HIGHWAY SAFETY INFORMATION SYSTEM

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U.S. Department of Transportation
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SAFETY-BASED DEPLOYMENT ASSISTANCE FOR LOCATION OF V2I APPLICATIONS

PILOT: RED-LIGHT-VIOLATION WARNING APPLICATION

HSIS Task Report

Submitted to:

Federal Highway Administration

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Submitted by:

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SAFETY-BASED DEPLOYMENT ASSISTANCE FOR LOCATION OF V2I APPLICATIONS PILOT: RED-LIGHT-VIOLATION WARNING APPLICATION

Background

V2I Applications

Vehicle-to-Infrastructure (V2I) is a component of the connected vehicles program. It is a wireless-based communication technology in which the exchange of critical operational and safety data between vehicles and roadway infrastructure is intended to help avoid crashes. Previous research commissioned by the U.S Department of Transportation (DOT) has identified eight applications that can provide safety benefits. Among those applications, Red-Light Violation Warning (RLVW), Stop Sign Gap Assist (SSGA) and Curve Speed Warning (CSW) were selected for accelerated evaluation. A prototype RLVW application was subsequently developed under an agreement between the Federal Highway Administration (FHWA) and the Crash Avoidance Metrics Partners, LLC (CAMP).

Red-Light-Violation Warning (RLVW) Application

The RLVW application is one of V2I accelerated-development applications. The intent of the application is to prevent crashes due to signal violations at signalized intersections by warning vehicles approaching the intersection that are potentially going to violate the signal based on the their approach speeds and distance to the signalized intersection. An equipped intersection broadcasts signal phase and timing, geometric intersection descriptions, and GPS location correction information. When an equipped vehicle approaches the intersection and the system determines that the vehicle is potentially going to violate the red-light based on current operating conditions, it will issue a warning to the driver. The driver is expected to heed the warning and stop their vehicle before entering the signal and potentially causing a crash.

Vehicle Deployment

The number of vehicles equipped to receive the message will affect the system's ability to prevent crashes. As more vehicles are equipped, more crashes may be prevented. The *National Connected Vehicle Field Infrastructure Footprint Analysis* presented estimates for the speed of deployment of equipped vehicles in the nation's vehicle fleet. The deployment scenarios are described as mandates (assuming a requirement is in place) or organic (assuming voluntary installation by manufacturers). Figure 1 presents three scenarios for potential deployment over a 25-year period: a 1-year mandate, a 5-year mandate, and a 15-year organic implementation. The 1-year mandate presents the most aggressive deployment with 60 percent of the vehicles equipped by year 10. The 15-year organic implementation represents the slowest deployment scenario with 20 percent of the vehicles equipped by year 10. For the purposes of this analysis, it is assumed that either a mandate or organic implementation of connected vehicle technologies in vehicles will occur beginning in 2020.

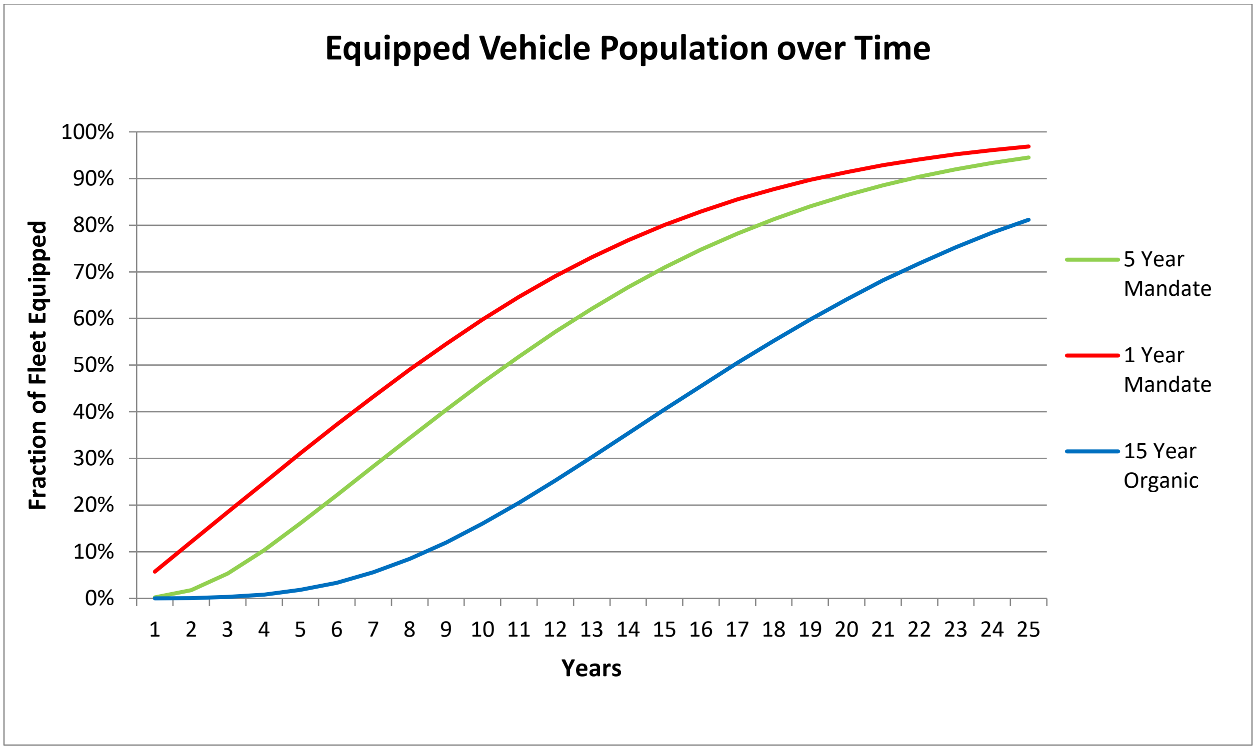

Figure 1. Three potential vehicle deployment scenarios.

(Source: *National Connected Vehicle Field Infrastructure Footprint Analysis*)

The National Highway Traffic Safety Administration (NHTSA) issued the Vehicle-to-Vehicle (V2V) Notice of Proposed Rulemaking on December 20, 2016. This NPRM proposes to mandate V2V communications for new light vehicles over a three-year period, beginning two years after issuance of a final rule.

Infrastructure Deployment

State DOTs and local transportation agencies will be the primary installers of the infrastructure component of the V2I RLVW systems. They will install these systems at signalized intersections with the goal of preventing signal violation crashes. Therefore, their selection of locations for deployment of these systems will be primarily based on the expected occurrence of signal violation crashes. These agencies need guidance in identifying locations that have experienced signal violation crashes and are expected to continue to experience these crashes unless there is an intervention such as the deployment of the RLVW system.

OBJECTIVE

The objective of this effort was to develop guidance for State and local agencies on how to select locations for deployment of the RLVW applications to achieve the greatest benefit to cost ratios by exploring the occurrence of target crashes, the annual fluctuations in crash occurrence by intersection, and the costs of the target crashes.

The selected method should have the following characteristics:

- Easy to implement by a State or local agency without rigorous statistical analysis.
- Applied using no more than five years of data.
- Results in the identification of those locations with the most opportunity to reduce target crashes.

This effort concentrated on understanding and characterizing the benefits of the application expressed as the comprehensive cost savings from preventing crashes based on historical crash occurrence.

DATA EMPLOYED

This analysis used intersection and crash data from the Highway Safety Information System (HSIS) and from the city of Charlotte, North Carolina. The economic analysis was performed based on crash cost information from the Federal Highway Authority (FHWA) and the Office of the Secretary of Transportation. These sources of data are described in the following sections.

Intersection and Crash Data

The intersection and crash data for this study came as part of the Highway Safety Information System (HSIS). The HSIS is a roadway-based system maintained by the FHWA that provides quality data on a large number of crash, roadway, and traffic variables linked to homogeneous sections of the entire highway system under State control. It is the only multi-State database that allows for the safety analysis of roadway design factors, as it is the only file system with the capability to link roadway inventory and exposure data to crash data for a large sample of primary route mileage, and the only file system to include both roadway sections with and without crashes. It is important to note that HSIS data are only available for State-maintained roadways in each State. As such, HSIS represents more rural areas, because roadways in urban areas are often maintained by a municipality. This is important to this analysis, as urban intersections are more likely to be signalized than rural intersections. Therefore, an analysis of signalized intersections using HSIS data in a State may include a higher proportion of rural signalized intersections than the State as a whole.

Currently, seven States are part of the HSIS: California, Illinois, Maine, Minnesota, North Carolina, Ohio, and Washington. (Historical data from Michigan and Utah are also available, but updated data are no longer captured.) HSIS also includes the City of Charlotte. This study analyzed data for the 10 most recent years of data for California, the three most recent years of data for Minnesota, and the three most recent years of data for Charlotte.

There are six types of data files available within HSIS. All States maintain three basic files: a crash file, a roadway inventory file, and a traffic volume file. Additional roadway geometry files are also available within selected States, including a horizontal curve file, a vertical grade file, and an intersection and interchange data file. California and Minnesota were selected for detailed intersection analyses, as these States provide intersection data files, which are critical to this analysis.

The Charlotte dataset was provided by the Charlotte Department of Transportation as part of the HSIS project. The dataset included intersection, roadway and crash data files and came in GIS shape files. Figure 2 illustrates the Charlotte GIS data.

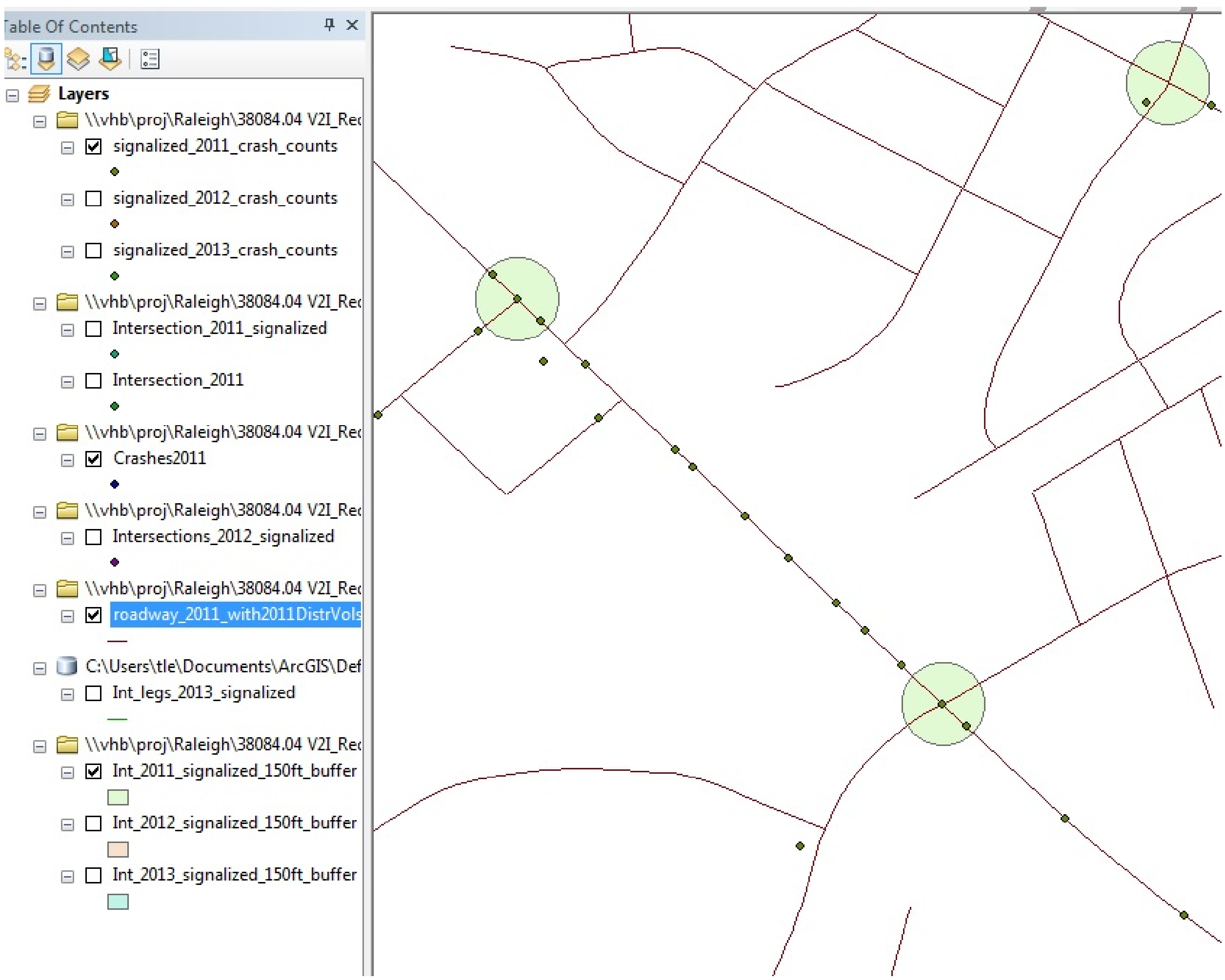

Figure 2. Process and merge Charlotte data layers in ArcGIS.

The study used ten most recent years of data available for California (2002 to 2011). The study also used three most recent years of Minnesota data (2010 to 2012) and Charlotte data (2011-2013). More years of California data were necessary for conducting a time series analysis. All 10 years of data were no longer necessary after a recommended time frame had been established and the primary analyses only needed most recent three years of data. Table 1 presents a summary of California, Minnesota, and Charlotte data used for this analysis including the years of data, the number of signalized intersections, and the number of crashes at those intersections.

Table 1. Summary of HSIS data from California, Minnesota, and Charlotte.

Variable	California	Minnesota	Charlotte
Years Analyzed (Trend Analysis)	10 (2002 – 2011)	N/A	N/A
Years Analyzed (Primary)	3 (2009-2011)	3 (2010-2012)	3 (2011-2013)
Number of Signalized Intersections	1,913	832	705
Average Annual Signalized Intersection Crashes	7,601	3,313	5,183
Average Annual Fatal and Incapacitating Injury Signalized Intersection Crashes	167.3	44.3	26.0
Average Annual Crashes per Signalized Intersection	3.97	3.98	7.35

Each intersection for California and Minnesota was characterized as urban or rural in the HSIS data. Approximately 10 percent of the signalized intersections were rural in both States. All intersections from Charlotte were categorized as urban.

A list of elements for each dataset is presented in Appendix A.

Crash Costs

The FHWA report *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries* provides mean comprehensive crash costs disaggregated by crash severity, location type, and speed limit.(1) The report is a useful reference for determining the cost of crashes and therefore the potential monetized benefits of preventing those crashes. However, the values in the report are based on 2001 dollars which are now out of date. Although not disaggregated by severity, location, and speed limit, the FHWA Office of Policy provides departmental guidance on valuing reduction of fatalities and injuries by regulations or investments. The most recent guidance was provided in the 2015 memorandum, *Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses – 2015 Adjustment.*(2) These values were used to modify the detailed crash costs by applying a proportion (the ratio of the 2015 fatality and the 2001 fatality costs) to the disaggregated 2001 costs to represent the costs in terms of 2015 dollars. Table 2 presents the resulting average cost per crash by the maximum injury severity in the crash in 2015 dollars. This cost represents all speed limits.

Table 2. Average cost per crash based on maximum injury severity (in 2015 dollars).

Maximum Injury Severity in Crash	Cost (in 2015 dollars)
Fatality (K)	$9,901,946
Incapacitating Injury (A)	$533,666
Injury, Non-incapacitating (B)	$197,049
Possible Injury (C)	$110,374
Property Damage Only (O)	$18,374

METHODOLOGY

Characterizing Intersections

Signalized intersections in California, Minnesota, and Charlotte represent a diverse set of intersections that vary by land use, functional class, and number of approach lanes. For example, the crash experience at the intersection of two-lane rural roads is likely remarkably different than the crash experience at the intersection of six-lane arterials in an urban environment. The urban intersection will likely experience more crashes than the rural intersection based on the differences in volume of the intersection although the rural intersection may experience a higher rate of target crashes or more severe crashes because of higher speeds.

A State or local agency may want to consider these types of intersections separately. Therefore, the intersections were characterized into groups of similar intersections based on the land use and number of approach lanes. Table 3 presents the intersection groups that the research team developed with the California data and the average number of total intersection crashes for each group. Generally, the intersection groups on average experience between three and five crashes per year.

Table 3. Intersection groups and crashes in California.

Intersection Group	Number of Intersections in Group	Average Annual Number of Total Intersection Crashes
Urban-2 mainline lanes x 2 cross street lanes	157	2.97
Urban-4 mainline lanes x 2 cross street lanes	687	3.56
Urban-4 mainline lanes x 4 cross street lanes	279	4.67
Urban-6 mainline lanes x 2 cross street lanes	182	3.90
Urban-6 mainline lanes x 4 cross street lanes	111	5.80
Urban-Others	289	4.63
Rural-2 mainline lanes x 2 cross street lanes	106	2.79
Rural-4 mainline lanes x 2 cross street lanes	63	3.93
Rural-Others	39	3.83

Table 4 presents similar information for the Minnesota data. For Minnesota, the research team grouped intersections by number of approaches (3 or 4-legged intersections), land use, and number of lanes to the extent possible given available sample sizes. Generally, groups of fewer than 30 intersections are too small to be representative. Therefore, the team decided to combine all urban 3-legged intersections into one group and all rural 3-legged into another regardless of the number of lanes. This resulted in a total of nine groups. The average annual number of crashes for each group varies more than the groups in California.

Table 4. Intersection groups and crashes in Minnesota.

Intersection Group	Number of Intersections in Group	Average Annual Number of Total Intersection Crashes
3-legged Urban	58	2.78
3-legged Rural	11	2.12
4-legged Urban-2 mainline lanes x 2 cross street lanes	155	2.03
4-legged Urban-4 mainline lanes x 2 cross street lanes	289	3.59
4-legged Urban-4 mainline lanes x 4 cross street lanes	141	7.10
4-legged Rural-2 mainline lanes x 2 cross street lanes	29	2.47
4-legged Rural-4 mainline lanes x 2 cross street lanes	29	4.30
4-legged Others	101	4.99
Others (e.g., 5-legged or more with all other lane configurations)	19	3.96

Table 5 presents the intersection groups that the research team developed with the Charlotte data and the average number of total intersection crashes for each group. This table does not categorize intersections by land use (i.e., urban vs. rural) because all intersections in Charlotte dataset were urban. The average annual number of crashes per intersection varies widely across different groups.

Table 5. Intersection groups and crashes in Charlotte.

Intersection Group	Number of Intersections in Group	Average Annual Number of Total Intersection Crashes
3-legged with 2 mainline lanes x 2 cross street lanes	34	2.89
3-legged with 4 mainline lanes x 2 or 4 cross street lanes	128	4.65
3-legged with 6 mainline lanes x 2 or 4 cross street lanes	27	8.72
3-legged, others	9	6.00
4-legged with 2 mainline lanes x 2 cross street lanes	85	4.43
4-legged with 4 mainline lanes x 2 cross street lanes	256	7.01
4-legged with 4 mainline lanes x 4 cross street lanes	48	13.88
4-legged with 6 mainline lanes x 2 cross street lanes	33	11.35
4-legged with 6 mainline lanes x 4 cross street lanes	40	15.62
4-legged, others	45	8.07

Identifying Target Crashes

Target crashes for this application are those resulting from a vehicle facing the red indication violating the signal and colliding with a vehicle on the perpendicular approach facing a green indication. These are primarily straight crossing path crashes (SCP) but may also include other crashes. Volpe's pre-crash scenarios identify signal violation crashes in GES and FAR data using variables that identify a signal violation.(3) Figure 3 shows an illustration of SCP crash scenario. The crashes in these databases undergo a more substantial characterization in the crash data than crashes in State-maintained databases and therefore the violation variable may be more robust than in State-maintained databases.

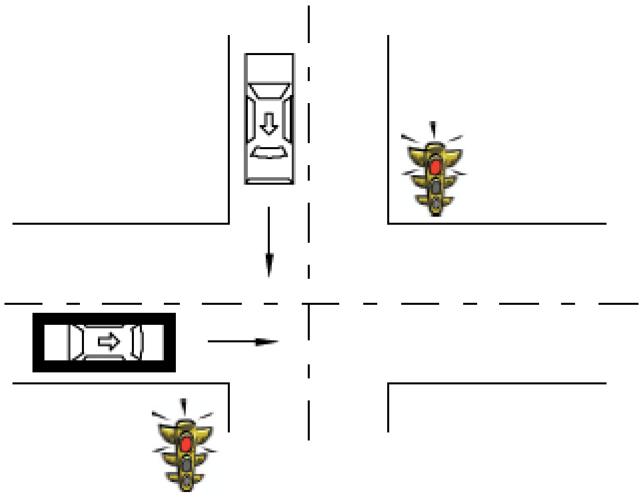

Figure 3. Straight Crossing Path (SCP) crash scenario. [3]

In California, the variable VIOL (Violation Category) is used to indicate when a driver receives a citation related to the crash reported. Specifically, the variable is coded as “Failure to Heed Stop Signal” for signal violation crashes. This is one of many choices for this variable. In the three-year period from 2009 to 2011, there were 63 crashes a year on average coded as a vehicle violating the traffic signal. This is about 0.033 crashes per signalized intersection per year. Similarly, in Minnesota, the variable CONTRIB1 (First Contributing Factor) is used to indicate a traffic signal violation. In the three-year period from 2010 to 2012, there were 349 crashes a year on average with a vehicle coded as violating the traffic signal, equating to approximately 0.42 crashes per signalized intersection.

These variables in the two States are likely greatly underreported, particularly in California. There are many potential reasons for this, for example the difficulty in determining which of two crash-involved vehicles on opposing approaches violated the signal. In both States, this is a vehicle level variable, and the reporting officer must be able to make this determination and issue a citation for the violation to be coded, which may contribute to the underreporting.

The potential underreporting in these variables would result in the analysis underestimating the number of target crashes if the analysis only relied on the violation variables to identify target crashes. Therefore, the definition for signal violation crashes in California and Minnesota was expanded beyond the violation code to include the crash circumstances. Specifically, travel direction of the vehicle prior to collision (DIR_TRVL) and crash type (ACCTYPE) were used to identify cross-path collisions at intersections in California (e.g. Vehicle 1 travels Northbound and Vehicle 2 travels Eastbound for a right angle collision).[4] For Minnesota data, a combination of vehicle's travel direction (VEH_DIR) and vehicle's action prior to collision (MISCACT1) were used.[(5)]

For the Charlotte dataset, target crashes are identified by a combination of a) primary cause (PRIMARY_CAUSE_CD=4, Disregarded traffic signals) and b) crash type (CRSH_TYPE_CD=30, angle) or direction of travel prior to collision (e.g. Vehicle 1 travels Northbound and Vehicle 2 travels Eastbound for a right angle collision). The definition of target crashes for Charlotte was also expanded beyond "disregard traffic signals" as the primary cause to include: fail to yield right of way, inattention, driver distracted, driver distracted by electronic communication device, driver distracted by other inside the vehicle, and driver distracted by external distraction.

The resulting number of average annual target crashes in California, Minnesota, and Charlotte are presented in Table 6. Using the number of intersections identified in Table 1, the number of average annual target crashes per intersection is also calculated. The table also includes the number of signalized intersections with one or more target crashes in the analysis period and the average annual target crashes for those intersections. The number of average annual target crashes is remarkably similar in the two States using both methods of calculating the average and higher in Charlotte. Most of the subsequent analysis in this report concentrates on only those intersections with one or more target crash in the analysis period.

Table 6. Average annual target crashes by dataset

Variable	California	Minnesota	Charlotte
Average Annual Target Crashes	1,313	538	571
Average Annual Target Crashes Per Intersection	0.69	0.64	0.81
Number of Signalized Intersections with One or More Target Crashes in three years	1,369	591	510
Average Annual Target Crashes per Intersection for Intersections Experiencing One or More Target Crashes over three years	0.96	0.91	1.12

Crash Severity

Minnesota, California and Charlotte all use the KABCO scale to identify the maximum reported injury in a crash. Table 7 presents the distribution of maximum injury severity for target crashes and other intersection crashes for California, Minnesota and Charlotte. The totals presented here are for three years of data.

Table 7. Summary of crash severity distribution for California, Minnesota, and Charlotte data.

Maximum Reported Crash Severity	California		Minnesota		Charlotte	
	Target Crashes	Other Intersection Crashes	Target Crashes	Other Intersection Crashes	Target Crashes	Other Intersection Crashes
K (fatal)	32	97	17	16	5	17
A (incapacitating injury)	86	405	32	68	11	45
B (non-incapacitating injury)	638	2,342	223	479	224	814
C (possible injury)	1,412	6,908	495	2,029	673	4,230
O (property damage only)	1,770	13,052	846	5,731	800	8,731

The research team explored limiting the target crashes used in the selection of candidate intersections to the more severe crashes (e.g., fatalities and incapacitating injuries) since some agencies limit the severities used in their network screening analysis. However, the process presented in this report uses all target crashes, a narrowed focus compared to total crashes that are generally used in network screening. Narrowing the focus further to include only those target crashes that resulted in fatalities, type A, or type B injuries would base the selection on those intersections that had demonstrated the most severe target crashes, but would also greatly limit the sample of intersections. For example, the California intersections experienced approximately one target crash of severity K, A, or B every five years. This subset is too narrow to account for annual fluctuations in crashes, and could lead to an agency installing the system at a location that was prioritized high on the list based on one or two crashes that are due to annual fluctuations, and do not necessarily represent a pattern of target crashes at the intersection. Therefore, this analysis considered target crashes of all severities.

Note that crash severity is considered in the calculation of benefit to cost. The recommended use of all severities is to identify those intersections where the target crash is occurring consistently across several years of data.

Timeframe

The overall objective of this effort was to develop a method to identify intersections that were good candidates for the applications based on crash data. To accomplish this objective, a method was needed to identify the timeframe that State and local agencies should use in their analysis of candidate intersections. In general, intersection crash counts fluctuate at any given intersection from year to year. One can reduce variation with more years of data, but also open door to possible operational or design changes having been implemented over time. This is particularly likely at intersections that experience a high frequency of crashes, as improvements may be implemented in response to crash occurrence.

Most agencies use historical crash data of some form in their network screening to identify locations that are expected to experience future crashes, and therefore require some form of remediation. In a sophisticated analysis, safety performance functions (SPFs) can be developed to predict future crashes based on past crashes and other factors such as volume. An SPF is a statistical model developed to estimate the "typical" crash frequency for a specific type of roadway entity, based on the traffic volumes and key characteristics. However, one of the goals of this effort was to develop a method that is easy to implement by a State or local agency without rigorous statistical analysis.

An analysis was conducted to select an approach to best identify those intersections that were expected to continue to experience crashes and are potential candidates for this system. Ten years of intersection data in California were used for this part of the analysis. The analysis used the intersection groups and target crashes described in the previous sections. Additionally, the research team screened out intersections with missing traffic volume information (traffic volumes for either the mainline or cross-street) and intersections with information that appeared to be incorrect (negative, abnormally small, or abnormally large numbers for daily traffic volumes). The volume thresholds for the traffic volume warrant for signalization in the Manual on Uniform Traffic Control Devices (MUTCD) was used to support this screening process. While traffic volume is not the only warrant for traffic signals, removing those intersections with traffic volumes that do not meet these criteria helps reduce the likelihood of having incorrect information in the dataset. The final dataset includes a total of 1,913 signalized intersections with Average Annual Daily Traffic volumes (AADTs) for both major and minor approaches, as well as crash counts. All three were necessary for the analyses conducted in this effort.

The intersection data file also has information on the date of last change in some element of the intersection (INT_DTE). In the last five years, over 90 percent of the signalized intersections underwent some change. While the data do not indicate a specific type of change, it could include fairly minor modifications (such as a change in phasing) to a change in the control at the intersection (e.g., conversion from stop control to signal control).

As previously stated, a method is needed to identify those intersections that consistently experience the target crashes. In order to achieve this, the research team considered several methods based on the three desired characteristics outlined in the objectives section (i.e., easy to implement, based on five years of data or less, and results in the identification of those locations with the most opportunity to reduce target crashes).

The following measures were evaluated, using all crash severities:

- Annual crash frequency.
- Two-year crash frequency.
- Three-year crash frequency.
- Five-year crash frequency.
- Number of years in top 100 over five-year period.
- Proportion of target crashes to total crashes.

All the measures tested met the first two characteristics (i.e., easy to implement and based on five years of data or less). To assess each method's ability to meet the last characteristic (i.e., results in the identification of those locations with the most opportunity to reduce target crashes), a baseline measure or ground truth measure was needed for comparison. Instead of looking at the raw crash counts or crash rate, the Potential Safety Improvement (PSI) based an Empirical Bayes (EB) approach was used as the baseline. This is the method recommended by the Highway Safety Manual and recent research.

A PSI is the difference between the expected number of crashes (long term average) for a roadway entity (in this case, an intersection) and the "typical" number of crashes for that entity, predicted by an SPF. (Note that SPFs were employed to determine which non-SPF based measure is best. This process is not recommended for future reproduction by agencies.) The EB-adjusted expected number of crashes is the long term average for a specific entity after taking regression to the mean bias and random fluctuation into account.

EB-adjusted potential safety improvement (PSI)

$$PSI_{EB} = N_{expected} - N_{predicted}$$

Where:

- PSI_{EB} is the Potential Safety Improvement based on an Empirical Bayes technique.

- $N_{expected}$ is the expected number of crashes (long term average) for this intersection, corrected by EB method.
- $N_{predicted}$ is the number of crashes predicted by the SPF for similar intersections.

The above descriptions of PSI is illustrated in Figure 4. More detailed descriptions of the SPFs and the EB technique are provided in Appendix B.

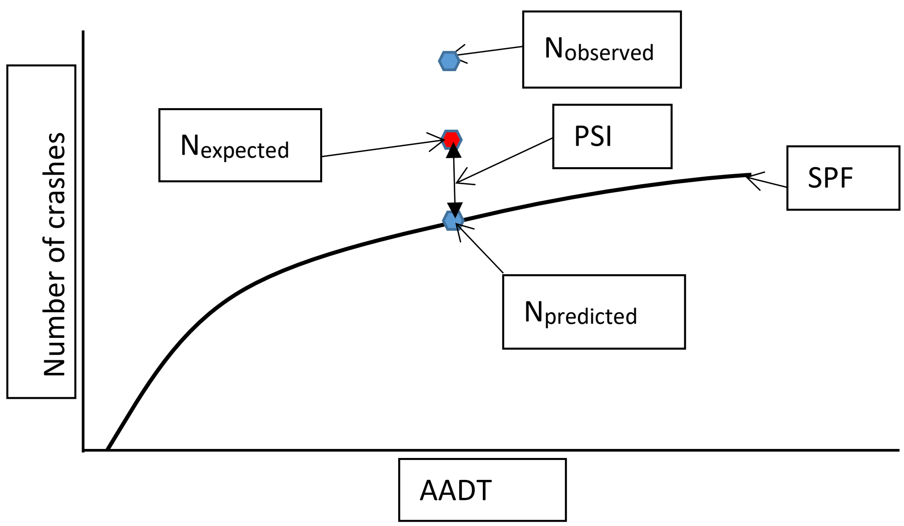

Figure 4. Concept of Potential Safety Improvement (PSI).

Two different SPFs were developed, one for urban and one for rural intersections. The research team initially estimated model parameters using several functional forms for each group of intersections presented in Table 3. However, none of them resulted in well-fit models. This may be attributable to small sample sizes in some categories. In the end, two separate SPFs for urban and rural intersections were found to be the best among the options that the team examined. Each of the nine categories of intersections were coded and included in the SPFs as an indicator variable. Using the SPFs, the predicted numbers of crashes ($N_{predicted}$), the EB-adjusted expected numbers of crashes ($N_{expected}$), and the PSIs were calculated for all 1,913 locations. These intersections were then ranked based on PSI as well as each of the other six measures being evaluated. Each of these six rankings was compared against the PSI-based ranking. For each intersection, the absolute difference in the position at which it is ranked and the position indicated by the PSI-based ranking was used to evaluate how close the other rankings were to the PSI method.

Table 8 provides an example of the top 10 intersections based on the PSI ranking and how two different alternative measures are compared and evaluated to demonstrate the method that was used. (The overall results of the comparison of methods are presented in the Results section.) The first column presents the PSI-based rankings. The second and third columns show how these same 10 intersections are being ranked based on three-year and two-year crash frequencies, respectively. The last two columns show the absolute differences between the rankings based on three-year, two-year crash frequencies and PSI. The bottom row of this table is the sum of the absolute differences. In this example, with a sum of four, the three-year crash frequency-based rankings are much closer to the PSI-based rankings than are the two-year rankings and are thus considered the better alternative to the ground truth (i.e., the PSI method).

Table 8. Example of comparison of ranking methods using PSI-based rankings.

PSI-based ranking	3-year crash frequency ranking	2-year crash frequency ranking	Difference between 3-year frequency ranking and PSI	Difference between 2-year frequency ranking and PSI
1	1	1	0	0
2	2	3	0	1
3	3	2	0	1
4	4	8	0	4
5	4	6	1	1
6	7	5	1	1
7	7	6	0	1
8	9	11	1	3
9	9	11	0	2
10	9	30	1	20
Total			**4**	**34**

Identifying Potential Benefits

The primary anticipated benefit of the RLVW application is the reduction in target crashes and the fatalities and injuries resulting from those crashes at intersections where the systems are used. This anticipated crash benefit is the focus of this analysis. There are other potential benefits such as a reduction in signal violations. However, these secondary benefits are not considered here.

As discussed in the data section, the cost of a target crash can be monetized by the severity of a crash. This monetary cost of a crash is considered an economic benefit if a crash is avoided by the RLVW application.

Differences in Candidate Intersections

The intersections identified as candidates for the RLVW application were reviewed to identify differences in these intersections compared to other signalized intersections in the State. Specifically, the following characteristics were explored:

- Volume (mainline, cross-street, estimated total entering).
- Width (Lane widths or crossing widths).
- Functional class of major roadway.
- Speed.
- Location type (interchanges, terrain).
- Intersection attributes (varies by State but may include lighting, channelization, etc.).

This information may be useful to FHWA, States, and other agencies for future efforts in analyses of safety issues and design of countermeasures. The findings of the comparison are presented in the Results section below.

RESULTS

The following sections present the results of California, Minnesota and Charlotte data analyses, including the identification of critical intersection types, the selection of a timeframe for use in the identification of candidates, the identification of the top ranked intersections in each State, potential deployment scenarios for each State, and a comparison of candidate intersections to other intersections.

Critical Intersection Types

As previously discussed, agencies may want to explore different types of environments (e.g., rural or urban, different intersection types) separately. For example, in some States, funds are allocated separately for rural roads. Table 9 presents the average annual target crashes for each of the nine intersection groups in California that were introduced in Table 3. This table is limited to those intersections that experienced one or more target crashes during a three-year period. The number of intersections in each group is also displayed in the table. The average annual target crashes for each group varied from 0.64 to 1.14 target crashes. Therefore, the frequency of target crashes is fairly consistent across the groups. The table also provides an average cost per target crash based on the average severity distribution of the target crashes in the group and the average cost per crash severity presented in Table 2. The average annual number of target crashes is multiplied by the average cost of the target crash to get the average annual costs of target crashes per intersection for each group in the final column.

Table 9: Average annual target crashes and average cost by intersection group in California for intersections with at least one target crash.

Intersection Group (number of intersections in group with at least one target crash)	Average Annual Number of Target Crashes	Average Cost of Target Crash	Average Annual Intersection Target Crash Costs
Urban-2 mainline lanes x 2 cross street lanes (95)	0.84	$209,681	$175,838
Urban-4 mainline lanes x 2 cross street lanes (473)	0.90	$160,509	$144,447
Urban-4 mainline lanes x 4 cross street lanes (216)	1.08	$186,393	$201,638
Urban-6 mainline lanes x 2 cross street lanes (136)	1.02	$107,845	$110,488
Urban-6 mainline lanes x 4 cross street lanes (92)	1.14	$103,822	$118,116
Urban-Others (217)	1.05	$197,602	$207,922
Rural-2 mainline lanes x 2 cross street lanes (61)	0.74	$233,723	$172,419
Rural-4 mainline lanes x 2 cross street lanes (47)	0.64	$441,183	$281,606
Rural-Others (32)	0.82	$85,534	$70,387

While intersection groups could be prioritized by the Average Annual Number of Target Crashes, the addition of target crash costs to the intersection groupings provides more insight to the prioritization. Crash costs can capture both frequency and severity of crashes. However, it should also be noted that crash costs are heavily weighted by a fatal crash. The group of rural 4 x 2 intersections (that is, rural intersections with a four-lane mainline and a two-lane cross street) has the lowest average annual target crashes of the nine intersection groups at 0.64 target crashes per year on average. Based solely on average target crashes, it appears this is not a priority type of intersection. However, once the average cost of target crashes is considered, the importance of this type of intersection becomes greater. The average cost of a target crash at rural 4 x 2 intersections is over $440,000 because the crashes at these intersections are more severe, likely a reflection of the higher speeds.

Table 10 presents similar information for Minnesota. As with the California data, only those intersections that experienced one or more target crashes in a three-year period are included in the table. As evidenced by the average cost of target crashes at each intersection, the three-legged intersections (both urban and rural) are not a priority. Rural 4-legged 2 x 2 intersections experience the highest average cost per intersection by nearly twice that of the next group. (It should be noted that there are only 18 intersections in this group, which is a small sample.) Urban 4-legged 4 x 4 intersections have a high number of target crashes and a high average cost of crashes for the group as a whole and may warrant more focused efforts.

Table 10. Average annual target crashes and average cost by intersection group in Minnesota for intersections with at least one target crash.

Intersection Group (number of intersections in group with at least one target crash)	Average Annual Number of Target Crashes	Average cost of Target Crash	Average Annual Intersection Target Crash Cost
3-legged Urban (37)	0.65	$77,314	$50,150
3-legged Rural (8)	0.42	$142,430	$59,346
4-legged Urban-2 mainline lanes x 2 cross street lanes (87)	0.61	$135,188	$81,838
4-legged Urban-4 mainline lanes x 2 cross street lanes (206)	0.90	$214,046	$193,265
4-legged Urban-4 mainline lanes x 4 cross street lanes (120)	1.20	$174,866	$210,325
4-legged Rural-2 mainline lanes x 2 cross street lanes (18)	0.59	$701,213	$415,534
4-legged Rural-4 mainline lanes x 2 cross street lanes (21)	1.05	$98,686	$103,386
4-legged Others (82)	1.06	$175,068	$185,031
Others (12)	0.67	$63,915	$42,610

Table 11 presents the average annual target crashes and crash costs for each of the ten intersection groups in Charlotte that were introduced in Table 5. Similar to previous discussions for California and Minnesota data, this table is also limited to those intersections that experienced at least one target crash during a three-year period. The average annual target crashes for each group varied widely, ranging from 0.48 to 1.76 target crashes. The table also provides an average cost per target crash based on the average severity distribution of the target crashes in the group and the average cost per crash severity presented in Table 2. The average annual number of target crashes is multiplied by the average cost of the target crash to get the average annual costs of target crashes per intersection for each group in the final column. The results show that most 3-legged intersection groups have a relatively low crash cost compared to 4-legged intersection groups. Among 3-legged intersections, the group with the highest cost is 6-mainline lanes with 2 or 4 cross street lanes. This group has the highest average target crashes at 1.3 per intersection and highest target crash cost at $92,242 per target crash, resulting in the highest target crash cost of $120,061 per intersection for 3-legged intersections.

Table 11. Average annual target crashes and average cost by intersection group in Charlotte for intersections with at least one target crash.

Intersection Group (number of intersections in group with at least one target crash)	Average Annual Number of Target Crashes	Average Cost of Target Crash	Average Annual Intersection Target Crash Costs
3-legged with 2 mainline lanes x 2 cross street lanes (9)	0.48	$81,647	$39,311
3-legged with 4 mainline lanes x 2 or 4 cross street lanes (79)	0.64	$72,097	$46,240
3-legged with 6 mainline lanes x 2 or 4 cross street lanes (21)	1.30	$92,242	$120,061
3-legged, others (6)	0.72	$60,410	$43,629
4-legged with 2 mainline lanes x 2 cross street lanes (85)	1.13	$84,818	$95,730
4-legged with 4 mainline lanes x 2 cross street lanes (256)	1.11	$115,227	$127,695
4-legged with 4 mainline lanes x 4 cross street lanes (48)	1.76	$117,976	$207,504
4-legged with 6 mainline lanes x 2 cross street lanes (33)	1.21	$185,058	$224,713
4-legged with 6 mainline lanes x 4 cross street lanes (40)	1.21	$157,355	$190,325
4-legged, others (45)	1.33	$70,622	$94,163

Selection of Timeframe and Candidate Intersections

As discussed in the methodology section, six measures were explored to determine the best method for State and local agencies to use crash data to identify candidate locations for RLVW systems. The six different measures tested using California data included:

- Annual crash frequency.
- Two-year crash frequency.
- Three-year crash frequency.
- Five-year crash frequency.
- Number of years in top 100 over five-year period.
- Proportion of target crashes to total crashes.

As noted in the Methodology section, in this analysis, all 1,913 signalized intersections were ranked using the PSI-based method and each of the alternative methods. Table 12 shows the sums of the absolute differences between PSI-based rankings and the rankings based on the six options. A lower sum of absolute differences means that the method ranked the candidates closer to the PSI-method.

Table 12. Comparison of six methods to PSI-based method for identifying priority intersections.

Ranking Method	Sum of Absolute Differences
5-year crash frequency rankings	516,505
3-year crash frequency rankings	414,821
2-year crash frequency rankings	639,123
1-year crash frequency rankings	925,922
Proportion of target crashes to total crashes rankings	690,045
Number of years in top 100 over 5 years	1,224,844

The results show that the rankings based on three-year crash frequency most closely replicates the PSI ranking (i.e., smallest absolute difference), followed by those based on the five-year, two-year, and proportion of target crashes to total crashes.

The results suggest that the three-year crash frequency is a better representation of the long term average than two-year or one-year frequency. However, the five-year crash frequency produces a worse result than the three-year does. This could be because of changes in operational and design characteristics previously mentioned.

For agencies with advanced analysis capabilities, the EB-based PSI approach is more sophisticated and more reliable. However, it is not suggested for use by the agencies unless they have the resource and capability to perform this type of EB-based analysis. The EB-based approach violates the first among three desired characteristics: ease of implementation. Based on the analysis results, the **three-year crash frequency method holds the most promise** for providing a reliable method that achieves the desired characteristics.

Based on this three-year frequency of crashes, the intersections in each dataset were ranked in priority order for implementation. The top 10 percent of these intersections in each agency are listed in priority order in Appendix C for California, Appendix D for Minnesota, and Appendix E for Charlotte. The lists provide the three-year average number of total and target crashes for each intersection.

Demonstration of Benefits

As previously discussed, the anticipated benefit of the RLVW systems is the monetized benefit of a reduction in target crashes. The potential economic benefit of a system at a specific candidate intersection will be influenced by the number and severity of expected target crashes, the effectiveness of the system in preventing target crashes, and the deployment of equipped vehicles. This is best demonstrated by selecting example intersections from each dataset and calculating the expected benefit.

The following section presents six examples, two for each dataset from California, Minnesota and Charlotte:

- Table 13 presents an intersection in California with **25 Target Crashes** per year on average. The example assumes that vehicle deployment follows the **5-Year Mandate** presented in Figure 1.
- Table 14 presents an intersection in Minnesota with **19 Target Crashes** per year on average. The example assumes that vehicle deployment follows the **5-Year Mandate** presented in Figure 1.
- Table 15 presents an intersection in Charlotte with **34 Target Crashes** per year on average. The example assumes that vehicle deployment follows the **5-Year Mandate** presented in Figure 1.

- Table 16 presents the same California intersection with **25 Target Crashes** per year on average that was presented in the first example. However, this example assumes that vehicle deployment follows the **15-Year Organic** penetration presented in Figure 1.
- Table 17 presents the same Minnesota intersection with **19 Target Crashes** per year on average that was presented in the second example. However, this example assumes that vehicle deployment follows the **15-Year Organic** penetration presented in Figure 1.
- Table 18 presents the same Charlotte intersection with **34 Target Crashes** per year on average that was presented in the third example. However, this example assumes that vehicle deployment follows the **15-Year Organic** penetration presented in Figure 1.

The start of system installation and vehicle penetration in all six examples is assumed to be 2020. For each scenario presented, the system is assumed to be 95 percent effective in reducing crashes when communicating with an equipped vehicle. Complete effectiveness (i.e., 100 percent) was not used because there may be some drivers that receive the warning message but intentionally violate the signal. This may occur when a vehicle is fleeing the police, a crime, or the scene of another crash.

The examples assume that total and target crashes would continue at current levels at the signalized intersections in the State (or city) without the installation of the system. Therefore, every year the same number of target crashes would be expected without the intervention. This assumption is a simplification intended for illustrative purposes. In reality, many other factors may affect the occurrence of crashes at the intersection, such as changes in traffic volume.

The tables all provide the total anticipated crashes prevented. These are represented to the nearest tenth. In reality, a tenth of a crash prevented is not possible (i.e., either a crash is prevented or it occurs). However, the table is intended to demonstrate the benefit that can be achieved over the twenty year period. For example, in Table 12, approximately 150 crashes are expected to be prevented over the twenty year period as a result of the system. The tables also provide the crash cost savings (based on the distribution of severity at the example intersection) and the percent of target crashes reduced each year. Using the example in Table 11 again, over twenty years the system provides over $20 million in benefits (i.e., crash savings).

The number of crashes anticipated to be prevented increases each year the system is in place because there is an increase in the penetration of connected vehicle technologies in the vehicle fleet in subsequent years. As would be expected, the 5-year mandate results in more crashes being prevented sooner as a result of more aggressive penetration. Using the example in Table 11, in the 20th year of installation, the system prevents 83.6 percent of the target crashes and prevents 48 percent of the target crashes over the entire 20 year period (which is the average of the last column over 20 years).

Note that all of the costs presented in these examples are presented in 2014 dollars. Inflation is not considered, again for simplification of the examples.

Table 13. Estimated number of crashes prevented and crash cost saved over time with 5-year mandate deployment scenario and an intersection with 25 target crashes expected without intervention (California).

Year	Deployment (percent)	Total crashes prevented	Crash cost saved	Percentage
2020	0.22	--	--	--
2021	1.79	0.6	$71,931	1.7%
2022	5.34	1.9	$214,587	5.1%
2023	10.33	3.6	$415,110	9.8%
2024	16.08	5.6	$646,173	15.3%
2025	22.14	7.8	$889,693	21.0%
2026	28.29	9.9	$1,136,830	26.9%
2027	34.42	12.1	$1,383,164	32.7%
2028	40.43	14.2	$1,624,675	38.4%
2029	46.25	16.2	$1,858,551	43.9%
2030	51.84	18.2	$2,083,184	49.2%
2031	57.14	20.0	$2,296,164	54.3%
2032	62.10	21.8	$2,495,481	59.0%
2033	66.70	23.4	$2,680,332	63.4%
2034	70.92	24.9	$2,849,912	67.4%
2035	74.76	26.2	$3,004,222	71.0%
2036	78.21	27.4	$3,142,860	74.3%
2037	81.30	28.5	$3,267,031	77.2%
2038	84.03	29.5	$3,376,736	79.8%
2039	86.43	30.3	$3,473,180	82.1%
2040	88.03	30.9	$3,537,475	83.6%
20 Year TOTAL		**353 Crashes**	**$40,447,292**	**48%**

Table 14. Estimated number of crashes prevented and crash cost saved over time with 5-year mandate deployment scenario and an intersection with 19 target crashes expected without intervention (Minnesota).

Year	Deployment (percent)	Total crash prevented	Crash cost saved	Percentage
2020	0.22	--	--	--
2021	1.79	0.3	$17,116	1.7%
2022	5.34	1.0	$51,060	5.1%
2023	10.33	1.9	$98,773	9.8%
2024	16.08	2.9	$153,754	15.3%
2025	22.14	4.0	$211,698	21.0%
2026	28.29	5.1	$270,503	26.9%
2027	34.42	6.2	$329,117	32.7%
2028	40.43	7.3	$386,584	38.4%
2029	46.25	8.3	$442,233	43.9%
2030	51.84	9.3	$495,684	49.2%
2031	57.14	10.3	$546,361	54.3%
2032	62.10	11.2	$593,788	59.0%
2033	66.70	12.0	$637,772	63.4%
2034	70.92	12.8	$678,123	67.4%
2035	74.76	13.5	$714,840	71.0%
2036	78.21	14.1	$747,828	74.3%
2037	81.30	14.7	$777,374	77.2%
2038	84.03	15.1	$803,478	79.8%
2039	86.43	15.6	$826,426	82.1%
2040	88.03	15.9	$841,725	83.6%
20 Year TOTAL		**181 Crashes**	**$9,624,238**	**48%**

Table 15. Estimated number of crashes prevented and crash cost saved over time with 5-year mandate deployment scenario and an intersection with 34 target crashes expected without intervention (Charlotte).

Year	Deployment (percent)	Total crashes prevented	Crash cost saved	Percentage
2020	0.22	0	--	--
2021	1.79	0.6	$64,102	1.7%
2022	5.34	1.7	$191,231	5.1%
2023	10.33	3.4	$369,927	9.8%
2024	16.08	5.2	$575,840	15.3%
2025	22.14	7.2	$792,855	21.0%
2026	28.29	9.2	$1,013,092	26.9%
2027	34.42	11.2	$1,232,614	32.7%
2028	40.43	13.2	$1,447,837	38.4%
2029	46.25	15.1	$1,656,257	43.9%
2030	51.84	16.9	$1,856,441	49.2%
2031	57.14	18.6	$2,046,239	54.3%
2032	62.10	20.2	$2,223,861	59.0%
2033	66.70	21.7	$2,388,592	63.4%
2034	70.92	23.1	$2,539,714	67.4%
2035	74.76	24.3	$2,677,228	71.0%
2036	78.21	25.5	$2,800,776	74.3%
2037	81.30	26.5	$2,911,432	77.2%
2038	84.03	27.3	$3,009,196	79.8%
2039	86.43	28.1	$3,095,142	82.1%
2040	88.03	28.7	$3,152,440	83.6%
20 Year TOTAL		**328 Crashes**	**$36,044,815**	**48%**

Table 16. Estimated number of crashes prevented and crash cost saved over time with 15-year organic deployment scenario and an intersection with 25 target crashes expected without intervention (California).

Year	Deployment (Percent)	Total crash prevented	Total crash cost saved	Percentage
2020	0.02	--	--	--
2021	0.09	0.0	$3,617	0.1%
2022	0.31	0.1	$12,457	0.3%
2023	0.83	0.2	$33,353	0.8%
2024	1.81	0.4	$72,735	1.7%
2025	3.38	0.8	$135,825	3.2%
2026	5.60	1.3	$225,035	5.3%
2027	8.49	2.0	$341,170	8.1%
2028	11.99	2.8	$481,817	11.4%
2029	16.03	3.7	$644,164	15.2%
2030	20.49	4.8	$823,388	19.5%
2031	25.27	5.9	$1,015,472	24.0%
2032	30.25	7.1	$1,215,593	28.7%
2033	35.35	8.3	$1,420,536	33.6%
2034	40.47	9.5	$1,626,282	38.4%
2035	45.53	10.6	$1,829,618	43.3%
2036	50.47	11.8	$2,028,131	47.9%
2037	55.23	12.9	$2,219,411	52.5%
2038	59.77	14.0	$2,401,851	56.8%
2039	64.04	15.0	$2,573,440	60.8%
2040	68.15	15.9	$2,738,600	64.7%
20 Year TOTAL		**83 Crashes**	**$21,842,494**	**26%**

Table 17. Estimated number of crashes prevented and crash cost saved over time with 15-year organic deployment scenario and an intersection with 19 target crashes expected without intervention (Minnesota).

Year	Deployment (Percent)	Total crash prevented	Total crash cost saved	Percentage
2020	0.02	--	--	--
2021	0.09	0.0	$3,013	0.1%
2022	0.31	0.1	$10,377	0.3%
2023	0.83	0.1	$27,784	0.8%
2024	1.81	0.3	$60,589	1.7%
2025	3.38	0.6	$113,144	3.2%
2026	5.60	1.0	$187,458	5.3%
2027	8.49	1.5	$284,199	8.1%
2028	11.99	2.2	$401,360	11.4%
2029	16.03	2.9	$536,597	15.2%
2030	20.49	3.7	$685,894	19.5%
2031	25.27	4.6	$845,903	24.0%
2032	30.25	5.5	$1,012,606	28.7%
2033	35.35	6.4	$1,183,326	33.6%
2034	40.47	7.3	$1,354,716	38.4%
2035	45.53	8.2	$1,524,098	43.3%
2036	50.47	9.1	$1,689,462	47.9%
2037	55.23	10.0	$1,848,801	52.5%
2038	59.77	10.8	$2,000,776	56.8%
2039	64.04	11.5	$2,143,712	60.8%
2040	68.15	12.3	$2,281,293	64.7%
20 Year TOTAL		**98 Crashes**	**$18,195,107**	**26%**

Table 18. Estimated number of crashes prevented and crash cost saved over time with 15-year organic deployment scenario and an intersection with 34 target crashes expected without intervention (Charlotte).

Year	Deployment (Percent)	Total crash prevented	Total crash cost saved	Percentage
2020	0.02	0	--	--
2021	0.09	0.0	$3,223	0.1%
2022	0.31	0.1	$11,101	0.3%
2023	0.83	0.3	$29,723	0.8%
2024	1.81	0.6	$64,818	1.7%
2025	3.38	1.1	$121,041	3.2%
2026	5.60	1.8	$200,541	5.3%
2027	8.49	2.8	$304,035	8.1%
2028	11.99	3.9	$429,374	11.4%
2029	16.03	5.2	$574,050	15.2%
2030	20.49	6.7	$733,767	19.5%
2031	25.27	8.2	$904,943	24.0%
2032	30.25	9.8	$1,083,282	28.7%
2033	35.35	11.5	$1,265,918	33.6%
2034	40.47	13.2	$1,449,270	38.4%
2035	45.53	14.8	$1,630,473	43.3%
2036	50.47	16.4	$1,807,380	47.9%
2037	55.23	18.0	$1,977,840	52.5%
2038	59.77	19.5	$2,140,422	56.8%
2039	64.04	20.8	$2,293,334	60.8%
2040	68.15	22.2	$2,440,518	64.7%
20 Year TOTAL		**177 Crashes**	**$19,465,052**	**26%**

Large-Scale Consideration for Agency-Wide Deployment Levels

As previously discussed, this analysis illustrates how interested agencies could focus on implementing RLVW systems at those intersections that have the most target crashes based on a three-year average of target crash occurrence. For each individual intersection, the agency can conduct a cost benefit analysis. An agency may also want to set a goal for a systemic deployment (e.g., top ten percent of all intersections) or a goal for reducing the number of target crashes agency-wide (e.g., reduce target crashes by 50 percent agency-wide over twenty years). For this broader scale consideration, the cumulative distribution of target crashes should be considered. The research team conducted an analysis for all signalized intersections in California, Minnesota, and Charlotte to demonstrate the benefit of these simple graphs. To develop these graphs, an agency would need a listing of signalized intersections and the average annual target crashes at each.

Figure 5, Figure 6, and Figure 7 present the cumulative distribution of average annual total target crashes (total target crashes over three years divided by three) compared to the number of signalized intersections that experienced at least one target crash in California, Minnesota and Charlotte, respectively. As shown on the graphs, 10 percent of these intersections are responsible for nearly 30 percent of the total target crashes in California and Minnesota. The number is a little higher, at about 32 percent in Charlotte. The percent is remarkably consistent for all three datasets.

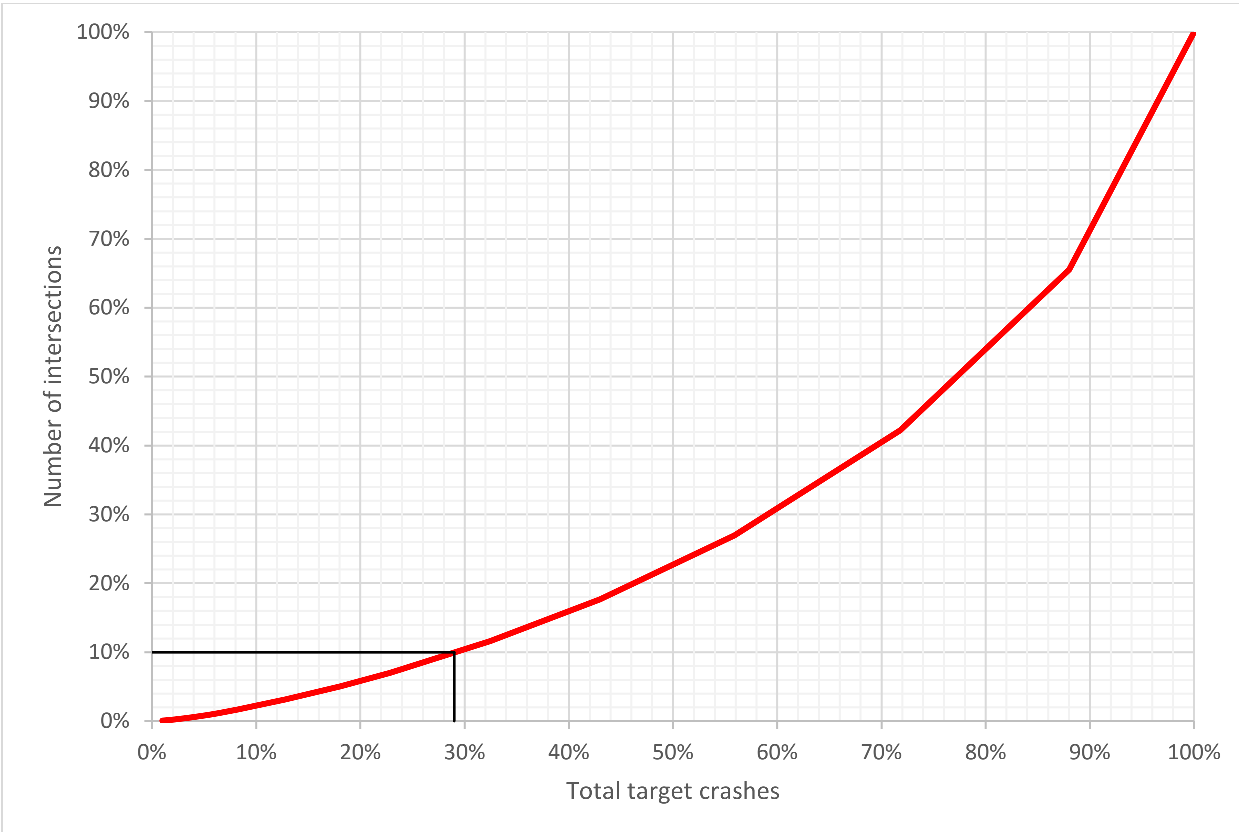

Figure 5. Relationship between cumulative number of signalized intersections and cumulative target crashes in California.

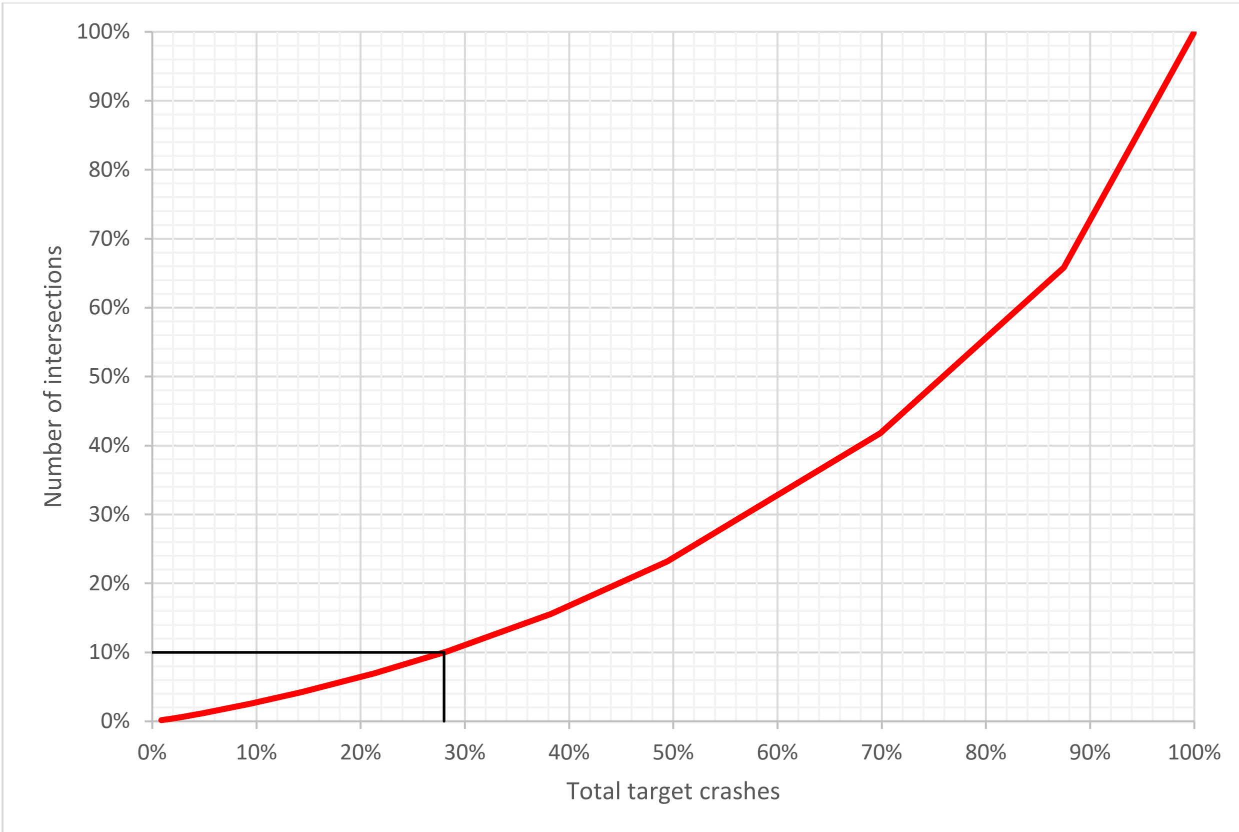

Figure 6. Relationship between cumulative number of signalized intersections and cumulative target crashes in Minnesota.

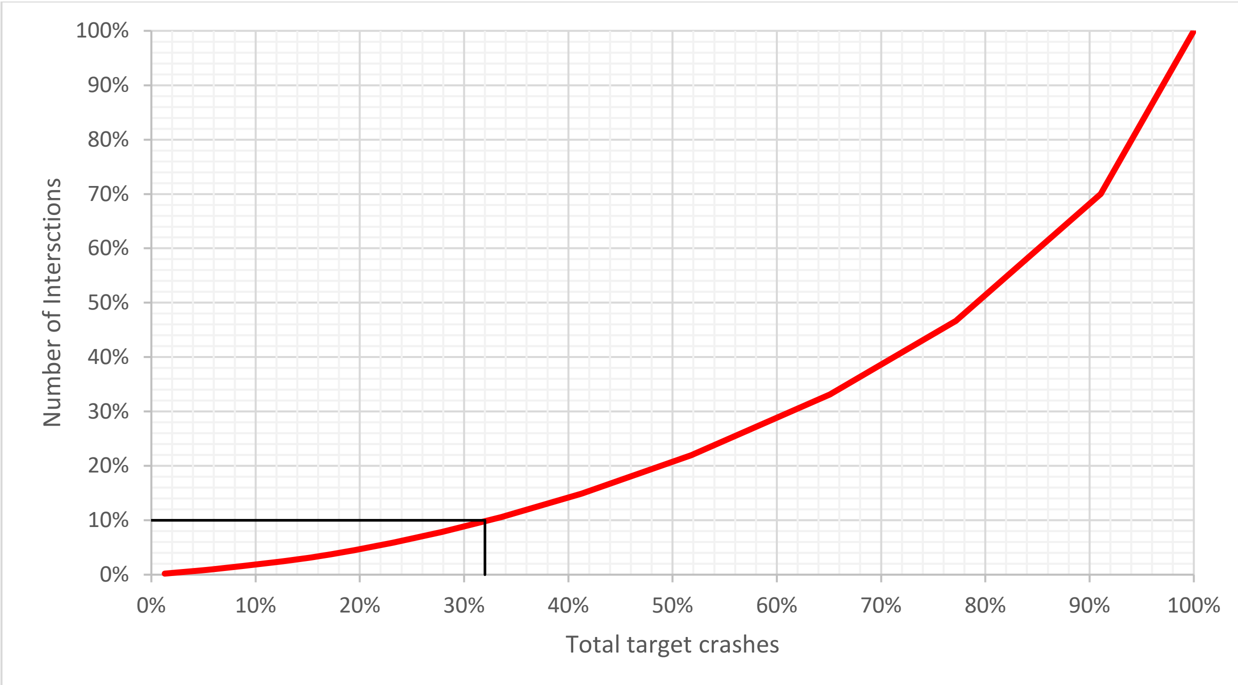

Figure 7. Relationship between cumulative number of signalized intersections and cumulative target crashes in Charlotte.

An agency may also want to consider the severity of the target crashes. Translating the maximum injury severity of the crashes to crash costs is a useful way to account for severity in these graphs. Figure 8 presents the cumulative distribution of annualized target crash costs compared to the number of signalized intersections in California that experienced at least one target crash in the last three years. The impact of deploying at the top 10 percent of intersections is more poignantly expressed once severity is included. The top 10 percent of intersections represents over 60 percent of total target crash cost. Similar graphs for Minnesota and Charlotte are presented in Figure 9 and Figure 10. The top 10 percent of intersections represent nearly 70 percent and more than 50 percent of total target crash cost in Minnesota and Charlotte, respectively.

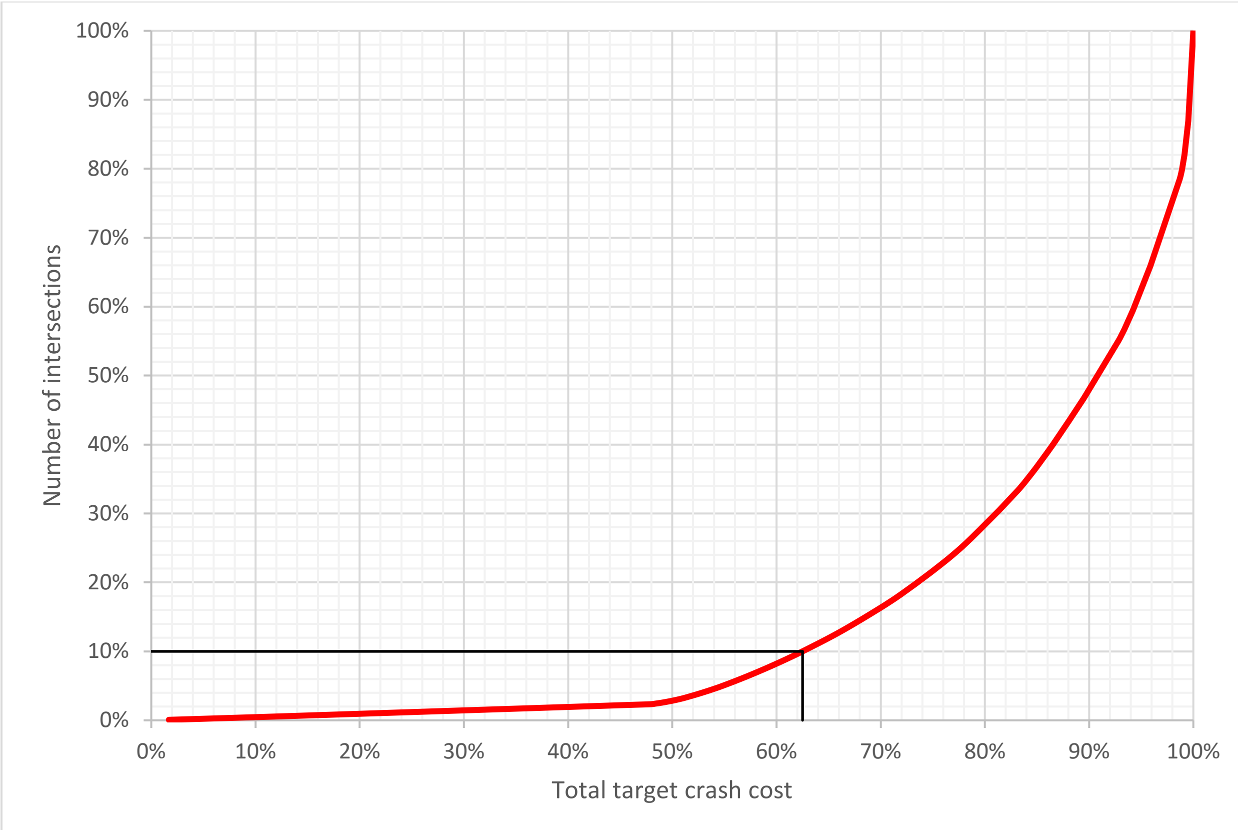

Figure 8. Relationship between cumulative number of intersections and cumulative target crash cost in California.

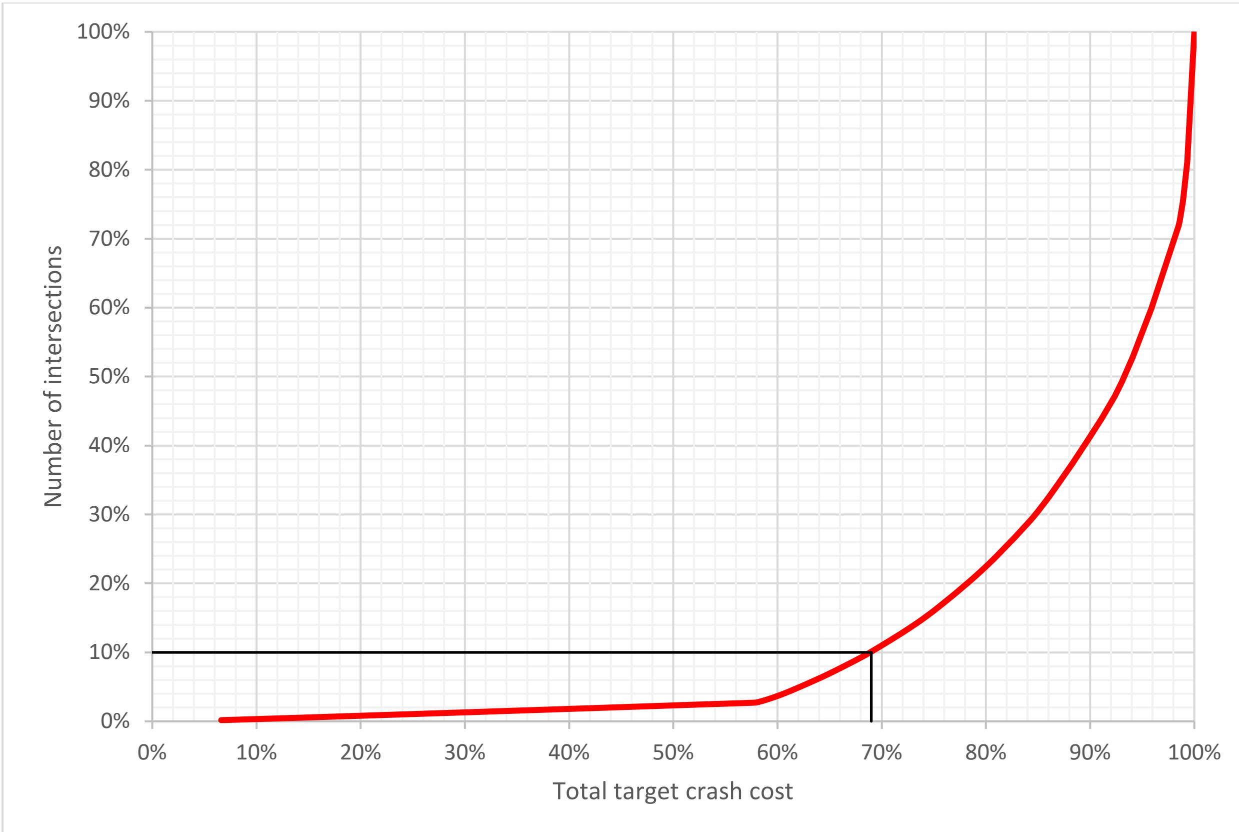

Figure 9. Relationship between cumulative number of intersections and cumulative target crash cost in Minnesota.

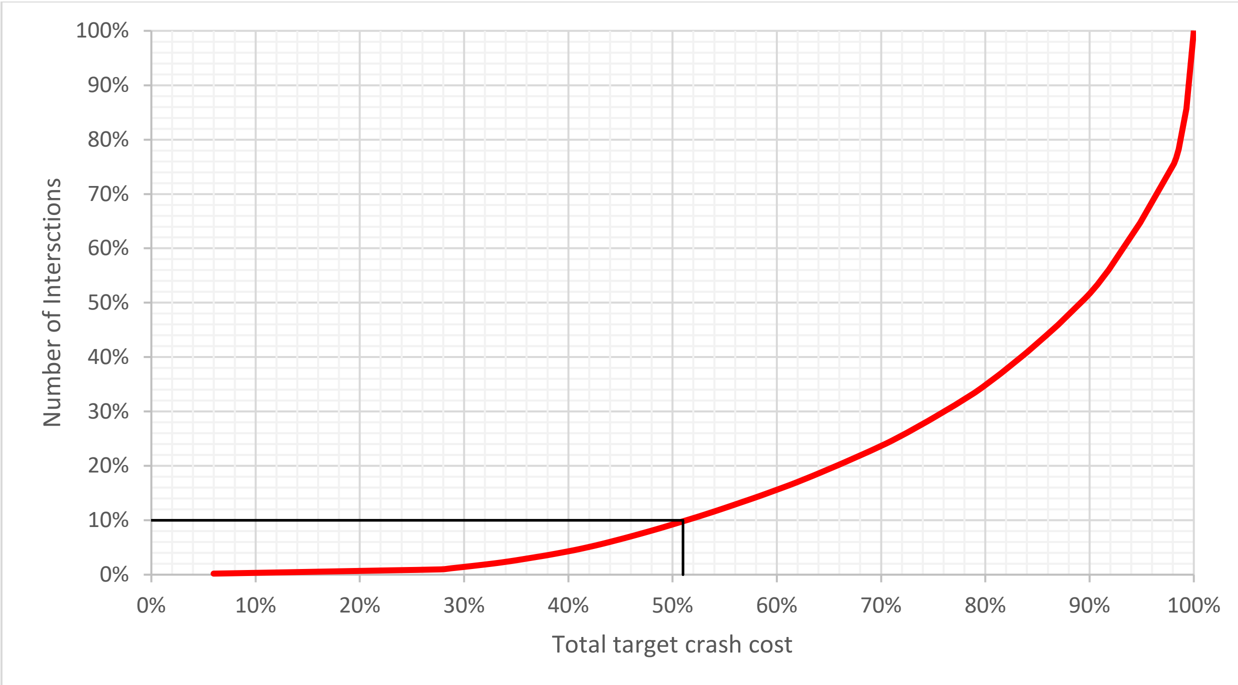

Figure 10. Relationship between cumulative number of intersections and cumulative target crash cost in Charlotte.

Consideration of Benefit to Cost Ratios

Implementing agencies compare the benefit to costs for safety countermeasures to comparable projects that compete for limited funding. Although the benefits may exceed the costs for a strategy at a given intersection, in most States, the number of projects proposed for installation greatly exceeds the available dollars to fund projects. Therefore, a very competitive benefit to cost ratio (i.e., not just benefits exceeding the costs) is needed for a project to be selected for funding and implementation. The anticipated benefit to cost ratio is critical to the decision to fund a project in a given year. In the early years of vehicle deployment, relatively few crashes will be prevented because few vehicles are equipped to receive the warning message. As more vehicles are equipped, more target crashes can be prevented. Therefore, for the RLVW system, the benefit to cost ratio at a given location will change as more vehicles are equipped as illustrated in the six examples presented in the previous subsection. As more and more vehicles are equipped with connected vehicle technologies, the RLVW systems become more competitive when compared to other countermeasures. This would mean that, unlike for other countermeasures where the anticipated number of crashes reduced increases as a function of traffic growth, for this RLVW system, the cost to benefits ratio must account for an increase in the reduction of annual crashes due to the growth in deployed vehicles as well.

An agency may want to consider the annual crashes that could be reduced (i.e., benefits) to the annual costs over the life cycle of the strategy. Annual costs include an annualized portion of the installation costs, the annual maintenance costs, and the annual operating costs. The costs of the RLVW system are still in development and will likely vary by agency and by individual location. The previously cited *Footprint Analysis* provides a range of estimates of the total cost of a system with an average total installation costs of $51,600 and annual operating, maintenance, and replacement costs ranging from $1,950 to $3,050 per year per site. For this analysis, annual costs of $10,000 are used for demonstration purposes. Of particular note, these costs only include the costs to the agency. The costs of equipping the vehicles are not considered.

Table 19 presents the annual target crashes needed to achieve a 2:1, 5:1, and 10:1 benefit cost ratios for signalized intersections in California for two deployment (5-year mandate and 15-year organic) and three installation (installation in 2020, 2025, 2030) scenarios. The table assumes that the systems would be 95 percent effective when communicating with equipped vehicles and that the systems would have a 20 year service life over which benefits would accumulate. It also assumes that the average cost of a target crash (in 2015 dollars) is approximately $171,000 per crash. This is based on the cost of each severity (K, A, B, C, and O) and the distribution of severity statewide for the target crashes in California.

Table 19. Annual target crashes to achieve three benefit cost ratios for various deployment and installation scenarios (California).

Deployment Scenario	Installation Year	Annual Target Crashes Needed to Achieve Benefit Cost Ratio		
		2 to 1	5 to 1	10 to 1
5-Year Mandate	2020	1.9	4.7	9.5
	2025	0.5	1.2	2.5
	2030	0.4	0.9	1.9
15-Year Organic	2020	27	67	133
	2025	1.2	3.1	6.2
	2030	0.6	1.4	2.8

Using this table, intersections with approximately five target crashes or more per year would meet a five-to-one benefit to cost ratio over the 20 year service life if the system installation begins in 2020 with a 5-year mandate for vehicle deployment scenario. A lower number of target crashes is needed to achieve a five-to-one benefit to cost ratio if the system is installed in later years (i.e., 2025 or 2030) because more vehicles are equipped and should prevent a correspondingly greater percentage of the target crashes.

The values in this table are only applicable to California, as the average crash cost is based on the average severity of the target crashes in California (i.e., $171,000 per crash). The data from Minnesota also show similar number with an average cost just a little higher at nearly $186,000. This number would result in a slight change in the values in Table 19. However, if an agency experiences much higher number of crashes or the crash severity distribution is heavily skewed, the overall average crash cost could differ significantly from the number calculated based on data from these two States. For example, the severity distribution of crashes from Charlotte is skewed towards PDO and less severe injuries. This resulted in a much lower overall crash cost at $110,000. This would require higher annual target crashes to achieve desired benefit to cost ratios.

Difference in Candidate Intersections

As discussed in the methodology section, the top 10 percent of the candidate intersections were compared to the other signalized intersections to identify any notable differences in the characteristics of the candidate intersections to the other intersections. This information is presented for the benefit of FHWA and their partners when relevant in any of the three datasets. (Note that only notable differences are discussed.) The implementing agencies may also find this useful for the preliminary screening of intersections or to initiate systemic improvements for RLVW or other signal violation countermeasures.

Volume

The California data included average AADT for the mainline and for the cross street. The mainline and cross-street AADTs for the top 10 percent of candidate intersections were compared to the remaining intersections and presented in Table 20. The candidate intersections have higher average mainline and cross street AADT. This is expected as more volume, both for the mainline and the cross street present more opportunity for crashes.

Table 20. Comparison of volume characteristics of priority candidate intersections to other intersections in California.

Variable	Priority Candidate Intersections (top 10%)	Other Intersections
Mainline AADT	Minimum 8,285 Average 34,890 Maximum 81,000	Minimum 4,050 Average 29,784 Maximum 93,000
Cross-Street AADT	Minimum 401 Average 10,567 Maximum 48,000	Minimum 301 Average 6,694 Maximum 77,000

The Minnesota data included average AADT for all legs of each intersection. Since Minnesota data is provided at the approach level, the mainline AADT was calculated as the average AADTs of the mainline approaches. The cross-street AADT was also calculated using the same process. Approach AADT was also a critical piece of information for identifying the mainline and cross-street because Minnesota data files do not include any variable indicating mainline or cross-street approaches.

The mainline and cross-street AADT for the top 10 percent candidate intersections were compared to the remaining intersections in Table 21. As with the California data, the candidate intersections in Minnesota have higher mainline and cross street AADT. In Minnesota, the candidate intersections average approximately twice the volume of the other intersections.

Table 21. Comparison of volume characteristics of priority candidate intersections to other intersections in Minnesota.

Variable	Priority Candidate Intersections (top 10%)	Other Intersections
Mainline AADT	Minimum 7,450 Average 31,186 Maximum 79,520	Minimum 1,112 Average 17,437 Maximum 60,180
Cross-Street AADT	Minimum 632 Average 10,636 Maximum 42,168	Minimum 70 Average 4,799 Maximum 33,796

For Charlotte data, the AADT information was extracted from GIS data. The number of legs and all information associated with each leg were determined by creating a circular buffer around each intersection. It was not possible to identify mainline or cross-street from the GIS data through this process. The research team were only able to calculate the minimum, the maximum and the total AADT for each intersection (i.e., of all legs within each circular buffer.). The research team calculated AADTs for mainline and cross-street based on these values and number of legs by assuming the larger AADT is for the mainline and the smaller one is the for the cross street. Table 22 presents a summary of AADT for Charlotte. Similar to California and Minnesota, this table also compares the top 10 percent candidate intersections and the rest of the dataset. This table shows that the top 10 percent candidate intersections have higher traffic volume on the mainline but there is almost no difference on the cross-street.

Table 22. Comparison of volume characteristics of priority candidate intersections to other intersections in Charlotte.

Variable	Priority Candidate Intersections (top 10%)		Other Intersections	
Mainline AADT	Minimum	13,313	Minimum	1,304
	Average	34,941	Average	30,205
	Maximum	45,766	Maximum	46,903
Cross-Street AADT	Minimum	828	Minimum	312
	Average	15,958	Average	15,592
	Maximum	45,053	Maximum	45,415

Roadway Classification

The roadway class of the mainline of the intersection was compared between the top ten percent of intersections and the other signalized intersections in California. The comparison is summarized in Table 23. Most of the functional classes are similarly represented in the two groups with the exception of the urban multi-lane divided functional class. Of the top 10 percent of intersections, over 82 percent are urban multi-lane divided functional class compared to nearly 66 percent of the other intersections.

Table 23. Comparison of roadway classification characteristics of priority candidate intersections to other intersections in California.

Priority Candidate Intersections (top 10%)		Other Intersections	
Urban Multi-lane divided roadway	82.2%	Urban Multi-lane divided roadway	65.8%
Others	17.8%	Others	34.2%

Speed

California includes design speed information in the HSIS roadway inventory data. The mainline design speed of the two groups of intersections were compared and presented in Table 24. Both groups include intersections with design speeds that range from 25 mi/hr to 70 mi/hr. However, as would be expected, the top 10 percent of intersections included more intersections with design speeds over 45 mi/hr (71 percent of the top 10 percent intersections versus 58 percent for the other intersections).

Table 24. Comparison of design speeds of priority candidate intersections to other intersections in California.

Priority Candidate Intersections (top 10%)		Other Intersections	
Design speed 50 mi/hr or greater	70.7%	Design speed 50 mi/hr or greater	58.6%
Design speed of 45 mi/hr or lower	29.3%	Design speed of 45 mi/hr or lower	41.4%

Minnesota intersection dataset includes posted speed limit for each approach. When the associated approaches were merged into intersections, the highest posted speed among intersection legs was adopted to represent the intersection. The posted speeds were compared and summarized in Table 25. Although the speed limits range from 30 mi/hr up to 65 mi/hr, the top 10 percent group included more intersections with speed limit higher than 45 mi/hr (48 percent versus 37 percent) and far fewer intersections with low speed limits.

Table 25. Comparison of posted speeds of priority candidate intersections to other intersections in Minnesota.

Priority Candidate Intersections (top 10%)		Other Intersections	
Posted speed 50 mi/hr or greater	48.2%	Posted speed 50 mi/hr or greater	36.8%
Posted speed of 45 mi/hr or lower	51.8%	Posted speed of 45 mi/hr or lower	63.2%
Posted speed of 30 mi/hr	21.7%	Posted speed of 30 mi/hr	35.6%

CONCLUSIONS AND DISCUSSION

This report presents a method for State or local agencies to screen their signalized intersections and develop a first prioritization of signalized intersections for deployment of a vehicle-to-infrastructure red-light violation warning system. This effort was based on two States (California and Minnesota) and one large city (Charlotte, North Carolina).

This effort included several assumptions for ease of analysis and to demonstrate the approach including the system effectiveness, vehicle penetration rates, and flat crash levels. Additionally, three system cost scenarios were presented. All of these assumptions were inputs to the analysis and can be changed as more reliable inputs are available.

Based on the analysis conducted, the following process is proposed for agencies in identifying potential signalized intersections for the installation of V2I RLVW systems:

Step 1. Identify Signalized Intersections and Attribute Crashes to Intersection

For this analysis, the Minnesota and California HSIS included an intersection inventory that provided information on signalization. Without such an inventory, agencies could rely on other lists of signalized intersections (such as energized dates or dates of first electrical power to the intersection based on billing) to identify signalized intersections. For each signalized intersection, attribute crashes to the intersection. This is generally done by identifying crashes within a 250 ft radial distance of the intersection, although the process varies by agency (e.g., some use 150 ft in urban areas) and the method should reflect agency practices for similar efforts.

Step 2. Remove Intersections Improved in the Last Three Years or Planned for Improvement

This step will likely require an agency to seek additional information beyond what is available in a roadway inventory likely including transportation improvement program documents, HSIP project lists, and local knowledge.

Step 3. Determine a Method to Identify Target Crashes in Crash Data

The target crashes for this application are crashes at a signalized intersection where a vehicle violated the traffic signal. Based on the analysis conducted here, this should be defined in the crash data with both violation variables and vehicle maneuver variables.

Step 4. Calculate Three-Year Average Annual Target and Crash Costs

Using the three most recent years of available crash data, calculate the average number of target crashes at each intersection and the average annual cost of the target crashes. The research team suggests that agencies include all severities in their screening efforts and apply the crash costs presented in this report (or their own agency developed costs) by severity to calculate the costs.

Step 5. Combine Signalized Intersections into Related Groups

The agency could use several variables to group intersections including number of legs, land use, and approach lanes. Groups of 30 intersections or more is a reasonable base. Calculate average cost (or average severity) of target crashes for each group. The purpose of this step is to identify groups that may need separate consideration, particularly if separate funds are available for certain function classes such as rural two-lane roads.

Step 6. Develop Prioritized List

The analysis here developed a prioritized list based on a three-year average of target crash frequency. The list could also be prioritized by the monetized cost of the target crashes or subdivided by the groups identified in step 5.

This method is based on the reported crashes and operational and geometric data available in a roadway inventory. The agency would use this list as an initial step in their efforts. The next step in prioritization would likely involve a detailed review (including field collection and observations) of intersections that the agency intends to move forward. The costs for individual intersection systems would be compared to the monetized benefit of the crashes that the system is expected to prevent. The ability of the system to prevent crashes will increase every year as more and more vehicles are equipped.

There are additional considerations that an agency may have in prioritizing intersections for these systems that could be incorporated into the initial prioritization efforts. The largest consideration is the agency's existing future plans for the intersection. For example, if the signalized intersection is part of a planned large-scale improvement such as a redesign to an interchange or a large corridor improvement program, the agency may remove the intersection from consideration for the system or consider how the system implementation could be scheduled as part of other construction at the intersection. Other considerations may include equity by district or region.

The agency may have additional measures to include in the initial prioritization. For example, specific to this treatment, the agency may also consider the ability to use traditional enforcement measures at the intersection. Many factors affect the ability of a police officer to enforce traffic signal compliance at an intersection approach, the most important being whether the officer can safely enforce the intersection. Examples include the intersection receiving leg geometry, the volume of the cross street, and the availability of a sufficient vantage point from which the officer can safely monitor the intersection. An agency may want to increase the priority of a signalized intersection that enforcement personnel have identified as difficult or dangerous to enforce using traditional methods.

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APPENDIX A: DATA ELEMENTS

HSIS Data Elements for Analysis: California

Total Variables: 45

*Note – Description: SAS Variable Name

Accident Subfile (Total: 10)

1. Type of Collision: ACCTYPE
2. Collision ACCYR: ACCYR
3. Accident Case Number: CASENO
4. Time of Accident: HOUR
5. Light Condition: LIGHT
6. Total number of vehicles: NUMVEHS
7. Road Surface: RDSURF
8. Collision Severity: SEVERITY
9. Type of Vehicle at Fault DOT: VTYPE_AT_FAULT_DOT
10. Weather: WEATHER, WEATHER 1
11. County Route: CNTY_RTE
12. Milepost: MILEPOST

Vehicle Subfile (Total: 4)

1. Direction of Travel: DIR_TRVL
2. Movement Preceding Accident: MISCACT1
3. Vehicle at Fault: VEH_AT_FAULT
4. Violation Category: VIOL

Roadway File (Total: 5)

1. Design Speed: DESG_SPD
2. Median Type: MED_TYPE

3. Median Width: MEDWID
4. Roadway Classification: RODWYCLS
5. Terrain: TERRAIN
6. Road County Route: CNTYRTE
7. Beginning Milepost: BEGMP
8. Average Annual Daily Traffic AADT
9. ADT Date: ADT_DTE

Intersection File (Total: 26)

1. County: COUNTY
2. Intersection Description: INT_DESC
3. Intersection Effective Date: INT_DTE
4. Intersecting Route Prefix: INT_PRF
5. Intersection Population Code: INT_POPGRP
6. Intersection Milepost: INTMP
7. Cross Street County Route: INTY_RTE
8. Junction Type: JUNCTYPE
9. Intersection Light Type: LGHT_TYP
10. Milepost: MILEPOST
11. Mainline AADT: ML_AADT
12. Mainline Number of Lanes: ML_LANES
13. Mainline Left Turn Channelization: ML_LEFT
14. Mainline Signal Mastarm: ML_MAST
15. Mainline Right Turn Channelization: ML_RIGHT
16. Mainline Traffic Flow: ML_TRFLO
17. Roadway Route Number: RTE_NBR
18. Traffic Control Type: TRF_CNTL
19. Intersection Type: TYPEDESC
20. X-Street AADT: XSTAADT

21. X-Street Number of Lanes: XSTLANES
22. X-Street Left Turn Channelization: XSTRTLFT
23. X-Street Signal: XSTRTMST
24. X-Street Right Turn: XSTRTRGH
25. X-Street State Route Indicator: XSTSTRT
26. X-Street Traffic Flow: XSTTRFLO
27. Cross Street County Route: INTY_RTE
28. Intersection Milepost: INTMP
29. Mainline ADT date: ML_ADTDT
30. Cross Street ADT date: XSTADTDT
31. Cross Street State Route Indicator: XSTSTRT

HSIS Data Elements for Analysis: Minnesota

Total Variables: 75

*Note – Description: SAS Variable Name

Intersection subfile (Total:50)

1. Route System: RTE_SYS
2. Route number: RTE_NBR
3. Calculated Beginning Milepost: BEGMP
4. Calculated Ending Milepost: ENDMP
5. Intersection Milepost: MPOFFSET
6. Intersection Type: TYPE
7. Intersection Description: DESC
8. Traffic Control Device: TRAF_DEV
9. Roadway Lighting: RDWY_LGH

10. General Environment: GEN_ENIV

11. Specific Environment: SPEC_ENV

12. Category Assigned by District: DIST_CAT

13. Central Office Category: CNTL_CAT

14. Date of Accident Geocoding: EFEC_DTE

15. Verbal Description of an Approach of Intersection/interchange: INT_DESC

16. Number of Routes into: NBR_RTES

17. Number of Legs into: NBR_LEGS

18. Update Date: UPT_DTE

19. Combined RTE_SYS/RTE_NBR: INT_SYNB

20. Traffic Control Devices: TRAFCNTL

21. Intersection Description-Revised: TYPEDESC

22. Leg route system: RTESYS2

23. Leg route number: RTENBR2

24. Leg milepost: MPOFSET2

25. Approach road description: RDESC

26. Lower limit: LOLIMT

27. Upper limit: UPLIMT

28. Leg/Approach Number: LEG_NBR

29. Approach direction: DIR

30. Year 1 AADT: AADT1

31. AADT Year 1: ADTYR1

32. Year 2 AADT: AADT2

33. AADT Year 2: ADTYR2

34. Year 3 AADT: AADT3

35. AADT Year 3: ADTYR3

36. Year 4 AADT: AADT4

37. AADT Year 4: ADTYR4

38. Year 5 AADT: AADT5

39. AADT Year 5: ADTYR5
40. Approach Speed Limit: AP_SPD
41. Approach Traffic Control: AP_CNTL
42. Number of Approach Through lanes during off-peak period: AP_TLOFF
43. Number of Approach Through lanes during peak period: AP_TLPEK
44. Number of Leaving Approach Through lanes during off-peak period: LV_TLOFF
45. Number of Leaving Approach Through lanes during peak period: LV_TLPEK
46. Approach bypass/turn lanes: AP_BP_TL
47. Approach Comments: AP_COMNT
48. Reference Point: REF_PNT
49. Unique identifier for each record: RECORD_ID
50. True leg milepost: LEG_TRUE_MP

Accident Subfile (Total: 19)

1. Diagram of Accident Code: ACCDIGM
2. Type of Accident: ACCTYPE
3. Year Accident Occurred: ACCYR
4. Accident Number: CASENO
5. Hour Accident Occurred: HOUR
6. Light Conditions: LIGHT
7. Location Description: LOC_NARR
8. Relation to Intersection: LOC_TYPE
9. Location Reliability: LOCN_REL
10. Modified Reference Point: MILEPOST
11. Number of Vehicles: NUMVEHS
12. Rural/Urban Pop Code: POP_GRP
13. Roadway Classification: RODWYCLS
14. Route Number: RTE_NBR
15. Route System: RTE_SYS

16. Combined Route System/Route Number: RTSYSNBR
17. Accident Severity: SEVERITY
18. Traffic Control Device: TRF_CNTL
19. Travel Direction: TRVL_DIR

Vehicle Subfile (Total: 6)

1. Accident Number: CASENO
2. First Contributing Factor: CONTRIB1
3. Sequence of Event: EVENT1, EVENT2, EVENT3, EVENT4
4. Action Prior to Accident: MISCACT1
5. Direction Vehicle was Traveling: VEH_DIR
6. Relative Vehicle Number: VEHNO

APPENDIX B: SAFETY PERFORMANCE FUNCTION AND EMPIRICAL BAYES (EB) CALCULATION

Safety Performance Function:

$$N_{predicted,urban} = exp\left(-2.35 + 0.15 * \ln(aadt_{mainline}) + 1.86 * \frac{ln(aadt_{xstreet})}{ln(aadt_{mainline})} - 0.28 * urban_{2by2} - 0.09 * urban_{4by2} + 0.05 * urban_{4by4} + 0.12 * urban_{6by2} + 0.13 * urban_{6by4}\right)$$

Dispersion parameter: 0.727

$$N_{predicted,rural} = exp\left(-4.65 + 0.37 * ln(aadt_{mainline}) + 2.05 * \frac{ln(aadt_{xstreet})}{ln(aadt_{mainline})} - 0.33 * rural_{2by2} - 0.28 * rural_{4by2}\right)$$

Dispersion parameter: 0.419

Where:

- $N_{predicted,urban}$ is the predicted number of crashes for an urban intersection (crashes/3 years)
- $N_{predicted,rural}$ is the predicted number of crashes for a rural intersection (crashes/3 years)
- Ln() is the natural logarithm
- $aadt_{mainline}$ is the average annual daily traffic entering the intersection from the mainline (both directions, veh/day)
- $aadt_{xstreet}$ is the average annual daily traffic entering the intersection from the cross street (both directions, veh/day)
- $urban_{2by2}$ is an indicator variable for intersection configuration in an urban area (=1 if the intersection is in an urban area and has 2 through lanes on both mainline and cross street approaches, =0 otherwise)
- $urban_{4by2}$ is an indicator variable for intersection configuration in an urban area (=1 if the intersection is in an urban area and has 4 through lanes on the mainline and 2 through lanes on the cross street, =0 otherwise)

- $urban_{4by4}$ is an indicator variable for intersection configuration in an urban area (=1 if the intersection is in an urban area and has 4 through lanes on both mainline and cross street approaches, =0 otherwise)
- $urban_{6by2}$ is an indicator variable for intersection configuration in an urban area (=1 if the intersection is in an urban area and has 6 through lanes on the mainline and 2 through lanes on the cross street, =0 otherwise)
- $urban_{6by4}$ is an indicator variable for intersection configuration in an urban area (=1 if the intersection is in a urban area and has 6 through lanes on the mainline and 4 through lanes on the cross street, =0 otherwise)
- $rural_{2by2}$ is an indicator variable for intersection configuration in a rural area (=1 if the intersection is in a rural area and has 2 through lanes on both mainline and cross street approaches, =0 otherwise)
- $rural_{4by2}$ is an indicator variable for intersection configuration in a rural area (=1 if the intersection is in an urban area and has 4 through lanes on the mainline and 2 through lanes on the cross street, =0 otherwise)

Empirical Bayes (EB)-adjusted number of expected crashes:

$$N_{expected} = w * N_{predited} + (1 - w) * N_{observed}$$

Where:

- $N_{expected}$ is the EB-adjusted number of expected crashes
- $N_{predicted}$ is the number of crashes predicted by the Safety Performance Function
- w is SPF weight, accounting for the accuracy of the SPF prediction:

$$w = \frac{1}{1 + k * N_{predicted}}$$

- k is the dispersion parameter of the SPF model

APPENDIX C: TOP 10 PERCENT OF INTERSECTIONS IN CALIFORNIA

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
1	06063 54LD 7.949	063	JCT 198 RMPS/NOBLE,RT	39	53
2	12039 30 D 5.641	039	EDINGER AVE	21	117
3	07090 19 D 1.201	090	MINDANAO WAY-LT RDWAY	20	29
4	10108 50 D 26.060	108	STANDIFORD LT SYLVAN RT	16	45
5	12039 30 D 3.120	039	MAIN ST-LT &ELLIS AV-RT	16	97
6	05025 35 U 54.048	025	JCT 156 (R11.369)	16	33
7	12039 30 D 7.634	039	WESTMINSTER AVE	14	65
8	08083 36 D 9.712	083	D ST	14	16
9	12039 30 D 4.131	039	SLATER AVE	13	91
10	08018 36 U100.956	018	JCT RTE 395	13	81
11	08083 36 D 10.971	083	6TH ST	13	27
12	12039 30 D 14.441	039	OFF RAMP FROM WB RTE 91	13	26
13	07001 19 D 5.261	001	WALNUT AVE	12	21
14	07019 19 D 5.888	019	ARTESIA BLVD	11	50
15	07019 19 D 7.403	019	SOMERSET BLVD	11	33
16	12039 30 D 12.685	039	LINCOLN AVE	11	50
17	12039 30 D 9.671	039	CHAPMAN AVE	10	48
18	12090 30RD 5.545	090	BREA PLZA LT/ON FR NB57	10	42
19	07019 19 D 3.980	019	DEL AMO BLVD	10	25
20	07001 19 D 5.761	001	MARTIN LUTHER KING BLVD	10	24
21	05135 42 D 14.470	135	ENOS DR	10	54
22	12039 30 D 7.371	039	13TH ST	10	18
23	07034 56 U 5.295	034	ROSE AVE	10	36
24	07001 19 D 5.011	001	CHERRY AVE	9	33
25	12039 30 D 2.141	039	YORKTOWN AVE	9	59
26	07232 56 D 0.293	232	ESPLANADE DR LR	9	48
27	05135 42 D 11.730	135	LAKEVIEW RD	9	30

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
28	06065 54 D 29.491	065	AVE 228, HERMOSA ST	9	38
29	08083 36 D 10.719	083	5TH ST	9	24
30	12039 30 D 6.141	039	MCFADDEN AVE	9	77
31	12039 30 D 2.651	039	GARFIELD AVE	9	65
32	10132 50LD 15.240	132	I ST (MOD)	9	18
33	06063 54 D 7.510	063	TULARE AVE	9	43
34	08083 36 D 6.913	083	WALNUT AVE	9	16
35	04082 43 D 13.821	082	POMEROY AVE	9	15
36	04092 01 D 6.780	092	SANTA CLARA ST	9	43
37	12039 30 D 19.671	039	LAMBERT RD	9	16
38	10132 50 D 17.140	132	EL VISTA L/MITCHELL R	9	16
39	12039 30 D 1.630	039	ADAMS AVE	9	54
40	05246 42 D 9.480	246	I ST	9	12
41	12001 30 D 20.370	001	SUPERIOR-RT;BALBOA-LT;	9	39
42	07001 56 D 18.068	001	SIXTH ST	9	17
43	08058 36 U 5.400	058	JCT RTE 395	9	38
44	03020 51RD 15.094	020	STABLER-LT/WALTON-RT	8	29
45	12039 30 D 5.471	039	STARK AVE	8	60
46	08083 36 D 7.413	083	PHILADELPHIA AVE	8	40
47	07001 56 D 19.621	001	GONZALES RD	8	52
48	07001 19 D 5.481	001	ALAMITOS AVE	8	37
49	08018 36 D 88.871	018	NAVAJO RD	8	29
50	05001 42 D 21.338	001	PINE AVE	8	18
51	10108 50 D 23.440	108	MORRIS AVE (MOD)	8	16
52	12039 30 D 5.721	039	CENTER DR/CONN SB 405	8	69
53	04237 43 D 9.571	237	ABBOTT AVE	8	48
54	12074 30 D 0.241	074	RANCHO VIEJO RD	8	23
55	07001 56 D 18.154	001	FIFTH ST-JCT RTE 34	8	32
56	08018 36 D 87.871	018	CENTRAL RD	8	18

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
57	04185 01 U 5.650	185	ESTUDILLO AVE	8	17
58	08395 36 U 16.225	395	BARTLETT AVE	8	29
59	07001 19 D 6.021	001	ATLANTIC AVE	8	35
60	07001 56 D 17.978	001	SEVENTH ST	8	29
61	04101 38 D 5.480	101	ELLIS ST	8	12
62	04082 43 D 14.540	082	HALFORD AVE	8	30
63	12039 30 D 13.211	039	CRESCENT AVE	8	27
64	08083 36 D 10.470	083	4TH ST	8	22
65	08074 33 D 41.840	074	YALE ST	8	17
66	04029 48 D 5.850	029	MINI DR	8	24
67	04082 43 D 17.035	082	MATHILDA AVE	8	34
68	07107 19 D 4.696	107	ARTESIA BLVD	8	31
69	07001 19 D 11.632	001	RMPS 110 SB; ON L/OFF R	8	15
70	10132 50 U 14.840	132	7TH ST (MOD)	7	10
71	04082 43 D 14.310	082	NB LAWRENCE EXPWY RAMPS	7	28
72	07138 19 D 51.410	138	PEAR BLOSSOM HWY RT.	7	21
73	05135 42 D 15.080	135	MORRISON AVE	7	32
74	10132 50 U 13.420	132	CARPENTER RD (MOD)	7	17
75	12039 30 D 15.011	039	9TH ST-LT;OID	7	20
76	04082 41 U 14.266	082	CARMELITA AVE	7	23
77	12039 30 D 7.131	039	HAZARD AVE	7	46
78	05135 42 D 13.260	135	MCCOY LANE	7	34
79	04101 38 D 6.000	101	SACRAMENTO ST	7	14
80	08074 33 D 38.480	074	SANDERSON AVE	7	21
81	10132 50LD 15.340	132	H ST (MOD)	7	12
82	12039 30 D 0.631	039	ATLANTA AVE	7	27
83	12039 30 D 5.301	039	MAC DONALD ST - LT OID	7	30
84	08083 36 D 9.960	083	G ST	7	27
85	07019 19 D 6.900	019	ALONDRA BLVD	7	33

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
86	10108 50 D 37.310	108	OAK AVE (OKDL)	7	23
87	06063 54 D 7.010	063	WALNUT AVE, AVE 288	7	63
88	05152 44 D 1.040	152	TUTTLE AVE	7	17
89	04116 49 U 33.610	116	STONY POINT RD	7	25
90	03049 31 D 6.380	049	BELL RD	7	42
91	05001 40 D 17.341	001	FOOTHILL BLVD	7	41
92	06063 54 D 6.010	063	AVE 280, CALDWELL AVE	7	36
93	04013 01 U 13.180	013	SAN PABLO AVE JCT 123	7	27
94	04084 01 U 10.819	084	MISSION BL (RTE 238)	7	20
95	04082 43 D 25.450	082	GALVEZ AV-EMBARCADERO R	7	28
96	03099 34 D 35.370	099	ELVERTA RD	7	24
97	04082 43 D 14.380	082	SB LAWRENCE EXPWY RAMPS	6	24
98	05009 44 U 6.460	009	GRAHAM HILL/BENNETT ST	6	26
99	07138 19 D 46.231	138	25TH ST. E	6	26
100	06184 15 D 1.506	184	HALL RD	6	17
101	08062 36 D 11.900	062	SAGE AVE	6	23
102	04237 43TU 9.692	237	SERRA WAY	6	21
103	07001 19 D 26.962	001	CENTURY BL-RT/WORLD WAY	6	10
104	05135 42 D 13.810	135	CARMEN LN	6	37
105	12001 30 D 24.551	001	LAKE (1ST ST) ST	6	39
106	05135 42 D 17.130	135	GRANT ST	6	24
107	07072 19 D 2.113	072	MILLS AVE	6	25
108	07066 19 D 0.793	066	WHEELER AVE	6	22
109	10152 24 D 20.590	152	7TH ST	6	31
110	07001 19 D 6.591	001	CEDAR AVE	6	17
111	07071 19 D 1.912	071	9TH ST	6	50
112	10108 50 D 26.350	108	UNION AVE	6	17
113	04123 01 D 3.600	123	CEDAR ST	6	16
114	04082 43 D 14.150	082	FLORA VISTA AVE	6	22

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
115	03016 34 U 6.220	016	BRADSHAW	6	24
116	08083 36 D 9.544	083	B ST	6	11
117	07001 19 D 36.110	001	CALIFORNIA INCLINE	6	34
118	07138 19 D 48.961	138	AVE R RT	6	21
119	03016 34 U 4.166	016	S WATT/ELK GROVE-FLORIN	6	17
120	06063 54 D 6.760	063	BEECH AVE (WEST)	6	36
121	06184 15 D 1.004	184	DIGIORGIO RD	6	16
122	05135 42 D 14.280	135	BATTLES ROAD	6	42
123	12039 30 D 16.130	039	STAGE RD/CASCADE WAY	6	21
124	04185 01 U 6.130	185	DUTTON AV R - BEST AV L	6	17
125	07138 19 D 47.251	138	35TH ST. E.	6	12
126	06063 54 D 1.010	063	AVE 240, PROSPERITY AVE	6	14
127	12039 30 D 3.611	039	TALBERT AVE	6	77
128	07019 19 D 6.394	019	FLOWER ST.	6	13
129	04082 43 D 14.832	082	HENDERSON AVE	6	21
130	03049 31 D 3.470	049	ELM AVE & FULWILER AVE	6	15
131	12090 30 D 5.191	090	STATE COLLEGE BLVD	6	69
132	05135 42 D 14.780	135	STOWELL RD	6	50
133	03020 51 D 16.060	020	CLARK AVE	6	19
134	10012 39 D 17.946	012	CHEROKEE LANE	6	24
135	04082 43 D 23.110	082	LOS ROBLES RD-CAMINO WY	6	14
136	02273 45 D 12.680	273	CEDARS L/BONNEYVIEW RT	6	44
137	12039 30 D 5.141	039	HEIL AVE	6	63
138	04237 43 D 9.438	237	RTE 237/NB880 OFFRAMP	6	30
139	07001 19 D 12.517	001	NORMANDIE AVE	6	15
140	07034 56 U 6.270	034	RICE AVE	6	38
141	10108 50 D 25.560	108	RUMBLE RD (MODESTO)	6	17
142	10108 50 D 25.320	108	FLOYD AVE RT	6	23
143	08074 33 D 41.338	074	SAN JACINTOST. JCT 79,N	6	22

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
144	07001 19 D 6.511	001	PACIFIC AVE	6	25
145	12039 30 D 11.681	039	BALL RD	6	35
146	11067 37 D 24.376	067	JCT78-PINE LT/10TH ST R	6	19
147	08038 36 U 1.445	038	UNIVERSITY ST	6	14
148	12039 30 D 10.660	039	KATELLA AVE	6	48
149	04001 38 D 4.050	001	LINCOLN WAY	6	18
150	04082 43 D 16.160	082	REMINGTON DR-F OAKS AVE	6	24
151	08018 36 U102.475	018	VERBENA RD - RT	6	11
152	07019 19 D 7.900	019	ROSECRANS AVE	6	20
153	04101 38 D 5.940	101	CALIFORNIA ST	6	17
154	07001 19 D 6.261	001	LONG BEACH BLVD	6	45
155	12090 30 D 2.497	090	HARBOR BLVD	6	23
156	07164 19 D 4.810	164	GARVEY AVE	6	35
157	04082 43 D 15.320	082	WOLFE RD	6	21
158	07001 19 D 0.591	001	2ND ST-LT WESTMINSTER A	6	45
159	03016 34 U 19.464	016	MURIETA PARKWAY	6	11
160	11125 37 D 22.301	125	MISSION GORGE RD	5	29
161	04092 41 U 0.200	092	MAIN ST	5	22
162	11076 37RD 6.207	076	COLLEGE BLVD	5	30
163	04101 38 D 5.550	101	O'FARRELL ST	5	21
164	08018 36 D 94.076	018	KASOTA RD	5	19
165	04082 41 U 13.690	082	FLORIBUNDA AVE	5	24
166	08074 33 D 39.588	074	LYON AVE	5	11
167	07138 19 D 45.710	138	20TH ST E	5	22
168	08074 33 D 40.837	074	BUENA VISTA ST	5	13
169	07001 56 D 17.062	001	DATE ST	5	21
170	02036 18 U 24.865	036	WEATHERLOW LT & RT	5	13
171	08074 33 D 42.838	074	STANFORD ST	5	18
172	05152 44TD 1.594	152	OHLONE PKWY/CLIFFORD DR	5	20

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
173	12072 30 D 11.917	072	VALLEY HOME AVE	5	14
174	11078 13 U 15.035	078	OLD HWY 111/BEST RD	5	11
175	08083 36 D 7.917	083	FRANCIS ST	5	13
176	05152 44RU 1.995	152	HOLOHAN L/COLLEGE RD RT	5	21
177	12039 30 D 22.219	039	CYPRESS ST	5	14
178	07138 19 D 45.971	138	22ND ST EAST - LT OID	5	17
179	07001 19 D 6.441	001	PINE AVE	5	16
180	08074 33 D 43.088	074	MERIDIAN ST	5	15
181	07001 19 U 19.271	001	GUADALUPE AV / RUBY ST	5	16
182	10108 50 D 24.950	108	TOKAY AVE RT/SHP CTR LT	5	17
183	07002 19 D 24.411	002	RTE 210 EB RAMPS	5	6
184	12001 30 U 8.781	001	THALIA ST	5	17
185	05152 44TD 1.195	152	GREEN VALLEY RD	5	34
186	12090 30 D 3.501	090	PUENTE ST	5	17
187	05135 42 D 16.000	135	FESLER ST	5	15
188	02273 45 D 5.206	273	SOUTH ST RT & LT	5	16
189	07001 19 U 19.141	001	SAPPHIRE ST/SO.FRANCISC	5	15
190	04012 48RD 3.206	012	BECK AVE(BYPASS 12)	5	23
191	04092 01 D 7.440	092	SOTO RD.	5	11

APPENDIX D: TOP 10 PERCENT OF INTERSECTIONS IN MINNESOTA

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
1	0200000061 135+00.275	61	BURNS AV MSAS216 LT CSAH 35 RT	14	39
2	0300000021 000+00.000	21	TH 60 CSAH 48 BHD/FARIBAULT	13	25
3	0200000010 000+00.428	10	S JCT TH 75 MAIN & 8TH/MRHD	11	31
4	0200000010 177+00.743	10	ST GERMAIN ST MSAS 128/ST CLD	11	42
5	0200000061 116+00.921	61	10TH ST MSAS133 RT M37 LT/HSTG	10	21
6	0300000065 011+00.484	65	CLOVERLF PKWY LT 93RD LN RT/BL	10	26
7	0300000194 016+00.821	194	3RD ST W MSAS 126/DULUTH	10	24
8	0200000010 000+00.516	10	W JCT TH 75 CENTER & 8TH/MRHD	9	13
9	0300000013 088+00.529	13	CSAH 42 140TH ST LT EGAN DR RT	9	24
10	0300000015 153+00.004	15	CR 134/ST CLOUD	9	33
11	0300000023 205+00.236	23	25TH AV MSAS 132/ST CLOUD	9	52
12	0300000055 202+00.171	55	N JCT TH 149 LT M1156 RT/EAGAN	9	23
13	0300000065 009+00.682	65	81ST AV MSAS 101/SPRING LK PAR	9	31
14	0300000252 000+00.607	252	66TH AV MSAS 111 M231/BRK CNTR	9	68
15	0300000252 003+00.236	252	85TH AV CSAH 109 MSAS140/BR PK	9	43
16	0200000012 100+00.458	12	5TH ST CSAH 11/LITCHFIELD	8	12
17	0300000013 094+00.594	13	CSAH 5 1 MI W I35W/BURNSVILLE	8	63
18	0300000015 150+00.644	15	N JCT TH 23 DIV ST/ST CLOUD	8	74
19	0300000015 151+00.066	15	3RD ST N CSAH 81 MSAS 114/ST C	8	65
20	0300000023 207+00.621	23	LINCOLN AV MSAS 120/ST CLOUD	8	39
21	0300000027 078+00.895	27	S JCT TH 29	8	18
22	0300000036 202+00.419	36	GREELEY ST OAKGREEN AV/STLWTR	8	20
23	0300000055 176+00.411	55	W JCT CSAH 101 LT SIOUX DR RT	8	16
24	0300000055 202+00.512	55	LONE OAK RD CSAH 26/EAGAN	8	26
25	0300000065 001+00.394	65	WASHINGTON AVE CSAH-152/MPLS	8	20
26	0200000010 002+00.346	10	34TH ST MSAS 135/MOORHEAD	7	29
27	0200000010 213+00.207	10	JACKSON AV MSAS 104/ELK RIVER	7	20

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
28	0200000065 312+00.579	65	NEWTON AV MSAS 116/ALBERT LEA	7	10
29	0200000071 312+00.377	71	N JCT TH 197/BEMIDJI	7	24
30	0300000005 194+00.023	5	HADLEY AVE MSAS 121/OAKDALE	7	17
31	0300000015 150+00.400	15	S JCT TH 23 2ND ST S/ST CLOUD	7	112
32	0300000015 151+00.561	15	8TH ST N CSAH 4/ST CLOUD	7	37
33	0300000023 203+00.559	23	2ND AV S MSAS 102/WAITE PARK	7	38
34	0300000029 077+00.393	29	DAKOTA ST MSAS128 LT M200/ALEX	7	17
35	0300000029 078+00.693	29	22ND AV CSAH 23 MSAS 121/ALEX	7	15
36	0300000036 203+00.146	36	OSGOOD AV CSAH 24/OAK PRK HGTS	7	38
37	0300000051 007+00.350	51	CR B CSAH 25/ROSEVILLE	7	57
38	0300000051 008+00.377	51	CR C CSAH 23/ROSEVILLE	7	71
39	0300000095 115+00.834	95	HUDSON RD WDB MSAS117 AFTN M90	7	14
40	0300000101 039+00.872	101	S DIAMOND LK MSAS110 RT M49 LT	7	48
41	0300000197 005+00.233	197	RIDGEWAY AV MSAS 131 M12/BMDJI	7	10
42	0200000053 005+00.639	53	JOSHUA AV TH94 RT MSAS202/DLTH	6	32
43	0200000053 005+00.819	53	MILLER MALL ENT LT COTTONWD RT	6	39
44	0200000075 248+00.140	75	30TH AVE S/MOORHEAD	6	22
45	0200000169 140+00.790	169	93RD AV N CSAH 30/BROOK PARK	6	25
46	0200000169 340+00.466	169	25TH ST MSAS 199/HIBBING	6	21
47	0200000810A237+00.906		CR-H M-63 LT CSAH 9 RT/MNDS VW	6	36
48	0300000005 047+01.044	5	EDEN PRAIRIE RD CSAH 4/EDEN PR	6	20
49	0300000007 181+00.951	7	MNTH 41 RT LINDEN DR LT/SHORWD	6	30
50	0300000007 186+00.196	7	CSAH 101/MINNETONKA	6	47
51	0300000029 079+00.651	29	10TH AV MSAS 109/ALEXANDRIA	6	16
52	0300000029 080+00.058	29	5TH AV MSAS 104/ALEXANDRIA	6	15
53	0300000036 201+00.906	36	WASHINGTON AVE LT NORELL AV RT	6	47
54	0300000047 003+00.491	47	20TH AVE NE M-253/MPLS	6	11
55	0300000047 010+00.328	47	OSBORNE RD CSAH 8/FRIDLEY	6	22
56	0300000055 178+00.570	55	ROCKFORD RD CSAH 24 CSAH 9/PLM	6	24

No.	Intersection ID	Route No.	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
57	0300000055 183+00.025	55	S SHORE DR LT CSAH 73 RT/PLMTH	6	18
58	0300000055 192+00.773	55	E 26TH ST MSAS-239/MPLS	6	53
59	0300000065 003+00.058	65	LOWRY AVE NE CSAH-153/MPLS	6	22
60	0300000065 009+00.167	65	OSBORNE RD CSAH 8/SPRING LK PK	6	18
61	0200000010 000+00.212	10	5TH ST/MOORHEAD	5	13
62	0200000010 000+00.760	10	11TH ST CSAH 3 MSAS 121/MOORHD	5	12
63	0200000010 162+00.846	10	CSAH 2 RICE ST EARLE ST/RICE	5	27
64	0200000010 203+00.712	10	LAKE ST TH 25 MSAS 102/BIG LK	5	22
65	0200000010 203+00.899	10	EAGLE LK RD CSAH5 MSAS106/B LK	5	20
66	0200000053 007+00.315	53	MALL DR M 106 LT/HERMANTOWN	5	14
67	0200000053 065+00.425	53	13 ST S M 102 MSAS 222/MT IRON	5	17
68	0200000061 159+00.615	61	MNTH 97 N JCT RT M346 LT/F LK	5	16
69	0200000065 312+00.252	65	FRONT ST MSAS 110&109/ALBT LEA	5	11
70	0200000075 248+00.645	75	24TH AVE S/MOORHEAD	5	12
71	0200000169 159+00.043	169	MAIN ST MSAS 113/ELK RIVER	5	33
72	0200000169 337+00.840	169	WOOLFAN RD NEWBERG RD/HIBBING	5	11
73	0300000005 044+00.883	5	CSAH 17 POWERS BLVD/CHANHSN	5	17
74	0300000013 000+00.561	13	1ST AVE MS 112 ALBERT LEA	5	12
75	0300000013 089+00.532	13	MCCOLL DR CSAH 16/SAVAGE	5	19
76	0300000013 099+00.074	13	12TH AVE LT PARKWOOD RT/BRNSVL	5	22
77	0300000013 101+00.231	13	DIFFLEY RD CSAH30 RT M796 LT	5	8
78	0300000013 107+00.099	13	MNTH 55/MENDOTA HEIGHTS	5	16
79	0300000023 204+00.975	23	29TH AV MSAS 139/ST CLOUD	5	25
80	0300000023 208+00.134	23	14TH AV SE CSAH 8 M 335/ST CLD	5	17
81	0300000029 079+00.976	29	6TH AV MSAS 105/ALEXANDRIA	5	15
82	0300000036 205+00.168	36	N JCT TH 95 CHESTNUT ST/STLWTR	5	20
83	0300000047 010+00.876	47	81ST AVE MSAS339 LT MSAS101 RT	5	22

APPENDIX E: TOP 10 PERCENT OF INTERSECTIONS IN CHARLOTTE

No.	Intersection ID	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
1	33031	ALBEMARLE RD_CENTRAL AV	22	69
2	32740	E 7TH ST_HAWTHORNE LN	20	59
3	32687	E 4TH ST_S CALDWELL ST	20	38
4	32698	E 6TH ST_N MCDOWELL ST	20	37
5	32451	J W CLAY BV_MCCULLOUGH DR_W W T HARRIS BV	18	95
6	32580	MILTON RD_N SHARON AMITY RD	16	55
7	32601	E 11TH ST_N COLLEGE ST	16	42
8	12520	CHARLOTTETOWNE AV_E JOHN BELK RA_KENILWORTH AV	16	86
9	32642	S CHURCH ST_W 4TH ST	15	25
10	32727	E 4TH ST_E JOHN BELK RA	15	37
11	11849	E JOHN BELK RA_S CALDWELL ST	15	42
12	32456	E W T HARRIS BV_N TRYON ST_W W T HARRIS BV	15	112
13	32673	E 5TH ST_N CALDWELL ST	14	27
14	32800	ALBEMARLE RD_LAWYERS RD	13	68
15	32627	N CHURCH ST_W 5TH ST	13	29
16	32848	BILLY GRAHAM PY_S TRYON ST_W WOODLAWN RD	13	111
17	32847	E INDEPENDENCE BV_IDLEWILD RD	11	110
18	32704	E MOREHEAD ST_S TRYON ST_W MOREHEAD ST	11	37
19	32695	E 3RD ST_S CALDWELL ST	11	31
20	32680	E TRADE ST_N CALDWELL ST_S CALDWELL ST	10	32
21	32711	CENTRAL AV_E 7TH ST_N KINGS DR	10	42
22	32746	CHARLOTTETOWNE AV_E 4TH ST	10	27
23	32795	EAST BV_KENILWORTH AV	10	28
24	32626	E 11TH ST_N CALDWELL ST	9	21
25	32804	ALBEMARLE RD_E W T HARRIS BV	9	116
26	32491	N I-85 EXIT 39 RA_STATESVILLE AV	9	33
27	32708	E MOREHEAD ST_S COLLEGE ST_S TRYON	9	24
28	32577	N I-77 EXIT 10B RA_W TRADE ST	9	31

No.	Intersection ID	Intersection Description	3-Year Target Crashes	3-Year Total Crashes
29	32653	E 6TH ST_N BREVARD ST	9	11
30	32596	E 12TH ST_N COLLEGE ST	9	17
31	32434	MALLARD CREEK RD_W W T HARRIS BV	8	77
32	32692	S CHURCH ST_W MOREHEAD ST	8	21
33	32731	E 3RD ST_E JOHN BELK RA	8	24
34	32414	IDLEWILD RD_MONROE RD_RAMA RD	8	44
35	32567	BILLY GRAHAM PY_SCOTT FUTRELL DR	8	57
36	32932	I-485 RA_S TRYON ST	8	60
37	32678	S MINT ST_W MOREHEAD ST	8	24
38	32885	TYVOLA RD_WESTPARK DR	8	45
39	32755	CAMDEN RD_EAST BV_WEST BV	8	22
40	32612	E 9TH ST_N COLLEGE ST	8	22
41	32806	ALBEMARLE RD_N SHARON AMITY RD	7	104
42	32766	E 3RD ST_QUEENS RD	7	27
43	3028	PERIMETER PY_W W T HARRIS BV	7	32
44	32560	DALTON AV_N GRAHAM ST	7	34
45	32430	BROOKSHIRE BV_MT HOLLY-HUNTERSVILLE RD	7	62
46	32799	ALBEMARLE RD_FARM POND LN	7	86
47	32662	E 6TH ST_N CALDWELL ST	7	12
48	32681	E 5TH ST_N DAVIDSON ST	7	17
49	32732	E STONEWALL ST_S MCDOWELL ST	7	24
50	3717	I-485 RA_N TRYON ST	7	29
51	32759	E 7TH ST_N CASWELL RD_PECAN AV	7	34