limitations of the frequency-based approaches identified in the preceding discussion. In the multinomial logit model, the probability that accident n will have severity i [$p_n(i)$] is given by

$$p_n(i)=\exp(\beta_i X_n)/\sum_I \exp(\beta_I X_n)$$

where X_n is a set of variables that will determine the crash severity and, β_i is a vector of parameters to be estimated. Utility functions are defined for the severity likelihoods as

$$S_{in} = \beta_i X_n + \varepsilon_{in}$$

where ε_{in} is a set of error terms that account for unobserved variables. The error terms for each choice should follow independent extreme value distributions (also called Gumbel or type I extreme value). The key assumption is that the errors are independent of each other. This independence means that the unobserved portion of utility for one severity alternative is unrelated to the unobserved portion of utility for another severity alternative. If the unobserved portion of utility is correlated over alternatives, then there are three options: (1) use a different model that allows for correlated errors, such as nested logit or mixed logit model, (2) re-specify the representative utility so that the source of the correlation is captured explicitly and thus the remaining errors are independent, or (3) use the logit model under the current specification of representative utility, considering the model to be an approximation.

The likelihood ratio index is used to assess the goodness of fit of the logit model. It measures how well the model, with its estimated parameters, performs compared with a model in which all the parameters except for the constant are zero (which is usually equivalent to having no model at all). The likelihood ratio index is defined as

$$\rho = 1 - \frac{LL(\beta)}{LL(0)}$$

Where LL (β) is the value of the log-likelihood function at the estimated parameters and LL(0) is its value when all the parameters are set equal to zero.

3.4 Summary

This section described the research methods used to study the effects of design exceptions on expected crash frequency and severity. The relationship between design exception presence and crash frequency will be explored using a negative binomial regression modeling approach. The relationship between design exception presence and crash severity will be explored in three ways: 1) computing severity distributions at locations with and without design exceptions, 2) estimating separate negative binomial regression models by severity level, and 3) estimating multinomial logit models. Design exception presence will be represented in the regression models by an indicator variable (1 = one or more design exceptions; 0 = no design exceptions). Other traffic and geometric variables will be included in the negative binomial regression models and multinomial logit models to minimize the chances of the models over- or under-estimating the safety effects of design exceptions. Data used for model estimation are described in Section 4.

4. DATA COLLECTION

4.1 Overview

This section provides an overview of all data collection efforts undertaken in this study. The data sources and data collection procedures are described in Section 4.2. Variable descriptions, quality control steps, and descriptive statistics for the “treatment” and “comparison” sites are also included in Section 4.2. Section 4.3 summarizes the background, methodology, and results of an assessment of the treatment group and comparison group similarity using propensity scores. Section 4.4 describes the crash data used for analysis.

4.2 Data Sources and Collection

Data were collected for design exceptions granted in the state of Utah in the years 2001 through 2006. Design exception request and approval forms were obtained from UDOT. Project numbers, PIN numbers, approval dates, routes, project locations (e.g., start and end mile post for the project), pavement types, pavement widths, right-of-way widths, clear zone distances, design exception elements, and mitigation information were obtained for each of the design exception locations from the forms.

UDOT assisted the research team with updating the mileposts on the design exception and approval forms to be consistent with milepost referencing in the crash data used for this project. UDOT also converted other location descriptions (e.g., a qualitative description of an intersection) to mileposts in the cases where milepost numbers were not directly used to define project boundaries. UDOT’s PDBS was used to find the start and end mileposts for the project as recorded by the RE on the project. If no milepost data was recorded in PDBS, a business analyst was contacted to help locate the originally advertised project plans. The coversheet of the advertised project plan showed the start and end milepost for each project. Milepost data was then taken to the crash studies supervisor to validate that the milepost recorded by the RE at the time the project was constructed was consistent with milepost referencing in the crash data used for this project. As a final check, the project locations and mileposts were checked in Google Earth to make sure that they made sense by comparing them with the location descriptions in the project files. PDBS was used to find the date the project was “substantially complete.” In the event that no substantially complete date was available, the “final acceptance date” was provided. In all cases, the project was completed prior to the data analysis years. PDBS was also used to verify the Project and PIN numbers collected from the original design exception data. If a Project or PIN was invalid, PDBS was used to locate the valid or updated number. In the event a valid number could not be located, it was concluded that the project was never constructed.

Other data were collected using Google Earth, Google Street View, UDOT functional classification maps, and UDOT Traffic Data. This data included information on area type (i.e., urban or rural), number of horizontal curves within the project boundaries, number of through lanes, presence and type of auxiliary lanes, and the number of intersections or interchanges within the project boundaries. Functional classification and daily traffic volumes for the years 2006 through 2008 were also obtained. A full description of all variables that were collected, coded, and considered in the model specifications are shown in Table 4.1.

Table 4.1 Variable Descriptions

Variable Notation	Variable Description
No.	Site number
Pin	Project PIN (assigned by UDOT)
Route	Route number
Start_MP	Beginning milepost of segment
End_MP	Ending milepost of segment
Type	Site type: segment, bridge, intersection, or interchange (only road segments used for this study)
Length	Segment length (miles)
LN_LEN	Natural logarithm of Length
AVE_AADT	Average AADT for years 2006 through 2008
LN_AADT	Natural logarithm of AVE_AADT
DE	Indicator variable for design exception presence (1=one or more approved and constructed design exceptions on segment; 0=no design exceptions on segment)
Non_FW	Indicator variable for facility type (1=non-freeway segment, 0=freeway segment)
TOT_KABCO	Total crashes on road segment in years 2006 through 2008 (all types and severities)
TOT_KABC	Crashes on road segment in years 2006 through 2008 resulting in at least one fatality or injury (any injury level)
TOT_K	Crashes on road segment in years 2006 through 2008 resulting in at least one fatality
TOT_O	Crashes on road segment in years 2006 through 2008 resulting in property damage only (i.e., no injuries)
Thru_Lanes	Total number of through lanes
TWO_TL	Indicator variable for number of through lanes (1=segment has two through lanes; 0=otherwise)
FOUR_TL	Indicator variable for number of through lanes (1=segment has four through lanes; 0=otherwise)
SIX_TL	Indicator variable for number of through lanes (1=segment has six through lanes; 0=otherwise)
EIGHT_TL	Indicator variable for number of through lanes (1=segment has eight through lanes; 0=otherwise)
NINE_TL	Indicator variable for number of through lanes (1=segment has nine through lanes; 0=otherwise)
TEN_TL	Indicator variable for number of through lanes (1=segment has ten through lanes; 0=otherwise)
SIX_TEN_TL	Indicator variable for number of through lanes (1=segment has six, eight, or ten through lanes; 0=otherwise)
EIGHT_TEN_TL	Indicator variable for number of through lanes (1=segment has eight or ten through lanes; 0=otherwise)
Aux_Lanes	Total number of auxiliary lanes present
Divided	Indicator variable for median presence (1=segment is divided, 0=segment is undivided

Table 4.1 Variable Descriptions (continued)

Trav_Div	Indicator variable for median type (1=segment has a traversable median; 0=otherwise)
2WLT	Indicator variable for presence of two-way-left-turn-lane (1=segment has two-way-left-turn-lane; 0=otherwise)
HC	Number of horizontal curves on segment
HC_MILE	Number of horizontal curves per mile on segment
Rural	Indicator variable for area type, defined by the location urban boundaries (1=rural; 0=urban)
Non_FW_INTS	Number of at-grade intersections on non-freeway segment (Non-FW_INTS = 0 if segment is a freeway)
FW_INTC	Number of interchanges on freeway segment (FW_INTC = 0 if segment is not a freeway)
Non_FW_INTS_M	Number of at-grade intersections per mile on non-freeway segment (Non_FW_INTS_M = 0 if segment is a freeway)
FW_INTC_M	Number of interchanges per mile on freeway segment (FW_INTC_M = 0 if segment is not a freeway)

Data for a total of 63 projects (48 on road segments, four on bridges, eight at intersections, and three at interchanges) that were built with design exceptions between 2001 and 2006 were collected. Due to the small samples of bridge, intersection, and interchange projects, only data collected for the road segment projects were used in this study. Design exceptions for structural capacity or bridge width were not explored. Two design exceptions for vertical clearance were included in the data. Crashes on the roadway passing underneath the bridge were modeled. The distribution of design exceptions across the 48 road segment projects used in this study is shown in Table 4.2. There was an average of 1.77 design exceptions per road segment project with a maximum of five design exceptions and minimum of one design exception.

Table 4.2 Design Exception Frequencies

Criteria	Count	Criteria	Count
Design Speed	3	Cross Slope	6
Lane Width	7	Stopping Sight Distance	7
Shoulder Width	24	Structural Capacity	0
Superelevation	7	Bridge Width	0
Horizontal Alignment	8	Vertical Clearance	2
Vertical Alignment	9	Horizontal Clearance	7
Grade	6	Total Exceptions	86

Google Earth, Google Street View, UDOT functional classification maps, and UDOT traffic volume data were also used to identify and define road segments without design exceptions. These road segments made up the comparison group. The comparison group was carefully built to include locations that were similar to the locations with design exceptions (i.e., the treatment group). The exact location(s) of the design exception(s) within the project boundaries was determined, when possible. In these cases, segments with design exceptions were defined as beginning one-half mile "before" the location of the exception and ending one-half mile "after" the exception. The comparison segments were then also defined, when possible, within the project boundaries at locations without any design exceptions. This was done to maximize similarity between the treatment and comparison segments and ensure that the comparison locations did not include design exceptions (otherwise, they would be identified in the project documents). When this approach was not possible, the entire project was defined as the design exception segment. Locations along the same route and in near proximity to the project segment were then searched for possible comparison segments. Other areas were searched for similar road segments without design exceptions as a second alternative when additional sites were needed.

For each treatment location, at least two comparison locations with the same area type classification, functional classification, number of through lanes, number and type of auxiliary lanes, and similar traffic volumes were defined. Data on any remaining variables that were defined for the treatment sites were then collected using Google Earth and Google Street View, including number of horizontal curves within the project boundaries, number of through lanes, presence and type of auxiliary lanes, and the number of intersections or interchanges within the segment boundaries.

Initially, 91 comparison segments were defined: two comparison locations for most design exception locations (two comparison locations were not available for urban freeway projects). Propensity scores were then used to assess the adequacy of the comparison site selection process. This process is described in greater detail in Section 4.3. The propensity score analysis resulted in the research team defining 43 more comparison locations in an attempt to have a group of comparison segments with propensity scores comparable to the group of road segments with design exceptions. A final logistic regression was performed and final propensity scores were calculated and analyzed. Ultimately, a total of 132 comparison segments were used for modeling. The descriptive statistics for the treatment locations and comparison locations are shown in Table 4.3 and Table 4.4, respectively. A map showing the locations of the design exception segments and comparison segments is shown in Figure 4.1.

Table 4.3 Descriptive Statistics for Design Exception Locations (n = 48)

Variable	Mean	Standard Deviation	Minimum	Maximum
Length	5.47	5.90	0.101	23.77
AVE_AADT	23,121	40,177	182	188,689
Thru_Lanes	3.52	2.16	2	9
Aux_Lanes	0.58	0.74	0	2
Divided	0.60	0.49	0	1
Trav_Div	0.40	0.49	0	1
2WLT	0.15	0.36	0	1
Rural	0.67	0.48	0	1
TOT_KABCO	318	1,088	0	6,501
TOT_KABC	74.7	238	0	1,318
TOT_K	0.92	1.65	0	9
TOT_O	243	852	0	5,183
Non_FW	0.708	0.46	0	1
Non_FW_INTS	3.79	4.61	0	18
FW_INTC	0.98	2.52	0	14
HC	13.90	37.38	0	239
HC_MILE	2.27	3.83	0	19.01
Non_FW_INTS_M	2.99	4.13	0	15.38
FW_INTC_M	0.15	0.33	0	1.53

Table 4.4 Descriptive Statistics for Comparison Locations (n = 132)

Variable	Mean	Standard Deviation	Minimum	Maximum
Length	4.53	5.85	0.1	32.99
AVE_AADT	27,260	30,067	41.67	117,748
Thru_Lanes	3.91	1.99	2	10
Aux_Lanes	0.46	0.67	0	3
Divided	0.68	0.47	0	1
Trav_Div	0.36	0.48	0	1
2WLT	0.20	0.40	0	1
Rural	0.54	0.50	0	1
TOT_KABCO	148	430	0	4,609
TOT_KABC	40.2	117	0	1,248
TOT_K	0.82	1.78	0	15
TOT_O	108	314	0	3,361
Non_FW	0.61	0.49	0	1
Non_FW_INTS	2.97	4.48	0	31
FW_INTC	1.22	3.39	0	29
HC	7.60	17.12	0	162
HC_MILE	1.50	1.55	0	8.69
Non_FW_INTS_M	2.38	3.83	0	18.75
FW_INTC_M	0.43	0.9	0	4.52

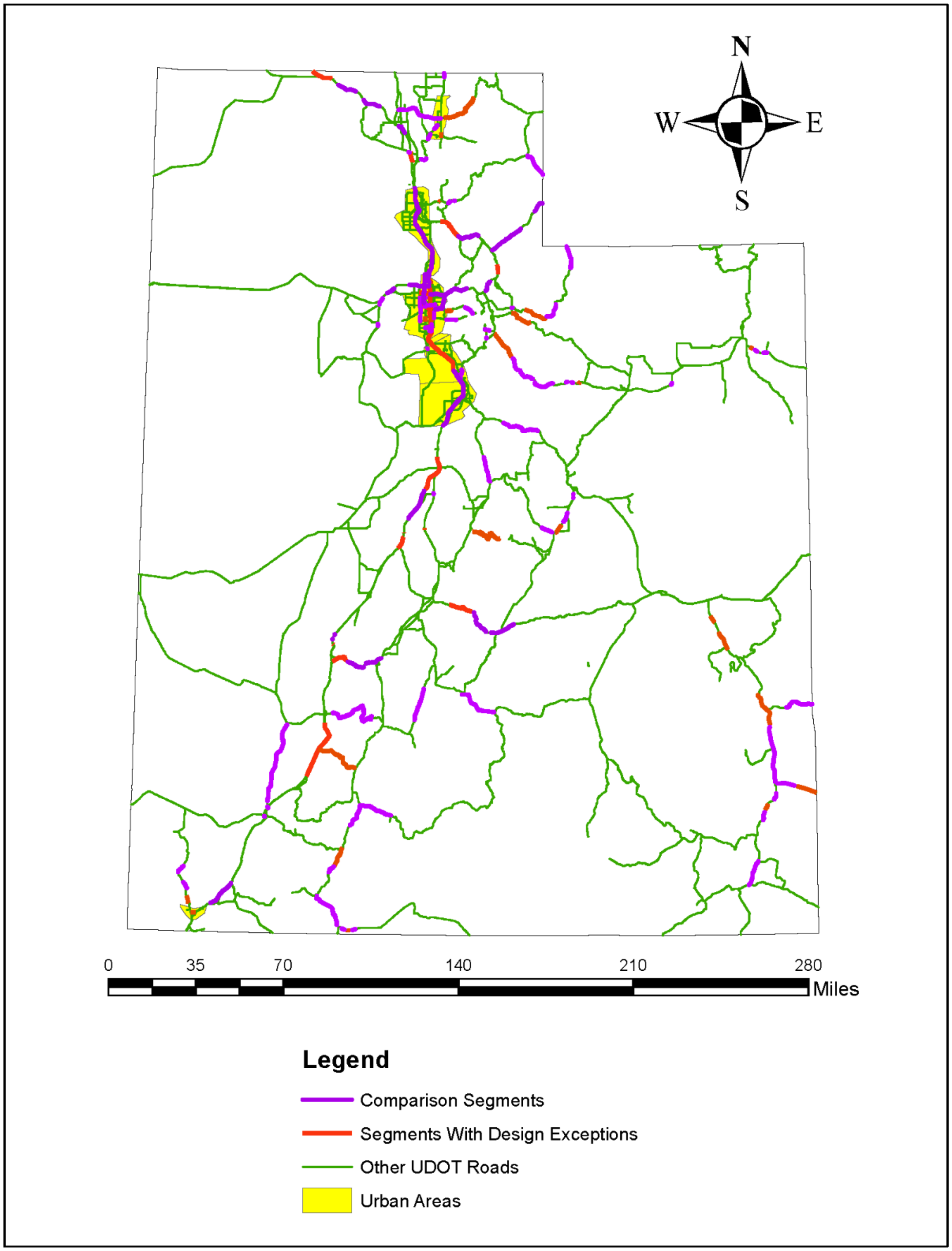

Figure 4.1 Map of Treatment and Comparison Locations

4.3 Assessing Comparison Sites with Propensity Scores

Most road safety studies, including this one, are observational studies (Hauer, 1997). "Treated locations" (i.e., locations with design exceptions in this case) and "untreated locations" (i.e., locations without design exceptions) are not determined at random in observational studies like they are in experiments. This characteristic of observational studies may introduce "selection bias" into model parameter estimates due to initial differences in the characteristics between units that receive a treatment and units that do not. Detected differences between treatment and comparison units that are uncovered during data analysis may reflect these initial differences and may not be the result of the treatment itself (Rosenbaum, 2005). Potential strategies to "adjust" for this selection bias have been proposed (see, for example, the discussion in Rosenbaum [2005]).

Propensity scores were used in this study to assess the selection of comparison sites (i.e., sites without design exceptions) and minimize selection bias. Propensity score analysis is used in observational studies conducted in the fields of epidemiology, medicine, economics, financing, education, and the social sciences (Sheyang & Fraser 2010). A propensity score is essentially the statistical probability that an observation did or did not receive a treatment. Binary logistic regression was used to model the chance of a design exception given the characteristics of a road segment. The model is then used to compute the probability of a design exception given a set of road characteristics. Similar probabilities between treatment and comparison groups are the goal; it is intended to mimic "covariate balance" achieved in experiments due to randomization. Cochran (1968) suggested this approach could reduce the bias in observational study results by more than 90%.

Propensity scores were initially analyzed for the 48 treatment sites with 91 comparison sites. Data used for model estimation were disaggregated into two datasets by facility type: freeway or non-freeway. Results indicated a need for additional comparison sites to improve "covariate balance." Forty-one additional comparison segments were then defined and included in the data set, resulting in 48 treatment sites and 132 comparison locations. Only the final results of the propensity score analysis are described in this report. The numbers of sites by facility type are shown in Table 4.5. Estimation results for the binary logistic regression models used to compute the propensity scores for freeways and non-freeways are provided in Table 4.6 and Table 4.7, respectively.

Table 4.6 Number of Sites by Facility Type

Facility Type	Design Exception Locations		Comparison Locations	
	Count	%	Count	%
Urban Freeway	6	13%	32	24%
Urban Major Arterial	4	8%	16	12%
Urban Minor Arterial	6	13%	8	6%
Urban Collector	0	0%	0	0%
Rural Freeway	8	17%	18	14%
Rural Major Arterial	11	23%	33	25%
Rural Minor Arterial	8	17%	12	9%
Rural Collector	5	10%	13	10%
Total	48	100%	132	100%

Table 4.7 Estimation Results for Binary Logistic Regression: Freeways

Number of Observations = 64						
LR Chi2(6) = 44.36						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.6503						
Log Likelihood = -11.927743						
Variable	Coefficient	Std. Error	z	P>|z|	[95% Confidence Interval]	
LN_AADT	2.89	1.91	1.51	0.13	-0.852	6.65
HC_Mile	9.13	3.50	2.61	0.009	2.27	16.00
FW_INTC_M	-11.74	4.16	-2.82	0.005	-19.90	-3.59
Thru_Lanes	0.987	0.71	1.38	0.168	-0.416	2.39
Rural	6.96	4.15	1.68	0.093	-1.17	15.11
Trav_Div	1.24	2.15	0.58	0.565	-2.98	5.46
Constant	-40.03	21.54	-1.86	0.063	-82.25	2.18

Table 4.8 Estimation Results for Binary Logistic Regression: Non-Freeways

Number of Observations = 114						
LR Chi2(5) = 8.91						
Prob > Chi2 = 0.1128						
Pseudo R2 = 0.0641						
Log Likelihood = -65.014652						
Variable	Coefficient	Std. Error	z	P>|z|	[95% Confidence Interval]	
LN_AADT	0.109	0.248	0.44	0.659	-0.377	0.597
HC_Mile	0.154	0.080	1.91	0.056	-0.003	0.312
Trav_Div	-0.591	0.605	-0.98	0.329	-1.77	0.594
Aux_Lanes	0.770	0.423	1.82	0.069	-0.060	1.60
Thru_Lanes	-0.186	0.241	-0.78	0.438	-0.659	0.285
Constant	-1.84	1.75	-1.05	0.295	-5.29	1.60

Propensity scores, defined for this study as the probability of a road segment having a design exception given a set of segment characteristics, were computed using the models in Table 4.6 and Table 4.7. The results of the propensity score analysis for freeways and non-freeways are shown in Figure 4.2 and Figure 4.3, respectively. For the freeway segments, there was a significant difference in the propensity scores for treatment and comparison segments (see Figure 4.2). The freeway segments in the treatment and comparison groups covered all of the urban freeways in Utah and some rural freeway segments. Due to a lack of additional freeway segments to choose from in urban areas, nothing additional could be done to balance out the propensity scores for the freeway segments. This means that there may be selection bias issues for freeway segments (i.e., freeway segments with design exceptions are inherently different than freeway segments without design exceptions in terms of the covariates specified in Table 4.6). Interpretations of the freeway results should consider these differences in propensity scores (see Park & Saccomanno [2007]) for related discussion]. The plot of propensity scores for the non-freeway segments, provided in Figure 4.3, shows that the propensity scores between treatment and comparison sites were well-balanced. The balance was checked using the stratification procedure described by Caliendo & Kopeing (2008). Results indicate that the possibility of selection bias in the non-freeway models is low.

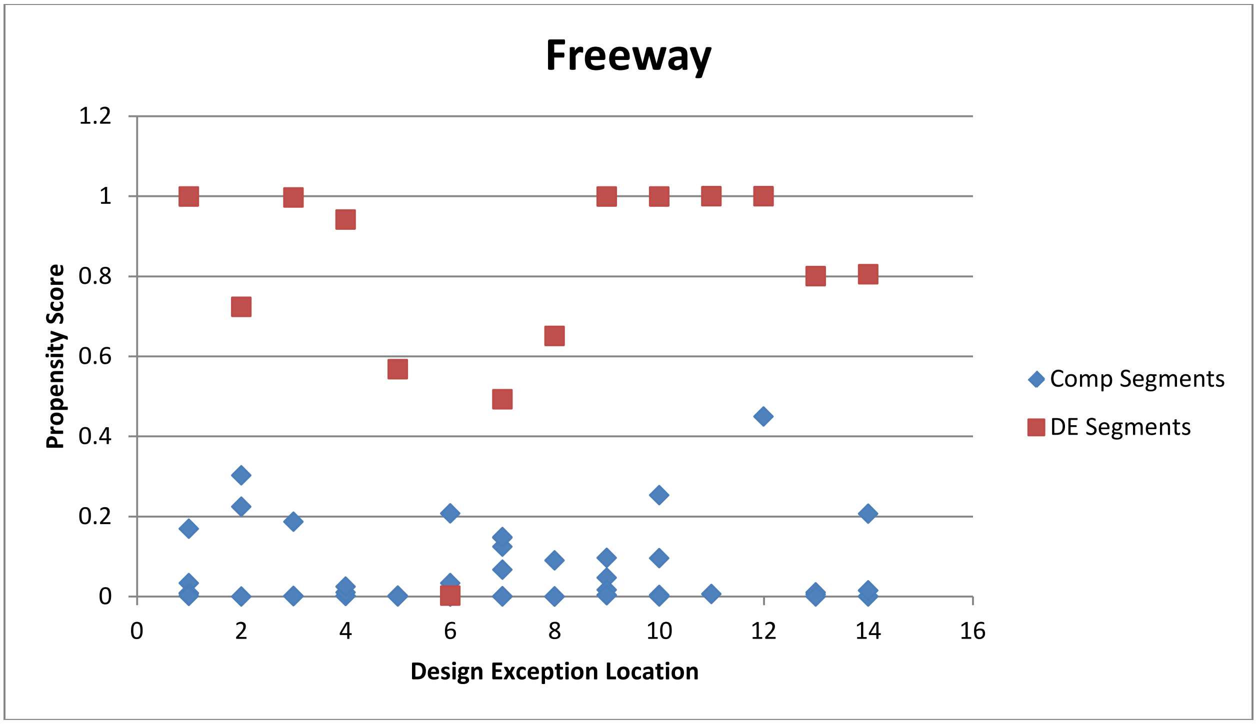

Figure 4.2 Propensity Scores: Freeways

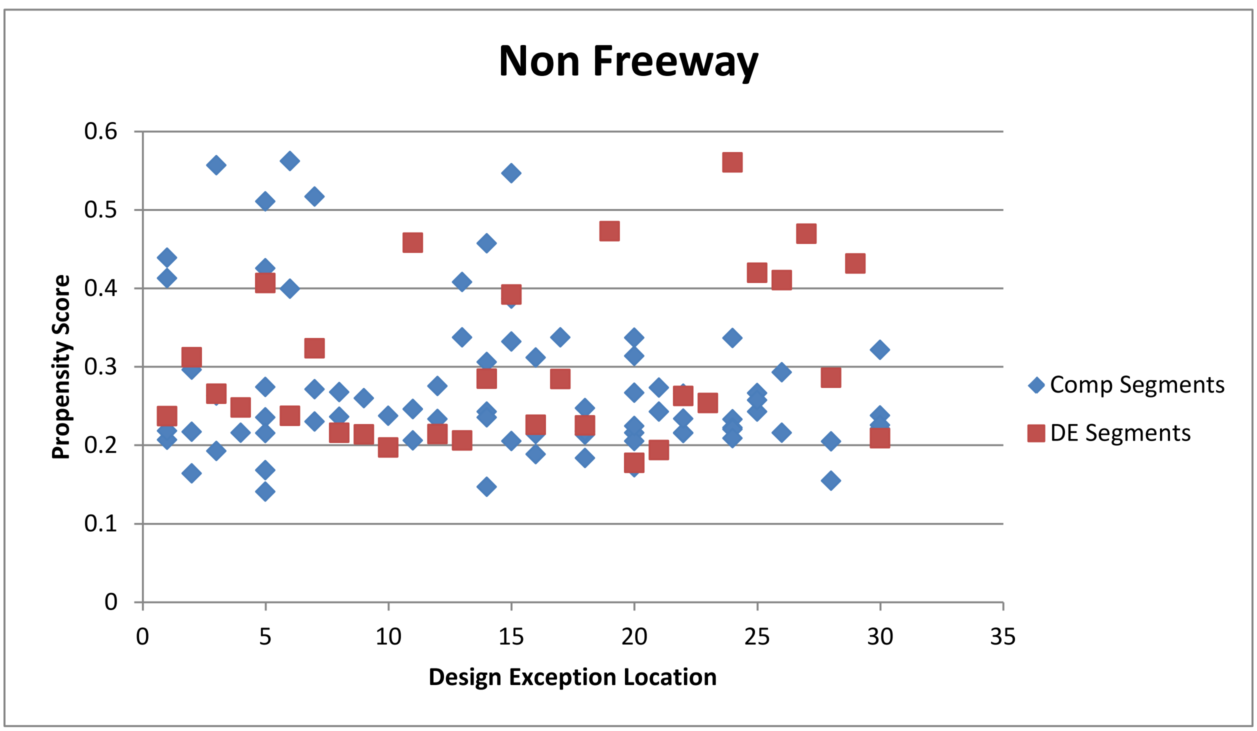

Figure 4.3 Propensity Scores: Non-Freeways

4.4 Crash Data

Crash data from the years 2006 through 2008 were obtained from UDOT and used for analysis. Crash, vehicle, and occupant files were provided. Crash location, defined by route and milepost, and crash severity were the primary variables of interest for this study. Crash severity was defined as the most severe injury sustained by any occupant involved the crash on the KABCO scale, where K = fatality, A = incapacitating injury, B = non-incapacitating injury, C = possible injury, and O = no injury (i.e., property damage only). Variable definitions and descriptive statistics related to the crash data are provided in Table 4.1, Table 4.3, and Table 4.4. The total numbers of crashes available for model estimation were:

- 34,828 crashes for the crash frequency models for all types and severities (KABCO) and the severity models of the KABCO crashes;
- 8,892 crashes for the fatal-plus-injury crash frequency models (KABC) and severity models of KABC crashes; and
- 25,936 crashes for the non-injury (property damage only) crash frequency models (O).

4.5 Summary

This section described data used to estimate the safety impacts of design exceptions. Data were collected for design exceptions granted in the state of Utah in the years 2001 through 2006. Design exception request and approval forms, Google Earth, Google Street View, UDOT functional classification maps, and UDOT traffic volume data were used to identify and define road segments with and without design exceptions. Ultimately, a total of 48 segments with design exceptions and 132 segments without design exceptions were used for analysis. Propensity scores were used in this study to assess the selection of comparison sites (i.e., sites without design exceptions) and minimize selection bias. The propensity scores showed that there were significant differences in the propensity scores for treatment and comparison segments on freeways. Nothing could be done to balance the propensity scores due to a lack of additional urban freeway segments to choose from. Propensity scores for the non-freeway segments showed that the propensity scores between treatment and comparison sites were well balanced. Crash data from the years 2006 through 2008 were obtained from UDOT and used for analysis.

5. DATA ANALYSIS

5.1 Overview

This section includes modeling results and interpretations related to the safety impacts of design exceptions. Design exception effects on expected crash frequency are quantified and described in Section 5.2. Design exception effects on crash severity, estimated using three alternative methodologies, are provided in Section 5.3. A summary of key findings is provided in Section 5.4. Additional model estimation results that supplement the models in this section are provided in Appendix A.

5.2 Results: Design Exception Effects on Expected Crash Frequency

Results of the analysis to estimate the effects of design exceptions on expected crash frequency are presented in this section. The primary analysis method was negative binomial regression modeling with the presence of one or more design exceptions coded as an indicator variable (1 = one or more design exceptions; 0 = no design exceptions). The methodology is described in greater detail in Section 3.2.

Estimation results for models of total crashes (all types and severities), fatal-plus-injury crashes (all types), and property-damage-only crashes (all types) are provided in Table 5.1, Table 5.2, and Table 5.3, respectively. The models presented in these tables were estimated using data from both freeways and non-freeways with variables and interactions that capture the expected differences in safety performance between these facility types (see Table 4.1). Models disaggregated by facility type were also estimated and are presented in Appendix A. Results in terms of the design exception parameter were generally consistent except for the freeway crash models. It is unclear whether this difference was due to some safety effect on freeways that is masked by the "pooled" model, the mismatch between freeway treatment and comparison sites indicated by the propensity score plots, or because of unstable estimation results due to the smaller sample sizes for the disaggregated model. There were only 14 design exception locations on freeways. At this stage, focus on the pooled models is recommended until additional freeway data can be collected.

The regression parameters associated with the presence of one or more design exceptions were very close to zero in the total, fatal-plus-injury, and property-damage-only crash models. Parameter estimates were also statistically insignificant (p-values > 0.90), indicating a very small chance that the parameter is different from zero at all. The parameter estimates show that road segments with one or more design exceptions had the same expected frequency of total crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes as segments without any design exceptions.

Table 5.1 Crash Frequency Model Estimation Results for Total (KABCO) Crashes

Pooled KABCO Model						
Number of Observations = 180						
LR Chi2(12) = 345.14						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.1688						
Dispersion = Mean						
Log Likelihood = -850.03						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.887	0.072	12.3	0.000	0.746	1.03
DE	0.009	0.110	0.08	0.935	-0.206	0.224
FOUR_TL	0.208	0.184	1.13	0.260	-0.154	0.569
SIX_TL	0.196	0.262	0.75	0.454	-0.317	0.710
EIGHT_TEN_L	0.244	0.309	0.79	0.429	-0.361	0.849
HC_MILE	0.120	0.025	4.86	0.000	0.072	0.169
Non_FW_INTS_M	0.071	0.017	4.15	0.000	0.038	0.105
FW_INTC_M	-0.183	0.063	-2.90	0.004	-0.307	-0.059
Aux_Lanes	0.084	0.084	1.00	0.317	-0.081	0.248
Trav_Div	-0.383	0.160	-2.40	0.017	-0.696	-0.070
2WLT	0.470	0.210	2.24	0.025	0.059	0.881
Rural	-0.480	0.199	-2.42	0.016	-0.869	-0.091
Constant	-5.23	0.662	-7.90	0.000	-6.53	-3.93
LN_LEN	1	(offset)				
alpha	0.317	0.040			0.248	0.404

Table 5.2 Crash Frequency Model Estimation Results for Fatal-Plus-Injury (KABC) Crashes

Pooled KABC Model						
Number of Observations = 180						
LR Chi2(12) = 317.41						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.2010						
Dispersion = Mean						
Log Likelihood = -630.72						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.852	0.081	10.6	0.000	0.694	1.01
DE	-0.009	0.119	-0.1	0.939	-0.243	0.225
FOUR_TL	0.265	0.204	1.30	0.194	-0.135	0.665
SIX_TL	0.085	0.280	0.30	0.762	-0.463	0.633
EIGHT_TEN_L	0.010	0.327	0.03	0.976	-0.632	0.651
HC_MILE	0.152	0.027	5.58	0.000	0.099	0.206
Non_FW_INTS_M	0.059	0.021	2.87	0.004	0.019	0.100
FW_INTC_M	-0.253	0.067	-3.78	0.000	-0.385	-0.122
Aux_Lanes	0.035	0.087	0.41	0.684	-0.135	0.206
Trav_Div	-0.271	0.181	-1.49	0.135	-0.626	0.084
2WLT	0.599	0.238	2.51	0.012	0.132	1.07
Rural	-0.727	0.227	-3.20	0.001	-1.17	-0.282
Constant	-6.08	0.755	-8.1	0.000	-7.56	-4.60
LN_LEN	1	(offset)				
alpha	0.310	0.044			0.234	0.409

Table 5.3 Crash Frequency Model Estimation Results for Property-Damage-Only (O) Crashes

Pooled PDO Model						
Number of Observations = 180						
LR Chi2(12) = 336.01						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.1739						
Dispersion = Mean						
Log Likelihood = -797.87						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.887	0.076	11.7	0.000	0.739	1.036
DE	0.014	0.113	0.12	0.901	-0.207	0.235
FOUR_TL	0.201	0.191	1.05	0.294	-0.174	0.576
SIX_TL	0.273	0.272	1.00	0.316	-0.260	0.806
EIGHT_TEN_L	0.376	0.321	1.17	0.241	-0.253	1.00
HC_MILE	0.109	0.026	4.25	0.000	0.059	0.159
Non_FW_INTS_M	0.081	0.018	4.59	0.000	0.046	0.116
FW_INTC_M	-0.159	0.065	-2.5	0.014	-0.287	-0.032
Aux_Lanes	0.103	0.086	1.20	0.231	-0.065	0.270
Trav_Div	-0.396	0.162	-2.4	0.015	-0.714	-0.077
2WLT	0.378	0.212	1.78	0.075	-0.037	0.793
Rural	-0.393	0.199	-2	0.049	-0.783	-0.002
Constant	-5.62	0.693	-8.1	0.000	-6.98	-4.27
LN_LEN	1	(offset)				
alpha	0.321	0.041			0.249	0.413

5.3 Results: Design Exception Effects on Expected Crash Severity

Results of the analysis to estimate the effects of design exceptions on expected crash severity are presented in this section. Three alternative analysis methods were used: 1) computing severity distributions at locations with and without design exceptions, 2) estimating separate negative binomial regression models by severity level and 3) estimating multinomial logit models. The first method is analogous to the method used to compute severity distributions in the *Highway Safety Manual* predictive method for rural, two-lane roads. Results of this approach are provided in Table 5.4. The severity distributions indicate that crashes on road segments with design exceptions tend to be less severe than crashes on road segments without design exceptions. The percentages of crashes that result in a fatality or any level of injury on road segments with design exceptions are lower than those same percentages on road segments without design exceptions. The percentage of crashes resulting in property damage only is therefore higher on design exception segments. This default distribution approach to crash severity has one major disadvantage: it does not capture additional differences between road segments with and without design exceptions that may also impact the crash severity distributions (e.g., traffic volumes).

Table 5.4 Default severity distributions for road segments with and without design exceptions

	Design Exception Locations		Comparison Locations		All Locations Combined	
	Total	%	Total	%	Total	%
K	44	0.29%	107	0.55%	151	0.43%
A	264	1.73%	476	2.43%	740	2.12%
B	1139	7.47%	1762	9.00%	2901	8.33%
C	2133	13.99%	2990	15.27%	5123	14.71%
O	11665	76.52%	14247	72.76%	25912	74.40%

The second method of estimating separate negative binomial regression models by severity level is analogous to the method used to compute severity distributions in the *Highway Safety Manual* predictive method for rural, multi-lane roads and urban and suburban arterials. The three frequency models presented in Section 5.2 are applied independently to predict average crash frequencies for total (KABCO), fatal-plus-injury (KABC), and property-damage-only (O) crashes. Adjustments are then made to the fatal-plus-injury and property-damage-only predictions so that they sum to equal the "total" crash prediction. Results of this approach are summarized in Figure 5.1 and show practically no difference in crash severity when comparing locations with and without design exceptions. Approximately 27% of predicted crashes result in a fatality or some level of injury; approximately 73% of predicted crashes result in property damage only.

The third analysis method used was multinomial logistic regression modeling with the presence of one or more design exceptions coded as an indicator variable (1 = one or more design exceptions; 0 = no design exceptions). The methodology is described in greater detail in Section 3.3. The data used for model estimation are described in Section 4. The road segments for this effort are the same as those used for the frequency analysis. The crash severity database itself is set up so that one row equals one crash. The databases used for model estimation included up to nearly 35,000 crashes. Therefore, the raw database in this format was not provided as an appendix.

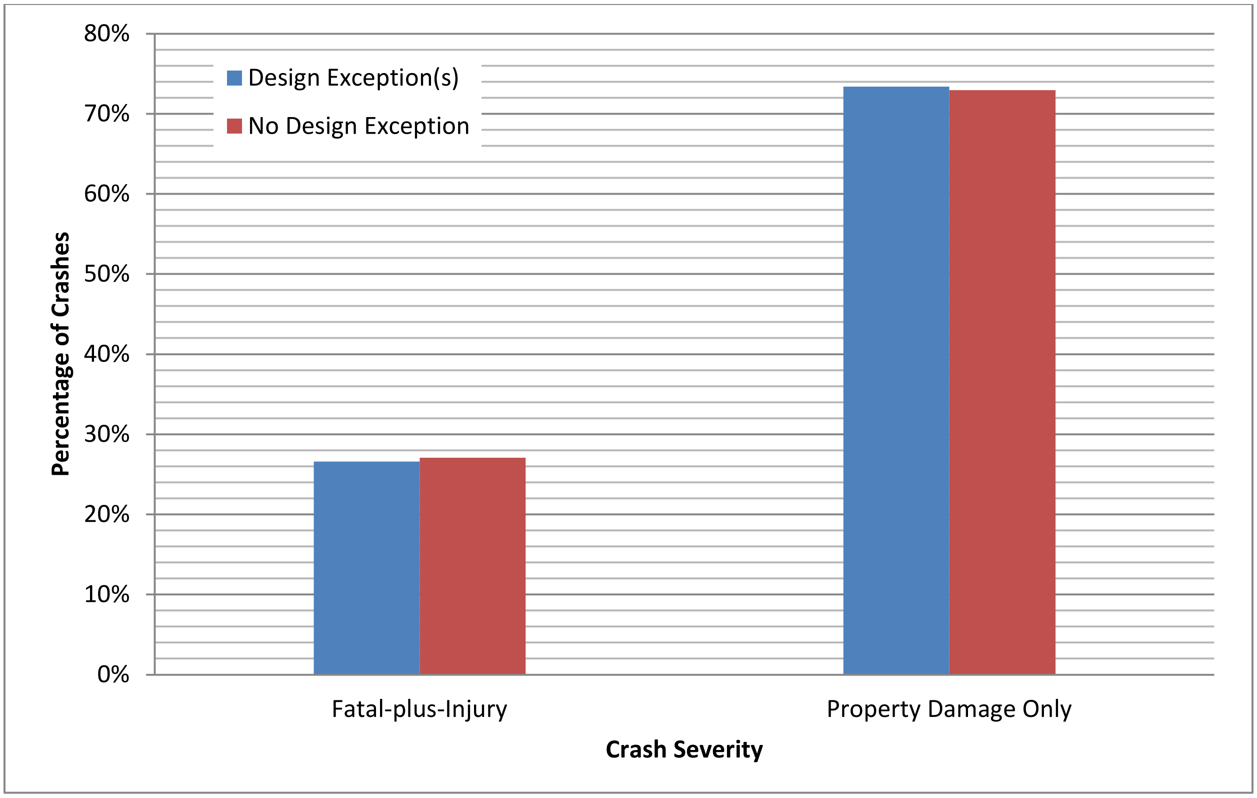

Figure 5.1 Distributions of injury and non-injury crashes on road segments with and without design exceptions (based on crash frequency models in Section 5.2)

Estimation results for models of total crashes (all types and severities) and fatal-plus-injury crashes (all types) are provided in Table 5.5, Table 5.6, respectively. The models presented in these tables were estimated using data from both freeways and non-freeways with variables and interactions that capture the expected differences in safety performance between these facility types. Models disaggregated by facility type were also estimated and are presented in Appendix A. Discussions in Section 5.2 related to the disaggregated frequency models in Appendix A apply to the disaggregated severity models as well.

The multinomial logit model estimation results show that the parameters associated with the presence of one or more design exceptions were not statistically significant (p-values ranging from 0.270 to 0.771). Signs of the parameter estimates indicate the possibility of less severe crashes on road segments with design exceptions. Design exception parameter estimates are negative for the “fatal” and “incapacitating injury” categories in the KABCO model (with property damage only serving as the base outcome). Design exception parameter estimates are negative for the “fatal,” “incapacitating injury,” and “non-incapacitating injury” categories in the KABC model (with possible injuries serving as the base outcome). These results indicate no difference in the severity distribution of crashes occurring on roads with one or more design exceptions when compared to roads without design exceptions. Results of the multinomial logit estimation results are illustrated in a more practical format for interpretation in Figure 5.2. This figure was developed by setting the values for all variables in the KABCO logit model to their average except for the design exception variable, which was coded as either “zero” (no design exceptions) or “one” (one or more design exceptions).

Table 5.5 Crash Severity Model Estimation Results for Total (KABCO) Crashes

Pooled Severity Model Number of Observations = 34827, LR Chi2(36) = 700.71,							
Prob > Chi2 = 0.0000, Pseudo R2 = 0.0124, Log Likelihood = -28012.138, Base Outcome = PDO							
Severity	Variable	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
Possible Injury	LN_AADT	0.035	0.048	0.73	0.468	-0.060	0.130
	DE	0.052	0.042	1.23	0.218	-0.031	0.135
	Non_FW	0.617	0.060	10.31	0.000	0.500	0.735
	FW_INTC	0.014	0.002	7.15	0.000	0.010	0.018
	HC_Mile	-0.020	0.015	-1.33	0.183	-0.049	0.009
	FOUR_TL	0.261	0.108	2.42	0.015	0.050	0.472
	SIX_TL	0.006	0.139	0.01	0.967	-0.267	0.278
	EIGHT_TEN_TL	-0.060	0.164	-0.37	0.715	-0.381	0.261
	Rural	-0.332	0.102	-3.27	0.001	-0.531	-0.133
	Constant	-2.27	0.490	-4.63	0.000	-3.23	-1.31
Non-Incapacitating Injury	LN_AADT	0.010	0.058	0.17	0.869	-0.104	0.123
	DE	0.021	0.053	0.39	0.694	-0.084	0.126
	Non_FW	0.334	0.075	4.44	0.000	0.187	0.482
	FW_INTC	0.013	0.003	4.95	0.000	0.008	0.017
	HC_Mile	-0.030	0.018	-1.65	0.100	-0.066	0.006
	FOUR_TL	0.198	0.122	1.62	0.106	-0.042	0.438
	SIX_TL	-0.208	0.165	-1.26	0.206	-0.530	0.114
	EIGHT_TEN_TL	-0.446	0.196	-2.28	0.023	-0.829	-0.062
	Rural	-0.062	0.115	-0.54	0.589	-0.288	0.164
	Constant	-2.22	0.585	-3.80	0.000	-3.369	-1.08
Incapacitating Injury	LN_AADT	-0.151	0.094	-1.60	0.109	-0.335	0.033
	DE	-0.096	0.098	-0.98	0.328	-0.289	0.097
	Non_FW	-0.284	0.136	-2.10	0.036	-0.550	-0.018
	FW_INTC	0.003	0.005	0.62	0.533	-0.006	0.012
	HC_Mile	0.017	0.030	0.58	0.560	-0.041	0.075
	FOUR_TL	-0.229	0.198	-1.15	0.249	-0.617	0.160
	SIX_TL	-0.943	0.272	-3.46	0.001	-1.48	-0.409
	EIGHT_TEN_TL	-1.21	0.322	-3.75	0.000	-1.84	-0.575
	Rural	-0.410	0.185	-2.21	0.027	-0.772	-0.047
	Constant	-0.966	0.946	-1.02	0.307	-2.820	0.888
Fatal	LN_AADT	-0.079	0.182	-0.43	0.666	-0.436	0.278
	DE	-0.080	0.223	-0.36	0.720	-0.516	0.357
	Non_FW	-0.973	0.344	-2.83	0.005	-1.65	-0.299
	FW_INTC	0.024	0.012	2.10	0.036	0.002	0.047
	HC_Mile	-0.109	0.070	-1.55	0.120	-0.246	0.028
	FOUR_TL	-1.35	0.409	-3.29	0.001	-2.15	-0.543
	SIX_TL	-1.63	0.565	-3.89	0.004	-2.74	-0.525
	EIGHT_TEN_TL	-2.82	0.684	-4.13	0.000	-4.16	-1.48
	Rural	0.489	0.368	1.33	0.184	-0.233	1.21
	Constant	-2.44	1.85	-1.32	0.186	-6.06	1.18

Table 5.6 Crash Severity Model Estimation Results for Fatal-Plus-Injury (KABC) Crashes

Pooled Model No PDO Number of Observations = 8915, LR Chi2(27) = 286.68							
Prob > Chi2 = 0.000, Pseudo R2 = 0.0168, Log Likelihood = -8409.221, Base Outcome = Poss. Injury							
Severity	Variable	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
Non-Incapacitating Injury	LN_AADT	-0.042	0.070	-0.59	0.552	-0.178	0.095
	DE	-0.019	0.064	-0.29	0.771	-0.143	0.106
	Non_FW	-0.278	0.088	-3.15	0.002	-0.451	-0.105
	FW_INTC	-0.001	0.003	-0.26	0.795	-0.007	0.005
	HC_Mile	-0.018	0.021	-0.83	0.407	-0.059	0.024
	FOUR_TL	-0.059	0.148	-0.4	0.690	-0.350	0.232
	SIX_TL	-0.187	0.194	-0.96	0.335	-0.566	0.193
	EIGHT_TEN_TL	-0.362	0.231	-1.57	0.117	-0.815	0.090
	Rural	0.259	0.142	1.83	0.067	-0.019	0.537
	Constant	0.200	0.711	0.28	0.778	-1.19	1.59
Incapacitating Injury	LN_AADT	-0.221	0.102	-2.17	0.030	-0.421	-0.021
	DE	-0.116	0.105	-1.1	0.270	-0.321	0.090
	Non_FW	-0.861	0.141	-6.11	0.000	-1.14	-0.584
	FW_INTC	-0.009	0.005	-1.76	0.079	-0.019	0.001
	HC_Mile	0.019	0.031	0.61	0.545	-0.043	0.081
	FOUR_TL	-0.424	0.211	-2.01	0.045	-0.838	-0.010
	SIX_TL	-0.817	0.284	-2.87	0.004	-1.37	-0.260
	EIGHT_TEN_TL	-1.03	0.338	-3.05	0.002	-1.69	-0.367
	Rural	-0.076	0.203	-0.38	0.708	-0.474	0.322
	Constant	1.56	1.03	1.52	0.129	-0.454	3.58
Fatal	LN_AADT	-0.137	0.184	-0.75	0.454	-0.497	0.222
	DE	-0.077	0.228	-0.34	0.734	-0.523	0.369
	Non_FW	-1.44	0.329	-4.39	0.000	-2.09	-0.799
	FW_INTC	0.015	0.012	1.26	0.209	-0.008	0.038
	HC_Mile	-0.119	0.069	-1.73	0.083	-0.254	0.015
	FOUR_TL	-1.52	0.399	-3.81	0.000	-2.30	-0.737
	SIX_TL	-1.44	0.548	-2.62	0.009	-2.51	-0.363
	EIGHT_TEN_TL	-2.62	0.672	-3.91	0.000	-3.94	-1.31
	Rural	0.893	0.375	2.38	0.017	0.159	1.63
	Constant	-0.124	1.86	-0.07	0.947	-3.76	3.51

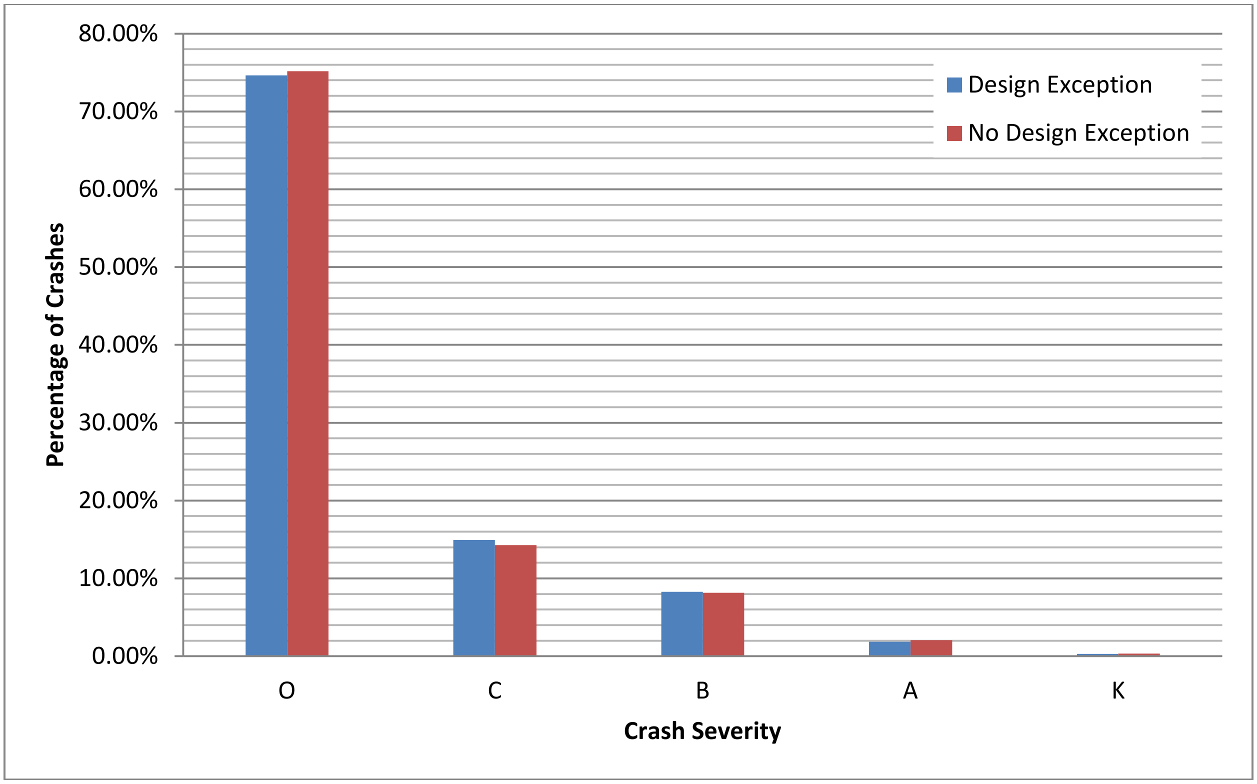

Figure 5.2 Severity distributions on road segments with and without design exceptions based on crash severity models in Table 5.5 (K = fatal; A = incapacitating injury; B = non-incapacitating injury; C = possible injury; O = property damage only)

5.4 Summary

This section contained modeling results and interpretations related to the safety impacts of design exceptions. Design exception effects on expected crash frequency were quantified using the negative binomial regression modeling approach described in Section 3.2. Parameter estimates indicated that road segments with one or more design exceptions had the same expected frequency of total crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes.

Design exception effects on expected crash severity were quantified using three approaches described in Section 3.3: 1) computing severity distributions at locations with and without design exceptions, 2) estimating separate negative binomial regression models by severity level, and 3) estimating multinomial logit models. The results of the first method showed that crashes on road segments with design exceptions tend to be less severe than crashes on road segments without design exceptions. However, this first approach was unable to capture additional differences between road segments with and without design exceptions that may also impact the crash severity distributions. The latter two methods addressed this limitation; results indicated no difference in the severity distribution of crashes for roads with one or more design exceptions when compared to roads without design exceptions.

The models presented in this section were estimated using data from both freeways and non-freeways with variables and interactions that capture the expected differences in safety performance between these facility types. Models disaggregated by facility type (e.g., freeway or non-freeway) were also estimated and are presented in Appendix A. The freeway dataset was relatively small; only 14 freeway design exception segments were in the dataset. Focus on the pooled models was recommended until additional freeway data can be collected.

6. CONCLUSIONS

6.1 Summary

State DOTs develop designs and prepare plans for road construction. Designers are guided by a set of state-adopted standards and policies that include design criteria. Design criteria are based on research and practice, and are generally expressed as minimums, maximums, or ranges of values for design elements (e.g., minimum horizontal curve radius, maximum grade). Meeting all design criteria is not always possible or practical. There are cases where meeting all design criteria would result in significant environmental impacts, community impacts, and/or construction costs. When this occurs, a design exception may be explored as an alternative. The potential safety implications of design exceptions are a central issue to design exception review and approval, but documentation of the process by which safety is considered varies from state to state. A survey of state DOTs indicated that safety analysis methods varied (Mason & Mahoney 2003). A literature review conducted as part of this project showed that attempts to analyze the safety performance of locations with design exceptions were limited.

The objective of this research was to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed. The project used data from the State of Utah. Data were collected for design exceptions constructed in Utah in the years 2001 through 2006. Design exception request and approval forms, Google Earth, Google Street View, UDOT functional classification maps, and UDOT traffic volume data were used to identify and define road segments with and without design exceptions. Ultimately, a total of 48 segments with design exceptions and 132 segments without design exceptions were used for analysis. Propensity scores were applied in this study to assess the selection of comparison sites (i.e., sites without design exceptions) and minimize selection bias.

Design exception effects on expected crash frequency were quantified using a negative binomial regression modeling approach. Parameter estimates indicated that road segments with one or more design exceptions had the same expected frequency of total crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes as road segments without design exceptions. Design exception effects on expected crash severity were quantified using three approaches: 1) computing severity distributions at locations with and without design exceptions, 2) estimating separate negative binomial regression models by severity level, and 3) estimating multinomial logit models. The results of the first method showed that crashes on road segments with design exceptions tend to be less severe than crashes on road segments without design exceptions. However, this first approach was not able to capture additional differences between road segments with and without design exceptions that may also impact the crash severity distributions. The latter two methods addressed this limitation; results indicated no difference in the severity distribution of crashes occurring on roads with one or more design exceptions when compared to crashes occurring on roads without design exceptions.

6.2 Findings

The major findings and conclusions of the research are:

1. Propensity scores were effective in assessing the selection of comparison sites (i.e., sites without design exceptions). For the freeway segments, there were significant differences in the propensity scores for treatment and comparison segments. This meant that there may be selection bias issues for freeway segments (i.e., freeway segments with design exceptions were inherently different than freeway segments without design exceptions). Propensity scores for the non-freeway segments showed that the treatment and comparison sites were well matched.

2. Road segments with one or more design exceptions had the same expected frequency of total crashes (all types and severities), fatal-plus-injury crashes, and property-damage-only crashes as road segments without design exceptions. This finding was based on parameter estimates for negative binomial regression models estimated using data from both freeways and non-freeways with variables and interactions that captured the expected differences in safety performance between these facility types.
3. There were no differences in the severity distributions of crashes occurring on roads with one or more design exceptions when compared to crashes occurring on roads without any design exceptions. This finding was based on parameter estimates for a series of negative binomial regression models separated by severity level as well as parameter estimates for two multinomial logit models (with and without property-damage-only crashes included). Models were estimated using "pooled" data from both freeways and non-freeways with variables and interactions that capture the expected differences in safety performance between these facility types.
4. The findings of this study show that the UDOT design exception review and approval process, as implemented in years 2001 through 2006, was effective from a safety perspective. Findings are not intended to support approving a greater number of design exceptions or fewer design exceptions.

6.3 Limitations and Challenges

Data elements available to characterize treatment and comparison segments were limited to those identified in Table 4.1. Additional detail on horizontal alignment (e.g., curve radius, superelevation) and vertical alignment (e.g., grade, rate vertical curvature) would be desirable, but could not be practically collected within the project scope and budget. UDOT's Project Wise System was used to try and find data on these design elements, but design information or drawings for the majority of the road segments could not be located.

The comparison segments were defined, when possible, within the same project boundaries as the project with the design exception, but at locations without any design exceptions. This was done to maximize similarity between the treatment and comparison segments and also ensure that the comparison locations did not have design exceptions on them (otherwise, they would be identified in the project documents). Locations along the same route and in near proximity to the project segment were identified as comparison segments when the first approach was not possible. UDOT's Project Wise System was used to try and find as-built plans at these secondary locations to confirm that all elements met design criteria. This was not always possible, so the available data sources (e.g., Google Earth, Google Street View) were used to confirm that design elements met criteria. Some design elements could not be directly measured in the available data sources (e.g., superelevation, grade, rate of vertical curvature).

Models disaggregated by facility type were estimated and are presented in Appendix A. Results in terms of the design exception parameters were generally consistent except for the freeway crash models. There was a significant difference in the propensity scores for treatment and comparison segments on freeways. The freeway segments in the treatment and comparison groups covered all of the urban freeways in Utah and some rural freeway segments. Due to a lack of additional freeway segments to choose from in urban areas, nothing additional could be done to balance out the propensity scores for the freeway segments. This means that there may be selection bias issues for freeway segments. This is why focus on the pooled models is recommended until additional freeway data can be collected.

7. RECOMMENDATIONS AND IMPLEMENTATION

7.1 Recommendations

This report presented a unique study on the safety impacts of design exceptions; only one other similar effort was identified (Malyshkina & Mannering 2010). Results will have the expected benefits identified in Section 7.2. Limitations and challenges were identified in Section 6. As with any observational study, a possibility of confounding effects from extraneous variables always exists and can never be completely excluded. Recommendations for future work are provided below:

- Continue to expand the dataset to include additional treatment and comparison locations and additional years of crash data. Given that all Utah urban freeways were included in the dataset, additional years of crash data combined with time-series and panel data analysis approaches appear to be the most practical option.
- This study looked at the safety effects of design exceptions at an aggregate level. Future work should estimate the safety effects of exceptions to individual design criteria or specific combinations of design criteria. Effects on specific crash types (e.g., single-vehicle; multiple-vehicle) should also be explored.
- Expand the current cross-sectional analysis to explore other model estimators, including the mixed multinomial logit model and the random parameters negative binomial model, modeling approaches that may capture additional, unmeasured site-to-site variations.

7.2 Implementation Plan

The objective of this research was to compare safety, measured by expected crash frequency and severity, on road segments where design exceptions were approved and constructed to similar road segments where no design exceptions were approved or constructed. The research objective was met and the entire research effort is documented in this report. The study and its results are expected to have the following benefits:

- Provide insights into the effectiveness of UDOT's current design exception preparation and approval process;
- Create additional documentation, as recommended by Martin (1994) and outlined by Mason & Mahoney (2003), that includes an evaluation of the designs resulting from the design exceptions; and
- Outline a methodology for other states to reference when conducting similar safety evaluations of design exceptions.

The research findings will provide guidance for risk assessment activities related to design exceptions and could support ongoing practical design initiatives within state DOTs. The research methodology and results will have national impacts for the same reasons stated above. The study was not intended to recommend any new additions or modifications to design exception policy.

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APPENDIX A: MODEL ESTIMATION RESULTS DISAGGREGATED BY FACILITY TYPE

The models presented in Section 5 were estimated using data from both freeways and non-freeways with variables and interactions that capture the expected differences in safety performance between these facility types. Models disaggregated by facility type were also estimated. Estimation results are presented in this appendix for the following models:

- Expected number of total crashes (all types and severities) for freeways (Table A.1)
- Expected number of fatal-plus-injury crashes for freeways (Table A.2)
- Expected number of property-damage-only crashes for freeways (Table A.3)
- Expected number of total crashes (all types and severities) for non-freeways (Table A.4)
- Expected number of fatal-plus-injury crashes for non-freeways (Table A.5)
- Expected number of property-damage-only crashes for non-freeways (Table A.6)
- Crash severity models for total crashes (all types and severities) on freeways (Table A.7)
- Crash severity models for fatal-plus-injury crashes (all types) on freeways (Table A.8)
- Crash severity models for total crashes (all types and severities) on non-freeways (Table A.9)
- Crash severity models for fatal-plus-injury crashes (all types) on non-freeways (Table A.10)

Table A.1 Crash Frequency Model Estimation Results for Total (KABCO) Crashes on Freeways

Freeway KABCO Model						
Number of Observations = 66						
LR Chi2(10) = 159.16						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.1843						
Dispersion = Mean						
Log Likelihood = -352.21						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.890	0.119	7.46	0.000	0.66	1.123
DE	0.326	0.147	2.21	0.027	0.04	0.614
FOUR_TL	-0.373	0.361	-1.03	0.302	-1.08	0.335
SIX_TL	-0.402	0.353	-1.14	0.255	-1.094	0.290
EIGHT_TEN_TL	-0.238	0.388	-0.61	0.539	-0.999	0.523
HC_MILE	-0.093	0.147	-0.64	0.524	-0.381	0.194
Aux_Lanes	0.182	0.067	2.72	0.007	0.05	0.313
Trav_Div	-0.176	0.178	-0.98	0.325	-0.525	0.174
Rural	-0.45	0.27	-1.66	0.097	-0.97	0.08
FW_INTC_M	0.183	0.152	1.20	0.231	-0.116	0.481
Constant	-5.13	1.25	-4.11	0.000	-7.57	-2.68
LN_LEN	1	(offset)				
alpha	0.108	0.023			0.071	0.163

Table A.2 Crash Frequency Model Estimation Results for Fatal-Plus-Injury (KABC) Crashes on Freeways

Freeway KABC Model						
Number of Observations = 66						
LR Chi2(10) = 146.21						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.2189						
Dispersion = Mean						
Log Likelihood = -260.81						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.872	0.126	6.93	0.000	0.625	1.118
DE	0.239	0.146	1.64	0.102	-0.047	0.524
FOUR_TL	-0.478	0.385	-1.24	0.214	-1.23	0.276
SIX_TL	-0.801	0.379	-2.11	0.034	-1.54	-0.059
EIGHT_TEN_TL	-0.643	0.415	-1.55	0.121	-1.46	0.170
HC_MILE	-0.065	0.148	-0.44	0.663	-0.355	0.226
Aux_Lanes	0.164	0.065	2.52	0.012	0.036	0.292
Trav_Div	0.242	0.203	1.19	0.234	-0.156	0.640
Rural	-0.93	0.30	-3.14	0.002	-1.51	-0.348
FW_INTC_M	0.128	0.154	0.83	0.407	-0.174	0.430
Constant	-6.01	1.31	-4.59	0.000	-8.58	-3.45
LN_LEN	1	(offset)				
alpha	0.090	0.025			0.052	0.154

Table A.3 Crash Frequency Model Estimation Results for Property-Damage-Only (O) Crashes on Freeways

Freeway PDO Model						
Number of Observations = 66						
LR Chi2(10) = 166.04						
Prob > Chi2 = 0.0000						
Pseudo R2 = 0.2001						
Dispersion = Mean						
Log Likelihood = -3531.85						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.923	0.121	7.66	0.000	0.687	1.16
DE	0.332	0.146	2.27	0.023	0.045	0.618
FOUR_TL	-0.182	0.372	-0.49	0.625	-0.911	0.547
SIX_TL	-0.117	0.366	-0.32	0.749	-0.835	0.601
EIGHT_TEN_TL	0.041	0.401	0.10	0.918	-0.744	0.826
HC_MILE	-0.087	0.146	-0.60	0.550	-0.374	0.199
Aux_Lanes	0.182	0.066	2.74	0.006	0.052	0.311
Trav_Div	-0.290	0.174	-1.67	0.095	-0.632	0.051
Rural	-0.265	0.266	-1.00	0.319	-0.787	0.257
FW_INTC_M	0.180	0.151	1.19	0.233	-0.1162611	0.4769464
Constant	-6.03	1.26	-4.80	0.000	-8.49	-3.56
LN_LEN	1	(offset)				
alpha	0.102	0.022			0.068	0.155

Table A.4 Crash Frequency Model Estimation Results for Total (KABCO) Crashes on Non-Freeways

Non-Freeway KABCO Model						
Number of Observations = 114						
LR Chi2(11) = 213.55						
Prob > Chi2 = 0.000						
Pseudo R2 = 0.1832						
Dispersion = Mean						
Log Likelihood = -475.95						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.938	0.092	10.2	0.000	0.758	1.12
DE	-0.279	0.227	-1.2	0.220	-0.725	0.167
FOUR_TL	0.644	0.347	1.85	0.064	-0.037	1.32
SIX_TL	0.361	0.416	0.87	0.386	-0.455	1.18
Non_FW_INTS_M	0.060	0.021	2.89	0.004	0.019	0.101
HC_MILE	0.114	0.028	4.10	0.000	0.059	0.168
Aux_Lanes	-0.096	0.163	-0.6	0.553	-0.415	0.222
Rural	-0.242	0.305	-0.8	0.427	-0.839	0.355
Divided	0.400	0.277	1.45	0.148	-0.142	0.943
Trav_Div	-0.443	0.321	-1.4	0.168	-1.07	0.186
2WLT	0.135	0.290	0.47	0.641	-0.434	0.705
Constant	-5.80	0.829	-7	0.000	-7.43	-4.18
LN_LEN	1	(offset)				
alpha	0.398	0.063			0.293	0.542

Table A.5 Crash Frequency Model Estimation Results for Fatal-Plus-Injury (KABC) Crashes on Non-Freeways

Non-Freeway KABC Model						
Number of Observations = 114						
LR Chi2(11) = 207.62						
Prob > Chi2 = 0.000						
Pseudo R2 = 0.2328						
Dispersion = Mean						
Log Likelihood = -342.13						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.956	0.105	9.10	0.000	0.750	1.16
DE	-0.028	0.254	-0.11	0.912	-0.527	0.470
FOUR_TL	1.12	0.365	3.07	0.002	0.404	1.84
SIX_TL	0.769	0.437	1.76	0.078	-0.086	1.63
Non_FW_INTS_M	0.039	0.025	1.55	0.121	-0.010	0.089
HC_MILE	0.140	0.030	4.65	0.000	0.081	0.199
Aux_Lanes	-0.192	0.185	-1.04	0.300	-0.555	0.171
Rural	-0.133	0.333	-0.40	0.689	-0.785	0.519
Divided	0.130	0.313	0.41	0.678	-0.484	0.744
Trav_Div	-0.300	0.372	-0.8	0.420	-1.03	0.429
2WLT	0.267	0.322	0.83	0.408	-0.365	0.898
Constant	-7.37	0.944	-7.8	0.000	-9.23	-5.52
LN_LEN	1	(offset)				
alpha	0.356	0.067			0.246	0.5147976

Table A.6 Crash Frequency Model Estimation Results for Property-Damage-Only (O) Crashes on Non-Freeways

Non-Freeway PDO Model						
Number of Observations = 114						
LR Chi2(11) = 194.31						
Prob > Chi2 = 0.000						
Pseudo R2 = 0.1793						
Dispersion = Mean						
Log Likelihood = -444.62						
Variable	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
LN_AADT	0.926	0.101	9.22	0.000	0.729	1.12
DE	-0.323	0.244	-1.3	0.185	-0.801	0.15
FOUR_TL	0.486	0.373	1.30	0.193	-0.246	1.22
SIX_TL	0.243	0.446	0.54	0.586	-0.632	1.12
Non_FW_INTS_M	0.072	0.022	3.24	0.001	0.028	0.115
HC_MILE	0.101	0.030	3.36	0.001	0.042	0.159
Aux_Lanes	-0.074	0.173	-0.43	0.670	-0.413	0.266
Rural	-0.268	0.320	-0.84	0.402	-0.896	0.360
Divided	0.444	0.295	1.50	0.133	-0.135	1.02
Trav_Div	-0.410	0.346	-1.2	0.236	-1.09	0.268
2WLT	0.036	0.312	0.11	0.909	-0.577	0.648
Constant	-6.00	0.902	-6.7	0.000	-7.77	-4.23
LN_LEN	1	(offset)				
alpha	0.442	0.071			0.322	0.607

Table A.7 Crash Severity Model Estimation Results for Total (KABCO) Crashes on Freeways

Freeway Model Number of Observations = 27293, LR Chi2(32) = 347.14							
Prob > Chi2 = 0.000, Pseudo R2 = 0.008, Log Likelihood = -20938.194, Base Outcome = PDO							
Severity	Variable	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
Possible Injury	LN_AADT	-0.027	0.068	-0.39	0.695	-0.161	0.107
	DE	0.062	0.055	1.12	0.261	-0.046	0.171
	Rural	-0.279	0.145	-1.93	0.053	-0.563	0.004
	HC_Mile	-0.132	0.031	-4.24	0.000	-0.193	-0.071
	FOUR_TL	-1.25	0.294	-4.26	0.000	-1.83	-0.676
	SIX_TL	-1.36	0.294	-4.63	0.000	-1.94	-0.786
	EIGHT_TEN_TL	-1.45	0.308	-4.69	0.000	-2.05	-0.842
	FW_INTC	0.015	0.002	7.25	0.000	0.011	0.019
	Constant	-0.056	0.727	-0.08	0.938	-1.48	1.37
Non-Incapacitating Injury	LN_AADT	0.013	0.085	0.15	0.880	-0.15	0.180
	DE	0.080	0.071	1.13	0.259	-0.059	0.219
	Rural	-0.104	0.165	-0.63	0.527	-0.427	0.218
	HC_Mile	-0.180	0.040	-4.54	0.000	-0.258	-0.102
	FOUR_TL	-0.804	0.379	-2.12	0.034	-1.55	-0.061
	SIX_TL	-1.18	0.382	-3.09	0.002	-1.93	-0.432
	EIGHT_TEN_TL	-1.54	0.401	-3.84	0.000	-2.33	-0.755
	FW_INTC	0.016	0.003	5.60	0.000	0.010	0.021
	Constant	-1.09	0.913	-1.20	0.231	-2.88	0.696
Incapacitating Injury	LN_AADT	-0.131	0.155	-0.85	0.398	-0.434	0.172
	DE	-0.046	0.133	-0.35	0.729	-0.306	0.214
	Rural	-0.459	0.278	-1.65	0.098	-1.00	0.085
	HC_Mile	-0.083	0.069	-1.21	0.225	-0.218	0.051
	FOUR_TL	-0.508	0.563	-0.90	0.367	-1.61	0.595
	SIX_TL	-1.18	0.578	-2.05	0.041	-2.32	-0.051
	EIGHT_TEN_TL	-1.58	0.616	-2.56	0.010	-2.79	-0.371
	FW_INTC	0.005	0.005	0.97	0.334	-0.005	0.015
	Constant	-0.787	1.625	-0.48	0.628	-3.97	2.40
Fatal	LN_AADT	-0.296	0.312	-0.95	0.343	-0.908	0.316
	DE	-0.580	0.296	-1.96	0.050	-1.16	0.001
	Rural	0.301	0.554	0.54	0.587	-0.785	1.39
	HC_Mile	-0.023	0.143	-0.16	0.870	-0.303	0.256
	FOUR_TL	12.01	571.51	0.02	0.983	-1108.13	1132.16
	SIX_TL	11.81	571.51	0.02	0.984	-1108.34	1131.95
	EIGHT_TEN_TL	11.12	571.51	0.02	0.984	-1109.02	1131.27
	FW_INTC	0.009	0.011	0.76	0.447	-0.014	0.031
	Constant	-13.39	571.52	-0.02	0.981	-1133.55	1106.77

Table A.8 Crash Severity Model Estimation Results for Fatal-Plus-Injury (KABC) Crashes on Freeways

Freeway No PDO Number of Observations = 6479, LR Chi2(24) = 165.89							
Prob > Chi2 = 0.000, Pseudo R2 = 0.014, Log Likelihood = -6070.915, Base Outcome = Poss. Injury							
Severity	Variable	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
Non-Incapacitating Injury	LN_AADT	0.018	0.101	0.18	0.859	-0.180	0.216
	DE	0.028	0.084	0.34	0.736	-0.137	0.193
	Rural	0.149	0.202	0.74	0.461	-0.247	0.544
	HC_Mile	-0.048	0.047	-1.02	0.309	-0.141	0.045
	FOUR_TL	0.453	0.414	1.10	0.173	-0.358	1.26
	SIX_TL	0.201	0.416	0.48	0.629	-0.615	1.02
	EIGHT_TEN_TL	-0.069	0.439	-0.16	0.875	-0.929	0.791
	FW_INTC	0.001	0.003	0.19	0.851	-0.006	0.007
	Constant	-0.814	1.07	-0.76	0.448	-2.92	1.29
Incapacitating Injury	LN_AADT	-0.137	0.162	-0.84	0.398	-0.453	0.180
	DE	-0.086	0.139	-0.62	0.538	-0.359	0.187
	Rural	-0.222	0.299	-0.74	0.457	-0.808	0.364
	HC_Mile	0.038	0.074	0.52	0.605	-0.106	0.182
	FOUR_TL	0.759	0.587	1.29	0.196	-0.391	1.91
	SIX_TL	0.222	0.600	0.37	0.711	-0.953	1.40
	EIGHT_TEN_TL	-0.093	0.639	-0.15	0.884	-1.34	1.16
	FW_INTC	-0.009	0.006	-1.70	0.089	-0.020	0.001
	Constant	-0.397	1.71	-0.23	0.816	-3.74	2.95
Fatal	LN_AADT	-0.324	0.307	-1.06	0.291	-0.925	0.277
	DE	-0.603	0.298	-2.03	0.043	-1.187	-0.020
	Rural	0.507	0.560	0.91	0.365	-0.589	1.604
	HC_Mile	0.092	0.145	0.63	0.528	-0.193	0.376
	FOUR_TL	13.43	612.72	0.02	0.983	-1187.49	1214.35
	SIX_TL	13.38	612.72	0.02	0.983	-1187.54	1214.30
	EIGHT_TEN_TL	12.77	612.73	0.02	0.983	-1188.15	1213.69
	FW_INTC	-0.005	0.012	-0.44	0.660	-0.028	0.018
	Constant	-12.92	612.73	-0.02	0.983	-1213.85	1188.01

Table A.9 Crash Severity Model Estimation Results for Total (KABCO) Crashes on Non-Freeways

Non-Freeway Model Number of Observations = 7534, LR Chi2(28) = 221.00							
Prob > Chi2 = 0.000, Pseudo R2 = 0.016, Log Likelihood = -7027.475, Base Outcome = PDO							
Severity	Variable	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
Possible Injury	LN_AADT	0.106	0.079	1.34	0.181	-0.049	0.261
	DE	0.060	0.082	0.72	0.469	-0.102	0.221
	Rural	-0.146	0.241	-0.60	0.545	-0.619	0.327
	Non_FW_INTS_M	0.007	0.011	0.65	0.515	-0.015	0.029
	HC_Mile	0.016	0.017	0.95	0.341	-0.017	0.050
	FOUR_TL	0.401	0.246	1.63	0.102	-0.080	0.883
	SIX_TL	0.098	0.270	0.36	0.716	-0.431	0.627
	Constant	-2.57	0.757	-3.40	0.001	-4.06	-1.09
Non-Incapac. Injury	LN_AADT	-0.090	0.084	-1.07	0.284	-0.253	0.074
	DE	-0.139	0.100	-1.38	0.167	-0.335	0.058
	Rural	0.191	0.289	0.66	0.508	-0.375	0.758
	Non_FW_INTS_M	0.010	0.014	0.75	0.450	-0.017	0.038
	HC_Mile	0.020	0.021	0.98	0.329	-0.020	0.060
	FOUR_TL	0.679	0.306	2.22	0.026	0.080	1.28
	SIX_TL	0.309	0.332	0.93	0.353	-0.343	0.960
	Constant	-1.43	0.798	-1.79	0.074	-2.99	0.136
Incapacitating Injury	LN_AADT	-0.229	0.121	-1.90	0.057	-0.466	0.007
	DE	-0.212	0.172	-1.23	0.220	-0.549	0.126
	Rural	-0.051	0.474	-0.11	0.915	-0.979	0.878
	Non_FW_INTS_M	0.003	0.026	0.11	0.913	-0.049	0.054
	HC_Mile	0.051	0.033	1.54	0.123	-0.014	0.115
	FOUR_TL	0.338	0.497	0.68	0.497	-0.636	1.31
	SIX_TL	-0.490	0.547	-0.90	0.370	-1.56	0.582
	Constant	-1.01	1.16	-0.87	0.383	-3.29	1.26
Fatal	LN_AADT	0.342	0.268	1.28	0.201	-0.183	0.867
	DE	0.733	0.350	2.10	0.036	0.048	1.42
	Rural	-0.892	0.759	-1.18	0.240	-2.38	0.595
	Non_FW_INTS_M	-0.150	0.085	-1.77	0.077	-0.317	0.016
	HC_Mile	-0.221	0.093	-2.37	0.018	-0.403	-0.039
	FOUR_TL	-3.03	0.798	-3.80	0.000	-4.60	-1.47
	SIX_TL	-3.71	0.983	-3.78	0.000	-5.64	-1.79
	Constant	-5.46	2.47	-2.21	0.027	-10.30	-0.616

Table A.10 Crash Severity Model Estimation Results for Fatal-Plus-Injury (KABC) Crashes on Non-Freeways

Non-Freeway No PDO Model Number of Observations = 2436, LR Chi2(21) = 157.44							
Prob > Chi2 = 0.000, Pseudo R2 = 0.033, Log Likelihood = -2317.677, Base Outcome = Poss. Injury							
Severity	Variable	Coefficient	Std. Error	z	P>|z|	[95% Conf. Interval]	
Non-Incapac. Injury	LN_AADT	-0.184	0.106	-1.74	0.082	-0.391	0.023
	DE	-0.180	0.118	-1.53	0.127	-0.411	0.051
	Rural	0.366	0.388	0.94	0.347	-0.396	1.13
	Non_FW_INTS_M	0.003	0.016	0.16	0.869	-0.029	0.034
	HC_Mile	-0.005	0.025	-0.20	0.843	-0.053	0.043
	FOUR_TL	0.267	0.384	0.70	0.487	-0.486	1.020
	SIX_TL	0.202	0.413	0.49	0.624	-0.607	1.011
	Constant	1.04	1.04	1.00	0.318	-1.00	3.08
Incapacitating Injury	LN_AADT	-0.331	0.138	-2.39	0.017	-0.602	-0.060
	DE	-0.236	0.185	-1.28	0.210	-0.598	0.126
	Rural	-0.066	0.587	-0.11	0.910	-1.22	1.08
	Non_FW_INTS_M	-0.010	0.028	-0.34	0.732	-0.065	0.045
	HC_Mile	0.017	0.036	-0.48	0.634	-0.054	0.089
	FOUR_TL	-0.229	0.576	-0.40	0.691	-1.36	0.900
	SIX_TL	-0.746	0.623	-1.20	0.231	-1.97	0.475
	Constant	1.72	1.39	-1.24	0.214	-0.992	4.44
Fatal	LN_AADT	0.143	0.267	0.54	0.591	-0.379	0.666
	DE	0.566	0.356	1.59	0.112	-0.132	1.263
	Rural	-1.00	0.901	-1.11	0.265	-2.77	0.763
	Non_FW_INTS_M	-0.168	0.091	-1.85	0.064	-0.347	0.010
	HC_Mile	-0.247	0.093	-2.67	0.008	-0.429	-0.066
	FOUR_TL	-3.51	0.844	-4.16	0.000	-5.17	-1.86
	SIX_TL	-3.93	1.03	-3.80	0.000	-5.95	-1.900
	Constant	-1.77	2.57	-0.69	0.492	-6.82	3.28