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Safety of high speed expressway signals: a comparison of classical and empirical Bayes methods

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Safety of high speed expressway signals: a comparison of classical and empirical Bayes methods

by

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This is to certify that the master's thesis of

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Signatures have been redacted for privacy

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Abstract

High speed expressways are becoming increasingly common as two-lane roads are improved to handle suburban traffic growth. Characterized by at-grade intersections and at least two lanes of traffic in each direction, these facilities are separated by a median and commonly have speed limits of 50 mph or greater. As traffic levels increase, stop controlled intersections are typically signalized to reduce delay or enhance safety. It is the safety performance of these signals that is the focus of this thesis.

This thesis reports on a study investigating the safety benefit of signalizing intersections of high speed divided expressways. Cross classification, matched (yoked) pairs, before and after, and empirical Bayes (EB) analyses were conducted on 50&55-mph and 55-mph only intersections comparing unsignalized and signalized intersections.

The results show that, generally, signalized intersections have a higher crash rate and lower costs per crash. However, in the before and after analysis (intersections that were signalized between 1994 and 2001), the after period experienced lower crash rates with higher costs per crash than before signalization. In the EB analysis, the crash rates changed from the before and after analysis (from 11.7% decrease to a 18.9% increase at the 50&55-mph intersections and from 31.4% decrease to a 6.8% decrease at the 55-mph only intersections).

Chapter 1: Introduction

High speed expressways are becoming increasingly common as two-lane roads are improved to handle suburban traffic growth. Characterized by at-grade intersections and at least two lanes of traffic in each direction, these facilities are separated by a median and commonly have speed limits of 50 mph or greater. As traffic levels increase, stop controlled intersections are typically signalized to reduce delay or enhance safety. It is the safety performance of these signals that is the focus of this thesis.

At-grade expressway intersections are the location of many crashes, and are almost always controlled by a stop sign or a traffic signal. At stop-controlled intersections, as traffic levels increase, cross-street drivers may be forced to accept increasingly shorter and fewer gaps. At light traffic levels, mainline drivers may experience unnecessary delay if signal-controlled. Adding signals may not increase safety, rather, the types and severities of crashes may shift. Turn lanes may be used to separate some movements to reduce some rear end crashes. Intersection skew is also a factor, particularly at angles of less than 75°.

This study presents four methods of analysis. Cross classification compares the safety performance of a large number of signalized and unsignalized locations. Matched (or yoked) pairs are then identified within the larger set of intersections to provide a controlled comparison. Conventional before and after analysis is then used to compare the safety performance for a smaller set of intersections. Finally, Empirical Bayes is employed to evaluate the safety impact of signalization.

Thesis Objectives and Outline

The first objective of this study is to assess the safety impact of signalization at high-speed expressway intersections. A second objective is to compare the results of the classical methods to those that may be obtained from the Empirical Bayes method, a technique which is new to many safety analysts. Negative Binomial models are developed using the entire database and for the matched pairs.

This report is organized into six sections. Following this introduction, the second chapter presents a brief review of existing intersection and expressway safety and statistical literature. The third chapter discusses the process used to create the databases used in this study, including intersection and crash selection techniques which make use of existing databases and aerial imagery. The fourth chapter presents the four analysis methods. In this chapter, material is presented to facilitate several key comparisons of intersection types and analysis methods, as described by the following bullets and Figure 1:

- comparison of all intersections (cross classification)
- comparison by speed group (50&55 to 55-mph only)
- comparison of unsignalized to signalized (or before to after) intersections
- comparison of methods (cross classification, matched (yoked) pairs, Before & After, EB)
- comparison of total to modified crash cost (discounting the value of the first fatal crash)
- comparison of collision types

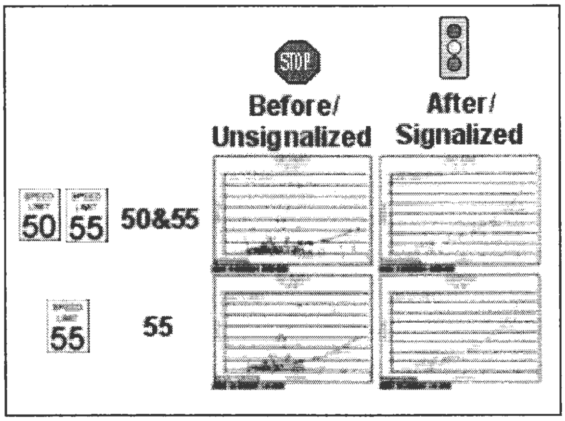

Figure 1: Convention for presentation of Comparisons

The final chapter of this thesis presents results, a summary of the safety impact of installing traffic signals at the high speed expressway intersections and a discussion of the policy implications of choice of analysis method.

Chapter 2: Literature Review

A principal focus of FHWA is intersection safety (1). In 2002, 20% or nearly 10,000 crash fatalities in the US occurred at intersections. Half of the nation's three million injuries occur at these locations. Signals are sometimes considered appropriate safety measures to address intersection safety problems. In fact, Warrant Seven for installation of traffic signals listed The Manual on Uniform Traffic Control Devices (MUTCD) is satisfied when an adequate trial of less restrictive remedies has failed to reduce the crash frequency of five or more reported crashes of types susceptible to correction by traffic signal control and minimum vehicle and pedestrian volumes are present.[1] (2).

Safety Characteristics of Unsignalized Intersections

Several studies conclude that error accounts for a large portion of intersection crashes. A study completed in 2000 by Kansas State University reported that driver error (judging vehicle speeds or seeing the vehicles) was the leading cause of failure-to-yield crashes, rather than ignoring the stop sign (3).

Preston and Storm conducted research on Minnesota two-way stop-controlled intersections and reached similar conclusions (4). Their report found that nearly 60% of the right-angle crashes involved vehicles stopping and proceeding into inappropriate gaps. The report also concluded that right angle crashes had the highest frequency of all collision types and accounted for over 70% of the fatal crashes at the intersections.

[1] MUTCD states that any decision to install a traffic signal should be based on engineering judgment not based solely on the "warrants."

Safety Characteristics of Expressway Intersections

High speed expressway intersection research is limited. Some studies recently completed give information on rural two-way stop controlled intersections. One report completed by Maze et al. in 2004 examines expressway segments in Minnesota and Iowa (5). The conclusions indicate an increase in crash rate as the volume on the segment increases. The research concludes that the increase in crash rate is mainly due to turning movements (mostly at intersections).

A second report by Maze et al. in 2004 extended the previous report by performing detail research on rural expressway intersections in Iowa (6). The researchers looked at intersection characteristics, such as approach volumes (major and minor), median width, and turn lanes, for the impact on safety. Their findings concluded that minor/side road volume had the strongest relationship to crash frequency for a particular intersection followed by major/expressway volume and median width.

Safety Characteristics of Signalized Intersections

Extensive research has been conducted on signalized intersections. Much of the research focuses on treatments for improving safety. A study conducted by the Midwest Research Institute examined the impact of geometric design, traffic control, and traffic volume for at-grade intersections (7). The installation of turn lanes was found to significantly improve intersection safety performance.

Two recent examine the effects of signalizing intersections. The first study, completed in 2001 by Thomas and Smith, examined different improvements that could be made to an intersection in Iowa (8). One of the improvements was installing traffic signals only. The researchers concluded that traffic signal installation reduced the total number of crashes at 16 intersections by 27%. The researchers also concluded that signal installation decreased right angle crashes by 71% and increased rear-end and left turn crashes by 44% and 41% respectively.

The second study, completed in 2004 by Sarchet (draft report), examined the safety effect of signalizing intersections in Colorado (9). The researcher examined 112 intersections that were signalized between January, 1993 and January, 2000. The study examined 65 crash characteristics (including crash/injury severity, crash type, light conditions, weather, and driver factors). Each characteristic was compared before and after signalization at each intersection and across all intersections. The researcher concluded that the total number of crashes increased at 75% of the intersections and increased the total number of crashes by 75% (contradicting the previous study). Only five of the 65 attributes decreased (or increased to a lesser amount) as compared to the increase in traffic volume at the intersections (these include broadside and overtaking turn crashes). Twenty-six attributes increased a greater amount than traffic volume (these include property damage only, injury, multi-vehicle, rear-end, and approaching turn (left turning) crashes and persons injured). It should be noted that confidence intervals were created for the attributes and were used in the comparison to the traffic volume increase.

Statistical Methods

Transportation Research Record No. 1897 is a collection of papers discussing various statistical methods. The paper by Oh, Washington, and Choi discusses Poisson and Negative Binominal regression processes, validation techniques, and variables used in creating three models of various intersection configurations (10). Variables that were considered include volume on approaches, driveways near intersection, percent of trucks, turning traffic (percent) during peak periods, speed, and intersection geometrics.

A paper by Hauer discusses the modeling process in general (11). The author explains how to select variables and the statistical background of the process. Hauer continues by giving an alternate way (from the Oh et al. paper) of verifying the model.

Another paper by Hauer, Council, and Mohammedshah looks at creating models for four-lane undivided roads in urban settings (12). The authors concluded that volume, commercial driveways, and speed limit were good variables to include in the model; where vertical alignment and lane and shoulder widths were not as good variables to include.

The paper by Zimmerman and Bonneson show the procedure researched to determine the number of vehicles in the dilemma zone at high speed signalized intersections (13). The authors feel that the number of vehicles in the dilemma zone should be a surrogate to estimate the safety of the intersection. However, no comparison was performed with direct evidence between crashes and vehicles in the dilemma zone.

The paper by Ivan discusses an alternative way to perform crash rate analysis (14). The author suggests using hourly traffic counts for crash rates instead of the daily traffic counts currently being used. The paper reports type of vehicular crashes varies based on the flow rate of the road.

The study that Midwest Research Institute performed on intersection improvements also compared statistical methods (7). The researchers evaluated yoked comparison, comparison group, and Empirical Bayes (EB). The authors recommend using EB were applicable, as EB accounts for the potential regression to the mean. When EB cannot be applied, the comparison group analysis was recommended (slightly) over the yoked comparison.

Hauer wrote a tutorial paper dedicated to EB (15). The author describes procedures that researchers could follow for estimating crashes along a road segment with one year or three years of crash records, applying accident modification factors, multiple segments, crash severity, and at an intersection. The procedure the author wrote for intersections was followed in the EB analysis used in this research.

To summarize, many reports discuss the possible impacts intersection treatments may have on safety (signalized and unsignalized), but few discuss the signalization impact at high-speed expressway intersections. This report will attempt to fill the gap in available literature and document the safety impacts of installing a traffic signal at a high speed expressway intersection.

Chapter 3: Data Preparation

While a centralized database for road segment characteristics is maintained by the Iowa DOT, it does not contain specific intersection[2] data (e.g., date of signal installation). A previous study (Hallmark) created a point database for all intersections in the State, but contains no attribute information. A different study (Garrett) produced a point file of unsignalized expressway intersections (45 mph or greater.) The DOT also maintains crash data which indicates the type of control present at the time of the crash.

The first step in creating a database of high speed expressway intersections was to select road elements from the DOT file meeting the following criteria: more than 4 lanes, presence of a median, not fully access controlled, and speed greater than or equal to 50 miles per hour.

Identification of signalized locations

From the DOT database, adjacent non-expressway road segments were selected, and queried for the presence of signal control. Nodes within 200 ft of any signalized high speed expressway segment were labeled and stored as a possible high speed intersection location. Figure 2 illustrates the erroneous selection of some intersections which were manually removed from the database. For each of the identified intersections, aerial imagery was examined to verify the presence of a traffic signal.

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[2] The database was not completely consistent with regard to identifying presence of signal, and did not include signal installation or modification date and hence was not capable of identifying all of the intersections of interest in the State.

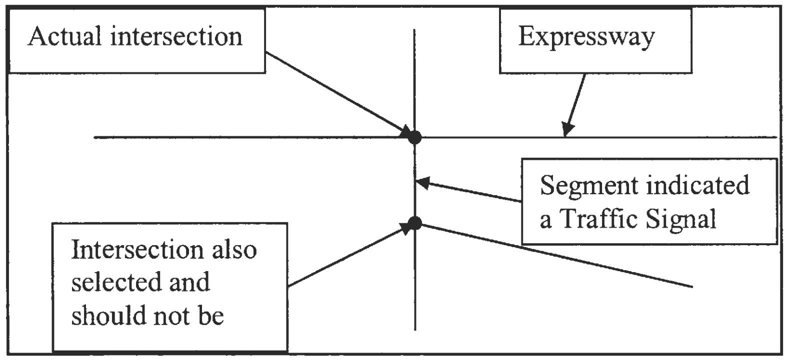

Figure 2: Intersection Identification Problem

For each signalized location, traffic volume and date of expressway construction were obtained from the DOT database. Date of installation was approximated from consistent reporting of presence of signal in the crash database. Figure 3 illustrates the method used to approximate date of installation. In the example, note that prior to 1996, most crash reports indicated no signalization. Similarly after 1996, stop control was reported infrequently. To confirm our estimates, the final list of installation dates was shared with DOT district personnel and in two cases, with local officials.

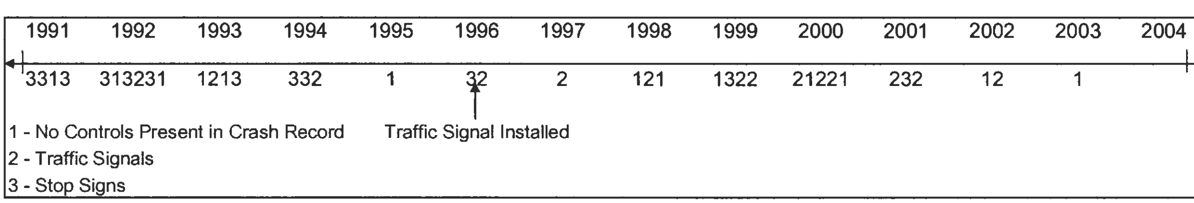

Figure 3: Example of Estimating the Date of Traffic Signal Installation

Identification of signalized locations

To create a comparison group of unsignalized locations, intersections were selected where minor road volumes were similar to the minor road volumes of the signalized locations. Aerial images at each of the intersections were examined to verify the intersections were unsignalized. Presence of turn lanes, median type, and skew angle (from the aerial photo) and traffic volume and speed limit (from the DOT database) were used to match the intersections. As the aerial photos sometimes suggested presence of a signal, higher resolution imagery was examined. For example, in Figure 4, a faint indication of the signal masts can be seen, confirmed the by higher resolution photography shown in figure 5.

Figure 4: Aerial Image Signalized Expressway Intersection

Figure 5: Higher Resolution Image

After the study intersections were identified, crash data were assembled. The allocation of crashes to an intersection can be subjective. One must use spatial proximity, but attribute queries should also be used for this process. As illustrated in Figure 6, the number of crashes assigned to a given intersection varies with selection methodology. In the figure, concentric circles show the approximate number of crashes at an intersection using 3 methods. The blue (outer) circle indicates the number of crashes within 150 feet. The yellow (middle) circle shows the number of crashes that are within 150 feet and where attributes indicate that an intersection crash is possible. The red (inner) circle shows the number of crashes that are likely to be intersection related using additional attribute queries. Two groups of attributes were used to define “possible” or “likely.” “At or near intersection” or similar, as indicated in the crash database, comprise group one. Group two indicates the type of crashes that occur at intersections (i.e. right angle, rear end). “Possible” is defined as meeting one or the other group types, whereas “likely” is defined by the indication of both attribute group types.

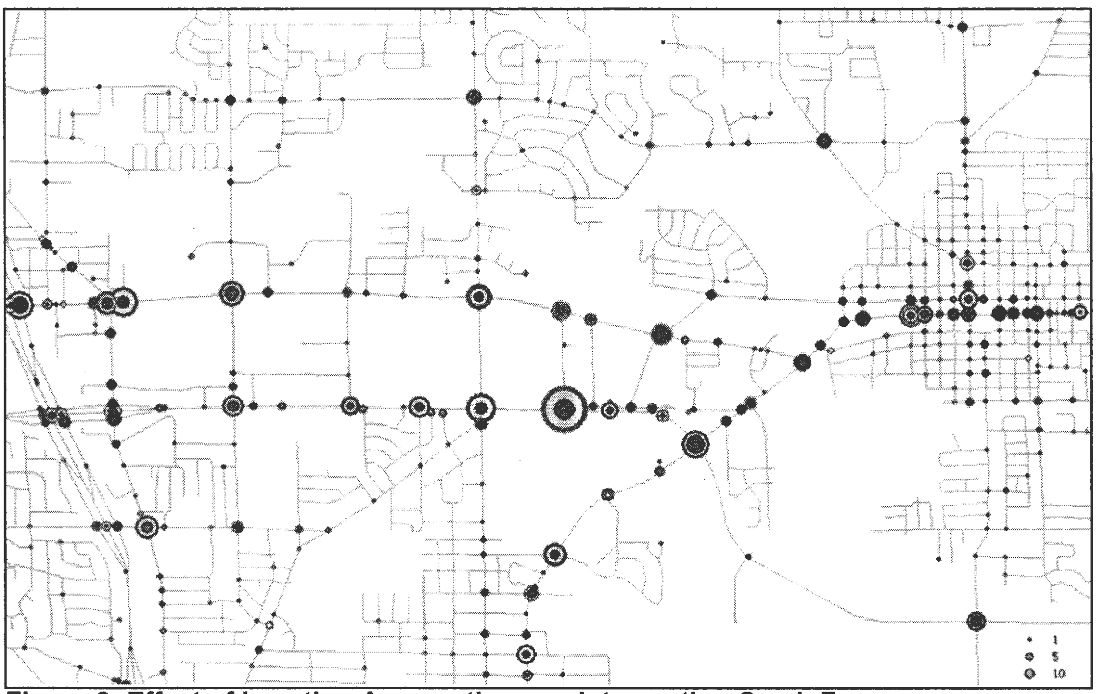

Figure 6: Effect of Location Assumptions on Intersection Crash Frequency

Figure 7 shows how the number of intersection related crashes would vary based on selection criteria over the time of interest of this study. Methods illustrated include:

- crashes within 500 ft or 150 ft.
- crashes that are “possibly” or “likely” to be intersection related

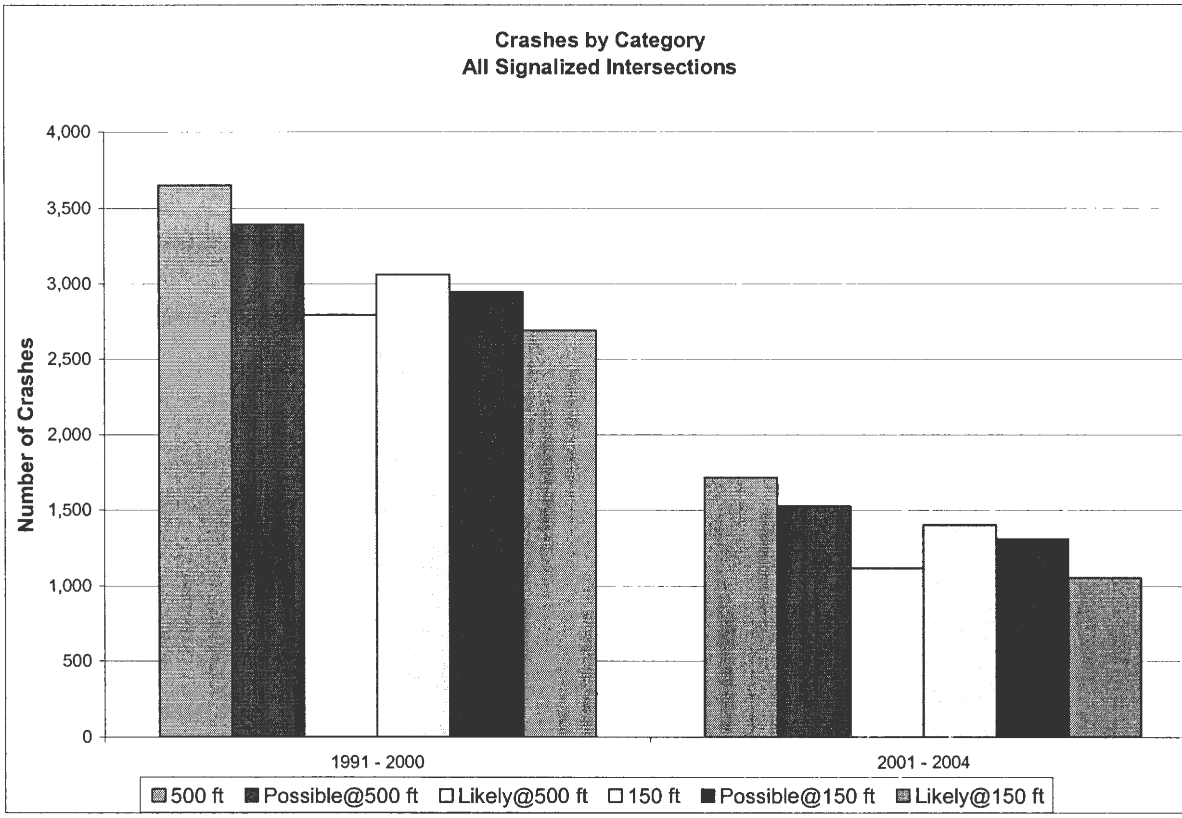

Figure 7: Crash Frequency by Location Assumption, 1991-2004

Limitations

Crashes prior to 2000 were located using a link-node system (nodes are typically an intersections). After 2000, crashes were located geo-spatially. Nodes (prior to 2000) and cartography (post 2000) are updated periodically, resulting in some discrepancies between crashes located on older versions and more recent crashes tied to underlying road cartography and attributes. To account for these spatial inaccuracies, intersection locations were located using both 1998 and the 2003 alignments. (It was determined that the 1998 and 2003 alignments had the largest discrepancies. Locating intersections along both alignments would account for all other shifts.) An problem creating two sets of intersections is illustrated in Figure 8. If the second location was offset from the expressway and/or the side road alignment, crashes could be selected that were outside the 150 ft spatial tolerance (intersection-related selection criteria may have eliminated these crashes, but was not verified). Within the study timeframe, the minimum crash reporting threshold also changed. During the time of interest of the study, the crash reporting form changed (2001). For 2001, approximately 5,000 of the 62,000 crashes were reported on the old form and have not been coded to the new form (and consequently are not in the database). (To account for the report form change, a second list of crash properties, used to determine intersection related crashes, was created and separated into two groups that are similar to the previous groups.)

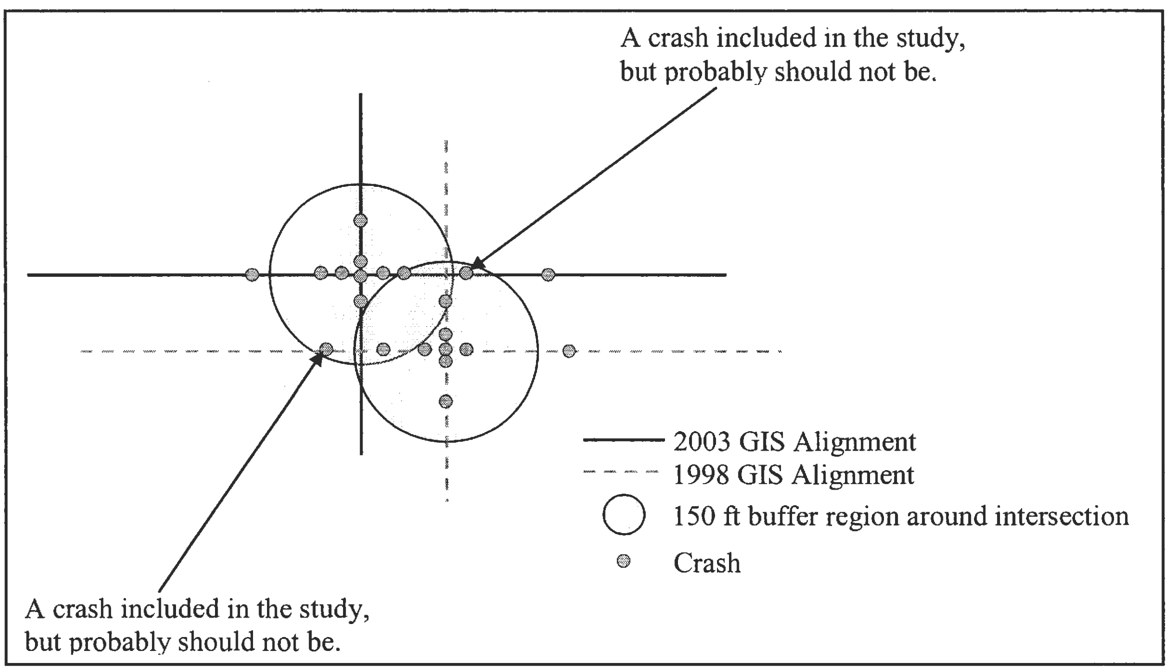

Figure 8: Crash Selection Problem

Using the Iowa DOT's injury severity costs, each crash was assigned a value depending on the severity. After assignment of an intersection identification number, the total number of crashes and total crash cost were identified for each intersection. To reduce the impact of the high cost of the rare fatal crash on the analysis, intersections with at least one fatal crash were modified by reducing one fatal crash to a major injury creating a modified crash cost, to facilitate comparison with the full cost analysis. Crash frequency was computed by intersection id for each type of collision. With the two different crash forms, a set of five collision types were created to be consistent with other reports and lists of collision types from the crash forms were created to match the set. Table 1 shows the definition of collision types for each of the two crash report forms used during the study period. Crash rates were developed for each collision type.

Table 1: Collision Types by Crash Report Form

Collision Type	Pre-2001 Crash Form	After 2001 Crash Form
Head-on	Head-on Head-on/Left Entering	Head-on
Broadside/Right Angle	Broadside/Left Turn Broadside/Right Angle Broadside/Right Entering Broadside/Left Entering	Broadside Angle, Oncoming Left Turn
Rear-end	Rear-end Rear-end/Right Turn Rear-end/Left Turn	Rear-end
Sideswipe	Sideswipe/Opposite Direction Sideswipe/Same Direction Sideswipe/Right Turn Sideswipe/Left Turn Sideswipe/Dual Left Turn Sideswipe/Dual Right Turn Sideswipe/Both Left Turning	Sideswipe/Same Direction Sideswipe/Opposite Direction
Other	Single Pedestrian Bicycle Parked Vehicle Other Unknown	Non-collision Unknown Not Reported

After the crash data were gathered for all the intersections, subsets of the intersections were queried to facilitate additional cross classification. The first subsets were all 55-mph intersections (unsignalized and signalized) giving a comparison of highest speed signalized expressway intersections. Subsets were created from the 50&55-mph and 55-mph intersections by matching signalized intersections to the unsignalized intersections. Finally, subsets containing only intersections that were signalized between January, 1994 and January, 2002 were created for the before and after analyses.

Once all the data were collected, analysis began by analyzing all expressway intersections. The analysis consisted of creating three safety performance functions (SPFs) (a technique used to estimate crash characteristics using unique variables to the crash location) and comparing crash rates of the type of collision. The SPFs were developed using SAS to generate negative binomial models. The first SPF modeled the total number of crashes as a function of volume – total daily entering vehicles (DEV). The next SPF modeled the total crash cost as a function of total DEV. The third SPF modeled a modified crash cost as a function of total DEV. A fourth analysis examined the crash rate against the type of collision that occurred.

Chapter 4: Analysis and Results

Two intersection speed classes were analyzed in this study: 50&55-mph and 55-mph. The safety of *signalized* as compared to *unsignalized* intersections was assessed using cross classification, matched intersection pairs, before and after analysis, and EB analysis. The following sections compare crash performance, crash cost, modified[3] crash cost and collision type.

Each section compares performance of 50&55-mph intersections to 55-mph only intersections. The total database of 50&55-mph intersections contains information on 182 unsignalized and 67 signalized intersections in Iowa. Fifty-nine unsignalized and signalized intersections were chosen for matched pairs analysis. The before and after and EB analyses use information on 19 intersections signalized between January 1, 1994 and January 1, 2002.

The total database for 55-mph intersections contains information on 158 unsignalized and 45 signalized intersections in Iowa. Forty-five unsignalized and signalized intersections were chosen for matched pairs analysis. The before and after and EB analyses use information on 12 intersections signalized between January 1, 1994 and January 1, 2002.

Cross Classification Analysis

This section presents the results of a cross classification analysis across all high speed expressway intersections using data for crashes occurring between January 1, 2002 and January 1, 2005. The sample of 182 50&55-mph unsignalized

[3] The crash cost analysis uses the Iowa DOT's crash cost values for various injury severity levels, and examines both total and modified crash cost (To reduce the effect of fatal crashes, the first fatal crash is considered as a major injury crash).

intersections had an average of 2.6 crashes in three years and an average traffic volume of 11,100 DEV. The corresponding sample of 67 signalized intersections had an average of 18 crashes in three years and an average traffic volume of 18,300 DEV.

The sample of 158 55-mph unsignalized intersections had an average of 2.6 crashes in three years and an average traffic volume of 10,900 DEV. The corresponding sample of 45 signalized intersections had an average of 16.9 crashes in three years and an average traffic volume of 17,000 DEV. Table 2 compares crash severities and fatalities for these intersections.

Table 2: Crash Severities & Fatalities for All Intersections

	50 + 55 mph Intersections		55 mph Intersections	
	Unsignalized	Signalized	Unsignalized	Signalized
Fatal Crashes	10	7	10	6
Fatalities	12	7	12	6
Major Injury Crashes	24	38	19	25
Minor Injury Crashes	68	124	57	74
Possible Injury Crashes	98	238	86	145
Property Damage Only Crashes	276	802	241	510

Cross Classification Models

Negative Binomial models are fit to the data. Previous research indicates that traffic volumes for both major and minor approaches affect the safety at intersections (5). For the available Iowa data, various model forms were tried including the use of total DEV, major and minor DEV, major*minor DEV (to account for interaction) and minor DEV only as independent variable. A comparison of model performance can be seen in Table 3. For model evaluation, Rho-squared[4] and P-values were

[4] Rho-squared is comparable to R-squared in that it represents how well the independent variable describes the variation in the dependent variable (in this case, the dependent variable was either

calculated using LIMDEP 7.0. Models based on total DEV had the most comparable average values to the actual data, the highest Rho-squared values (for unsignalized) and best P-values (for signalized). Two outliers in the data base (intersections with very high minor road volumes) created significant problems with the unsignalized models based on minor road DEV.

No models had superior P-values, rho-squared values and comparable average values, therefore, the models using total DEV as the independent variable were used in this study[5].

For consistency, total DEV was used to model crash cost, modified crash cost and matched pair data presented below. Models, p-values and rho-squared statistics are provided on each graph, as applicable.

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crashes, total crash cost, or modified crash cost). Rho-squared values range from zero to one with zero not describing the variation well and one describing the variation flawlessly.

[5] It is important to note that while a single model with an indicator variable for presence of signal could be developed to test the significance of the impact of signalization, a main purpose of this study was to evaluate the difference between classical and Empirical Bayes results. As EB requires a single safety performance function (SPF) be developed for the specific type of intersection studied (signalized or unsignalized), we developed models for each type separately. To test the significance of the signalization, confidence intervals were placed around each model form (see figure 9). Clearly, as the confidence intervals overlap, there is no statistical difference between the models for signalized and unsignalized intersections.

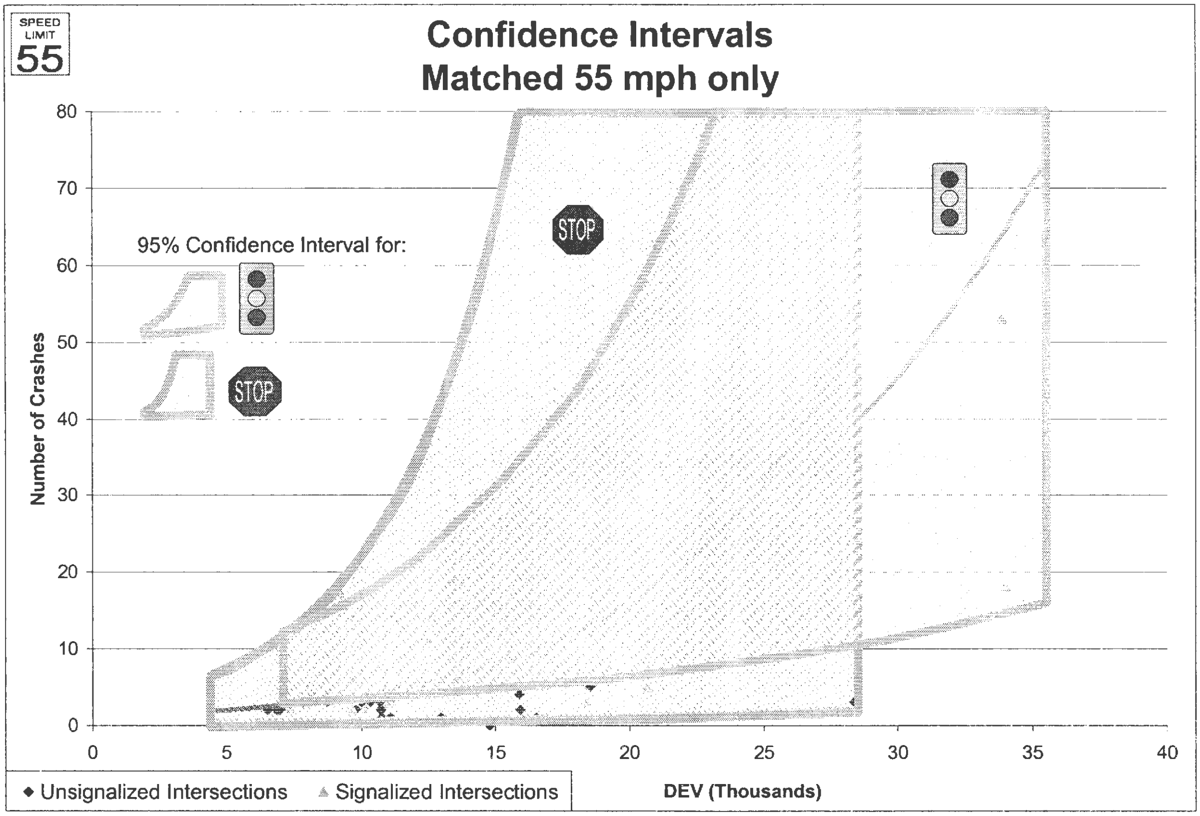


Figure 9: Confidence Intervals for Crash Models

Table 3: Model Comparisons

50&55 mph Intersections

	Actual Data			Based on Total DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized	Signalized	% Difference
Average Crash Rate	21.1	84.3	299.5%	21.3	86.5	306.1%
Rho-Squared Value (Crash Model)				0.331	0.285	
P-value (intercept)				0.6683	<0.0001	
P-value (coefficient)				0.0003	<0.0001	
Average Crash Cost	$44,046	$18,994	56.9%	$44,856	$21,141	52.9%
Average Modified Crash Cost	$27,838	$14,007	49.7%	$22,523	$13,749	39.0%
Number of Intersections	182	67		182	67	

	Based on Major & Minor DEV			Based on Major & Minor DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized [#]	Signalized	% Difference
Average Crash Rate	60.2	86.4	43.5%	23.6	86.4	266.1%
Rho-Squared Value (Crash Model)	0.233	0.270		0.150	0.270	
P-value (intercept)	0.7859	<0.0001		0.7154	<0.0001	
P-value (Major DEV coefficient)	0.5013	<0.0001		0.403	<0.0001	
P-value (Minor DEV coefficient)	<0.0001	<0.0001		<0.0001	<0.0001	
Average Crash Cost	$11,146,343	$20,928	99.8%	$153,083	$20,928	86.3%
Average Modified Crash Cost	$1,167,461	$13,772	98.8%	$42,678	$13,772	67.7%
Number of Intersections	182	67		180	67	

	Based on Minor DEV			Based on Minor DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized [#]	Signalized	% Difference
Average Crash Rate	60	96.6	61.0%	24.3	96.6	297.5%
Rho-Squared Value (Crash Model)	0.232	0.354		0.155	0.354	
P-value (intercept)	0.0589	<0.0001		<0.0001	<0.0001	
P-value (coefficient)	<0.0001	<0.0001		0.0027	<0.0001	
Average Crash Cost	$8,610,682	$19,697	99.8%	$127,569	$19,697	84.6%
Average Modified Crash Cost	$1,220,287	$13,388	98.9%	$43,026	$13,388	68.9%
Number of Intersections	182	67		180	67	

	Based on Major * Minor DEV			Based on Major * Minor DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized [#]	Signalized	% Difference
Average Crash Rate	88.2	92.1	4.4%	21.0	92.1	338.6%
Rho-Squared Value (Crash Model)	0.219	0.332		0.139	0.332	
P-value (intercept)	0.0284	<0.0001		<0.0001	<0.0001	
P-value (coefficient)	<0.0001	<0.0001		0.0033	<0.0001	
Average Crash Cost	$11,938,737	$21,159	99.8%	$85,819	$21,159	75.3%
Average Modified Crash Cost	$2,250,399	$14,003	99.4%	$35,545	$14,003	60.6%
Number of Intersections	182	67		180	67	

Rates are units per HMEV
Hundred Million Entering Vehicles
[#] The 2 highest Minor DEV Unsignalized Intersections were removed

Table 3: Model Comparisons (continued)

55 mph Intersections

	Actual Data			Based on Total DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized	Signalized	% Difference
Average Crash Rate	21.2	96.7	356.1%	21.3	86.6	306.6%
Rho-Squared Value (Crash Model)				0.342	0.302	
P-value (intercept)				0.3265	<0.0001	
P-value (coefficient)				0.0001	<0.0001	
Average Crash Cost	$47,229	$21,861	53.7%	$47,964	$27,010	43.7%
Average Modified Crash Cost	$28,706	$16,269	43.3%	$22,592	$15,279	32.4%
Number of Intersections	158	45		158	45	

	Based on Major & Minor DEV			Based on Major & Minor DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized [#]	Signalized	% Difference
Average Crash Rate	85.6	86.6	1.2%	24.8	86.6	249.2%
Rho-Squared Value (Crash Model)	0.251	0.302		@	0.302	
P-value (intercept)	0.7111	<0.0001		0.8181	<0.0001	
P-value (Major DEV coefficient)	0.7606	<0.0001		0.6796	<0.0001	
P-value (Minor DEV coefficient)	<0.0001	0.0001		<0.0001	0.0	
Average Crash Cost	$36,478,489	$27,499	99.9%	$278,306	$27,499	90.1%
Average Modified Crash Cost	$2,101,706	$15,088	99.3%	$50,293	$15,088	70.0%
Number of Intersections	158	45		156	45	

	Based on Minor DEV			Based on Minor DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized [#]	Signalized	% Difference
Average Crash Rate	86.1	94.8	10.1%	25.3	94.8	-274.7%
Rho-Squared Value (Crash Model)	0.251	0.383		0.149	0.3830	
P-value (intercept)	0.1292	<0.0001		0.748	<0.0001	
P-value (coefficient)	<0.0001	0.0001		<0.0001	0.0001	
Average Crash Cost	$31,313,799	$22,389	99.9%	$172,434	$22,389	87.0%
Average Modified Crash Cost	$2,033,571	$14,520	99.3%	$43,764	$14,520	66.8%
Number of Intersections	158	45		156	45	

	Based on Major * Minor DEV			Based on Major * Minor DEV		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized [#]	Signalized	% Difference
Average Crash Rate	123.4	92.7	24.9%	21.8	92.7	325.2%
Rho-Squared Value (Crash Model)	N/A	N/A		N/A	N/A	
P-value (intercept)	0.0613	<0.0001		0.6653	<0.0001	
P-value (coefficient)	<0.0001	<0.0001		<0.0001	<0.0001	
Average Crash Cost	$28,092,630	$26,445	99.9%	$102,727	$26,445	74.3%
Average Modified Crash Cost	$3,328,138	$16,629	99.5%	$34,434	$16,629	51.7%
Number of Intersections	158	45		156	45	

Rates are units per HMEV
Hundred Million Entering Vehicles
[#] The 2 highest Minor DEV Unsignalized Intersections were removed
N/A - Limdep indicated regressors are collinear
@ - Limdep did not give the same regression equation as SAS

Crash Performance – Cross Classification

Figure 10 compares the performance of signalized to unsignalized, and 50&55 to 55-mph intersections. Figure 11 compares the performance of signalized and unsignalized intersections on the same graph. The Negative Binomial models for each dataset are displayed on the graphs.

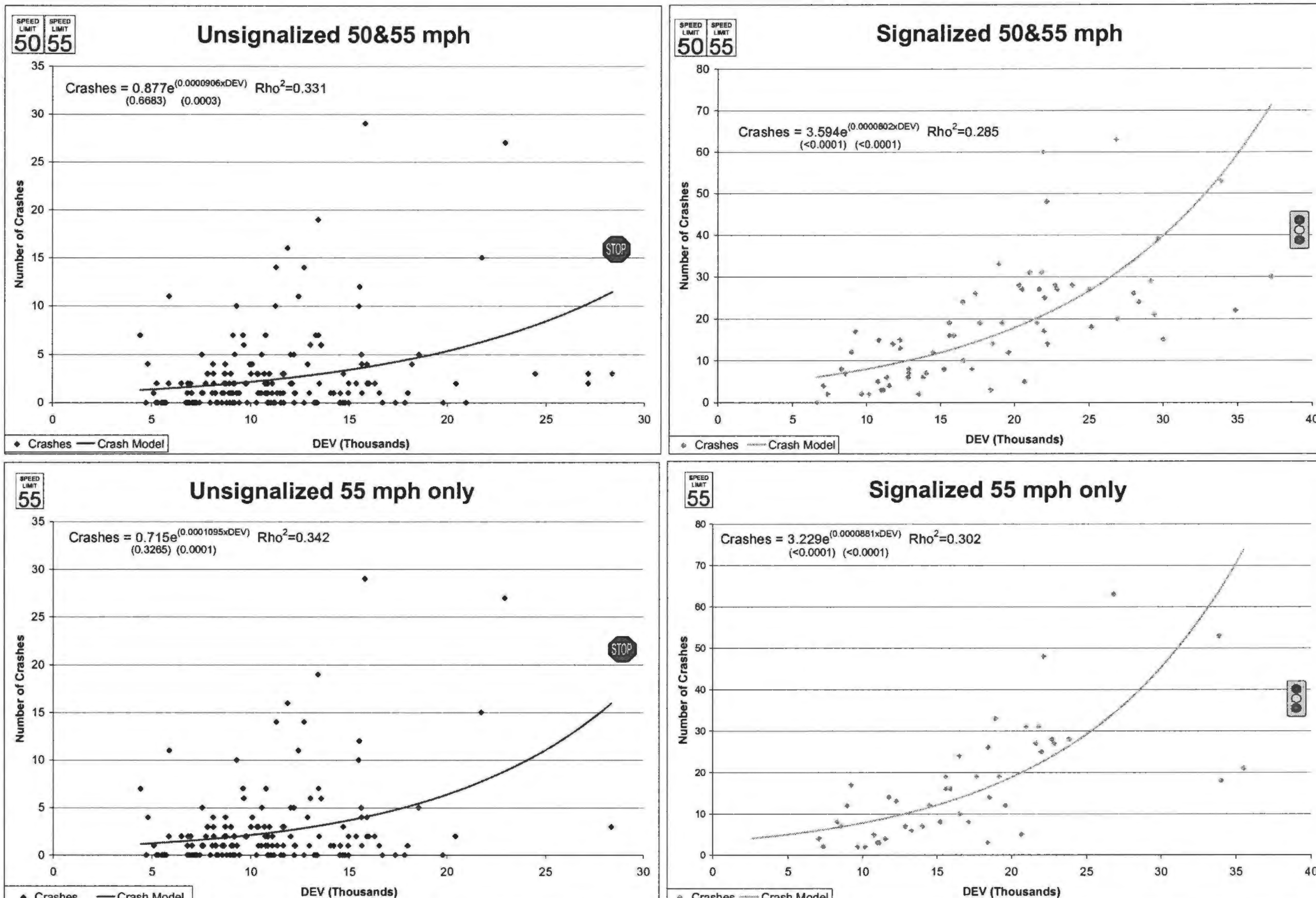
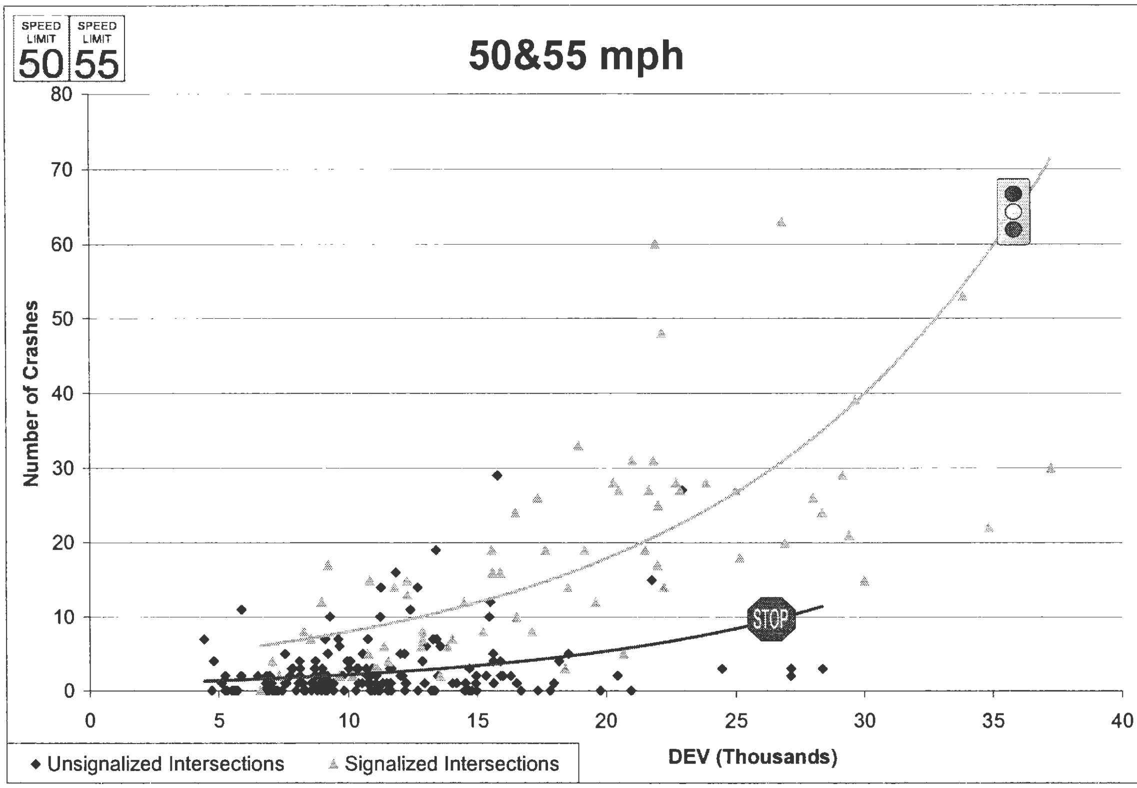


Figure 10: Crash Performance, Cross Classification Analysis, 2002-2004



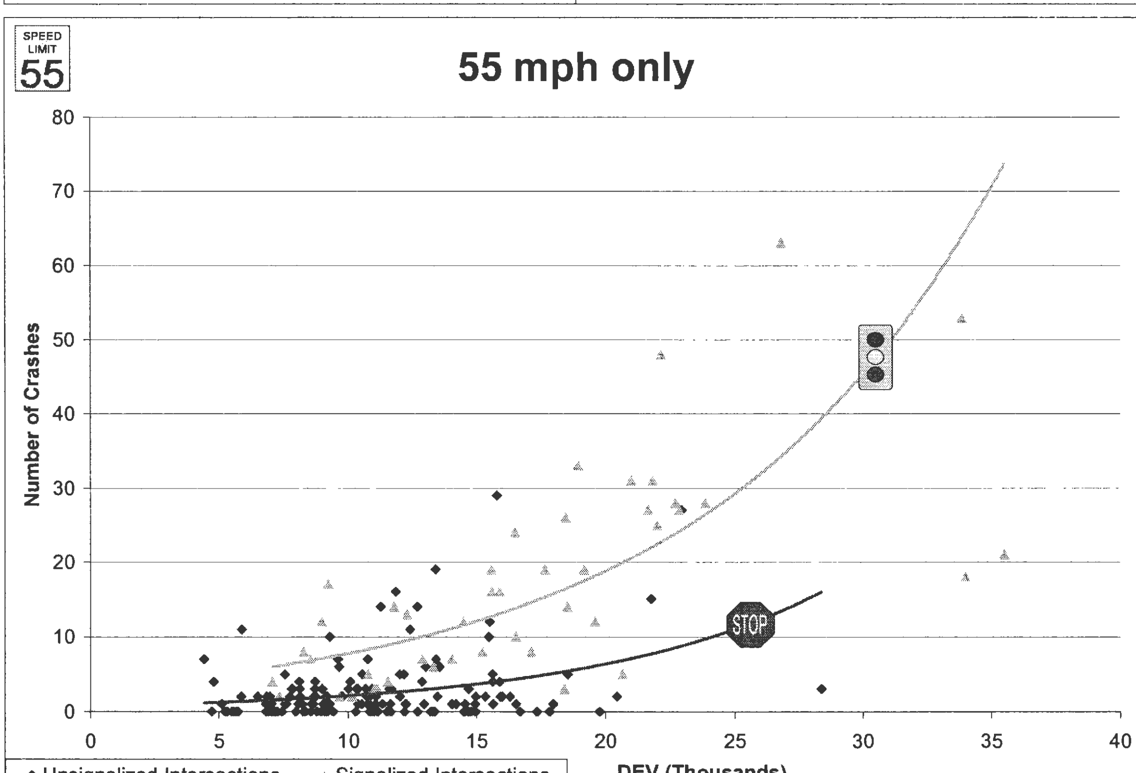


Figure 10: Comparison of Signalized and Unsignalized Crash Performance, Cross Classification Analysis, 2002-2004

Crash Cost – Cross Classification

This section compares crash cost of unsignalized to signalized intersections. Figure 12 presents total crash cost for unsignalized and signalized 50&55-mph and 55-mph intersections. Due to the high cost of fatalities, the data fall into two distinct groups. The intersections grouped in the middle of the figure have one fatal and some less severe crashes. The intersections grouped at the bottom of the figure have mostly property damage only crashes. For unsignalized intersections, fatal crashes are spaced randomly and have little effect of the negative binomial crash cost model which is almost linear. For signalized intersections, fatal crashes seem to be clustered around 20,000 DEV (probably due to randomness and small sample size).

Figure 13 presents modified crash cost, a technique used to reduce the influence of rare fatal crashes on mitigation priority. Circled points indicate where first fatal cost has been reduced to that of a major injury.

To facilitate comparison, Figure 14 presents both the unsignalized and signalized crash costs (total and modified) on the same graphs. Modified cost does not appear to affect the unsignalized intersection analysis as much as the signalized analysis where several intersections with major injuries become a higher priority for mitigation than some with only one fatal.

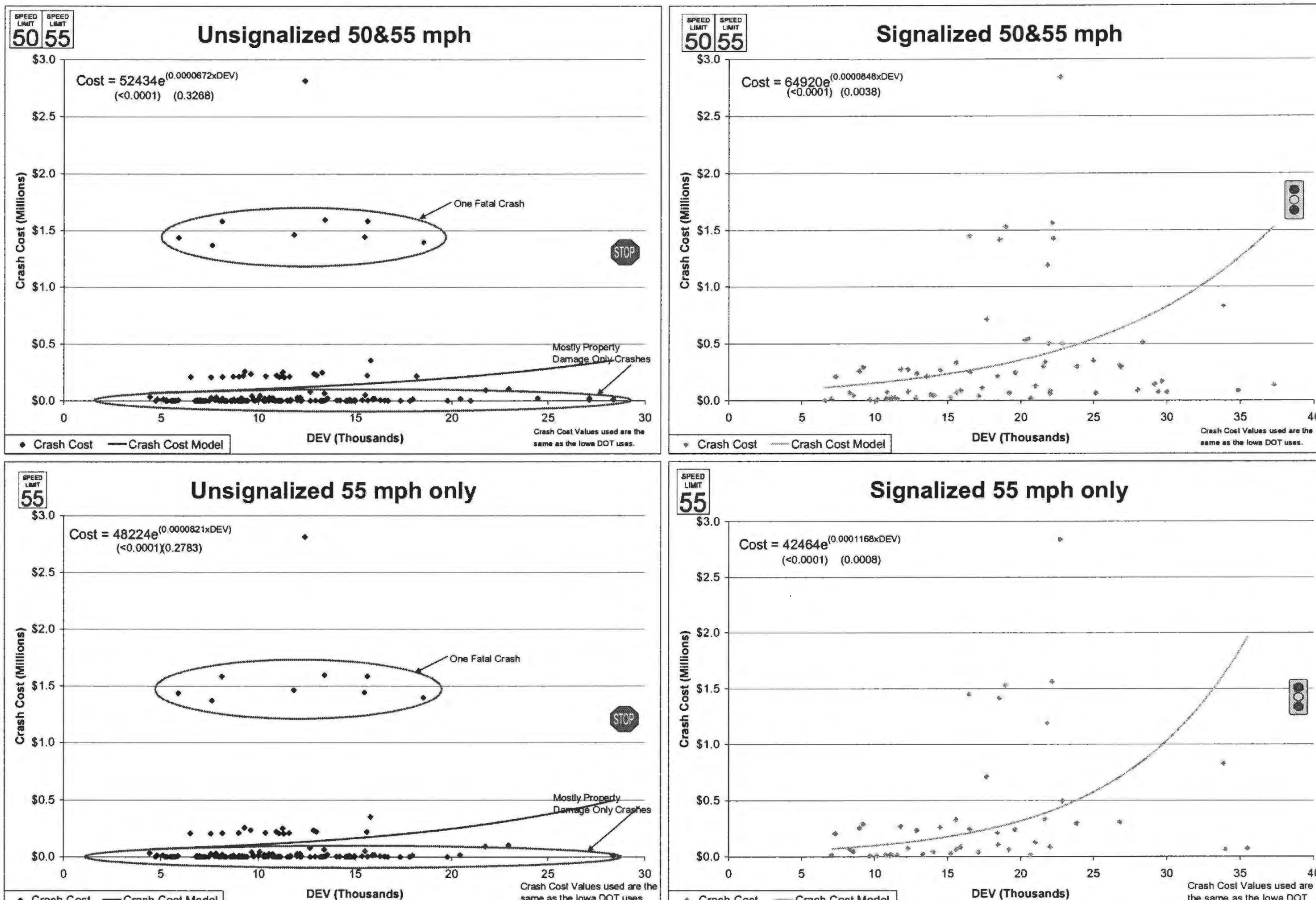


Figure 12: Crash Cost, Cross Classification Analysis, 2002-2004

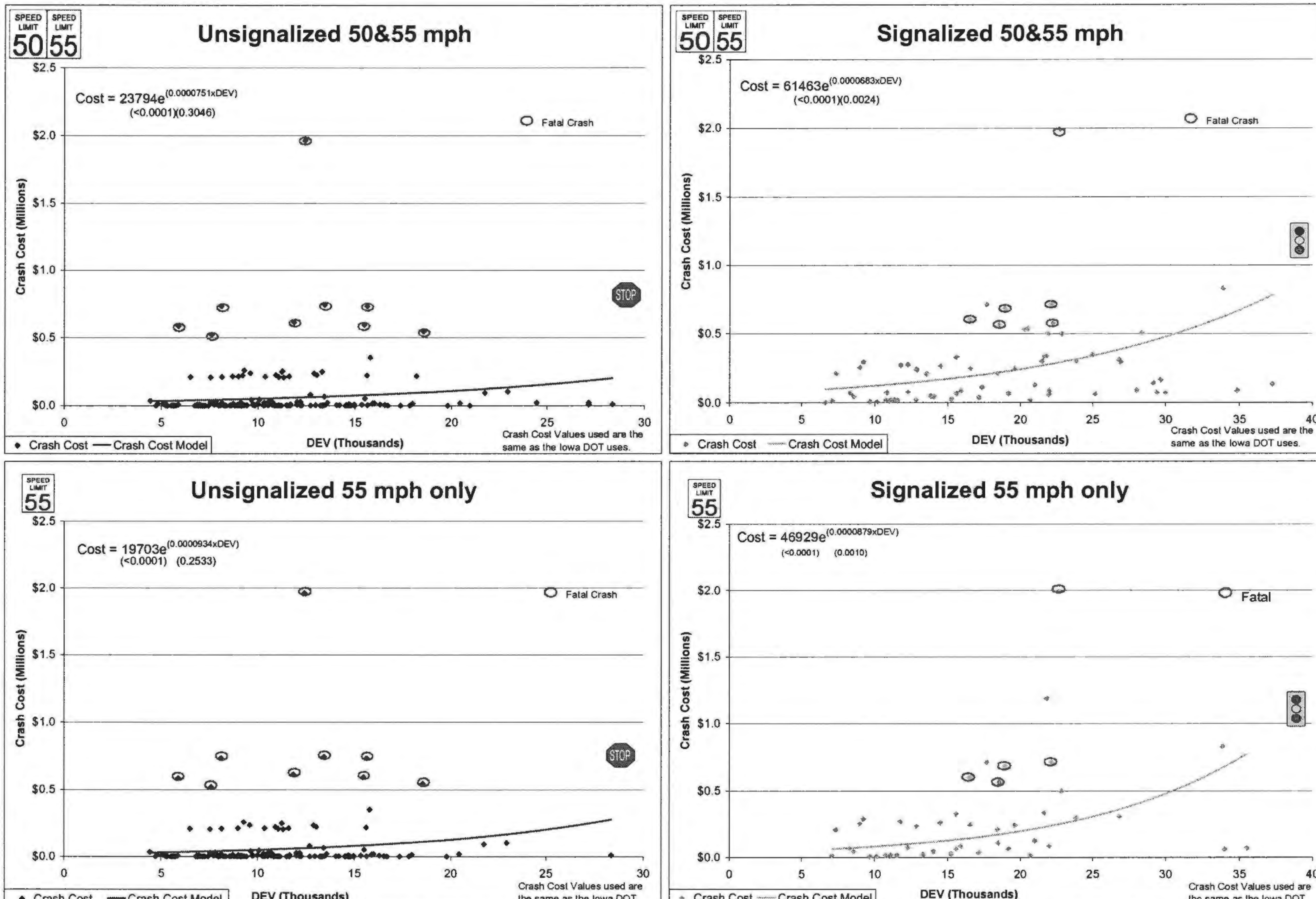


Figure 13: Modified Crash Cost, Cross Classification Analysis, 2002-2004

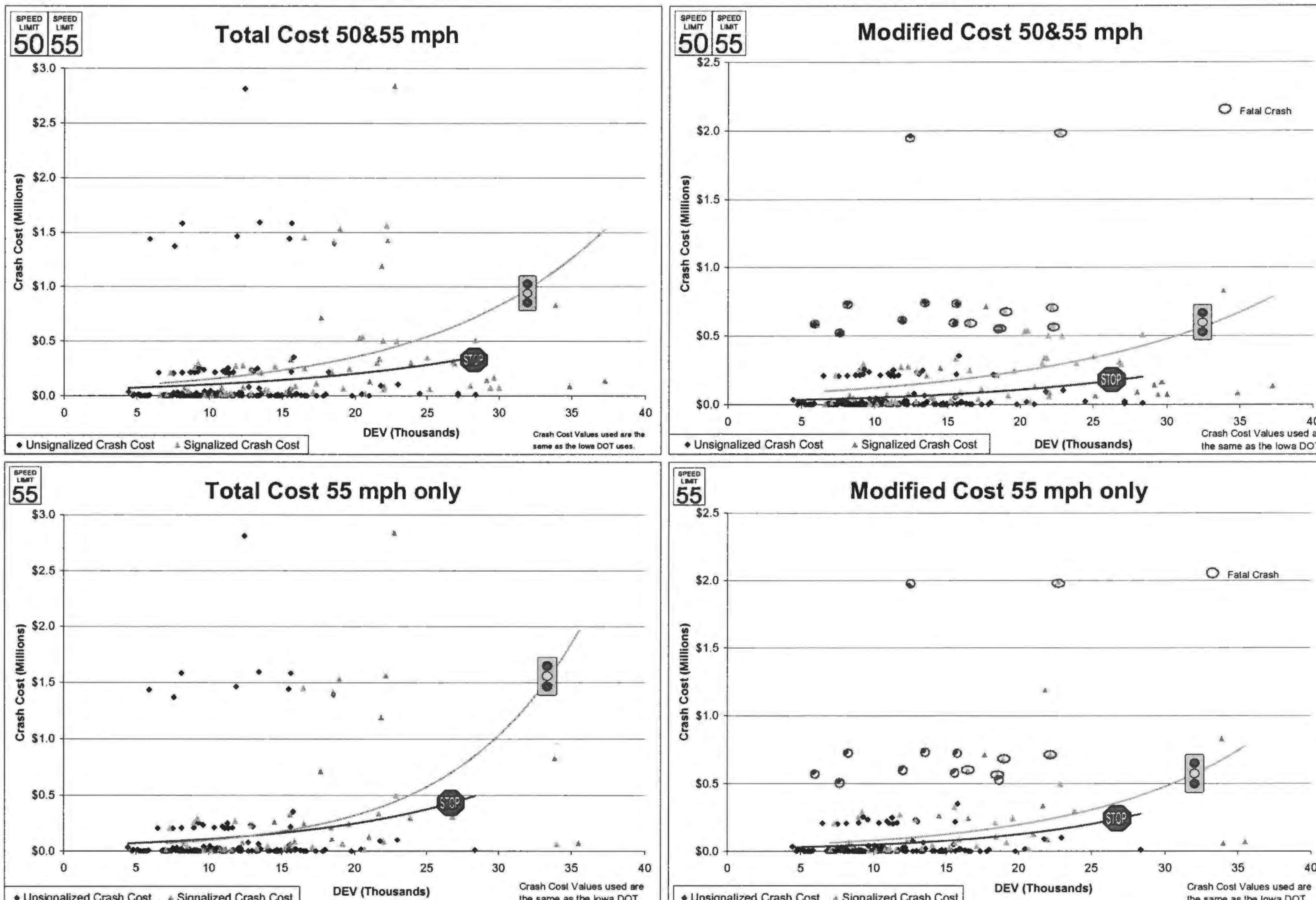


Figure 14: Comparison of Total and Modified Crash Cost, Cross Classification, 2002-2004

Collision Type – Cross Classification

Figure 15 presents the effect of signalization on crash rates for different types of collisions. Rates for broadside, rear-end, and sideswipe crashes for intersections are presented, stratified by volume range (less than 10,000 DEV, 10,000-20,000 DEV, and greater than 20,000 DEV). Intersections with less than 20,000 DEV generally have a higher broadside crash rate. Intersections with greater than 20,000 DEV generally have a higher rear-end crash rate. Interestingly, type of control does not affect these observations, for the cross classified data set.

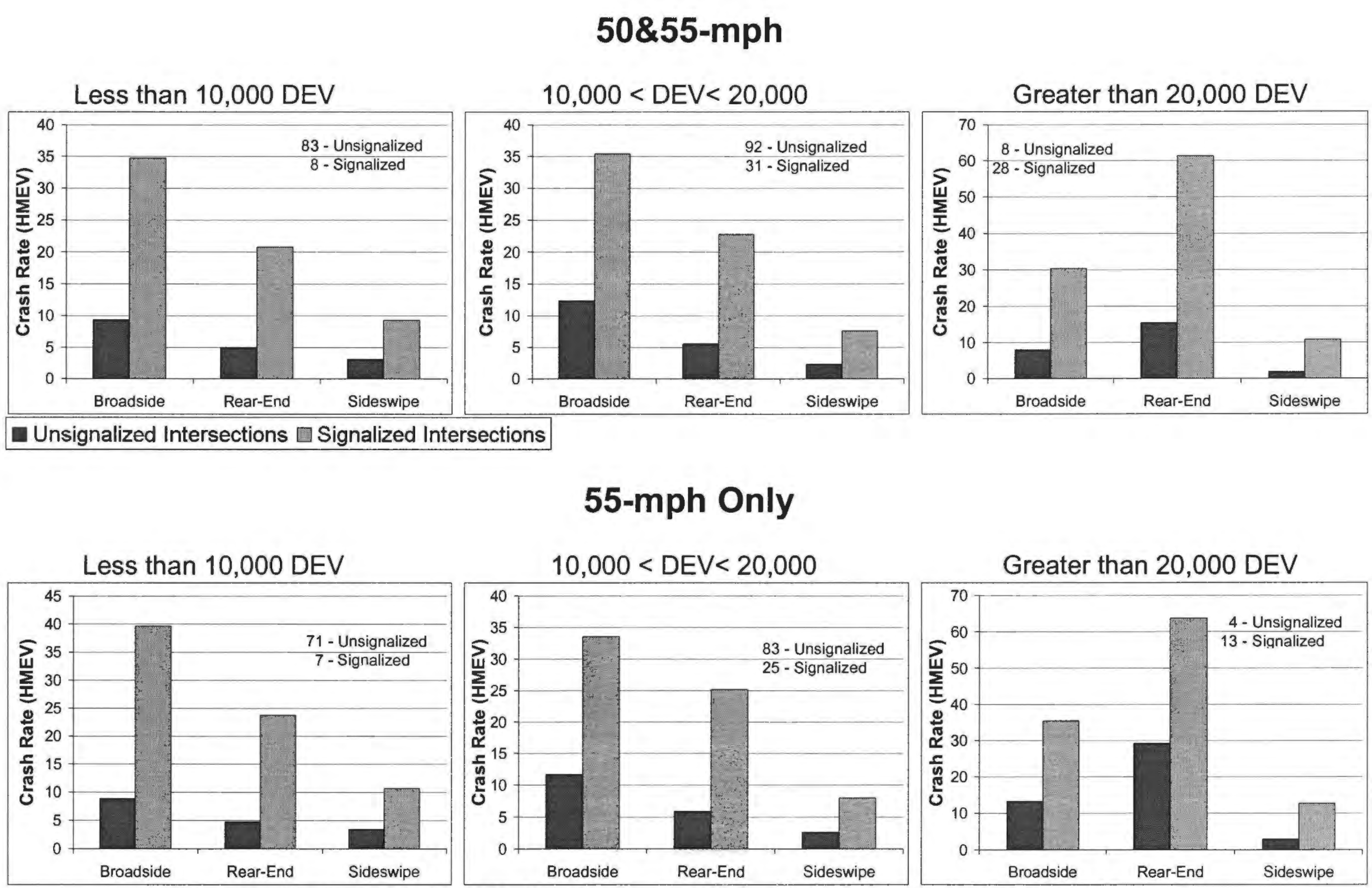


Figure 15: Crash Rate by Collision Type, Cross Classification Analysis, 2002–2004

Matched (Yoked) Pair Analysis

To control for exogenous factors that may influence intersection safety performance, this section presents the results of a matched pairs analysis again using data for crashes occurring between January 1, 2002 and January 1, 2005. Eight of the previously identified 67 signalized 50&55-mph intersections could not be matched to similar unsignalized intersections. The remaining sample of 59 unsignalized intersections had and average of 4.8 crashes in three years and an average traffic volume of 11,900 DEV. The matched sample of signalized intersections had an average of 16.7 crashes in three years and an average traffic volume of 18,000 DEV.

All 45 signalized 55-mph intersections were matched to similar unsignalized intersections. The sample of 45 unsignalized intersections had an average of 5.8 crashes in three years and an average traffic volume of 11,600 DEV. The matched sample of signalized intersections had an average of 16.9 crashes in three years and an average traffic volume of 17,000 DEV. Table 4 compares crash severities and fatalities for these matched intersections.

Table 4: Crash Severities & Fatalities for Matched Intersections

	50 + 55 mph Intersections		55 mph Intersections	
	Unsignalized	Signalized	Unsignalized	Signalized
Fatal Crashes	6	6	6	6
Fatalities	7	6	7	6
Major Injury Crashes	8	33	7	25
Minor Injury Crashes	43	99	42	74
Possible Injury Crashes	57	186	54	145
Property Damage Only Crashes	167	664	153	510

Crash Performance – Matched Pairs

Figure 16 compares the performance of signalized to unsignalized, and 50&55 to 55-mph matched-pair intersections. Negative Binomial models for each dataset (using DEV as the independent variable) are displayed on the graphs.

Figure 17 compares the performance of signalized and unsignalized intersections on the same graph. Signalized intersections generally have higher crash frequency for a given traffic level except in the case of 55-mph locations with DEV above 23,000 DEV. However, the model at this point for unsignalized intersections has been extrapolated. Further, confidence in the intercept coefficient of the unsignalized model is low (high p-value).

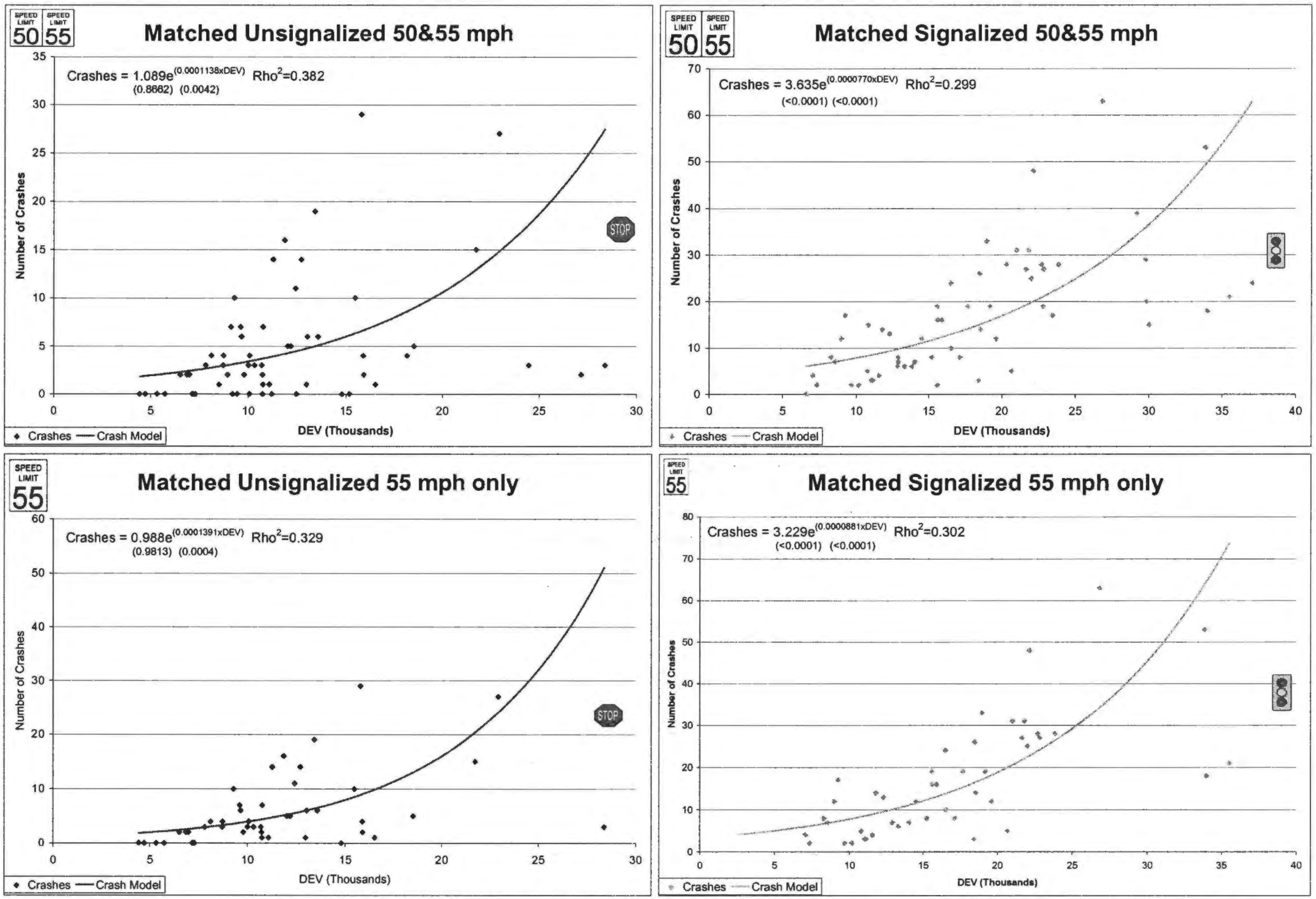


Figure 16: Crash Performance, Matched-Pair Analysis, 2002-2004

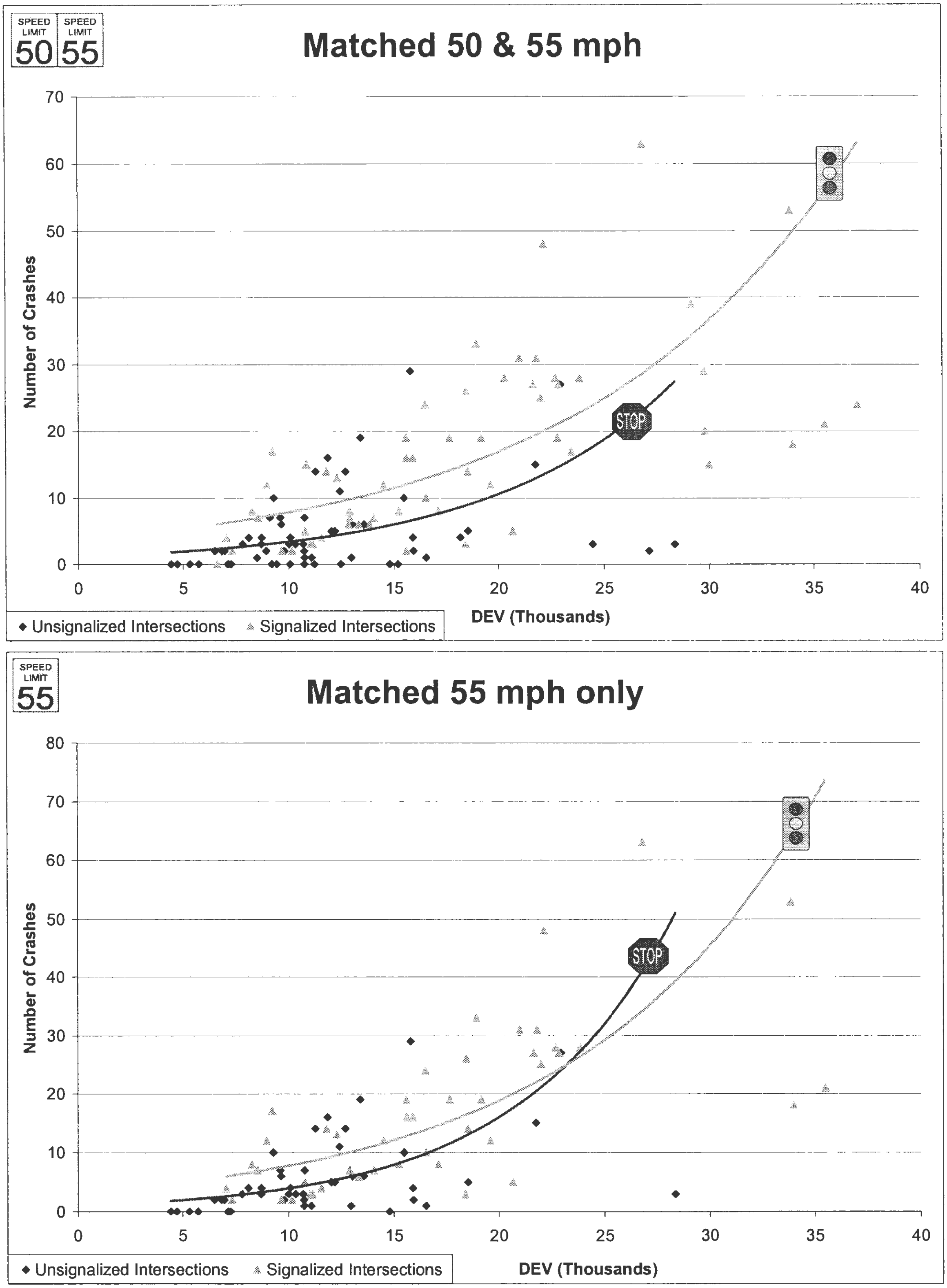


Figure 11: Comparison of Signalized and Unsignalized Crash Performance, Matched Pair Analysis, 2002-2004

Crash Cost – Matched Pairs

This section compares the crash cost of matched intersection pairs. Figure 18 shows the total crash cost of the matched intersections. Figure 19 compares modified crash cost. Again, circled points indicate where first fatal cost has been reduced to that of a major injury. The intersections with fatal crashes appear randomly with respect to DEV. Most of the intersections have quite low crash costs, and fatal crashes have little effect of the crash model. The signalized intersections generally have a higher crash cost than their unsignalized counterparts and fatal crashes are again clustered around 20,000 DEV.

In keeping with the graphing convention presented in the cross-classification analysis, Figure 20 presents both the unsignalized and signalized crash costs (total and modified) on the same graph to facilitate comparison. The figure indicates that if the matched-pair analysis was to be used to prioritize intersections for improvement, cost modification would have little effect on priority.

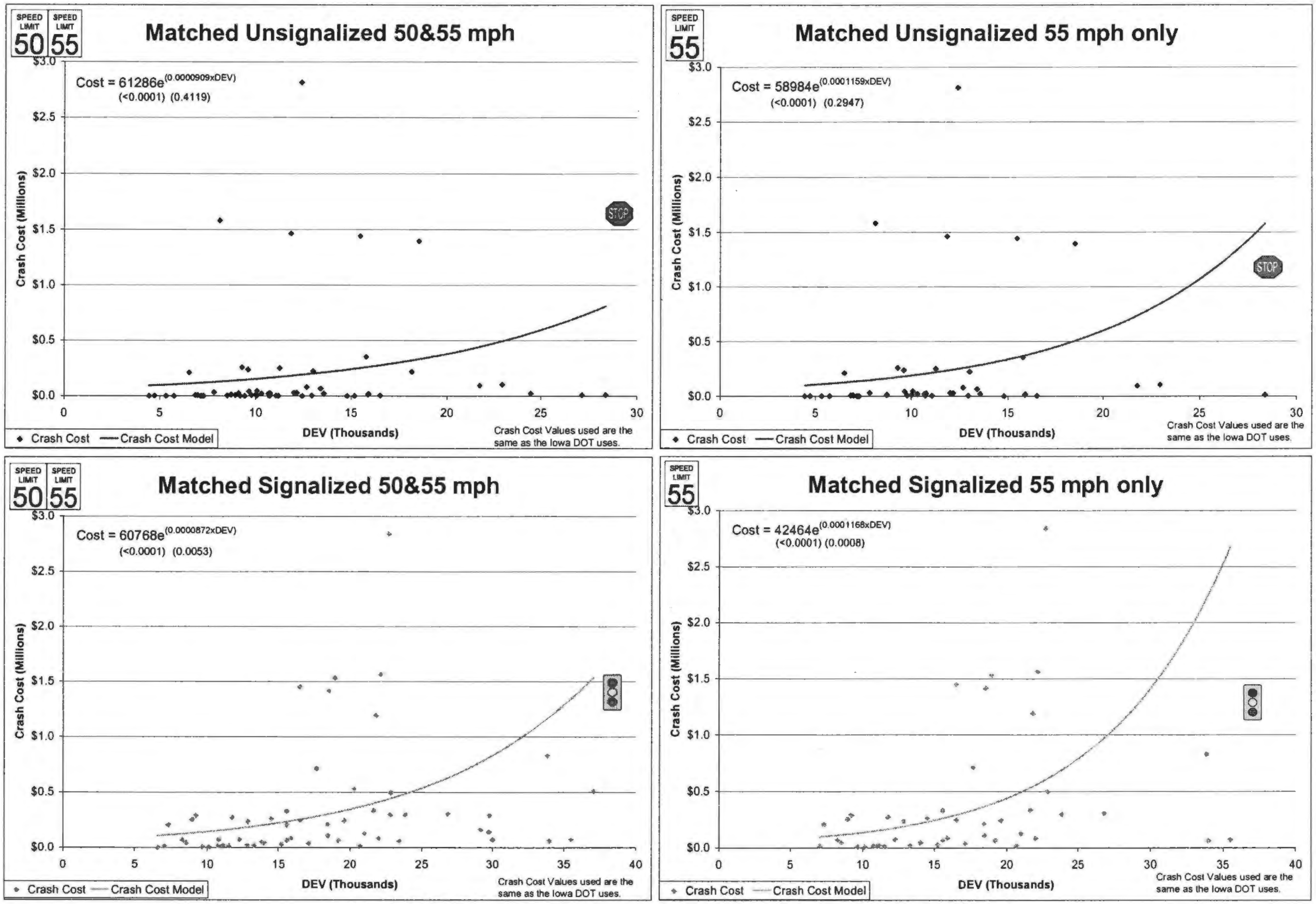


Figure 18: Crash Cost, Matched-Pair Analysis, 2002-2004

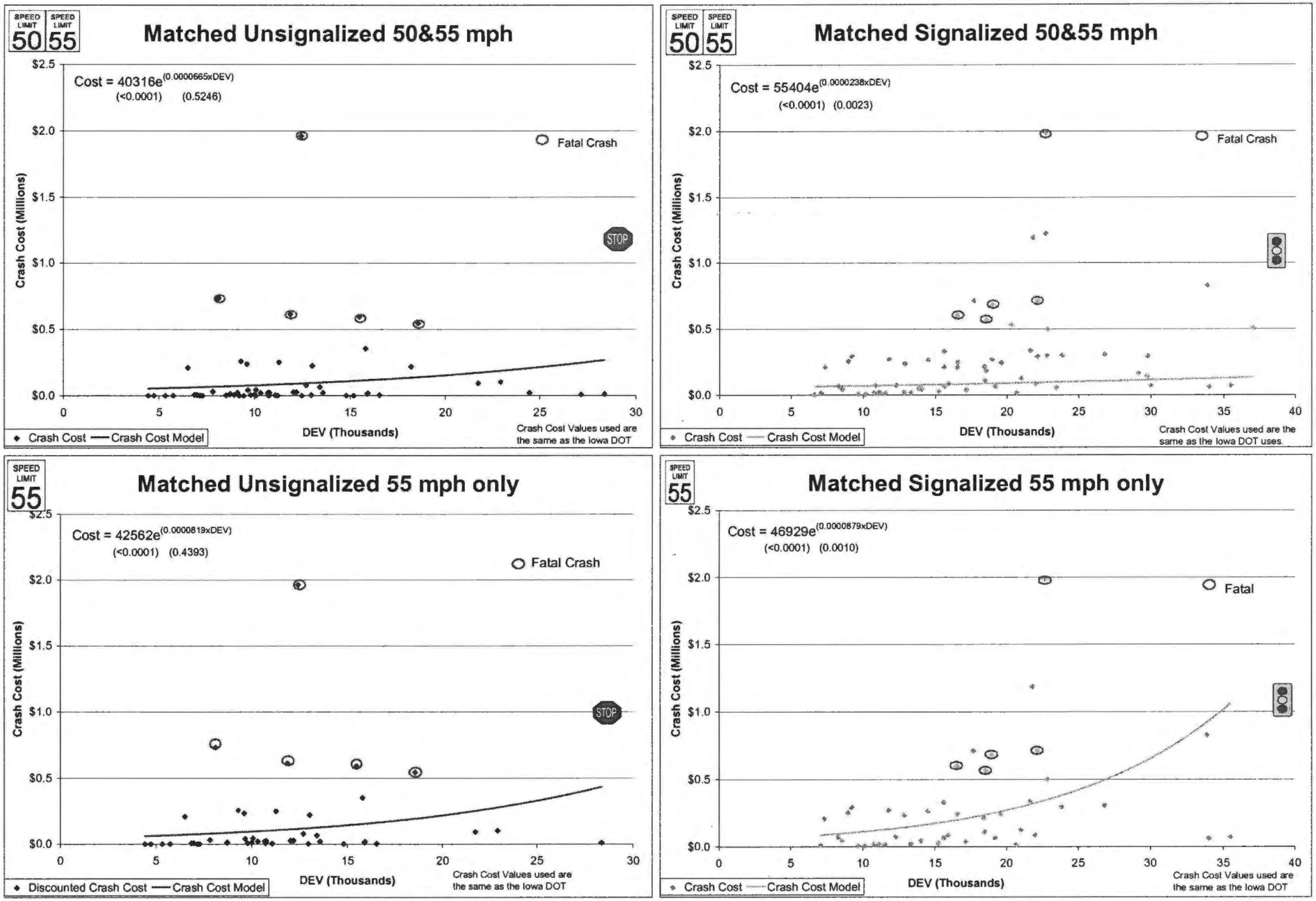


Figure 19: Modified Crash Cost, Matched-Pair Analysis, 2002-2004

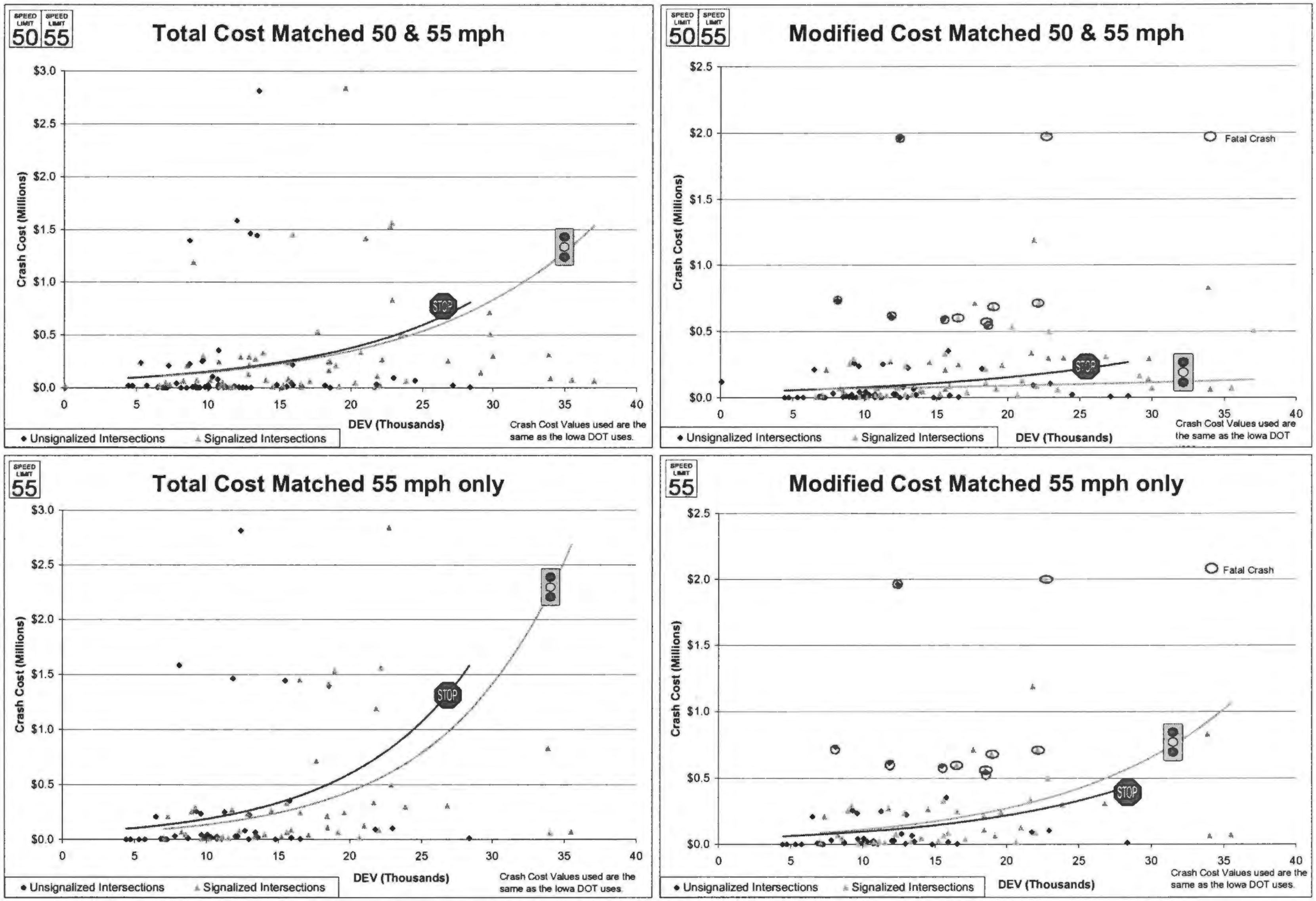


Figure 20: Comparison of Total and Modified Crash Cost, Matched-Pairs, 2002-2004

Collision Type – Matched Pairs

Figure 21 presents the effect of signalization on crash rates for different types of collisions using the matched pair data. While the matched-pair unsignalized locations have higher crash rates for each collision type when compared to the full dataset used in the cross-classification analysis, the relationship of collision type to volume (DEV) range is the same.

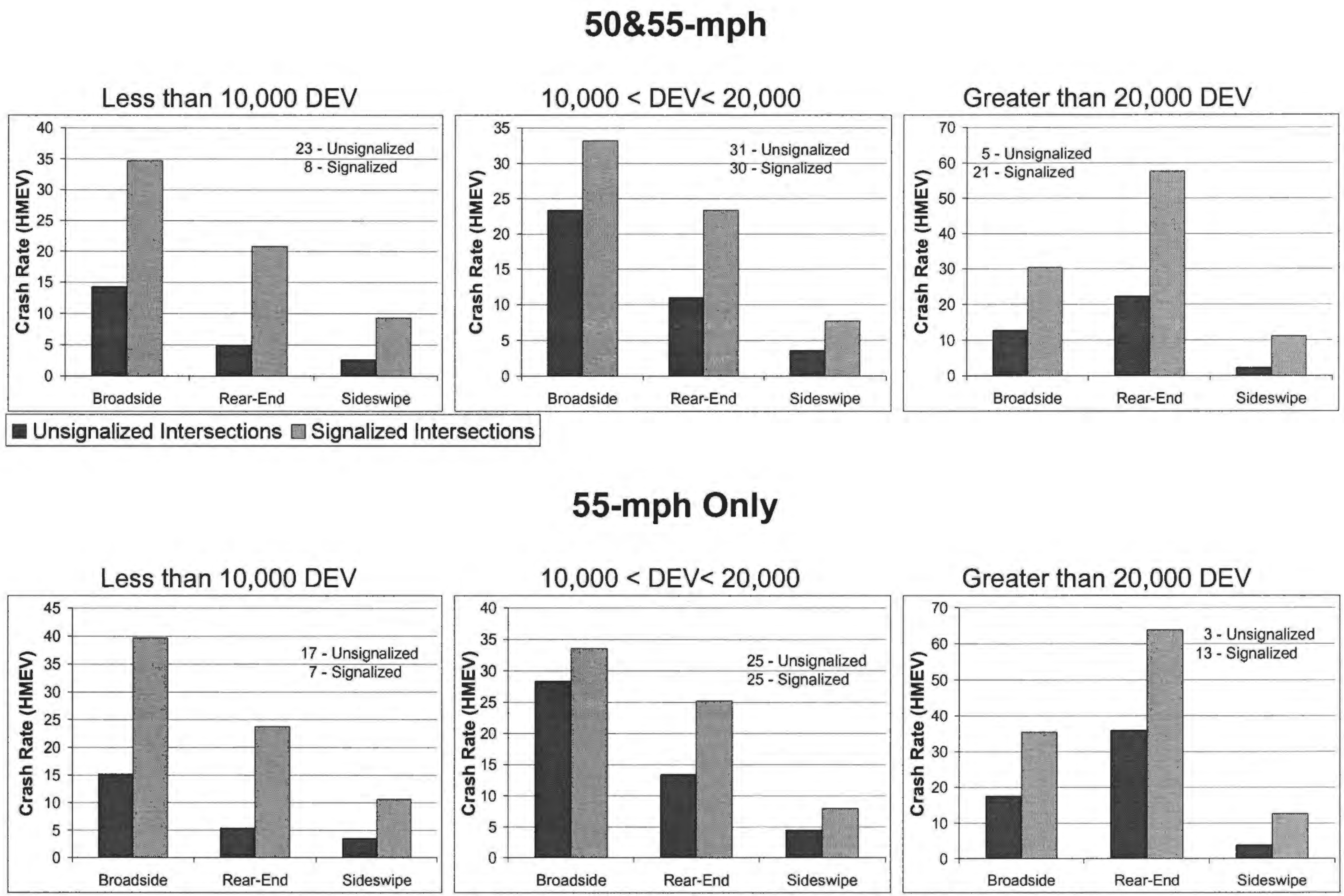


Figure 21: Crash Rate by Collision Type, Matched-Pairs, 2002–2004

Before & After Analysis

This section presents a typical (or classical) before and after analysis of 19 intersections (7 at 50mph, 12 at 55mph) that were signalized between January 1, 1994 and January 1, 2002 on expressways that were not constructed or reconstructed for 3 years prior or following signalization. These intersections had on average 12.9 crashes during the three year periods before installation and average DEV of 14,500. For the three year period following installation, these intersections had an average of 12.6 crashes/3 years and average DEV of 15,600 (no adjustment-period was evaluated).

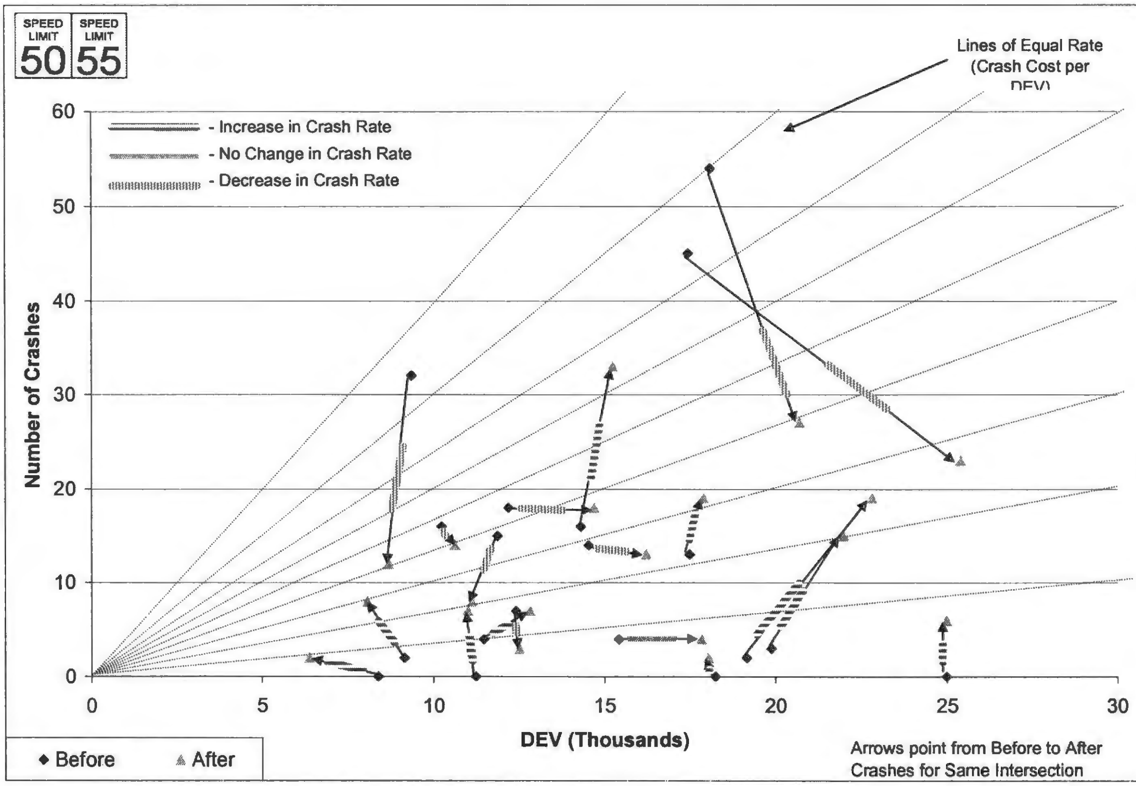
The 55-mph intersections averaged 17.1 crashes/3 years with average DEV of 13,600 during the before period and 12.7 crashes/3 years with average DEV of 14,800 during the after period. Table 5 presents comprehensive descriptive statistics for the before and after analysis.

Table 5: Crash Statistics, Before & After

	50 + 55 mph Intersections		55 mph Intersections	
	Before	After	Before	After
Fatal Crashes	2	3	2	2
Fatalities	3	4	3	2
Major Injury Crashes	10	12	8	7
Minor Injury Crashes	48	35	39	21
Possible Injury Crashes	64	63	54	38
Property Damage Only Crashes	121	127	102	84
Total Crashes	245	240	205	152
Average Crash Rate	85.4	75.4	111.3	76.3
Average DEV	14,500	15,600	13,600	14,800
Average Total Crash Cost	$24,800	$32,100	$26,600	$32,100
Average Modified Crash Cost	$21,400	$21,500	$22,450	$20,900
Average Fatal Crash Rate	0.79	0.82	1.25	0.87
Average Fatality Rate	1.18	1.08	1.87	0.87
Average Fatal & Major Injury Crash Rate	4.54	4.44	6.01	4.36
Average Broadside Crash Rate	40.3	23.2	52.2	26.8
Average Rear-end Crash Rate	14.7	29.5	30.4	21.0

Crash Performance – Before and After

Figure 22 demonstrates the change in crash frequency before and after signalization. The arrows indicate the direction and magnitude of change (green hatching indicates reduction, red indicates increase and purple indicates no change). For the 19 intersections studied, the frequency of crashes was just as likely to increase as to decrease. The diagonal lines represent equal crash rates (crashes per DEV).



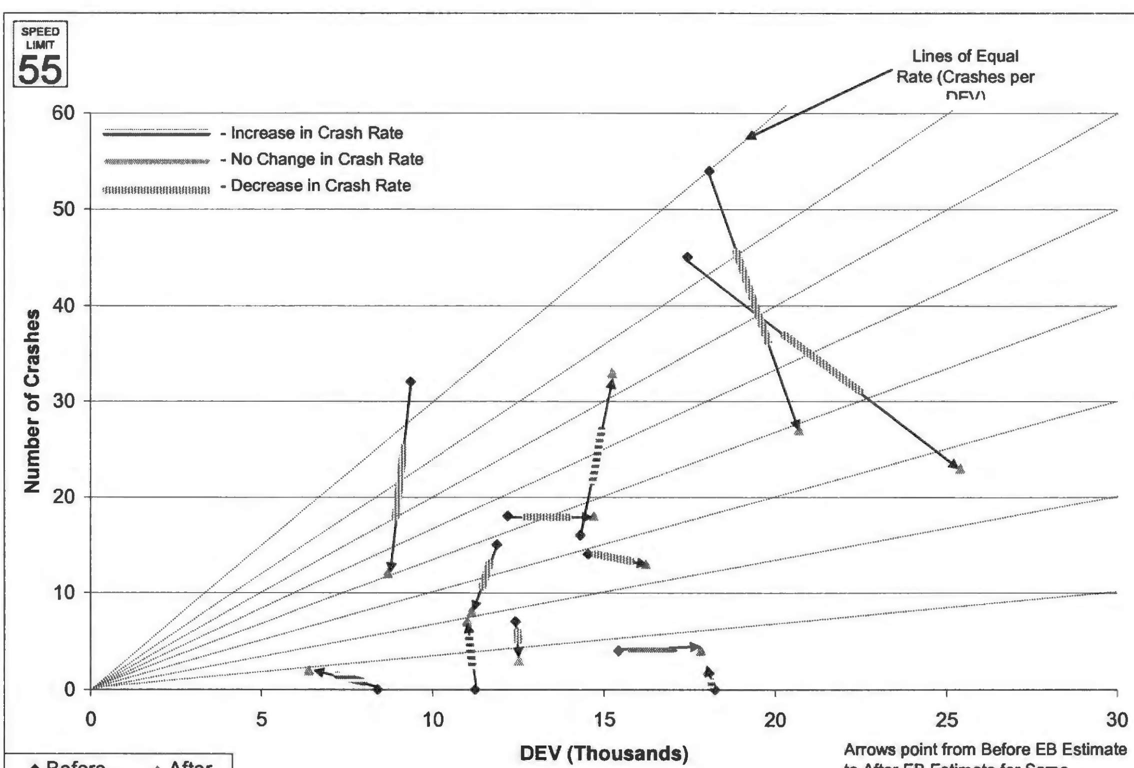


Figure 12: Crash Performance, Before & After Analysis

Crash Cost - Before & After

Fatal crashes influence the data greatly, so much so that that the data show a decreasing trend between the crash cost and DEV. Figure 23 illustrates the total cost of crashes at study area intersections before and after signalization. Crash cost can be observed to increase slightly after signalization.

Figure 24 shows the effect of signalization on modified crash cost, which does not appear to affect the results.

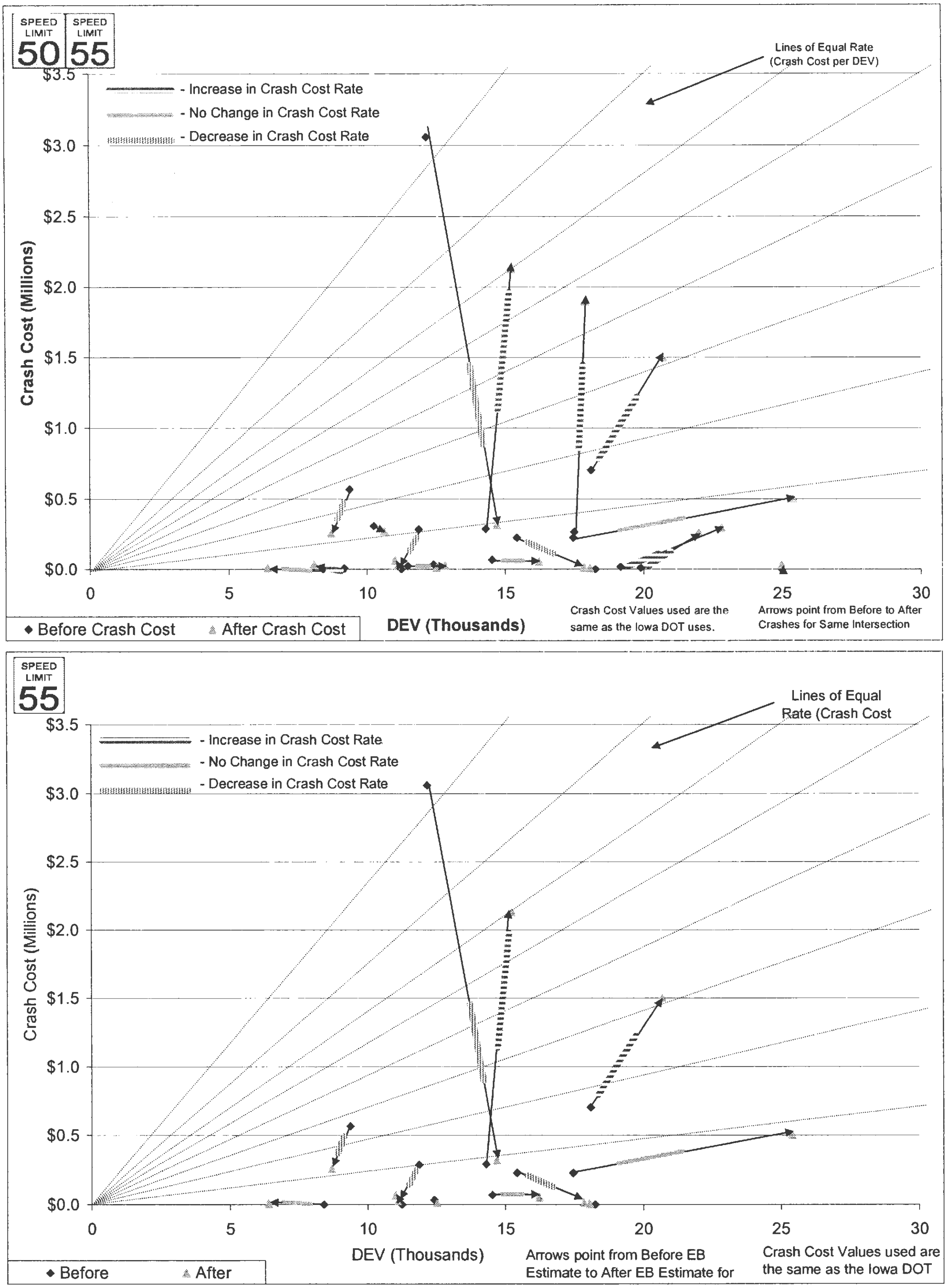


Figure 13: Crash Cost, Before and After Analysis

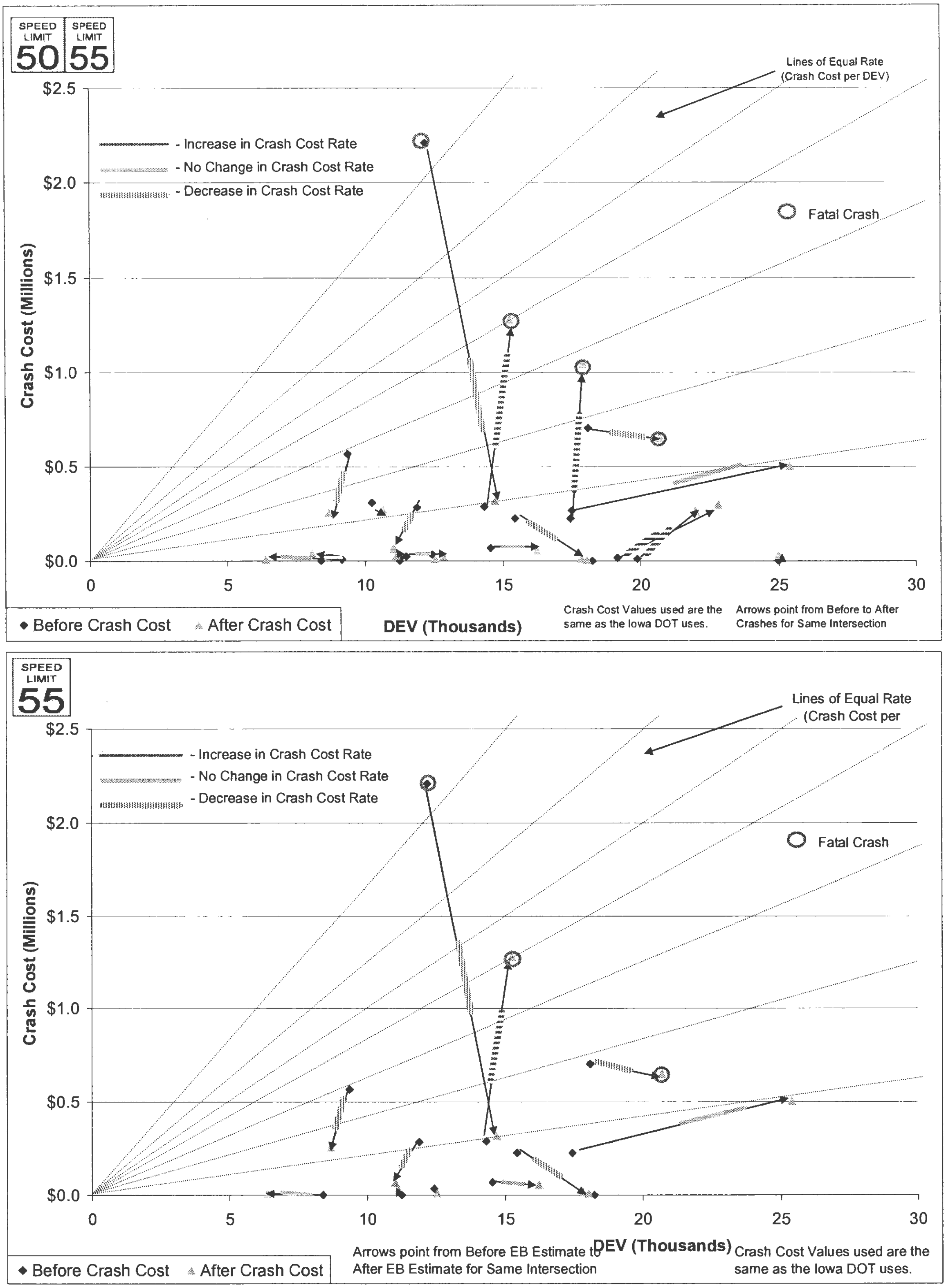
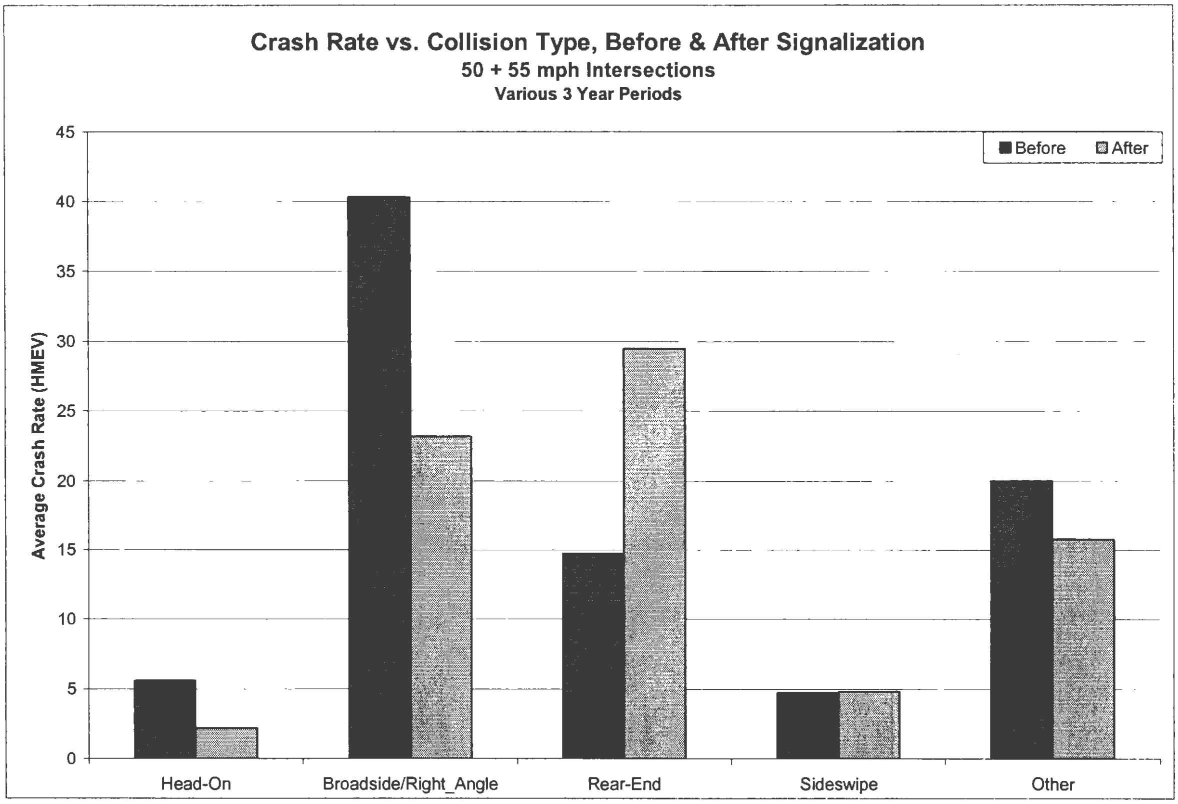


Figure 14: Modified Crash Cost, Before & After Analysis

Collision Type - Before & After

Figure 25 shows how collision type changes after signal installation. The most significant impact of signalization occurs in the right angle and rear-end collision types, where as expected, signalization causes a decrease in the former (about 40%) and an increase (about 100%) in the latter. Head-on collisions are also reduced by more than a factor of two, although this result is based on a smaller sample set.

The most significant difference between 50&55 and 55-mph only intersections is the rear-end collision rate, which did not change after signalization.



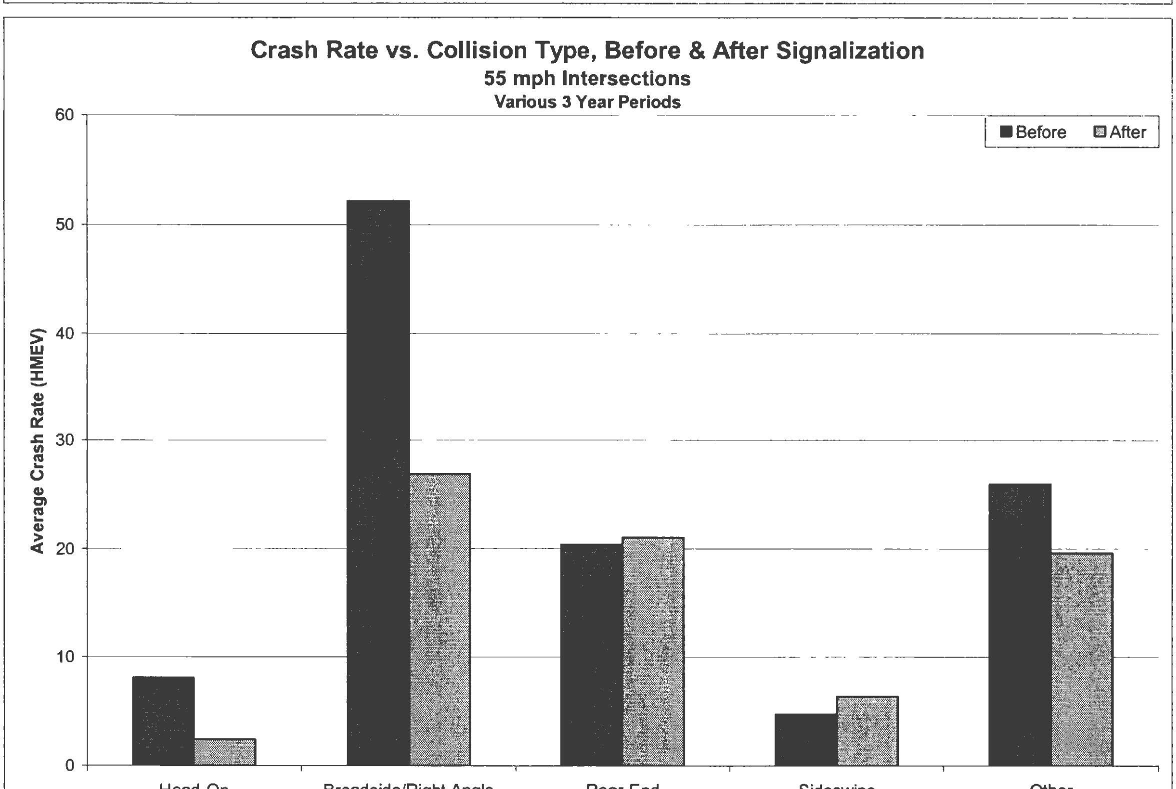


Figure 15: Crash Rate by Collision Type, Before & After Analysis

Empirical Bayes Analysis

Empirical Bayes, EB, was used to improve upon the estimates of signal effect produced in the before and after analysis. The negative Binomial models developed in the cross-classification section are used in the EB adjustment. The overdispersion factors (an output of NB regression, estimated with maximum likelihood) were used to compute weighting factors for the EB adjustment. These are presented in the sections to follow.

Crash Performance – Empirical Bayes

The overdispersion factor for unsignalized intersection crash performance (frequency in 3 years) was found to be 1.52 for 50&55-mph intersections and 1.59 for 55-mph intersections. The weight for EB adjustment is computed for each observation in the data set, with the formula: 1/(1+expected number of crashes/(1/overdispersion parameter)).

Figure 26 shows site data and EB estimates for total number of crashes for the before and after signalization periods. The figure shows how the method adjusts sites which are further from the model more than intersections close to the model. Intersections with lower DEV were adjusted a greater amount than intersections with a high DEV. (This was due to the nature of the weight calculation.)

The crash rate, based on the EB estimate, for the before period of the 50&55-mph intersections was 79.2 crashes per HMEV. The crash rate for the EB Estimation of the before period was 96.5 crashes per HMEV for the 55-mph intersections.

Typically, EB adjustment is applied only to the before period site crash average. However, it makes sense that if cyclical variation prior to signalization is to be damped by the EB process (to account for potential regression to the mean), after period cyclical variations should also be damped. For example, if after period crash performance is observed to be much lower than the average of similar signalized sites, one might expect regression to the mean to pull the average back up in future years. To make sure regression to the mean does not influence the after period analysis, EB was applied to the after crashes using the negative binomial model (and overdispersion parameter) from the all signalized crash models. For signalized intersections, the overdispersion parameters were 0.26 for 50&55-mph intersections and 0.27 for 55-mph intersections. However, as the after period crash performance of study area intersections was not far below that expected from the cross-classification signalized NB model and the overdispersion parameters are small, the EB adjustment did not have a large effect on the after period crash data.

The crash rate using the EB estimate of the after period of 50&55-mph intersections was 75.7 crashes per HMEV. The crash rate, using the EB estimate, of the after period was 76.8 crashes per HMEV for the 55-mph intersections.

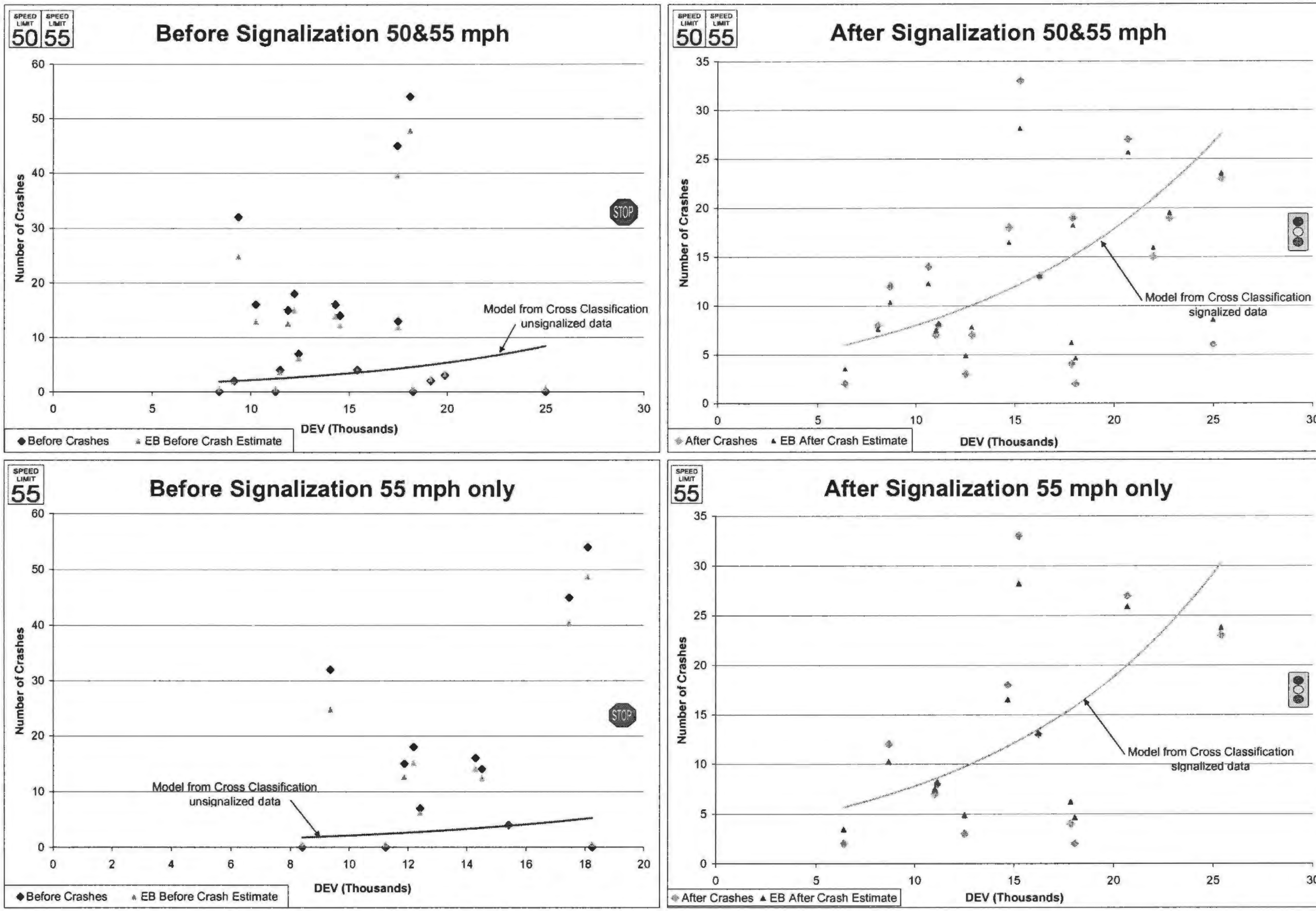


Figure 26: Crash Performance, Empirical Bayes Analysis

Figure 27 shows the total number of crashes for both the before and after signalization of the intersections. The trapezoidal areas on the chart represent the effect of EB adjustment. The vertical faces represent the EB adjustment (toward the model) and the arrows point in the direction from before to after. For the 50&55-mph intersections, five intersections decreased, thirteen intersections increased, and one intersection showed no change in crash rate. When compared to the classical before and after analysis, three intersections changed from a decrease in crash rate to an increase. For the 55-mph intersections, five intersections decreased, six intersections increased, and one intersection showed no change in crash rate. When compared to the classical analysis (figure 22), two intersections changed from a decrease in crash rate to an increase.

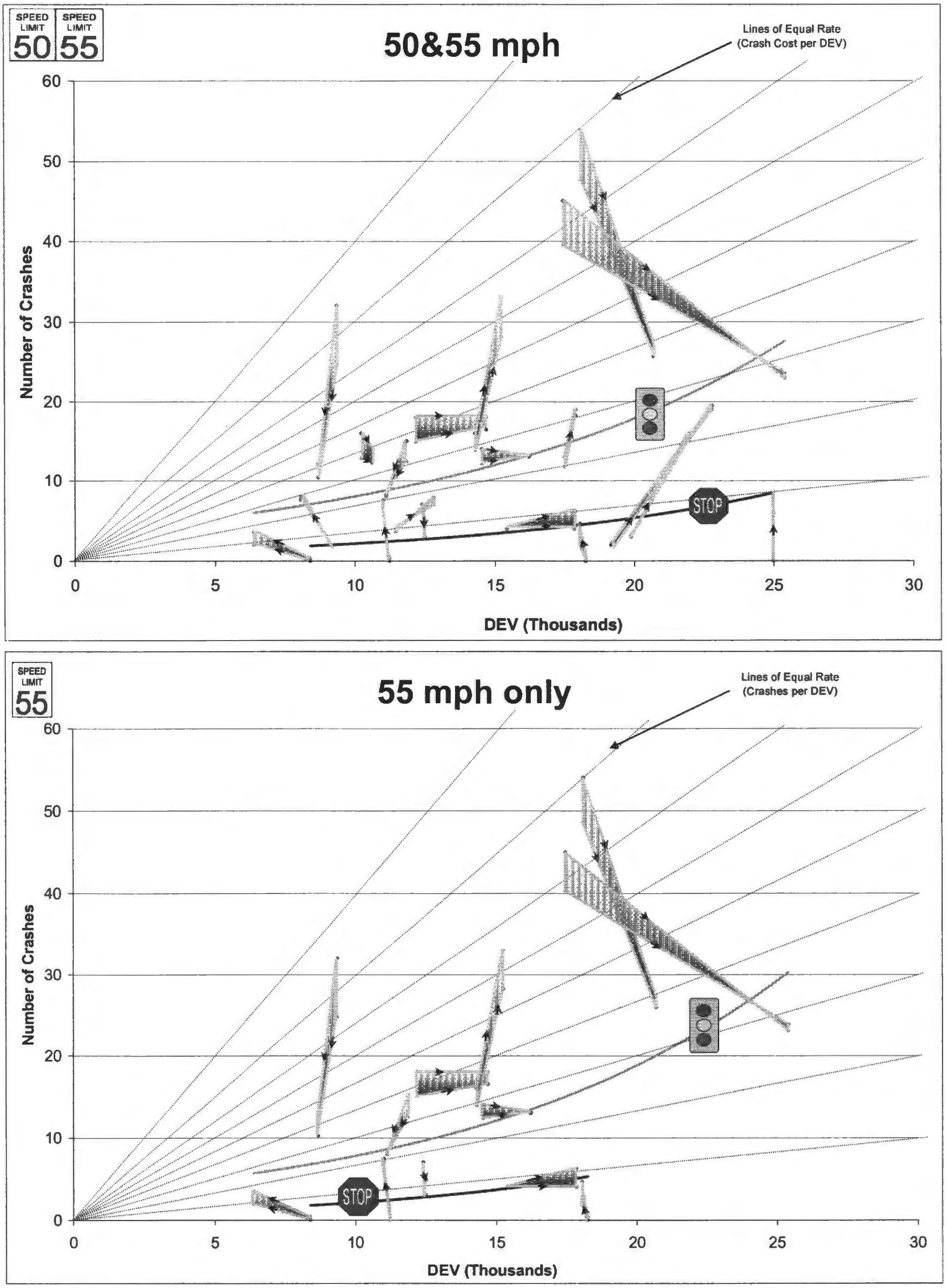


Figure 16: Comparison of Signalized and Unsignalized Crash Performance, Empirical Bayes Analysis

Crash Cost – Empirical Bayes

Empirical Bayes crash analysis can be used to compute crash cost by multiplying the average cost of an unsignalized crash by the before period adjusted crash frequency and subtracting the average cost of a signalized crash by the after period adjusted crash frequency. Results of this analysis are included in Table 6, and vary greatly depending on the pool of data used to compute the average crash cost. The largest database (cross classification) produced average crash costs for signals ($19,000) that was much lower than stop controlled ($44,000). Clearly, use of these cost averages will result in significant benefits for signalization. Average cost figures derived from the matched-pair pool are similar. However, when average crash costs from the before and after dataset are used ($25,000 for unsignalized vs. $32,000 for signalized), crash costs actually increase.

Table 6: Empirical Bayes Crash Cost Estimate

50&55 mph	EB Estimates Before Total Cost	After Total Cost	Difference
Cross Classification	$9,401,625	$4,526,429	$4,875,197
Matched Pairs	$8,525,565	$4,720,073	$3,805,492
Before & After	$5,299,098	$7,769,966	-$2,470,868

55 mph only	EB Estimates Before Total Cost	After Total Cost	Difference
Cross Classification	$8,485,446	$3,341,892	$5,143,554
Matched Pairs	$7,514,654	$3,341,892	$4,172,762
Before & After	$4,782,052	$4,898,389	-$116,337

Chapter 5: Conclusions and Recommendations

This chapter presents results of the analysis, conclusions and policy implications and suggestions for further results.

Conclusions

To summarize some of the key findings of the analysis, tables were created with measures of effectiveness for comparison. Table 7 presents information related to the 50&55-mph expressway intersections.

The cross classification analysis using all data resulted in a crash rate of 21.1 crashes per HMEV for unsignalized intersections. By comparison, the crash rate for signalized intersections was 84.3 crashes per HMEV. While most indicators of intersection safety are worse for signalized intersections, fatal crash rate is the same and fatality rates are slightly lower for these intersections. It should be noted however, that sample size for fatal crashes is extremely low for the database and the results must be used with care. Also, the cross classification analysis does not adjust for volume or other potential causal factors. However, the Negative Binomial cross classification model based on these data (which does adjust for volume) also indicates that signalized intersections have much higher crash rates and lower average crash cost and average modified crash cost.

The matched-pair analysis resulted in less difference in crash rate between signalized and unsignalized location, with signalized crash rates still exceeding those of their unsignalized counterparts. However, the analysis results indicated a 35% lower fatal crash rate and fatality rate for signalized intersections.

The conventional before and after analysis and Empirical Bayes analyses indicate very small changes in all severities of crashes as compared to the other methods. In fact, whereas before and after analysis indicates a reduction of 11.7% in crash rate, EB indicates 4.8% reduction.

Table 7: Summary of the Results for 50&55-mph Intersections

Unsignalized & Signalized, 50&55 mph Intersections 2002 - 2004 Crash Data

Measure of Effectiveness	Cross Classification Unsignalized	Cross Classification Signalized	Cross Classification % Difference	Models Unsignalized	Models Signalized	Models % Difference	Match Pairs Unsignalized	Match Pairs Signalized	Match Pairs % Difference
Number of Intersections	182	67		182	67		59	59	
Average DEV	11,100	18,300	64.9%				11,900	18,000	51.3%
Average Crash Rate	21.1 (31.2)*	84.3 (49.3)*	299.5%	21.3 (0.331)**	86.5 (0.285)**	306.1%	34.0 (38.8)*	79.9 (47.4)*	135.0%
Average Fatality Rate	0.53	0.47	11.3%				0.84	0.47	44.0%
Average Fatal Crash Rate	0.47	0.47	0.0%				0.75	0.47	37.3%
Average Fatal & Major Injury Crash Rate	1.60	3.40	112.5%				1.95	3.33	70.8%
Average Crash Cost	$44,000	$18,700	57.5%	$44,900	$20,900	53.5%	$39,900	$19,500	51.1%
Average Modified Crash Cost	$27,800	$13,800	50.4%	$22,500	$13,600	39.6%	$24,800	$15,200	38.7%
Rear-End Crash Rate	5.74	38.6	572.5%				9.56	35.2	268.2%
Broadside Crash Rate	10.8	33.2	208.0%				18.9	32.4	71.3%

Before and After Installation - 3yrs Before & After

Measure of Effectiveness	Classical Before	Classical After	Classical % Difference	EB Before	EB % Adjustment	EB After	EB % Adjustment	EB % Difference
Number of Intersections	19	19		19		19		
Average DEV	14,500	15,600	7.6%					
Average Crash Rate	85.4 (96.7)*	75.4 (47.1)*	11.7%	79.2	-9.8%	75.4	0.0%	4.8%
Average Fatality Rate	1.18	1.08	8.5%					
Average Fatal Crash Rate	0.79	0.82	3.8%					
Average Fatal & Major Injury Crash Rate	4.54	4.44	2.2%					
Average Crash Cost	$24,800	$32,100	29.4%					
Average Modified Crash Cost	$21,400	$21,500	0.5%					
Rear-End Crash Rate	14.7	29.5	100.7%					
Broadside Crash Rate	40.3	23.2	42.4%					

Rates are units per HMEV
Hundred Million Entering Vehicles

* Standard Deviation
** Rho-Squared of the model

Table 8 contains information related to the 55-mph expressway intersections.

The cross classification analysis using all data resulted in a crash rate of 21.2 crashes per HMEV for unsignalized intersections. By comparison, the crash rate for signalized intersections was 96.7 crashes per HMEV. Most rates are much higher for signalized as compared to unsignalized intersections (only the fatality rate is similar). As in the case of the 50&55-mph database, the cross classification model also indicates that signalized intersections have much higher crash rates and lower average crash cost and average modified crash cost.

Matched-pair, before and after, and Empirical Bayes results for the 55-mph intersections are also similar to the 50&55-mph results. In the case of the EB analysis, only a slight improvement in crash rate can be expected from signalizing a 55-mph expressway intersection (82 to 76.4/HMEV).

Table 8: Summary of the Results for 55-mph Intersections

Unsignalized & Signalized, 55 mph Intersections 2002 - 2004 Crash Data

	Cross Classification			Models			Match Pairs		
Measure of Effectiveness	Unsignalized	Signalized	% Difference	Unsignalized	Signalized	% Difference	Unsignalized	Signalized	% Difference
Number of Intersections	158	45		158	45		45	45	
Average DEV	10,900	17,000	56.0%				11,600	17,000	46.6%
Average Crash Rate	21.2 (32.4)*	96.7 (49.3)*	356.1%	21.3 (0.342)**	86.6 (0.302)**	306.6%	41.5 (40.5)*	96.7 (49.3)*	133.0%
Average Fatality Rate	0.61	0.61	0.0%				1.10	0.61	44.5%
Average Fatal Crash Rate	0.54	0.61	13.0%				0.99	0.61	38.4%
Average Fatal & Major Injury Crash Rate	1.59	3.62	127.7%				2.45	3.62	47.8%
Average Crash Cost	$47,200	$21,900	53.6%	$48,000	$27,000	43.8%	$41,800	$21,900	47.6%
Average Modified Crash Cost	$28,700	$16,300	43.2%	$22,600	$15,300	32.3%	$25,500	$16,300	36.1%
Rear-End Crash Rate	5.94	36.1	507.7%				11.9	36.1	203.4%
Broadside Crash Rate	10.4	35.1	237.5%				22.6	35.1	55.1%

Before and After Installation - 3yrs Before & After

	Classical			EB				
Measure of Effectiveness	Before	After	% Difference	Before	% Adjustment	After	% Adjustment	% Difference
Number of Intersections	12	12		12		12		
Average DEV	13,600	14,800	8.8%					
Average Crash Rate	111.3 (109.3)*	76.3 (55.2)*	31.4%	96.5	-15.3%	76.8	0.7%	20.4%
Average Fatality Rate	1.87	0.87	53.5%					
Average Fatal Crash Rate	1.25	0.87	30.4%					
Average Fatal & Major Injury Crash Rate	6.01	4.36	27.5%					
Average Crash Cost	$26,600	$32,100	20.7%					
Average Modified Crash Cost	$22,450	$20,900	6.9%					
Rear-End Crash Rate	30.4	21.0	30.9%					
Broadside Crash Rate	52.2	26.8	48.6%					

Rates are units per HMEV
Hundred Million Entering Vehicles

* Standard Deviation
** Rho-Squared of the model

Policy Implications

The choice of method can have significant impacts on the results. Naïve cross classification, with no consideration of exogenous factors such as volume, volume split, turning lanes, etc. indicates that signals decrease safety dramatically whereas matched pairs analysis, indicated a fairly significant benefit, at least for major injury and fatal crashes, the types of crashes of most interest. And while conventional before and after analysis using 3 years of before and after data (a method many safety analysts would be very comfortable with) concludes a marginal safety benefit of signalization (as defined by crash rate), the state of the art EB method reduces or even negates this benefit.

Two policy questions can be addressed using results of this thesis. First, the effect of signalization of high speed intersections in general is now better known. The EB estimates account for potential regression to the mean in the before and after data. Crash rates are demonstrated to stay more or less the same or increase with signalization, and the cost analysis (using before and after data and EB crash frequency estimates) projects that the total cost of crashes is much higher for signalized intersections. This finding is in keeping with current thinking on the safety benefits of signalization, which has been challenged in recent reports.

Second, when estimating the benefits of signalization for any particular intersection, whether for ranking or for benefit cost assessment, the EB models developed in this research can be used. However, as the models are statistically weak, as discussed in the next section.

Future Research

The models developed as part of this research by in large have low explanatory power and/or statistically insignificant parameters. While the study relied upon a rather large set of intersection data (at lease for the cross classification anaylsis), model independent variables were lacking (e.g., turn lanes, …) This study applies EB in the manner suggested by the technique's developers (Harwood, Hauer) using SPFs created as a function of volume. This method suggests the development of AMFs to address varying site characteristics. However, additional explanatory variables may be built directly into the SPFs. This is left to future research.

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Appendix: List of High Speed Signalized Expressway Intersections

Table 9: List of Signalized Intersections

List of High Speed Signalized Expressway Intersections

Intersection ID	City	County	Major St	Minor St	Year of Signal Installation	Speed Limit	Before & After Intersection
696890	Fort Dodge	Webster	2nd Ave S	Country Club Dr	1994	50	Yes
40711	Waterloo	Black Hawk	Broadway St	Cedar Bend St	Pre 1991	55	No
40633	Waterloo	Black Hawk	Broadway St	W Donald St	Pre 1991	55	No
619371	Waterloo	Black Hawk	Broadway St	Wagner Rd	1997	55	Yes
648660	Williamsburg	Iowa	Co Rd V-77	Evans St	1993	55	No
37239	Waterloo	Black Hawk	Dubuque Rd	Evans Rd	Pre 1991	55	No
37021	Elk Run Heights	Black Hawk	Dubuque Rd	Gilbertville Rd		55	No
32101	Raymond	Black Hawk	Dubuque Rd	Plaza Dr	1995	55	Yes
38445	Waterloo	Black Hawk	E San Marnan Dr	Hammond Ave	1991	55	No
38437	Waterloo	Black Hawk	E San Marnan Dr	Hawkeye Rd	Pre 1991	55	No
41967	Waterloo	Black Hawk	E San Marnan Dr	Shopper Blvd	1997	55	Yes
293365	Iowa City	Johnson	IA 1	Mormon Trek Blvd	1994	55	Yes
286187	Iowa City	Johnson	IA 1	Sunset St	Pre 1991	50	No
556462	Carlisle	Warren	IA 5	Scotch Ridge Rd	1998	55	No
373361	Marshalltown	Marshall	IA 14	Iowa Ave (Old US 30)	Pre 1991	50	No
449804	Des Moines	Polk	IA 28	Park Ave	Pre 1991	50	No
672080	Des Moines	Polk	IA 28	SW McKinley Ave	2001	50	Yes
616615	Cedar Falls	Black Hawk	IA 58	Green Hill Rd	1994	55	No
704067	Cedar Falls	Black Hawk	IA 58	Viking Rd	1994	55	No
616614	Cedar Falls	Black Hawk	IA 58	W Ridgeway Ave	1993	55	No
466667	Council Bluffs	Pottawattamie	IA 92	Old IA 275	Pre 1991	50	No
466951	Council Bluffs	Pottawattamie	IA 92	Valley View Dr	1992	50	No
92495	Mason City	Cerro Gordo	IA 122	Eisenhower Ave	Pre 1991	50	No
92511	Mason City	Cerro Gordo	IA 122	N Roosevelt Ave	1999	50	Yes
139759	Granger	Dallas	IA 141	190th St	2000	55	Yes
139421	Perry	Dallas	IA 141	IA 144 (J Ave)	Pre 1991	50	No
436398	Urbandale	Polk	IA 141	I-35 Ramp (NB)	2000	55	No
439944	Grimes	Polk	IA 141	NW 54th Ave	1994	55	Yes
443428	Ankeny	Polk	IA 160	DMACC, Ankeny	Pre 1991	55	No
439025	Ankeny	Polk	IA 160	US 69	Pre 1991	55	No
678350	Pleasant Hill	Polk	IA 163	NE 56th St	1995	50	Yes
440241	Pleasant Hill	Polk	IA 163	NE 64th St	2001	55	Yes
440263	Pleasant Hill	Polk	IA 163	NE 80th St	1998	55	Yes
440191	Pleasant Hill	Polk	IA 163	Copper Creek Dr	2000	50	Yes
601876	Sioux City	Woodbury	IA 376 (Lewis)	28th St	Pre 1991	50	No
439974	Ankeny	Polk	IA 415 - IA 160	State St	Pre 1991	55	No
440506	Ankeny	Polk	IA 415	Irvingdale Dr	1995	55	No
38431	Waterloo	Black Hawk	San Marnan Dr	Kimball Ave	Pre 1991	55	No
671970	Altoona	Polk	US 6	9th St NW (Adventureland)	Pre 1991	55	No
437945	Altoona	Polk	US 6	US 65 Ramp	2001	55	Yes
461842	Urbandale	Polk	US 6	104th St	Pre 1991	50	No
437493	Clive	Polk	US 6 (Hickman)	128th	2000	55	No
138963	Clive	Dallas	US 6 (Hickman)	156th St	2001	55	No
138937	Waukee	Dallas	US 6 (Hickman)	Alice S Rd (R 30)	1997	55	No

List of High Speed Signalized Expressway Intersections (cont.)

Intersection ID	City	County	Major St	Minor St	Year of Signal Installation	Speed Limit	Before & After Intersection
436330	Urbandale	Polk	US 6	I-35 Ramp NB Exit	1992	50	No
436333	Urbandale	Polk	US 6	I-35 Ramp SB Exit	1992	50	No
448837	Clive	Polk	US 6 (Hickman)	NW 111th St	Pre 1991	50	No
139007	Clive	Dallas	US 6 (Hickman)	SW 142nd	1997	55	No
138903	Waukee	Dallas	US 6	Warrior Ln	2000	55	No
637373	Dubuque	Dubuque	US 20	Crescent Ridge	1993	50	No
173317	Dubuque	Dubuque	US 20	NW Arterial	Pre 1991	50	No
176233	Dubuque	Dubuque	US 20	Old Highway Rd	2001	50	Yes
161895	West Burlington	Des Moines	US 34	Beaverdale Rd	Pre 1991	55	No
629254	Osceola	Clarke	US 34	Warren Ave	1998	50	Yes
173795	Sageville	Dubuque	US 52	IA 386/Kennedy Rd	Pre 1991	50	No
402971	Muscatine	Muscatine	US 61	Cedar St	Pre 1991	55	No
493339	Davenport	Scott	US 61	140 St	1996	55	No
667226	Muscatine	Muscatine	US 61	Mulberry Ave	1998	55	Yes
667227	Muscatine	Muscatine	US 61	Isett Ave	1998	55	Yes
165939	Burlington	Des Moines	US 61	West Ave	Pre 1991	55	No
724905	Ottumwa	Wapello	US 63	Court St	Pre 1991	55	No
30148	Waterloo	Black Hawk	US 63	US 20 Ramp EB	2000	55	No
30144	Waterloo	Black Hawk	US 63	US 20 Ramp WB	1993	55	No
618365	Waterloo	Black Hawk	US 63	W Ridgeway Ave	Pre 1991	55	No
30701	Waterloo	Black Hawk	US 218	Shaulis Rd	Pre 1991	55	No
38421	Waterloo	Black Hawk	W San Marnan Dr	Ansborough Ave	1997	55	Yes
323505	Cedar Rapids	Linn	Wright Brothers Blvd	6th St SW	2001	55	No