Evaluation of the Conversion from Two-Way Stop Sign Control to All-Way Stop Sign Control at 53 Locations in North Carolina

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Abstract

Due to the perceived safety benefits, relative low cost, and ease of implementation of all-way stop control, there is growing interest in the conversion of intersections from two-way to all-way stop control in North Carolina. While all-way stop controlled intersections are commonly used, there are few current, up-to-date studies quantifying their safety benefits, especially for higher speed rural locations or locations equipped with flashing beacons. The purpose of this project was to develop crash reduction factors for the conversion from two-way to all-way stop control at a diverse group of intersections that reflect North Carolina conditions and decision-making. Other places with similar conditions might benefit from the findings as well.

A total of 53 treatment sites located in urban, suburban, and rural areas were chosen for analysis in this project. The treatment locations were divided into three groups based upon presence of an overhead and/or sign mounted flashing beacon. Group 1 consisted of 33 intersections without flashing beacons; Group 2 consisted of 8 intersections with flashing beacons in both the before and after period; and Group 3 consisted of 8 intersections where the flashing beacon was installed with the all-way stop control.

The results show a substantial decrease in total, injury, and frontal impact crashes in the after period when analyzing all locations and Groups 1, 2, and 3. The recommended crash reduction factors for conversion from two-way to all-way stop control are the factors calculated by the Empirical Bayes method with consideration for traffic increase. The recommended crash reduction factors from the overall group are a 68 percent reduction in total crashes, a 77 percent reduction in injury crashes, a 75 percent reduction in frontal impact crashes, and a 15 percent reduction in “ran stop sign” crashes.

Keywords

Transportation Safety, All Way Stop, Crash Reduction Factor, Flashing Beacon, Intersection

1. Introduction

All-way stop control is a countermeasure used to help alleviate crash problems at intersections with a pattern of high severity frontal impact crashes. As the North Carolina Department of Transportation (NCDOT) looks to solve safety problems with tools that are both low cost and quick to implement, there is growing interest in the conversion of intersections from two-way stop control to all-way stop control, especially in higher speed rural areas. While all-way stop controlled intersections are commonly used, there are few current, up-to-date studies quantifying their safety benefits. Most of the studies that have been completed focused primarily on urban locations and are now at least twenty-five years old, using data from the 1960s and 1970s. The purpose of this project was to evaluate the effects of converting an intersection from two-way stop sign control to all-way stop control under a variety of conditions and using current data. The goal was to develop crash reduction factors that reflect North Carolina conditions and decision-making. Other places with similar conditions might benefit from the findings as well.

The objectives of this paper were to:

(1) Determine if there was a reduction in total and target crashes at intersections converted from two-way to all-way stop control.

(2) Determine if there was a difference in crash reductions when all-way stop control intersections are equipped without a flashing beacon, as opposed to all-way stops with a flashing beacon.

(3) Determine if the approach speed limits and/or the intersection volume played a role in crash reductions at intersections converted from two-way to all-way stop control.

The measures of effectiveness for this project include total crashes, injury crashes, and frontal impact crashes. We also analyzed crashes involving a vehicle running the stop sign.

2. Literature Review

The crash reduction factors that NCDOT currently uses for all-way stop installation are from the National Cooperative Highway Research Program (NCHRP) Digest 299, the interim report to NCHRP Report 617: Accident Modification Factors for Traffic Engineering and ITS Improvements (Harkey et al., 2008). NCHRP Report 617 provides Accident Modification Factor (AMF) values for conversion to all-way stop control based on a study conducted by Lovell and Hauer (1986). The results of the Lovell and Hauer study are also used as the recommended AMF for this treatment within the Federal Highway Administration (FHWA) Interactive Highway Safety Design Model.

Lovell and Hauer’s study, which focused primarily on treatment sites located in an urban environment, is regarded as the most comprehensive review of the safety effects of converting intersections to all-way stop control. They reanalyzed data from three previous safety studies in San Francisco, Philadelphia and Michigan, and added a new data set from Toronto. Intersections were converted from either two-way stop control or one-way streets to all-way stop control. Reference sites were used to account for regression-to-the-mean.

The San Francisco data consisted of one year before and after comparisons of crashes occurring at 49 urban intersections converted from two-way to all-way stop control between 1969 and 1973. The San Francisco reference data was obtained for a different time frame than the treatment data, from 1974 to 1977. The unbiased results for the San Francisco data showed a 62 percent reduction in total crashes, an 83 percent reduction in right-angle crashes, and a 74 percent reduction in injury crashes. The Philadelphia data contained the largest treatment sample, with 222 urban intersections. The data contained only intersections converted from one-way streets to all-way stop control between 1968 and 1975, and used two year before and after comparisons. The unbiased results for the Philadelphia data showed a 43 percent reduction in total crashes, a 77 percent reduction in right-angle crashes, and a 73 percent reduction in injury crashes. Along with the data from San Francisco and Philadelphia, the Toronto data contained only urban intersections. The Toronto data analyzed 79 intersections converted from two-way to four-way stop control between 1975 and 1982. The unbiased results for the Toronto data showed a 40 percent reduction in total crashes, a 50 percent reduction in right-angle crashes, and a 63 percent reduction in injury crashes.

The Michigan data was the only group pertaining to low-volume, high-speed rural roads and contained a set of ten intersections. The Michigan data used two and three year before and after periods for intersections converted from two-way to all-way stop control between 1971 and 1977. The reference data was obtained from 1974 though 1976. The unbiased results for the Michigan data showed a 53 percent reduction in total crashes, a 65 percent reduction in right-angle crashes, and a 61 percent reduction in injury crashes.

Lovell and Hauer’s study reveals consistent safety effectiveness for all-way stop conversion. In the four data sets, total crashes were reduced by 40 to 62 percent, right-angle crashes were reduced by 50 to 83 percent, and injury crashes were reduced by 61 to 74 percent. Likelihood functions were then used to merge the four sets of results into joint estimates of crash reduction factors. After combining results, they found that the conversion to all-way stop control reduced total crashes by 47 percent and right-angle and injury crashes by 72 and 71 percent, respectively.

Persaud (1986) used the Philadelphia sample converted from one-way streets to all-way stop control in a study that examined how traffic volumes and other issues play a role in crash reductions at urban all-way stops. The results show that the effectiveness of all-way stop conversion in urban areas is not limited to a certain range of entering volumes that follow Manual of Uniform Traffic Control Devices (MUTCD) warrants. When analyzing total and right angle crashes, it "can be just as effective for total entering volumes less than 6,000 per day as it is for higher volumes" (Persaud, 1986). The study also showed that for total and right angle crashes, all-way stop conversion in urban areas is no less effective when approach volumes are unbalanced as when they are equal on all approaches. For rear end crashes, which make up a small percentage of total crashes, the effectiveness decreases as total entering volumes increase and as the minor road volume drops below 25 percent. The study examined whether there is an increase in crashes in the acquaintance period immediately after conversion, and found there is no significant difference in crashes during the first six months after conversion to all-way stop. The study also suggests that the effectiveness of all-way stop control does not decrease as its use becomes commonplace.

A preliminary safety evaluation of all-way stop control was conducted by the NCDOT Safety Evaluation Group in October 2008 using eighteen locations that had at least three years of after period crash data (Simpson, unpublished results). This preliminary evaluation provided results using naïve before and after analysis and before and after analysis with a linear adjustment for traffic volumes. When adjusting for traffic volumes, the results were a 67, 79, and 82 percent reduction in total, frontal impact, and injury crashes, respectively, at a mix of urban, suburban, and rural intersections converted to all-way stop control without flashing beacons. At intersections with flashing beacons, the results were a 76, 80 and 83 percent reduction in total, frontal impact and injury crashes, respectively. This paper is an update of that evaluation so we may provide more objective and definite information regarding actual crash reduction factors, including a more in-depth analysis to account for regression-to-the-mean.

3. Site Selection

Treatment sites were selected by surveying the NCDOT Regional Traffic Engineering staff to obtain a statewide listing of known all-way stop installation locations. The listing is not necessarily all-inclusive but contains all known locations at the time. Some locations were removed from the list because either the installation year was unknown, there was not adequate before period crash data (crash data are not available prior to 1990), or there was not adequate after period crash data available.

Each treatment site was field inspected to ensure that they were operating under all-way stop control and that certain criteria were met. The criteria for selecting treatment sites are listed below:

- Intersection of two roads with four approaches
- Two-way stop sign control in the before period
- At least three years of ‘before’ crash data available
- At least one year of ‘after’ crash data available

A total of 53 intersections met these criteria. Forty-three treatment sites have at least three years of after period data and an additional ten treatment sites have at least one year of after period data. All intersections in the three groups have only one lane on each approach. The treatment locations were divided into three groups based upon presence of an overhead and/or sign mounted flashing beacon. Group 1 consists of 33 intersections without flashing beacons; Group 2 consists of 8 intersections with flashing beacons in both the before and after period; and Group 3 consists of 8 intersections where the flashing beacon was installed with the all-way stop control. Four locations were analyzed but not included in one of the three groups because the intersection geometry was different, i.e. there were slip lanes, turn lanes, and/or median dividers. At the locations where a flashing beacon was present under two-way stop control, we assumed that the beacons were converted to an all-red display at the same time as all-way stop control was installed. Where flashing beacons were installed as part of the treatment, we assumed that the flashers were operational on the same date as the all-way stop control was installed, with the exception of two intersections where the beacons were known to have been installed at a later date.

It was our intention to include a broad range of treatment sites, and not just those in urban and suburban areas. There has not been much research on converting intersection control from two-way to all-way stop in rural areas with high speed approaches. Therefore, sites include intersections with a range of volumes and approach speeds. Twenty-two sites are located in urban and suburban areas, while 31 sites are located in rural areas. The signing and marking vary at each intersection. Some intersections have a combination of treatments to alert motorists of the all-way stop condition, including oversized stop signs, dual stop signs, advanced warning signs, “stop ahead” pavement markings, stop bars, florescent markers on stop signs, and/or flags posted above stop signs. Because we are unable to determine installation dates on the signs and markings, we are unable to attribute specific crash reductions to these additional treatments. Table 1 shows some key characteristics of treatment sites.

4. Results

4.1. Naïve Before and After Analysis

A before and after crash analysis was performed at each intersection utilizing the Traffic Engineering Accident Analysis (TEAAS) software developed by NCDOT's Traffic Engineering Branch. The software accesses the North Carolina Traffic Records Database which contains all reported crashes in the State since 1990. Because the installation dates varied from 1994 through 2008, the time periods analyzed for each location varied depending on when the all-way stop control was installed and, in some cases, when new flashing beacons were installed. In most cases, the ending dates for the analyses were determined by the available crash data at the time the crash analysis was completed, which was through March 31, 2009. At several of the older locations, the beginning date was limited by the lack of crash data prior to 1990. Note that the before and after time periods consisted of an equal number of years when available; however, there was an unequal number of years at some locations with less than three years of after period data available. At these locations an adjustment was made to account for the different before and after time periods. To account for a construction and installation period, several months before and after the provided installation dates were omitted from this analysis. The crash analyses were terminated before any other known countermeasures were implemented. The data consisted of all crashes within 150 feet of the treatment intersections.

Crash data are provided for total, injury, frontal impact, and "ran stop sign" crashes. Injury crashes include fatal and non-fatal injury crashes combined. Frontal impact crash types considered are as follows: left turn, same roadway; left turn, different roadways; right turn, same roadway; right turn, different roadways; head on; and angle. Frontal impact crashes occurring in the intersection or related to the intersection are considered target crashes for this countermeasure. Note that a "ran stop sign" crash was defined as a crash in which the investigating officer noted that the vehicle disregarded the stop sign or it could be reasonably inferred from the speeds at impact that the vehicle did not stop at the stop sign. For example, if the crash involved a frontal impact and both vehicle speeds were greater than 20 mph at the time of the collision, then it was considered a "ran stop sign" crash. Table 2 provides a listing of before and after crash data at each site.

Table 3 provides the results of the naïve before and after analysis for all locations, as well as for Groups 1, 2 and 3. Note that the value after the "+/-" notation indicates the standard deviation of an estimated value. Conventional Hauer (1997) symbology and methology was used in the countermeasure evaluation. Therefore, in the following tables, parameter estimates are denoted as follows:

λ = Actual number of after period crashes,

π = Predicted number of after period crashes, and

θ = Ratio of what safety was with the treatment to what it would have been without the treatment (Index of effectiveness).

When considering all treatment locations, the results of the naïve before and after analysis yielded a 65% (+/- 2%) reduction in total crashes, a 77% (+/- 3%) reduction in injury crashes, a 74% (+/- 2%) reduction in frontal impact crashes, and an 18% (+/- 10%) reduction in "ran stop sign" crashes. Note that in the before period, there were ten crashes involving fatal injuries at all treatment locations. In the after period, there were none.

Group 1 sites, without flashing beacons, experienced a 56% (+/- 4%) reduction in total crashes, a 71% (+/- 4%) reduction in injury crashes, a 68% (+/- 3%) reduction in frontal impact crashes, and a 5% (+/- 15%) reduction in "ran stop sign" crashes.

Group 2 sites, with flashing beacons in the before and after period, experienced a 77% (+/- 4%) reduction in total crashes, an 86% (+/- 5%) reduction in injury crashes, an 83% (+/- 4%) reduction in frontal impact crashes, and an 18% (+/- 34%) reduction in “ran stop sign” crashes.

Group 3 sites, with flashing beacons only in the after period, experienced an 82% (+/- 3%) reduction in total crashes, an 87% (+/- 4%) reduction in injury crashes, an 86% (+/- 3%) reduction in frontal impact crashes, and a 48% (+/- 17%) reduction in “ran stop sign” crashes. Note that the Group 2 and 3 results for injury, frontal impact, and “ran stop sign” crashes should be viewed with some reserve due to the small sample size for these crash types.

We also analyzed non-target crash types using a naïve before and after analysis because there was a concern that rear-end crashes and other crash types would increase after intersections were converted to all-way stop control. Overall, there was a 6% (+/- 22%) increase in rear-end crashes, a 47% (+/- 12%) reduction in ran-off-road crashes, and a 6% (+/- 24%) increase in all other non-target crashes. It appears that the concern of creating a substantial increase in rear-end crashes and other crash types is not showing itself. There was a substantial reduction in ran-off-road crashes, which may be attributed to a decrease in avoidance type crashes.

There are notable limitations with using a naïve before and after analysis because it assumes that nothing changed from the before period to the after period except for the treatment, and that any changes in collisions can be attributed to the treatment. It does not account for selection bias, other factors that change over time such as traffic volumes, other countermeasures and improvements, and motorist behavior. The results of the naïve before and after analysis are provided for completeness and for comparison to the Empirical Bayes analysis, which is the preferred method of evaluation.

4.2. Empirical Bayes Method

Empirical Bayes before and after techniques were utilized to overcome the threat of regression to the mean, along with other deficiencies in the naïve before and after analysis. Regression to the mean is the presumption that a site will return to its long-term mean crash frequency after an extraordinarily high or low period. Regression to the mean was a significant threat in our case because crash history was known to be a factor in the selection of treatment at many of the locations.

The Empirical Bayes approach requires the use of reference sites as well as before period data from the treatment site to estimate the expected safety of the treatment site had no improvements been made. We then compare the actual number of after period crashes at the treatment site to the expected number of after period crashes at the treatment site without improvements. The Empirical Bayes before and after analysis does not account for changes in traffic volume experienced at the treatment sites. Changes in traffic volume will be accounted for in the next section.

The criteria used for selecting reference sites were:

- Intersection of two roads with four approaches, and
- Two-way stop sign control.

Aerial maps and NCDOT traffic volume maps were used in the selection of reference sites and to confirm they met these criteria. Two hundred and sixty eight reference sites, or approximately five reference sites per treatment site, were chosen and include a cross-section similar to the treatment sites in urban, suburban and rural areas. Reference site crash data were compiled separately for the individual before periods at all 53 treatment sites. Table 4 provides the results of the Empirical Bayes analysis for all locations, as well as Groups 1, 2 and 3. Generally, the results were similar to the results from the naïve before-after analysis presented in Table 3.

4.3. Empirical Bayes with Consideration for Traffic Increase

In this step we adjusted for the increase in traffic volumes, which were not accounted for with the previous Empirical Bayes analysis. The increase in traffic volumes was a concern because of the long duration of before and after periods at each of the sites. Some of the analysis periods were over nine years in duration, and the average before period was approximately five years. The average change in volume at the treatment sites was approximately 15% from the middle of the before period to the middle of the after period. A linear assumption was made to account for the increase in traffic volumes. Table 5 provides the results from combining the Empirical Bayes analysis with the traffic volume adjustment for all locations, as well as Groups 1, 2 and 3. Again, the results were not much different from the naïve before-after results provided in Table 3.

4.4. Influence of Speed Limits on All-Way Stop Safety Performance

The treatment sites provided us with a diverse group of all-way stop intersections with approach speed limits ranging from 20 mph to 55 mph. Of the 53 sites, there were 18 low speed sites (with speed limits of 20 to 35 mph on all approaches), 16 moderate speed sites (with speed limits of 35 to 45 mph on all approaches and at least one approach greater than 35 mph), and 19 high speed sites (with speed limits of 45 to 55 mph on all approaches and at least one approach greater than 45 mph). We wanted to determine what role the speed limits approaching the treatment intersections play in the crash reductions. Figure 1 provides a graph showing the relationship between speed limits and total crashes at all treatment sites. It appears that there are greater crash reductions at the higher speed sites.

We wondered if the presence of flashing beacons was skewing the data in Figure 1 because a majority of Group 2 and 3 sites with flashers were in the moderate and high speed limit ranges. We ran the analysis again using only Group 1 sites without flashers. Figure 2 provides a graph showing the relationship between approach speed limits and total crashes at the 33 Group 1 treatment sites. At the Group 1 sites, there were still greater crash reductions at the higher speed sites. It appears that the relationship between speed limits and crash reductions holds true for our data set, whether analyzing sites with or without flashing beacons.

We wanted to determine what factors may have contributed to the difference in crash reductions between the higher speed limit and lower speed limit sites. If not for the higher percentage of flashing beacons at the higher speed sites, maybe some other intersection characteristics played a role. Table 1 showed that a high percentage of the moderate and high speed sites had additional signing and marking treatments to supplement the stop signs, including oversized stop signs, dual stop signs, advanced warning signs, “stop ahead” pavement markings, stop bars, florescent markers on stop signs, and/or flags posted above stop signs. For example, all of the moderate and high speed limit sites had “stop ahead” signs, while only about half of the low speed sites had this treatment. It seems that the moderate and higher speed limit sites (typically located in more rural areas) generally have a more visible all-way stop condition. The greater crash reductions at the higher speed sites may be attributed to the use of additional signing and marking to alert motorists of the all-way stop condition. Figure 3 provides an example of a rural, 45-mph non-flasher location with a very visible all-way stop condition created by additional signing and marking. These photos were taken two weeks after installation. At the time, the converted approaches had dynamic message signs, “new traffic pattern" signs and two sets of "stop ahead" signs with flagging, "stop ahead" and "stop" pavement markings, stop bars, and dual stop signs.

The relationship between speed limits and crash reductions suggests that the gap between flasher and non-flasher sites may not be as large as the results initially indicate. The presence of a flasher may not be the main contributor to Group 2 and 3 sites having crash reductions over 20 percent higher than Group 1 sites. Eighty-seven percent of Group 2 sites and 75 percent of Group 3 sites had approach speed limits in the moderate and high ranges, while only 58 percent of Group 1 sites had approach speeds within these ranges. We found that the sites with higher speed limits generally had higher crash reductions, so it seems plausible that the difference between crash reductions at flasher versus non-flasher sites may be influenced as much by other factors such as additional signing and marking at the higher speed limit sites as by the presence of a flasher.

4.5. Influence of Volume on All-Way Stop Safety Performance

Intersection volumes varied from 680 to 15,400 entering vehicles per day in the after period, with the average AADT (annual average daily traffic) for all locations being approximately 6,400 entering vehicles per day. As mentioned earlier, Persaud (1986) studied the influence of volumes on crash reductions at urban one-way streets converted to all-way stops and found all-way stop conversion is effective for a wide range of volumes. Our analysis of intersections converted from two-way to all-way stop control shows similar results. Figure 4 is a scatter plot of the after period intersection AADT versus percent reduction in total crashes for all treatment locations. There is no apparent trend between entering volumes and crash reductions. The conversion to all-way stop control is consistently effective at a wide range of intersection volumes, and can be just as effective at higher entering volumes as it is at lower.

We also examined the effect of traffic volume share on safety. There is a still a prevailing belief that all-way stop control has more safety benefit when the approach volumes are nearly equal, even though Persaud's (1986) results suggest it is just as effective when approach volumes are unbalanced. The minor road volume share varied from 18 percent to 50 percent of the total entering volume at the treatment sites. Figure 5 is a plot of minor road volume share versus percent reduction in total crashes for all treatment locations. The sites are divided into a higher and lower volume group using 6,000 entering vehicles per day as the break point.

In the group of treatment sites, it appears that the conversion from two-way to all-way stop control was effective when intersection volumes are unbalanced between the minor and major approaches under a variety of conditions. There is no evidence to suggest that approach volumes have to be nearly equal for the countermeasure to be effective. The results were similar whether the intersection volumes are lower or higher. Note that NCDOT typically does not install all-way stop control when the minor road volume share is low, so there are fewer samples in the 15-30 percent range.

5. Discussion

The results demonstrate that converting the intersection control from two-way stop to all-way stop led to a substantial reduction in the frequency and severity of crashes at a diverse group of treatment locations. In most cases, the results using Empirical Bayes analysis are very close to the results using naïve before and after analysis, which may suggest that regression to the mean did not have much of an affect on the data. The closeness of results may also be explained by the reference sites having a relatively high variance in crash frequency, which means there was relatively moderate weight given to the reference site data. The average weight given to the reference sites in the total crash group was around 30 percent. The reference set represents a broad array of intersections in rural and urban areas with a wide range of entering volumes, similar to the treatment sites. Therefore there was a high variability in the number of total crashes at the reference sites.

The influence of speed limits on crash reductions were investigated because some question how appropriate all-way stop control is at rural intersections with 45 to 55 mph speed limits. Contrary to this common belief, it appears that there were greater crash reductions at the higher speed treatment sites. This relationship between speed limits and crash reductions held true when analyzing sites without flashing beacons as well as those with them. We concluded that many more of the sites with moderate and high speed limits utilize a combination of additional signing and marking treatments to emphasize the all-way stop condition. The additional signing and marking likely contributed to the greater crash reduction.

In addition to the aggregated results, the data were grouped separately by presence of an overhead and/or sign mounted flashing beacon. It appears that the groups with flashing beacons (Groups 2 and 3) performed better than those without (Group 1). However, as discussed earlier, the difference in crash reductions may be attributed to the large percentage of high speed sites with additional signing and marking in Groups 2 and 3 as much as to the presence of flashers. Groups 2 and 3 outperformed Group 1 when it came to "ran stop sign" crashes, but again the results may be skewed by additional signing and marking at the higher speed sites and may not be solely attributed to the presence of flashers. The sample sizes of "ran stop sign" crashes for Groups 2 and 3 were small, making it difficult to draw definitive conclusions. After accounting for regression to the mean, Group 2 (sites with newly installed flashers in the after period) and Group 3 (sites where flashers were present in both the before and after period) performed about the same.

The injury and frontal impact crash categories seem to especially benefit from the conversion to all-way stop control, as expected. Due to the all-way stop condition, vehicles in crashes tend to be traveling at much lower speeds at impact. At the treatment sites, we specifically found a substantial decrease in vehicle speeds at impact in “ran stop sign” crashes. In “ran stop sign” crashes, the average speeds at impact were approximately 32 mph in the before period and 21 mph in the after period, a decrease of over 10 mph.

Based on the data set, the current selection and placement of all-way stop control in North Carolina implies that the countermeasure is most effective within a narrow range of volume conditions and under nearly balanced volumes. However, our results found that the conversion to all-way stop control is consistently effective at a wider range of intersection volumes, and can be just as effective at higher entering volumes as it is at lower. The results also show that the conversion to all-way stop control can be as effective when intersection volumes are unbalanced between the minor and major approaches as when they are nearly equal. Of course, this does not mean that volumes play no part in the safety of all-way stop controlled intersections, only that in our limited sample there was no apparent trend between these volume characteristics and crash reductions.

In North Carolina, the current cost for conversion from two-way to all-way stop control is approximately $5,000, which includes use of dual oversized stop signs, “stop ahead” signs, and “stop ahead” pavement markings on the converted approaches. When converting existing flashing beacons or adding new flashing beacons, recent projects have been set up with up to $20,000. Benefit-cost analyses at several of the sites with known installation and maintenance cost have resulted in benefit-cost from 11:1 to 86:1. In many cases the conversion from two-way to all-way stop control creates extremely competitive projects that can be funded quickly and implemented quickly as well, especially at intersections with a strong pattern of frontal impact crashes that do not meet traffic signal warrants.

5.1. Recommended Crash Reduction Factors

The recommended crash reduction factors for conversion from two-way stop control to all-way stop control are the factors calculated by the Empirical Bayes method with consideration for traffic increase, which are:

Total Crashes	-68%
Injury Crashes	-77%
Frontal Impact Crashes	-75%
Ran Stop Sign Crashes	-15%

The recommended crash reduction factors use data from the overall group of 53 locations, regardless of whether a flasher is present or whether the intersection is rural, low volume and high speed or urban, higher volume and low speed. The overall conclusion is based on the most expansive group to provide the widest scope possible. The results were run both with and without the four extra sites with geometry differences, and there was not a significant change in the results with their inclusion in the group.

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Table 1 Listing of Treatment Sites

Site	Group	Flashing Beacon	Oversized Stop Signs	Dual Stop Signs	Advance Signing	Advance Pavement Marking	Stop Bars	Flags on Signs	Flourescent Markers on Sign Posts	Speed Limit 1	Speed Limit 2
1	1	None	No	No	Yes	No	Yes	No	No	25	35
2	1	None	No	Yes	Yes	No	Yes	No	No	55	55
3	1	None	Yes	Yes	Yes	No	No	No	No	45	45
4	1	None	No	No	Yes	Yes	Yes	No	Yes	35	35
5	1	None	No	Yes	Yes	No	Yes	No	No	25	25
6	1	None	No	Yes	Yes	No	Yes	No	No	45	45
7	1	None	No	No	Yes	No	Yes	No	No	45	45
8	1	None	No	No	Yes	No	No	No	No	55	55
9	1	None	No	No	Yes	No	Yes	No	No	35	35
10	1	None	No	Yes	Yes	No	Yes	No	No	45	35
11	1	None	No	No	Yes	No	No	No	No	55	55
12	1	None	Yes	Yes	Yes	No	Yes	Yes	No	45	45
13	1	None	No	No	No	No	Yes	No	No	25	25
14	1	None	No	No	Yes	No	Yes	No	No	55	55
15	1	None	No	No	Yes	No	Yes	No	No	45	55
16	1	None	Yes	Yes	Yes	Yes	Yes	Yes	No	45	45
17	1	None	No	No	No	No	No	No	No	20	25
18	1	None	No	Yes	Yes	No	Yes	No	No	50	55
19	1	None	No	No	No	No	No	No	No	25	25
20	1	None	No	No	No	No	No	No	No	25	25
21	1	None	No	No	No	No	No	No	No	25	25
22	1	None	No	Yes	Yes	No	Yes	No	Yes	35	30
23	1	None	No	No	No	No	No	No	No	25	25
24	1	None	No	No	No	No	No	No	No	25	25
25	1	None	No	No	Yes	Yes	Yes	No	No	45	45
26	1	None	No	No	Yes	No	Yes	Yes	No	35	35
27	1	None	No	Yes	Yes	No	Yes	No	No	45	45
28	1	None	No	No	Yes	No	Yes	No	No	45	55
29	1	None	Yes	Yes	Yes	Yes	Yes	No	No	55	55
30	1	None	No	Yes	Yes	Yes	Yes	No	No	45	55
31	1	None	Yes	Yes	Yes	Yes	Yes	Yes	No	55	55
32	1	None	Yes	Yes	Yes	Yes	Yes	Yes	No	45	45
33	1	None	No	No	Yes	Yes	Yes	Yes	No	35	25
34	2	Overhead	No	Yes	Yes	Yes	Yes	No	No	45	45
35	2	Overhead	Yes	Yes	Yes	No	Yes	Yes	No	45	45
36	2	Overhead	No	Yes	Yes	Yes	Yes	No	No	35	35
37	2	Overhead	No	Yes	Yes	Yes	Yes	Yes	No	45	45
38	2	Overhead	Yes	Yes	Yes	Yes	Yes	Yes	No	55	45
39	2	Overhead & Sign Mounted	Yes	Yes	Yes	Yes	Yes	Yes	No	55	55
40	2	Overhead	Yes	Yes	Yes	Yes	Yes	No	No	45	55
41	2	Overhead	Yes	Yes	Yes	Yes	Yes	Yes	No	55	45
42	3	Overhead	Yes	Yes	Yes	Yes	Yes	No	No	45	45
43	3	Overhead	No	No	Yes	No	Yes	No	No	55	55
44	3	Overhead	No	Yes	Yes	Yes	Yes	No	No	35/45	45
45	3	Overhead	No	Yes	Yes	No	Yes	Yes	No	55	55
46	3	Overhead & Sign Mounted	No	No	Yes	No	Yes	Yes	No	35	35
47	3	Overhead	No	Yes	Yes	No	Yes	No	Yes	55	50
48	3	Sign Mounted	No	No	Yes	No	Yes	Yes	No	30	30
49	3	Sign Mounted	No	Yes	Yes	Yes	Yes	No	No	45	55
50		None	Yes	Yes	Yes	Yes	Yes	Yes	No	35/45	45
51		Overhead	Yes	Yes	Yes	Yes	Yes	Yes	No	45	35
52		Overhead & Sign Mounted	Yes	No	Yes	Yes	Yes	Yes	No	45	50
53		Sign Mounted	No	No	No	No	Yes	No	No	30	35

Table 2 Before and After Crash Data at Treatment Sites

		Before Period						After Period					
Site	**Group**	**Years**	**Intersection AADT**	**Total Crashes Per Year**	**Injury Crashes Per Year**	**Frontal Impact Crashes Per Year**	**Ran Stop Crashes Per Year**	**Years**	**Intersection AADT**	**Total Crashes Per Year**	**Injury Crashes Per Year**	**Frontal Impact Crashes Per Year**	**Ran Stop Crashes Per Year**
1	1	4	9700	4.00	0.75	2.75	0.50	4	9400	6.25	1.25	3.50	2.25
2	1	5.75	6700	4.00	2.09	3.13	0.35	5.75	8950	1.74	0.87	1.74	0.87
3	1	6.58	2900	1.52	0.91	1.37	0.61	6.58	4450	1.37	0.30	0.91	0.91
4	1	6.5	6150	6.92	2.15	5.38	1.69	6.5	9450	6.31	2.77	2.92	1.38
5	1	7	4200	1.29	1.00	1.14	0.43	7	3400	0.43	0.00	0.14	0.14
6	1	8.58	3775	3.38	1.28	3.26	0.47	8.58	4150	0.35	0.12	0.12	0.12
7	1	8.58	5400	2.45	1.86	2.45	0.47	8.58	5100	0.47	0.23	0.23	0.12
8	1	7.92	1820	3.41	1.77	2.90	0.88	7.92	2670	0.63	0.25	0.38	0.38
9	1	7.5	8600	4.93	2.40	4.00	1.33	7.5	7400	1.07	0.13	0.40	0.00
10	1	7.58	10800	1.98	0.92	1.19	0.00	7.58	12250	2.51	0.66	1.58	0.79
11	1	7.09	3850	1.55	1.13	1.41	0.14	7.09	3900	1.13	0.71	0.71	0.56
12	1	6.5	5600	4.92	3.23	4.77	0.62	6.5	7650	1.85	0.92	1.38	1.23
13	1	6.09	2000	0.33	0.16	0.33	0.00	6.09	2400	0.16	0.00	0.16	0.00
14	1	5.84	5500	2.74	1.20	1.20	0.17	5.84	9200	2.40	0.86	1.37	1.20
15	1	5.33	12100	6.19	3.56	5.82	1.50	5.33	15100	1.13	0.56	0.75	0.56
16	1	5.16	6000	5.23	2.91	5.04	1.16	5.16	5300	0.78	0.19	0.78	0.58
17	1	4.75	2000	0.63	0.21	0.42	0.00	4.75	2400	0.21	0.21	0.21	0.00
18	1	4.75	8950	3.58	1.89	2.74	0.21	4.75	11750	1.05	0.63	1.05	0.21
19	1	4.67	730	0.00	0.00	0.00	0.00	4.67	680	0.00	0.00	0.00	0.00
20	1	4.67	730	0.21	0.00	0.21	0.21	4.67	680	0.00	0.00	0.00	0.00
21	1	4.67	730	0.00	0.00	0.00	0.00	4.67	680	0.21	0.00	0.00	0.00
22	1	4.67	5600	0.64	0.43	0.21	0.00	4.67	5000	0.86	0.43	0.21	0.00
23	1	4.33	730	0.00	0.00	0.00	0.00	4.33	680	0.00	0.00	0.00	0.00
24	1	4.25	1000	1.18	0.47	1.18	0.47	4.25	1200	0.47	0.00	0.47	0.00
25	1	3.5	5750	4.57	2.29	4.29	0.86	3.5	7000	2.29	0.57	2.00	1.14
26	1	3.25	4750	3.08	2.77	2.77	0.31	3.25	5100	0.31	0.00	0.31	0.31
27	1	3.16	8800	9.81	7.28	8.86	0.63	3.16	11450	3.80	1.27	2.53	1.27
28	1	3.16	5350	5.38	2.85	4.43	0.32	3.16	8150	1.58	0.63	0.95	1.27
29	1	3	6350	5.33	1.67	4.67	0.00	1.58	6300	1.33	0.00	1.33	0.33
30	1	3	5600	4.00	3.00	3.67	1.00	1.75	6200	0.33	0.00	0.33	0.33
31	1	3	4300	7.33	3.33	6.33	1.67	1.58	5300	0.33	0.33	0.33	0.00
32	1	3	8200	5.00	3.33	4.67	1.67	1.58	8800	0.00	0.00	0.00	0.00
33	1	3	2800	1.00	0.00	0.33	0.33	1	3000	0.00	0.00	0.00	0.00
34	2	9	6650	3.44	1.89	3.00	0.44	9	7500	0.67	0.22	0.44	0.11
35	2	9.34	3550	3.96	1.18	3.43	0.00	9.34	5650	0.43	0.00	0.32	0.00
36	2	7.09	7600	3.10	0.71	2.54	0.28	7.09	9650	0.85	0.14	0.28	0.00
37	2	4.08	6650	3.68	2.70	3.68	0.00	4.08	5300	2.45	0.98	1.96	1.47
38	2	3.41	5500	4.11	1.17	3.23	0.29	3.41	6100	0.88	0.00	0.59	0.29
39	2	3	5600	6.67	6.00	4.67	0.33	1.92	6300	0.67	0.33	0.33	0.33
40	2	3	10150	3.33	1.67	3.00	1.00	1.83	13650	0.33	0.33	0.33	0.00
41	2	3	4920	1.33	0.33	1.33	0.33	1.5	5500	0.00	0.00	0.00	0.00
42	3	4.25	4250	5.65	4.94	5.41	1.41	4.25	5100	1.41	0.47	1.18	0.71
43	3	9.42	1340	0.96	0.32	0.74	0.00	9.42	1400	0.32	0.11	0.11	0.11
44	3	5.25	7100	3.43	1.52	3.24	0.38	5.25	9900	0.76	0.38	0.19	0.00
45	3	6.42	3050	6.23	4.83	5.61	0.62	6.42	3350	1.09	0.62	0.78	0.47
46	3	5.92	6800	9.29	3.72	7.26	1.18	5.92	6900	1.35	0.34	0.68	0.51
47	3	4.58	4900	3.71	1.53	3.49	0.66	4.58	5000	0.22	0.22	0.22	0.22
48	3	3.33	5000	4.50	1.80	2.70	0.90	3.33	6000	1.20	0.00	1.20	0.60
49	3	3	6900	5.00	2.67	4.67	0.67	1.16	7350	0.33	0.33	0.33	0.33
50		5.84	4200	2.74	1.71	2.23	0.51	5.84	4775	0.34	0.00	0.00	0.17
51		5.08	6400	7.09	4.13	7.09	1.57	5.08	7000	3.35	1.57	2.36	0.98
52		3	15350	9.33	6.33	8.33	2.67	3	15400	2.67	1.33	2.67	1.33
53		2.41	10000	1.33	0.41	1.24	0.33	2.41	11000	0.83	0.41	0.83	0.41

Table 3 Parameter Estimates Using Naïve Before and After Analysis

	λ			π			θ			Percent Reduction		
Total Crashes												
All Sites	312.0	+/-	17.7	898.8	+/-	30.0	0.347	+/-	0.023	-65.3%	+/-	2.3%
Group 1	217.0	+/-	14.7	491.9	+/-	22.2	0.440	+/-	0.036	-56.0%	+/-	3.6%
Group 2	32.0	+/-	5.7	139.9	+/-	11.8	0.227	+/-	0.044	-77.3%	+/-	4.4%
Group 3	34.0	+/-	5.8	183.8	+/-	13.6	0.184	+/-	0.034	-81.6%	+/-	3.4%
Injury Crashes												
All Sites	111.0	+/-	10.5	475.4	+/-	21.8	0.233	+/-	0.025	-76.7%	+/-	2.5%
Group 1	76.0	+/-	8.7	260.4	+/-	16.1	0.291	+/-	0.038	-70.9%	+/-	3.8%
Group 2	9.0	+/-	3.0	63.1	+/-	7.9	0.140	+/-	0.049	-86.0%	+/-	4.9%
Group 3	13.0	+/-	3.6	101.1	+/-	10.1	0.127	+/-	0.037	-87.3%	+/-	3.7%
Frontal Impact Crashes												
All Sites	201.0	+/-	14.2	770.8	+/-	27.8	0.260	+/-	0.021	-74.0%	+/-	2.1%
Group 1	136.0	+/-	11.7	418.5	+/-	20.5	0.324	+/-	0.032	-67.6%	+/-	3.2%
Group 2	21.0	+/-	4.6	119.5	+/-	10.9	0.174	+/-	0.041	-82.6%	+/-	4.1%
Group 3	22.0	+/-	4.7	156.4	+/-	12.5	0.140	+/-	0.032	-86.0%	+/-	3.2%
"Ran Stop Sign" Crashes												
All Sites	116.0	+/-	10.8	140.9	+/-	11.9	0.817	+/-	0.102	-18.3%	+/-	10.2%
Group 1	82.0	+/-	9.1	85.4	+/-	9.2	0.950	+/-	0.145	-5.0%	+/-	14.5%
Group 2	9.0	+/-	3.0	10.0	+/-	3.2	0.820	+/-	0.343	-18.0%	+/-	34.3%
Group 3	14.0	+/-	3.7	25.8	+/-	5.1	0.523	+/-	0.167	-47.7%	+/-	16.7%

Table 4 Parameter Estimates Using Empirical Bayes Methods

	λ			π			θ			Percent Reduction		
Total Crashes												
All Sites	312.0	+/-	17.7	871.7	+/-	27.3	0.358	+/-	0.023	-64.2%	+/-	2.3%
Group 1	217.0	+/-	14.7	481.8	+/-	20.3	0.450	+/-	0.036	-55.0%	+/-	3.6%
Group 2	32.0	+/-	5.7	140.1	+/-	11.0	0.227	+/-	0.044	-77.3%	+/-	4.4%
Group 3	34.0	+/-	5.8	173.8	+/-	12.2	0.195	+/-	0.036	-80.5%	+/-	3.6%
Injury Crashes												
All Sites	111.0	+/-	10.5	436.0	+/-	18.4	0.254	+/-	0.026	-74.6%	+/-	2.6%
Group 1	76.0	+/-	8.7	240.9	+/-	13.7	0.314	+/-	0.040	-68.6%	+/-	4.0%
Group 2	9.0	+/-	3.0	62.6	+/-	7.0	0.142	+/-	0.049	-85.8%	+/-	4.9%
Group 3	13.0	+/-	3.6	89.5	+/-	8.4	0.144	+/-	0.042	-85.6%	+/-	4.2%
Frontal Impact Crashes												
All Sites	201.0	+/-	14.2	728.3	+/-	24.6	0.276	+/-	0.022	-72.4%	+/-	2.2%
Group 1	136.0	+/-	11.7	400.2	+/-	18.2	0.339	+/-	0.033	-66.1%	+/-	3.3%
Group 2	21.0	+/-	4.6	116.3	+/-	9.9	0.179	+/-	0.042	-82.1%	+/-	4.2%
Group 3	22.0	+/-	4.7	144.3	+/-	11.0	0.152	+/-	0.034	-84.8%	+/-	3.4%
"Ran Stop Sign" Crashes												
All Sites	116.0	+/-	10.8	121.9	+/-	8.5	0.947	+/-	0.110	-5.3%	+/-	11.0%
Group 1	82.0	+/-	9.1	76.1	+/-	6.8	1.068	+/-	0.150	6.8%	+/-	15.0%
Group 2	9.0	+/-	3.0	11.7	+/-	2.7	0.731	+/-	0.281	-26.9%	+/-	28.1%
Group 3	14.0	+/-	3.7	20.5	+/-	3.4	0.665	+/-	0.204	-33.5%	+/-	20.4%

Table 5 Parameter Estimates Using Empirical Bayes Methods with Consideration for Traffic Increase

	λ			π			θ			Percent Reduction		
Total Crashes												
All Sites	312.0	+/-	17.7	976.7	+/-	36.4	0.319	+/-	0.022	-68.1%	+/-	2.2%
Group 1	217.0	+/-	14.7	551.3	+/-	27.6	0.393	+/-	0.033	-60.7%	+/-	3.3%
Group 2	32.0	+/-	5.7	160.3	+/-	15.1	0.198	+/-	0.039	-80.2%	+/-	3.9%
Group 3	34.0	+/-	5.8	184.5	+/-	15.4	0.183	+/-	0.035	-81.7%	+/-	3.5%
Injury Crashes												
All Sites	111.0	+/-	10.5	481.1	+/-	24.5	0.230	+/-	0.025	-77.0%	+/-	2.5%
Group 1	76.0	+/-	8.7	273.7	+/-	18.7	0.276	+/-	0.037	-72.4%	+/-	3.7%
Group 2	9.0	+/-	3.0	65.6	+/-	8.9	0.135	+/-	0.048	-86.5%	+/-	4.8%
Group 3	13.0	+/-	3.6	96.0	+/-	10.8	0.134	+/-	0.04	-86.6%	+/-	4.0%
Frontal Impact Crashes												
All Sites	201.0	+/-	14.2	812.1	+/-	32.8	0.247	+/-	0.02	-75.3%	+/-	2.0%
Group 1	136.0	+/-	11.7	454.1	+/-	24.7	0.299	+/-	0.03	-70.1%	+/-	3.0%
Group 2	21.0	+/-	4.6	133.2	+/-	13.6	0.156	+/-	0.037	-84.4%	+/-	3.7%
Group 3	22.0	+/-	4.7	153.0	+/-	13.9	0.143	+/-	0.033	-85.7%	+/-	3.3%
"Ran Stop Sign" Crashes												
All Sites	116.0	+/-	10.8	134.5	+/-	12.7	0.855	+/-	0.112	-14.5%	+/-	11.2%
Group 1	82.0	+/-	9.1	85.7	+/-	10.3	0.943	+/-	0.152	-5.7%	+/-	15.2%
Group 2	9.0	+/-	3.0	12.4	+/-	3.7	0.667	+/-	0.275	-33.3%	+/-	27.5%
Group 3	14.0	+/-	3.7	22.1	+/-	5.0	0.601	+/-	0.201	-39.9%	+/-	20.1%

Figure 1 Relationship between Speed Limits and Total Crashes at Treatment Sites – All Locations

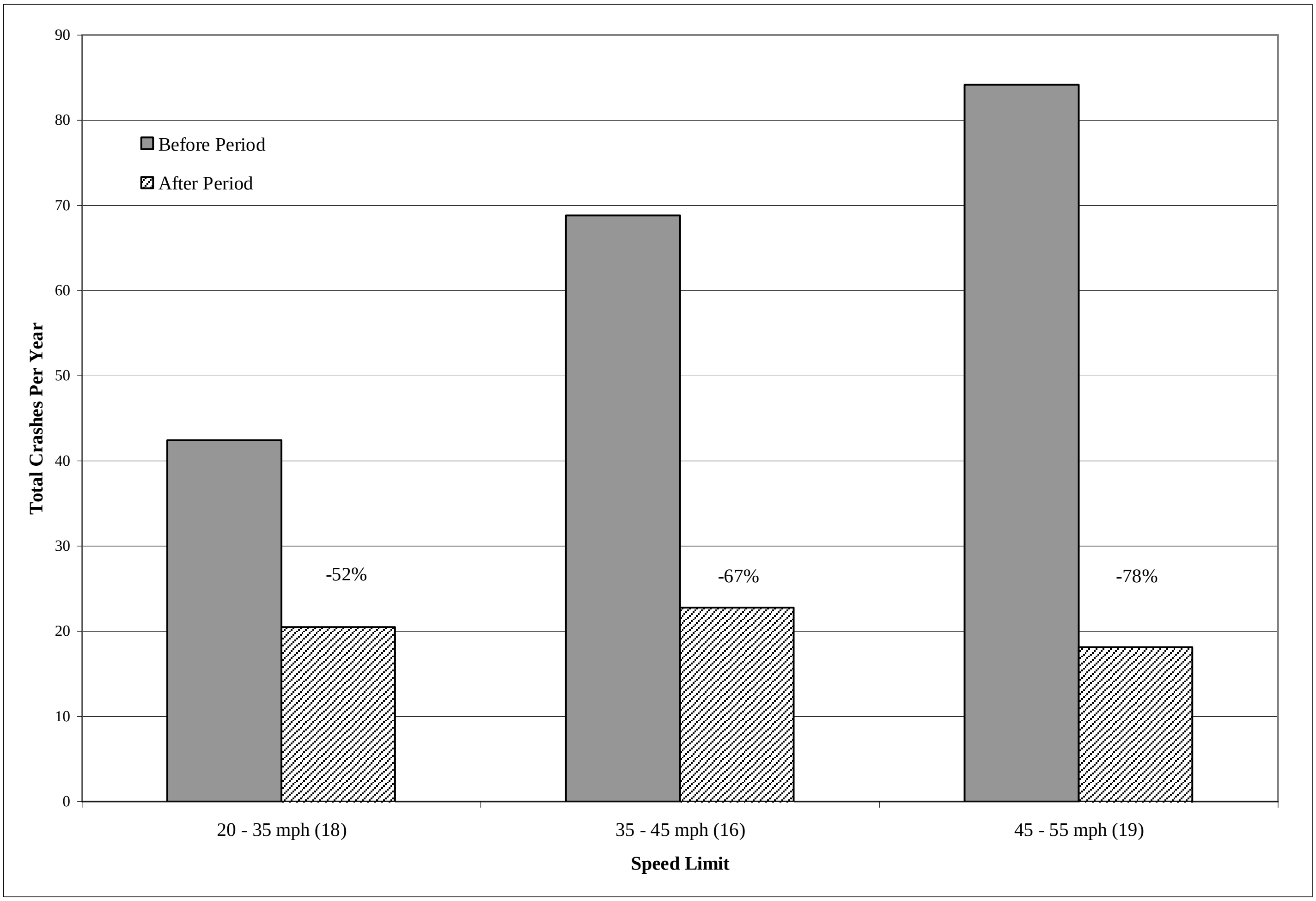

Figure 2 Relationship between Speed Limits and Total Crashes at Treatment Sites – Group 1 Locations

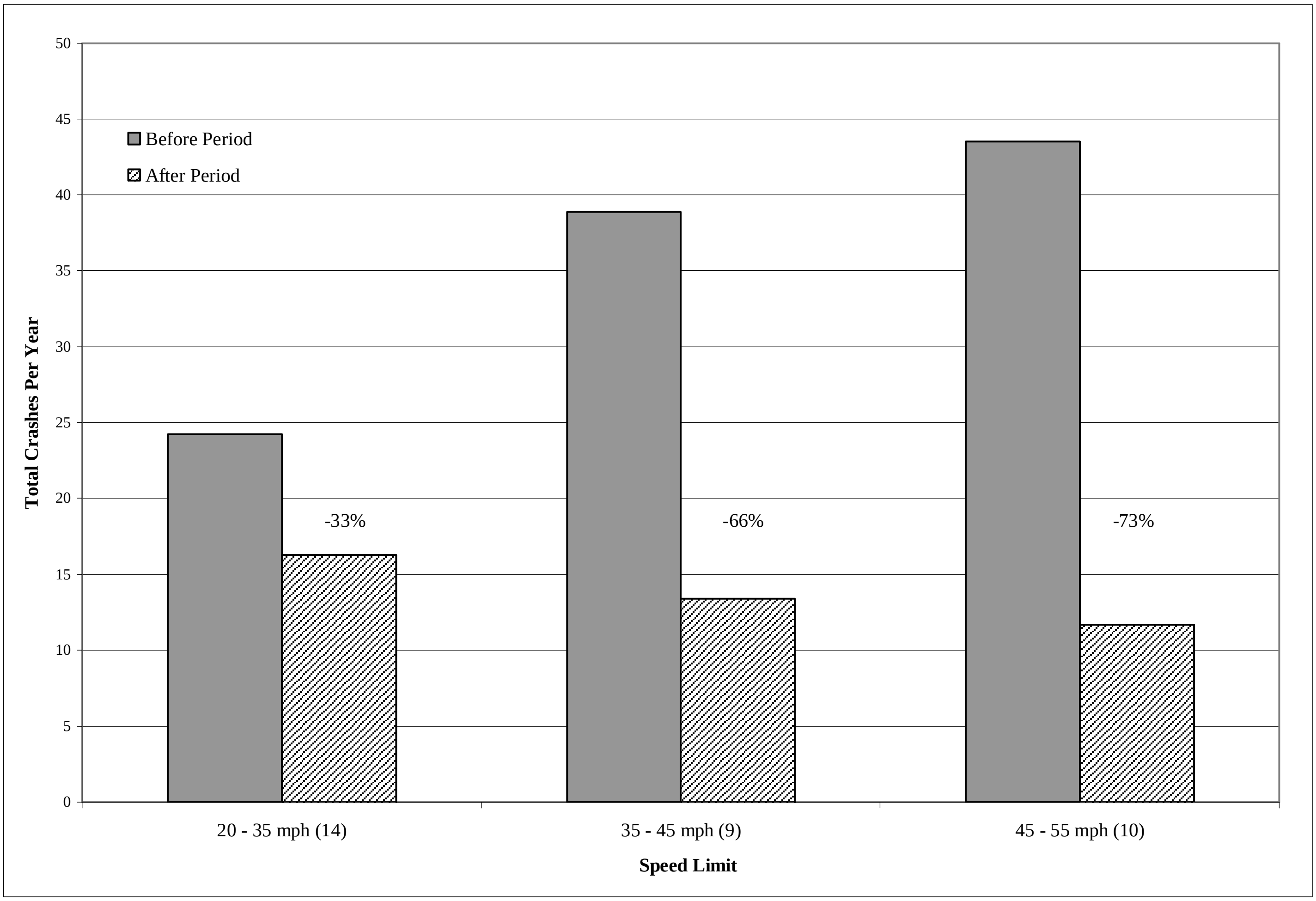

Figure 3 Signing and Marking on a Recently Converted 45-mph Approach

Figure 4 Influence of Intersection AADT on Crash Reductions at Treatment Sites

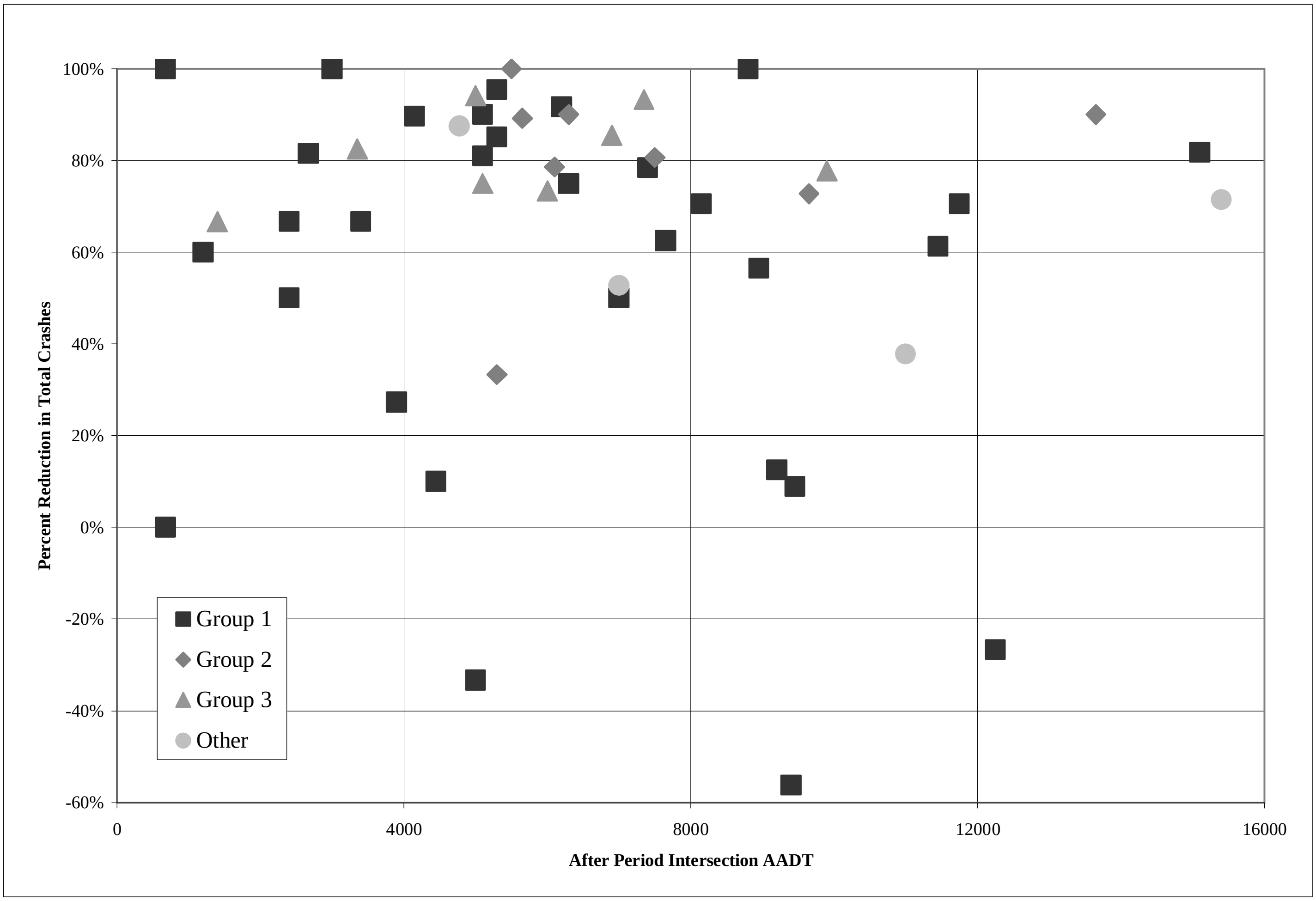

Figure 5 Influence of Minor Road Volume Share on Crash Reductions at Treatment Sites