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Calibration of Safety Performance Functions for Massachusetts Urban and Suburban Intersections

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16. Abstract

The American Association of State Highway and Transportation Officials (AASHTO) 2010 Highway Safety Manual (HSM) introduces various Safety Performance Functions (SPFs) to assist state Departments of Transportation (DOTs) with assessing the safety performance of urban and suburban arterial intersections. However, the functions included in the HSM were developed based on crash data collected from a limited number of states, and they do not account for jurisdiction-specific differences.

This research first calculated the calibration factors for the SPFs in the HSM using Massachusetts data. The results show that the calibration factors for 3SG and 4SG intersections are substantially greater than 1.0, suggesting that the observed crashes at these two types of intersections are significantly higher than those predicted using the HSM SPFs. This research also developed new SPFs for urban and suburban intersections in Massachusetts. Given the limited amount of data, this research was able to generate statistically meaningful SPFs for multiple-vehicle crashes only. A simplified approach was developed for predicting single-vehicle, vehicle-bicycle, and vehicle-pedestrian crashes. The calibration factors were calculated again based on the new SPFs. The new factors are all reasonably close to 1.0.

The HSM SPFs for vehicle-pedestrian collisions at signalized intersections require daily pedestrian volumes. In this research, regression models were developed to estimate daily pedestrian volumes. Additionally, Excel spreadsheets were developed to (1) implement the SPFs in the HSM and the newly developed ones for predicting crash frequencies at urban and suburban arterial intersections; and (2) identify high-risk intersections.

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Calibration of Safety Performance Functions for Massachusetts Urban and Suburban Intersections

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Disclaimer

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Executive Summary

This study of Calibration of Safety Performance Functions for Massachusetts Urban and Suburban Intersections was undertaken as part of the Massachusetts Department of Transportation Research Program. This program is funded with Federal Highway Administration (FHWA) Statewide Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The American Association of State Highway and Transportation Officials (AASHTO) 2010 *Highway Safety Manual* (HSM), 1st Edition, introduces various Safety Performance Functions (SPFs) to assist state Departments of Transportation (DOTs) with assessing the safety performance of urban and suburban arterial intersections and quantifying the crash reduction effects of safety countermeasures. However, the functions included in Chapter 12 of the HSM were developed based on crash data collected from several states other than the Commonwealth of Massachusetts. They do not account for jurisdiction-specific differences and need to be carefully assessed or calibrated before being applied to Massachusetts.

This research first calculated the calibration factors for the SPFs in Chapter 12 of the HSM for the following four types of urban and suburban arterial intersections in Massachusetts:

- 3-Approach Signalized Intersections (3SG)
- 3-Approach Stop-Controlled Intersections (3ST)
- 4-Approach Signalized Intersections (4SG)
- 4-Approach Stop-Controlled Intersections (4ST)

The results show that the calibration factors for 3SG and 4SG are substantially greater than 1.0, suggesting that the observed crashes at these two types of intersections are significantly higher than those predicted using the HSM SPFs.

Because of the aforementioned significant differences, this research also developed new SPFs for the four types of intersections in Massachusetts. In the HSM, separate SPFs are provided for multiple-vehicle, single-vehicle, vehicle-bicycle, and vehicle-pedestrian crashes. Given the limited amount of data, this research was able to generate statistically meaningful SPFs for multiple-vehicle crashes only. A simplified approach was developed for predicting single-vehicle, vehicle-bicycle, and vehicle-pedestrian crashes. Such a simplified approach is also adopted in the HSM for certain cases where statistically meaningful SPFs are unavailable. Based on the new SPFs, the calibration factors were calculated again, and they are all reasonably close to one, indicating the necessity of developing new SPFs instead of calibrating them.

In the HSM, the SPFs for vehicle-pedestrian collisions at signalized intersections require daily pedestrian volumes, and a very simple table is provided to estimate those volumes. To address this issue, regression models were developed to estimate daily pedestrian volumes in this research. Additionally, Excel spreadsheets were developed to (1) implement the SPFs in the HSM and the newly developed ones for predicting crash frequencies at urban and suburban arterial intersections; and (2) implement the empirical Bayes method for identifying high-risk intersections.

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List of Acronyms

3SG	3-Approach Signalized Intersections
4SG	4-Approach Signalized Intersections
3ST	3-Approach Stop-Controlled Intersections
4ST	4-Approach Stop-Controlled Intersections
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ABCC	Alcoholic Beverages Control Commission
ADT	Average Daily Traffic
AMF	Accident Modification Factor
CCC	Cape Cod Commission
CMF	Crash Modification Factor
CMRPC	Central Massachusetts Regional Planning Commission
DEF	Daily Expansion Factor
DOT	Department of Transportation
ESRI	Environmental Systems Research Institute
FI	Fatal and Injury
GEE	Generalized Estimating Equations
GPS	Global Positioning System
HEF	Hourly Expansion Factor
HPMS	Highway Performance Monitoring Systems
HSM	Highway Safety Manual
MAPC	Metropolitan Area Planning Council
MassDOT	Massachusetts Department of Transportation
MassGIS	Massachusetts Office of Geographic Information
MEF	Monthly Expansion Factor
MRI	Midwest Research Institute
MRPC	Montachusett Regional Planning Commission
MVPC	Merrimack Valley Planning Commission
NB	Negative Binomial
NBPD	National Bicycle and Pedestrian Documentation
NMCOG	Northern Middlesex Council of Governments
PDO	Property-Damage-Only
PVPC	Pioneer Valley Planning Commission
SPF	Safety Performance Function
SRPEDD	Southeast Regional Planning and Economic Development District
TMCs	Turning Movement Counts
TxDOT	Texas Department of Transportation
WEF	Weekly Expansion Factor

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1.0 Introduction

This study of Calibration of Safety Performance Functions for Massachusetts Urban and Suburban Intersections was undertaken as part of the Massachusetts Department of Transportation Research Program. This program is funded with Federal Highway Administration (FHWA) Statewide Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The AASHTO 2010 Highway Safety Manual (HSM) [*1*] introduces various Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) to assist state Departments of Transportation (DOTs) with assessing the safety performance of urban and suburban arterial intersections and quantifying the crash reduction effects of various safety countermeasures. However, the functions and factors included in Chapter 12 of the HSM were developed based on crash data collected from several states other than the Commonwealth of Massachusetts. They do not account for jurisdiction-specific differences and need to be carefully assessed or calibrated before being applied to Massachusetts. Note that the HSM provides crash predictive methods for several different facilities, such as rural multilane highway segments and rural multilane highway intersections. This research focused only on urban and suburban arterial intersections.

The main objective of this research was to calibrate the calibration factors used in the HSM, develop new SPFs, and to update other relevant parameters used in the 2010 HSM for the following four types of urban and suburban arterial intersections in Massachusetts:

- 3-Approach Signalized Intersections (3SG)
- 3-Approach Stop-Controlled Intersections (3ST)
- 4-Approach Signalized Intersections (4SG)
- 4-Approach Stop-Controlled Intersections (4ST)

To carry out this research, vehicle and pedestrian traffic counts, crash reports, data from schools, bus stops, and alcohol sales establishments, and intersection geometries were collected from randomly selected intersections. Tools were developed to process the collected raw data. The processed data was fitted using many statistical methods to identify the most appropriate new SPFs. The best-fitting new SPFs and the corresponding SPFs in the HSM were compared using the collected data, and calibration factors were calculated for them. Based on the SPFs and calibration factors, Excel spreadsheet tools were developed for Massachusetts Department of Transportation (MassDOT) to predict intersection crash frequencies and identify high-risk intersections for further improvements.

Chapter 2 presents a comprehensive literature review of studies on calibrating SPFs, CMFs, and calibration factors related to the HSM. Special attention was paid to the sample sizes of the data considered in these studies. Chapter 3 provides a summary of the crash prediction methods for urban and suburban arterial intersections in the HSM. It also includes a brief description of the Negative Binomial regression that is commonly used in crash count modeling. Chapter 4 summarizes the data collection effort provided for this research and covers site selection, turning movement counts (e.g., vehicle, pedestrian, and bicycle counts) collection, and a review of crash reports. In addition, the locations of schools, bus stops, and alcohol sales establishments within 1,000 feet of the selected intersections were obtained, since they are needed in calculating the CMFs for vehicle-pedestrian crashes. Intersection geometry and traffic control data was also collected to calculate the CMFs for multiple- and single-vehicle crashes. The SPFs in the HSM depend heavily on Annual Average Daily Traffic (AADT) data. Unfortunately, such data is not readily available for most intersections. Chapter 5 describes a procedure developed for estimating AADT based on short-duration intersection turning movement counts. It also includes models developed for estimating daily pedestrian volumes based on short-duration pedestrian counts. Chapter 6 presents the processes and results of the calibration factors estimation and new SPFs development. Chapter 7 discusses the various problems encountered in the data collection, estimation, and model development and provides recommendations for future HSM model calibration, and new SPFs development work is provided.

2.0 Literature Review

Calibrating the safety predictive models in the HSM for urban and suburban arterial intersections may include the following four aspects:

- Calibrating the calibration factor C_i (see Eq. 12-1 in the 2010 HSM).
- Calibrating SPFs (i.e., updating parameters *a*, *b*, and *c* in Eq. 12-21 of the 2010 HSM).
- Developing new SPFs with functional forms that are different from those in the HSM.
- Calibrating Crash Modification Factors (CMFs).

Calibrating the calibration factor C_i is the easiest task among the four, which was considered in most of the studies reviewed in this research. It requires collecting crash and explanatory data from intersections. The intersections selected do not need to satisfy the base conditions defined in the HSM. Actually, it would be better to select intersections that do not satisfy the base conditions if the only purpose is to calibrate C_i.

Alternatively, if the objective is to calibrate SPFs or develop new SPFs, it would be ideal to collect data from intersections that strictly satisfy the base conditions. However, to find enough such intersections in practice is very difficult. Fortunately, the HSM includes an alternative approach for calibrating and developing SPFs, which can utilize data from both intersections, those that satisfy the base conditions and those intersections those do not satisfying the base conditions.

The last aspect is to calibrate CMFs. During the literature review, no studies by state DOTs were found that calibrated CMFs. We assume that because calibrating CMFs requires significantly more data and effort than the previous three aspects, most state DOTs chose to calibrate the C_i parameter, while only a few state DOTs developed their own SPFs based on jurisdiction-specific data. In this research, studies on calibrating the HSM models for both roadway segments and intersections were reviewed.

2.1. Calibrating/Developing SPFs

Saito et al. [*2*] conducted a study to calibrate the SPFs for rural two-lane roadway segments in Utah. They collected data from 157 roadway segments between 2005 and 2007. Based on the SPFs for rural two-lane, two-way roads in the HSM, they obtained a calibration factor of 1.16 for Utah. Four Negative Binomial regression models and a hierarchical Bayesian model were developed and compared to the SPFs in the HSM. The four Negative Binomial regression models were finally recommended, which considered log-transformed AADT as a model input. The inputs to these jurisdiction-specific models also included road segment length, percentage of combo-unit trucks, and speed limit. Harwood et al. [*3*] conducted a study to develop SPFs for intersections on urban and suburban arterials. In their study, intersection characteristics data, including geometric design, traffic control, and traffic volume, were collected from Minnesota (1998–2002) and North Carolina (1997–2003). To determine whether a crash is intersection related, they reviewed the corresponding crash report filled out by the investigating officer and only considered crashes that occurred within 76 meters (250 feet) of an intersection. In their study, SPFs based on Negative Binomial models were developed for total crashes, fatal/injury crashes, and property-damage-only crashes separately. Also, separate models were fitted for multiple-vehicle and single-vehicle crashes. Harwood et al. considered four types of urban and suburban arterial intersections (i.e., 3ST, 3SG, 3ST, and 4SG). A different set of SPFs was developed for each of the four intersection types. The Harwood study was unable to fit a model for vehicle-pedestrian and vehicle-bicycle crashes in some cases. Such crashes were predicted by multiplying total vehicle crashes (crashes involving only vehicles) with some safety adjustment factors. In a separate study, Harwood et al. [*4*] developed SPFs for vehicle-pedestrian crashes using data from Charlotte, North Carolina, and Toronto, Canada.

Persaud et al. [*5*] developed SPFs for ten types of urban intersections categories based on traffic control, number of lanes, and geometric design (i.e., divided/undivided). They used data provided primarily by the Colorado Department of Transportation (CDOT) from 2000 to 2004. The ten intersection types and their corresponding data sample sizes are listed in Table 1. The authors adopted the cumulative residuals method proposed by Hauer and Bamfo [*6*] to measure the goodness-of-fit of the developed SPFs. The covariates considered in their study included average major road AADT, average minor road AADT, and average major road AADT/10,000.

Table 1 - Intersection Types and Sample Sizes

Intersection Type	Sample Size
Urban 4-Lane Divided Signalized 4-Leg	101
Urban 6-Lane Divided Signalized 4-Leg	46
Urban 4-Lane Divided Signalized 3-Leg	34
Urban 2-Lane Undivided Unsignalized 4-Leg	47
Urban 4-Lane Divided Unsignalized 4-Leg	49
Urban 2-Lane Undivided Unsignalized 3-Leg	34
Urban 4-Lane Divided Unsignalized 3-Leg	45
Urban 4-Lane Undivided Unsignalized 4-Leg	57
Urban 2-Lane Divided Unsignalized 3-Leg	78
Urban 4-Lane Undivided Unsignalized 3-Leg	52

Washington et al. [7] conducted a study to validate crash predictive models for five types of rural intersections:

1. 3-approach stop-controlled intersection of two-lane roads.
2. 4-approach stop-controlled intersection of two-lane roads.
3. 3-approach stop-controlled intersection with two-lanes on minor road and four lanes on major road.
4. 4-approach stop-controlled intersection with two lanes on minor road and four lanes on major road.
5. Signalized intersection of two-lane roads.

The Washington study considered covariates such as AADT, number of approaches, number of lanes, and traffic control. It was found that models with only AADT covariates have the best generalization ability. The data used in their study was collected from several states, including Minnesota, California, Michigan, Georgia, and Washington. The authors fitted five types of models with different dependent variables. Some of them used police-reported, intersection-related crashes as the dependent variable, while others used all crashes within 250 feet of an intersection as the dependent variable. Table 2 shows the sample sizes of the data used for fitting the five types of models.

Table 2 - Model Types and Sample Sizes

Model Type	Original Data Set (Collected from Minnesota, California, Michigan, and Washington)	Georgia Data
I	389	121
II	327	114
III	84	52
IV	72	52
V	49	51

For the SPFs in the HSM to be applicable, the calculated calibration factor should be close to 1.0. If the calibration factor is significantly different from 1.0, local transportation agencies may consider either calibrating the SPFs or developing their own SPFs. Some benefits of developing jurisdiction-specific SPFs are discussed in the HSM, and studies conducted by Young and Park and Srinivasan et al [1,8,10]. For instance, jurisdiction-specific SPFs can fit local data better and provide more accurate crash frequency predictions than the HSM SPFs.

Recently, Srinivasan et al. [9,10] developed a six-step guide to help local transportation agencies fit their own SPFs. They identified many issues that may arise when developing jurisdiction-specific SPFs, including over-dispersion, selection of explanatory variables, functional form, model overfitting, correlation among explanatory variables, homogeneous segments and aggregation, presence of outliers, endogenous explanatory variables, SPFs for different crash types and severities, and goodness-of-fit. Some countermeasures were suggested to address these issues. They also discussed some recent advances in SPF development, including variance of crash estimates obtained from SPFs, temporal and spatial correlation, generalized additive models, random parameters models, and Bayesian estimation methods.

When collecting data for calibrating intersection SPFs, it is common practice to collect multiple years of crash and traffic data for the same intersection. These data are likely to be correlated. Treating them as independent records to fit Negative Binomial regression models may violate the independence assumption of standard analysis of variance. To address this issue, one option is to only consider data from a particular year and ignore the rest of the data. However, this option would result in wasting much useful information and may require sampling substantially more intersections. In many cases, it is desirable to keep the sample size as small as possible from a cost-effective standpoint.

To address the potential correlation among panel crash data (crash data from multiple years at the same intersection), fixed- and random-effects models have been introduced. Chin and Quaddus [*11*] developed a random-effects Negative Binomial model that can accommodate the spatial and temporal correlation in crash data. They used crash data collected from 52 four-approach intersections in Singapore between 1992 and 1999, which resulted in a total of 832 observations. They found that 11 variables are significant contributors to intersection crashes, including total approach volume, number of phases per cycle, uncontrolled left-turn lane, and presence of surveillance camera. Qi et al. [*12*] also conducted a study to model panel crash data. They used a random-effects ordered Probit model to account for potential temporal correlation in the crash data.

In our effort to develop new SPFs for Massachusetts, multiple years of crash and site characteristics data from the same intersection were collected in order to minimize the intersection sample size needed. Also, both random- and fixed-effects Negative Binomial models were tested in this research.

2.2. Calibrating CMFs

To apply the HSM safety predictive models, the predicted crash counts need to be adjusted by a set of CMFs. For intersections satisfying the base conditions, all these CMFs are equal to a value of 1. Many intersections in practice do not satisfy the base conditions. For such intersections, their corresponding CMFs usually have a value of less than 1. In the HSM safety predictive models for urban and suburban arterial intersections, there are six CMFs for multiple-vehicle and single-vehicle collisions and three CMFs for vehicle-pedestrian collisions at signalized intersections. These CMFs are summarized in Table 3 [*1*].

Table 3 - CMFs Used in HSM Urban and Suburban Arterial Intersection Models

Applicable SPF	CMF	CMF Description
Multiple-Vehicle and Single-Vehicle Collisions at All Intersections	CMF_{1i}	Number of Approaches with Left-Turn Lanes
	CMF_{2i}	Type of Left-Turn Signal Phasing
	CMF_{3i}	Number of Approaches with Right-Turn Lanes
	CMF_{4i}	Number of Approaches with Prohibited Right-Turn-on-Red
	CMF_{5i}	Intersection Lighting
	CMF_{6i}	Presence of Red-Light Cameras
Vehicle-Pedestrian Collisions at Signalized Intersections	CMF_{1p}	Number of Bus Stops within 1,000 feet
	CMF_{2p}	Presence of Schools within 1,000 feet
	CMF_{3p}	Number of Alcohol Sales Establishments with 1,000 feet

The CMFs in the HSM were developed by different researchers. Specifically, those for left-turn and right-turn lanes were developed by Harwood et al. [*13*]; left-turn signal phasing by Hauer [*14*] and Lyon et al. [*15*]; right-turn-on-red by Clark et al. [*16*]; intersection lighting by Elvik and Vaa [*17*]; and red-light cameras by Persaud et al. [*18*]. The three CMFs for vehicle-pedestrian collisions at signalized intersections were developed by Harwood et al. [*3*].

Many methods have been proposed to estimate CMFs for different safety countermeasures. Gross et al. [*19*] summarized nine study designs for developing CMFs, as follows:

1. Before-After with Comparison Group
2. Before-After with Empirical Bayes
3. Full Bayes
4. Cross-Sectional
5. Case-Control
6. Cohort
7. Meta-Analysis
8. Expert Panel
9. Surrogate Measures

The first three methods belong to before-after studies that have been widely used for developing CMFs (see Hauer, Persaud et al., and Ye and Lord) [*20*,*21*,*22*]. The before-after with comparison group method is simple but cannot properly account for the regression to the mean effect. The before-after with empirical Bayes can better account for the regression to the mean effect but cannot incorporate prior knowledge of treatments and spatial correlations (see Persaud and Craig) [*23*]. The full Bayes method can incorporate prior knowledge of treatments. Using the full Bayes method, CMFs are calculated based on a probability distribution function instead of as a point estimate. Thus, the generated CMFs are expected to be more accurate. However, developing a full Bayes model is fairly complicated and requires high-level statistical training (Persaud et al.) [*24*]. Therefore, its applications so far have been limited to academia.

Although the before-after methods are considered more rigorous than the cross-sectional method, they are less practical. It is often difficult to collect adequate before-after data to support the analysis. Also, the observed safety performance changes may be caused by factors (such as traffic volume change) other than the countermeasure being investigated. If the impact of such factors is not properly included in the model, bias will very likely be introduced (Shen and Gan) [*25*]. The cross-sectional analysis eliminates the regression to the mean effect and works well when limited before-after data is available. But this method may suffer from omitted variables bias and potential correlation among variables. In summary, before-after studies focus on the safety changes over time caused by a particular countermeasure, while the cross-sectional analysis aims to identify the safety benefits of certain site characteristics using data from the same year (Tarko et al.) [*26*]. The pros and cons of the remaining methods can be found in Gross et al.'s study [*19*] and will not be repeated here.

CMFs are sometimes referred to as Accident Modification Factors (AMFs). Fitzpatrick et al. [*27*] developed AMFs for median characteristics on urban and rural freeways and rural multilane highways by using the cross-sectional analysis. The geometric characteristics data was obtained from the Texas Department of Transportation (TxDOT) Reference Marker database, and the crash data (1997–2001) was from the Texas Department of Public Safety. A series of Negative Binomial regression models were fitted to explore the relationship between crash frequencies and explanatory factors such as Average Daily Traffic (ADT), left shoulder width, barrier offset, median (with shoulder) width, and pole density. The AMFs were estimated directly from the coefficients of the models.

Bonneson and Pratt [*28*] conducted a case-control study to develop AMFs by using cross-sectional data. They selected roadway segment pairs with similar site characteristics for AMF development. For each segment pair, the only differences between the two segments were associated with the AMF variables. Similar to the before-after models (Gross et al.) [*19*], this case-control method is difficult to apply because of the limited number of matched pairs.

Li et al. [*29*] applied a generalized additive model for estimating AMFs. The data was collected from 123 segments of rural frontage roads in Texas. It was concluded the generalized additive model is flexible in characterizing the joint safety effects of explanatory variables such as roadway geometry and operational features, whose safety effects were modeled separately and assumed independent in most other studies. Their results suggest that changes in lane and shoulder widths are not linearly related to crash risk.

Another study by Washington et al. [*7*] investigated the AMFs for left-turn lane on major road, right-turn lane on major road, intersection skew, and sight distance based on expert judgment and previous research findings. They concluded that none of the AMFs have any significant safety impact on signalized intersections on two-lane roads. The magnitudes of their derived AMFs are similar to those developed by Harwood et al. [*13,30*]. The AMF for intersection skew was found to be significant for three- and four-approach stop-controlled intersections with two lanes for minor road and four lanes for major road. Also, the AMF for right-turn lane on major road was found to be significant for four-approach stop-controlled intersections with two lanes on minor road and four lanes on major road.

2.3. Calibrating the Calibration Factor for Intersections

The calibration factor C_i (see Eq. 12-1 in the 2010 HSM) is introduced to account for jurisdiction-specific characteristics that are difficult to incorporate into either SPFs or CMFs. However, they may have a significant impact on intersection safety. These jurisdiction-specific characteristics may include crash reporting procedures, driver population, and weather.

Dixon et al. [*31*] conducted a study to calibrate the calibration factors for Oregon DOT. The types of facilities they considered included road segments and intersections on rural two-lane, two-way roads, rural multilane highways, and urban and suburban arterials. The sample sizes they chose for intersections ranged from 25 to 200. They used a sample size of 200 for rural stop-controlled intersections because of their low crash frequencies. The historical crash frequency data from 2004 to 2006 was used in the calibration. In their study, some of the selected intersections did not have AADT data available for minor streets. Dixon et al. adopted the method proposed by Mohamad et al. [*32*] to estimate the minor-approach AADT ($AADT_{minor}$) for rural intersections. For urban intersections, the missing $AADT_{minor}$ data was obtained by multiplying the known major-approach ($AADT_{major}$) with a factor. The authors also recommended that local crash type proportions be used in predicting crashes of different types.

Srinivasan and Carter [*33*] calibrated the SPFs for rural and urban/suburban roadway segments and intersections for North Carolina DOT. The Srinivasan and Carter study concluded that the need to develop jurisdiction-specific SPFs or not may depend on how the SPFs will be applied. For network screening purpose, it is sufficient to calibrate the calibration factors. However, it is better to develop jurisdiction-specific SPFs for project-level applications in order to obtain accurate crash predictions. Srinivasan et al. [*34*] also calculated the calibration factors for rural and urban/suburban roadway segments and intersections in Florida. In their study, the default CMFs and collision-type distributions in the HSM were used.

2.4. Sample Size

The HSM recommends that calibrating the calibration factors should include data from a minimum of 30 to 50 sites of each facility type. These sites should be selected randomly from eligible facilities without intentionally considering their crash frequencies or traffic volumes. For each facility type, the selected sites collectively should represent at least 100 crashes per year. Otherwise, additional sites should be included. Moreover, all available sites should be selected if the study area has fewer than 30 sites for a specific facility type. The sample selection should consider the geographical and weather characteristics of the study area. If these characteristics change substantially across the area, it may be necessary to separate the study area into subareas and develop different calibration factors for each one of them.

For the selected sites, the HSM recommends that crash data from one, two, or three full calendar years be used for calculating the calibration factors. For example, Dixon et al. [*31*] used a total of 227 intersections to calibrate the calibration factors for urban and suburban arterial intersections in Oregon. As shown in Table 4, they selected approximately 50 intersections for 3SG, 4ST, and 4SG, respectively. The sample size was increased to 73 for 3ST (i.e., 3-approach stop-controlled intersections) to ensure that there were at least 100 crashes per year. In a study for North Carolina DOT, Srinivasan and Carter [*33*] selected 246 urban and suburban arterial intersections for calibrating the calibration factors. A breakdown of the selected intersections for their study is also shown in Table 4. Another study by Srinivasan et al. [*34*] for Florida DOT calibrated the calibration factors for signalized intersections only. They included 45 3SG and 121 4SG intersections.

Table 4 - Summary of Sample Sizes Used in Previous Studies

Type of Study	Area	3ST	3SG	4ST	4SG	Total
Developing New SPFs by MRI	Minnesota	36	34	48	64	182
	North Carolina	47	42	48	44	181
	Combined	87	78	96	111	372
Calibrating Calibration Factor	North Carolina DOT	73	31	20	122	246
	Oregon DOT	73	48	49	57	227
	Florida DOT	--	45	--	121	166

The sample size requirement for developing new SPFs is different, as the 2010 HSM does not include a recommended sample size for developing new SPFs. A study by the Midwest Research Institute (MRI) [*3*] included a selection of 182 intersections from the Twin Cities metropolitan area, Minnesota, and 181 intersections from Charlotte, North Carolina. A breakdown of these intersections by type is again provided in Table 4. These intersections were used to fit two sets of SPFs for Minnesota and North Carolina, respectively. The Minnesota and North Carolina data were combined to fit a third set of SPFs. These models were the basis for the urban and suburban arterial intersection SPFs in the 2010 HSM. Based on the sample sizes for Minnesota and North Carolina in Table 4, a sample of at least 50 intersections for each intersection type seems to be necessary for developing new SPFs.

In a 2013 report by Srinivasan et al. [*10*], it was recommended that larger sample sizes should be considered when developing jurisdiction-specific SPFs, as compared to simply calculating the calibration factors. For developing new SPFs, Srinivasan et al. recommended a sample of 100 to 200 intersections with at least 300 crashes per year. Obviously, more time and effort will be needed to develop jurisdiction-specific SPFs. However, the study by Midwest Research Institute [*3*] suggests that a smaller sample size (e.g., 50 intersections) may also work. For this research, our strategy was to start with a sample size of 50 for each intersection type. Based on the initial model-fitting results, additional intersections could be included if necessary.

2.5. Summary of Literature Review

This literature review covers four main topics that are important to this research: (1) calibrating/developing SPFs; (2) calibrating CMFs; (3) calibrating the calibration factor; and (4) sample size selection. This literature review found that Negative Binomial regression models were often considered when developing new SPFs. A reasonable approach is to calculate the calibration factor first. If a calibration factor is significantly different from 1.0, a new SPF in general should be developed for the corresponding facility type.

When calibrating/developing SPFs, an important issue is how to properly handle panel crash data (i.e., multiple years of data from the same intersection). Based on the review, mixed- and random-effects models were typically used to address this issue. The review results also suggest that a sample of at least 50 intersections for each intersection type is necessary for calibrating/ developing SPFs. Additional intersections will be included if the total number of crashes cannot meet the minimum HSM standard (at least 100 crashes/year) or the model fitting results are unsatisfactory. Similar to calibrating/developing SPFs, calibrating CMFs often requires a large sample size. To the best of our knowledge, no state DOTs have conducted CMF calibration studies.

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3.0 Methodology

This chapter first provides an overview of the SPFs and the safety modeling procedures for urban and suburban arterial intersections in the 2010 HSM. Such an overview makes this report self-contained and helps readers understand the discussions in Chapters 4 through 7. Since the HSM safety predictive models urban and suburban arterial intersections are all based on Negative Binomial regression, this chapter also includes a summary of the Negative Binomial regression model.

3.1. SPFs for Urban and Suburban Arterial Intersections in the HSM

The *Highway Safety Manual* (HSM) was initially published by AASHTO in 2010. It includes a series of methods for predicting crash frequencies for different transportation facilities. The method for urban or suburban arterial intersections is given in Eqs. (1) and (2):

$$N_{predicted\_int} = C_i \times \left(N_{bi} + N_{pedi} + N_{bikei}\right) \quad (1)$$
$$N_{bi} = N_{spf\_int} \times (CMF_{1i} \times CMF_{2i} \times \cdots \times CMF_{6i}) \quad (2)$$

where,

$N_{predicted\_int}$ = final predicted average crash frequency of an intersection for a selected year;
N_{bi} = predicted average crash frequency of an intersection (excluding vehicle-pedestrian and vehicle-bicycle collisions);
N_{pedi} = predicted average crash frequency of vehicle-pedestrian collisions;
N_{bikei} = predicted average crash frequency of vehicle-bicycle collisions;
N_{spf_int} = predicted average crash frequency of an intersection (excluding vehicle-pedestrian and vehicle-bicycle collisions) satisfying the base conditions defined in the HSM;
$CMF_{1i}, \cdots, CMF_{6i}$ = intersection crash modification factors; and
C_i = calibration factor for use in a particular geographical area.

N_{spf_int} in Eq. (2) is often referred to as the Safety Performance Function (SPF). In this particular case, this SPF predicts the average crash frequency involving only vehicles for an intersection under the base conditions defined in the HSM. To account for intersections that do not satisfy the base conditions, a set of CMFs is provided in the HSM. As shown in Eq. (2), the original average crash frequency, N_{spf_int}, is multiplied by these CMFs to adjust for those non-base conditions. In the 2010 HSM, N_{spf_int} is separated into N_{bimv} and N_{bisv} as shown in Eq. (3), and they are further described in Eq. (4). Two different sets of SPFs are provided for N_{bimv} and N_{bisv} in the HSM [*1*], respectively. Each set consists of SPFs for 3ST, 3SG, 4ST, and 4SG intersections.

$$N_{spf\ int} = N_{bimv} + N_{bisv} \tag{3}$$

where,

N_{bimv} = predicted average number of multiple-vehicle collisions for base conditions; and

N_{bisv} = predicted average number of single-vehicle collisions for base conditions.

The SPFs for urban and suburban arterial intersections in the HSM cover four types of collisions: multiple-vehicle, single-vehicle, vehicle-pedestrian, and vehicle-bicycle collisions. For example, the SPF for collisions involving only vehicles is described in Eq. (4) [*1*], in which N_{spf_int} can represent the predicted crash frequency for either multiple-vehicle or single-vehicle intersection-related collisions.

$$N_{spf\_int} = exp(a + b \times ln\left(AADT_{maj}\right) + c \times l\,n(AADT_{min}) \tag{4}$$

where,

$N_{spf\ int}$ = predicted average crash frequency for base conditions;

$AADT_{maj}$ = average daily traffic volume for major road (both directions of travel combined), vehicle/day;

$AADT_{min}$ = average daily traffic volume for minor road (both directions of travel combined), vehicle/day; and

a, *b*, *c* = regression coefficients.

A basic assumption for the SPF in Eq. (4) is that the number of collisions (y) at an intersection is a random variable following Negative Binomial distribution. The expected value of y is characterized by Eq. (4). Based on this Negative Binomial assumption and the crash frequencies and site characteristics (e.g., traffic volume) of intersections, regression coefficients *a*, *b*, *c* can be determined, and so does the corresponding SPF.

For vehicle-pedestrian collision modeling (N_{pedi} in Eq. (1)), signalized and stop-controlled intersections are treated differently. For signalized intersections, a set of Negative Binomial SPFs and three CMFs are defined in the HSM. While for stop-controlled intersections, the number of vehicle-pedestrian collisions is estimated by multiplying N_{bi} (see Eq. (2)) with a pedestrian crash adjustment factor f_{pedi}. For vehicle-bicycle collisions (N_{bikei} in Eq. (1)), both signalized and stop-controlled intersections are treated in the same way. The number of vehicle-bicycle collisions per year for an intersection is estimated by multiplying N_{bi} with a bicycle crash adjustment factor f_{bikei}.

For multiple-vehicle and single-vehicle crashes, separate SPFs are provided for total, fatal and injury (FI), and property-damage-only (PDO) crashes. While for vehicle-pedestrian crashes at signalized intersections, SPFs are provided only for total crashes. This is mainly because vehicle-pedestrian crashes are rarer events than multiple-vehicle and single-vehicle crashes. If they are separated by crash injury types (e.g., FI and PDO crashes), there will be many zero observations. This makes it difficult to fit statistically meaningful models. A large sample size may help address this issue. However, increasing the sample size will be costly and time-consuming.

There are many SPFs defined in the HSM for different types of transportation facilities. Such SPFs can be applied to determine the expected safety impacts of design changes, identify locations with disproportionately high crash frequencies, and evaluate the effects of engineering treatments. Depending on the type of facilities being modeled, the required covariates can include a variety of site characteristics such as traffic volume, lane width, shoulder width, presence of turn lanes, and traffic control.

There are four sets of SPFs included in the HSM for 3ST, 3SG, 4ST, and 4G intersections. Using these SPFs and the CMFs (see Eq. (2)), the total number of predicted crashes can be obtained for each intersection type. Given the total number of observed crashes for the same intersection type, the corresponding calibration factor can be calculated using Eq. (5). If this factor is significantly greater or less than one, it would be desirable to develop a new SPF using local data.

$$C_r(\text{or } C_i) = \sum\nolimits_{\text{all sites}} \text{observed crashes} / \sum\nolimits_{\text{all sites}} \text{predicted crashes} \tag{5}$$

3.2. Negative Binomial Regression Model

This section introduces the Negative Binomial regression model. Assume that the crash data for an intersection consists of n records $\{(\boldsymbol{x_1}, y_1), \dots, (\boldsymbol{x_i}, y_i), \dots, (\boldsymbol{x_n}, y_n)\}$, where $\boldsymbol{x_i}$ is a vector representing the crash-related characteristics of intersection i, and y_i is the corresponding number of crashes reported at this intersection. A typical Negative Binomial regression model is given by Eqs. (6)–(9) (see also Miaou) [*35*].

$$Pr(Y_i = y_i) = \frac{\Gamma(y_i+\phi)}{\Gamma(y_i+1)\Gamma(\phi)} \left(\frac{\mu_i}{\mu_i+\phi}\right)^{y_i} \left(\frac{\phi}{\mu_i+\phi}\right)^{\phi} \tag{6}$$

$$E(Y_i) = \mu_i = g(\boldsymbol{x_i}) \tag{7}$$

$$Var(Y_i) = \mu_i + \frac{\mu_i^2}{\phi} \tag{8}$$

where,

Y_i = independent and identically distributed Negative Binomial random variable;
y_i = reported number of crashes at intersection $(i = 1,2, \dots, n)$;
ϕ = inverse dispersion parameter of Negative Binomial distribution;
μ_i = expected number of crashes for intersection i; and
$g(\boldsymbol{x_i})$ = functional form of Negative Binomial regression model (i.e., SPF).

If the inverse dispersion parameter $\boldsymbol{\phi}$ is large enough (or the over-dispersion parameter $\boldsymbol{k = 1/\phi}$ is small enough), a Poisson regression model can be used instead of the Negative Binomial model. For successful applications of the Negative Binomial regression model, one important thing is to find an appropriate functional form (also called SPF in this study and in the HSM). The following SPF is used for both multiple-vehicle and single-vehicle crashes in the HSM.

$$\boldsymbol{\mu_i = \exp\left(a + b \times ln\left(AADT_{maj}\right) + c \times ln(AADT_{min})\right)} \tag{9}$$

where $AADT_{maj}$ is the total AADT for major approaches and $AADT_{min}$ is the total AADT for minor approach(es). By taking the logarithm on both sides of Eq. (9), one can have Eq. (10). Thus, for the SPF in Eq. (9), the relationship between the natural logarithm of the expected number of crashes ($ln(\mu_i)$) and other explanatory variables (e.g., $ln\left(AADT_{maj}\right)$) is assumed to be linear.

$$\boldsymbol{ln(\mu_i) = a + b \times ln\left(AADT_{maj}\right) + c \times ln(AADT_{min})} \tag{10}$$

For this study, three years of crash and traffic data were collected from each intersection. It is likely that crash counts for the same intersection in different years are correlated. Therefore, a mixed-effects Negative Binomial regression model was considered in this project. Based on the SPF in Eq. (10) and the collected data, both Negative Binomial and mixed-effects Negative Binomial regression models were fitted.

4.0 Data Collection and Preliminary Data Analysis

The data collection conducted for this research primarily consisted of the following five tasks: sample size determination, intersection selection, data request, field data collection, and preliminary data analysis. Once the sample size was determined, qualified intersections on urban and suburban arterials in Massachusetts were selected randomly. From the selected intersections, the following data in the period of 2009–2012 was either requested or collected by the research team. The data needed for this research are summarized below and are also listed in Figure 1. Data items 1-3 and 7 were used to determine CMFs. The remaining data items were used for evaluating the SPFs in the HSM and for developing new SPFs.

1. Locations of schools within 1,000 feet of the selected intersections.
2. Locations of bus stops within 1,000 feet of the selected intersections.
3. Locations of alcohol sales establishments within 1,000 feet of the selected intersections.
4. Annual Average Daily Traffic (AADT) data for major and minor approaches of each intersection. This required turning movement count data and expansion factors.
5. Pedestrian volume.
6. Numbers of single-vehicle, multiple-vehicle, vehicle-pedestrian, vehicle-bicycle, fatal and injury, and property-damage-only crashes at each intersection.
7. Detailed intersection-related data for calculating Crash Modification Factors (CMFs) for vehicle-pedestrian crashes.

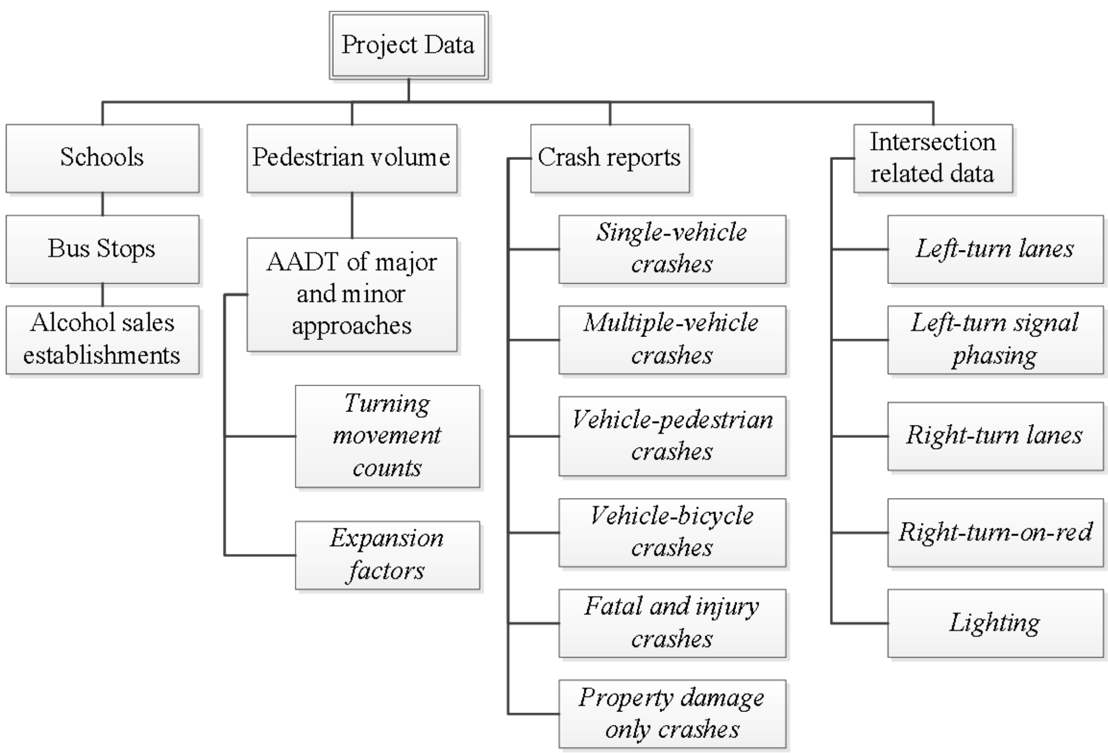


Figure 1 - Summary of Data Collection.

4.1. Sample Size Determination and Intersection Selection

Based on the review of the HSM and relevant studies (see Section 2.4), a two-step approach was adopted for intersection selection. For each of the four intersection types, a sample of approximately 50 intersections was initially selected. Based on the data analysis results, additional intersections would be included as needed.

In Massachusetts, most intersections are maintained by local governments. Roughly 10% of them are maintained by the state DOT (i.e., MassDOT). Since local governments and MassDOT may have different maintenance standards and frequencies, it is necessary to evaluate the potential impact of such maintenance differences on intersection safety performance. If a significant impact exists, two different sets of SPFs or calibration factors may need to be developed for MassDOT and locally maintained intersections, respectively. For this purpose, approximately 15 of the 50 intersections were selected from state-maintained sites, and the remaining ones were from locally maintained sites.

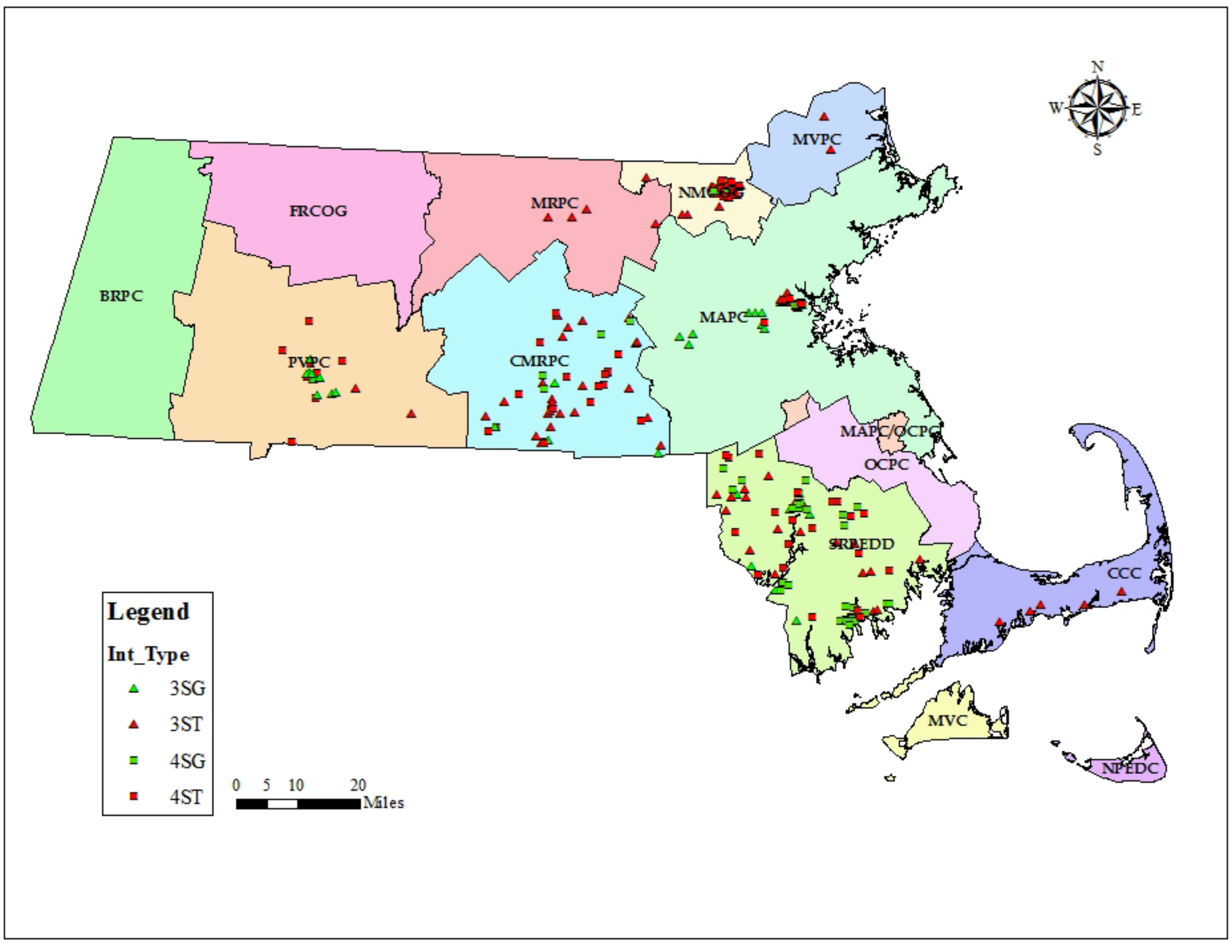


Figure 2 - Selected Intersections in Massachusetts.

An ideal intersection selection procedure is to perform completely random selections. Using 3SG as an example, all qualified 3SG on Massachusetts urban/suburban arterials are identified first. A sample is then drawn from these 3SG, such that each of them has the same probability to be chosen. This method can be costly and time-consuming, because the research team needs to travel to those selected intersections scattered all over the region to collect data (e.g., lane configuration). Also, some cities in Massachusetts do not have well-documented crash reports. Therefore, it would be better to exclude intersections in those cities from the data collection. Given these considerations, the research team identified several representative cities and regions (shown in Figure 2) with well-documented crash reports and selected intersections randomly from them.

For calibrating SPFs, it is desirable to select intersections satisfying the base conditions defined in the HSM. This requirement was relaxed during the data collection, since it was difficult to find enough such intersections. Due to this relaxation, a slightly different approach described in the HSM (see Volume 2, Page A-10) was taken to calibrate SPFs. The following six criteria were considered during the intersection selection:

1. Intersections should not have one-way approaches.
2. Intersections must be on urban or suburban arterials.
3. Intersections must be within urban boundaries.
4. For 3ST and 4ST, only minor streets can be controlled by stop signs.
5. Intersections should not have geometry and traffic control changes during the data collection period.
6. Intersections with available AADT during the data collection period would be preferred.

The following data (as described in Table A-2 in Part C of the HSM) was either collected or estimated for the intersections selected.

1. Two-way AADTs of the major ($AADT_{maj}$) and minor ($AADT_{min}$) streets.
2. Pedestrian volumes.
3. Observed crash data (including police reports).
4. Intersection geometric design features (e.g., number of approaches, number of left-turn lanes, number of right-turn lanes).
5. Traffic control features (e.g., type of traffic control, left-turn signal phasing, right-turn-on-red).
6. Site characteristics (e.g., intersection lighting, number of bus stops, number of schools, number of alcohol sales establishments).

Based on the intersections initially selected, it was found that there were less than 100 crashes per year for 3ST and 4ST. Therefore, the sample sizes for 3ST and 4ST were increased. Finally, 245 intersections were selected, as summarized in Table 5. Table 6 lists the cities where intersections were selected from. To see if there was any significant difference in safety performance between state and locally maintained intersections (due to different maintenance standards and frequencies), approximately 30% of the intersections were selected from state-maintained sites. Table 5 only summarizes the number of intersections of each type in different planning commissions of Massachusetts. A detailed list of these intersections with their names and locations can be found in Appendix A.

Table 5 - Summary of Intersections Selected

Study Areas		**Intersection Type**				
		3SG	**3ST**	**4SG**	**4ST**	**Total**
Cape Cod Commission (CCC)	*Local*	0	5	0	0	5
	State	0	0	0	0	0
	Subtotal	0	5	0	0	5
Central Massachusetts Regional Planning Commission (CMRPC)	*Local*	2	12	1	11	26
	State	4	9	4	6	23
	Subtotal	6	21	5	17	49
Metropolitan Area Planning Council (MAPC)	*Local*	14	10	11	6	41
	State	2	0	0	0	2
	Subtotal	16	10	11	6	43
Montachusett Regional Planning Commission (MRPC)	*Local*	0	3	0	0	3
	State	0	1	0	0	1
	Subtotal	0	4	0	0	4
Merrimack Valley Planning Commission (MVPC)	*Local*	0	2	0	0	2
	State	0	0	0	0	0
	Subtotal	0	2	0	0	2
Northern Middlesex Council Of Governments (NMCOG)	*Local*	8	18	5	9	40
	State	1	1	2	0	4
	Subtotal	9	19	7	9	44
Pioneer Valley Planning Commission (PVPC)	*Local*	6	3	0	7	16
	State	3	0	0	0	3
	Subtotal	9	3	0	7	19
Southeastern Regional Planning and Economic Development District (SRPEDD)	*Local*	4	14	20	7	45
	State	4	8	9	13	34
	Subtotal	8	22	29	20	79
Total	*Local*	**34**	**67**	**37**	**40**	**178**
	State	**14**	**19**	**15**	**19**	**67**
	Subtotal	**48**	**86**	**52**	**59**	**245**

Table 6 - Cities from Which Intersections Were Selected

Study Area	Cities
Cape Cod Commission (CCC)	Barnstable, Harwich, Mashpee, Yarmouth
Central Massachusetts Regional Planning Commission (CMRPC)	Auburn, Blackstone, Charlton, Dudley, Grafton, Holden, Mendon, Millbury, Oxford, Leicester, Northborough, Shrewsbury, Southbridge, Sturbridge, Sutton, Upton, Webster, Westborough, West Boylston, Worcester
Metropolitan Area Planning Council (MAPC)	Cambridge, Framingham, Newton
Montachusett Regional Planning Commission (MRPC)	Ayer, Fitchburg, Lunenburg, Westminster
Merrimack Valley Planning Commission (MVPC)	Georgetown, Haverhill
Northern Middlesex Council Of Governments (NMCOG)	Chelmsford, Lowell, Pepperell, Tewksbury, Westford
Pioneer Valley Planning Commission (PVPC)	Chicopee, Holyoke, Ludlow, Monson
Southeastern Regional Planning and Economic Development District (SRPEDD)	Attleboro, Berkley, Dartmouth, Dighton, Fairhaven, Fall River, Lakeville, Mattapoisett, Middleborough, New Bedford, North Attleboro, Norton, Raynham, Rehoboth, Rochester, Somerset, Seekonk, Swansea, Taunton, Wareham, Westport

4.2. Data Collection

4.2.1. Turning Movement Count and AADT

The Turning Movement Counts (TMCs) for some of the selected intersections were provided by local transportation agencies. The remaining intersections' TMCs were collected by the research team. Based on the TMCs and some expansion factors, AADT values for major and minor approaches were estimated. The detailed AADT estimation method is described in Section 5.1.

Table 7 and Table 8 provide basic descriptive statistics of the estimated AADT and other intersection-related data for stop-controlled and signalized intersections, respectively. The major and minor AADT values are also plotted in Figure 3. To apply the HSM models for urban and suburban arterial intersections, the AADT values for major and minor intersections should not be substantially greater than the values shown in Table 9. A further examination of the AADT values in Table 7, Table 8, and Figure 3 suggests that this requirement in general has been met.

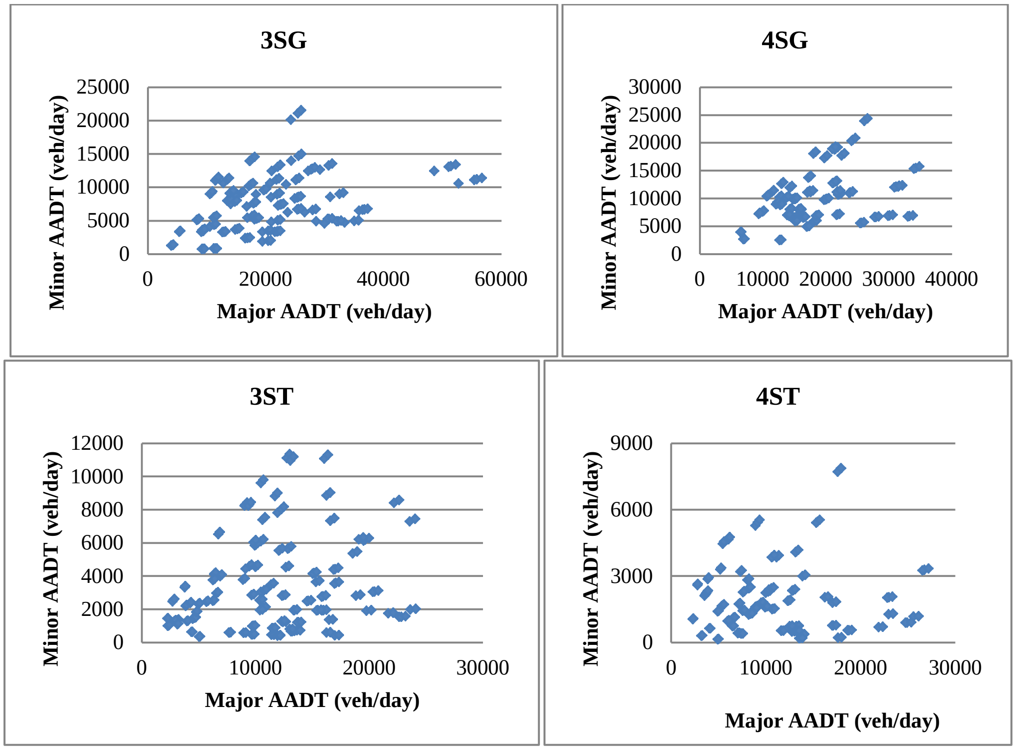


Figure 3 - Estimated Major and Minor AADT Values.

Table 7 - Descriptive Statistics of Stop-Controlled Intersections

Approach/Intersection (unit: vehicles/day)	3ST				4ST			
	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max
Major	11656	5467	2268	24115	11134	6126	2293	27173
Minor	3562	2848	359	11348	1972	1533	154	7878

Table 8 - Descriptive Statistics of Signalized Intersections

Approach/Intersection (unit: vehicles/day)	3SG				4SG			
	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max
Major	20588	10335	3981	56745	18501	6553	6465	34846
Minor	7517	4212	761	21532	10359	4593	2507	24376

Table 9 - Maximum AADT Values for the HSM Models

Approach/Intersection (unit: vehicles/day)	3ST	4ST	3SG	4SG
Major	45700	46800	58100	67700
Minor	9300	5900	16400	33400

4.2.2. School, Bus Stop, and Alcohol Sales Establishment

The school data was obtained from the MassGIS website [*36*] and includes pre-kindergartens through high schools. The types of schools included in the data set are public, private, charter, collaborative programs, and approved special education programs. In addition to pre-kindergartens through high schools, the research team also collected locations of colleges and universities [*36*]. All school data sets were provided in ESRI shapefile format. The bus stop data was obtained from the MassDOT website [*37*] in ESRI shapefile format.

Two sets of alcohol sales establishment data were obtained from the Massachusetts Alcoholic Beverages Control Commission (ABCC). The first set was for alcohol sales establishments that sell beverages to be consumed at point of sale (licensed under M.G.L. c. 138, §12). The second set was for alcohol sales establishments that sell beverages not to be consumed at point of sale (licensed under M.G.L. c. 138, §15). In the HSM, it is not mentioned explicitly whether both types of alcohol sales establishments should be considered, or only those licensed under M.G.L. c. 138, §12. Therefore, both sets of data were kept and geocoded using ArcGIS. The research team developed an address locator using the road network data obtained from the United States Census Bureau website [*38*] to geocode the alcohol sales establishment data with the assistance of Google Maps.

Buffer and spatial join tools in ArcGIS were used to determine how many schools, bus stops, and alcohol sales establishments were within 1,000 feet of each selected intersection. The detailed analysis results have been documented in *Report #3 - Data Collection and Preliminary Data Analysis* and are not duplicated in this report.

4.2.3. Pedestrian Traffic Volume

The pedestrian traffic volume data was collected during the TMC data collection trips. Table 10 lists some descriptive statistics of the pedestrian data. It can be seen that the average hourly pedestrian counts for signalized intersections are higher than those for stop-controlled intersections, which is not surprising. Similar to the conversion from TMC to AADT data, the short-duration pedestrian count data was expanded to daily pedestrian count data, which is an important input to the HSM SPFs for predicting vehicle-pedestrian crashes at signalized intersections. The pedestrian data expansion method is detailed in Section 5.2.

Table 10 - Basic Descriptive Statistics of Hourly Pedestrian Count Data

Intersection Type	Mean	Std. Dev.	Min	Max
3SG	41.7	21.3	5	78
3ST	25.5	19.3	3	77
4SG	36.7	15.9	16	56
4ST	25.9	19.5	5	74

4.2.4. Crash Data

Based on the HSM, crashes that occurred in *Zone A* (see Figure 4) or within 250 feet from the center of an intersection are usually intersection related.

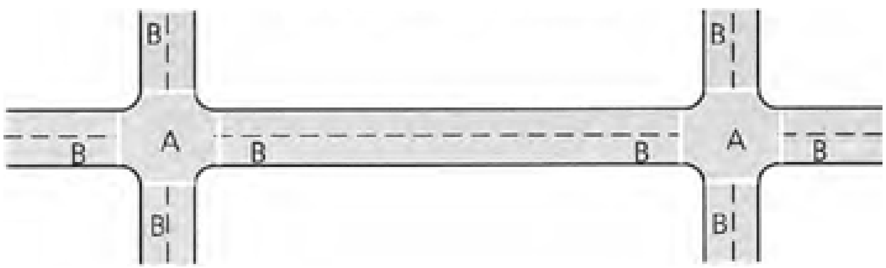


Figure 4 - Definition of Intersection Related Crashes.

In practice, a 250-foot circular buffer can be created around each selected intersection using GIS. Crashes within these buffers are then selected. However, some of these crashes could be caused by adjacent driveways but were geocoded to intersections due to their proximities. Therefore, the research team requested the police reports for all crashes that occurred within 250 feet of the selected intersections from 2010 to 2012. Based on the preliminary data analysis results, crash reports for 3SG in 2009 were also requested to improve the model fitting for 3SG. Each of these police reports was reviewed to determine whether the corresponding crashes were intersection related. Based on the guidelines in the HSM [*1*], the review of crash reports was conducted using the following rules:

1. A crash is likely to be intersection related if:
   - It occurred within the curb line limits of an intersection;
   - It was a rear-end crash and occurred on the approach to an intersection; and
   - It was indicated to be caused by a signal malfunction or improper traffic control at the intersection.
2. A crash report typically includes a field that allows the reporting officer to designate the crash as intersection related. This information can help reviewer make a decision;
3. Other fields on a crash report, such as collision type, number of vehicles involved, contributing circumstances, weather condition, pavement condition, and traffic control malfunction, could provide helpful information in making a decision.
4. The following crashes might not be considered as intersection-related: collisions related to driveways; and single-vehicle run-off-the-road crashes.

Distribution of Crashes by Type

The crash reports were reviewed twice and identified 2,426 intersection-related crashes. Table 11 lists the number of crashes by type (e.g., multiple-vehicle crashes and single-vehicle crashes). Among them, the numbers for 3SG reflect crashes occurring in 2009–2012. For the remaining intersection types, the numbers pertain to crashes that occurred in 2010–2012. As the data suggests, 4SGs have the highest average crashes per intersection for almost all crash types. The last two columns in Table 11 show the distributions for all crashes. The results for state- and locally maintained intersections are presented in Table 12 and Table 13, respectively.

Table 11 - Total Number of Crashes for All Intersections

Crash Type	3ST		3SG		4ST		4SG		All Types	
	Total	Ave	Total	Ave	Total	Ave	Total	Ave	Total	Ave
Multiple-Vehicle	263	3.06	688	14.33	321	5.44	899	17.29	2171	8.86
Single-Vehicle	31	0.36	48	1.00	10	0.17	44	0.85	133	0.54
Vehicle-Pedestrian	6	0.07	15	0.31	5	0.08	27	0.52	53	0.22
Vehicle-Bicycle	10	0.12	16	0.33	3	0.05	40	0.77	69	0.28
All Crashes	310	3.60	767	15.98	339	5.75	1010	19.42	2426	9.90
# of Intersections	86		48		59		52		245	

Table 12 - Total Number of Crashes for State-Maintained Intersections

Crash Type	3ST		3SG		4ST		4SG		All Types	
	Total	Ave	Total	Ave	Total	Ave	Total	Ave	Total	Ave
Multiple-Vehicle	77	4.05	237	16.93	98	5.16	305	20.33	717	10.70
Single-Vehicle	6	0.32	11	0.79	2	0.11	15	1.00	34	0.51
Vehicle-Pedestrian	0	0.00	3	0.21	0	0.00	1	0.07	4	0.06
Vehicle-Bicycle	0	0.00	0	0.00	1	0.05	3	0.20	4	0.06
All Crashes	83	4.37	251	17.93	101	5.32	324	21.60	759	11.33
# of Intersections	19		14		19		15		67	

Table 13 - Total Number of Crashes for Locally-Maintained Intersections

Crash Type	3ST		3SG		4ST		4SG		All Types	
	Total	Ave	Total	Ave	Total	Ave	Total	Ave	Total	Ave
Multiple-Vehicle	186	2.78	451	13.26	223	5.58	594	16.05	1454	8.17
Single-Vehicle	25	0.37	37	1.09	8	0.20	29	0.78	99	0.56
Vehicle-Pedestrian	6	0.09	12	0.35	5	0.13	26	0.70	49	0.28
Vehicle-Bicycle	10	0.15	16	0.47	2	0.05	37	1.00	65	0.37
All Crashes	227	3.39	516	15.18	238	5.95	686	18.54	1667	9.37
# of Intersections	67		34		40		37		178	

To compare the safety performance of state- and locally maintained intersections, a two-sample *t*-test was conducted for each intersection type. The *t*-test results in Table 14 suggest that locally maintained 3SG intersections appear to have lower proportions of fatal and injury crashes than state-maintained ones. For other intersection types, there are no significant differences between state- and locally maintained intersections in terms of proportions for fatal and injury crashes.

Table 14 - Two-Sample *t*-test of State- and Locally Maintained Intersections

Intersection Type	Jurisdiction	Proportion of Fatal & Injury Crashes			
		Average	Local < State	Local ≠ State	Local > State
3SG	Local	0.985	***0.02***	***0.05***	0.98
	State	1.464			
3ST	Local	0.303	0.31	0.63	0.69
	State	0.351			
4SG	Local	1.658	0.52	0.96	0.48
	State	1.644			
4ST	Local	0.700	0.50	0.99	0.50
	State	0.702			

Distribution of Crashes by Manner and Injury Severity

Table 15 lists the distribution of multiple-vehicle crashes by manner (e.g., rear-end) and injury severity (e.g., PDO). As illustrated, the distributions of multiple-vehicle crashes by manner derived by using the Massachusetts data in some cases are significantly different from those in the HSM. For example, the Massachusetts data show significantly lower proportions of *rear-end collision* crashes and higher proportions of *angle collision* crashes for 4ST. Also, the HSM data has a consistently higher proportion of *other multiple-vehicle collision* crashes than the Massachusetts data.

Table 15 - Proportion of Multiple-Vehicle Crashes by Manner and Injury Severity

Manner of Collision	3ST		3SG		4ST		4SG	
	FI	PDO	FI	PDO	FI	PDO	FI	PDO
Massachusetts Data								
Rear-end collision	0.411	0.337	0.580	0.605	0.157	0.185	0.452	0.422
Head-on collision	0.014	0.011	0.034	0.014	0.008	0.015	0.036	0.039
Angle collision	0.562	0.579	0.341	0.265	0.818	0.720	0.492	0.425
Sideswipe	0.014	0.074	0.039	0.116	0.017	0.080	0.020	0.112
Other multiple-vehicle collision	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.002
HSM Data (Table 12-11)								
Rear-end collision	0.421	0.440	0.549	0.546	0.338	0.374	0.450	0.483
Head-on collision	0.045	0.023	0.038	0.020	0.041	0.030	0.049	0.030
Angle collision	0.343	0.262	0.280	0.204	0.440	0.335	0.347	0.244
Sideswipe	0.126	0.040	0.076	0.032	0.121	0.044	0.099	0.032
Other multiple-vehicle collision	0.065	0.235	0.057	0.198	0.060	0.217	0.055	0.211

Table 16 displays the distribution of single-vehicle crashes by manner (e.g., animal) and injury severity level. The HSM and Massachusetts proportions are generally consistent with each other. The HSM data has significantly higher proportions of 3SG and 4ST *noncollision* crashes, while the Massachusetts data has higher proportions of 3ST and 4ST *with other object* crashes.

Table 16 - Proportion of Single-Vehicle Crashes by Manner and Injury Severity

Manner of Collision	3ST		3SG		4ST		4SG	
	FI	PDO	FI	PDO	FI	PDO	FI	PDO
Massachusetts Data								
With parked vehicle	0.000	0.043	0.000	0.053	0.000	0.143	0.000	0.028
With animal	0.000	0.043	0.000	0.000	0.000	0.286	0.000	0.028
With fixed object	0.625	0.870	0.900	0.895	0.667	0.571	0.625	0.861
With other object	0.125	0.043	0.000	0.026	0.000	0.000	0.000	0.056
Other single-vehicle collision	0.000	0.000	0.000	0.026	0.000	0.000	0.125	0.028
Noncollision	0.250	0.000	0.100	0.000	0.333	0.000	0.250	0.000
HSM Data (Table 12-13)								
With parked vehicle	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.001
With animal	0.003	0.018	0.001	0.003	0.001	0.026	0.002	0.002
With fixed object	0.762	0.834	0.653	0.895	0.679	0.847	0.744	0.870
With other object	0.090	0.092	0.091	0.069	0.089	0.070	0.072	0.070
Other single-vehicle collision	0.039	0.023	0.045	0.018	0.051	0.007	0.040	0.023
Noncollision	0.105	0.030	0.209	0.014	0.179	0.049	0.141	0.034

Instead of proportions, Table 17 and Table 18 show the numbers of multiple- and single-vehicle crashes, respectively, by manner and injury severity level. The same information for vehicle-bicycle and vehicle-pedestrian crashes is provided in Table 19. Obviously, Table 15 and Table 16 can be calculated based on Table 17 and Table 18, respectively.

Table 17 - Number of Multiple-Vehicle Crashes by Manner and Injury Severity

Manner of Collision	3ST		3SG		4ST		4SG	
	FI	PDO	FI	PDO	FI	PDO	FI	PDO
Rear-end collision	30	64	119	292	19	37	113	274
Head-on collision	1	2	7	7	1	3	9	25
Angle collision	41	110	70	128	99	144	123	276
Sideswipe	1	14	8	56	2	16	5	73
Other multiple-vehicle collision	0	0	1	0	0	0	0	1
Total	73	190	205	483	121	200	250	649

Table 18 - Number of Single-Vehicle Crashes by Manner and Injury Severity

Manner of Collision	3ST		3SG		4ST		4SG	
	FI	PDO	FI	PDO	FI	PDO	FI	PDO
With parked vehicle	0	1	0	2	0	1	0	1
With animal	0	1	0	0	0	2	0	1
With fixed object	5	20	9	34	2	4	5	31
With other object	1	1	0	1	0	0	0	2
Other single-vehicle collision	0	0	0	1	0	0	1	1
Noncollision	2	0	1	0	1	0	2	0
Total	8	23	10	38	3	7	8	36

Table 19 - Vehicle-Pedestrian and Vehicle-Bicycle Crashes by Manner and Injury Severity

Manner of Collision	3ST		3SG		4ST		4SG	
	FI	PDO	FI	PDO	FI	PDO	FI	PDO
Vehicle-Pedestrian	6	0	11	4	5	0	26	1
Vehicle-Bicycle	8	2	10	6	2	1	30	10
Total	14	2	21	10	7	1	56	11

Other Local Crash Data

Other than the proportions in Table 15Table 15 lists the distribution of multiple-vehicle crashes by manner (e.g., rear-end) and injury severity (e.g., PDO). As illustrated, the distributions of multiple-vehicle crashes by manner derived by using the Massachusetts data in some cases are significantly different from those in the HSM. For example, the Massachusetts data show significantly lower proportions of *rear-end collision* crashes and higher proportions of *angle collision* crashes for 4ST. Also, the HSM data has a consistently higher proportion of *other multiple-vehicle collision* crashes than the Massachusetts data.

Table 15 and Table 16, there are three tables in the HSM that need to be updated using the Massachusetts data. These three tables and their updated values are shown in Table 20 through Table 22. In some cases, the differences between the Massachusetts and the HSM data are quite significant (e.g., the vehicle-bicycle crash adjustment factors in Table 21). Also, the HSM model estimates vehicle-bicycle crashes by applying some adjustment factors (in Table 12-17 of the HSM) to multiple- and single-vehicle crashes. It assumes all predicted vehicle-bicycle crashes to be either fatal or injury crashes. However, the collected Massachusetts crash data suggests that some vehicle-bicycle crashes were PDO crashes (see Table 19).

Table 20 - Vehicle-Pedestrian Crash Adjustment Factors for Stop-Controlled Intersections

Intersection Type	Massachusetts Data	Table 12-16 in HSM
3ST	0.020	0.021
4ST	0.015	0.022

Table 21 - Vehicle-Bicycle Crash Adjustment Factors

Intersection Type	Massachusetts Data	Table 12-17 in HSM
3ST	0.034	0.016
3SG	0.022	0.011
4ST	0.009	0.018
4SG	0.042	0.015

Table 22 - Nighttime Crash Proportions for Unlighted Intersections

Intersection Type	Massachusetts Data	Table 12-27 in HSM
3ST	--	0.238
4ST	0.273	0.229
3SG	--	0.235
4SG	0.214	0.235

Additionally, the HSM model requires the proportions of crashes occurring during night at unlighted intersections. Both the HSM proportions and the corresponding Massachusetts data are provided in Table 22. For the selected Massachusetts intersections, all 3SGs were lighted. Although one 3ST was unlighted, there was no nighttime crash at that intersection during the data collection period. Therefore, no Massachusetts proportions for 3ST and 3SG are provided in Table 22. The Massachusetts proportions for 4ST and 4SG should be interpreted with caution, as only one 4ST and one 4SG were unlighted, and the proportions can be unreliable. Therefore, the HSM nighttime crash proportions were used in this research to determine the corresponding CMFs.

4.2.5. Other Local Data

In addition to traffic and crash data, this research also required intersection traffic control and geometry data, including:

1. Number of approaches with left-turn lane(s).
2. Number of approaches with right-turn lane(s).
3. Left-turn signal phasing (i.e., protected, permitted, and protected plus permitted).
4. Number of approaches with right-turn-on-red prohibited.
5. Whether the intersection is lighted.
6. Whether the intersection has red-light cameras.
7. Maximum number of traffic lanes crossed by a pedestrian.

Data categories 1–6 listed above are for calculating CMFs for multiple- and single-vehicle crashes at all intersections. Data category 7 is used for predicting vehicle-pedestrian crashes at signalized intersections. Since red-light cameras are prohibited in Massachusetts, no data was collected for data item 6. The remaining data were collected in conjunction with the TMC data, using the form shown in Figure 5. The collected data is summarized in Table 23.

Table 23 - Descriptive Statistics of Signalized Intersections

Number of Approaches with	3SG				4SG			
	Mean	**Stdev**	**Min**	**Max**	**Mean**	**Stdev**	**Min**	**Max**
1) left-turn lane(s)	1.03	0.85	0.00	3.00	1.27	1.32	0.00	4.00
2) right-turn lane(s)	0.69	0.71	0.00	2.00	0.48	0.85	0.00	3.00
3) permitted left-turn phases	0.52	0.50	0.00	1.00	2.96	1.33	0.00	4.00
3) protected + permitted left-turn phases	0.29	0.45	0.00	1.00	0.42	0.87	0.00	4.00
3) protected left-turn phases	1.21	0.54	0.00	3.00	0.62	1.15	0.00	4.00
4) prohibited right-turn-on-red	0.52	0.77	0.00	2.00	1.69	1.91	0.00	4.00
	3ST				**4ST**			
	Mean	**Stdev**	**Min**	**Max**	**Mean**	**Stdev**	**Min**	**Max**
1) left-turn lane(s)	0.05	0.21	0.00	1.00	0.03	0.26	0.00	2.00
2) right-turn lane(s)	None of the intersections had right-turn lane(s)							

City: ______________________ Date (mm/dd/yy): ___/___/___

Indicate north in the circle

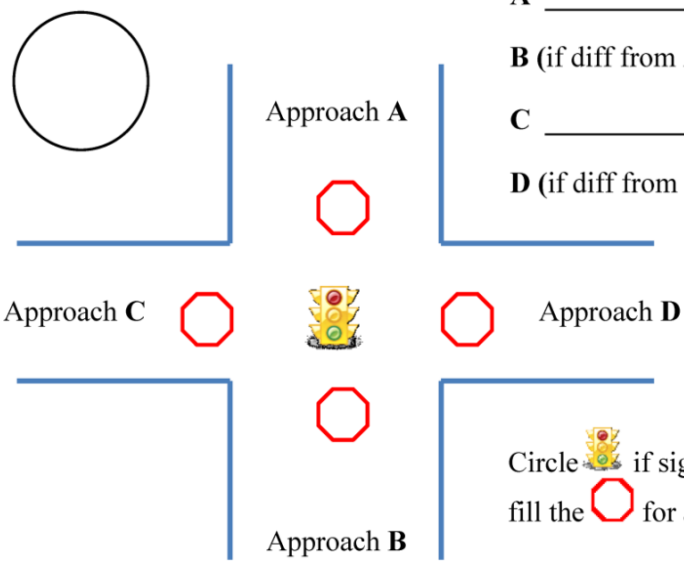
Street Names

A ______________________

B (if diff from **A**) ______________________

C ______________________

D (if diff from **C**) ______________________



Circle [signal icon] if signalized intersection. **Otherwise**, fill the [stop sign icon] for approaches with stop signs

Row #	CMF	CMF Description		Approach A	Approach B	Approach C	Approach D
1	CMF_{1i}	Left turn **prohibited**? (if yes, go to **Row #3**)					
		Left-turn lane(s) indicated by **pavement marking**?					
		Has a **left-turn bay**?					
2	CMF_{2i}	left-turn signal phasing	**Permissive**				
			Protected/permissive				
			permissive/protected				
			Protected				
3	CMF_{3i}	Right turn **prohibited**? (if yes, go to **Row #5**)					
		Intersection right-turn lane(s) indicated by **pavement marking**?					
		Has a **right-turn bay**?					
4	CMF_{4i}	Right-turn-on-red **allowed**?					
5	CMF_{5i}	Intersection **lighted**? Please circle one.		Yes		No	
6	Maximum # of traffic lanes crossed by a pedestrian						
7	Has sidewalk available?						
8	Has marked pedestrian crossing?						
9	Has pedestrian signal?						

Figure 5 - Intersection Data Collection Form.

5.0 Data Processing and Preliminary Data Analysis

To apply the SPFs in the HSM, both AADT and average daily pedestrian traffic volumes are needed. During the data collection process, TMC and pedestrian traffic volumes were collected for a short time period of two to three hours. This chapter describes the methods used to estimate AADT and average daily pedestrian volumes based on the short-duration counts.

5.1. AADT Estimation

Based on the short-duration TMCs, the AADT values for major and minor approaches of each intersection were estimated using a series of expansion factors, including the Daily/Hourly Expansion Factor (DEF/HEF), the Weekly Expansion Factor (WEF), and the Monthly Expansion Factor (MEF). These expansion factors were calculated using the data from the permanent counting stations on major Massachusetts highways. Utilizing the MassDOT Transportation Data Management System (http://mhd.ms2soft.com/tcds/tsearch.asp?loc=Mhd&mod=), a total of 269 permanent counting stations were identified as shown in Figure 6. Each permanent counting station has a set of HEF, WEF, and MEF associated with it.

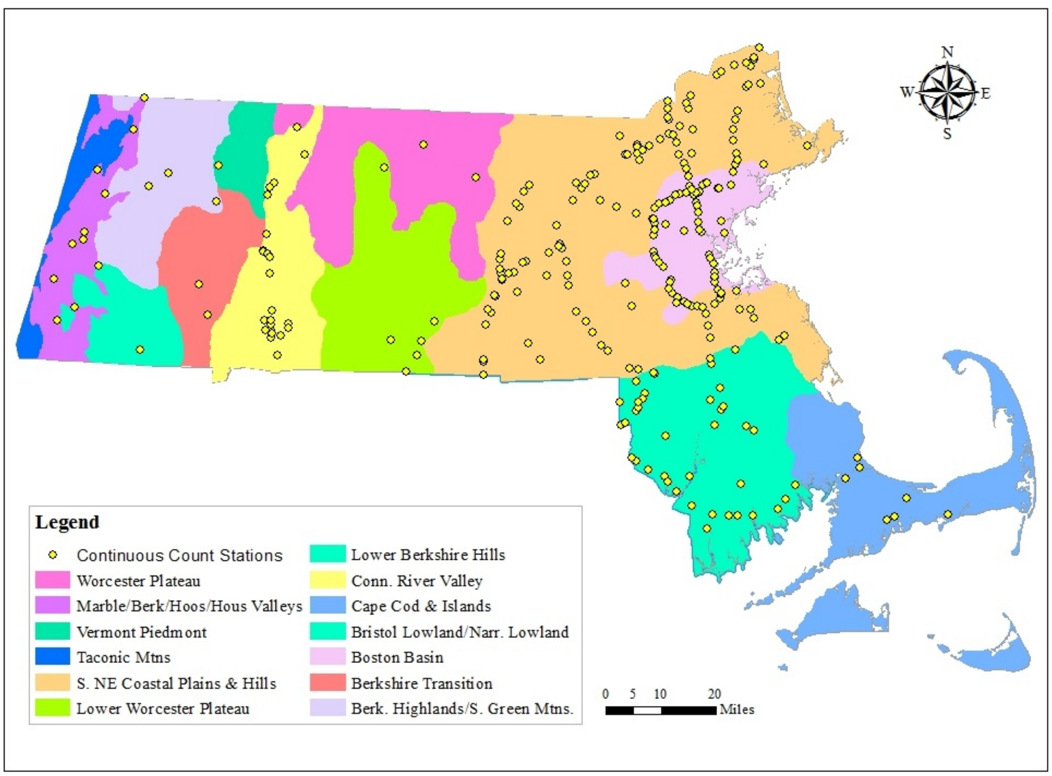


Figure 6 - Permanent Counting Stations in Massachusetts.

To develop expansion factors, this research first divided Massachusetts into different zones. For permanent counting stations in each zone, their expansion factors (i.e., HEF, WEF, and MEF) were averaged. The average expansion factors were applied to intersections in the same zone. Specifically, the research team utilized an ecoregion shapefile (see Figure 6) from the MassGIS website that divides Massachusetts into regions based on geological and climatic characteristics. The background of Figure 6 is color-coded based on these ecoregions. For each permanent counting station, its traffic volume data from 2006 to 2013 was obtained and used to calculate HEF, WEF, and MEF. For permanent counting stations in each ecoregion, their HEFs, WEFs, and MEFs were averaged and applied to all intersections in the same ecoregion for estimating AADT.

Using Eq. (11) below, a short-duration TMC data set collected on day m and month n can be converted into AADT. In Eq. (11), i and j represent the start and end hours of a short-duration TMC data set; $Volume_k$ represents the k^{th} hourly traffic count; HEF_k is the hourly expansion factor for the k^{th} hour; WEF_m represents the weekly expansion factor, $m \in$ (Monday, Tuesday, …, Friday); and MEF_n represents the monthly expansion factor, $n \in$ (January, …, December). This expansion method is also illustrated in Figure 7.

$$AADT = \frac{\sum_{k=i}^{j}(Volume_k/HEF_k)}{j-i+1} \times WEF_m \times MEF_n \qquad (11)$$

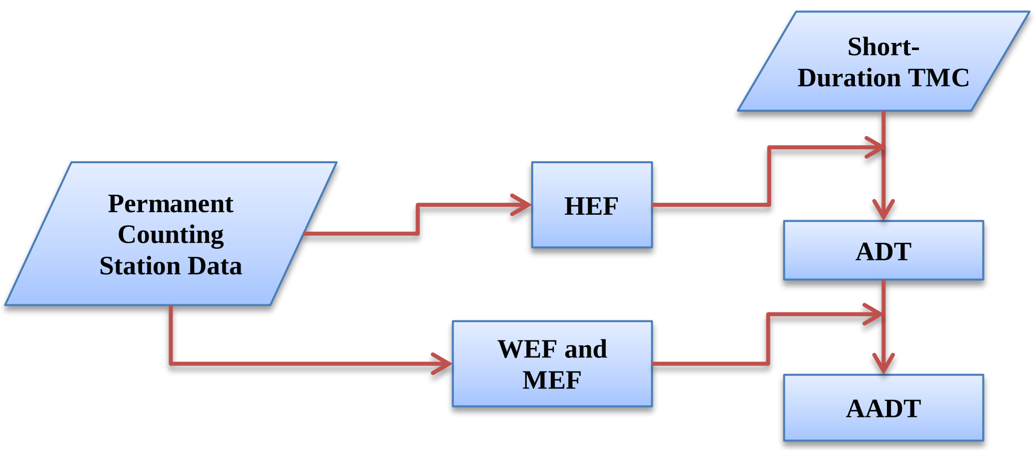


Figure 7 - Estimation of AADT Using Short-Duration Count Data.

Using a short-duration TMC data set collected in 2008 as an example, its 2008 AADT was first estimated using Eq. (11). The AADT values for 2010 to 2012 were then calculated using the corresponding average annual growth rates. For TMC collected in 2014, there were no HEFs, MEFs, and WEFs available in the MassDOT Transportation Data Management System. To solve this problem, average monthly growth rates (e.g., the ratio of July ADT in 2013 to July ADT in 2014) were used to convert the 2014 TMC data into 2013 TMC data of the same month and day. The same method illustrated in Eq. (11) and Figure 7 was then applied to the newly converted TMC data set.

5.2. Average Daily Pedestrian Volume Estimation

Average daily pedestrian volumes are required by the HSM to predict vehicle-pedestrian crashes at signalized intersections. However, the HSM only provides a very simple table to estimate average daily pedestrian volumes. This research collected short-duration pedestrian volumes at some of the selected intersections during the TMC data collection trips. For the remaining selected intersections, TMC data was provided by various local transportation agencies, and these agencies do not have pedestrian volumes available.

Using the collected pedestrian data, the research team developed regression models for predicting hourly pedestrian volumes. These models considered population and employment opportunities within 0.25 miles of an intersection as the covariates. In some previous studies (see Handy, Ivan, and Shriver studies) [*39,40,41*], factors found to be related to pedestrian volumes include population density, median household income, and area type, though median household income was found to be an insignificant factor in Ivan's study [*40*]. In another study, Schneider et al. [*42*] identified four significant covariates for predicting weekly pedestrian volumes. These covariates are the total population within a 0.5-mile radius, number of jobs within a 0.25-mile radius, number of commercial retail properties within a 0.25-mile radius, and the presence of a regional transit station within a 0.1-mile radius of an intersection. Due to the lack of data, the research only considered population and employment opportunities within 0.25 miles of an intersection as the covariates.

Since the HSM vehicle-pedestrian SPFs require average daily pedestrian volumes, the following Eq. (12) was used to convert the observed/predicted hourly pedestrian volumes into average daily pedestrian volumes (see Hocherman et al.) [*43*].

$$Vol_D = Vol_{ijk} \times D_i \times W_j \times S_k \tag{12}$$

where,

Vol_D = Average daily pedestrian volume for a site;
Vol_{ijk} = Short-duration pedestrian volume in hour i, day j of week, and month k;
D_i = Daily expansion factor;
W_j = Weekly expansion factor; and
S_k = Seasonal/monthly expansion factor.

Unlike the TMC data, MassDOT does not have 24-hour pedestrian data for developing the expansion factors (i.e., D_i, W_j, S_k) in Eq. (12). Therefore, a literature review was conducted to identify relevant information. Schneider et al. [*44*] counted one-hour pedestrian volumes at 50 intersections and collected 100 days of pedestrian volume data continuously from 11 of those intersections. Zegeer et al. collected one-hour pedestrian volumes from 2,000 crosswalks to calculate adjustment factors [*45*]. They also collected 8 to 12 hours of pedestrian volumes from 22 crosswalks for the same purpose. Recently, the National Bicycle and Pedestrian Documentation (NBPD) project developed a strategy to expand hourly pedestrian data into daily, weekly, monthly, and yearly pedestrian volumes [*46*]. This strategy has been applied to areas such as Denver, Colorado [*47*]. Among these existing studies, the NBPD study appears to be the most authoritative and comprehensive one. Given the limited time and resources, the research team chose not to develop its own pedestrian adjustment factors and adopted the NBPD method. More information about this method can be found at http://bikepeddocumentation.org/.

The collected short-duration pedestrian counts were initially converted into average daily pedestrian volumes based on the method proposed by the NBPD project. The converted data were then used to develop regression models to predict average daily pedestrian volumes at other intersections, using the population and employment covariates. The employment data was obtained from the Census Transportation Planning Products (http://ctpp.transportation.org/Pages/5-Year-Data.aspx), and the population data was obtained from the 2010 Census. The regression models for signalized intersections are shown in Eq. (13) and the fitted coefficients are presented in Table 24. The predicted average daily pedestrian volumes can be directly used in the HSM SPFs. However, to ensure consistency with the HSM crash predictive method, we matched the predicted pedestrian volume data with those in Table 12-15 in the 2010 HSM, and used the predicted data as a guide to choose from the suggested values in Table 12-15.

$$ln(Vol_D) = a + b \times ln(Pop) + c \times ln(Emp) + \varepsilon \quad (13)$$

where,

Vol_D = Average daily pedestrian volume for an intersection;
Pop = Population within 0.25 miles of the intersection;
Emp = Employment within 0.25 miles of the intersection;
a, b, c = coefficients; and
ε = random term.

Table 24 - Daily Pedestrian Volume Models

Intersection Type	No. of Sites	Regression Coefficients			R^2	Adj. R^2
		Intercept (a)	Population within 0.25 miles (b)	Employment within 0.25 miles (c)		
3SG	23	-4.43	0.76	0.66	0.76	0.74
4SG	8	-5.32	1.09	0.47	0.89	0.85

The HSM method does not require pedestrian volumes for modeling stop-controlled intersections. Nevertheless, the same strategy can be used to develop pedestrian volume models for stop-controlled intersections if needed in the future.

6.0 Model Calibration and Development of New SPFs

The research team initially calculated the calibration factors (C_i in Eq. (1)) for the SPFs in the HSM. The calibrations factors for 3SG and 4SG were found to be much higher than 1.0. Therefore, the coefficients in the HSM SPFs were calibrated using local data. The calibration results show that only the coefficients for multiple-vehicle crash SPFs are statistically meaningful. The coefficients for the remaining SPFs are all statistically insignificant, which is probably due to the small sample sizes and low sample means. To solve this problem, an alternative approach was proposed to predict single-vehicle, vehicle-pedestrian, and vehicle-bicycle crashes. Both the calibrated SPFs for multiple-vehicle crashes and the alternative approach are described in Section 6.1.

When calibrating the SPFs for multiple-vehicle crashes, major- and minor-approach AADTs and the covariates discussed in Section 4.2.5 were considered. The two AADT variables all have statistically significant coefficients. However, the coefficients for some of the remaining covariates are either statistically insignificant or have unreasonable signs. For instance, the CMFs in the HSM suggest that having left-turn lanes will improve 3SG safety. However, in the calibrated SPFs, coefficients for left-turn lane covariates sometimes are positive, suggesting that adding left-turn lanes will increase crash risk. This research adopted Bayesian Negative Binomial regression analysis to address this problem. In this way, safety experts' prior experience (e.g., CMFs in the HSM) can be incorporated into the modeling fitting process. Section 6.2 describes the Bayesian Negative Binomial regression results.

The last section of this chapter presents and compares the calibration factor results, which were calculated using the HSM SPFs and the newly calibrated SPFs based on the Bayesian method. The results suggest that the Bayesian SPFs in general produced calibration factors closer to 1.0 than those factors generated by the HSM SPFs. This is especially true for 3SG and 4SG. Therefore, it is recommended to use the new Bayesian SPFs for modeling urban and suburban arterial intersection safety in Massachusetts.

6.1. Negative Binomial (NB) Regression Results

This research first developed Negative Binomial (NB) SPFs for multiple-vehicle crashes, and the results are shown in Table 25. A very large *p*-value usually means the regression coefficient is not statistically significantly different from zero, and the corresponding variable can be removed from the model. A threshold *p*-value of 0.20 was used in developing the HSM SPFs and was also adopted in this study. The data in Table 25 suggest that almost all AADT coefficients are statistically significant at the 0.20 level. The *p*-value for the coefficient for $\text{Ln}(AADT_{minor})$ and 3SG is 0.21, which is close enough to 0.20. The NB models for 3ST, 4ST, and 4SG were based on data collected from 2010 to 2012. For 3SG, additional data from 2009 was used to calibrate the NB SPF (see discussion in Section 4.2.4). This was because the NB SPF based on 2010 to 2012 data could not generate statistically significant coefficient for Ln($AADT_{minor}$) for 3SG at the 0.20 level. This result suggests that increasing sample size is an effective strategy to improve model fitting.

Table 25 - Negative Binomial Model for Total Multiple-Vehicle Crashes

Variable	3ST		3SG		4ST		4SG	
	Coef.	***p*-value**	**Coef.**	***p*-value**	**Coef.**	***p*-value**	**Coef.**	***p*-value**
Ln($AADT_{major}$)	1.61	*0.00*	0.79	*0.00*	0.28	*0.03*	0.71	*0.00*
Ln($AADT_{minor}$)	0.54	*0.00*	0.13	*0.21*	0.87	*0.00*	0.42	*0.00*

This research also calibrated the HSM SPFs for single-vehicle crashes, and the results are shown in Table 26. As can be seen, six out of the eight coefficients are statistically insignificant at the 0.20 level. Due to the unsatisfactory modeling results for single-vehicle crashes, these calibrated single-vehicle SPFs should not be used. Similar situations also exist in the HSM. For example, there are no SPFs available for fatal and injury single-vehicle crashes at 3ST and 4ST. There are no SPFs available for total vehicle-pedestrian crashes at 3ST and 4ST, either. A simplified approach is provided in the HSM to predict vehicle-pedestrian crashes for 3ST and 4ST, as shown in Eq. (14). The same approach is used to predict vehicle-bicycle crashes for all four intersection types in the HSM. The main reason is that vehicle-pedestrian and vehicle-bicycle crashes are rarer events than multiple- and single-vehicle crashes. It is difficult to fit a statistically meaningful model for them. Increasing the sample size may help. However, doing so can be costly and time-consuming.

$$N_{pedi} = N_{bi} \times f_{pedi} \tag{14}$$

where,

N_{bi} = predicted average crash frequency of an intersection (excluding vehicle-pedestrian and vehicle-bicycle collisions); and

f_{pedi} = pedestrian crash adjustment factor.

Table 26 - Negative Binomial Model for Total Single-Vehicle Crashes

Variable	3ST		3SG		4ST		4SG	
	Coef.	**p-value**	**Coef.**	**p-value**	**Coef.**	**p-value**	**Coef.**	**p-value**
Ln($AADT_{major}$)	0.04	***0.92***	0.26	***0.52***	-0.10	***0.88***	0.02	***0.98***
Ln($AADT_{minor}$)	1.01	*0.00*	0.21	***0.48***	0.26	***0.52***	1.14	*0.01*

Various methods were experimented with when calibrating the HSM SPFs to improve the model fitting. These methods included mixed-effects NB regression, Generalized Estimating Equations (GEE), and Bootstrap. These methods generated statistically significant AADT coefficients for multiple-vehicle crashes. However, their goodness-of-fit results are not better than those of the regular NB models. Therefore, the corresponding results are not included in this report. None of these methods were able to generate AADT coefficients for single-vehicle crashes that are statistically significant at the 0.20 level. This was mainly due to the limited sample sizes and the fact that many intersections in Massachusetts had zero or very few single-vehicle crashes during the data collection period. To address this problem, the following Eq. (15) was proposed to predict single-vehicle crashes. Similar to f_{pedi} in Eq. (14), f_{bisv} can be estimated from the collected historical crash data in Massachusetts. A very similar approach was used to predict vehicle-bicycle and vehicle-pedestrian crashes.

$$N_{bisv} = N_{bimv} \times f_{bisv} \tag{15}$$

where,

N_{bisv} = predicted average number of single-vehicle collisions for base conditions;
N_{bimv} = predicted average number of multiple-vehicle collisions for base conditions; and
f_{bisv} = adjustment factor for single-vehicle collisions.

To help illustrate the difference between the HSM and the proposed MassDOT approaches, two flowcharts have been prepared and are shown in Figure 8 and Figure 9. For the HSM approach, separate NB models are provided for total crashes, Fatal & Injury (FI) crashes, and Property-Damage-Only (PDO) crashes. In the proposed MassDOT method, NB models are provided for total crashes only, as separating the total crashes into different injury types will lead to statistically insignificant models. For the MassDOT approach, FI and PDO crashes can be estimated by multiplying the predicted total crashes with proportions, which were derived for FI and PDO crashes using local data (see Table 15 and Table 16).

6.2. SPFs based on Bayesian Negative Binomial (NB) Model

Since many of the selected intersections do not satisfy the base conditions defined in the HSM, it is necessary to consider covariates such as number of approaches with left-turn lanes, number of approaches with right-turn lanes, and left-turn signal phasing in calibrating the HSM SPFs. The Bayesian NB model was adopted in this research for this purpose. It allowed us to incorporate our prior knowledge about the safety impacts of these new covariates. The Bayesian NB modeling results are shown in Table 27. This study did not fit the Bayesian NB model for single-vehicle crashes either, because of the unsatisfactory single-vehicle results reported in Table 26. The coefficients in Table 27 were used in the final version of the proposed MassDOT approach.

Table 27 - Bayesian NB Model for Total Multiple-Vehicle Crashes

Intersection Type	No. of Sites	Regression Coefficients			Over-dispersion Parameter (k)
		Intercept (a)	$AADT_{maj}$ (b)	$AADT_{min}$ (c)	
3SG	191	-8.30	0.81	0.21	0.41
3ST	258	-20.02	1.66	0.54	0.24
4SG	156	-11.79	0.92	0.52	0.10
4ST	177	-8.70	0.31	0.86	0.36

6.3. Model Calibration

The HSM SPFs and the newly developed Bayesian SPFs were applied to all the selected intersections. The calculated calibration factor results are presented in Table 28. Based on the calibration factor definition in Eq. (5), it can be concluded that the HSM SPFs significantly underestimate crashes for 3SG and 4SG, and overestimate crashes for 3ST.

The newly developed Bayesian SPFs perform well for 3SG, 4SG, and 4ST. They tend to slightly underestimate crashes for 3ST. This underestimation can be caused by a number of factors, including outliers in the data and inaccurate crash modification factors in the HSM. In any case, it is difficult to obtain a calibration factor that is precisely equal to 1.0. Overall, the calibration factor results from the Bayesian SPFs appear to be more reasonable than those from the HSM SPFs. Therefore, it is recommended to use the Bayesian SPFs for all four intersection types.

Table 28 - Comparisons of the HSM Model and the Bayesian NB Model

Model	Calibration Factors (C_i)			
	3SG	3ST	4SG	4ST
Bayesian NB Model	0.95	1.13	1.00	1.04
HSM Model	**1.50**	0.77	**1.49**	1.03

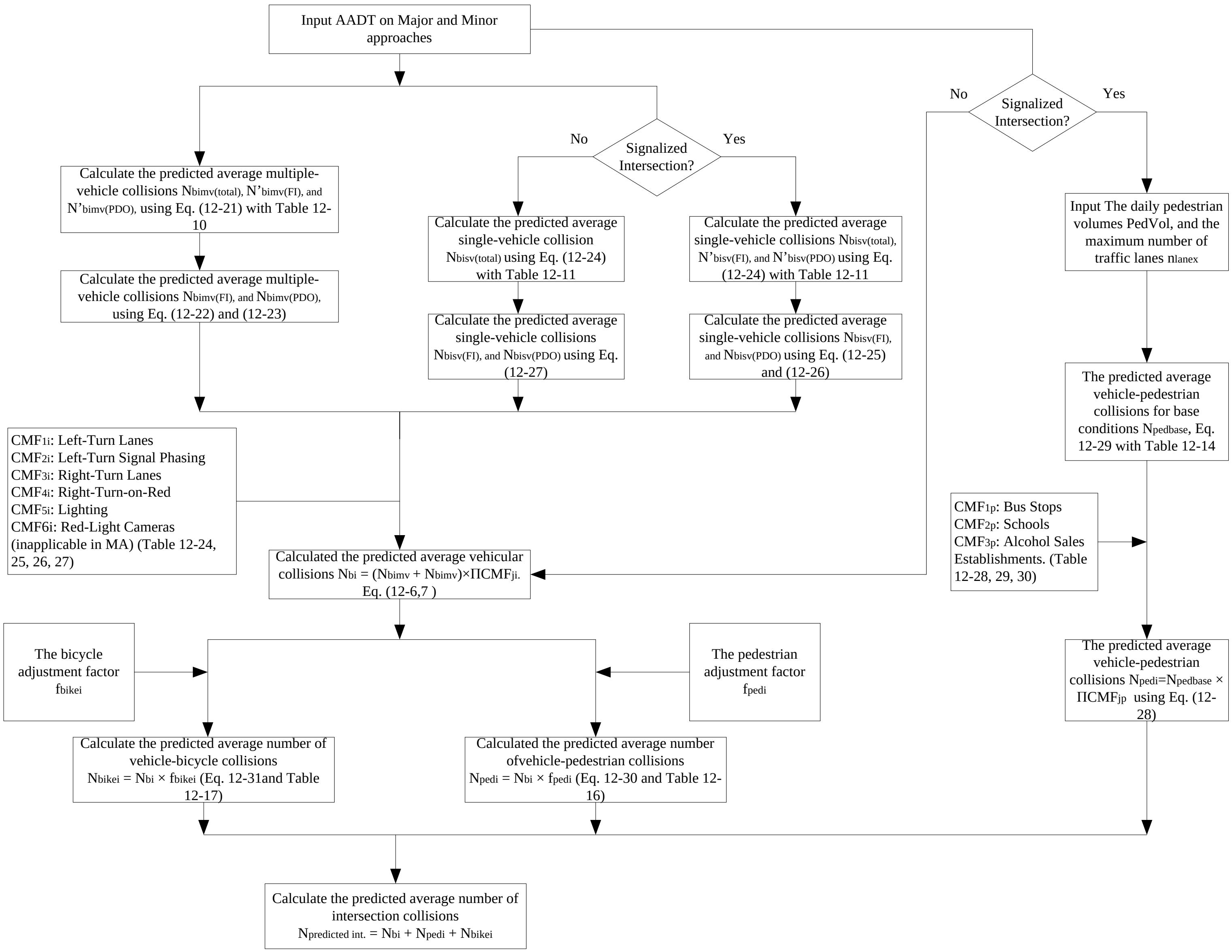


Figure 8 - The HSM Crash Predictive Procedure.

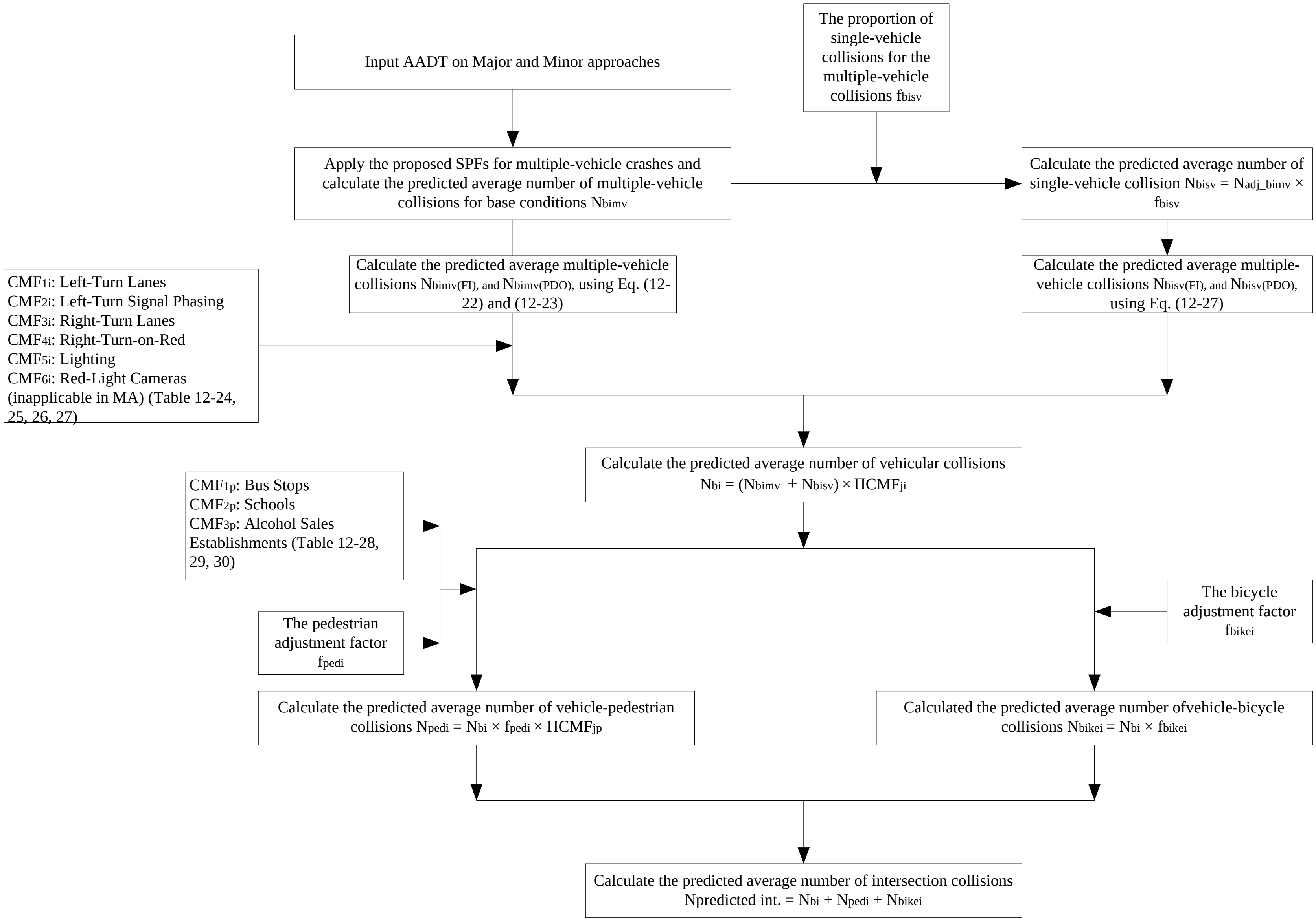


Figure 9 - The Proposed MassDOT Crash Predictive Procedure.

7.0 Conclusions

Overall, this study suggests that it is necessary to calibrate the HSM SPFs using Massachusetts data for urban and suburban arterials intersections. The Bayesian NB regression model was adopted to calibrate the HSM SPFs, so that prior knowledge of the safety impacts of various factors can be incorporated. The calibration factor results show that the new SPFs overall are more accurate than those provided in the HSM.

The HSM SPFs and the calibrated SPFs have been implemented in Excel spreadsheets to facilitate future applications. Due to the limited sample sizes, the calibrated SPFs are only for predicting total multiple-vehicle crashes. The remaining crashes (e.g., single-vehicle crashes) can be estimated based on the predicted multiple-vehicle crashes and some adjustment factors. The procedure for applying the calibrated SPFs is described in the flowchart in Figure 9.

During the course of this study, a number of practical issues regarding the data collection and applications of the HSM crash predictive method were identified. These problems are discussed in Sections 7.1 and 7.2.

7.1. Issues with Data Collection

For calibrating the calibration factor, the HSM recommends a sample size of 30 to 50 sites with at least 100 crashes per year for each facility type. However, the HSM does not provide any information to justify this recommendation. The average number of crashes per intersection at stop-controlled intersections is usually less than that for signalized intersections. Therefore, larger sample sizes (more than 50) were considered for stop-controlled intersections than for signalized intersections in this study to satisfy the 100 crashes per year requirement. Sample size significantly affects the cost and time needed for data collection. This study determined sample sizes empirically based on several previous projects [*3,10,31,33,34*]. In a recent study, Shi et al. [*48*] proposed an approach based on the finite population correction (FPC) factor to determine the minimum sample size for calibrating HSM models. It is important to look further into this issue and to develop a more detailed guideline for determining appropriate sample sizes.

Since the HSM SPFs need to be updated on a regular basis, it would be helpful for state DOTs to maintain a list of intersections and keep monitoring their traffic volume, crash, traffic control, and geometry data. The most time-consuming part of this research involved the collection of traffic count data and the review of police crash reports. Theoretically, data from the Highway Performance Monitoring Systems (HPMS) can be used to derive the AADT values needed by the HSM SPFs. However, it is important to note that major driveways may be located between the HPMS data collection points and the selected intersections. This research found quite a few major discrepancies between the AADT data from the Massachusetts HPMS and those estimated based on the collected TMCs. Therefore, all the calculations in this research were based on the TMC data collected by local transportation agencies and the research team.

The research team reviewed approximately 4,000 crash reports. Most of these crash reports were handwritten, and some of the handwriting was difficult to recognize. Some crash reports were poorly documented, and the research team had to match the description with the Google Maps street view to find out what caused the crash and whether it was intersection related. Also, information from the crash reports had to be translated into electronic format manually. It would be very helpful for cities and states to use laptops/tablets and GPS to prepare crash reports and store them electronically.

7.2. Issues with the HSM Crash Predictive Method

The HSM SPFs for vehicle-pedestrian crashes require average daily pedestrian volumes as the input. However, most transportation agencies do not routinely collect intersection pedestrian traffic data. The HSM does include a table (i.e., Table 12-15) to estimate daily pedestrian crossing activities. To use this table, the safety analyst needs to choose a pedestrian crossing activity level (i.e., low, medium, and high) based on experience and find the corresponding pedestrian crossing volume (e.g., 1,500 pedestrians/day). This method is completely based on the safety analyst's subjective judgement and requires the analyst to be very familiar with the study area. This research developed a preliminary pedestrian volume model for Massachusetts. Additional research is needed to develop more sophisticated models for accurately predicting pedestrian crossing volumes.

The HSM SPFs for urban and suburban arterial intersections assume that the impacts of various safety countermeasures are independent. Therefore, their joint effect is modeled by multiplying different crash modification factors, as in Eq. (2). While this assumption may make the algorithm implementation straightforward, it may not always be valid.

The CMFs in the HSM cover limited factors such as left-turn lanes, right-turn lanes, left-turn signal phasing, right-turn-on-red, and intersection lighting. There are other factors that may affect intersection safety, including but not limited to intersection skew, land use, lane width, and pavement marking. Among these factors, intersection skew is commonly seen in Massachusetts.

In this research, the Negative Binomial results for single-vehicle crashes are unsatisfactory. There are many statistically insignificant coefficients at the 0.20 level, and some coefficients are even negative. Some negative coefficients are also observed in *NCHRP Report 129* [*3*], which is the basis used for developing the HSM. A major reason could be the low sample means for single-vehicle crashes. As shown in Figure 10, single-vehicle crashes did not occur at many intersections in this study between 2010 and 2012. Given so many zero observations, it might be necessary to consider other modeling techniques, such as zero-inflated NB regression.

In the HSM, separate models are provided for crashes of different types (e.g., vehicle-pedestrian) and injury levels (e.g., PDO). Crashes of different manners (e.g., rear-end) are then estimated by multiplying the predicted total crashes with corresponding proportions. An alternative option could be to develop separate models for crashes of different manners directly.

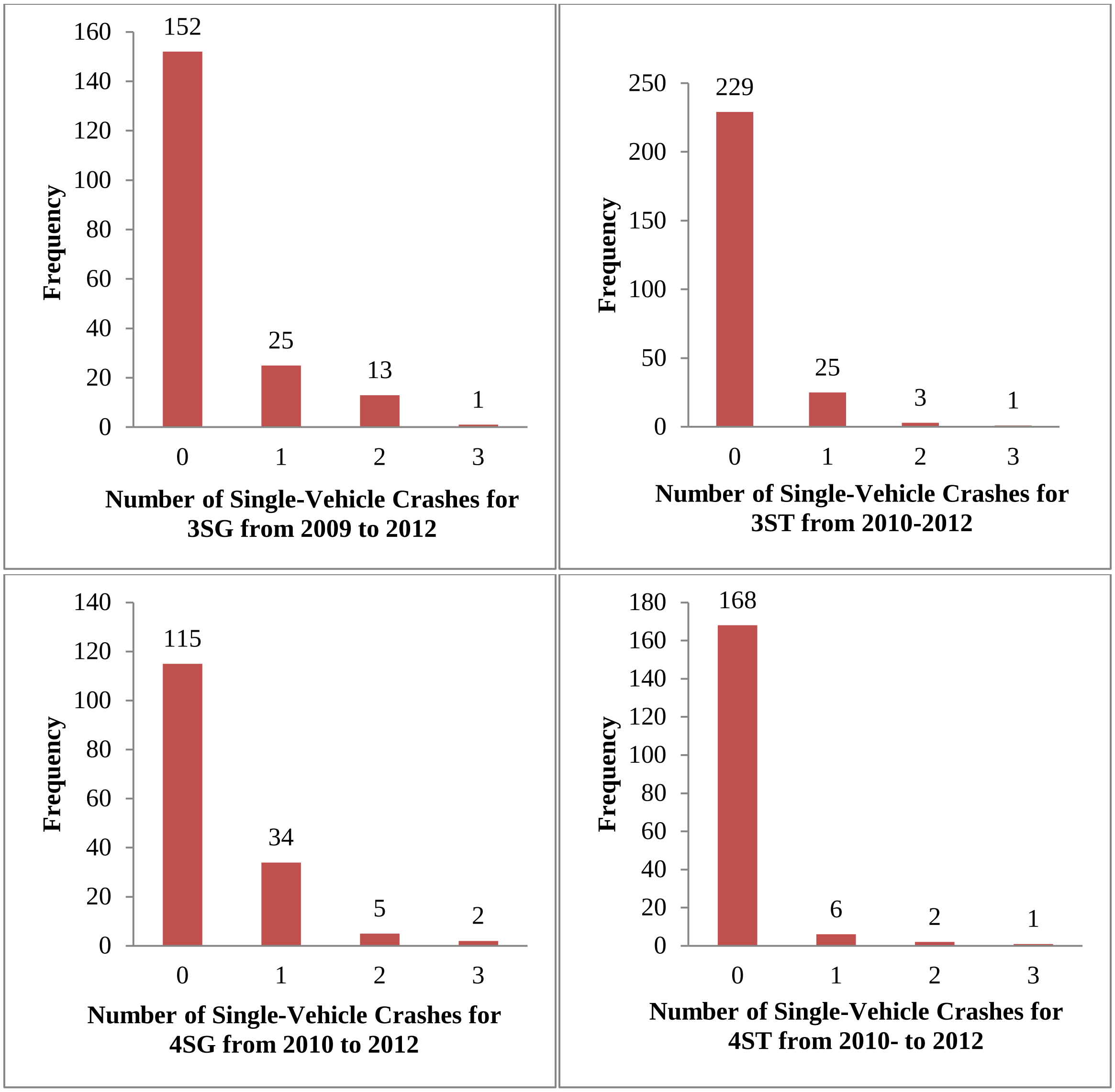


Figure 10 - Frequency Distribution for Single-Vehicle Crashes.

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9.0 Appendices

9.1 Appendix A – Lists of Intersections

Table A.1 - List of 3SG Intersections

ID	Road EW	Road NS	State	Area	City	Y	X
4	Concord Ave	Craigie St	0	Cambridge	Cambridge	42.379464	-71.125738
5	Mason St	Garden St	0	Cambridge	Cambridge	42.376589	-71.122203
7	Krikland St	Quincy St	0	Cambridge	Cambridge	42.376638	-71.114096
8	Main St	Sidney St	0	Cambridge	Cambridge	42.363412	-71.099377
9	Massachusetts Ave	Beech St	0	Cambridge	Cambridge	42.390288	-71.121014
10	Mass Ave	Walden St	0	Cambridge	Cambridge	42.391377	-71.123246
11	University Rd	Mt Auburn St	0	Cambridge	Cambridge	42.373354	-71.122954
12	Mt Auburn St	Aberdeen Ave	0	Cambridge	Cambridge	42.375254	-71.145830
1	E Main St	Lyman St	0	CMRPC	Westborough	42.279366	-71.606270
2	(S) Main St	Lake St	0	CMRPC	Webster	42.050156	-71.880118
3	Main St	Pleasant St	1	CMRPC	Southbridge	42.081622	-72.046345
4	Southbridge St	Prospect St	1	CMRPC	Auburn	42.183084	-71.860871
5	Main St	St Paul St	1	CMRPC	Blackstone	42.018748	-71.532818
7	Main St	Salisbury St	1	CMRPC	Holden	42.344000	-71.851926
1	Boston Worcester TPK	Country Club Ln	1	Framingham	Framingham	42.293968	-71.467272
3	Worcester Rd	Prospect St	1	Framingham	Framingham	42.298191	-71.422396
5	Waverly St	Winter St	0	Framingham	Framingham	42.274208	-71.436621
1	Bridge St	French St	0	Lowell	Lowell	42.646255	-71.306806
3	Pawtucket St	Middlesex St	0	Lowell	Lowell	42.638304	-71.343292
4	Pawtucket Blvd	Bedford Ave	0	Lowell	Lowell	42.640783	-71.352924
5	Pawtucket Blvd	Old Ferry Rd	0	Lowell	Lowell	42.640345	-71.360891
6	Pawtucket Blvd	Rourke Bridge	0	Lowell	Lowell	42.640547	-71.357355
7	University Ave (Merrimack St)	Pawtucket St	0	Lowell	Lowell	42.650704	-71.323970
9	Thorndike St	Highland St	0	Lowell	Lowell	42.636029	-71.312540
12	Pawtucket Blvd	Varnum Ave	1	Lowell	Lowell	42.647241	-71.336998
13	Westford St	Wood St	0	Lowell	Lowell	42.629714	-71.355024
1	Walnut St	Lincoln St	0	Newton	Newton	42.321813	-71.206287
5	Washington St	Highland St	0	Newton	Newton	42.349169	-71.227457
7	Wheeler Rd	Parker St	0	Newton	Newton	42.311970	-71.196592
8	Cabot St	Walnut St	0	Newton	Newton	42.347733	-71.206640
9	Wolcott St	Lexington St	0	Newton	Newton	42.348569	-71.247253
1	Vernon St	Main St	0	PVPC	Holyoke	42.189525	-72.621527
4	Sargeant St	Northampton St	0	PVPC	Holyoke	42.205201	-72.630788
5	Cherry St	Homestead Ave	1	PVPC	Holyoke	42.201133	-72.642340
7	E Main St	Carew St	0	PVPC	Chicopee	42.156032	-72.559692
8	Simard Dr	Yelle St	0	PVPC	Chicopee	42.191084	-72.598821
11	E Main St	Veterans Memorial Bridge	0	PVPC	Chicopee	42.156982	-72.549100
20	Beech St	Hospital Dr	0	PVPC	Holyoke	42.199334	-72.628491
86	Granby Rd/Rt. 116	Springfield St	1	PVPC	Chicopee	42.150981	-72.607715
87	Mt Park Rd	Northampton St	1	PVPC	Holyoke	42.234082	-72.6281
1	Locust St	S Main St	0	SRPEDD	Attleboro	41.924464	-71.289069
2	Columbia St	Broadway	0	SRPEDD	Fall River	41.699745	-71.167000
4	Dean St	Arlington St	0	SRPEDD	Taunton	41.903818	-71.081952
5	Mozzone Blvd	County St	1	SRPEDD	Taunton	41.875593	-71.059705
6	River Wy Ext	County St	0	SRPEDD	Taunton	41.894507	-71.074259
7	American Legion Hwy	Sanford Rd	1	SRPEDD	Westport	41.627039	-71.101514
8	Grand Army of the Republic Hwy	Bushee Rd	1	SRPEDD	Swansea	41.756257	-71.243344
9	Winthrop St	Warner Blvd	1	SRPEDD	Taunton	41.888976	-71.120702

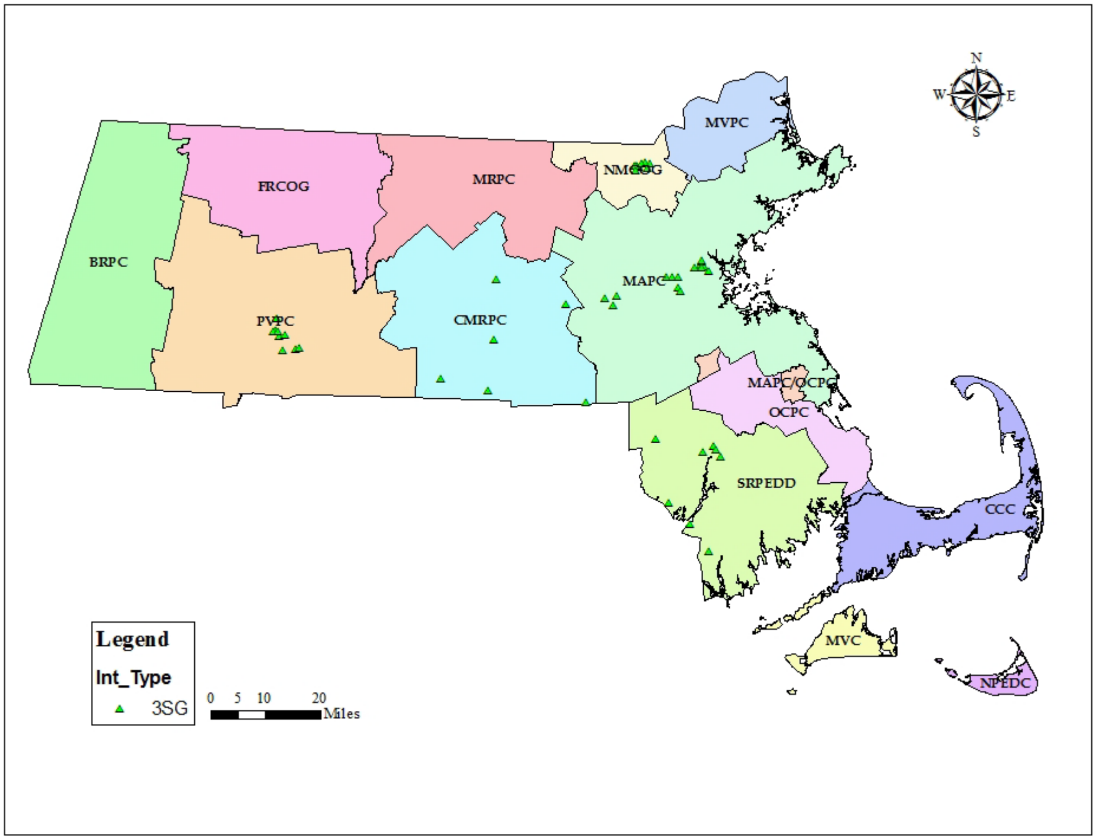

Figure A.1 - Selected 3SG Intersection in Massachusetts.

Table A.2 - List of 3ST Intersections

ID	Road EW	Road NS	State	Area	City	Y	X
14	Brattle St	Lakeview Ave	0	Cambridge	Cambridge	42.376602	-71.138505
15	Broadway	Boardman St	0	Cambridge	Cambridge	42.367488	-71.096395
16	Concord Ave	Buckingham St	0	Cambridge	Cambridge	42.381137	-71.128874
17	Webster Ave	Hampshire St	0	Cambridge	Cambridge	42.366847	-71.092425
18	Huron Ave	Larchwood Dr	0	Cambridge	Cambridge	42.378925	-71.146375
19	Main St	Albany St	0	Cambridge	Cambridge	42.362837	-71.091945
20	Mass Ave	Garfield St	0	Cambridge	Cambridge	42.383793	-71.119485
21	Cambridge St	Hovey Ave	0	Cambridge	Cambridge	42.374640	-71.107883
22	Portland St	Albany St	0	Cambridge	Cambridge	42.361802	-71.093894
24	Mass Ave	Meacham Rd	0	Cambridge	Cambridge	42.395089	-71.127656
69	Quinaquisset Ave	Orchard Rd	0	Cape Cod	MASHPEE	41.621369	-70.468401
84	Old Mill Rd	Bumps River Rd	0	Cape Cod	Barnstable	41.644694	-70.371761
208	Great Marsh Rd	Phinneys Ln	0	Cape Cod	Barnstable	41.658478	-70.338378
220	Old Main St	South St	0	Cape Cod	Yarmouth	41.658056	-70.202041
311	Main St	South St	0	Cape Cod	Harwich	41.686322	-70.084449
6	Main St	Old Worcester Rd	1	CMRPC	Oxford	42.147769	-71.869032
8	Hudson St	Colburn St	0	CMRPC	Northborough	42.336633	-71.625447
9	E Main St	Flanders Rd	0	CMRPC	Westborough	42.281754	-71.601689
10	W Main St	Beach St	0	CMRPC	Millbury	42.177545	-71.773349
11	Prospect Ave	W Main ST	1	CMRPC	Dudley	42.044438	-71.900084
12	Dudley Oxford Rd	Mason Rd	0	CMRPC	Dudley	42.058529	-71.916844
13	Main St	Cudworth Rd	1	CMRPC	Oxford	42.081422	-71.869505
14	Main St	Federal Hill Rd	1	CMRPC	Oxford	42.136601	-71.866118
15	Main St	Hall Rd	1	CMRPC	Sturbridge	42.105216	-72.075863
16	Sturbridge Rd	Sampson Rd	1	CMRPC	Charlton	42.138741	-72.019675
17	Uxbridge Rd	Hartford Ave W	1	CMRPC	Mendon	42.103043	-71.567152
18	Leichester St	Pleasant St	0	CMRPC	North Oxford	42.183274	-71.898035
19	Charlton St	Dudley Rd	0	CMRPC	Oxford	42.112768	-71.878738
20	Central Turnpike	Boston Rd	0	CMRPC	Sutton	42.115947	-71.796919
21	Sutton Ave	Fort Hill Rd	0	CMRPC	Oxford	42.113339	-71.841728
22	Main St	Malden St	1	CMRPC	Holden	42.113333	-71.841728
23	Main St	Merriam Way	1	CMRPC	Upton	42.172170	-71.626997
654	Summer St	Federal St	0	CMRPC	Blackstone	42.038943	-71.522794
1825	Salisbury St	Moreland St	0	CMRPC	Worcester	42.292234	-71.834696
2017	Ararat St	Brattle St	0	CMRPC	Worcester	42.314397	-71.818424
2043	Shrewsbury St	Paul X Tivnan Dr	0	CMRPC	W Boylston	42.330638	-71.772674
11	Varnum Ave	Old Ferry Rd	0	Lowell	Lowell	42.643644	-71.363112
14	Andover St	Douglas Rd	0	Lowell	Lowell	42.644690	-71.281542
15	Andover St	Wentworth Ave	0	Lowell	Lowell	42.643210	-71.288706
16	Bridge St	12th St	0	Lowell	Lowell	42.655533	-71.302780
17	Gorham St	London St	0	Lowell	Lowell	42.627190	-71.307730
18	5th Ave	Mammoth St	0	Lowell	Lowell	42.652516	-71.335690
20	Nesmith St	Porter St	0	Lowell	Lowell	42.639790	-71.295913
21	Pawtucket St	Wilder St	0	Lowell	Lowell	42.645305	-71.334431
22	Princeton Blvd	Pine St	1	Lowell	Lowell	42.633718	-71.345462
23	Westford St	Stedman St	0	Lowell	Lowell	42.629540	-71.349839
24	Spencer St	Boston Rd	0	Lowell	Lowell	42.619820	-71.310520
25	Boylston St	Bishop St	0	Lowell	Lowell	42.625487	-71.285122
26	Varnum Ave	Totman St	0	Lowell	Lowell	42.644993	-71.360978
3493	Westford St	Sandy Pond Rd	0	MRPC	Ayer	42.559180	-71.540771
3523	South Ashburnham Rd	Bean Porridge Hill Rd	0	MRPC	Westminster	42.572432	-71.883848
3564	Rollstone St	Pratt Rd	0	MRPC	Fitchburg	42.573925	-71.807179
3629	Mass Ave	White St	1	MRPC	Lunenburg	42.591395	-71.760578

ID	Road EW	Road NS	State	Area	City	Y	X
4022	North St	Mill St	0	MVPC	Georgetown	42.732012	-70.985338
4066	E Main St	Amesbury Line Rd	0	MVPC	Haverhill	42.809502	-71.004556
1	Billerica Road (Route 129)	Riverneck Road	0	NMCOG	Chelmsford	42.598913	-71.338273
3	Groton St	Tarbell St	0	NMCOG	Pepperell	42.666067	-71.572944
4	Main St	Graniteville Rd	0	NMCOG	Westford	42.580763	-71.442209
5	Andover St	River Rd	0	NMCOG	Tewksbury	42.646144	-71.271071
3599	Forge Village Rd	Patten Rd	0	NMCOG	Westford	42.580853	-71.456432
3757	Lawrence St	Moore St	0	NMCOG	Lowell	42.628443	-71.298732
969	Brimfield Rd	Bethany Rd	0	PVPC	Monson	42.111763	-72.310006
1258	Cady St	Fuller St	0	PVPC	Lundlow	42.168132	-72.485642
1338	Hitchcock St	Westfield Rd	0	PVPC	Holyoke	42.194335	-72.635601
10	Main St	Robinson Rd	1	SRPEDD	Acushnet	41.737102	-70.895566
11	Park St	Maple St	0	SRPEDD	Attleboro	41.936254	-71.264024
12	Wilmarth St	Park St	0	SRPEDD	Attleboro	41.918113	-71.257634
13	S Main St	Tiffany St	0	SRPEDD	Attleboro	41.916508	-71.303596
14	Elm St	S Main St	0	SRPEDD	Berkley	41.835594	-71.088845
15	Willaims St	Center St	0	SRPEDD	Dighton	41.842177	-71.158122
16	Beford St	Long Point Rd	0	SRPEDD	Lakeville	41.807773	-70.918367
17	County St	Highland Rd	1	SRPEDD	Lakeville	41.809325	-70.975936
18	County St	Hawthorn St	0	SRPEDD	New Bedford	41.629591	-70.928604
19	Taunton St	Howard St	1	SRPEDD	Norton	41.965137	-71.186920
20	Robinson Rd/Hartley Rd	Cushman Rd	1	SRPEDD	Rochester	41.742426	-70.868719
21	Broadway	Jackson St	1	SRPEDD	Taunton	41.926020	-71.090057
22	County St	Willims St	0	SRPEDD	Taunton	41.895519	-71.075987
23	Tremont St	Shores St	0	SRPEDD	Taunton	41.904936	-71.105322
24	Weir St	Harrison St	0	SRPEDD	Taunton	41.896829	-71.091480
25	Cranberry HWY	Charge Pond Rd	1	SRPEDD	Wareham	41.769274	-70.716283
26	Huttleston Ave	New Boston Rd	1	SRPEDD	Fairhaven	41.648736	-70.861204
27	Huttleston Ave	Shaw Rd	1	SRPEDD	Fairhaven	41.651750	-70.850692
384	Read St	Brayton Point Rd	0	SRPEDD	Somerset	41.736789	-71.168343
416	Providence St	Pleasant St	0	SRPEDD	Rehoboth	41.794256	-71.244654
481	Woodland Ave	Pine St	0	SRPEDD	Seekonk	41.886031	-71.322498
516	May St	Newport Ave	0	SRPEDD	Attleboro	41.923877	-71.351589

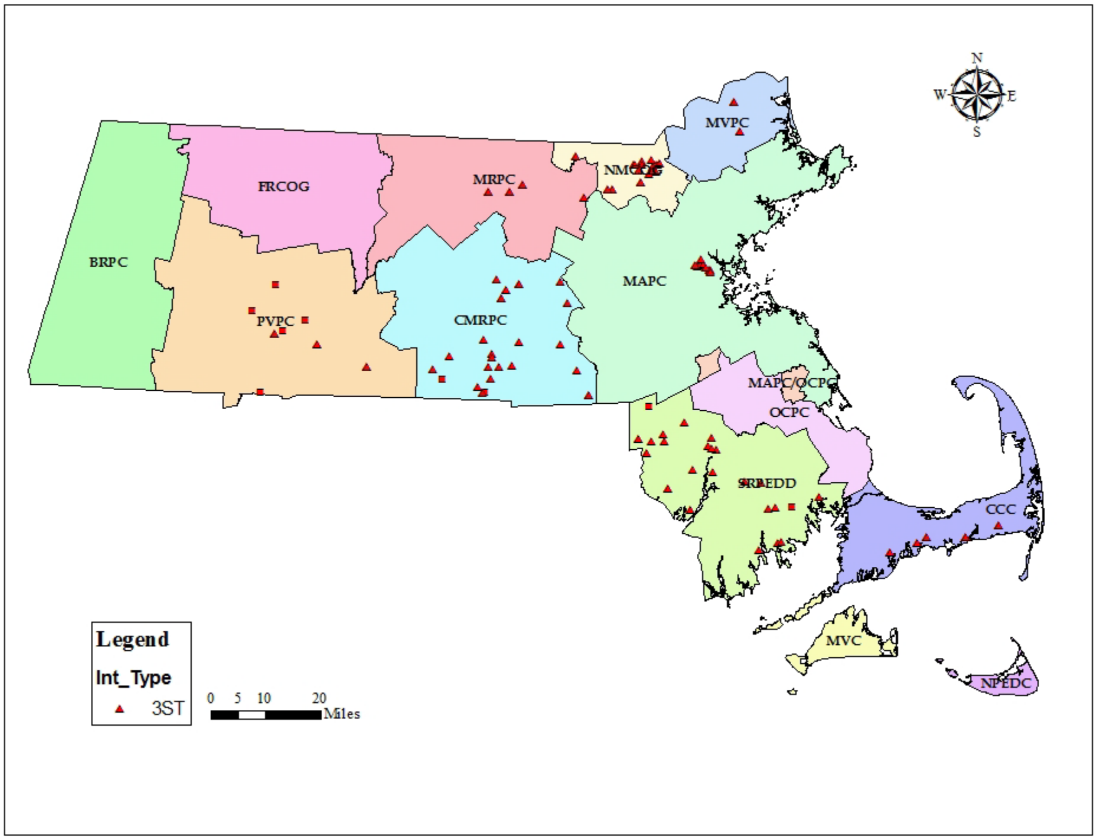

Figure A.2 - Selected 3ST Intersections in Massachusetts.

Table A.3 - List of 4SG Intersections

ID	Road EW	Road NS	State	Area	City	Y	X
25	Massachusetts Ave	Albany St	0	Cambridge	Cambridge	42.360823	-71.096038
26	Binney St	First St	0	Cambridge	Cambridge	42.365132	-71.078206
27	Binney St	Third St	0	Cambridge	Cambridge	42.365687	-71.082423
28	Broadway	Columbia St	0	Cambridge	Cambridge	42.367867	-71.097368
30	Massachusetts Ave	Sidney St	0	Cambridge	Cambridge	42.362952	-71.099586
31	Portland St	Main St	0	Cambridge	Cambridge	42.362972	-71.093640
34	Massachusetts Ave	Vassar St	0	Cambridge	Cambridge	42.360142	-71.094878
35	Broadway	Windsor St	0	Cambridge	Cambridge	42.367097	-71.095406
36	Main St	Windsor St	0	Cambridge	Cambridge	42.363209	-71.096710
37	Hampshire St/Technology Square	Broadway	0	Cambridge	Cambridge	42.365433	-71.091127
38	Broadway	Galileo Galilei Way	0	Cambridge	Cambridge	42.364791	-71.089421
24	Grafton St/Boylston St	Main St	1	CMRPC	Shrewsbury	42.296643	-71.713633
26	Main St	Bartlett St	1	CMRPC	Northborough	42.328040	-71.619934
34	Millbury St	Providence Rd	1	CMRPC	Grafton	42.205212	-71.692934
36	Southbridge Rd	Leicester St	1	CMRPC	Oxford	42.167505	-71.893921
37	Huntoon Memorial Hwy(Leicester St)	Stafford St	0	CMRPC	Leicester	42.199718	-71.898623
30	Broadway St	Wilder St	0	Lowell	Lowell	42.641867	-71.333340
32	Father Morissette Blvd	Aiken St	0	Lowell	Lowell	42.650209	-71.319353
33	Pawtucket St	School St	0	Lowell	Lowell	42.648269	-71.328812
35	Princeton Blvd	Baldwin St	1	Lowell	Lowell	42.633408	-71.349110
36	Princeton Blvd	Wood St	1	Lowell	Lowell	42.632862	-71.355342
38	Riverside St	University Ave	0	Lowell	Lowell	42.653806	-71.327006
40	Westford St	School St	0	Lowell	Lowell	42.635416	-71.325137
28	Pleasant St	Lindsey St(Haggerty Hwy)	0	SRPEDD	Attleboro	41.952876	-71.268999
29	Thachet St	County St	0	SRPEDD	Attleboro	41.933568	-71.300388
30	Allen St	Slocum Rd	0	SRPEDD	Dartmouth	41.622533	-70.963244
31	Huttleston Ave (Route 6)	Adams St	1	SRPEDD	Fairhaven	41.643714	-70.900935
32	Huttleston Ave (Route 6)	Alden Rd	1	SRPEDD	Fairhaven	41.641393	-70.885143
33	President Ave (Route 6)	Robeson St	0	SRPEDD	Fall River	41.714069	-71.140910
34	New Boston Rd	N Eastern Ave(Route 6)	0	SRPEDD	Fall River	41.709257	-71.124620
35	Rodman St	Plymouth Ave	0	SRPEDD	Fall River	41.695401	-71.152265
36	Main St(Precinct St)	Bedford St	1	SRPEDD	Lakeville	41.846148	-70.949045
37	Rhode Island Rd	Bedford St	1	SRPEDD	Lakeville	41.873422	-70.953425
38	Center St(Wareham St)	N Main St(S Main St)	0	SRPEDD	Middleborough	41.892422	-70.909089
40	Coggeshall St	Belleville Ave	0	SRPEDD	New Bedford	41.656032	-70.923642
41	Union St	County St	0	SRPEDD	New Bedford	41.633760	-70.930365
42	Hathaway Rd	Shawmut Ave	0	SRPEDD	New Bedford	41.659373	-70.947097
43	Hawthorn St	Cottage St	0	SRPEDD	New Bedford	41.629471	-70.932374
44	Hawthorn St	Rockdale Ave	0	SRPEDD	New Bedford	41.628106	-70.947404
45	Potomska St	JFK Memorial Highway	0	SRPEDD	New Bedford	41.622829	-70.920977
46	Allen St	Rockdale Ave	0	SRPEDD	New Bedford	41.624609	-70.946446
47	Rockdale Ave	Dartmouth St	0	SRPEDD	New Bedford	41.615053	-70.937530
48	Elm St	E Washington St (Route 1)	1	SRPEDD	North Attleborough	41.981307	-71.329703
49	Carver St	Broadway	1	SRPEDD	Raynham	41.954097	-71.070323
52	E Britannia St	Broadway	0	SRPEDD	Taunton	41.921573	-71.090700
53	Hart St	County St	1	SRPEDD	Mattapoisett	41.884672	-71.066807
54	1st St	Somerset Ave	0	SRPEDD	Taunton	41.888387	-71.092683
55	Summer St	Spring St/Church Green	0	SRPEDD	Taunton	41.900700	-71.088464
56	Winthrop St	High St	0	SRPEDD	Taunton	41.899302	-71.095786
57	Winthrop St	Highland St	0	SRPEDD	Taunton	41.890202	-71.114761
58	Main St	County Rd	1	SRPEDD	Mattapoisett	41.662000	-70.819148
59	County Rd	North St	1	SRPEDD	Mattapoisett	41.663861	-70.812434

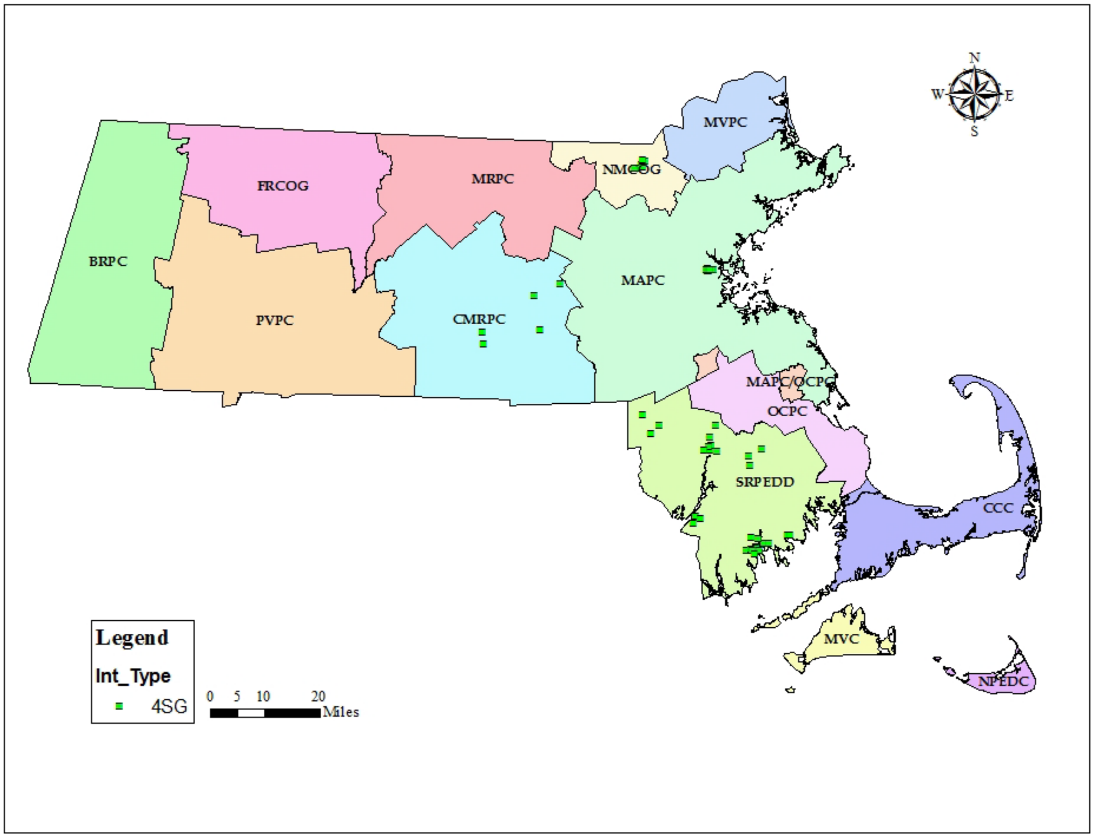

Figure A.3 - Selected 4SG Intersections in Massachusetts.

Table A.4 - List of 4ST Intersections

ID	Road EW	Road NS	State	Area	City	Y	X
39	Brattle St	Channing PI	0	Cambridge	Cambridge	42.377043	-71.135932
40	Cambridge St	5th St	0	Cambridge	Cambridge	42.371446	-71.083139
41	Cambridge St	Sciarappa St	0	Cambridge	Cambridge	42.371241	-71.081495
42	Hurley St	Third St	0	Cambridge	Cambridge	42.368299	-71.080566
43	Mellon St	Mass Ave	0	Cambridge	Cambridge	42.380837	-71.119840
41	George St (Chase Ave)	Schofield Ave	1	CMRPC	Dudley	42.041435	-71.891176
42	South St	Breakneck Rd	0	CMRPC	Southbridge	42.068331	-72.065420
43	Center Depot Rd	Stafford St	0	CMRPC	Charlton	42.156162	-71.973364
44	Charlton St	Monument Dr	0	CMRPC	Oxford	42.115071	-71.870544
46	Providence Rd	Brigham Hill Rd	1	CMRPC	Grafton	42.208936	-71.692771
47	Uxbridge Rd	Mowry St	1	CMRPC	Mendon	42.093474	-71.587518
48	Washington St (Route 20)	Mill St/Old Common Rd	1	CMRPC	Auburn	42.195434	-71.821623
49	Millbury St	Hudson St	0	CMRPC	Grafton	42.203972	-71.698457
50	Central Turnpike	Uxbridge Rd	0	CMRPC	Sutton	42.138072	-71.746351
51	Nourse St	Glen St	0	CMRPC	Westborough	42.250929	-71.657982
52	Church St	Main St	0	CMRPC	Oxford	42.120729	-71.864265
53	Paxton St	Marshall St	0	CMRPC	Leicester	42.277018	-71.906266
54	Bailey St (Mayo Rd)	Main St	1	CMRPC	Holden	42.345743	-71.854951
55	Pleasant St(Leland Hill Rd)	Main St	0	CMRPC	Grafton	42.177705	-71.705847
56	Providence St	Depot St	0	CMRPC	Sutton	42.175135	-71.720527
632	Schofield Ave	Brandon Rd	1	CMRPC	Dudley	42.043522	-71.890893
800	South St	Sayles St	0	CMRPC	Southbridge	42.076866	-72.043921
27	Riverside St	Sparks St	0	Lowell	Lowell	42.658418	-71.325413
43	Andover St	Trull Ln(Adam Trrace)	0	Lowell	Lowell	42.645634	-71.276994
44	Bridge St	(W) 5th St	0	Lowell	Lowell	42.651314	-71.303233
45	11th St (Hildreth St)	Bridge St	0	Lowell	Lowell	42.655051	-71.302619
46	Broadway St	Mt Vernon St	0	Lowell	Lowell	42.643464	-71.323764
47	Ellis Ave(3rd Ave)	Mammoth Rd	0	Lowell	Lowell	42.651382	-71.333682
48	Steven St	(W) Jenness ST	0	Lowell	Lowell	42.620467	-71.328189
49	University Ave	6th Ave	0	Lowell	Lowell	42.657242	-71.332345
50	Middlesex St	Stevens St	0	Lowell	Lowell	42.638544	-71.334819
52	Allerton Rd	Centre St	0	Newton	Newton	42.324379	-71.200061
66	Vadnais St(Bemis Rd)	Northampton St	0	PVPC	Holyoke	42.223625	-72.629100
72	Stonia Dr(Burton St)	Hampden St	0	PVPC	Chicopee	42.141406	-72.610058
679	Pine St	Barry St	0	PVPC	Agawam	42.038610	-72.685138
1418	Appleton St	Race St	0	PVPC	Holyoke	42.202659	-72.605638
1519	East St	South St	0	PVPC	Granby	42.231359	-72.526949
1575	Glendale Rd	Pomeroy Meadow Rd	0	PVPC	Southampton	42.253462	-72.719298
4729	State St	Trumbull St	0	PVPC	Northampton	42.321769	-72.634577
50	Winthrop St	Blanding Rd	1	SRPEDD	Rehoboth	41.834138	-71.292950
60	Padelford St	Anthony St (Plain St E)	0	SRPEDD	Berkley	41.840428	-71.051775
61	County St	Hart St	1	SRPEDD	Dighton	41.804814	-71.125307
62	Church St	Green St	0	SRPEDD	Fairhaven	41.633017	-70.901195
63	Main St	North St	0	SRPEDD	Fairhaven	41.648513	-70.909271
64	Main St	Vaughan St/Clear Pond Rd	1	SRPEDD	Lakeville	41.870260	-70.931619
65	Cherry St	E Grove St	1	SRPEDD	Middleborough	41.873853	-70.887950
67	North Ave	Braley Hill Rd	0	SRPEDD	Rochester	41.780981	-70.906907
68	Railroad Ave	Somerset Ave	1	SRPEDD	Taunton	41.861569	-71.113571
69	Washingto St	Jackson St	0	SRPEDD	Taunton	41.924899	-71.096371
70	Winthrop St (Route 44)	Burt St	1	SRPEDD	Taunton	41.878488	-71.168089
71	Harding St (Route 44)	Mill St	1	SRPEDD	Middleborough	41.902182	-70.972411
72	Cape Hwy (Route 44)	Richmond St	1	SRPEDD	East Taunton	41.902505	-70.989370
73	N Main St	Benefit St (Aspen St)	1	SRPEDD	Mansfield	42.017026	-71.214264

ID	Road EW	Road NS	State	Area	City	Y	X
74	Washington St (Route 1)	George St	1	SRPEDD	Plainville	42.013753	-71.319391
75	American Legion Hwy	Forge St	1	SRPEDD	Westport	41.635083	-71.054115
76	Wilbur Ave	Alsada Rd	1	SRPEDD	Swansea	41.733906	-71.220766
77	Washington St	County St	1	SRPEDD	Somerset	41.749917	-71.143254
375	Mary's Pond St	Walnut Plain Rd	0	SRPEDD	Rochester	41.740173	-70.811871
602	East Bacon St	Everett Skinner Rd	0	SRPEDD	Plainville	42.008661	-71.312681

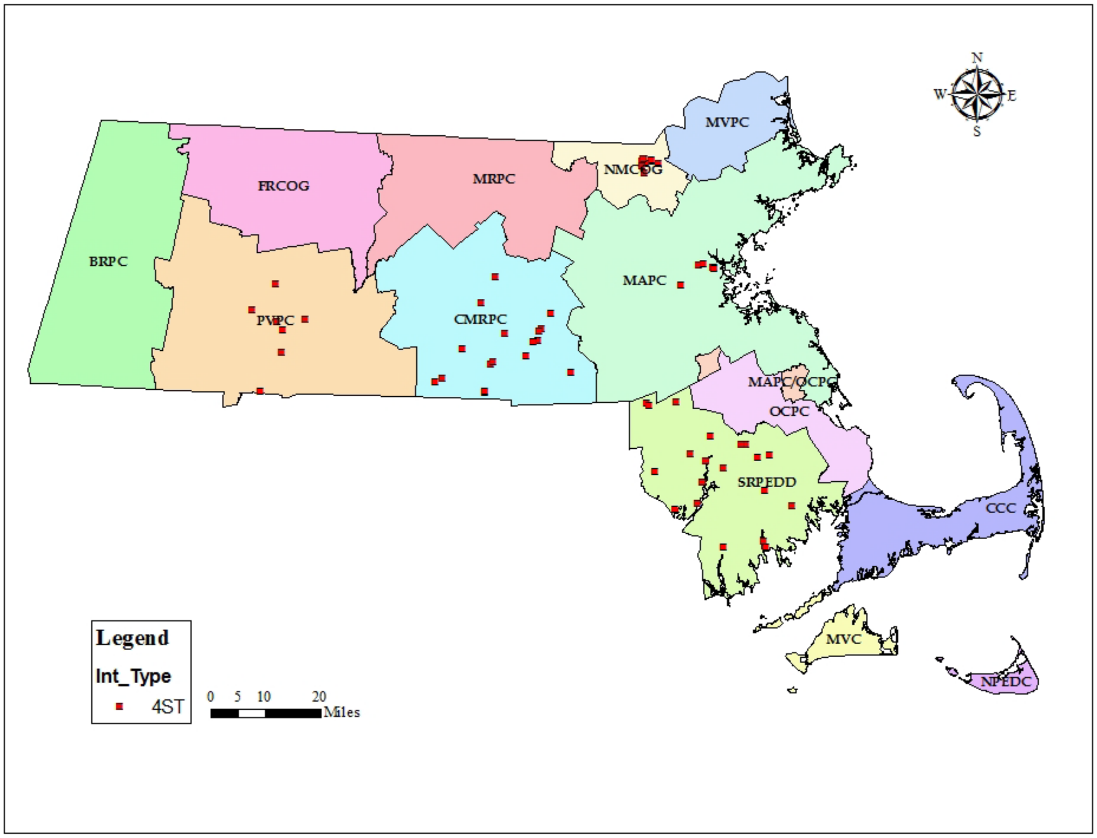

Figure A.4 - Selected 4ST Intersections in Massachusetts.

9.2 Appendix B – Lists of Bus Stops, Schools, and Alcohol Sales

Table B.1 - List of Bus Stops, Schools, and Alcohol Sales Establishments within 1,000 ft. of the Center of 3SG Intersections

ID	Road EW	Road NS	City	School	Bus Stop	Alcohol Sales Establishment
4	Concord Ave	Craigie St	Cambridge	2	7	1
5	Mason St	Garden St	Cambridge	0	7	12
7	Krikland St	Quincy St	Cambridge	1	6	1
8	Main St	Sidney St	Cambridge	3	6	32
9	Massachusetts Ave	Beech St	Cambridge	1	12	10
10	Mass Ave	Walden St	Cambridge	0	9	5
11	University Rd	Mt Auburn St	Cambridge	0	10	46
12	Mt Auburn St	Aberdeen Ave	Cambridge	0	10	1
1	E Main St	Lyman St	Westborough	1	0	0
2	(S) Main St	Lake St	Webster	3	1	5
3	Main St	Pleasant St	Southbridge	1	0	10
4	Southbridge St	Prospect St	Auburn	0	2	4
5	Main St	St Paul St	Blackstone	0	0	3
7	Main St	Salisbury St	Holden	0	0	0
1	Boston Worcester	Country Club Ln	Framingham	0	0	1
3	Worcester Rd	Prospect St	Framingham	1	0	6
5	Waverly St	Winter St	Framingham	1	0	1
1	Bridge St	French St	Lowell	3	3	13
3	Pawtucket St	Middlesex St	Lowell	0	1	1
4	Pawtucket Blvd	Bedford Ave	Lowell	0	0	0
5	Pawtucket Blvd	Old Ferry Rd	Lowell	0	0	3
6	Pawtucket Blvd	Rourke Bridge	Lowell	0	0	2
7	University Ave	Pawtucket St	Lowell	2	3	0
9	Thorndike St	Highland St	Lowell	0	1	1
12	Pawtucket Blvd	Varnum Ave	Lowell	0	0	0
13	Westford St	Wood St	Lowell	0	0	1
1	Walnut St	Lincoln St	Newton	0	8	6
5	Washington St	Highland St	Newton	1	9	6
7	Wheeler Rd	Parker St	Newton	1	4	0
8	Cabot St	Walnut St	Newton	2	5	3
9	Wolcott St	Lexington St	Newton	0	6	4
1	Vernon St	Main St	Holyoke	1	2	0
4	Sargeant St	Northampton St	Holyoke	1	5	0
5	Cherry St	Homestead Ave	Holyoke	1	6	0
7	E Main St	Carew St	Chicopee	0	0	0

ID	Road EW	Road NS	City	School	Bus Stop	Alcohol Sales Establishment
8	Simard Dr	Yelle St	Chicopee	0	2	3
11	E Main St	Veterans	Chicopee	0	0	1
20	Beech St	Hospital Dr	Holyoke	2	0	6
86	Granby Rd/Rt. 116	Springfield St	Chicopee	0	3	1
87	Mt Park Rd	Northampton St	Holyoke	0	0	0
1	Locust St	S Main St	Attleboro	0	0	0
2	Columbia St	Broadway	Fall River	0	0	9
4	Dean St	Arlington St	Taunton	1	0	0
5	Mozzone Blvd	County St	Taunton	1	0	2
6	River Wy Ext	County St	Taunton	0	0	0
7	American Legion	Sanford Rd	Westport	0	0	0
8	Grand Army of the	Bushee Rd	Swansea	0	0	1
9	Winthrop St	Warner Blvd	Taunton	0	1	2

Table B.2 - List of Bus Stops, Schools, and Alcohol Sales Establishments within 1,000 ft of the Center of 4SG Intersections

ID	Road EW	Road NS	City	School	Bus Stop	Alcohol Sales Establish-ment
25	Massachusetts Ave	Albany St	Cambridge	0	8	10
26	Binney St	First St	Cambridge	0	0	5
27	Binney St	Third St	Cambridge	1	0	7
28	Broadway	Columbia St	Cambridge	2	9	5
30	Massachusetts Ave	Sidney St	Cambridge	3	6	32
31	Portland St	Main St	Cambridge	1	0	6
34	Massachusetts Ave	Vassar St	Cambridge	0	7	2
35	Broadway	Windsor St	Cambridge	2	8	8
36	Main St	Windsor St	Cambridge	1	4	15
37	Hampshire St/Technology Square	Broadway	Cambridge	1	6	17
38	Broadway	Galileo Galilei Way	Cambridge	1	6	18
24	Grafton St/Boylston St	Main St	Shrewsbury	5	4	1
26	Main St	Bartlett St	Northborough	1	0	8
34	Millbury St	Providence Rd	Grafton	1	0	0
36	Southbridge Rd	Leicester St	Oxford	0	0	2
37	Huntoon Memorial	Stafford St	Leicester	0	0	0
30	Broadway St	Wilder St	Lowell	0	0	0
32	Father Morissette Blvd	Aiken St	Lowell	2	0	6
33	Pawtucket St	School St	Lowell	2	1	0
35	Princeton Blvd	Baldwin St	Lowell	0	1	0
36	Princeton Blvd	Wood St	Lowell	0	2	1
38	Riverside St	University Ave	Lowell	1	1	3
40	Westford St	School St	Lowell	0	1	5
28	Pleasant St	Lindsey St (Haggerty Hwy)	Attleboro	1	0	1
29	Thachet St	County St	Attleboro	3	1	2
30	Allen St	Slocum Rd	Dartmouth	1	0	0
31	Huttleston Ave (Route 6)	Adams St	Fairhaven	4	0	0
32	Huttleston Ave (Route 6)	Alden Rd	Fairhaven	0	0	1
33	President Ave (Route 6)	Robeson St	Fall River	1	0	1
34	New Boston Rd	N Eastern	Fall River	0	0	0
35	Rodman St	Plymouth Ave	Fall River	1	0	5
36	Main St(Precinct St)	Bedford St	Lakeville	1	0	0
37	Rhode Island Rd	Bedford St	Lakeville	0	0	1
38	Center St(Wareham St)	N Main St (S Main St)	Middleborough	1	1	1
40	Coggeshall St	Belleville Ave	New Bedford	0	0	9

ID	Road EW	Road NS	City	School	Bus Stop	Alcohol Sales Establish-ment
41	Union St	County St	New Bedford	5	0	9
42	Hathaway Rd	Shawmut Ave	New Bedford	0	0	0
43	Hawthorn St	Cottage St	New Bedford	3	0	0
44	Hawthorn St	Rockdale Ave	New Bedford	1	0	0
45	Potomska St	JFK Memorial	New Bedford	1	0	4
46	Allen St	Rockdale Ave	New Bedford	1	0	0
47	Rockdale Ave	Dartmouth St	New Bedford	0	0	3
48	Elm St	E Washington St	North	3	1	15
49	Carver St	Broadway	Raynham	0	0	1
52	E Britannia St	Broadway	Taunton	1	1	3
53	Hart St	County St	Mattapoisett	0	1	1
54	1st St	Somerset Ave	Taunton	1	2	2
55	Summer St	Spring St/Church	Taunton	1	0	0
56	Winthrop St	High St	Taunton	1	1	7
57	Winthrop St	Highland St	Taunton	0	0	0
58	Main St	County Rd	Taunton	1	0	2
59	County Rd	North St	Mattapoisett	1	0	4