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**EQUITABLE RESOURCE ALLOCATION TO IMPROVE SAFETY:
AN EVALUATION BASED ON RISK**

A Dissertation Presented

by

ALYSSA M. RYAN

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

February 2022

Civil & Environmental Engineering

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ABSTRACT

EQUITABLE RESOURCE ALLOCATION TO IMPROVE SAFETY:

AN EVALUATION BASED ON RISK

FEBRUARY 2022

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Transportation safety continues to be a serious issue throughout the world. Proven safety measures have been developed to increase the safety on all roadways, but have not been universally and equitably implemented due to lack of resources, inefficiencies, and understanding. Additionally, the relative level of mobility safety remains higher in certain environments than others, creating an inequitable landscape. In this dissertation, the efficiency of using local and state resources to improve safety is investigated while controlling for level of safety risk in vulnerable environments and locations using a comprehensive approach. Several methodologies and techniques are employed and developed to examine both systematic resource allocation and location-specific resource allocation methods from the perspective of equitably and efficiently using limited funds to increase safety. The approaches in this research include machine learning and regression methods, key informant interviews, employment of surveys, and the development of a geospatial tool. When combined and employed at the regional level, the methods presented in this dissertation can impact regional safety from a myriad of perspectives. The results and conclusions of this research informs transportation policymakers', officials', and researchers' abilities to equitably increase road safety through informed state and regional systematic and site-specific resource allocation processes.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iv
ABSTRACT	vi
LIST OF TABLES	xii
LIST OF FIGURES	xiv
 CHAPTER	
1. INTRODUCTION	1
1.1 Problem Statement	2
1.2 Research Hypotheses	2
1.3 Research Scope	4
1.4 Dissertation Organization	4
2. LITERATURE REVIEW	5
2.1 Municipal Composition and Efficiency	5
2.2 Urban and Rural Road Safety	8
2.3 Equity Considerations in Resource Allocation at the Local Level	11
2.4 Horizontal Curve Safety	16
2.4.1 Risk and Demand	17
2.4.2 Driver Performance and Contributing Factors	20
2.5 Geospatial Transportation Safety Tool Development	22
2.6 Crash Proximity Calculation	23
2.7 Equivalent Property Damage Calculation	24
2.8 Summary of Literature Review	28

3. MUNICIPAL HIGHWAY EXPENDITURES AND SOCIO-DEMOGRAPHIC STATUS	30
3.1 Introduction	31
3.2 Application Areas	33
3.2.1 Municipal Structure and Road Ownership in New York State	34
3.2.1.1 Service Distribution	36
3.2.1.2 Roadway Ownership	36
3.2.1.3 Town Funding	37
3.2.2 Municipal Structure and Road Ownership in the Commonwealth of Massachusetts	40
3.2.2.1 Service Distribution	42
3.2.2.2 Roadway Ownership	42
3.2.2.3 Town Funding	42
3.2.3 Application Areas Summary	43
3.3 Methods	44
3.3.1 Data	45
3.3.1.1 Demographic and Population Data	46
3.3.1.2 Highway Expenditure Data	47
3.3.1.3 Local Mileage Data	48
3.3.1.4 Distance from Urbanized Region Data	49
3.3.2 Model Development	49
3.4 Results	51
3.5 Discussion	54
3.6 Conclusions	56
3.6.1 Limitations	57
3.6.2 Research Implications and Recommendations	58
4. AN APPROACH TO EQUITABLE RESOURCE ALLOCATION	61
4.1 Introduction	62
4.2 Methods	64

4.2.1	Data Envelopment Analysis Method	64
4.2.2	Application Areas	67
4.2.3	Survey	67
4.2.4	Key Informant Interviews with Local Highway Officials	73
4.2.5	Selection of Inputs, Intermediate Factors, and Outputs	74
4.2.5.1	Input	77
4.2.5.2	Intermediate Factors	77
4.2.5.3	Output	77
4.3	Results	80
4.3.1	Interviews	80
4.3.1.1	Discussion of Survey Results	81
4.3.1.2	Municipal Highway Funding	83
4.3.1.3	Working with Local MPO/RPO	86
4.3.1.4	Primary Safety Concerns	86
4.3.1.5	Perspective on Training	88
4.3.1.6	Summary	89
4.3.2	DEA Results	90
4.4	Discussion	94
4.4.1	Findings using Massachusetts EPDO Weighting Method	94
4.4.1.1	Municipal Government Composition and Physical Environment Findings	94
4.4.1.2	Equity Considerations of Findings	97
4.4.2	Countermeasure Selection	100
4.4.3	Comparison of Cost Method and Weighting Method using New York Data	102
4.5	Conclusions	103
4.6	Limitations	105
5.	DEVELOPING A GEOSPATIAL SAFETY ANALYSIS TOOL	106
5.1	Introduction	107
5.2	Methods	108

5.2.1	Preliminary Tangent versus Horizontal Curve Analysis	108
5.2.1.1	Data Gathering	109
5.2.1.2	Spatial Analysis and Modeling Approach	109
5.2.2	Safety Tool Development	111
5.2.2.1	Application Areas	112
5.2.2.2	Data Gathering	114
5.2.2.3	Geospatial Analysis	115
5.2.2.4	Data Organization	116
5.2.2.5	Model Development	117
5.2.2.6	Model Application in GIS	120
5.3	Results and Discussion	122
5.3.1	Tangent versus Horizontal Curve Safety	122
5.3.2	Horizontal Curve Safety Tool	126
5.3.2.1	Horizontal Curve Safety Implications of Model Results	126
5.3.2.2	Horizontal Curve Safety Geospatial Application and Tool Development	130
5.4	Conclusions	134
5.4.1	Limitations	135
6.	CRASH PROXIMITY AND EQUIVALENT PROPERTY DAMAGE CALCULATION TECHNIQUES	137
6.1	Introduction	138
6.2	Methods	140
6.2.1	Horizontal Curve Data	140
6.2.2	Roadway Inventory Data	141
6.2.3	Geolocated Crash Data	142
6.2.4	Geospatial Analysis	142
6.2.5	Data Preparation	143
6.2.6	Model Development	148
6.3	Results and Discussion	150

6.3.1	Impact of Crash Distance Calculations.....	150
6.3.2	Impact of EPDO Calculation Method	151
6.3.3	Horizontal Curve Safety Implications	155
6.4	Conclusions.....	157
6.4.1	Limitations	159
7.	CONCLUSIONS, PRACTICAL IMPLICATIONS, AND FUTURE EXTENSIONS	160
7.1	Conclusions.....	160
7.2	Conclusions of Research Hypotheses	163
7.3	Practical Implications.....	166
7.4	Research Contributions	168
7.5	Future Extensions	169
7.5.1	Systematic Analyses.....	169
7.5.2	Location-Specific Analyses	171
	APPENDIX: NEW YORK AND MASSACHUSETTS MUNICIPAL SURVEYS AND CORRESPONDENCE	172
	BIBLIOGRAPHY	187

LIST OF TABLES

Table	Page
2.1 Massachusetts weighting methods of equivalent property damage only (EPDO).	27
3.1 Summary statistics of New York Town data.	46
3.2 Summary statistics of Massachusetts town data.	46
3.3 OLS regression models predicting town highway expenditures (million USD) per local lane mile in New York.	52
3.4 OLS regression models predicting town highway expenditures (million USD) per local centerline mile in Massachusetts.	53
4.1 Summary statistics of survey-collected variables.	72
4.2 Summary statistics of crash, expenditure, geographic, and demographic variables.	76
4.3 Pearson Correlation Matrix of New York data.	91
4.4 Pearson Correlation Matrix of Massachusetts data.	91
5.1 Summary of Maryland categorical variables.	118
5.2 Summary of Vermont categorical variables.	119
5.3 Summary of continuous variables prior to scaling.	120
5.4 Preliminary analysis model coefficient summary.	123
5.5 Maryland model results.	127

5.6	Vermont model results.....	128
6.1	Summary of curve crash calculations of example curve.....	145
6.2	Summary of continuous variable values (per curve per year) prior to scaling.	146
6.3	Summary of categorical variables (per curve per year).	147
6.4	Summary of model results.	153
6.5	Summary of RSME model results.	154

LIST OF FIGURES

Figure	Page
2.1 United States Rural and Urban Interstate Fatality Rates. Adapted from the Federal Highway Administration Road Safety Data Dashboards (Federal Highway Administration, b)	9
2.2 United States Rural and Urban Non-Interstate Fatality Rates. Adapted from the Federal Highway Administration Road Safety Data Dashboards (Federal Highway Administration, b))	10
4.1 Data envelopment analysis results.	93
5.1 Massachusetts curve segments and crashes in 2017.	110
5.2 Methodology flowchart.	113
5.3 Probability of EPDO crashes per mile depending upon traffic volume and segment type.	124
5.4 Probability of EPDO crashes per mile depending upon road operation and segment type.	124
5.5 Predicted total crash severity of all curves on state roads in Vermont.	131
5.6 Predicted total crash severity of all curves on state roads in Maryland.	132
5.7 Curve details using identify function in ArcMap.	133
6.1 Example of calculation of crashes at curve.	144

CHAPTER 1

INTRODUCTION

Safety remains a serious problem for all modes of transportation throughout the world. The cost for mobility safety remains too high because, as noted by the World Health Organization, proven safety measures exist that could be implemented (World Health Organization, 2018). However, due to inefficiencies and lack of resources, these safety measures are not implemented to the highest extent. In 2018, the number of road traffic deaths reached 1.35 million worldwide (World Health Organization, 2018). With a more efficient use of resources, lives could be saved.

Surface transportation safety remains a serious issue at all road ownership levels and in a variety of environments; however, the relative level of safety remains higher in certain regions and environments than others. For example, urban and rural regions experience different rates of traffic fatalities in the United States. Rural areas have a fatal crash rate per vehicle mile traveled (VMT) that is 2.1 times higher than urban areas (National Center for Statistics and Analysis, 2019). A number of socio-economic and/or socio-demographic characteristics may be related to the potentially inequitable distribution of resources for transportation safety purposes amongst different regions.

Vulnerable roadway locations are of increased concern, particularly municipally-owned roadways and horizontal curve locations. The municipally-owned roadway fatality rate per 100 million VMT in the U.S. in 2018 was 3.6 times higher than the fatality rate on interstates and arterial roadways (Federal Highway Administration, 2019). Horizontal

curves have been recognized as high risk safety locations for decades (Elvik, 2019; Fildes and Triggs, 1985; Khan et al., 2013). While several countermeasures exist that would lead to safer conditions in these roadway environments, they are not always implemented. Further, if they are implemented, they may be implemented inefficiently, leading to less available funding for other unsafe roadway locations. Overall, identifying both systematic and location-specific allocation methods that can be used in tandem is critical to improve safety.

1.1 Problem Statement

Municipal, regional, and state officials have difficulty making safety decisions for their roadways and may not have the ability to prioritize more beneficial investments in their resource allocation processes over others. Thus, a need exists to investigate the appropriate investments and countermeasures to optimize funding to improve safety accounting for multiple funding perspectives, including regional funding and site-specific funding mechanisms. To fulfill this need, this research investigates multiple methods of efficient and safety-conscious resource allocation at the local and state level. With safety and equity at the forefront of this research, the following research hypotheses were developed to address the aforementioned problems.

1.2 Research Hypotheses

The objective of this research is to identify and develop solutions to improve surface transportation safety equitably and efficiently based on risk through improved resource allocation methods both at the systematic and location-specific levels. This dissertation uses a variety of methods to address this problem. The following research hypotheses describe the specific problems that this research confronted. The first two hypotheses aim

to investigate systematic resource allocation issues related to safety, and the following two hypotheses investigate how resources, once they are obtained by regional or local agencies, may be allocated at the location-specific level to create safer roadway networks.

Research hypothesis 1: Municipal roadway funds are issued disproportionately depending on the socio-demographic and socio-economic makeup of a given region. Municipalities that are less impoverished, are less racially diverse, are closer to urbanized areas, and have an older population receive more municipal roadway funding.

Research hypothesis 2: There is a direct connection between the organization structure of a municipal government and socio-demographic characteristics of a region and their ability to efficiently use local highway funding to improve roadway safety. Specifically, the presence of specific municipal staff with a lower level of education and regions that are more rural and more racially diverse are correlated with inefficiencies in spending towards local road safety.

Research hypothesis 3: Safety issues are heightened on horizontal curve segments and geospatial tool development is not well documented in current literature. A methodology to create a comprehensive statewide horizontal curve safety tool can be developed and implemented for a given region, streamlining the safety improvement process.

Research hypothesis 4: There remains a lack of consensus among safety practitioners and researchers as to the optimal method for locating these high-risk locations. A proximity technique that weights crashes more heavily based on their distance to a target roadway segment and less specific crash severity weighting method provides optimal results compared to other commonly used approaches.

1.3 Research Scope

Many potential factors influence mobility safety, equity, and resource allocation. However, the scope of this particular research focused only on the above research hypotheses using data there were able to be collected. This research focused on a set of factors that are not commonly included in studies on resource allocation or safety, thereby adding to our existing knowledge.

1.4 Dissertation Organization

This dissertation constitutes of seven chapters. Chapter 1 presents the problem statement, corresponding research hypotheses, and scope of this research. The literature review on equity, safety, resource allocation, horizontal curves, geospatial tool development, and high-risk crash analysis techniques pertaining to this research is discussed in Chapter 2. Chapter 3 discusses the relationship between municipal highway expenditures and socio-demographic status. Chapter 4 covers an approach to equitably and efficiently distribute and use resources to improve municipal safety. The following two chapters investigate extensions of these first two chapters and demonstrate specific methods to prioritize safety projects at the regional level. Chapter 5 discusses the development of a methodology to create a regional geospatial horizontal curve safety tool. Chapter 6 presents crash proximity and equivalent property damage calculation techniques to improve the accuracy of high-risk crash analyses. The dissertation concludes in Chapter 7 with the conclusions, contributions, and future extensions of this research.

CHAPTER 2

LITERATURE REVIEW

Resource allocation, safety, and equity is influenced by numerous regional and environmental factors. The following chapter introduces prevalent safety disparities and influencing factors of these differences through a review of research studies. Section 2.1 discusses the efficiency, funding, and composition of municipal governments that own over 77% of roads in the United States (Federal Highway Administration, 2018). Section 2.2 summarizes the safety disparities, and therefore different needs, of urban and rural regions. Section 2.3 then presents the equity disparities at the local road level, including in terms of safety. Following, Section 2.4 summarizes the safety literature at horizontal curves, locations of increased safety concern, especially in rural areas. This includes the environmental, perceptual, and other factors that lead to the safety issues at these locations. Geospatial safety tool development is then discussed in Section 2.5, followed by Section 2.6 which presents considerations of proximity to crashes to specific locations in crash analysis. Section 2.7 discusses the use of equivalent property damage only calculations in the identification of high-risk crash locations. Finally, this Chapter concludes with a summary of the reviewed literature.

2.1 Municipal Composition and Efficiency

Over 77% of roads in the U.S. are owned by local governments (Federal Highway Administration, 2018). To consider adequately road safety, or any road factor, local

agencies must be considered in the process (Magnusson et al., 2020). At the same time, municipal road safety remains a serious concern. The municipally-owned roadway fatality rate per 100 million VMT in the U.S. in 2018 was 3.6 times higher than the fatality rate on interstates and arterial roadways (Federal Highway Administration, 2019). To work towards improving road safety on any widespread scale, individual communities, and therefore, local agencies, must be considered (Magnusson et al., 2020).

In the U.S., the idea that smaller governments lack financial resources to provide basic services to residents is not a new concept (Brown, 1980). MacManus and Pammer (1990) suggest that smaller municipalities may be more likely to reduce expenditures than create revenue; due to the lack of flexibility of smaller municipalities, they may rely on cutting spending when federal aid programs are reduced rather than resort to revenue approaches to adjust for losses. Since more populated areas have a larger tax base and economic mix than non-urban areas, MacManus and Pammer (1990) suggest that municipalities in those areas have a greater capacity to generate additional revenue. Given this disparity, smaller municipalities historically did not have the same access to hire professional staff or consultants to provide expert advice or complete projects (Snavely and Sokolow, 1987). This has not changed in recent years. Landes (2009) stated that in Pennsylvania, smaller municipalities often cannot afford to hire professional recreation staff. Instead, they rely on volunteers or neighboring municipalities. Furthermore, this observation that smaller governments are unable to hire professional staff aligns with data collected in this study and is a trend that is still present today.

From an educational perspective, some municipalities have a less skilled workforce. In Canada, more rural municipalities with smaller populations have lower levels of literacy and numeracy proficiency as compared to medium, large, and urban areas (Zarifa et al., 2019). Further, populations in more rural areas are less likely to enter lucrative Science

Technology Engineering, and Mathematics (STEM) fields than populations in more urban areas (Hango et al., 2019). Thus, the workforce of these smaller communities, and therefore, government officials, are likely less skilled on average than their urban counterparts. Historically and to this day, as demonstrated later in this chapter, municipal governments tend to be run by elected officials who lack education or skills relevant to transportation decision-making (Snaveley and Sokolow, 1987). In general, since expertise is in short supply, policy decisions, such as funding and/or highway decisions at the municipal level, can often be ill informed. Often, elected officials take to their own source of “expertise” on a given matter to run their municipality (Sokolow, 1984). Deller and Halstead (1991) found that in northern New England, only 50.8% of town road officials had received any formal road maintenance or management practice training. Of those towns, survey data analysis revealed an annual road maintenance budget cost savings of \$11,600 (\$22,800 in 2019 USD) on average for towns who had officials complete formal training (Deller and Halstead, 1994). Yet, no research to date has been identified that compares the safety of local roads with the educational expertise of municipal highway officials.

Smaller towns have been shown to use resources less efficiently. Empirical evidence from a sample of Midwestern towns suggests that larger towns are more efficient than smaller towns (Deller and Nelson, 1991). One reason may be due to managerial inefficiencies. Data from local governments within three states implied that nearly 45% of rural road expenditures may be “unnecessarily incurred due to managerial inefficiencies” (Deller et al., 1992). To solve these inefficiencies, Deller et al. (1992) does not suggest that it is necessary to consolidate these governments, but rather create policies of cooperative agreements or jointly hired engineers by multiple municipalities in close proximity. Today in New York, it is recommended by the Association of Towns that town governments create similar cooperative agreements to share equipment or services (Association of Towns,

2017), likely done out of necessity to lower costs. No literature has been found on cases of jointly hired engineers between local governments to date anywhere in the U.S.

2.2 Urban and Rural Road Safety

Local road safety is more critical in areas that are more rural. In 2017, 20% of fatalities in rural areas occurred on local roads, 39% on collectors, and 41% on arterials (Insurance Institute for Highway Safety, 2018). In urban areas, local roadways and collectors accounted for 14% and 9% of fatalities, with arterials accounting for the majority of fatalities (77%) (Insurance Institute for Highway Safety, 2018). This disparity is heightened by the volume of roads in rural areas and the various types of jurisdictions that own them. In the U.S., 2.9 million of the 4.1 million miles of public roads, or 71%, are in rural areas (Congressional Research Service, 2018). Research by González-González and Nogués (2019) in Spain suggests that the implementation of new transportation infrastructure has been poorer in areas that are more rural, likely due to factors such as human capital development and rural economy diversification. At the same time, drivers in the United States in areas defined as “urban” by the National Household Travel Survey traveled an average of 9,930 miles annually in 2009, while drivers living in rural areas drove 150% that amount, an average of 14,856 miles that same year (Baxandall, 2013). This creates a disparity in terms of safety, as those in rural areas must travel longer distances to access the same services as those in urban areas, which increases their risk of experiencing a crash. On top of increased risk in rural areas simply due to increased vehicle miles traveled (VMT) in rural areas, the risk of a fatal crash per VMT is 2.1 times higher in rural areas than urban. In 2017, the fatality rate per 100 million VMT on rural roadways was 1.79, compared to urban roadways with a rate of 0.85 (National Center for Statistics and

Analysis, 2019). On federally owned roads, significantly higher fatality rate in rural areas than in urban areas is presented in Figure 2.1 (Federal Highway Administration, 0b).

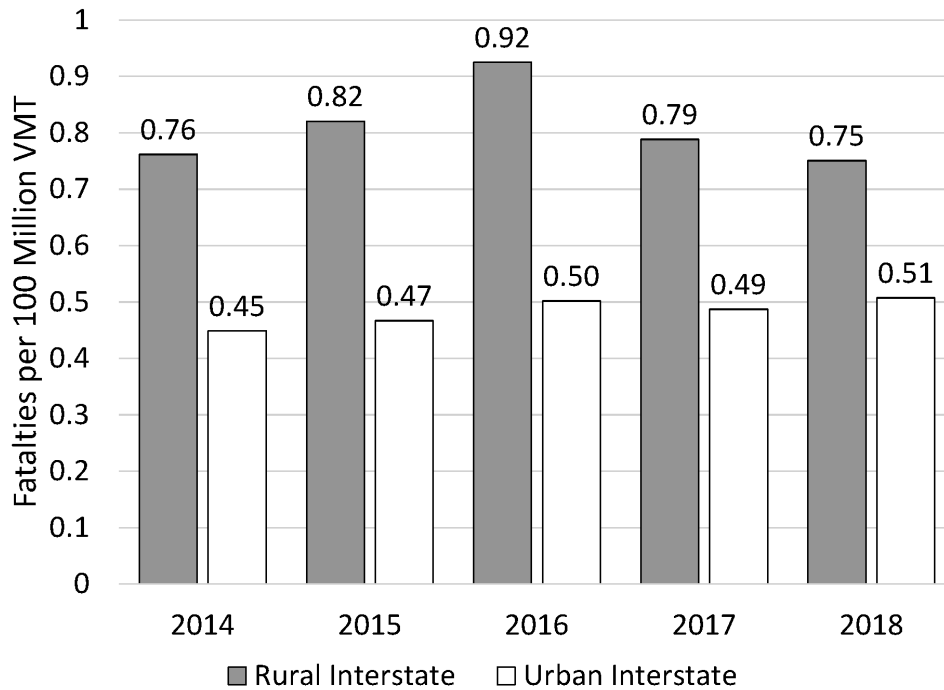


Figure 2.1. United States Rural and Urban Interstate Fatality Rates. Adapted from the Federal Highway Administration Road Safety Data Dashboards (Federal Highway Administration, b)

The fatality difference between rural and urban roadways is also prominent on non interstate roadways as represented in Figure 2.2 (Federal Highway Administration, 0b). This disparity is likely related to numerous factors. One may be the proximity to hospitals as they are more widely spread in rural areas. Drivers in rural areas represented 52% of drivers who died en route to a hospital compared to 47% for drivers in urban areas in 2017 (National Center for Statistics and Analysis, 2019). This disparity is likely not due to driving under the influence or speeding, as of the 10,874 alcohol-impaired-driving fatalities

in 2017, there were 4,935 that occurred in rural areas, 5,702 that occurred in urban areas, and of the 9,717 speeding-related-driving fatalities, 4,660 occurred in rural areas (National Center for Statistics and Analysis, 2019). However, rural areas often have higher speed limits and thus, drivers travel at higher speeds even if they aren't speeding. In 2017, 71% of roadway fatalities in rural areas occurred on roadways with speed limits of 55 mph or higher, while 29% of fatalities in urban areas occurred on these roads (Insurance Institute for Highway Safety, 2018).

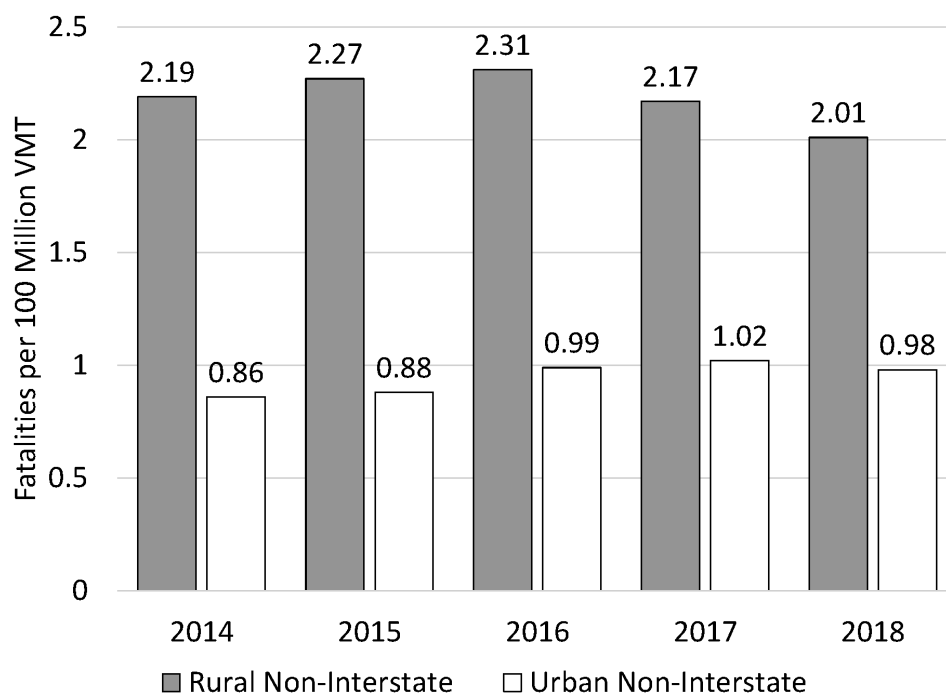


Figure 2.2. United States Rural and Urban Non-Interstate Fatality Rates. Adapted from the Federal Highway Administration Road Safety Data Dashboards (Federal Highway Administration, b))

Non-motorist safety is also remains major concern in rural areas. In 2017, 19% of pedestrian deaths and 24% of bicyclist deaths occurred in rural areas. While no data was

found that related these values to distance traveled to provide relativity, a comparison can be made as approximately 19% of the U.S. population lives in rural areas (U.S. Census Bureau, 2012).

2.3 Equity Considerations in Resource Allocation at the Local Level

With a wide range of municipal government types and residential characteristics, different needs by varying population groups and regions should be expected. Among all transportation facility types, research has proven that benefits of transportation systems are unevenly distributed to different regions and population groups (Dodson et al., 2006). This discrepancy can be detrimental for already disadvantaged communities as wealth inequality is correlated with different levels of transportation accessibility and safety. Cycling infrastructure is unequally distributed in Bogotá, Colombia, with wealthier areas having more infrastructure than poorer areas (Torres-Barragan et al., 2020; Rosas-Satizábal et al., 2020). Potvin et al. (2019) found that low-income individuals are less protected by the presence of noise barriers than high-income individuals and are over-represented in proximity to major traffic routes in Montreal, Canada. Air quality is disproportionately worse for Black and non-white Hispanics residents in the U.S. People who are white experience 17 percent less air pollution than what they cause through consumption, while people who are Black and Hispanic experience 56 percent and 63 percent more air pollution, respectively, than they cause by their consumption (Tessum et al., 2019). Previous literature has shown that accessibility levels are lower for older aged individuals, those who are lower-income residents, those born in an ethnic minority or economically disadvantaged family (Alsnih and Hensher, 2003; Pereira et al., 2017; Guzman and Oviedo, 2018). The level of accessibility within a region depends upon the transportation funding that is available. Into the future, as sea levels rise with climate change, lower-income residents will experience even

greater reductions in accessibility (Noland et al., 2019). Noland et al. (2019) suggests that transportation justice must be considered in all planning stages to actively prevent these disparities from continuing in the future. Pereira et al. (2017) suggested accessibility should be the primary focus of transport researchers and policy-makers when addressing questions and decisions aimed to combat transport disadvantage and social exclusion. This issue is of increased concern at the municipal level due to the varying population groups and regional characteristics. For example, residents of small municipalities in the U.S. have been shown to walk less than those living in larger metropolitan regions (Doescher et al., 2014). These residents may make up for this walking in driving, as drivers in rural regions in the U.S. drive approximately 150% more than drivers in urban regions (Baxandall, 2013). These differences represent some of the varying transportation needs at the municipal level. Differences in transportation needs can exist for members of certain socio-demographic and/or socio-economic population groups. Travel behavior has also been shown to differ based on race (Mauch and Taylor, 1997; Giuliano, 2003; Klein et al., 2018), income (Kotval-K and Vojnovic, 2015; Bills and Walker, 2017; Cui et al., 2019; Boarnet et al., 2020), gender (Mauch and Taylor, 1997; McGuckin et al., 2005; Klein et al., 2018), ability (Cochran, 2020; Low et al., 2020; Prescott et al., 2021), age (Buehler and Nobis, 2010; Corran et al., 2018), and remoteness (Pyrialakou et al., 2016b; Shirgaokar et al., 2020), yet these characteristics are not currently accounted for in local highway funding distribution algorithms. Poverty has also been found to have a relationship with the crash rate in specific regions (Wier et al., 2009; Lindsey et al., 2019). Disproportionately providing resources to different communities could be unintentional in these processes, yet it still has a negative impact. To avoid these disparities in decision-making and resource allocation, local socio-economic and socio-demographic characteristics need to be considered.

Boyles (2015) describes how resource allocation is often subject to budget constraints that aim to minimize the total cost or prioritize projects with high benefit/cost ratios (Boyles, 2015). One common benefit/cost ratio funding allocation method focuses on increasing road safety. For this reason, several methods have been developed to identify high crash locations, often referred to as “hotspots” (e.g., Schultz et al. (2015); Lee and Khattak (2019)). Funding allocation based on safety-related issues has proven to effectively improve highway safety in those areas and prevent future crashes; however, crashes also occur in areas with low traffic volumes, where a large density of crashes has a very low chance of occurring. Rather, in these often more rural areas, crashes are less concentrated and more likely to be scattered throughout a roadway network. These regions are also more likely to experience higher fatal crash rates (National Center for Statistics and Analysis, 2019). While the funding “hotspots” may maximize the cost/benefit in terms of safety, benefited areas will also always be concentrated in urban areas as even a small roadway improvement is multiplied by the volume of road users in the funding allocation formulas that are used. Boyles (2015) notes this funding decision mechanism alone is not feasible, as concentrating funds in urban areas is not responsible or fair (Boyles, 2015). In short, this process can lead to inequitable maintenance and transportation infrastructure funding allocation decisions.

To overcome this issue and account for equity within the funding process, some regions have developed scoring methods for project funding decisions that include equity, noise, accessibility, safety, air quality, and physical activity considerations of a project along with other economic features (Christofa et al., 2020). However, these project scoring methods are not yet widely used, and none of them consider all of these factors (Christofa et al., 2020). Further, these developed scoring methods are framed on a project-basis, not from a systematic funding perspective. In urbanized areas with populations of 50,000 or more,

metropolitan planning organizations (MPOs) are required to consider equity implications of their transportation plans and processes and ensure that underserved communities receive a fair distribution of benefits from a regional system (Williams et al., 2019). A study of equity considerations within project prioritization across Florida MPOs found that they are making major strides towards incorporating equity in their processes (Williams et al., 2019). However, even in these processes, widespread equity performance measures and targets for project prioritization are lacking for MPOs and regional planning organizations (RPOs) across the United States (Karner, 2016; Williams et al., 2019). Overall, studies investigating current MPO processes and regional transportation plans conclude there is a need to improve equity analyses and have a clearer understanding of the impacts of transportation policies on underserved communities (Sanchez et al., 2004; Karner and Niemeier, 2013; Karner and London, 2014; Golub and Martens, 2014; Karner, 2016). What's more, many municipalities do not fall within MPO boundaries. In New York, approximately 60% of towns are not within MPO regions and therefore, do not directly benefit from MPO funding. Thus, equitable distribution of municipal funding remains an important concern worthy of studying and improving. Yet, municipal roadway funding distribution is still primarily based on fixed formulas developed at the state level. Equity, to date, has not been considered in these formulas. Grants have also been developed to increase transportation equity in certain regions (i.e., Federal Transit Administration (2020); Moving California (2020)). However, these grants are only available to those who have the means to apply for these grants, such as the staff to prepare such grant applications. Grants also offer a less stable funding source than a systematic, fixed funding source. These grants, when received, also have the ability to potentially distort the current investment planning, decision-making, and evaluation processes of equity considerations that existed prior to receiving these grants. This could be exacerbated further if the grant funding is only

allowed to be used for specific equity purposes that may not equally benefit all granted municipalities. For example, assume that municipal highway funding was planned to be allocated to build sidewalks in an underserved neighborhood. Later, an equity-centered grant was received that provided funds to improve bicycle facilities for the same underserved neighborhood. Since the municipality now might have felt that their communities were provided with an improvement, they may not plan to continue with their plan to provide sidewalks for the neighborhood. Further, safety specifically is not the primary consideration in these types of funding, or sometimes not considered at all. In a systematic review of transportation equity literature, Guo et al. (2020) found that researchers have not adequately assessed safety impacts from an equity perspective.

In summary, municipal transportation funding can be gathered through a number of capacities, including through individually applied-for grants, emergency aid, and generated revenue from a tax base, among other avenues, at the local, regional, state, and federal levels. Overwhelmingly, the highest revenue generator for local highway funds in the U.S. comes from state general funds (Ohlms, 2014; Federal Highway Administration, 0c). Property taxes are the second highest source of revenue (Ohlms, 2014). Generating revenue may be more difficult for some municipalities with certain characteristics, such as being more rural or having a smaller tax base. Previous literature suggests rural municipalities may not have the ability to use their resources efficiently and/or may have fewer resources to begin with due to their inability to generate their own revenue from municipal service fees and/or taxes (MacManus and Pammer, 1990; Brown, 1980). This lack of revenue generation in rural areas likely stems from their lack of services that could generate funding through user fees in these regions and/or lower per-capita income levels (MacManus and Pammer, 1990). Further, rural governments have smaller tax bases; as a result, highway costs are higher per capita for rural residents (Long, 1987). Overall, rural areas are negatively associated

with revenue-generating capabilities. Still, the relationship between socio-demographic and socio-economic characteristics and municipal highway funding decisions are limited in the literature. Further, the current fixed formulas that control the distribution of roadway funding from state governments to municipal governments allocate an equal distribution of resources often based solely upon population size and/or local roadway mileage. This equal distribution would be equitable if the populations receiving these funds had equal abilities and equal needs (Theobald, 2001). However, this is not the case, as the infrastructural, socio-economic, and socio-demographic differences between population groups and regions lead to varying transportation needs (Pereira et al., 2017). Thus, this current funding method is inequitable and likely disproportionately affects disadvantaged population groups. Without an equitable municipal highway funding method, accessibility and road safety cannot be equally considered across different population groups.

2.4 Horizontal Curve Safety

Horizontal curves are curves that “change the alignment or direction of the road (as opposed to vertical curves, which change the slope)” (Federal Highway Administration, 2014b). Design standards for horizontal curves in the National Highway System (NHS) in the United States are regulated by the Federal Highway Administration and are stated within the Green Book (American Association of State Highway and Transportation Officials, 2018). State transportation agencies are able to adopt standards that are more restrictive than the Green Book prescribes, but are not allowed to be less restrictive. Horizontal curves have disproportionately high crash rates and have been recognized as high safety risk locations for decades (Elvik, 2019; Fildes and Triggs, 1985). In 2019, an estimated 36,120 people were killed in motor vehicle crashes on U.S. roadways (National Center for Statistics and Analysis, 2020). Horizontal curve segment crashes have an average fatal-

ity rate more than three times the fatality rate of all crashes on all roads and are estimated to account for nearly 25 percent of all people who die each year on U.S. roadways (Hummer et al., 2010; Torbic et al., 2004). The safety risk on horizontal curves has been found to be influenced by a number of factors, including the road surface friction, use of signage, median type, curve radius, pavement condition, and speed limit (Elvik, 2019; Fitzpatrick et al., 2001; Gong and Stamatiadis, 2008; Buddhavarapu et al., 2013; Donnell et al., 2019). Extensive research has identified that behavioral factors influence the occurrence of such crashes, e.g., inappropriate speed monitoring, poor lane positioning, etc. (Charlton, 2007; Khan et al., 2013). Further, statistics show that curve safety is most critical on two-lane rural highways compared to urban, single lane, and lower speed roadways (Donnell et al., 2019). To assist drivers in these situations, countermeasures can offer guidance, leading drivers to anticipate a curve more accurately. However, the most beneficial countermeasure for a curve is not always implemented or is implemented inefficiently due to a lack of full understanding of driver behavior at curves compared to tangent roadway segments. Overall, horizontal curve safety remains a significant safety issue that is of high concern at all government levels.

2.4.1 Risk and Demand

Several theories explain why people adjust their behavior while driving. Jiang et al. (1992) provides a review of many of these theories. The theory of risk homeostasis is of particular concern at horizontal curve locations. This theory suggests all people adjust their behavior in response to their desired level of perceived risk (Wilde, 1982; Taylor, 1964). At any moment in time, Wilde (1982) suggests a road user perceives a certain level of subjective risk and compares it with the level that they would like to accept, or their “target risk.” If the level of risk is perceived to be higher or lower than their target level of risk, the individual will attempt to eliminate this discrepancy. In these instances, the way

in which a driver behaves and performs on the road is effected by three skills: perceptual skills determine the level of subjective risk compared to objective risk, decisional skills determine what should be done to produce the desired adjustment, and vehicle handling skills determine if the road user has the ability to carry out what should be done for the desired adjustment (Wilde, 1982). These skills can differ depending on the driver. For example, young/novice drivers tend to overestimate their skill level (Matthews and Moran, 1986; Finn and Bragg, 1986; De Craen et al., 2011). Further, overconfident drivers have shown to adapt their driving behavior less in complex traffic situations than other drivers and thus, are less adequate in their adaption in new environments (de Craen et al., 2007).

Wilde (1982) originally assumed that these feelings of risk were the same as drivers' estimates of the probability of crashing. However, Fuller (2005) concluded these two were not the same. Drivers may target a level of risk, but that is not to say they target a level of crash involvement. The two statistical risks will only begin to converge when task demand approaches capability and the driver speculates there will be no unexpected increase in demand and no unexpected decrease in capability (Fuller, 2005). This is due to the relationship between feelings of risk and the perception of task difficulty. As a driving task, or vehicle handling task, becomes more difficult, the margin between what must be done and a driver's capability shrinks. The driver then becomes closer to losing control (Fuller, 2005). Thus, if a driver feels their task difficulty is increasing and they are aware of their capabilities, then their feeling of risk also increases.

Driver task, or vehicle handling, demand is effected by a number of interacting elements. Environmental factors such as visibility, road alignment, road signs, road surfaces, curve radii, and so on, impact demand. Other road users and operational features of vehicles impact demand. Further, the elements that drivers have direct control over impact their demand, such as their speed and trajectory. Thus, in driving situations where

a change of safety is needed to be evaluated due to these changing factors, a driver is tasked with determining their perceived risk, deciding how to produce their desired risk adjustment and carrying out the adjustment. One common circumstance of change for drivers is during the transition from a tangent section to a curved section. McDonald and Ellis (1975) found that negotiating curves requires more cognitive demand than tangent sections. As drivers transition from a tangent to a curve segment, drivers must evaluate the geometric factors of the curve prior to adapting their speed and steering to conform to the new conditions.

Given this increased driver task demand at curves, research suggests that speed perception underestimation could increase crash risk, particularly at sharp curves (Milošević and Milić, 1990). Additionally, drivers' perceptions are predominately influenced by a curve's deflection angle and less by a curve's radius (Fildes and Triggs, 1985). Small deflection angle curves are also seen as less curved than large angle curves (Fildes and Triggs, 1985). Thus, driver performance along horizontal curves in varying roadway environments is directly connected to the safety of these locations (e.g., Fildes and Triggs (1985); McDonald and Ellis (1975)).

Overall, horizontal curve safety is influenced by a number of contributing factors including the median type, curve deflection angle, road surface friction, time of day, and pavement condition (Elvik, 2019; Buddhavarapu et al., 2013; Donnell et al., 2019; Stamatidis et al., 2020). A study by Stamatidis et al. (2020) found that crashes at night are observed at higher rates than during the day on small radii curves. Previous research has also suggested that curves with smaller radii are less safe per mile or per kilometer (Elvik, 2019). Research has suggested that a roadway with many sharp curves will have a lower crash rate than an otherwise identical roadway with less sharp curves (Elvik, 2019; Hayward, 1980; Khan et al., 2012, 2013). Thus, the perceptual challenges of horizontal

curves can either be perpetuated or mitigated by the characteristics of a curve. These characteristics should be considered when evaluating appropriate safety countermeasures at specific horizontal curves.

2.4.2 Driver Performance and Contributing Factors

Driver performance on horizontal curves has been shown to be influenced by a number of factors including the perceived level of rise, use of signage, and curve radius (Elvik, 2019; Fitzpatrick et al., 2001; Gong and Stamatiadis, 2008; Buddhavarapu et al., 2013; Donnell et al., 2019). Curve negotiation requires that drivers anticipate the curve through the adjustment of their speed and lane position to accommodate the severity of the curve (Reymond et al., 2001). This event requires enhanced attention compared to tangent sections, given the need for drivers to evaluate geometric factors before adapting their speed and steering to conform to the new roadway condition (McDonald and Ellis, 1975). Speeds have been found to be underestimated by drivers at curves (Milosević and Milić, 1990), particularly during the approach section (Retting and Farmer, 1998).

Edge lines along curves have been shown to visually guide driver steering and reduce crashes (Coutton-Jean et al., 2009; Taylor et al., 1972). However, drivers still continue to travel differently along curves than tangent sections with edge lines. In a simulation study by Coutton-Jean et al. (2009), drivers did not remain in the middle of the lane during curve negotiation, but rather traveled on the outside of the lane on their approach to the curve and then cut into the curve, passing through the middle at the entry of the curve. These “cutting” paths have been reported by other studies and it is theorized that such a trajectory allows drivers to maintain a higher speed through the curve (Fitzsimmons et al., 2013). Lane width has also been found to influence a driver’s position within their lane, with a 7.60 meter wide lane having more deviation from the middle towards the inside of the curve than a 3.80 meter wide lane (Coutton-Jean et al., 2009).

Several studies have found that driver speed on horizontal curves is influenced by the radius. Research by Calvi (2015) found that drivers drove at higher average speeds at wider curves. Montella et al. (2015) found that on smaller radius curves, deceleration ended closer to the center of the curve, while acceleration started closer to the end of the curve. When the curve radius was increased, the end point of deceleration was further towards the start of the curve, while the beginning of acceleration began further towards the center of the curve (Montella et al., 2015). Further, Bella (2014) found the speed at the midpoint of a curve was affected solely by the radius, not by the curve direction.

While previous studies have the ability to offer insight into the expected performance of drivers at horizontal curves, it is critical to acknowledge that horizontal curve speeds can be impacted by their location. In challenging local or regional road conditions, design standards are often lowered to reduce cost and avoid compromising the environment in relation to conservation. Lower design standards of horizontal curve alignment often takes the shape of curves designed with a reduced design speed compared to their adjacent tangent sections (Figueroa Medina and Tarko, 2007). Given this discrepancy, advisory speeds are posted together with warning signs at these locations. However, as stated, previous research has indicted that advance warning signs at curves, even with advisory speed plates, do not provide an adequate safety change (Charlton, 2004, 2007). This issue becomes exacerbated by the underestimation of speed by drivers. Perception of vehicle speed by a drivers has been shown to be underestimated on straight roadways, particularly at faster speeds or after deceleration (Evans, 1970; Denton, 1966, 1967; Triggs and Berenyi, 1982). Milosević and Milić (1990) found speed underestimation to be true at curves as well. Given the increased driver task demand required at curves, speed perception underestimation could increase crash risk, particularly at sharp curves (McDonald and Ellis, 1975; Milosević and Milić, 1990). The perception of curves themselves by drivers

further increases this issue. Overall, the dynamics of driver speeds at horizontal curves are complex and must be further considered in further research.

2.5 Geospatial Transportation Safety Tool Development

Several safety tools exist in current practice in the transportation sector. These tools range from countermeasure selection tools (Federal Highway Administration, 0a) to speed-selection tools (Federal Highway Administration Safety Program, 2014). However, these tools are not geospatially based. The use of geographic information systems (GIS) allows for a dynamic display of results that can be more easily interpreted by a broader audience, including non-specialists (Mavroulidou et al., 2004). GIS is commonly used to support practitioners and researchers in the transportation decision-making process (Olsen et al., 2013). State and regional agencies have used GIS to improve decision making and increase efficiency, among other uses (Colton et al., 2015). However, the methodologies that would describe the development of these tools is not well documented. Thus, they are difficult to reproduce, especially for smaller agencies with potentially less staff and/or technical expertise. Mavroulidou et al. (2004) developed a GIS tool to perform preliminary air quality assessments at the local level for local authorities and transport planners. The study concluded that the developed methodology did not require highly skilled numerical modellers to implement, and thus, would be useful for local authorities and urban planners (Mavroulidou et al., 2004). Further, Mavroulidou et al. (2004) found that the maps could be analyzed at varying levels of complexity depending upon the specific user ability. Scaini et al. (2014) found that the methodology they used to create a tool to support air traffic management during explosive volcanic eruptions could be flexible to include different inputs. This was also stated by Ortega et al. (2014), as the creation of a GIS tool for a specific purpose and region allows researchers to use their own data as inputs rather than

relying on other tools that use predefined data or are created for different regions. However, Scaini et al. (2014) included the creation of a geospatial tool relies on the availability of required data, software, and computational requirements.

Overall, the documentation of the development of GIS tools and the benefits and challenges of creating regional and goal-specific tools in the transportation sector is limited in current literature. For the purposes of this research, curve identification tools have been developed to extract horizontal curve information within a given region (Li et al., 2012; Faghri and Harbeson, 1999; Ai and Tsai, 2015); however, none have been expanded to be used as a safety tool to identify critical curves.

2.6 Crash Proximity Calculation

The buffer technique is commonly used to define the affected safety area associated with a target segment in traffic safety analysis (e.g., Pyrialakou et al. (2016a); Khan et al. (2013); Zhang et al. (2015); González et al. (2019); Avelar et al. (2015)). If a crash occurs within the defined buffer, or defined threshold distance, of a target segment, it is assumed that the crash is likely associated with that specific target road segment. Previous research has discussed that the size of buffers for different target road segment types (such as buffers that include all intersection-related crashes for an intersection study) is not agreed upon in current research (Briz-Redón et al., 2019; Das et al., 2008; Avelar et al., 2015). Larger buffer sizes lead to more crashes being associated with each target road segment, potentially even including those that should not be associated with the safety of the target segment. Yet, smaller buffer sizes may not include all of the associated crashes that are associated with the safety of the target segment. Previous studies have analyzed the same data with different buffer sizes to investigate this predicament (e.g., Zhang et al. (2015); Kang et al. (2019); Hobday and Meuleners (2018); Pulugurtha and Mathew (2021)). However, the

method of investigating the impact of different buffer sizes using varying models creates two issues that are unaccounted for. First, all crashes within each buffer size are still analyzed as if they are at the same level. For example, even if one crash occurred directly on the target segment and another at the edge of the buffer, each crash would still have the same weight. Second, this method creates several different models rather than one cohesive model. Thus, resource allocation and countermeasure selection decisions would be difficult to ascertain compared to an analysis using a single model. The development and use of a crash distance weighting factor based on the distance from the crash to the target segment in modeling may resolve these issues.

Very few cases of weighting factors incorporated into safety analyses of target road segments of any type were revealed through the literature review. Truong and Somenahalli (2011) investigated the relationship between pedestrian-vehicle crash hot spots and bus stops using a simple weighting factor method. A weighting factor of 1.5 was assigned to crashes within 50 meters of a bus stop and crashes from 50 to 100 meters were assigned a weighting of 1. However, the study lacked a large dataset and no modeling or other advanced statistics methods were conducted. Given this, no conclusions were able to be drawn whether or not this weighting method was beneficial or optimal in this study (Truong and Somenahalli, 2011).

2.7 Equivalent Property Damage Calculation

The method of identifying hazardous roadway segments using EPDO (equivalent property damage only) values was originally developed by Deacon et al. (1975). The advantage of using the EPDO method in hot spot identification (HSID) rather than other common methods, such as crash frequency, is its ability to incorporate crash severity information (Bandyopadhyaya and Mitra, 2015; Vadlamani et al., 2011). The EPDO method

with traffic volume exposure accounted for (e.g., annual average daily traffic [AADT], vehicle miles traveled [VMT]) has been commonly used in practice and in research to screen roadway networks to identify problematic hot spot locations for resource distribution purposes for the past several decades throughout the United States (e.g., Herbel et al. (2010); Wemple and Colling (2014); Montella (2010); Rodrigues et al. (2015); Wang et al. (2020a); Christofa et al. (2020)). This network screening process is critical to road safety as it aims to identify roadway segments that would benefit the most from a safety improvement, often referred to as “hot spot,” “blackspot,” or “high-risk” locations (Young and Park, 2014). The EPDO method is included as the standard procedure of the network screening process in the first step of the six-step roadway safety management process of the Highway Safety Manual commonly used in North America (American Association of State Highway and Transportation Officials, 2010).

While the EPDO method is commonly used in a standard procedure in transportation safety processes, a significant drawback of the method when identifying hot spot locations is its weight that it assigns to fatal crashes. The weight assigned to fatal crashes is much higher than the weight of other crash types. Thus, locations experiencing a high number of serious injury crashes may not be weighted as highly as a single fatal crash location even if the difference between the fatal crash and serious injury crashes was a single factor, such as emergency services arrival time or impaired driving (Lee et al., 2018; Young and Park, 2014; Washington et al., 2014; Ma et al., 2016). This can result in underreporting of minor injury and property damage only crashes, as discussed as a problem of the EPDO method in Washington et al. (2014). To avoid this case of only “chasing fatal crashes,” the Massachusetts Department of Transportation began to use a different EPDO weighting method in their resource allocation processes in 2016 that weights all fatal and injury crash types together (MassDOT Highway Division, 2020). This weighting

method was developed by taking the mean EPDO cost value of fatal crashes, suspected serious injury crashes, suspected minor injury crashes, and possible injury crashes and dividing it by the property damage only cost value (MassDOT Highway Division, 2020; Massachusetts Department of Transportation, 2019; UMassSafe, 2019). The definitions of each crash severity type used in Massachusetts Department of Transportation reporting align with the current Model Minimum Uniform Crash Criteria (MMUCC) and can be found in UMassSafe (2019). The EPDO “cost” method values in Massachusetts and the original “factor method” values that are now used in Massachusetts as the standard values are presented in Table 2.1. Research has yet to identify which of the two methods is the most appropriate EPDO method for traffic safety analyses and other analyses pertaining to resource allocation and safety improvements for target road segments.

Table 2.1. Massachusetts weighting methods of equivalent property damage only (EPDO).

Crash Severity	Cost Method (2019 Massachusetts Dollars)	Weighting Factor Method
Fatal	\$16,257,800	21
Suspected serious injury	\$941,300	21
Suspected minor injury	\$284,600	21
Possible injury	\$179,600	21
No apparent injury/property damage only	\$16,700	1

2.8 Summary of Literature Review

Literature on safety disparities on municipal roadways and at horizontal curves has shown that there are numerous factors that influence the relative safety in a given region or environment. The existing approaches to create safer roadway environments is summarized in this subsection.

The review of literature on municipal roadway ownership and rural areas revealed the lack of diversification and education that is prevalent in small communities compared to their urban counterparts. It has previously been noted that small communities have less flexibility in how they allocate their resources and lack the ability to generate revenue. In the investigation of municipal communities and municipally-owned roadways, it was found that there is a diverse variety of needs in communities that should be considered in the funding and allocation processes to equitably provide for all transportation users. Overall, to date, literature has not investigated the potential funding disparities affecting different municipalities characterized by different socio-economic and socio-demographic characteristics.

Current resource allocation methods that currently exist and are in use for safety purposes are not always useful at the municipal level as they are unable to generate revenue in the same way as larger entities. What's more, the fixed formulas used to distribute local highway funding from the state level to the municipal level do not consider population characteristics or environmental characteristics. Thus, while current resource allocation models are useful in many instances for improving safety, models must exist that consider funding on a regional level and with regularity, rather than only through hotspot analyses to achieve a more equitable and efficient distribution of resources.

At the same time, it was found that site-specific distribution of resources can be necessary in addition to equitable regional funding. The review of literature of horizontal

curve safety found that those locations in particular remain a critical safety issue given the unique perceptual and task challenges that the environment of horizontal curves creates. The lateral position and speeds of drivers are influenced by their perceived risk depending on the curve environment, such as the radius, length, and number of lanes, among other factors. However, while several horizontal curve safety relationships have been studied in literature, there remains a gap in the development of an analysis method and safety tool to efficiently analyze horizontal curve safety on a substantial scale. A literature review of geospatial safety tools throughout the field of transportation revealed that the development of existing tools is not thoroughly documented in current literature. Thus, there is a need to develop a reproducible methodology for regions to create their own safety tools, especially at high-risk locations such as horizontal curve locations.

The literature review also revealed that despite the many recent breakthroughs in crash analytics, there remains a lack of consensus among safety practitioners and researchers as to the optimal method for locating high-risk locations in general. This includes the calculation of crash proximity that is used to define the specific crashes that are associated with a road segment and the weights that are assigned to those crashes through the use of a severity weighting method or simple frequency method. The equivalent property damage only (EPDO) method in particular is a standard weighting method used in the U.S. However, there are drawbacks of using this method to identify high-risk locations as it significantly weights fatal crashes higher than all others.

Overall, this literature review revealed many disparities that must be investigated to improve equity and safety through revised resource allocation and countermeasure selection techniques. The following chapters aim at developing solutions that would create safety benefits for all roadway users.

CHAPTER 3

MUNICIPAL HIGHWAY EXPENDITURES AND SOCIO-DEMOGRAPHIC STATUS

This Chapter investigates the extent to which the distribution of resources is not equal when evaluated by municipalities with diverse population characteristics. Specifically, the relationship between municipal highway expenditures and poverty levels, population aged 65 years and older, race, and remoteness is investigated using data from the states of New York and Massachusetts. Using linear regression techniques, several models were developed that relate municipal highway expenditures with the socio-economic and socio-demographic characteristics of municipalities. The results indicate that there are clear municipal highway expenditure disparities between different population groups. Municipalities that have higher poverty levels experience a lower highway expenditure rate per local mile. Further, municipalities located in remote areas far from large metropolitan regions experience a disproportionately lower highway expenditure rate per local mile. Moreover, the results of this study indicate the need to consider how funding methods can address social differences.

This Chapter is organized into six sections. The motivation for this study is first described in the introduction of this Chapter. Then the application regions of New York and Massachusetts in the United States is described to provide the context of the study. The analysis methods are then presented, followed by the results of the study. The Chapter concludes with a section that presents the research implications and recommendations as well as the limitations of this research.

3.1 Introduction

Local roadways are a central component of any roadway network. These roads generate access to services necessary for the livability of communities and must often serve numerous transportation modes for diverse trip purposes. Despite the diverse variety of needs of communities, the funding and resources distributed from state agencies to municipal governments for local roadway maintenance, development, and improvements in the United States are often based upon fixed formulas that do not consider population characteristics. For example, the Michigan State local roadway funding formula for municipalities is based only on the reported U.S. Census Bureau population for each municipality (60%) and their local road mileage (40%) (Hamilton, 2018). Several states have similar funding decision mechanisms. The primary New York State local roadway aid formula is based on local lane-miles within each municipality and the Georgia State local roadway aid formula is based upon the U.S. Census Bureau population and the total centerline mileage (New York State Department of Transportation, a; Georgia Department of Transportation, 2019).

Despite the existence of consistent funding allocation mechanisms that are followed by state government agencies in the U.S., the diversity of needs within communities and of municipal government structures and efficiencies could result in inconsistent funding of different population groups throughout a region's local roadway networks. This could lead to certain population groups experiencing different levels of accessibility and roadway safety. The Tennessee Advisory Commission on Intergovernmental Relations has reported that additional measures should be considered in local road aid funding allocation to account for the wide variation in spending patterns, including types of vehicles on roads and types of roads (gravel, asphalt, concrete) (Green et al., 2005). However, these measures are often not included due to the lack of statewide data (Green et al., 2005). This can lead to

unintended disparities in municipal roadway funding distributions which uniquely impact vulnerable populations.

Research has demonstrated that individuals have different transportation needs based on their region type, socio-economic, and socio-demographic characteristics (Doescher et al., 2014; Pereira et al., 2017). While collaborative efforts of professionals are critical to achieve environmental justice goals (Fields et al., 2020), these conversations cannot exist without adequate funding mechanisms. At the state and regional government level, project scoring methods and specific grant funding mechanisms are beginning to focus on these differences of needs in their monetary distribution methods to a greater extent (i.e. Christofa et al. (2020); Federal Transit Administration (2020)). Yet, developed project scoring methods that include population characteristics are not found in systematic funding. The current fixed-formula methods for municipal highway funding distribution are founded on the basis of equal distribution of resources (i.e. the same quantity to all groups) rather than the equitable distribution of resources (i.e. the fair distribution of resources based upon unique needs and abilities) (Theobald, 2001). Thus, the increased needs of certain population groups are not being met using the current funding allocation method. To date, literature has not investigated the potential funding disparities affecting different population groups at the municipal level. To investigate these potential disparities, this study analyzes the distribution of highway funding with socio-economic, socio-demographic, and location characteristics at the municipal level through an application of municipalities within the states of New York and Massachusetts over a four-year period. Specifically, this research investigates the relationship between municipal highway expenditures and municipal poverty levels, population aged 65 years and older, race, and remoteness from urban centers from a safety perspective. The results of this study assist in the determination of an equitable distribution of resources, revealing potential environ-

mental justice concerns and policy implications. Specific recommendations are identified for the application regions to achieve a more equitable distribution of funds for municipally owned roads for an increased equitable safety level across all regions.

3.2 Application Areas

This research used town data from New York State and the Commonwealth of Massachusetts in the U.S. to apply this study. For consistency, cities and villages were not included. Given the differences in funding and government structures between New York and Massachusetts, the two areas were studied separately. The choice of two states that differ in their types of funding and government structures allowed for a more general method to be developed that can be representative. In addition, focusing on two specific application regions allowed for a more complex study with specific data measures that would not otherwise be available, a common motivation for application-based studies (Feagin and Orum, 1991).

Both New York and Massachusetts are diverse, with large rural areas and substantial urban areas existing within each state. These states also experience similar seasons and weather patterns, making road maintenance requirements similar in nature. Thus, through these similarities, while acknowledging the structure differences between each state, comparisons within the results of this study can be made. Furthermore, it is noted that while the primary local highway state aid funding source is described for each state in the following sections, multiple funding sources, such as MPOs, may provide additional funding for a given region. These additional funding sources are accounted for in this study within the municipal highway funding expenditures.

3.2.1 Municipal Structure and Road Ownership in New York State

The municipal structure of a region controls many aspects of how projects and services are completed. In New York State specifically, local regions are broken into villages, towns, cities, and counties (Division of Local Government Services, 2018). This differs from other states, which may have only towns, cities, and counties. In New York State, towns, cities, and villages are separate entities in terms of their government for most services. However, geographically, all villages are within towns.

Village, town, city, and county local governments provide most local government services and serve as the vital link in the relationship between the state and federal government. The 62 counties of New York are municipal corporations which provide an array of services to its residents, where municipal refers to a governing body. Counties have evolved, to a degree, to form a “regional” government that performs specified functions within its jurisdiction of cities, towns, and villages. Outside of New York City, New York State is divided into 61 counties, varying in population from Suffolk County’s 1.49 million residents to Hamilton County’s 4,800 residents as of 2010 (Division of Local Government Services, 2018). The geographical area in which these counties cover also varies, from St. Lawrence County at 2,700 square miles to Rockland County at 175 square miles. Further, 21 counties contain no cities, and the number of villages and towns varies greatly from county to county. These statistics demonstrate the diversity of counties within New York State. The State has some of the most urban and rural counties in the nation; thus, concerns and government expectations of the residents within New York State are, too, diverse.

Villages themselves are municipalities within towns that were originally formed in areas that had large numbers of people living in close proximity to one another and met statutory requirements according to Village Law in New York State (Division of Local Government Services, 2018). A region of 500 or more residents may incorporate as a village

in New York State (Division of Local Government Services, 2018). Generally, this region must contain no more than five square miles at the time of incorporation. Highway superintendents in villages are elected positions in New York State, with reelections occurring every two years.

In terms of cities, there exists no statutory minimum size which must be met for a region to become a city (Division of Local Government Services, 2018). Thus, there is no progression from a status of “village” to “city”; the primary difference between the two is that a village is part of a town and its residents pay town taxes and receive town services, which is not the case in a city. Most of New York State’s 62 cities have population sizes that are smaller than the population of the largest village, ranging from around 3,000 residents to over 8 million.

There are more towns in New York State than there are cities and villages combined. Every resident of the state who lives outside of a city or an Indian reservation lives in a town (Division of Local Government Services, 2018). Given this, town governments are responsible for a major portion of the state’s population on a number of levels. Towns in the state can range in population from 38 residents in the Town of Red House to almost 0.76 million in the Town of Hempstead. In total, there are 932 towns in the state. Towns are not evenly dispersed among counties, with the populations and number of towns ranging in values between each county. One large difference between town governments within New York State and other states is their process to elect highway superintendents as opposed to appointed by a town board or formal application process. Elections occur every two years.

Another organization structure that exists in the state are Metropolitan Planning Organizations (MPOs). These exist in urbanized areas of 50,000 or more residents throughout the state and are responsible for planning, programming, and coordinating federal highway and transit investments. Within the state, there are twelve MPOs (Division of

Local Government Services, 2018). Similar structures outside of these urbanized areas do not exist in New York State. In the greater United States, approximately half of the 408 MPOs represent urbanized areas with fewer than 200,000 residents as of 2015 (Karner, 2016). Cities surrounded by MPOs in NYS include Binghamton, Rochester, Syracuse, and Poughkeepsie.

3.2.1.1 Service Distribution

Some services offered by towns run town-wide, for regions within and outside villages, while other services are only offered outside villages. Highway maintenance and construction is required by the town to be provided to only residents living outside villages. However, certain highway maintenance costs are town-wide (even within villages) charges (Division of Local Government Services, 2018). The State Highway Law exempts residents of villages from paying the costs of repair and improvement of town highways; however, unless exempted by the town board, they must help pay the costs of town highway equipment and snow removal on town roads. Villages must finance the maintenance of their own village roads.

3.2.1.2 Roadway Ownership

As of 2018, the state transportation network had a state and local highway system with over 110,000 miles of roadway and 17,000 bridges, carrying an annual volume of 100 billion vehicle miles traveled (Federal Highway Administration; Office of Asset Management, 2003). The New York State Department of Transportation (NYSDOT) certifies municipal applications for State funding of local highway improvements. These include the Consolidated Local Street and Highway Improvement Program (CHIPS) funds. In terms of responsibility, NYSDOT is responsible for the state and highway systems. However, it does not maintain those portions of state highways within cities. Within towns, state

highways remain NYSDOT responsibility, although counties and towns may provide snow and ice control under a contract. At the county level, county governments maintain the county road system, which is designated by the legislative body of the county. Similarly to the NYSDOT, counties do not maintain roads within cities. Further, the level to which counties perform maintenance on the county roadway system varies from county to county; some counties maintain most of the necessary work, while others contract towns to do much of the work (Division of Local Government Services, 2018).

In New York State, jurisdiction of roadway differs depending upon location and type. There are 113,559 public roadway center line miles in New York State, with 85% of those maintained by county or local governments (NYSDOT Highway Data Services Bureau, 2017)¹. These roadway miles under the jurisdiction of counties and local governments are inventoried through the Local Highway Inventory (LHI) by the NYSDOT Highway Data Services Bureau annually (NYSDOT Highway Data Services Bureau, 2018). This inventory assists in the application of funding at the federal level for New York State, as well as provides the annual mileage and lane-mileage needed to fulfill the funding distribution formulas of the Consolidated Local Street and Highway Improvement Program (CHIPS) for the State. CHIPS is a major funding source for local highway programs. Only roadways open to the public for motor vehicle traffic are recorded in this inventory and counted towards funding under the CHIPS program.

3.2.1.3 Town Funding

As of 2019, there are two main state funding opportunities for municipal (town, village, and city) roadways: CHIPS and PAVE-NY (New York State Department of Trans-

¹Mileage is measured along the center line of a roadway in a single direction, regardless of the number of lanes or type of roadway in New York State (New York State Department of Transportation, 2018).

portation, 2019). To be eligible to receive any of these Capital reimbursements, projects and tasks undertaken under these funds must be undertaken by a municipality for highway-related purposes and have a service life of ten or more years with normal maintenance (or comply with exceptions). As previously explained, the CHIPS program is the major component of local highway program funding (NYSDOT Highway Data Services Bureau, 2018). CHIPS was established in 1981 by the NYS Legislature to provide State funds to municipalities “to support the construction and repair of highways, bridges, highway-railroad crossings, and other facilities that are not on the State highway system” under Section 10-c of the State Highway Law (New York State Department of Transportation, 2019). These funds are appropriated by the NYSDOT after approval of the annual State Budget and provided to local governments in June of each year. It is noted that each local government is responsible for maintenance of their roadways and has CHIPS eligibility whether it maintains the roadway itself or pays another group to do so (NYSDOT Highway Data Services Bureau, 2018).

Individual allocations of funding to municipalities under CHIPS are calculated annually primarily based on LHI mileage at the municipal level and motor vehicle registrations at the county level (New York State Department of Transportation, a). However, these allocations can be better understood when looking at the greater picture. Under Section 10-c of the State Highway Law, all roadways not under the maintenance and/or operational jurisdiction of the state receive funding based on a specific allocation system. To begin, 41.40% of funding is appropriated to New York City and to all counties outside of New York City. Fifty percent of this funding is on the basis of their relative motor vehicle registration and the other 50% is relative to the number of center line highway miles under the jurisdiction of New York City and the surrounding counties. Secondly, the balance of funding available (58.60%) is appropriated to various jurisdiction systems based

on the relative vehicle miles traveled, with cities receiving 42.7% (or 25.02% of the total), counties receiving 18.5% (10.84% of total), villages receiving 10.7% (6.27% of total), and towns receiving 28.1% (16.47% of total). From this, within each jurisdictional system, the distribution of funding allocated to each municipality is based on the ratio of lane miles under their maintenance jurisdiction (excluding lanes devoted to the parking of vehicles or non-movement of vehicles), to the total number of lane under operational jurisdictional.

PAVE-NY is a new program that began in the 2015/16 State Fiscal Year State Transportation Plan and continued through 2019/20. This program assists municipalities in rehabilitating and reconstructing local roadways through the allocation of an annual \$100 million (NYSDOT). While the program follows the same reimbursement requirements as CHIPS, eligible project activities are limited to Highway Resurfacing and Highway Reconstruction.

Data from 2012 reported by the Office of the New York State Comptroller presents that the median highway budget in dollars per center line mile were approximately \$14,000 for rural towns, \$22,000 for suburban towns, \$29,000 for urban towns, \$27,000 for villages, \$35,000 for counties, and \$31,000 for cities (not including New York City) (Orr et al., 2016). These values are the amounts that each municipality spend in their annual budget for a given year divided by the total center line miles within their municipality. The annual budget funding can consist of CHIPS funds, PAVE-NY funds, other grant funds, generated revenue, municipal taxes, etc. Costs for highways include “expenditures for administration, construction, repairs and maintenance of highways and walkways”, including engineering, snow removal, street lighting, machinery, permanent improvements, and maintenance of roads (Division of Local Government and School Accountability, 2016). Overall, municipalities themselves are responsible for deciding which projects and tasks will be completed with the funds and how each dollar will be used. Additionally, in an effort to improve

productivity due to low budgets or mobilization issues, some agencies work together to share services or outsource services (Orr et al., 2016). For example, a County government may contract out to a Town to plow snow on County roads that are a far distance from the closest County facility, but within that given Town.

3.2.2 Municipal Structure and Road Ownership in the Commonwealth of Massachusetts

The municipal government structure in Massachusetts differ quite a fair amount from those in New York State. The Commonwealth of Massachusetts governments are broken into towns, cities, and counties. Towns and city definitions have less formal definitions of Massachusetts than New York State. In towns, all residents meet, deliberate, act, and vote, and in cities, this is generally completed by their representatives (Massachusetts Municipal Association, 2014). However, at the same time, some towns within Massachusetts use the “town” designation, but have adopted “city” forms of government. It is noted that any town of fewer than 12,000 residents are not allowed to adopt a city form of government (Massachusetts Municipal Association, 2014). Two forms of town governments are recognized by the state. The first is a “Representative Town Meeting-Board of Selectmen,” an option available only for towns with a population of 6,000 residents or more. In this form, representatives are elected from precincts of the town and town meeting sizes are determined locally, but are often in the range of 200 to 250 voters. The second is an “Open Town Meeting-Board of Selection,” an option for all towns, but the only option for towns with 6,000 residents or fewer. In this form, all registered voters may participate in a town meeting (Massachusetts Municipal Association, 2014). As of 2014, 261 towns operate with an open town meeting, while 36 towns have a representative town meeting. Of the 312 towns within the state, there are a diversity of town sizes. The smallest town in Massachusetts is Gosnold at 75 residents, with the largest being the town of Brookline

at 58,732 (United States Census Bureau, 2010). It is also noted that Massachusetts does have villages, sections, and neighborhoods within their municipalities. However, they are not a formal government type as in New York State.

Compared to the rest of the country, Massachusetts have a very inactive County government structure. Out of the fourteen counties in Massachusetts, nine have been abolished (meaning there are is no separate county budget), with all county governments serving very limited functions (Concannon, 2014). County governments do not have authority over any roadways within the Commonwealth; the state and local governments have authority over all roadways (Galvin). Thus, from a transportation services perspective, County governments do not play a role. However, Regional Planning Agencies (RPAs) and MPOs completely serve in the role of transportation planning at a regional level.

There are ten MPOs and three rural Transportation Planning Organizations that function like MPOs within the Commonwealth. Each of these MPOs have co-terminus boundaries with the RPAs (Massachusetts Department of Transportation, a). Thus, all towns in Massachusetts are within RPA/MPO boundaries. According to the Massachusetts Department of Transportation (Massachusetts Department of Transportation, a), an MPO is a “federally required regional transportation policy-making organization made of representatives from local government, regional transit operators, and state transportation agencies. MPOs were created to ensure that existing and future expenses for transportation projects and programs were based on a ‘3-C planning process.’ ” This 3-C planning process includes continuing planning as an ongoing activity addressing both short-term needs and long-term vision, cooperating a wide variety of parties through a public participation process, and having a comprehensive process covering all transportation modes and staying consistent with regional and local land-use and economic-development plans (Massachusetts Department of Transportation, a). Regional Planning Agencies (RPAs)

have co-terminus boundaries with MPOs (Massachusetts Department of Transportation, a). It is important to note that RPAs and MPOs overall serve different purposes; RPAs support the transportation planning, data collection, and analysis that supports MPO decision-making (Massachusetts Department of Transportation, 2017b).

3.2.2.1 Service Distribution

Snow removal is the responsibility of the roadway owner in Massachusetts, either the municipality or the state (MassDOT, 2016). However, ownership of a specific road may be held by multiple jurisdictions, creating a more complex situation in terms of service distribution and responsibility.

3.2.2.2 Roadway Ownership

As of 2016, the Massachusetts Department of Transportation (MassDOT) owned 9,578 lane-miles of roadway (Leavenworth, 2016). Approximately 30,000 more centerline miles of pavement was owned by 351 municipalities, including 1,106 miles on the National Highway System (Leavenworth, 2016). Counties in Massachusetts are not responsible for any roadway miles. Municipalities are responsible for assets on their roadways; they may be responsible for signs, streetlights, sidewalks, traffic signals, and maintenance vehicles and equipment (Leavenworth, 2016).

3.2.2.3 Town Funding

Municipalities in Massachusetts are allocated base highway funds for highways and bridges from the state called “Chapter 90 funds” (Leavenworth, 2016). These funds are allocated based on a composite of three factors: 58.33% centerline road miles, 20.83% population, and 20.83% employment (Massachusetts Department of Transportation, 2017a; Leavenworth, 2016). Unlike New York, funds are not distributed prior to spending; rather,

Chapter 90 funds are distributed through reimbursements on a project-by-project basis. These roadway projects are 100% reimbursable through the program, meaning that municipalities are not required to contribute to them. Still, this reimbursement cannot exceed the annual budgeted funding allocation amount. Funding expenditures those relating to highway street lighting, snow and ice removal, salaries and wages, construction, and capital outlays (Massachusetts Department of Revenue Division of Local Services).

3.2.3 Application Areas Summary

This research used town data from New York State and the Commonwealth of Massachusetts in the U.S. from a 2015–2018 period to apply this research. Villages and cities were not included due to the different funding structures that exist for villages and cities compared to towns in the application regions. Thus, to maintain consistency in both the needs of certain regions and their funding structures that have been set by the state, this research only included town data. Town data was chosen over village or city data as towns are mid-sized compared to the two other options and included the highest count of data. Overall, towns offered the greatest diversity of characteristics given the large sample size.

Given the differences in funding and government structures between New York and Massachusetts, the two areas were studied separately. The choice of two states that differ in their types of funding and government structures allowed for a more general method to be developed that can be representative. In addition, focusing on two specific application regions allowed for a more complex study with specific data measures that would not otherwise be available, a common motivation for application-based studies (Feagin and Orum, 1991).

In New York, individual allocations of funding to municipalities under CHIPS are calculated annually primarily based on LHI mileage at the municipal level and motor ve-

hicle registrations at the county level (New York State Department of Transportation, a). Within each jurisdictional system, the distribution of funding allocated to each municipality is based on the ratio of lane miles under their maintenance jurisdiction to the total number of lane miles under operational jurisdiction (New York State Department of Transportation, a). In Massachusetts, municipalities are allocated base highway funds from the state called “Chapter 90 funds” (Leavenworth, 2016). These funds are allocated based on a composite of three factors: 58.33% centerline road miles, 20.83% population, and 20.83% employment (Massachusetts Department of Transportation, 2017a; Leavenworth, 2016). Unlike New York, funds are not distributed prior to spending; rather, Chapter 90 funds are distributed through reimbursements on a project-by-project basis. These roadway projects are 100% reimbursable through the program, meaning that municipalities are not required to contribute to them. Still, this reimbursement cannot exceed the annual budgeted funding allocation amount.

3.3 Methods

In this research, municipality location, as well as socio-economic and socio-demographic characteristics of municipalities were studied alongside highway funding expenditures to investigate potential disparities. The measures used within this study were decided based on information that was available for the application regions and do not constitute an exhaustive list. To avoid multicollinearity between variables as much as possible, only specific socio-demographic and socio-economic variables were selected. These variables were based upon previous research findings related to funding and inequities (Pereira et al., 2017; Alsnih and Hensher, 2003; MacManus and Pammer, 1990; Brown, 1980). Specifically, variables of remoteness, population size, poverty, age, and race were included as the measures for analysis. Prior to analysis, data was gathered and processed. The variable

representing remoteness from an urban region was estimated using geographic information system (GIS) methods. The planned model development consisted of various combinations of the independent variables to investigate different relationships with municipal highway expenditure rates. The following section describes these processes in further detail.

3.3.1 Data

Town data from New York and Massachusetts were gathered for the 2015–2018 period. The scope of this research was only within the context of towns for the two application regions. Villages and cities were not included due to the different funding structures that exist for villages and cities compared to towns in the application regions. Thus, to maintain consistency in both the needs of certain regions and their funding structures that have been set by the state, this research only included town data. Town data was chosen over village or city data as towns are mid-sized compared to the two other options and included the highest count of data. Overall, towns offered the greatest diversity of characteristics given the large sample size.

Many data sets were required to complete for this research from a variety of sources. The following sections describe how these data were gathered and/or calculated. The final data used in the analysis is shown in Table 3.1 and Table 3.2. It is noted that the Town of Gosnold, Massachusetts, which has a population of approximately 75 residents and only 2 local centerline miles, had \$0 in highway expenditures for only the year of 2015 (MassGIS, 2020; Massachusetts Department of Revenue Division of Local Services; Massachusetts Department of Transportation, 2017a). No other towns in Massachusetts or New York had \$0 in recorded highway expenditures for any year that was included in this study.

Table 3.1. Summary statistics of New York Town data.

Variable	Mean	Standard Dev.	Min	Max
Annual Highway Expenditures	\$1,232,639	\$3,192,302	\$22,551	\$63,133,168
Local Lane Miles per Town	124.7	187.2	6.4	3,499.1
Annual Highway Expenditures per Local Lane Mile	\$8,712	\$6,105	\$1,062	\$90,676
Population	9,672	37,566	34	768,103
Miles to Population 50,000 +	33.4	27.7	0	146.8
Population in Poverty	11.0%	5.3%	0%	37.1%
Population White Alone	93.8%	6.8%	48.9%	100%
Population 65 and Over	18.7%	4.8%	2.0%	44.4%

Table 3.2. Summary statistics of Massachusetts town data.

Variable	Mean	Standard Dev.	Min	Max
Annual Highway Expenditures	\$1,542,422	\$1,286,352	\$0	\$7,267,605
Local Lane Miles per Town	69.9	36.6	2.0	228.2
Annual Highway Expenditures per Local Centerline Mile	\$21,538	\$13,042	\$0	\$96,437
Population	10,853	10,158	75	60,803
Miles to Population of 50,000 +	16.4	11.9	0.0	50.4
Population in Poverty	5.9%	3.2%	0%	20.9%
Population White Alone	92.0%	6.5%	65.4%	100%
Population 65 and Over	19.1%	6.1%	7.8%	44.9%

3.3.1.1 Demographic and Population Data

Demographic and population information for both New York and Massachusetts towns was gathered from the United States Census Bureau. The American Community Survey was used to gather annual city and town population estimation totals for the 2015 to 2018 period for both New York and Massachusetts (Population Division of the U.S. Census Bureau, 2020). Socioeconomic data were also gathered from the Census Bureau using a Census Data API Key and the R package “tidycensus” (Walker, 2020). Population estimates of people in poverty, people whose race is white alone, and people who are 65 years and older were gathered. Poverty is measured by the U.S. Census Bureau using a

set of money income thresholds that vary by family size and composition (U.S. Census Bureau, 2019). Since the required data specificity were on a subcounty scale and included non-urbanized areas, these socio-economic and socio-demographic data were not available for every individual study year. Rather, they were available as an estimated value from 2014 through 2018 through the American Community Survey. As a result, the values for these data were kept constant for each individual year in the data organizing process. Given the significant volume of towns in each study area (932 in New York and 312 in Massachusetts) and explanatory, not predictive, focus of this research, this was determined to not be a significant limitation of this research. The socio-economic and socio-demographic data variables were processed as percentages of the town population for analysis.

3.3.1.2 Highway Expenditure Data

Town highway expenditures for both New York and Massachusetts were gathered for this research. Town highway expenditure data for New York were obtained from the Office of the New York State Comptroller for each town for the years 2015 through 2018 (Office of the New York State Comptroller). Highway expenditures in New York are defined as “expenditures for administration, construction, repairs and maintenance of highways and walkways” (Division of Local Government and School Accountability, 2016). These include expenditures related to engineering, permanent improvements, machinery, and sidewalks. Further details of what is considered a highway expenditure in NYS can be found in the Accounting and Reporting Manual (Division of Local Government and School Accountability, 2016). Massachusetts town highway expenditures were obtained from the Massachusetts Department of Revenue Division of Local Services Municipal Databank/Local Aid Section (Massachusetts Department of Revenue Division of Local Services). Highway, street lighting, and snow and ice removal expenditures, related salaries and wages, construction, and capital outlays were combined to form the annual highway expenditures for a given town.

These expenditures included spending from all funding sources, including from tax bases and from funding provided by the state.

3.3.1.3 Local Mileage Data

Local roadway mileage within each town was gathered. In New York, this data was obtained from the 2017 Highway Data Services Repository (New York State Department of Transportation, b). As the highway funding decision mechanisms at the state level in New York are primarily based upon local lane mileage data, not centerline mileage data, the former was gathered for this research (New York State Department of Transportation, a). As defined by the Highway Data Services Bureau (New York State Department of Transportation, 2018), town, village, or city highway mileage is “the mileage under the jurisdiction of each town, village, or city within the county. Mileage is measured along the centerline of the highway (in one direction) regardless of the number of lanes or whether the highway is divided or undivided.” Local road mileage data for Massachusetts towns was obtained from the 2016 Massachusetts Road Inventory Year End Report (Massachusetts Department of Transportation, 2017a). Unlike New York, town centerline miles are most often used for allocating State Aid to communities rather than lane miles. Thus, town centerline mileage data was recorded and gathered instead of lane mileage data in Massachusetts (Massachusetts Department of Transportation, 2017a). According to the Office of Transportation Planning (Massachusetts Department of Transportation, 2017a), “centerline miles” refer to the “linear length of a road segment.” For divided highways, “only the length of one side of the roadway is counted.” “Lane miles” are defined differently, as they refer to the “linear length of lanes of a road segment.” In this case, “the number of lanes on both sides of the roadway are counted in the mileage calculation.”

3.3.1.4 Distance from Urbanized Region Data

The distance from each town center to the closest urbanized region within the same state was calculated using ArcMap version 10.7.1. GIS municipal boundary and 2010 U.S. Census population data was gathered for New York and Massachusetts from the New York State GIS Program Office and MassGIS, respectively (New York State GIS Program Office, 2020; MassGIS, 2020). ArcMap was used to calculate the planar, or straight-line, distance from the center of each town to the closest city/town with a population of 50,000 or more residents according to the 2010 U.S. Census. This specific population was chosen as the U.S. Census defines urbanized regions as those that have a population of 50,000 or more residents (Ratcliffe et al., 2016). It is noted that planar distance measurements do not account for geographic and infrastructure barriers, which on the contrary is captured by measures such as travel time or road miles; however, this approximation of distance was determined adequate for this study given the strong correlation between planar distance and travel time on roads (Phibbs and Luft, 1995). This distance data was collected to include in the study as the distance from urbanized areas represents the remoteness of a town. This allows for an investigation of the relationship between highway expenditures and remoteness. The use of this distance variable, alongside population size, is necessary to include as municipalities of the same size will experience differences in their lived experiences depending on their distance to an urban region. Residents living in a municipality that resides closer to an urban region will have different living experiences and transportation needs than residents living in a municipality in a very remote region, even if the municipality has the same population size (McKnight et al., 2019).

3.3.2 Model Development

The development of multiple regression models were considered for this research. Separate models were developed for both New York data and Massachusetts data due to

their different funding structures for roadways, including different local highway program funding algorithms. New York local highway expenditures were normalized by the number of local lane miles while Massachusetts expenditures were normalized by the number of local centerline miles as these different figures are used in their independent state highway funding algorithms. Additionally, current funding decisions are completed at the state level for municipalities; thus, having one model per state allows the results to be compared more directly to their funding allocation algorithms. Socio-economic and socio-demographic variables tend to be highly correlated, depending on the specific variables and regions/individuals studied. Multicollinearity in regression can lead to highly skewed or misleading results. Thus, regression analysis methods that can account for highly correlated variables were first considered, including profile regression and ridge regression (Liverani et al., 2016). However, these methods were found to be unnecessary after Variance inflation factor (VIF) tests using ordinary least squares (OLS) regression methods were completed. More specifically, all variable combinations were tested through several OLS regression models using R version 3.5.3. Using the “car” package (Fox and Weisberg, 2019), the VIF values were calculated, revealing that all VIF values from all possible model combinations were below 2.5, with the majority of VIF values below 2. VIF values provide a direct indication of the effects of multicollinearity on the variance of the i th regression coefficient (O’Brien, 2007). In other words, these values reveal how much the variance of a variable has been inflated by a lack of independence. Given the relatively large sample sizes in this study and low reported standard errors, the data was determined to not be highly correlated (O’Brien, 2007). Thus, OLS regression models were determined to be most appropriate for this study.

The goal of this study was to investigate and test causal hypotheses related to highway funding and socio-economic and socio-demographic factors of municipalities. This

type of analysis is considered an explanatory analysis, as statistical methods are used to test hypotheses related to theoretical constructs (Shmueli, 2010). The explanatory power of a model in this case is often reported as adjusted R-squared values and statistical significance, or p-values. There are multiple approaches that can be used to investigate exploratory relationships. These include methods of splitting by population group and transforming data, as used by Chen et al. (2017) or performing Chi-square and Kruskal-Wallis tests to determine correlation, as done by Ragaini et al. (2020). A simple linear regression and multivariate regression approach was identified and chosen to be applied to this study. This method allowed us to specifically investigate each primary independent variable through simple linear regression and multivariate linear regression to uncover the individual correlation strength of each variable through the resulting adjusted R squared value, identifying which variables are more influential than others and avoid high variance. Using simple linear regression to investigate exploratory relationships is common in transportation engineering literature (e.g., Iyer and Jain (2020); Jun (2012); Yared et al. (2020)). Further, these modeling methods are commonly used in the social science domain, allowing for this research to have broad applicability and familiarity with non-engineering scholars (e.g., Beroho et al. (2020); Abraham et al. (2020); O'Brien et al. (2018)).

3.4 Results

After the OLS regression modeling was concluded, several relationships were identified. Tables 3.3 and 3.4 report the models and model results of the selected variables on town highway expenditures per local lane (for New York) or centerline mile (for Massachusetts). Models 1 through 4 include a single explanatory variable in the model. Model 5 includes all of these variables and Model 6 adds the population size as an additional independent variable.

Table 3.3. OLS regression models predicting town highway expenditures (million USD) per local lane mile in New York.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Percent of Population in Poverty	-.0316*** (.0019)	-	-	-	-.0155*** (.0018)	-.0153*** (.0018)
Percent of White Alone Population	-	-.0353*** (.0014)	-	-	-.0325*** (.0014)	-.0300*** (.0015)
Percent of Population 65 years and older	-	-	-.0079*** (.0021)	-	.0066*** (.0019)	.0063*** (.0063)
Distance to Town/City 50,000+ (miles)	-	-	-	-.0064*** (.0003)	-.0047*** (.0003)	.0045*** (.0003)
Population	-	-	-	-	-	.0128*** (.0026)
Constant	.0122*** (.0002)	.0418*** (.0013)	.0102*** (.0004)	.0108*** (.0002)	.0412*** (.0012)	.0387*** (.0013)
Adjusted R-squared	.07	.16	.00	.08	.24	.24

*p≤.05, **p≤.01, ***p≤.001

Table 3.4. OLS regression models predicting town highway expenditures (million USD) per local centerline mile in Massachusetts.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Percent of Population in Poverty	-.0513*** (.0119)	-	-	-	-.0113 (.0118)	-.0166 (.0058)
Percent of White Alone Population	-	-.0760*** (.0054)	-	-	-.0680*** (.0055)	-.0544*** (.0060)
Percent of Population 65 years and older	-	-	-.0079 (.0062)	-	.0523*** (.0065)	.0502*** (.0064)
Distance to Town/City 50,000+ (miles)	-	-	-	-.0369*** (.0030)	-.0389*** (.0037)	-.0286*** (.0041)
Population	-	-	-	-	-	.2309*** (.0442)
Constant	.0246*** (.0008)	-.0914*** (.0050)	.0230*** (.0012)	.0276*** (.0006)	.0811*** (.0050)	.0652*** (.0058)
Adjusted R-squared	.02	.14	.00	.11	.24	.25

*p≤.05, **p≤.01, ***p≤.001

3.5 Discussion

As demonstrated in Tables 3.3 and 3.4, the percent of the population in poverty variable was found to be significant in Model 1 for both states. This demonstrates that an increase in the population portion living in poverty within a municipality is correlated with a decrease in highway expenditures per local mile. Yet, poverty level is no longer significant after accounting for other variables in Models 5 and 6 in Massachusetts, while it remains significant for New York. This may be due to the Massachusetts highway funding allocation method considering the employment rate within their formula. Still, this significance in New York demonstrates a need to investigate the funding revenues of municipalities with high poverty rates compared to those with low poverty rates, such as the potentially differing tax rates and service fees of these communities. Further, this disparity may be connected to the history of federal housing, tax, and transportation policies that have traditionally reinforced racial and low-income residential segregation (Oliver and Shapiro, 2001). This finding also aligns with previous research stating that those born into an economically disadvantaged family have reduced accessibility levels (Pereira et al., 2017; Deka and Lubin, 2012). Municipalities with a lower expenditure rate per local mile may also have lower accessibility, simply due to the fact that they have fewer resources. The investments made with the resources these municipalities do have may also favor the modes of transportation used by wealthier population groups, such as highways, rather than pedestrian or bicycle facility improvements. Even in a single city, infrastructure has been shown to be significantly worse in poor areas compared to wealthy areas, as demonstrated in a study by Torres-Barragan et al. (2020) where conditions for cyclists were shown to be worse in areas of poverty than in wealthier areas in Bogotá, Colombia. Overall, it is noted that more nuanced planning and land use considerations could change or improve our understanding of the influence of these specific factors. While beyond the

scope of this research, studies investigating where funding is spent by municipal highway departments and the influence of local tax rates and land use factors should be considered in future research.

The percent of white alone population variable was significant in Model 2 for both states. In both cases, an increase in the white alone population is correlated with a decrease in municipal highway expenditures per local mile. This variable maintained significance in Models 5 and 6. Thus, the racial disparity of highway expenditures cannot be confirmed through this study. Further, given the known racial injustices within the transportation system (Pereira et al., 2017), this study does not provide clarity to arrive at a conclusion as to whether or not the current expenditure rate per local mile is equitable between white and non-white population groups. Future analysis within communities must first be conducted to determine if all transportation needs within a community are met.

The percent of population aged 65 years and older variable was significant in Model 3 for New York, but not for Massachusetts. In New York, the results demonstrate that for an increase in the population percentage aged 65 years and older, there was a decrease in highway expenditures per local mile. Again, this may be due to employment as a formula consideration in Massachusetts municipal funding allocation methods. After accounting for the other variables through the more comprehensive models, the correlation changed. In Models 5 and 6 for both states, the results demonstrated that for an increase in the percentage of older population, there was an increase in highway expenditures per local mile. Given the increased needs and vulnerability of those in older population groups (Pereira et al., 2017), this result does not immediately demonstrate a need for change. Nonetheless, an investigation of the transportation funding needs and costs for older populations would be beneficial to reveal if accessibility and road safety needs are being met.

The distance to the nearest urban municipality of 50,000 residents or more variable was significant in Model 4 for both states. The results demonstrate that for an increase in distance from a highly urban municipality, there is a decrease in highway expenditures per local mile. This correlation holds true for Models 5 and 6 as well for both states. This result aligns with previous research demonstrating the limited resources rural regions have for highway expenditures (MacManus and Pammer, 1990; Brown, 1980). Further, the results of Model 6 demonstrate that remoteness leads to a lower highway expenditure rate, while a larger population leads to an increase in the expenditure rate. Thus, smaller populations that also tend to be more remotely located are more likely to experience the lowest expenditure rate. Based on the evidence from previous research, this result confirms what would have been expected. Further, this lower expenditure rate in rural regions is of increased concern, as rural regions experience a higher fatal crash rate and are less likely to register as safety hotspots, where additional funding is commonly targeted (National Center for Statistics and Analysis, 2019).

3.6 Conclusions

Previous research has demonstrated that transportation equity disparities exist between different population groups. The objective of this study was to investigate the relationship between socio-economic, socio-demographic, and location characteristics of municipalities with their highway expenditures rate per local mile with a safety focus. OLS regression models were developed that included independent variables representing these characteristics using data from the states of New York and Massachusetts. The methods of this research are easily scalable given the availability of data used to any U.S. state. State population data and location data is widely available throughout the U.S. Local mileage data and municipal highway expenditure data can likely be obtained from any state agency,

given the requirement to often report these measures to federal agencies. The results of this study reveal that there exist highway expenditure disparities between different population groups. The limitations as well as the research implications and recommendations for policymakers and practitioners are included in the following sections.

3.6.1 Limitations

The primary limitation of this study is the application of these methods to only two U.S. states and its focus on safety and accessibility. Several equity considerations/factors (i.e. air quality, noise, walkability, etc.) were not considered in this research. This study also did not include international data. Further, only specific socio-economic and socio-demographic variables were selected for this study to narrow the scope. This study only included the overall municipal highway expenditure rate and did not consider local tax rates or land use factors, nor did this study investigate the explicit reasons for the revealed disparities. Factors such as home ownership and education levels within communities, should be also considered in future studies. This study did not directly investigate the impact of declining versus growing regions, both economically and by population, which should be considered in future research. This study is also limited by the investigation of expenditures only at the municipal level and did not include federal or state capital investments or other types of funding that were not captured by the expenditure values. Municipalities were chosen at the level of analysis due to data limitations and current funding allocation mechanisms; however, municipalities can often be comprised of very heterogeneous populations with widely varying socio-economic status and socio-demographic characteristics. Thus, future research should consider smaller blockgroups and regions of towns to capture differences across these populations. Finally, this study did not consider how local highway funding was used and how each investment was allocated. This is important to consider when assessing the equity of investments. Overall, future stud-

ies should consider these limitations that were beyond this current scope to further the state-of-literature in this area of research. Additionally, next steps of this research should consider alternative methods that would consider different perspectives and reveal new aspects to these relationships, such as splitting and transforming population group methods used by Chen et al. (2017).

3.6.2 Research Implications and Recommendations

Despite the study limitations, this research found that there are clear municipal highway expenditure rate differences between varying municipalities with different characteristics. These results indicate the need to consider social differences in systematic funding methods for equitable accessibility and road safety, as is done in some current project scoring methods in the U.S. (Christofa et al., 2020). The research implications and recommendations from this study include:

- Municipalities with high poverty levels spend less on their transportation per local mile than municipalities with lower poverty levels. To improve transportation equity, state governments and other funding agencies should consider methods to support different revenue streams that could assist these low-income municipalities. This could be in the form of adding a variable demonstrating poverty to a funding formula or through the creation of accessible transportation grants specifically built for regions in poverty, such as the Helping Obtain Prosperity for Everyone (HOPE) program by the Federal Transit Administration (Federal Transit Administration, 2020). This application-based program provides funding to local, state, and transit agencies to support projects that address transit challenges faced by areas of poverty.

- Racial disparities of municipal highway expenditures could not be concluded from this study. However, based upon the current state of literature, there is a need to conduct additional research on racial disparities from a highway funding perspective, including the municipal mobility and infrastructure needs of different population groups based on race. Further, transportation studies have shown that Black, Indigenous, and People of Color (BIPOC) have higher levels of poverty compared to white persons (e.g., (Deka and Lubin, 2012; Klein et al., 2018)).
- Municipalities with a higher percentage of older populations have a higher expenditure rate. While this result does not immediately demonstrate a need for funding changes, an investigation of the transportation funding needs and costs to accommodate older populations' travel needs would be beneficial. This may reveal whether accessibility needs are being met at the current funding level for this population group, which is necessary to evaluate given their increased vulnerability as a population in terms of crash recovery and safety. As "aging in place" continues to be an important planning challenge to consider, these safety investments are critical to senior safety within both the transportation and planning conversations as these professionals look towards the future. Further, despite these findings, there are other local investments that support the accessibility issues that this population group faces, including distance to health care service locations, paratransit availability, and walk-ability of their community. These other funding sources should be considered by agencies when evaluating the needs of their older population and ageing population to allow their residents to safely and equitably age in place.
- Increased remoteness and decreased population size are characteristics of municipalities with lower municipal highway expenditure rates. This disparity is in addition to

the higher fatal crash rates experienced by rural driving populations (National Center for Statistics and Analysis, 2019). Further, a lack of non-automotive transportation options in rural regions makes this type of investment even more critical for maintaining safe and accessible options for these populations. To combat this inequality, state agencies and other funding agencies should investigate methods to increase financial support for small, remote municipalities. This could be in the form of adding a variable demonstrating remoteness to a funding formula or the creation of grants based on remoteness and population size. Additionally, other factors such as land use and modal connection to urban centers should be considered in future research to investigate if there exist additional layers to this finding in certain contexts.

CHAPTER 4

AN APPROACH TO EQUITABLE RESOURCE ALLOCATION

Local highway expenditures of municipalities were found to be disproportionate based on a region's socio-demographic and socio-economic characteristics. However, it is unknown whether these differences in fact impacted the level of safety within a given region. Thus, to explore this, this Chapter focuses on determining the factors that impede the ability of municipalities to efficiently and equitably distribute highway funding to improve local road safety. The methodology employs a data envelopment analysis by fusing municipal highway staff data, municipal highway expenditure data, crash data, geographic data, and demographic data. Among other findings, the research in this Chapter concludes that non-white and rural regions require more financial support to equitably improve safety. Further, the data envelopment analysis method is demonstrated to be a beneficial method for considering equity disparities at a local level. Overall, the results suggest where local highway resources should be invested to efficiently and equitably improve local roadway safety.

This Chapter is comprised of five sections. The introduction section discusses the motivation and general background for this study. Following, the methods and data collection efforts used are described. The study results are then presented, followed by a discussion of the implications and recommendations stemming from the results. The Chapter concludes with the primary research results and recommendations.

4.1 Introduction

Transportation safety remains a serious problem throughout the world. Each year, approximately 1.35 million people die on the world's roads (World Health Organization, 2021). Yet, while proven countermeasures exist to improve safety, they are not always implemented in the most efficient manner based on available resources. In other words, countermeasures that would be less costly and greatly improve safety are not always implemented, leading to more spending for the same safety outcome. Surface transportation safety in particular remains a critical issue at all road ownership levels regardless of the environment. However, the relative level of safety remains higher in certain regions and environments than others. Safety disparities are prevalent on locally owned roadways, which present a 3.6 times higher fatality rate compared to interstates and arterial roadways (Federal Highway Administration, 2019). At this local level, a wide range of municipal government types and residential characteristics exist. As a result, resource allocation decisions should be made in context, accounting for the needs of population groups and/or regions and their associated safety risks. For example, residents of smaller U.S. municipalities have been shown to walk less than those living in larger metropolitan regions (Doescher et al., 2014). Failure to consider these different needs in the allocation of resources may lead to safety disparities, with some regions and groups experiencing less safe municipal surface transportation than others.

Despite diverse needs of different communities, current funding and resource allocation distribution from state agencies to municipal governments for local roadway maintenance and improvements are often based upon fixed formulas. These formulas do not consider population characteristics or environmental characteristics. For example, in New York, municipal funding is distributed based upon local roadway mileage (New York State Department of Transportation, a). Further, state agencies do not offer detailed guidance

to municipalities on how they should be spending their highway funding to work towards specific goals, such as increasing local road safety. Given the many differences that exist between municipalities, it is critical to investigate the types of government official compositions and resources that lead to efficient spending to improve safety on local roadways for a given region.

This research analyzes the relationship between municipal highway expenditures and local road crashes. The objective is to reveal which factors affect the effectiveness of municipality financial resource allocation to efficiently improve local roadway safety. Efficiency in this study is defined as the ability of a municipality to minimize their local highway spending while also minimizing the number of local road crashes. This research investigates the relationship between municipal government composition and decisions, and geographic, socio-economic, and socio-demographic characteristics with the efficiency of using funds to improve local road safety. Using the data envelopment analysis (DEA) method, these additional characteristics can be factored into this relationship between funding and safety. These “intermediate” characteristics allow for the physical environment and other demographic or economic characteristics that may influence this efficiency to be considered. The DEA method is unique in this sense as it can identify characteristics that impact the efficiency between two factors within a system. The use of this analysis method and the fusion of new data from a variety of sources reveals new findings in this domain. To collect municipal government information, a survey was distributed to local highway and town officials. Expenditure data, crash data, spatial information, and demographic details were gathered through a variety of sources and fused together with the collected survey data. The results reveal intermediate characteristics that lead to less safe local roads within a given municipality when compared to the same roadway spending of another municipality. In this study, an equitable resource distribution and investment system is defined as a

system that achieves the same high level of roadway safety in all communities, regardless of geographic location and socio-demographic characteristics of a municipality. Differing results from using different crash severity weighting methods are also investigated to identify the role these hold in the creation of an equitable safety prioritization process. Specific policy and practice recommendations are identified for both state and local agencies.

4.2 Methods

Data from many sources were needed for this research, including key informant interviews, survey data, and pre-existing publicly available data. Extensive data collection, organization, cleaning, processing, and fusing was completed prior to analysis. The following sections describe these processes.

4.2.1 Data Envelopment Analysis Method

The purpose of this study was to investigate the relationship between survey-collected data and municipal highway expenditure data with local road safety outcomes, while accounting for intermediate factors, such as percent of the population in poverty. The DEA method was chosen to investigate these relationships as this method has the ability to relate input and output of systems while considering potential intermediate factors impacting these efficiencies. For example, the DEA method can investigate the efficiency of a production line given a certain amount of money of several different companies to determine which companies are most efficient in their production of the highest amount of product given the least amount of spending. The efficiency of a municipality in this case is reflected in its ability to maximize local roadway expenditure dollars to achieve as few crashes as possible, while considering intermediate factors such as local highway department staff levels and education, the percent of the population in poverty, etc. Other more commonly used analysis methods were considered for this study, such as Poisson and

negative binomial modeling. However, unlike DEA, these methods do not offer the benefits of comparing input factors and output factors of systems while also including intermediate characteristics. The use of the DEA method is not limited to applications at the regional transportation level, but can be considered for uses throughout the fields of transportation, planning, safety, and equity when their relationship with funding or other resources and efficiency is aimed to be investigated.

Developed by Charnes et al. (1978), the DEA method is a performance measurement technique used to evaluate the relative efficiency of decision making units (DMUs). This method is a non-parametric approach that accounts for both inputs and outputs of a system by measuring the efficiency of each DMU. A primary characteristic of the DEA method is its versatility and capacity to be adapted to a variety of cases (Mariano et al., 2015). From 1978 to 2010, the DEA method was used primarily in banking, health care, agriculture and farming, transportation, and education applications, though it has also been applied in several other fields (Liu et al., 2013). From a transportation perspective, the DEA method has been used in transportation safety literature (e.g., Alper et al. (2015); Hermans et al. (2009, 2008); Fancello et al. (2020); Sadeghi and Mohammadzadeh Moghadam (2016); Shen et al. (2012); Antić et al. (2020)). This method allows risk to be measured outside of the common method of “risk per person” or rate. Hermans et al. (2008) used the DEA method to investigate road safety performance indicators at a country-level using data from 21 European countries. Out of a comparison of five common methods for assigning weights to indicators in transportation safety, DEA proved to be the best modeling approach to investigate efficiency related to the number of traffic fatalities per million inhabitants within a region (Hermans et al., 2008). Alper et al. (2015) used the DEA method to assess local municipalities’ road safety in Israel. While the study focused on socio-economic and socio-demographic factors within a municipality and did not include

factors related to the municipal governments, the study presented the effective use of the DEA method for analysis of traffic safety on a local scale.

The simple DEA method uses a single-stage approach with a set of inputs and a set of outputs. This approach does not allow for the inclusion of intermediate factors, or those that may bias a result and are parts of the system, but are not directly system inputs or outputs. To account for intermediate factors in DEA modeling, two-stage methods have been developed. As described by Simar and Wilson (2007), efficiency is estimated in the first stage of this approach. These estimated efficiencies are then regressed on covariates that are typically different than those in the first stage. These covariates are viewed as representing intermediate variables. This method has been used often in DEA literature Simar and Wilson (2007). However, this approach leads to biases from serially correlated error terms, leading to questionable statistical inference of the results (Simar and Wilson, 2007; Bogetoft and Otto, 2011). To overcome these problems, Simar and Wilson (2007) developed an approach to the two-stage DEA using a double bootstrap DEA method. This method allows for the estimation and inference of marginal effects of intermediate factors on the efficiency of systems; a more detailed description about this can be found in Simar and Wilson (2007). This double bootstrap DEA method has been transformed to be used in statistics software packages for more widespread use (Badunenko and Tauchmann, 2019; Simm and Besstremyannaya, 2020). The R package rDEA was used in this research to employ the bias-corrected bootstrapping output-oriented DEA method developed by Simar and Wilson (2007). The number of replications for bootstrap operations was 2000, which is the default number of replications in the rDEA package (Simm and Besstremyannaya, 2020) and the number used in Simar and Wilson (2007) as well as in other works employing this method (e.g., Güngör-Demirci et al. (2017, 2018); Sellers-Rubio and Casado-Díaz (2018); Salazar-Adams (2021)).

The DMU is defined as a municipality in this study. In simple terms, the output-oriented version of DEA modeling identifies the factors that most efficiently increase the safety of municipally owned roadways while maintaining the input of municipal highway expenditures. Once this most efficient municipality is benchmarked, all other municipalities are assigned a comparative efficiency rating. The Simar and Wilson (2007) method also considered the intermediate factors in these processes. To confirm the DEA method would be appropriate for this study's objective and dataset, pre-analysis was completed. This included checking the data to ensure the municipalities that responded to the survey had the necessary number of crashes throughout the data set to run this analysis. This pre-check confirmed that the data contained a feasible number of crashes to run the DEA method based on crash values identified in other DEA transportation safety studies.

4.2.2 Application Areas

Town data from New York and Massachusetts in the U.S. were also the basis of this analysis, as the data for these areas to maintain consistency across the equity-focused portions of the dissertation given the direct connection. Again, it is noted that the funding and government structure of each state differs, allowing for a comprehensive understanding of the relationships between funding, crashes, staffing levels, and demographic characteristics.

4.2.3 Survey

Municipal government level data was required to investigate the impact of government composition with expenditure efficiency and local road safety outcomes for this study. Yet, this data is not collected on a large scale in New York or Massachusetts. Two surveys were created and distributed to Massachusetts and New York municipal government officials to gather this data. The surveys were developed using the online software Qualtrics. Before survey development began, discussions occurred with both the Cornell

Local Roads Program (CLRP) and the University of Massachusetts Transportation Center (UTMC). These organizations are familiar with the local highway departments throughout their respective states as the state Local Technical Assistance Program (LTAP). These conversations, in combination with the literature review, assisted in the selection of appropriate and reasonable questions that would be beneficial for this project. While the questions varied for each state, including different town name options within the survey itself and state-specific structural considerations, the nature of each question remained the same between the two surveys. The questions are presented below and each state-specific survey is presented in the Appendix.

1) Government Level

- Village
- Town
- City
- Other (Specify)

2) Municipality Name (selection from drop-down)

3) County Name (selection from drop-down)

4) Does your municipality have a town/city/village engineer on staff?

- Yes
- No

5) Does your municipality have a town/village/city traffic or highway engineer on staff?

- Yes

No

5) Please select all that are applicable to your municipality:

Has own Transportation Committee or Board (non-safety specific, [examples provided with links to town web pages with these committees])

Has own Traffic Safety Committee or Board ([examples provided with links])

Have a Traffic Department (separate from the Highway Department)

None of the above

6) Has your municipality received assistance from your County Highway Department or County Engineer for assisting on a highway or transportation-related project or issue on a local roadway under your jurisdiction in the last 3 years?

Yes

No

Unsure

7) Has your municipality hired a consultant for a transportation/highway/traffic project in the last 3 years?

Yes

No

Unsure

8) How many full time highway/maintenance staff members does your municipality have on staff?

0

- 1 to 2
- 3 to 5
- 5 to 10
- 10 to 15
- 15 to 25
- 25+

9) Does your Highway Superintendent (or primary highway department official) have a college degree in any of the following?

- Civil Engineering
- Planning
- Engineering (other)
- Other, related to traffic/engineering:
- None of the above pertains

10) Does anyone on your current municipal staff have a Civil Engineering (or equivalent) degree?

- Yes, their title is:
- No
- Unsure

11) Has your municipality conducted or been a part of a Road Safety Audit (RSA) in the last 3 years?

- Yes

- No
- Unsure

12) If we may have any clarification questions, could we contact you? If so, please provide your name and contact information below.

Each question included in the survey aimed to be concise, easy to answer, and relevant to the analysis. The surveys were sent out in December 2019 to at least one New York town official from each municipality, often the highway superintendent, town supervisor, or town clerk in coordination with the Cornell Local Roads Program and the New York State Association of Towns. Details of the emails used to send out this survey is provided in the Appendix. For towns with missing or invalid email addresses from the above resources, contact information was searched online. Only 34 out of 932 towns in New York were unable to be contacted. A follow-up email was sent to those towns in New York who had not yet responded to the survey in March 2020. In total, complete data from 275 unique towns was gathered. To collect data in Massachusetts, the survey was sent via email by UMTC in February 2020 to all Massachusetts municipal officials included in their contact list, from town administrators to highway staff. A follow-up email was sent again in May 2020. In total, complete data from 125 out of 294 Massachusetts towns was collected. The relevant survey results converted into variable form are summarized in Table 4.1.

Table 4.1. Summary statistics of survey-collected variables.

Variable	Variable Description	New York		Massachusetts	
		Mean	Std. Dev.	Mean	Std. Dev.
<i>Eng</i>	Municipal engineer on staff	16%	36%	38%	49%
<i>Hwy_eng</i>	Municipal traffic or highway engineer on staff	4%	20%	11%	32%
<i>RPO/cnty</i>	Received assistance from County Highway Dept. or County Engineer (New York) or Regional Planning Agency (Massachusetts) on a municipal road project/issue in last 3 years	57%	49%	44%	50%
<i>Consult</i>	Hired a consultant for a transportation project in last 3 years	23%	42%	73%	45%
<i>Staff</i>	Has a full time highway/maintenance staff of:				
	0	0%	6%	1%	9%
	1-2	6%	24%	4%	20%
	3-5	43%	50%	26%	44%
	5-10	29%	45%	35%	48%
	10-15	8%	28%	21%	41%
	15-25	7%	25%	10%	29%
	25+	6%	25%	3%	18%
<i>Civil</i>	Someone on staff has a civil engineering (or equivalent) degree	5%	21%	42%	49%
<i>RSA</i>	Conducted or been a part of a Road Safety Audit in last 3 years	4%	19%	25%	43%
		N = 275/932		N = 125/294	

4.2.4 Key Informant Interviews with Local Highway Officials

The complexities of how government highway officials operate, fund, and maintain their municipal roadways are not well understood in current literature. Thus, before analysis, five municipal highway officials were interviewed to determine the potential intermediate variables that should be included in the DEA modeling process. The goal of these key informant interviews was to identify variables not previously determined through the literature review and potential countermeasures that should be considered in different environments, depending on the results of analysis. The interviews were conducted via online video meetings in September 2020 and included individuals from a diverse set of municipalities in terms of population size in Massachusetts and New York. Each highway official was contacted using the results of the distributed municipal surveys described in the previous section, as they each stated that they would be open to answering future related questions. The following questions were discussed in each interview:

- What is your official title?
- How long have you served in this role? What was your professional background before you served in this role?
- Discussion of survey-collected data
- How is your municipal highway funding typically allocated? (safety improvements, maintenance, etc.)
- Where does your highway funding come from? Are there any regulations that impact where/how this funding can be spent?
- How discretionary is your municipal highway funding? Who makes the decisions on how highway funding is spent? What does this decision-making process look like? How collaborative/hierarchical is the process?

- How much of the control for the funding use lies with the primary highway supervisor? And/or who makes the final call when an allocation decision is in a dispute? Or what priority areas take precedence for funding decisions in a dispute? (safety, congestion, etc.?)
- How much does the use of this funding change year to year? Why?
- Do you work with your MPO/RPO? What is your relationship with your MPO/RPO?
- What is your perspective on trainings for highway superintendent/commissioners of public works related specifically to safety? Beneficial for some, important, etc.?

These interview discussions shaped the interpretation of the DEA results in some cases, and provided a more holistic perspective into the spending, operation, and safety considerations at the local level.

4.2.5 Selection of Inputs, Intermediate Factors, and Outputs

The purpose of this study was to identify the characteristics and resources of a municipality that lead to safer local roads. Thus, the selection of variables was based on the available physical environment and resource factors potentially influential to municipal spending and local road safety. Municipal staff composition data was collected using surveys sent to local highway officials in New York and Massachusetts in 2019 and 2020, as previously described. Accompanying datasets were then gathered and/or calculated. Four years of geographic, crash, expenditure, and demographic town data was gathered for both Massachusetts and New York for the 2015 to 2018 period. Geographic and expenditure data were the same data gathered for the analysis in Chapter 3. The R statistical software was used to organize the data for analysis, fuse datasets, and run the DEA models (R Core Team, 2019). Before the application of the DEA method, all data was scaled to be

on the same magnitude, as imbalance in data magnitudes can lead to output or processing inconsistencies (e.g., Avkiran (2006); Güngör-Demirci et al. (2017)). Because DEA models cannot process negative values, data were scaled using the same minimum and maximum values instead of standardization (Avkiran, 2006). The following sections describe these data collection and organization processes in more detail. The final variables are presented in Tables 4.1 and 4.2. Separate models were created for Massachusetts and New York as the DEA method assumes homogeneity between DMUs, or that they are operating under similar structures. This is a limitation of the DEA method and normalization schemes should be considered in future research. To overcome this, separate models are recommended as a solution (Avkiran, 2006).

Table 4.2. Summary statistics of crash, expenditure, geographic, and demographic variables.

Variable	Variable Description	New York		Massachusetts	
		Mean	Min	Mean	Min
<i>Expen</i>	Annual municipal highway expenditures	\$1,203,538	\$40,223.9	\$1,804,018	\$199,103
<i>Lane_mi</i>	Local lane miles	\$2,140,563	\$26,970,057	\$1,369,131	\$7,267,605
<i>Ctr_mi</i>	Local centerline miles	123.5	6.4	113.9	24.9
<i>Pop</i>	American Community Survey population	136.2	1576.8	69.2	413.8
-	Fatal crashes on local roads per year	62.5	3.2	77.2	14.1
-	Injury crashes on local roads per year	67.9	788.5	38.0	228.2
-	PDO crashes on local roads per year	8822	103	12,894	316
<i>EPDOc</i>	EPDO crashes on local roads per year (cost)	21,694	212,293	10,848	59,310
<i>EPDOw</i>	EPDO crashes on local roads per year (weighting)	0.1	0	0.4	0
<i>Mi_50+</i>	Miles to population of 50,000+	0.5	8	0.7	6
<i>%white</i>	Percent of white alone population	7.2	0	31.3	0
<i>%pov</i>	Percent of population in poverty	48.6	595	29.6	157.0
<i>%older</i>	Percent of population 65+ years	28.4	0	101.8	0
		151.6	2021	95.6	450
		1,106,812	0	-	-
		6,716,906	91,003,591	-	-
		180.5	0	767.8	0
		1175.8	14,663	712.2	3667
		32.5	0	15.2	0
		27.7	139.3	11.1	46.9
		93%	48.9%	90.7%	69.6%
		7.6%	100%	7.2%	98.8%
		10.8%	1.8%	5.8%	0.9%
		5.3%	31.6%	3.2%	17.9%
		18.4%	2%	19.1%	7.8%
		4.9%	34.4%	6.5%	41.4%

4.2.5.1 Input

Because spending influences the ability for other resources to be obtained and/or safety to be improved, the input variable for this research was annual municipal highway expenditures. This expenditure data encompasses spending from funding collected by the state government, property taxes, and other revenue sources. Again, town highway expenditure data for New York were obtained from the Office of the New York State Comptroller for each town for the years 2015 through 2018 (Office of the New York State Comptroller) and Massachusetts town highway expenditures were obtained from the Massachusetts Department of Revenue Division of Local Services Municipal Databank/Local Aid Section for the years 2015 through 2018 (Massachusetts Department of Revenue Division of Local Services).

4.2.5.2 Intermediate Factors

Several intermediate variables were included in analysis. Intermediate variables that influence spending and safety were determined through literature review and key informant interviews. All survey-collected data variables are presented in Table 4.1. The variable encompassing the number of full time highway/maintenance staff per municipality was converted to be an ordinal variable before analysis. As the DEA method measures relative efficiency and impact, this is an acceptable method of variable translation for analysis (Avkiran, 2006). All other survey variables were converted to dummy variables to account for the presence of certain additional resources. Geographic location and demographic municipal data were obtained from the previous study in Chapter 3.

4.2.5.3 Output

The output of each model was the annual number of crashes occurring on local roads within a given municipality in a given year to represent the level of safety on local roadways.

These crash numbers are represented in Table 4.2. New York State crash data was obtained through a Freedom of Information Law (FOIL) request as crash data on the TSSR website did not provide the required amount of detail for this analysis. All crashes outside of the New York City region in New York State from 2015 through 2018 were requested and granted. A crash in NYS is reported if there was property damage of \$1,001 or more and/or anyone was injured or killed, according to the New York Vehicle and Traffic Code Section 605. It is noted that some crashes were missing one of these pieces of information and therefore were unable to be included in this analysis. Massachusetts crash data was obtained from the IMPACT tool built by the Massachusetts Department of Transportation (Massachusetts Department of Transportation, b). As described in Massachusetts General Law Chapter 90, Section 26, crashes are reported in cases in which any person was killed, any person was injured, and/or there was damage in excess of \$1,000 to any one vehicle or other property. Detailed crash data from 2015 through 2018 was gathered and organized by severity, road type of crash, and locality. Again, it is noted that some crashes were missing one of these pieces of information and therefore were unable to be included in this analysis.

The DEA method allows for multiple output variables to be included within one model. However, to ensure each crash type was weighted appropriately, all crashes occurring in each municipality on local roads were converted to EPDO crash values. These values were first calculated per each state's current guidelines. In Massachusetts, a weighting value of 21 is assigned to each fatal, injury, or possible injury crash, and a value of one is assigned to all property damage only (PDO) crashes (MassDOT Highway Division, 2020). In New York, EPDO values are calculated by estimated crash cost. Fatal crashes, injury crashes, and PDO crashes are estimated to be \$3,686,232, \$91,136, and \$4,443, respectively (Harmon et al., 2018). Thus, the EPDO processes used in each state are dif-

ferent, with fatal and injury crashes in Massachusetts taking on the same weight, while in New York these crash types are different by a factor of approximately 40. The weighting method used in Massachusetts was developed to avoid only “chasing fatal crashes,” as the difference between an injury crash and fatal crash can sometimes be due to a single factor, such as emergency services arrival time (MassDOT Highway Division, 2020; Lee et al., 2018).

Given the noteworthy difference in weighting factors and cost association with varying crash types between Massachusetts and New York, an additional analysis of New York data was completed using the same weighting factors as those used in Massachusetts. This was done to allow for two primary comparisons: 1) a comparison of the results of New York with those of Massachusetts using the same weighting system and 2) a comparison of the two methods, as results of the two methods differ between one another when one of them prioritizes fatal crashes substantially more than injury crashes. Thus, the New York crash data was transformed and then modeled twice: once using the “cost method” and another using the Massachusetts “weighting method.”

A final change to the output variable of these models was necessary before running the DEA analysis. This is because the DEA method is based on the theory that a more efficient system is one that creates the maximum output with the minimum input. However, in traffic safety studies, the output of crashes is an undesirable output. To account for this, all EPDO crash values were replaced by their reciprocals, as suggested by Golany and Roll (1989) and done in other traffic safety studies using the DEA method (e.g., Alper et al. (2015); Antić et al. (2020)). To avoid infinity values for municipalities with zero crashes of any type during a given year, these values were transformed to be approximately two orders of magnitude smaller than the smallest EPDO value before this conversion to reciprocals. Given the partial uncertainty of crash rates, the small cases where this was implemented,

and the need to maintain these data points, this approach was determined to be more acceptable than deleting these data points.

4.3 Results

The results of the interviews and DEA method provide insight into the relationships of local road safety and municipal expenditures. The following sections include these results in the form of a summary of the conducted interviews and modeling results of the DEA method.

4.3.1 Interviews

Five highway officials were interviewed before analysis: two from New York and three from Massachusetts. These officials are described as follows:

- **Official A.** A Commissioner of Public Works in a town of approximately 17,000 residents in New York who had served in their current role for over ten years at the time of this interview.
- **Official B.** A Highway Superintendent of a town of approximately 2,000 residents in New York who has worked for the town as a motor equipment operator prior to serving in their current role. They had been serving as Highway Superintendent, an elected role in many towns in New York including this town, for three years.
- **Official C.** A Highway Division Manager in a Massachusetts town of approximately 38,000 residents who had served in this role for two years but had worked for the town for 16 years in various roles.
- **Official D.** A Commissioner of Public Works and City Engineer in a city of approximately 40,000 residents in Massachusetts who had served in this role for about 14

months. Prior to this role, they had worked in a nearby city as a transportation engineer and then city engineer.

- **Official E.** A Town Engineer in a town of approximately 32,000 residents in Massachusetts who had served for over 15 years in their current role, but had previously worked as a staff engineer for a different town. This Town Engineer is a certified as Professional Engineer.

The resulting conversations with these individuals provided many insights that were considered before analysis. Specifically, these conversations informed which variables should be considered in the DEA modeling analysis and revealed which countermeasures should be considered to improve safety in specific environments. It is noted that these conversations focused on times before the COVID-19 pandemic. Several noteworthy points were discussed. This section provides the details of these interviews and concludes with an overall summary.

4.3.1.1 Discussion of Survey Results

The survey data was discussed with each highway official using a presentation of the data in graphical form. From these conversations, several insights were gathered. First, Official A thought town engineers in New York were not common. However, they stated that their town works closely with their county engineers and works closely with all other 15 highway superintendents in the county. This relationship was found to be helpful to their town, with the largest benefit being that the service is free; there is no cost for the town to work with the county engineer. Official A also mentioned that it is quite common for towns to work with private engineering companies when needed. Official B also stated the frequency of using a consultant in their field of work. The resulting conversations with Massachusetts local highway officials on this topic were similar in nature. Generally,

all three officials from Massachusetts stated that highway engineers were not common in towns. In terms of an engineer, it was surprising to Official D that 48% did not have any sort of engineer on staff.

In regards general town road safety, it was reiterated by each highway official in Massachusetts that safety is predominately driven by the police. Police will take input from the local Department of Public Works (DPW) and Engineering Department, according to Official E, but overall, traffic functions and safety are delegated to police. Official D stated they work closely with police for transportation projects such as traffic signals. They noted that in several towns, the police department of the town is left to maintain the traffic engineering within the town, such as stop signs and crosswalks. From their perspective, the police may try to use the Manual on Uniform Traffic Control Devices (MUTCD) or just “wing it.”

County financial assistance is only received in New York, as Massachusetts no longer has functioning county structures. Official B stated they have received assistance from the county. From a consultant perspective, Official B also stated they have hired one, which they stated may be more common in busier areas. Overall, they stated that the Highway Department is more focused on maintenance, while engineering may be done by the Engineering Department or another department outside of the Highway Department. Furthermore, they stated that sometimes there is a different group that focuses on highway construction outside of the Highway Department itself. Official A stated that they believed many towns may not hire a consultant due to the cost of doing so. Official E in Massachusetts stated that they rely on consultants as they and the Public Works Director do not have a focus on traffic engineering itself, only a “basic fundamental understanding.” Additionally, Official E stated that there is a liability related to traffic engineering so they would prefer to have someone else work on these types of projects. However, Official D

had a negative experience with trying to hire a consultant, as the DPW in their city is not allowed to hire consultants, which is where the City Engineer position is held. Their point was that some municipalities are not set up to be able to do certain tasks that other towns are able to do. Finally, Official C stated that a consultant has not been hired as they have an Engineering Department and thus, it was considered not as necessary.

In terms of the number of full time highway maintenance staff, officials had similar responses. Many towns have both full time and part-time highway staff, with some only employed seasonally for snowplowing, mowing, or driving paving trucks. Official B stated that the number of staff likely depends on the number of lane miles more so than the population. Furthermore, they stated it depends upon the scope of the work done by the Highway Department. For example, sometimes parks and buildings are managed by the Highway Department when there is nobody else to do it. They also stated that the staff are not paving every day of the year, and so these types of jobs may employ staff during these times. Official C said they do not have enough full time staff with six on the road and three mechanics and over 600 lane miles.

RSAs were found to not be commonly done by the interviewed town officials. Official B stated they had no formal RSA process; however, their working group does do them more consistently given the nature of the group. Official D stated they had a formal RSA process as well, such as just bringing out the police to particular locations to have safety discussions about problem locations. Official C stated MassDOT spearheads most RSAs and the Engineering Department is more involved on that end. However, MassDOT does not help with local roads; they only focus on their own roadways.

4.3.1.2 Municipal Highway Funding

The following section discusses the responses to the questions pertaining to the allocation of highway funding within towns. In New York, the largest budget allocations

were found to be towards maintenance and paving. Sometimes this could be equipment as well, depending upon the year and need. Official B stated that money for road safety improvements specifically are funneled through the traffic safety group in terms of prioritizing what safety improvements are critical. In Massachusetts, there was a similar theme, with maintenance generally being the highway budget allocation item. Official D stated that they try to break up where funding is going. Specifically, the current focus is on sidewalks, as there are a lot of sidewalks within the city. About 20% of the funding goes towards sidewalks given how expensive they are to make sure they last a long time.

As previously mentioned, in New York, CHIPS funding is the primary state highway funding program for towns. This funding is allocated each year to towns prior to the beginning of their fiscal year. In Massachusetts, their primary highway funding source from the state is Chapter 90. Chapter 90 funds are reimbursable funds, meaning they cannot be accessed until after the money has been spent. Official D brought up a problem with the distribution of Chapter 90 funds; they are allocated based on population, number of road miles, and employment, and their specific city has a lot of infrastructure but not much employment. Their city is generally a poorer city. Given this, Official D believes they are missing out on a lot of funding due to this current formula.

Some officials provided exact values for how much they get approximately from different funding sources to work with annually. Official D stated their highway fund is essentially only from Chapter 90 funds, at approximately \$1.1 million annually. In their town, they did not receive much in tax dollars, only enough to “run the department or to fill potholes, but no capital money.” To fill these gaps, Official D mentioned they apply for Community Development Block Grants (CDBG), Complete Streets Funding, Safe Routes to School funding, among others. They did note, however, that they have a staff that is aware of how to get these grants, so while it is a necessity since they do not have much

funding, they stated smaller communities likely do not apply to them. Further, once a grant is awarded, it can be difficult to manage them according to Official D.

Other officials had different experiences in terms of where local highway funding is received. Official C has a budget each year of around \$2 million, with \$985,000 of that funding coming from Chapter 90. While they noted the funding is “never enough”, their town is fortunate as they “get more than the surrounding towns based on the formula.” Official C said that approximately 80% of highway funds for their town come from Chapter 90. They also mentioned they try to stay away from using Chapter 90 funds for funding equipment, even though it can be used for that; they primarily use Chapter 90 funds for maintenance. In New York, Official A stated a that around \$180,000 in funding was provided from the state between CHIPS, Extreme Winter Recovery (EWR), and PAVE-NY, with “a lot of funding” coming from tax dollars. In total this past year, their local highway funding budget was \$1.3 million. Official A also discussed a project in which they did a project that was paid for by the state on a local road related to high water issues; however, the funding did not cover the cost of the hours of labor, only the materials, which is stated was common for state grants in New York. Official B stated that they use funding from both taxes and CHIPS funding, with CHIPS accounting for approximately a quarter of paving funding and the town tax dollars covering the other three-quarters at approximately \$1 million per year.

In terms of how discretionary the municipal highway funding was, officials consistency stated that in general, it is essentially all discretionary. Multiple officials stated that it is often a cumulative effort between a few individuals, such as the Director of the Department of Public Works, the Town Engineer, the primary highway official, and/or the Town Supervisor. However, in all cases, the “final say” in how funding would be used was left to each official interviewed, except for Official E, where in their town, the this role is

held by the Director of Public Works. Sometimes an approval process may need to play a role in larger decisions as well, such as purchasing equipment. Overall, it was gathered from the officials that the budget-making process is a group effort with multiple players with very little need to work through disputes as they do not commonly arise.

4.3.1.3 Working with Local MPO/RPO

There was a divide among officials when it came to working the interviewed officials working with their respective MPO/RPO. Official A's town is not within a MPO boundary, while Official B's town is within one. Official B stated they work with the organization only to a "limited degree." Official C stated that their group does not work with them, while Officials D and E stated they do work with their RPOs. Official E stated they are helpful and assist with TIP projects. They also attend regional meetings with the group and provides input on the overall transportation policy. Official D also stated they are part of meetings with their RPO and that they sit on a joint transportation committee. However, they stated it is difficult to get a TIP project within their jurisdiction.

4.3.1.4 Primary Safety Concerns

Crashes at the municipal level were discussed with each official. For Official B, speeding was stated as the primary concern as it is "common to hear about from people" and in response, their group tries to implement traffic calming measures. Intersections were also stated as a significant issue, particularly at intersections with state-owned roadways where the volume is higher. Their largest concern was noted as pedestrian crashes as they are more likely to result in injury or death. In an attempt to counteract this, their town is currently installing rapid flashing beacons. Finally, Official B noted that their municipality has a "a lot of bicyclists." While they said there are not too many crashes, there is an importance to stress bicycle safety. Their main focus on this issue is on education for road

users. Finally, Official B noted that distracted driving was a significant issue, leading to crashes such as rear end crashes at intersections. To deal with this issue, they have focused on education and increasing signage, which from their perspective, provided less of a safety benefit.

Official A noted also intersections as one of the largest issues from a crash perspective for their town. Intersections were also a problem for their town in terms of fatal crashes; however, they noted that “there is only so much they can do.” Official C stated that speeding complaints were common in their town, as were requests for speed bumps and speed studies. They noted a lot of this issue correlates with enforcement. However, they said that they do not often complete traffic studies on these roads requested because once they are done, the town must post the speed limit that was determined by the speed study and these speeds are “typically higher” than their residents want to see. These speed studies are done by MassDOT. Instead, Official C stated that they have put in striping and traffic calming measures, such as road narrowing. Intersections were also noted as an issue in the more urbanized areas of the municipality due to sight line obstructions, drivers not stopping, and drivers not yielding at crosswalks for pedestrians. Official D noted similarly that many crashes were speed-related and much of solving this issue is “working with the police department through enforcement.” They noted that many people want an engineering solution; however, they also said that they “need to” focus on solving the issues with education and enforcement first. Meetings still occur if necessary to move on to other solutions. At one high crash location, their group met with police and decided to install stop signs with flashing LEDs.

The experience of Official E aligned with that of Officials C and D, creating a focus that safety and crash issues fall on police departments rather than DPWs or local highway divisions. Official E stated that for crashes, they defer to the police department and noted

that side and rear end crashes were more common of the types. In terms of serious and fatal crashes, while they are not common, they noted that these events do happen. They believed these crashes occur due to substandard intersections and some of the geometry of the roadway networks in older sections of the town.

4.3.1.5 Perspective on Training

Training programs and workshops are offered by a few agencies and organizations throughout Massachusetts and New York. The largest of these are organized by the LTAP for each respective state: Cornell Local Roads Program in New York and the University of Massachusetts Transportation Center (UMTC) in Massachusetts. Official A noted that they had attended some trainings hosted by their LTAP, and while they serve a purpose, some are “pretty repetitious.” they noted that from their perspective, they focus on engineers discussing different crash scenarios or new techniques which is interesting, but they discuss maintenance less. Official A did say that they thought these trainings would still be helpful to new people who are not familiar with these types of focus areas. Official B had a similar perspective on who trainings are important for. Specifically, Official B noted that these trainings would be important for superintendents who are new and “didn’t grow up in the field”; however, it varies with background. They thought the state LTAP was great in terms of expertise. They also included that connecting with the Association of Towns in New York is a great resource.

Training by Massachusetts officials was viewed slightly differently. Official C believed trainings are “always helpful” as there are new techniques and technologies. Additionally, networking is always helpful. Their highway group signs up to any class by the Massachusetts LTAP that is applicable to what they do. In addition, they noted that they talk to other nearby towns often to exchange plans and ideas. For example, they may discuss what each of them are doing for snowstorm management to learn from each other.

They noted that they were not sure if this type of group dynamic between town highway groups was common, but they thought it was very beneficial.

Official D also had a positive experience with the Massachusetts LTAP, noting that they were a Road Scholar through the LTAP. They said they signed everyone from DPW up when they get the email on trainings and believed it is great too. They believed all DPWs should be on the mailing list to receive these trainings. They stated that the LTAP has trainings on safety trainings and sources, traffic control, work zone management, and more. They try to send all of their staff to the ones that are offered. They said that they found some towns are good about participating in trainings, while others do not, as they “don’t think about it.” Official E overall had a similar perspective and believed the LTAP trainings were “very beneficial” and “great for team building and networking.” Overall, they thought the LTAP trainings were a great resource.

4.3.1.6 Summary

Overall, officials found that working with a local consultant on a transportation project was common among municipalities. Town engineers were considered less common, along with Road Safety Audits (RSAs). Maintenance was reiterated as the primary cost faced by highway departments. However, Official D suggested that they received less funding due to the MA formula for funding distribution, as their specific municipality has a lot of infrastructure but not much employment. Official D also stated that they receive little funding from tax dollars; only enough to “run the department or to fill potholes, but no capital money.” To fill these gaps, Official D mentioned that they also apply for Community Development Block Grants (CDBG), Complete Streets Funding, and Safe Routes to School funding, among other sources. They noted that this form of obtaining funds is not accessible to smaller communities who may not have staff who know how to get these grants. In addition, once these grants are received, they can be difficult to manage.

In terms of working with their local MPO/RPA, some officials stated they did, while others did not. One official was not within the boundaries of any MPO in New York. In Massachusetts, working with RPAs was noted as important to get a Transportation Improvement Program (TIP) project. However, one official still considered this difficult. From a safety perspective, each Massachusetts official stated that safety issues typically fell on the police departments rather than local highway divisions or Departments of Public Works (DPWs). New York officials focused on safety challenges that have been attempted to be fixed using infrastructure and educational strategies and did not mention police. Finally, training for local highway officials was considered by all interviewees to be helpful, at least in some instances. One official noted that the amount it may be helpful may depend upon the level of expertise an official already has in their current position.

4.3.2 DEA Results

Correlation matrices were created to confirm the variables to be included in the final DEA models. Specifically, these matrices were built to determine whether the state-specific DEA models should include the centerline miles variable or lane miles variable. Tables 4.3 and 4.4 present these results. In New York, the number of centerline miles and lane miles were equally correlated to a significant degree with a higher expenditure rate. Neither was significantly correlated with the EPDO rate alone, i.e., without first considering other variables. However, in Massachusetts, the number of centerline miles had a higher correlation with the municipal highway expenditures and EPDO crash rate compared to lane miles. Thus, for consistency across models and due to this stronger relationship, centerline miles was used across all DEA models. In terms of other variables, all were either significantly correlated with the expenditure variable or the EPDO rate variable, if not both, so all intermediate variables were deemed appropriate to include in the DEA models.

Table 4.3. Pearson Correlation Matrix of New York data.

Variable	Expen	EPDOc_R	Lane_mi	Ctr_mi	Pop	Eng	Hwy_eng	RPO/cnty	Consult	Staff	Civil	RSA	Mi_50+	%white	%pov
EPDOc_R	-0.04														
Lane_mi	0.91**	0.00													
Ctr_mi	0.91**	0.00	1.00**												
Pop	0.93**	-0.10**	0.85**	0.86**											
Eng	0.30**	-0.06	0.23**	0.23**	0.31**										
Hwy_eng	0.56**	-0.04	0.44**	0.44**	0.59**	0.44**									
RPO/cnty	-0.21**	-0.18**	-0.17**	-0.17**	-0.16**	-0.07*	-0.05								
Consult	0.26**	-0.06	0.24**	0.24**	0.24**	0.12**	0.16**	0.03							
Staff	0.62**	0.01	0.59**	0.59**	0.57**	0.39**	0.31**	-0.20**	0.29**						
Civil	0.36**	-0.10**	0.28**	0.28**	0.33**	0.48**	0.40**	-0.02	0.18**	0.36**					
RSA	0.13**	0.00	0.12**	0.12**	0.16**	-0.03	0.16**	0.02	0.15**	0.01	0.05				
Mi_50+	-0.25**	0.37**	-0.19**	-0.19**	-0.26**	-0.27**	-0.15**	0.07*	-0.18**	-0.27**	-0.15**	-0.04			
%white	-0.41**	-0.11**	-0.30**	-0.30**	-0.44**	-0.26**	-0.37**	0.11**	-0.15**	-0.45**	-0.28**	-0.03	0.07*		
%pov	-0.23**	0.18**	-0.18**	-0.18**	-0.20**	-0.30**	-0.15**	0.06*	-0.21**	-0.34**	-0.17**	-0.02	0.35**	0.19**	
%older	-0.08**	0.08*	-0.04	-0.04	-0.12**	-0.05	-0.09**	0.10**	0.01	-0.09**	-0.02	-0.04	0.07*	0.31**	-0.05

Note: EPDOc_R = EPDO cost reciprocal, **p-value <0.01, *p-value <0.05

Table 4.4. Pearson Correlation Matrix of Massachusetts data.

Variable	Expen	EPDO_R	Lane_mi	Ctr_mi	Pop	Eng	Hwy_eng	RPO/cnty	Consult	Staff	Civil	RSA	Mi_50+	%white	%pov
EPDO_R	-0.15**														
Lane_mi	0.62**	-0.16**													
Ctr_mi	0.65**	-0.17**	0.93**												
Pop	0.78**	-0.17**	0.72**	0.74**											
Eng	0.66**	-0.13**	0.55**	0.55**	0.67**										
Hwy_eng	0.47**	-0.06	0.28**	0.32**	0.41**	0.40**									
RPO/cnty	-0.10*	-0.06	0.10*	0.14**	0.02	0.03	0.09*								
Consult	0.31**	-0.17**	0.36**	0.36**	0.33**	0.26**	0.16**	0.32**							
Staff	0.56**	-0.15**	0.58**	0.60**	0.59**	0.31**	0.31**	0.18**	0.22**						
Civil	0.58**	-0.14**	0.48**	0.46**	0.57**	0.65**	0.36**	0.02	0.31**	0.21**					
RSA	0.09*	-0.09*	0.10*	0.12**	0.12**	0.08	0.21**	0.20**	0.27**	0.05	0.18**				
Mi_50+	-0.51**	0.28**	-0.32**	-0.39**	-0.59**	-0.49**	-0.21**	-0.06	-0.29**	-0.31**	-0.39**	-0.10*			
%white	-0.48**	0.11*	-0.27**	-0.28**	-0.54**	-0.51**	-0.24**	0.04	-0.16**	-0.27**	-0.41**	-0.14**	0.41**		
%pov	-0.20**	0.11*	-0.11*	-0.13**	-0.06	-0.18**	0.04	0.07	-0.02	-0.02	-0.08	0.00	0.36**	0.03	
%older	-0.19**	0.19**	-0.05	-0.18**	-0.34**	-0.18**	-0.09	-0.18**	-0.20**	-0.24**	-0.06	-0.21**	0.57**	0.36**	0.24**

Note: EPDO_R = EPDO reciprocal, **p-value <0.01, *p-value <0.05

Figure 4.1 presents the final DEA results from the models run using the rDEA package in R (R Core Team, 2019; Simm and Besstremyannaya, 2020). The red solid lined box contains the results of the New York and Massachusetts data using the Massachusetts EPDO weighting method. The gray dashed box in the figure contains results from both analyses of the New York data, one using the Massachusetts EPDO weighting method and another using the EPDO cost method. From a practical perspective, under the null hypothesis of the DEA method for each variable, there is no difference in a system's efficiency at different variable values. The null hypothesis can be rejected at the 95% significance for a specific variable if the lower bound and upper bound confidence intervals have the same sign, a common method to identify significance using Simar and Wilson (2007)'s method (e.g., Sickles and Zelenyuk (2019); Salazar-Adams (2021); Güngör-Demirci et al. (2017)). A positive sign of a coefficient ($\hat{\beta}$) in Figure 4.1 shows that an increase in this variable leads to a decrease in the crash rate per expenditure dollar. As previously noted, all data was scaled to be on the same magnitude before analysis, so the magnitude of the variables present which make a larger impact than others. As DEA models cannot contain negative values, scaling was performed instead of standardization (Avkiran, 2006). These findings are discussed in the following section.

Variable	MA with weighting method			NY with weighting method			NY with cost method		
	Coefficient (β)	Confidence Interval		Coefficient (β)	Confidence Interval		Coefficient (β)	Confidence Interval	
		2.5%	97.5%		2.5%	97.5%		2.5%	97.5%
Intercept	18690*	1360	24784	-18192*	-33606	-26361	-11886*	-23869	-17813
<i>Chr_mi</i>	1005*	888	1302	1023*	1236	1625	1280*	1586	1937
<i>Pop</i>	1218*	855	1331	1171*	656	1007	977*	469	795
<i>Eng</i>	67.4*	12.2	156	-60.9*	-108	-36.1	-43.5*	-74.4	-5.34
<i>Hwy_eng</i>	-30.5	-114	47	-357*	-466	-310	-396*	-567	-410
<i>RPO/cnty</i>	-54.9*	-113	-12.7	136*	168	218	109*	131	180
<i>Consult</i>	7.56	-34.5	84.4	34.8*	14.0	72.4	18.6	-3.04	55.6
<i>Staff</i>	200*	101	406	466*	693	813	385*	642	766
<i>Civil</i>	18.3	-48.6	85.6	141*	76.0	187	65.4	-14.5	95.7
<i>RSA</i>	115*	66.4	177	195*	231	332	300*	411	504
<i>Mi_50+</i>	-749*	-978	-685	-1213*	-2034	-1876	-1166*	-2024	-1874
<i>%white</i>	170*	86.5	305	99.8*	35.6	157.9	-42.5*	-190	-74.3
<i>%pov</i>	59.7	-15.0	254	-480.7*	-743	-582	-504*	-824	-670
<i>%older</i>	-68.7	-215	86.8	-424*	-741	-599	-414*	-745	-605
		n = 500			n = 1043			n = 1043	

*p-value < 0.05

Figure 4.1. Data envelopment analysis results.

4.4 Discussion

Many noteworthy relationships were revealed in this study. The Massachusetts and New York results using the Massachusetts EPDO weighting method investigating the efficiency of the municipalities contained in the red solid lined box in Figure 4.1 are first discussed. This is followed by a discussion of the results shown in the gray dashed box on the right of Figure 4.1, which compare the two EPDO methods using the data collected in New York. Discussions from the interview portion of this study are tied into these sections as appropriate.

4.4.1 Findings using Massachusetts EPDO Weighting Method

The Massachusetts EPDO weighting method findings contained in the red solid lined box in Figure 4.1 are discussed in the following section.

4.4.1.1 Municipal Government Composition and Physical Environment Findings

The physical environment was identified as a key factor in the efficiency of municipal governments towards improving local road safety. To begin, in Massachusetts and New York, an increase in centerline miles in a town was associated with a higher efficiency of expenditures to decrease crashes. An increase in municipal population was also associated with a higher efficiency in both states. This aligns with the findings of Deller and Nelson (1991) that larger, more populated regions are more efficient at producing roads and road services. Having an engineer of any kind on a municipal staff was associated with a higher efficiency in Massachusetts and a lower efficiency in New York; yet this impact was lesser than the impact of the population and local centerline mile variables as shown by the relative order of magnitude of these variables. The same finding was observed in New York for municipalities with a highway engineer on staff, while this factor was insignificant in

Massachusetts. This may be due to a lower reporting of crashes or fewer crashes in towns in New York compared to Massachusetts; a higher proportion of towns in New York spanning all sizes reported zero crashes on local roads compared to Massachusetts. This may also be connected with New York municipalities working with their county engineer more often and having a lower proportion of towns with an engineer on staff compared to Massachusetts, as presented in Table 4.1. The key informant interview results also confirm that engineers on staff in New York are not common. New York officials vocalized that consultants are often hired if safety support is needed and/or county engineers are brought in for assistance, as their responsibilities and schedules allow. However, bringing in consultants may be more difficult for towns with less money. Given the complexity of this finding, future research should further consider this specific relationship, i.e., the importance of certain municipal highway officials having an engineering or similar degree in increasing local road safety. The results reveal that support from the county highway department and hiring a consultant are associated with a higher efficiency towards safer local roadways in New York. At the same time hiring a consultant did not have a significant effect in Massachusetts.

In Massachusetts, receiving support from a local RPO had a negative impact on efficiency. The interviews of local officials suggest that working with their local RPO was helpful and RPOs assisted with TIP projects; yet, one official noted that obtaining TIP projects from the RPOs was difficult. Thus, the results may suggest that towns who have benefited from RPO support in the past three years have an increased safety need as the TIP project prioritization process benefits those municipalities who have higher safety needs. These towns would be less efficient due to the higher crash locations within these jurisdictions. This increased safety need may take the form of a high-crash location or other unsafe infrastructural/environmental factors of the roadways themselves that were

not considered directly in this analysis. Additional research into this finding is suggested for the future.

Municipal staff composition was identified as a significant factor in the resulting efficiency of municipalities. The results of the DEA models suggest that having a larger staff is associated with a higher efficiency in both New York and Massachusetts. Having a staff member with a civil engineering degree (or equivalent) was associated with a higher efficiency in New York, although to a lesser extent than the number of staff as presented by a smaller coefficient variable. This aligns with previous research findings showing that trained, skilled officials can make informed decisions that lead to budget cost savings (Sokolow, 1984; Deller and Halstead, 1994, 1991). Additionally, officials that have been educated in the specific field of civil engineering can make more informed safety decisions than non-trained officials who may be making decisions without sufficient information, as described in Snavely and Sokolow (1987). This research did not consider the direct benefits of having officials attend LTAP or other training opportunities in cases where officials do not have a civil engineering degree. Future research should consider this potential impact on efficiency and safety.

RSAs were found to be associated with more efficient systems in both states. This demonstrates the importance of RSAs and acting upon their results with a type of regularity on local roads. RSAs in municipalities occurred less in New York than Massachusetts, as shown in Table 4.1. From the key informant interviews, it was confirmed that RSAs performed by municipalities are generally not common. Further, given the order of magnitude of the RSA results in both states, RSAs have a greater efficiency impact than hiring a consultant or having a general engineer on staff. Given this, RSAs have a high potential to improve local roadway efficiency and safety if done regularly and equitably among municipalities. The interviews suggest that the reason RSAs may not be performed of-

ten in Massachusetts is due to road safety being considered something that police handle without municipal government input. Furthermore, performing RSAs requires time and an interdisciplinary group of experts and professionals, which a municipality may not have. These barriers, among others, must be overcome to perform and act upon RSA results. Specific guidance to perform RSAs on local roadways has been provided in literature, such as Mahgoub et al. (2010).

4.4.1.2 Equity Considerations of Findings

The demographic characteristics of municipalities were shown to have a significant role in their efficiency for increasing safety on local roads. To begin, the variable representing distance from an urban area was found to be associated with a lower efficiency in both New York and Massachusetts. Thus, more rural municipalities were found to be less efficient, as found in prior research (Deller and Nelson, 1991; Deller et al., 1992). This also aligns with the current statistics in the U.S. that serious crashes occur at a higher rate in rural areas (National Center for Statistics and Analysis, 2019). This factor was shown to play a critical role in both states, given its larger magnitude compared to other variable coefficients, including the RSA variable and percent of white population variable. Overall, this signifies the need for additional financial and/or other resource state support for rural municipalities to achieve the same level of road safety as their urban counterparts. Other opportunities to increase safety on a given budget in more rural areas could include decreasing travel time to emergency care, which can sometimes be the difference between life and death. Emergency arrival times to crashes are longest on conventional rural roads, resulting in more severe injuries (Lee et al., 2018).

An increase in white alone residents also leads to an increase in efficiency in both states, although to a lesser extent than geographic location. These results show that non-white people continue to be underserved in the transportation system. This signifies

that additional funding and/or resource support is needed for municipalities with higher percentages of non-white alone residents to achieve the same level of safety as primarily white municipalities. These results align with previous research on equity and safety. For example, a study by Kravetz and Noland (2012) found that areas with a higher percentage of Black and Latino populations were associated with high numbers of pedestrian crashes. Kravetz and Noland (2012) noted their results suggested that there was a potential environmental justice issue at the crux of this problem: pedestrian-friendly road infrastructure was not distributed equitably. Historical injustices remain embedded in the transportation system, as demonstrated by the complexity of resource distribution and the resulting inequitable investments (Power, 2012; Golub et al., 2013). In order to address these injustices, it is critical that states help eliminate the safety disparity between different population groups by providing context-specific funding to better meet the needs of communities. Outreach to these communities is additionally needed to understand these context-specific needs. Specific guidance, education, and expertise-related resources should also be provided to municipal officials to support minority communities. Future research should consider additional resources that could be leveraged to improve safety outcomes, such as addressing the role that planning and zoning plays in the creation of creating safe, equitable communities.

The percentage of residents in poverty coefficient had mixed results between the two states. Specifically, the percentage of municipal residents in poverty was not a significant factor of municipal efficiency in Massachusetts. In New York, however, an increase in the percentage of residents in poverty was found to significantly lead to lower efficiency of municipal spending on safer local roads. This discrepancy was also shown in the percentage of the older population variable. An increase in older residents in a given municipal population was not associated with a more efficient system in Massachusetts, but was in New

York, where an increase in the percentage of people aged 65 and over was associated with a lower efficiency. The lower efficiency of municipalities due to high poverty rates in New York may be connected to the lower healthcare accessibility of these communities (Kirby, 2008). Thus, they may experience higher injury and fatality rates than those with greater access to healthcare. Additionally, people in poverty are more likely to travel by a mode that is more vulnerable to more serious injuries, such as walking or cycling, compared to wealthier people who are more likely to travel by automobile (Bills and Walker, 2017). Further, residents with lower incomes are more likely to need to travel longer distances than residents with higher incomes (Rosas-Satizábal et al., 2020). To rectify this disparity, future research should consider why this inefficiency is occurring among communities with higher poverty levels, including how local highway funding is spent in these communities. Potential short-term solutions could include providing more financial and expert resources to communities with high poverty levels and conducting outreach to these communities to understand what their specific needs are to improve safety.

The significant finding of increased older residents within a population on efficiency in New York may be attributed to older people being more susceptible to more serious injuries in similar crash conditions compared to younger people (Cicchino, 2015; Insurance Institute for Highway Safety, 2019). Thus, if local roadway funding is used to improve roadway infrastructure, such as through the installation of guardrails on a curve, this would increase the safety of both municipalities with a younger-skewed population and an older-skewed population. However, if a crash were to occur at a location with guardrails, an older occupant would still be more likely to experience a worse, and, potentially fatal injury than a younger occupant. This result potentially signifies the need to provide additional financial support to municipalities with a higher percentage of older residents as additional infrastructural, educational, or access to alternative transportation

modes may need to be in place to achieve the same level of safety. Further research is required to consider the types of crashes that are occurring on local roads that impact older population groups. Future research should consider why poverty levels and percentage of older residents within a population was not significant in Massachusetts but was in New York. This is likely connected to the different funding and support structures in New York and Massachusetts. One reason for this discrepancy may be the inclusion of employment rates in the algorithm to distribute local highway funding to municipalities in Massachusetts, something that is not included in the New York distribution process. Thus, in Massachusetts, municipalities with higher employment rates receive more funding to use towards improving safety than municipalities with lower employment rates. This was noted as a major issue by one interviewed official in a municipality characterized by high poverty rates with high unemployment among their residents. Research has found that areas with higher poverty and older aged populations are associated with lower employment rates (Corcoran and Hill, 1980; Gallie et al., 2003; Hoynes et al., 2006; Akanni and Čepar, 2015). Future research should consider more detailed data to investigate this potential discrepancy to ensure equitable access to safe infrastructure.

4.4.2 Countermeasure Selection

Appropriate countermeasure selection for local roads is a critical component to improving safety. As discussed in the literature review, this process can be more challenging on local roads rather than state-owned roads. Several potential countermeasures to increase local road safety can be identified based on the discussions during the key informant interviews. To begin, Officials B, C, and D stated that speeding was a primary concern of residents in their jurisdiction, or that crashes were often speed-related. Thus, traffic calming countermeasures should be considered in areas where speed-related crashes are of concern. Several speed management countermeasures have proven to be effective in local

environments, ranging in cost and effectiveness depending upon the countermeasure (Federal Highway Administration, 2014a). Proven countermeasures include speed humps and raised intersections. A list of countermeasures for speeding reduction for specific environments is described further in Federal Highway Administration (2014a).

Intersections were discussed as significant locations where crashes occur on local roads by Officials A, C, and E. Depending upon the particular issue at each intersection, several potential countermeasures could improve safety. For example, flashing yellow arrows for left turns have proven to increase the safety of serious injury crashes in cases of left turns, yet many older signal systems still use a green ball and yield for left turn movements (Brehmer et al., 2003). A description of intersection countermeasures and selection assistance for local roadway owners in specific environments is described comprehensively in Golembiewski and Chandler (2011). Other road safety issues were discussed during the key informant interviews, but were less consistent. These included bicycle safety concerns and distracted driving concerns. Countermeasures to increase safety with bicyclists including complete street concepts and dedicated bicycle lanes (Riverón, 2018). Distracted driving countermeasures can include awareness campaigns, eye tracking technology, and increased enforcement (Arnold et al., 2019).

Countermeasure selection process often depends upon the environment that the roadway is in. Different countermeasures have proven to be more and less effective in specific conditions, such as rural or urban conditions. This is important to consider in relation to the findings of this study, as particular environments were found to require increased support to achieve the same level of safety. For example, rural environments required additional support to achieve the same level of safety as urban areas as it can be difficult to develop and maintain infrastructure in low-density rural areas with the current funding levels. Given these challenges, as well as the funding allocation inequity revealed

in this chapter, we suggest that transportation planners and engineers evaluate and review a variety of approaches for improving safety in rural areas to more efficiently use their limited resources. Effective, efficient countermeasures in these areas often include those that are low cost, but high in impact, such as pavement markings, crosswalks, flashing beacons, and road diets (Anderson and McCabe, 2020). These types of countermeasures are able to be installed across a larger region as they are less costly to install and maintain over time.

4.4.3 Comparison of Cost Method and Weighting Method using New York Data

As previously mentioned, calculating EPDO crashes is done differently in Massachusetts than other states as injury crashes and fatal crashes are weighted on the same level to avoid “chasing fatal crashes” (MassDOT Highway Division, 2020). Using the New York cost method, fatal crashes are weighted 40 times more than injury crashes, even though the difference between an injury outcome and fatal outcome can sometimes be one minor factor. Only New York data was applied across both EPDO methods as it is the only state that uses the more traditional EPDO method and it would reveal if a more in-depth comparison in future studies should be considered.

The results in the dashed gray box in Figure 4.1 contain the DEA results using the Massachusetts EPDO weighting method on the New York data and the EPDO cost method on the same data. The results present multiple noteworthy differences. To begin, the hiring of a consultant and having a civil engineer on staff are not significant in the cost EPDO method results, but are in the EPDO weighting method results. Thus, if there is a focus on fatal crashes over all other crash types, these variables are no longer significant. These differing results highlight the importance of determining what crash types are valued before analysis that will be used for decision-making, as they can result in significantly different

findings. It is also noted that the RSA coefficient increased in magnitude by 100 from the EPDO weighting method to the cost EPDO method. This result signifies that RSAs are more important for municipalities with more fatal crashes than other crash severity types.

One result that stands out between the EPDO weighting method and the cost EPDO method results is the impact to the percentage of white alone variable. In analysis using the weighting method, an increase in white alone residents was associated with an increase in efficiency, meaning also that communities with higher numbers of non-white residents were associated with lower efficiency. Yet, the results of the cost method reveal the opposite: an increase in white alone residents was associated with a decrease in efficiency. This may be connected to the different travel patterns of white residents compared to Black, Hispanic, and other minority populations (Mauch and Taylor, 1997; Gallie et al., 2003; Klein et al., 2018). This result emphasizes the need to carefully consider how crashes of different severities are weighted and included in analyses before decision-making and/or the distribution of resources. The consideration of which method is the more equitable approach is beyond the scope of this chapter. However, future research should consider the relationships between equity, resource allocation, and different EPDO weighting methods to serve all population groups equitably.

4.5 Conclusions

This chapter explored the influential factors that affect the ability of municipalities to efficiently use highway funding to increase local road safety. Local road safety is a multidimensional issue that is connected to environment characteristics, socio-economic characteristics, municipal government composition, and local road funding capabilities. Yet, state agencies do not consider environmental or population characteristic differences in their funding allocation algorithms to local governments, nor are municipalities provided

with guidance on how they can increase their local safety through their spending. To explore these issues, and to investigate which factors most efficiently and equitably improve local road safety, a comprehensive analysis was conducted using the data envelopment analysis method. Data was collected from surveys and by fusing various data sources. The results of this study revealed several ways in which local road safety can be equitably improved through informed resource allocation.

From a municipal government perspective, the results suggest that municipalities should consider increasing the number of highway maintenance staff and increasing the number of RSAs on local roads to increase the efficiency of their highway funding to improve their local roadway safety outcomes. From a state agency perspective, the results reveal that it is critical that geographic, socio-economic, and socio-demographic characteristics are considered in the funding allocation process to equitably improve local road safety. The results of this research suggest that additional funding and/or other types of support is necessary in rural areas to achieve the same level of safety as urban areas, given that rural areas are found to be less efficient. Additionally, the results demonstrate the importance of considering the racial profile of a population in funding algorithms as communities that include more non-white residents are less efficient. To provide the same level of safety as within white communities, minority communities need additional financial, infrastructural, and/or expert support from state agencies. Finally, from a research and practice perspective, this work demonstrates the ability of DEA methods, with the required data cleaning and scaling of the data before analysis, to reveal local road safety, equity, and resource allocation relationships in future studies and demonstrates the importance, from an equity perspective, of considering how EPDO crashes are calculated in the resource distribution process. Future research should consider the specific cases for which different weighting methods are appropriate.

4.6 Limitations

While these findings are important, there are limitations which should be considered in future research. First, future research work should consider similar analyses using different data and different application regions. Future work should also consider specifically how highway funding is spent at the municipal level (e.g., for pavement maintenance, sidewalk development, bicycling lane maintenance, etc.) which this study did not cover. An evaluation of the impact of long-term planning on safety should also be considered as well as additional and diverse interviews of local highway and state highway officials. Although the primary research question was isolated based on the specific study locations and transportation perspective, there is prior literature that states that there are likely other contextual factors at play that were not considered, such as mode choice characteristics of a municipality, but are opportunities for future research to consider. This research was also limited by the specific key informant interviews conducted. Additional interviews in future work should consider the perspectives of planners, those in charge of multi-modal plans, and local transportation activist groups. Finally, future research should consider analysis methods that allow different regions with varying funding structures to be analyzed at the same time, as a limitation in this research was that Massachusetts and New York data had to be analyzed separately. Overall, these limitations that were beyond the scope of this study should be considered in future work to further the current state-of-literature on this topic.

CHAPTER 5

DEVELOPING A GEOSPATIAL SAFETY ANALYSIS TOOL

The amount of available resources a given region has is influenced by a number of socio-demographic, socio-economic, and environmental factors, as found in Chapters 3 and 4. However, if funding algorithms are corrected to adequately provide for all municipalities and regions, there is still a need for these municipalities and regional entities to apply their funds towards projects at the most safety-critical locations. Thus, this Chapter investigates horizontal curve safety and the development of a methodological approach to create a region-specific geospatial safety tool. Geolocated crash data, roadway infrastructure data, and curve data were spatially integrated using a geographic information system (GIS). Bayesian hierarchical models were developed to gain region-specific safety results. A GIS tool was then derived from the applied model coefficients. This research most substantially contributes to the identification of the most safety-critical horizontal curves and the countermeasure selection process at horizontal curves. The results of this research benefit regional agencies in their aim to efficiently distribute investments and identify the most appropriate countermeasures to improve roadway safety in their region. The tool was created using two different regions as application areas to ensure the methodological approach was reproducible and transferable.

This Chapter is organized into four sections. The first section presents the motivation of this study. The analysis methods are presented next, including a step-by-step recreation of the methodology for reproduction. The results are then presented and dis-

cussed. The Chapter concludes with a section that presents the contributions of this study, the benefits and challenges of the developed tool, as well as the research limitations.

5.1 Introduction

Transportation agencies must often make substantial investments and efforts to implement safety improvement countermeasures to mitigate safety hazards. However, it is often not clear where safety investments should be made and what safety mitigation techniques should be implemented if funded. Horizontal curve safety in particular remains a critical safety issue given the unique perceptual and task challenges that the environment creates. The elevated safety risk on horizontal curves has been found to be influenced by a number of factors, including the median type, curve deflection angle, road surface friction, and pavement condition (Elvik, 2019; Buddhavarapu et al., 2013; Donnell et al., 2019). However, this elevated safety risk compared to tangent segments is not fully understood in literature. Further, while the Highway Safety Manual is commonly used in North America to identify horizontal curve safety problems and appropriate countermeasures, there remains a need to consider region-specific safety problems and solutions (American Association of State Highway and Transportation Officials, 2010). What's more, while several horizontal curve safety relationships are understood in literature, there remains a gap in the development of an analysis method and safety tool to efficiently analyze horizontal curve safety on a substantial scale.

Several agencies have developed their own unique geospatial tools to investigate regional problems and solutions (Colton et al., 2015). However, the development of these tools is not well documented in current literature. Additionally, a safety tool for horizontal curve safety has not been created for any region to date. First, an analysis of horizontal curve safety compared to tangent segments was conducted to identify specific

differences between tangent and curve segments. Following this, there is a need to develop a reproducible methodology that results in a safety tool that assists in the identification of countermeasures and solutions at all safety-critical locations within a given region. To additionally fill the gap in horizontal curve safety tools, the development of a comprehensive method to analyze horizontal curves within a given region using GIS and available surface transportation data is investigated in this research. Throughout this research and development of the safety tool methodology, specific steps are documented to ensure it is reproducible for the development of other safety tools, such as for vertical curve or intersection safety. Thus, this research identifies the factors that impact safety at curve locations compared to tangent segment locations through a new safety analysis of curve and tangent segment data using a novel dataset that includes curve data and contributes to the development of safety tools using GIS on a larger scale within transportation. Overall, the developed methodology allows practitioners and regional and state government officials to create their own horizontal curve safety investigation and safety tool for their particular region, streamlining the safety improvement process.

5.2 Methods

Several steps were required to complete this research, including the preliminary tangent versus horizontal curve safety analysis and the development of the horizontal curve safety tool. The following section describes the methodology in further detail.

5.2.1 Preliminary Tangent versus Horizontal Curve Analysis

The preliminary analysis of this research aimed to identify the factors that impact safety at curve locations compared to tangent segment locations through a new safety analysis of curve and tangent segment data using a novel dataset that includes curve data. The methods involved in this analysis are described in this section.

5.2.1.1 Data Gathering

The preliminary analysis used a novel data set of horizontal curves across the state of Massachusetts. Curve location and measurement data were derived using the available vehicle GPS trajectory data and the GIS basemap data through an automated routine developed by Ai and Tsai (2015). This developed dataset includes curve data for all linear referencing system (LRS) roads within a given state (Ai and Tsai, 2015; Wang et al., 2019, 2020b). LRS road networks managed by state agencies often only include state routes or federal highways that the state agency is responsible for maintaining. Thus, this research only considered those curves that were located within the LRS of a given state. The basemap data source for the creation of this curve data for Massachusetts was developed by MassDOT. Crash data for Massachusetts was collected through the MassDOT IMPACT data tool for the years 2014 through 2017 (Massachusetts Department of Transportation, b). Roadway inventory data for all state roadways was collected from the Massachusetts Department of Transportation (Massachusetts geoDOT, 2019). Figure 5.1 presents the 2017 crash data in Massachusetts with the curve segment data.

5.2.1.2 Spatial Analysis and Modeling Approach

Spatial analysis using ArcGIS was performed to identify the crashes that were correlated with different roadway segments. To begin, tangent sections between curve segments were created using Massachusetts road data and the horizontal curve data. Following, crashes for each year were connected to the nearest segments for both tangent and curve segments. All crashes within a 200-foot buffer of each segment were considered correlated with that segment. The 200-ft distance was determined to avoid more overlap between the curve and tangent segments. Each segment was then combined with the correlated crash data and roadway inventory data for that given segment. To identify the crash value associated with each roadway segment, each crash was assigned an EPDO crash value

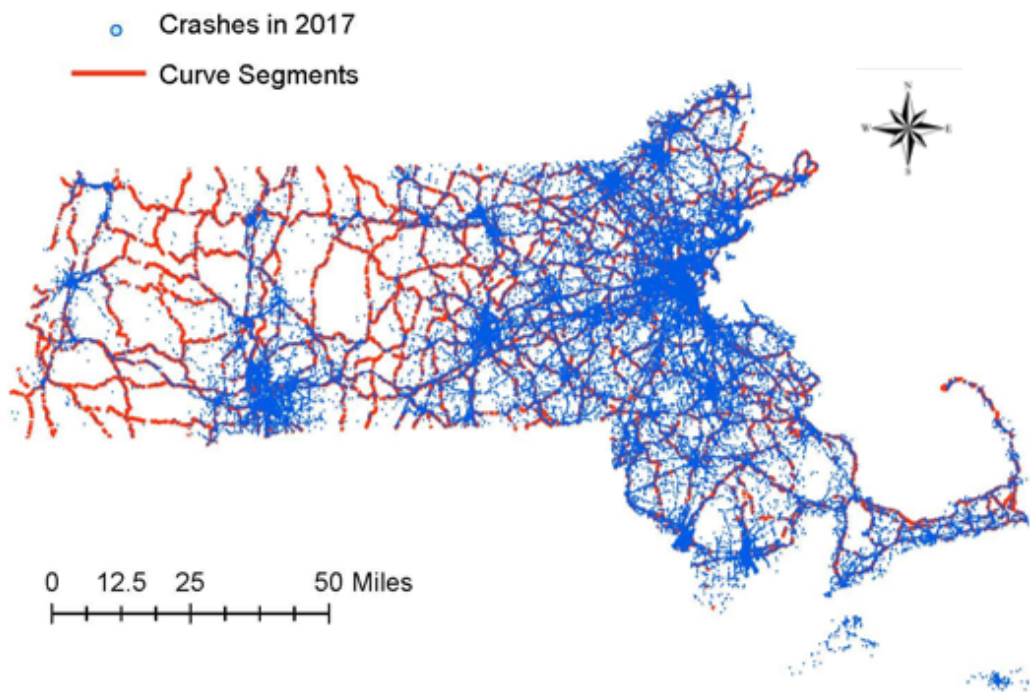


Figure 5.1. Massachusetts curve segments and crashes in 2017.

based upon the severity of each crash. In Massachusetts, different severities of crashes are weighted differently, often for identifying areas in need of countermeasure implementation. Property damage only (PDO) crashes are weighted at a level of 1, while injury, severe injury, and fatal injury crashes are weighted at a level of 21 as described in the previous chapters.

A model was built to determine the different environmental conditions leading to higher severity crashes at horizontal curves and tangent sections. Specifically, a generalized linear regression model was developed predict the EPDO crash rate per mile on a segment that included the AADT count in vehicles, roadway operation (one-way or two-way), and segment type (horizontal curve or tangent), given the availability of the roadway inventory data and previous literature. Interactions between the segment type and other factors were included in the final model. Given the exponential increase in crashes and to account for the segments with an EPDO value of zero crashes per mile, a log transformation of the EPDO rate plus one was included as part of the model. Finally, rows with missing values of the factors to be included in the regression and outliers were identified and excluded from analysis prior to modeling. Linear regression was implemented using R. The final dataset that was analyzed consisted of 324,336 segments, with 15.5 percent being curve segments. The final model is presented in Equation 5.1.

$$\log(\text{crashes per mile} + 1) \sim (\text{segment type} \times \text{roadway operation}) + (\text{segment type} \times \text{AADT}) \quad (5.1)$$

5.2.2 Safety Tool Development

The development of the horizontal curve safety tool included application area selection, data collection and processing, geospatial analysis, model development, and model

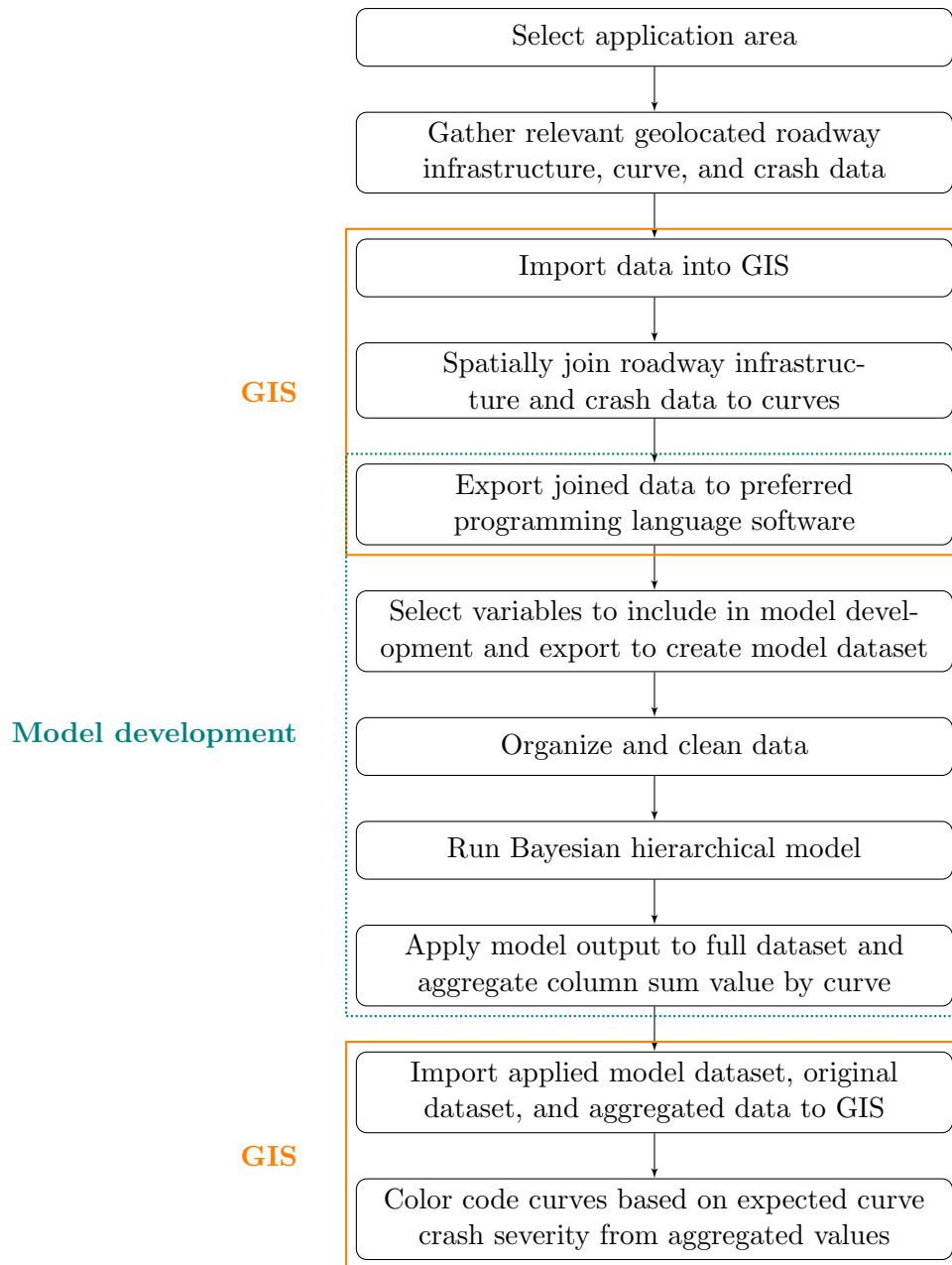
application in GIS. The developed horizontal curve safety tool methodology can be broken down into a series of steps, as outlined in Figure 5.2 and is described in further detail in this section.

5.2.2.1 Application Areas

The development of the horizontal curve safety tool methodology was created using two regions as application areas. The size of the region was determined to be most useful at the state level, given safety funding allocation and countermeasure implementation decisions are often connected to this government level in the United States and only United States horizontal curve data was available. The application of this methodology across two regions allowed for the investigation of potential regional considerations that should be considered in the development process and in the interpretation of the results. Additionally, applying the method twice allowed for more potential challenges to arise, and therefore, ensure the methodology is reproducible and transferable across regions with different characteristics.

Horizontal curve data for several states were available from the method developed by Ai and Tsai (2015). The two states to employ this methodology were chosen through a series of steps. Available geolocated crash data from 2015 through 2019 was first identified for each of the available states with curve data to determine if at least three years of recent crash data would be available for analysis. To create robust analyses, it is often suggested that at least three years of crash data be used in traffic safety studies (Carter et al., 2017). Secondly, roadway infrastructure geospatial data was identified for each state, including annual average daily traffic (AADT) data, vehicle miles traveled (VMT) data, guardrail inventory data, pavement condition data, and road width data. From this research, it was determined that the states of Vermont, Massachusetts, and Maryland had adequate data publicly available for analysis. Vermont had the most relevant geospatial roadway

Figure 5.2. Methodology flowchart.



infrastructure available, while Maryland had the least. These two states were chosen as the application areas for this methodology development from the three options for two primary reasons: 1) Vermont had the most geospatial roadway infrastructure data available, and therefore, a more robust safety model could be created, and 2) Maryland had the least amount of roadway infrastructure data available, so the impact of having more or less roadway data in a geospatial tool could be compared.

5.2.2.2 Data Gathering

Statewide geospatial roadway infrastructure and crash data was gathered for both Maryland and Vermont. Geospatial horizontal curve data was gathered through the developed datasets by Ai and Tsai (2015); Wang et al. (2019, 2020b). The basemap data source for the creation of this curve data for Maryland and Vermont were developed by Maryland Department of Transportation (2017) and Vermont Department of Transportation (2016), respectively.

Geolocated roadway infrastructure data were required for this research. These data were gathered for both application areas primarily by searching through each respective state agency geospatial data portal. The three most recent years (2017 through 2019) of completed geospatial crash data was collected for Maryland from Maryland Department of Transportation (2020). Annual average daily traffic (AADT) data was collected from Maryland's GIS Data Catalog (Maryland Department of Transportation). Similarly, crash data in Vermont from 2016 through 2018 was gathered from Vermont Department of Transportation (2017b, 2019a,b). Roadway inventory data was collected from the VT Open Geodata Portal and included geolocated infrastructure data such as guardrail inventory data, annual average daily traffic (AADT) data, among other data (Vermont Department of Transportation, 2018a, 2017a, 2019c, 2017c, 2018b). All roadway inventory data included in this research is presented later in the methodology through Table 5.2, Table 5.1,

and Table 5.3. It is noted that roadway infrastructure data can be collected manually or through a separate process if little geolocated infrastructural roadway data is available data for a particular region of study. At the same time, even datasets with little available data may be able to provide insight into potential relationships. To include this perspective in this study, data from Maryland, which has less geolocated roadway data than other states, was used as one application state for this methodology.

5.2.2.3 Geospatial Analysis

Each horizontal curve needed to be merged with the nearby crashes and corresponding infrastructure segments in each state prior to analysis. Geospatial buffer techniques around target features are often used to join crashes with these target features in traffic safety analysis. A buffer of 91.44 meters (300 feet) was used to identify those crashes within the area of safety influence of a horizontal curve, as has been applied in horizontal curve literature (Khan et al., 2012). Thus, all crash data within a 300-foot buffer were joined with the particular corresponding curve and all other crashes were excluded from analysis. The roadway infrastructure data was then spatially joined to the horizontal curve segment data in ArcMap using the Spatial Join (Analysis) tool. A challenge arose during this step with some data in Maryland. Some roadway infrastructure data did not perfectly overlap with the curve data, potentially due to some slight offset distances that originated during the data projections due to differing coordinate systems. To overcome this issue, a spatial join in ArcMap was run where the curve data was joined by the nearest geodesic roadway infrastructure data line within a five meter distance. All data was then exported from ArcMap into R for data organization.

5.2.2.4 Data Organization

The goal of the data organization step was to develop a data frame for model development for both states. As a mixed methods model was used for development, only horizontal curves that had at least one crash occurrence in a given year were included in the final data frame. For each state, all crashes were joined with the corresponding roadway infrastructure data based on the unique curve identification number. The result of this join was a data frame that consisted of each crash as a row with the corresponding horizontal curve data and roadway infrastructure data on that curve segment where the crash occurred. The variables to be included in model development were decided at this stage based on characteristics impacting horizontal curve safety found previous literature and excluding terms that may interact too closely, such as number of lanes and road width. The variables included in the analysis may vary depending upon the availability of data as well. For example, the inclusion of speed limit data was considered for the analysis of Vermont; however, this data was not widely available and therefore, it could not be included in the final data frame.

Following variable selection, the final data frames to be used in model development were then organized and cleaned to exclude random missing data. In Maryland, this left 2643 crashes that were excluded from analysis, leaving a total of 29,172 crashes in the proximity of 6021 curves for model development. In Vermont, 6833 crashes were excluded from analysis, leaving a total of 11,455 crashes in the proximity of 3565 curves for model development. Collision types were sorted into larger categories to create a more robust analysis, rather than remain specific to the crash type as to avoid collision types with less than ten or fewer cases in the dataset. All independent continuous data variables were then scaled to be a value between zero and one to place all variables on the same level, including as the categorical variables. This was done because magnitude of the coefficient results

would represent the impact of a particular variable on curve safety. Thus, using this scaling method, countermeasures which would be more likely to make a larger safety impact could be identified. If this was not done, the range and magnitude of the continuous variables would have to be considered at the same time as the results analysis, making it difficult to interpret within the developed tool. The dependent variable was the crash severity outcome of the crash. Given the application of crash data within the models, only curve locations with crash occurrences could be included in the final data frames for model development. A value of zero was assigned to all property damage only (PDO), or nonsevere crashes, and a value of one was assigned to all injury and fatal, or severe, crashes. This created a binary crash outcome of a severe or nonsevere crash, as is commonly applied in transportation safety analyses (e.g., Savolainen et al. (2011); Ahmed et al. (2018); Fanyu et al. (2021)). A summary of the final data frame variable values per curve per year prior to scaling are presented in Table 5.1, Table 5.2, and Table 5.3.

5.2.2.5 Model Development

A Bayesian hierarchical modeling method was applied in this research as it has been found to outperform other commonly used hot spot identification methods, including the empirical Bayesian hot spot identification method and crash rate method (Guo et al., 2019). Applying a hierarchical, or multilevel, modeling approach offers the ability for group-level characteristics to be considered. In the case of this research, it allowed curve characteristics to be considered at the group level and crash characteristics to be considered at the base level simultaneously. In multilevel models, the group level characteristics are those that are shared by multiple cases. In this case, multiple crash cases may occur on a single curve. The base level characteristics only occur at the case level and are not shared between different cases, such as the crash type. Basic hierarchical models only allow for linear predictor terms (Bürkner, 2018). The R package “brms” was used to implement the

Table 5.1. Summary of Maryland categorical variables.

Variable	Levels	Count	%
Injury	Property Damage Only (PDO)	19,543	67.0
	Injury or Fatal	9629	33.0
Collision Type	Rear End	10,151	34.8
	Sideswipe or Angle	7859	26.9
	Single Vehicle	7209	24.7
	Head On	1991	6.8
	Other	1962	6.7
Light Condition	Daylight	18,348	59.0
	Dark (Light Present)	6537	21.0
	Dawn	2667	8.6
	Dark (No Light Present)	2512	8.1
	Dusk	659	2.1
	Dark (Unknown Lighting)	306	1.0
	Other	61	0.2
Surface Condition	Dry	22,104	75.8
	Wet	6363	21.8
	Snow	344	1.2
	Ice	312	1.1
	Other	49	0.2

Table 5.2. Summary of Vermont categorical variables.

Variable	Levels	Count	%
Injury	Property Damage Only (PDO)	8714	76.3
	Injury or Fatal	2714	23.7
Collision Type	Rear End	2952	25.7
	Single Vehicle	3678	32.0
	Sideswipe or Angle	3123	27.2
	Head On	616	5.4
	Rear-to-Rear	147	1.3
	Other	969	8.4
	Time of Day	Day	8788
Night		2667	23.3
Weather	Clear	6558	57.3
	Cloudy	2321	20.3
	Freezing Precipitation	1612	14.1
	Rain	935	8.2
	Wind	29	0.3
Impairment	No	10,836	94.6
	Yes	619	5.4
Guardrail	No	7391	64.5
	Yes	4064	35.5
Pavement Condition	Good	4303	37.6
	Fair	3628	31.7
	Poor	2635	23.0
	Very Poor	889	7.8

Table 5.3. Summary of continuous variables prior to scaling.

State	Variable	Mean	St. Dev.	Min	Median	Max
Maryland	Deflection Angle	14	11.4	0.03	11.4	90
	AADT	54,909	59,262	111	32,692	253,921
	Total Number of Lanes	4.5	1.9	1	4	11
Vermont	Deflection Angle	16.7	14.1	0.2	12.9	90
	AADT	8,607	6,232	186	7,151	32,623
	Total Number of Lanes	2.2	0.7	1	2	6

modeling method as it can fit nonlinear models and can be tailored to fit the needs of this research (Bürkner, 2018). All data were grouped by a curve identification number within the “brms” function to specify the group-level characteristics. After a number of trials with different iteration values, chain values, and core values within the function in R, the models each converged with the parameters set to 2000 iterations, four chains, and four cores. Smaller iteration, chain, and core values resulted in models that would not converge. These values may change depending upon the computational power, the system used, and the data used in the model. The family parameter of the function, or the distribution of the dependent variable, was set to be the Bernoulli distribution as crash events have been shown to follow a Bernoulli trial with unequal probability of independent events (Lord et al., 2005; Ma et al., 2017).

5.2.2.6 Model Application in GIS

To create the safety tool, the model results needed to be represented through a mapping system. The aim of this step is to be able to identify the crash severity of each curve in an accessible manner and identify the contributing factors to that curve crash severity. To accomplish this, the full crash datasets for each state that included missing values were first scaled between zero and one to correctly apply the model outputs to

the datasets. The crashes with missing data were included at this stage to ensure that all geolocated crashes within the vicinity of a curve would be highlighted in the final developed tool. Thus, if some data was missing from a crash case, such as pavement condition data, and the crash still had a characteristic that made it of a higher priority in the model, such as a head on crash case, it would still impact the final curve safety severity output value. This ensures that all crashes within a curve's area of influence are taken into consideration and accounted for in the safety tool.

The final model outputs were then applied to these full crash datasets. This was done by multiplying each variable value within the actual dataset by the model mean coefficient output value for continuous variables. In the case of categorical variables, the model mean coefficient output value was assigned to match the specific category of the variable accordingly. All variable values in these revised datasets were then added together in a new column to represent the predicted severity of an individual crash case. These values were then aggregated by the curve identification number to develop a new dataset that represented the safety severity of a particular curve. This dataset and the revised dataset that had the model applied to it in full were then imported into ArcMap for each state. Additionally, the original crash dataset that consisted of the original curve and crash geolocated information was also imported. Each of these datasets was joined to the appropriate geolocated curve data by the unique curve identification number. Color coding was then applied to the map based on the aggregated sum of the model output values to represent which curves were predicted to have a higher or lower crash severity by the model. This final map also included curves which had no crash occurrences; however, as the model could not be applied without crash data, the curve crash severity value remained at zero. Future research should consider how multilevel models can be applied to curves

that have yet to have a crash occurrence. The resulting maps developed from this process are presented in the following section.

5.3 Results and Discussion

The results of the tangent versus horizontal curve preliminary study and safety tool development study are presented in this section. The preliminary study results are first presented and discussed, followed by the horizontal curve safety tool development and applications.

5.3.1 Tangent versus Horizontal Curve Safety

The regression model coefficient results of the preliminary study are presented in Table 5.4. As shown, all terms were statistically significant in the model. Figures 5.3 and 5.4 present the interaction of the segment type with AADT and the roadway operation.

Table 5.4. Preliminary analysis model coefficient summary.

Term	Coefficient	Standard Error of Coefficient	P-Value
Constant	0.522	0.0068	0.000
Segment type (reference = tangent)	0.468	0.0168	0.000
Roadway operation (reference = two-way)	0.416	0.0266	0.000
AADT	0.000053	0.0000004	0.000
Segment type * Roadway operation	0.935	0.0785	0.000
Segment type * AADT	0.000056	0.000001	0.000

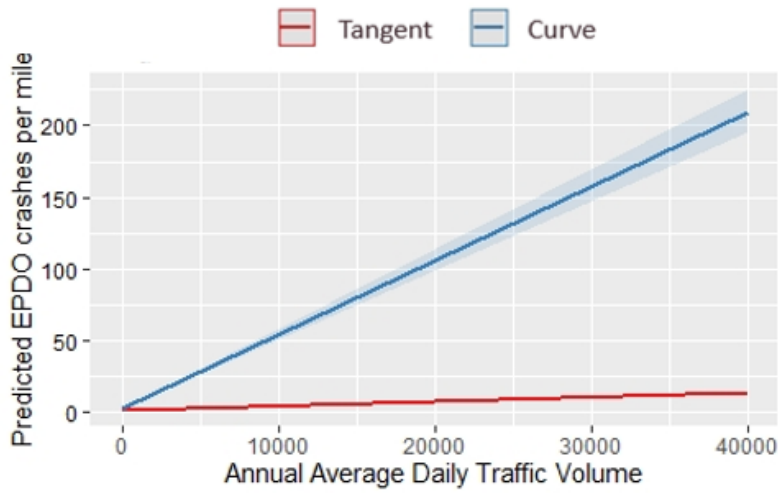


Figure 5.3. Probability of EPDO crashes per mile depending upon traffic volume and segment type.

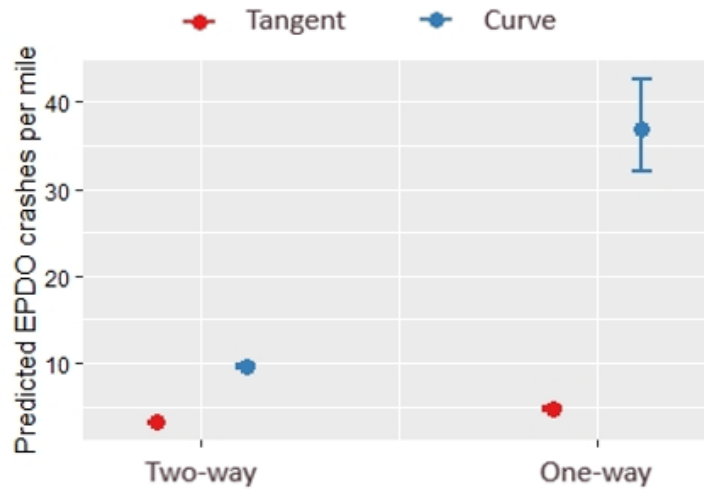


Figure 5.4. Probability of EPDO crashes per mile depending upon road operation and segment type.

Previous literature has found that horizontal curves remain a significant safety issue given the increase of higher severity crashes at these locations compared to tangent sections. Perception of risk and task demand create environments that make it difficult for drivers to transverse curves in a safe manner. The lateral position and speeds of drivers are then influenced by their perceived risk depending on the curve environment, such as the radius, length, and number of lanes, among others. However, while several studies have proven the specific safety issues and in turn, types of countermeasures that should be placed at horizontal curves, it is not yet clear how the likelihood of higher severity crashes at horizontal curves is influenced by different roadway environments and conditions from a large-scale case study with recent data. This preliminary study using a novel dataset of curve data revealed that horizontal curve segments have higher crash rates than tangent segments even in cases accounting for the operational roadway type, speed limit, and AADT, as presented in Table 5.4 and aligning with previous literature. The interaction of variables with the segment type in the model allowed for a deeper understanding of the relationship differences in crash rates that occur at both tangent and curve segments, as presented in Figures 5.3 and 5.4.

As the AADT volume of a segment increased, the EPDO crash rate per mile increased at a faster rate for curve segments than tangent segments, as presented in Figure 5.3. It is known from previous research that while the crash rate increases as traffic volume increases, the crash rate increases at a lower rate per vehicle added (Høyve and Hesjevoll, 2020). This is also depicted in Figure 5.3, aligning the findings of this study with previous literature. The contribution of this study to literature is that this is true for both horizontal curve segments and tangent segments, although curve segments still maintain a higher crash rate. Thus, it is critical for future research to consider the safety of curves in areas of high AADT compared to tangent segments. In terms of operation, horizontal

curve segments were found to have a higher crash rate per mile than tangent segments in both one-way and two-way operations, as presented in Figure 5.4. This is likely connected to the operation of one-way conditions on high-speed highway road segments, where higher severity crashes are more likely. Human performance in one-way operation conditions should be considered in future research, especially for curve segments, to identify the cause of this increased safety issue. Thus, horizontal curve safety at tangent segments and horizontal curves differs and should be considered in different contexts. Overall, the conditions of tangents and curves should be more carefully considered in transportation safety literature.

5.3.2 Horizontal Curve Safety Tool

The results of the Bayesian hierarchical models are presented in Table 5.5 and Table 5.6. Each reference variable is labeled accordingly in each table for each category. The maps of the developed tools are presented in Figure 5.6 and Figure 5.5. In this section, the output of the developed models is first discussed in terms of implications for horizontal curve safety, followed by a discussion of the developed horizontal curve safety tools for both states.

5.3.2.1 Horizontal Curve Safety Implications of Model Results

The results of the developed models on their own represent the characteristics that influence the likelihood of a higher severity crash occurring on a curve in each state. As the independent variables were scaled prior to analysis, the magnitude of the mean coefficient values presented in Table 5.5 and Table 5.6 represent the more influential and less influential characteristics of a crash and curve case that would likely lead to a higher severity crash. Thus, these values can assist in the determination of what countermeasures make a larger impact on safety overall at a curve in the given region of study. A positive

Table 5.5. Maryland model results.

Variable		Mean	Std. Dev.	2.5%	97.5%
	Intercept	-0.55	0.04	-0.63	-0.46
	Deflection Angle	-0.12	0.11	-0.33	0.09
	AADT	-0.49	0.10	-0.70	-0.29
	Number of Lanes	0.12	0.12	-0.12	0.36
Collision Type	Rear End (Reference)				
	Sideswipe or Angle	0.02	0.03	-0.05	0.08
	Single Vehicle	-0.22	0.04	-0.29	-0.15
	Head On	0.67	0.05	0.57	0.77
	Other	-0.03	0.05	-0.14	0.07
Light Condition	Daylight (Reference)				
	Dark (Light Present)	-0.13	0.03	-0.19	-0.06
	Dawn	-0.13	0.08	-0.29	0.03
	Dark (No Light Present)	-0.18	0.05	-0.28	-0.08
	Dusk	-0.06	0.09	-0.23	0.10
	Dark (Unknown Lighting)	-0.27	0.13	-0.53	-0.01
	Other	0.47	0.28	-0.09	1.00
Surface Condition	Dry (Reference)				
	Wet	-0.17	0.03	-0.24	-0.11
	Snow	-0.35	0.13	-0.60	-0.10
	Ice	-0.25	0.13	-0.52	0.00
	Other	-0.54	0.36	-1.28	0.14

sign of a coefficient illustrates that a crash with that characteristic is more likely to be a higher severity crash, while a negative sign of a coefficient illustrates that it is more likely to be a less severe crash. For example, in Maryland and Vermont, head on crashes would most likely result in the highest injury severity compared to all other crash types, aligning with previous findings in literature (Wang and Kim, 2019). Further, in Maryland, a dry road surface condition would result in a higher injury severity crash than a wet, snowy, icy, or other surface condition. Similarly, in Vermont, clear weather is more likely to result in a higher injury crash than cloudy, freezing precipitation, rainy, or windy conditions. This

Table 5.6. Vermont model results.

Variable		Mean	Std. Dev.	2.5%	97.5%
	Intercept	-1.19	0.12	-1.42	-0.96
	Deflection Angle	0.33	0.21	-0.07	0.78
	AADT	-1.08	0.23	-1.55	-0.63
	Number of Lanes	-0.19	0.34	-0.84	0.48
Collision Type	Rear End (Reference)				
	Single Vehicle	0.42	0.08	0.27	0.57
	Sideswipe or Angle	-0.22	0.08	-0.37	-0.06
	Head On	1.24	0.12	1.01	1.48
	Rear-to-Rear	-2.23	0.51	-3.32	-1.31
	Other	-0.47	0.12	-0.70	-0.24
Time of Day	Day (Reference)				
	Night	-0.19	0.07	-0.33	-0.06
Weather	Clear (Reference)				
	Cloudy	-0.07	0.07	-0.20	0.06
	Freezing Precipitation	-0.51	0.09	-0.68	-0.35
	Rain	-0.01	0.10	-0.20	0.19
	Wind	-0.27	0.54	-1.40	0.74
Impairment	No (Reference)				
	Yes	1.16	0.11	0.93	1.38
Guardrail	No (Reference)				
	Yes	0.19	0.06	0.06	0.31
Pavement Condition	Good (Reference)				
	Fair	-0.11	0.08	-0.25	0.05
	Poor	0.01	0.08	-0.14	0.18
	Very Poor	0.07	0.12	-0.17	0.31

is likely due to drivers being more careful in poor conditions, which is an instance of the theory of risk homeostasis. Risk homeostasis is a theory that suggests people adjust their behavior in response to their desired level of perceived risk (Wilde, 1982). In the case of potentially slippery pavement conditions and/or lower visibility, the risk could be perceived as higher than in dry and/or clear conditions. The rest of the categorical results can be interpreted in a similar fashion.

The resulting continuous variables are slightly more difficult to interpret on their own, as each continuous variable was scaled prior to analysis. These results can be more easily interpreted by their sign first, and then magnitude when the specific range of data used to create each variable is considered. In Maryland, the results show that as the AADT or the deflection angle increases on a curve, the level of safety increases. In Vermont, the results show the same finding for the AADT variable, but the opposite finding for the deflection angle variable. In Vermont, as the deflection angle increases, the safety of a curve decreases. This result in Vermont aligns with previous research findings that sharper curves are less safe (Schneider IV et al., 2010). The result in Maryland may be due to it being a denser, more congested state than Vermont, and/or Maryland having more roadways with lower posted speeds. For example, a horizontal curve on a congested highway would likely be a less sharp curve than on a rural roadway. Additionally, higher posted speeds result in more crashes on sharper curves (Khan et al., 2012). This difference between Vermont and Maryland may be better understood with additional roadway infrastructure data in a future model, such as average vehicle speed data, impairment data, and guardrail data, all of which were not available across Maryland at the time of this study. Overall, this difference highlights the need for safety analyses to be context specific and the benefit of including more data in the model development process.

In summary, the results of the horizontal curve models can be useful to interpret on their own to identify what conditions lead to more severe crashes on curves in both states. With this information, it can be understood what conditions that are unique to a specific region increase or decrease safety, and therefore, countermeasure development or other curve safety decisions in practice, policy, and research can be better informed for the particular region of study.

5.3.2.2 Horizontal Curve Safety Geospatial Application and Tool Development

The developed horizontal curve safety tool highlights the predicted crash severity on all linear referenced roads within each state. The maps created from the developed tool for Maryland and Vermont is presented in Figure 5.6 and Figure 5.5. This tool is housed in ArcMap and would have the ability to be published online using ArcGIS if the developer had the applicable permissions, making it accessible to a larger audience. As presented, the predicted severity of the curves range from low to high by color coding the aggregated model results for each curve, making it accessible to a nonspecialist audience.

The most useful aspect of the tool is its ability to present information for each curve that is critical in the safety countermeasure selection process. Within the ArcMap software, any curve can be “identified” using the identify function. An example of using this function on a curve in Vermont and Maryland is presented in Figure 5.7. As shown, the crash types that have occurred within the buffer distance of the curve during the specific three-year period can be selected. Each crash can be selected to show the actual crash characteristics or the results of the model applied to the crash. The window that shows the model applied to the crash allows a user to understand what likely increased the chance of the crash occurring and potentially what increased the severity of the crash. For example, in Vermont, the model identified that the collision type was a leading factor

that led to the occurrence of an injury crash, given that the collision type had the largest coefficient value. At the same time, the deflection angle in the Vermont example still likely could be attributed to the increased severity, just to a much lower extent than the

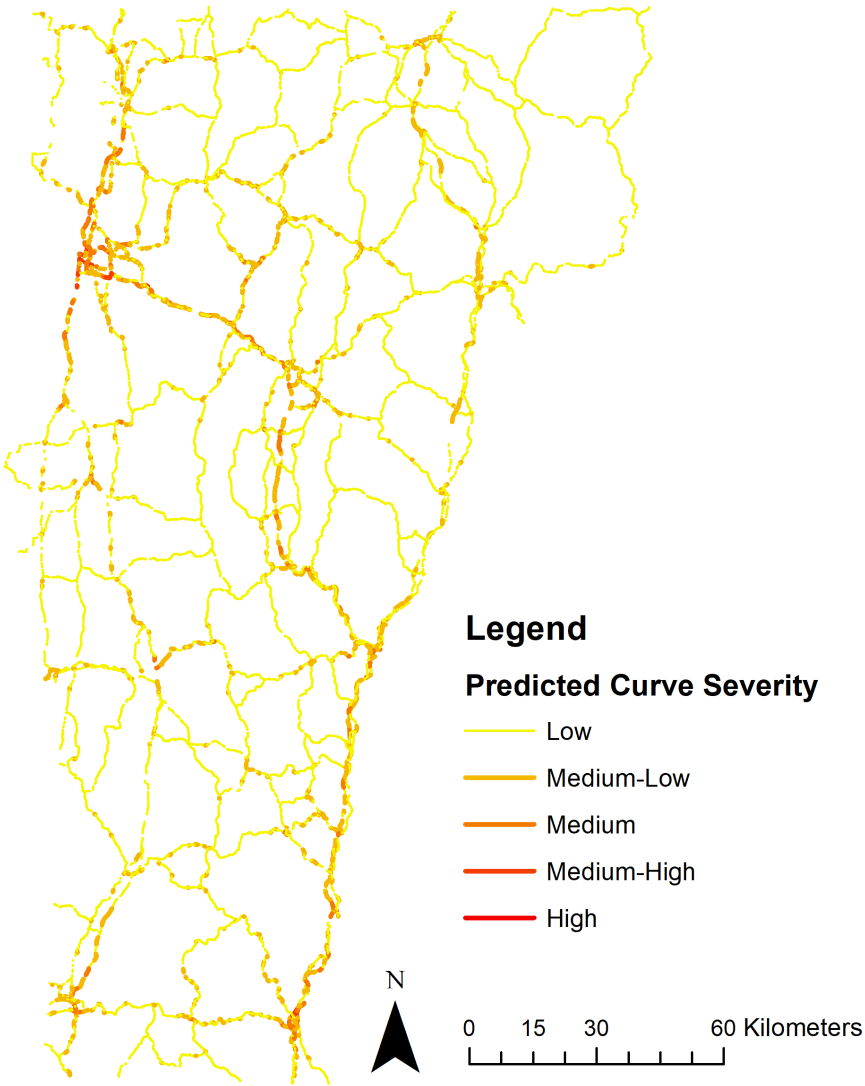


Figure 5.5. Predicted total crash severity of all curves on state roads in Vermont.

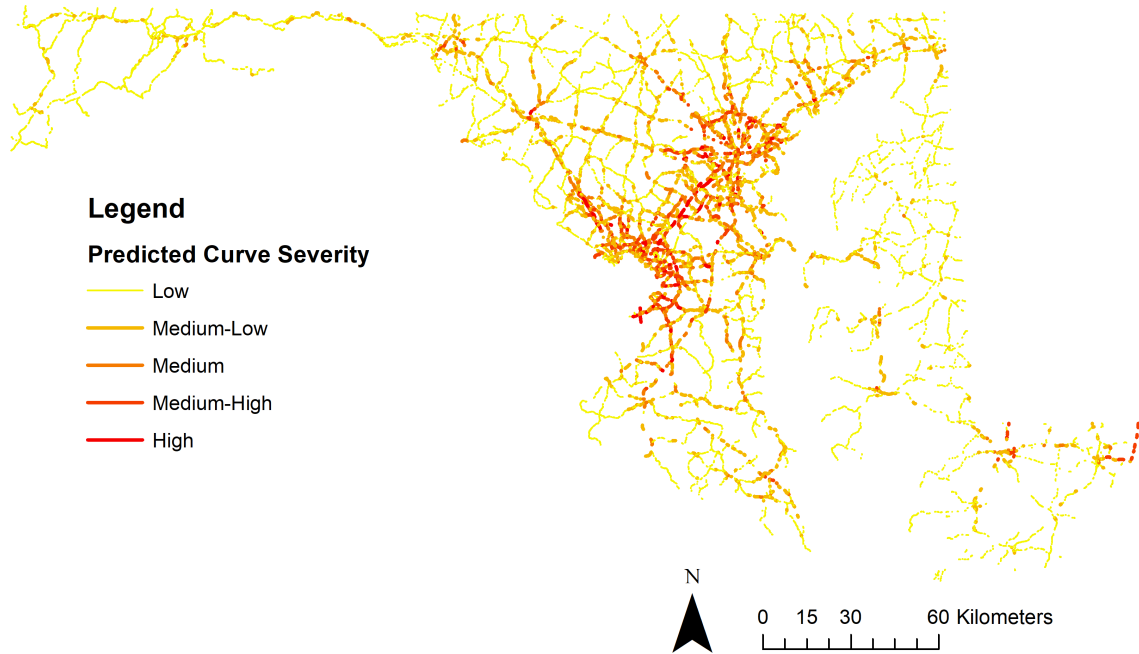


Figure 5.6. Predicted total crash severity of all curves on state roads in Maryland.

collision type. Depending upon the results of the other crashes that occurred at that curve location, it may be beneficial to consider countermeasures that decrease the likelihood of single vehicle crashes, such as implementing rumble strips or additional signage.

This tool can be used in numerous ways depending on the goal of the user. One noteworthy example would be the identification of ideal locations to use funding that has been allocated for a specific purpose. For example, if funding was available that had to be used on a pavement reconstruction project to improve pavement condition, all horizontal curves could be queried to identify the curves with the largest sum of pavement condition coefficient values in Vermont. These locations would be those that would benefit the most from this funding compared to other horizontal curve locations.

Maryland

Identify

Identify from: < Top-most layer >

- Curve
 - IS000068
 - MD Model Results
 - MD Road Crash Characteristics
 - Property Damage Crash
 - Injury Crash
 - Property Damage Crash
 - Injury Crash
 - MD Road Crash Characteristics

Location:

Field	Value
OBJECTID	16792
Field1	16792
OBJECTID_1	5958
Collision Type	SideswipeAngle
Light Condition	Daylight
Injury Severity	Property Damage Crash
Surface Condition	Dry
Radius	470.84
Angle	9.980874
Number of Lanes	5
AAADT	28560
Curve Length (meters)	164.040921
Crash Year	2018

Identified 1 feature

Actual crash characteristics

Model applied

Vermont

Identify

Identify from: < Top-most layer >

- Curve
 - U004
 - VT Road Crash Characteristics
 - Property Damage Only
 - Property Damage Only
 - Property Damage Only
 - Property Damage Only
 - Property Damage Only
 - Injury
 - Property Damage Only
 - VT Model Results

Location:

Field	Value
OBJECTID	10107
Field1	10107
OBJECTID_1	3458
Injury Severity	Injury
Impairment	No
Weather	Rain
Day/Night	Day
Collision Type	SingleVehCrash
Radius	624.26
Angle	10.71
Curve Length (meters)	233.280054
Guardrail	No
AAADT	5500
Road Condition	Fair
Number of Lanes	2
Crash Year	2017

Identified 1 feature

Actual crash characteristics

Model applied

Actual crash characteristics

Figure 5.7. Curve details using identify function in ArcMap.

Overall, this tool is able to dissect the potential causation of crashes at horizontal curves throughout a region and assist in the decision making processes for countermeasure selection at specific horizontal curves. The benefits and challenges of this tool are presented in the following section.

5.4 Conclusions

Horizontal curve safety remains a critical safety issue. However, region-specific safety considerations and the most ideal investment decisions to increase safety are often unclear. Horizontal curve safety and tangent safety must be considered in different contexts. At the same time, the development of geospatial safety tools is not well documented in current literature. This research filled these gaps in literature through the development of a reproducible and transferable methodology that results in a horizontal curve safety tool. The development and execution of this methodological process in this research most substantially contributes to 1) the identification of the most safety-critical horizontal curves and 2) the countermeasure selection process at horizontal curves, especially for specific investment needs.

The benefits of employing the developed methodological approach within a given region include the following:

- Flexible to include different data of interest
- Flexible to fit specific goals, such as revealing high-crash locations related to poor pavement condition or investigating intersection safety throughout a region
- Ability to be region-specific
- Identifies safety-critical road segments
- Assists in the selection of appropriate countermeasures at specific road segments

- Results can be easily communicated to a broad audience through maps

The challenges that may occur when employing the developed methodological approach within a given region include the following:

- Limited geolocated data availability across a region
- Lack of trained staff to employ the methodology
- Lack of equipment, software, or computational power
- Data joining problems depending upon data accuracy and available data details
- Extensive missing data for key contributing variables

Overall, the methodological approach and results of this research benefit regional agencies in their aim to efficiently distribute investments and identify the most appropriate countermeasures to improve roadway safety in their region. Future research should consider the challenges identified in this methodological approach to make it more accessible to non-technical groups.

5.4.1 Limitations

The limitations of this research should be considered in future studies. First, crash locations are not always accurate due to human error and/or equipment failure. Additionally, while filing all crashes that exceed specific thresholds is required by law in Massachusetts, Maryland, and Vermont, crash reporting is not always done, nor are all crashes always submitted by local police departments to state agencies. This limitation should be noted when considering the results of this study and others including road crash data in the United States. Additional roadway infrastructure data was also not included in this research, such as warning signage or speed data, due to the lack of available data. Future

research should consider these, the cost/benefit of different countermeasures, other additional factors, and potentially interacting variables in model development for horizontal curve safety analysis.

CHAPTER 6

CRASH PROXIMITY AND EQUIVALENT PROPERTY DAMAGE CALCULATION TECHNIQUES

The development of region-specific geospatial safety tools can inform funding allocation towards specific countermeasures and projects that provide the most benefit for their region. However, the analysis methods commonly used in high-risk location identification applications may not be the most robust of methods. This Chapter focuses on the development of robust crash weighting techniques for use in high-risk location identification using an application of a novel horizontal curve dataset. Specifically, a heteroscedastic censored regression approach was used to investigate the impact of different crash proximity weighting techniques and crash severity weighting methods on model outcomes. The findings demonstrate that the use of a linear distance weighting factor used in conjunction with the buffering technique as well as a less precise EPDO weighting factor method results in more robust safety analysis outcomes. The improved results have the potential to improve hot spot identification and resource allocation at both the federal and regional levels by employing models that more accurately link specific crash segments with contributing crash characteristics.

This Chapter is comprised of four sections. The introduction is first presented to discuss the motivation of this research. The methods are then presented, followed by the results and discussion section. The Chapter concludes with recommendations and implications of the results of this study.

6.1 Introduction

The goal of many resource allocation strategies in transportation safety is to achieve the greatest safety benefit with a given amount of resources. State and federal resource allocation methods aimed at increasing the safety of specific target road segment types (such as intersections, freeway ramps, horizontal curves, etc.) often provide these resources to the most safety-critical locations. In other words, locations that are determined to have the highest safety problem are selected for countermeasure implementation above others. However, despite the many recent breakthroughs in crash analytics, there remains a lack of consensus among safety practitioners and researchers as to the optimal method for locating these high-risk locations. In current practice, the method of determining these locations often depends upon how two steps are completed at the analysis stage: 1) the proximity technique that is used to define the specific crashes that are associated with each target road segment and 2) the weights that are assigned to those crashes through the use of a severity weighting method or simple frequency method.

In most cases in traffic safety analysis, a buffer area around a target road segment is set to determine the crashes that are assumed to be associated with the target area (e.g., Pyrialakou et al. (2016a); Khan et al. (2013); Zhang et al. (2015); González et al. (2019); Avelar et al. (2015)). However, no specific buffer distance has been agreed upon in practice or research as the ideal buffer size, even for a specific target segment type (Briz-Redón et al., 2019; Das et al., 2008; Avelar et al., 2015). The common buffering technique also places all crashes within the buffer at the same level or weight. Crashes that have occurred closer to a target road segment are not weighted more heavily in the analysis, even if the crash is more likely associated with the target road segment characteristics.

The EPDO weighting method of crashes is commonly used as a standard in transportation safety analysis in North America (American Association of State Highway and

Transportation Officials, 2010). Using this method, crashes are converted to equivalent costs based on crash severity outcomes. However, a noteworthy drawback of the method when identifying high-risk locations is its significantly higher weight that it assigns to fatal crashes. To avoid only “chasing fatal crashes,” the Massachusetts Department of Transportation uses a different EPDO weighting method for resource allocation purposes (MassDOT Highway Division, 2020). Their analysis approach weights all fatal and injury crash types into a single value of 21 and weights property damage only (PDO) crashes into a value of 1 (MassDOT Highway Division, 2020). Previous research has yet to identify which of the two EPDO weighting methods is most meaningful in practice and research for high-risk location analysis.

Resource allocation methods aimed at improving safety are often dependent upon traffic safety analyses that apply standard procedure methods that have not been proven to be the most optimal method. This includes the buffer technique that is used to determine which crashes are within the area of influence of a target segment. It also includes the use of the EPDO cost weighting method (American Association of State Highway and Transportation Officials, 2010). However, these methods may not result in the most beneficial safety outcome.

This study proposes more robust crash weighting techniques for use in high-risk location identification using an application of a novel horizontal curve dataset with the aim of creating a safer roadway system. Specifically, the objective of this research is to determine if some crash proximity methods and EPDO weighting methods are more robust and beneficial than others at evaluating the safety of specific target road segments. An evaluation of horizontal curve safety in Massachusetts was selected for the application of this study given the development of a novel horizontal curve database within the state (Ai and Tsai, 2015). The improved results have the potential to improve hot spot identification

and resource allocation at both the federal and regional levels by employing models that more accurately link specific crash segments with contributing crash characteristics.

6.2 Methods

Several steps were required to complete this research, including data collection and processing, geospatial analysis, and model development. The following section describes these processes in further detail.

6.2.1 Horizontal Curve Data

The primary focus area for this particular study was horizontal curve data. Several other target segment types could be applied using this methodological approach, including signalized intersections, stop-controlled intersections, crosswalks, roundabouts, vertical curve segments, toll approaches, widening/narrowing roadway sections, bus stops, etc. The application of horizontal curves was chosen for this study as curves have been recognized as high-risk safety locations for decades (Elvik, 2019; Fildes and Triggs, 1985; Khan et al., 2013). The level of safety on curves has been shown in literature to be dependent upon a number of physical factors, including the curve radius, median type, and speed limit, among others. To date, horizontal curve measurement and location data have not been available across large regions. Thus, this study is unique as it applies analyses on a novel detailed geolocated horizontal curve dataset that includes curve radii data. This dataset allowed for widespread analyses of curve safety with environmental characteristics to be conducted that have yet to be completed in current research.

This study required the identification of horizontal curve road segments and the data details of these curves, which was available through the data collected from Chapter 5. This data was collected using a GPS data collection method developed by Ai and Tsai (2015). LRS roadways were targeted for this analysis as GIS data for these roadways are

widely available. Additionally, these roadways are those that are of the highest priority for state agencies. Several state horizontal curve databases have been produced by this data extraction method as of June 2021, including Alabama, Alaska, Maryland, Massachusetts, New Hampshire, Pennsylvania, and Vermont, among others (Ai and Tsai, 2015; Wang et al., 2019, 2020b). Massachusetts was identified as the appropriate application area for this research as detailed geolocated crash data for several years was able to be obtained from the UMassSafe Traffic Safety Data Warehouse, a tool built for maximizing the use of highway safety data (UMassSafe, 0).

6.2.2 Roadway Inventory Data

All geolocated roadway data available for the applicable roadway sections required for this research. Except for the horizontal curve data, all other geolocated roadway data used in this research were publicly available through the Massachusetts Bureau of Geographic Information (MassGIS). The roadway inventory data included in this study was collected by Massachusetts Department of Transportation staff in 2018 and consists of the spatial line work for all public roadways in Massachusetts. The roadway attributes included in this geolocated data file include roadway classification, ownership, physical structural condition, and traffic volume in average annual daily traffic (AADT), among others. The roadway inventory data variables included in the development of the final models consisted of attributes that were found to be widely available on state-owned roadways, have been found in previous horizontal curve literature to potentially impact the safety of curves, and would not be highly correlated to avoid multicollinearity. A summary of the final roadway inventory attributes included in the final analyses are presented along with all other included variables in Table 6.2 and Table 6.3.

6.2.3 Geolocated Crash Data

Five years of geolocated crash data from 2014 through 2018 were collected from the UMassSafe Traffic Safety Data Warehouse UMassSafe (0). To create robust analyses, it is often suggested that three to five years of crash data be used in traffic safety studies (Carter et al., 2017). It is noted that in Massachusetts, crashes are reported in cases in which any person was killed, any person was injured, and/or there was damage in excess of \$1,000 to any one vehicle or other property (UMassSafe, 2019). Definitions of each crash severity type and further details of crash reporting in Massachusetts can be found in the Massachusetts Law Enforcement Crash Report Manual (UMassSafe, 2019). Two EPDO values were calculated for each crash case according to the methods presented in Table 6.1.

6.2.4 Geospatial Analysis

The distance of each crash to the nearest horizontal curve was needed for this study. As discussed, geospatial buffer techniques around target features (such as horizontal curves) are used to join crashes with these target features in traffic safety analysis. However, this technique does collect the distance data from the crash within that buffer to the target feature. Thus, a different geospatial analysis technique was applied using the spatial join technique in ArcMap to join every crash in a given year with the nearest curve feature segment. This also avoided cases of crashes being attached to two or more curves, as can occur in cases of overlapping buffers (Kang et al., 2019). Using this technique, each crash point was given all attributes of the curve segment that was closest to it and a distance field consisting of the distance length between the crash and the curve segment line. Using this distance field, all crashes with a distance field of 91.44 meters (300 feet) or less were extracted, as this buffer distance has been applied in horizontal curve literature (Khan et al., 2012). Thus, all crash data within a 300-foot buffer of a curve were kept for analysis and all other crashes were excluded. This process was repeated for each year of crash data.

The roadway inventory data was then spatially joined in a similar fashion to the horizontal curve data. All data was exported from ArcMap into R for data preparation.

6.2.5 Data Preparation

The goal of the data preparation step was to develop a data frame for model development that consisted of EPDO outcome values and associated roadway inventory data for each year from 2014 to 2018 for each horizontal curve. Crash proximity calculations were developed and completed using the distance value from each curve. All crashes within 300 ft (91.44 m) were included as the first distance column. The second distance weighting method that was developed aimed to encompass the distance of a crash to a curve using a linear weighting system. This calculation is presented in Equation 6.1. The goal of this equation was to create a linear distance weighting value between zero and one that could be multiplied with the EPDO crash values. This would weigh crashes that occurred closer to a curve more heavily, and those that occurred further away from a curve with less weight. The distance used in the weighting factor equations was calculated as the shortest distance in all directions from the curve, encompassing the length of the curve, rather than from a single point on the curve. This is a novel method compared to other methods analyzing horizontal curve safety, which often base the buffer of a curve or other locations of interest on a single point. Encompassing the length of the curve in the distance calculation and the buffer allow the analysis to contain even crashes that are potentially related to curves that are longer in length.

$$\text{Linear distance factor} = \frac{1}{1 + \text{distance}} \quad (6.1)$$

The third distance weighting method that was developed in this study was aimed to encompass the distance of a crash to any point using an exponential weighting system.

This calculation is presented in Equation 6.2. The goal of this equation was to create an exponential distance weighting value between zero and one that could be multiplied by the EPDO values, weighting crashes that occurred closer to a curve even more heavily than in the linear method.

$$\text{Exponential distance factor} = \frac{1}{1 + \log(1 + \text{distance})} \quad (6.2)$$

The final data frame that included all crash cases included six different EPDO outcome columns. An example presenting how these EPDO outcome columns were calculated for each curve is presented in Figure 6.1 and Table 6.1.

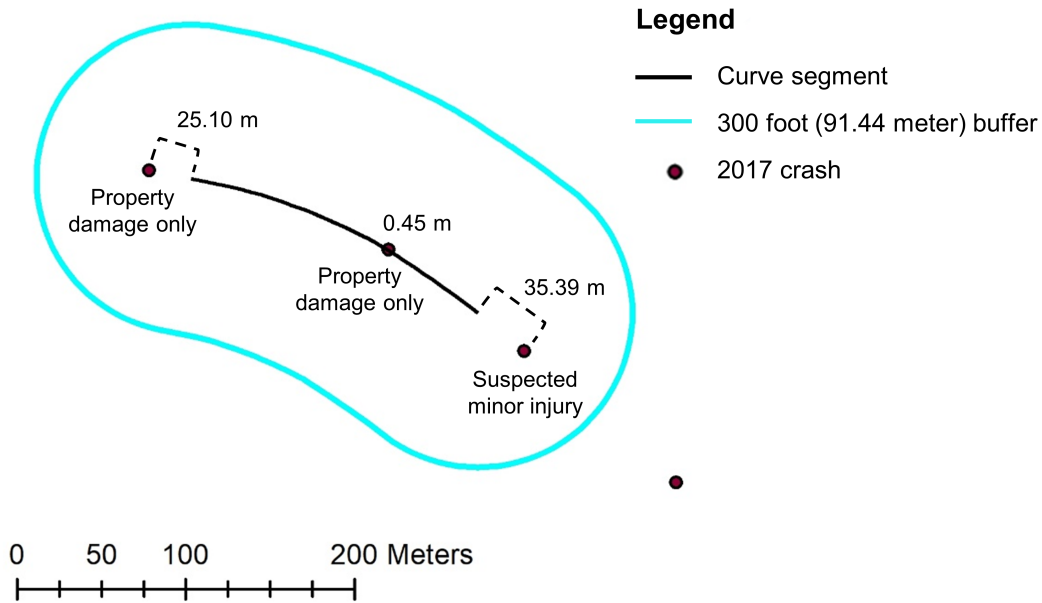


Figure 6.1. Example of calculation of crashes at curve.

Table 6.1.1. Summary of curve crash calculations of example curve.

Variable	Crashes within buffer in 2017			Total crash value
Crash severity	PDO	PDO	Suspected minor injury	
Distance	25.10 m	0.45 m	35.39 m	
Linear distance factor	0.0383	0.6897	0.0275	
Exponential distance factor	0.5862	0.8611	0.3905	
Weighting factor EPDO	1	1	21	23
- with linear distance factor	0.0383	0.6897	0.5775	1.3055
- with exponential distance factor	0.5862	0.8611	8.2005	9.6478
Cost EPDO	16,700	16,700	284,600	318,000
- with linear distance factor	639.61	11,517.99	7826.5	19,984.10
- with exponential distance factor	9789.54	14,380.37	111,136.3	135,306.21

Following these calculations, all crashes were aggregated based on the unique curve identification number and crash year. The result of this merge was a data frame that included the sum of each EPDO outcome for every horizontal curve in each year. The roadway inventory data was then merged with each row using the unique horizontal curve identification number. The result of this aggregated included some curves that had an N/A result for their EPDO outcome values in a given year as some curves did not have any associated crashes in a given year. These N/A values were converted to zeros. This final data frame to be used in model development was then organized and cleaned to exclude missing data, such as curves with no speed limit data or median type data. From this process, 1470 curves were excluded from analysis, leaving a total of 64,795 curves for model development. A summary of the final data frame variable values per curve per year prior to data scaling for model development is presented in Table 6.2 and Table 6.3.

Table 6.2. Summary of continuous variable values (per curve per year) prior to scaling.

Variable	Min	Median	Mean	Max
Average Annual Daily Traffic (AADT)	31	9092	15,191.6	224,513
Curve radius	6.4	348.7	513.7	6965.3
Speed limit	15	35	38.0	65
Number of lanes in both directions	1	2	2.11	4
Weighting factor EPDO	0	1	17.4	1007
- with linear distance factor	0	0.0	7.1	502.0
- with exponential distance factor	0	0.2	9.0	553.1
Cost EPDO	0	16,700	367,630.3	36,777,500
- with linear distance factor	0	429.3	152,059.2	23,241,986.1
- with exponential distance factor	0	3603.1	191,887.7	25219,097.4

All independent continuous data variables were scaled to be a value between zero and one before model development. This was done so the magnitude of the results could represent which variables make a larger impact on curve safety than others. A scale of zero to one was chosen for the independent continuous variables so the continuous variables would be at the same level as the categorical or binary variables. All dependent variables

Table 6.3. Summary of categorical variables (per curve per year).

Variable	Levels	Count	%
Functional Class	Interstate	3082	4.8
	Principal arterial	9621	14.8
	Rural minor arterial or urban principal arterial	24,208	37.4
	Urban minor arterial or rural major collector	27,473	42.4
	Urban collector or rural minor collector	396	0.6
	Local	15	0.0
Structural Condition	Good	31,489	48.6
	Fair	29,759	45.9
	Deficient	3453	5.3
	Intolerable	94	0.1
Terrain	Level	58,872	90.9
	Rolling	5923	9.1
Median Type	None	56,411	87.1
	Curbed	2819	4.3
	Positive barrier - Unspecified	1305	2.0
	Unprotected	286	0.4
	Positive barrier - Semi-Rigid	2252	3.5
	Positive barrier - Rigid	1722	2.7

were scaled to be between 0 and 1000 to be able to directly compare the results between different models.

6.2.6 Model Development

The purpose of this study was to investigate the impact that different EPDO crash outcome values have on the model outcomes of a horizontal curve safety analysis. Crash count values often fit negative binomial models and Poisson regression models (e.g., Srinivasan et al. (2009); Khan et al. (2012); Bauer and Harwood (2014); Mohammadi et al. (2014); Washington et al. (2014); Obelheiro et al. (2020)). However, the conversion of crash count values to EPDO crash values created a new distribution of the data that no longer fit a Poisson or negative binomial distribution. The data was heavily skewed by the high number of zeros. To account for this preponderance of zeros in a continuous distribution, multiple modeling types were considered that can accommodate skewed data. Tobit (Tobin, 1985) and truncated regression models (Cragg, 1971) are commonly applied models for skewed data. Typically, both of these model types assume homoscedasticity, meaning that the error term is the same across all values of the independent variables. A spread-level plot in R was created to confirm that the data for this study did not display homoscedasticity. Due to the uncertain or unaccounted-for conditions of crashes, models involving crash values are often subject to errors. Further, as all EPDO crash outcome values are non-negative with many zero observations, a censored regression or a two-part model is often suitable for modeling (Messner et al., 2016). However, a two-part model is unable to easily present a single relationship equation that can be applied to potential countermeasure selection of all curves. Thus, a heteroscedastic censored regression with a logistic distribution modeling approach was applied.

Heteroscedastic censored regression was run using the `crch()` function in R given its ability to be tailored to fit to a logistic distribution (Messner et al., 2016, 2019). To specify

the distribution and limits of the dependent variable within the function, the left limit for the censored dependent variable was set to zero and the right limit for the censored dependent variable was set to infinity. Additionally, a boosting method of the algorithm was applied using a cross validation technique to obtain the strongest best-fit models. Boosting is a method which is intended to “boost” the accuracy of a learning algorithm (Schapire et al., 1999). Cross validation was used as the technique for boosting using $k = 10$ equal subsets. In 10-fold cross validation, 90% of data is used to build a model and 10% of data is used to test its accuracy. The method then repeats until all subsets of data have been used once for validation of the model. Ten-fold cross-validation was used in this analysis given its ability to make predictions compared to other data splits as 90% of the data is more likely to be generalizable to the full dataset (Refaeilzadeh et al., 2009). The number of maximum boosting iterations was set to 100 within the function. This value was found to be most ideal to develop the most robust model as iteration values above and below this value resulted in worse RMSE results. The boosting step size was also maintained at the default size of 0.1. This value was acceptable for the analysis, as the model converged with this value and the dependent variables that were used in the analyses were not more precise than this value. After testing the `crch()` function with both the non-boosting and boosting methods, the models with the boosting technique were found to have stronger model fits, as presented through their root mean square error (RMSE) values. Thus, boosting was determined as the more robust modeling method and was used to run all developed models. All variables included in model development were found to be statistically significant and were shown in previous literature to impact safety.

Data partitioning was performed prior to modeling to test the accuracy of each model at predicting. The application of evaluating the performance of a model on a “test” data set that was not used to build the model has become a standard preprocessing step

in predictive modeling (Shmueli, 2010). Thus, for analysis, data was randomly split into a training dataset for model development consisting of 80% of the data and a test data set for model validation, consisting of 20% of the data. After modeling, RMSE values were calculated for both the train and test datasets for comparison.

6.3 Results and Discussion

The results of the heteroscedastic censored regression models are presented in Table 6.4 and Table 6.5. Using the boosting method, some variables converged to zero, meaning that there was no significant difference found between the reference variable. Each reference variable is labeled as such in the table for each category. In this section, the impact of the crash distance calculations is first presented and discussed, followed by the difference between the two EPDO calculation methods. Finally, horizontal curve safety implications from these models are presented and discussed.

6.3.1 Impact of Crash Distance Calculations

The use of a distance weighting factor for each crash based on the distance to a target segment to create more robust models was investigated in this study. It was inferred that the closer a crash was to the target segment (in this case, a horizontal curve), the more likely the crash was associated with the target segment. The resulting RMSE values demonstrate that the use of both the linear and exponential distance factors produced stronger models than the models that accounted for all crashes within the 300 ft (91.44 m) buffer, a common buffer value found in horizontal curve literature (Khan et al., 2012). Between the linear and exponential distance factor models, the linear distance factor model was found to result in a slightly more robust RMSE. As a factor was included in the model that would only be associated with a curve (the curve radius), the finding that the strongest models included the linear distance factor weighting demonstrates that it is meaningful to

weigh crashes that are closer to target road segments more heavily as they are more likely to be associated with that particular target segment. Given this, future practice and research should consider the use of linearly weighting methods in addition to buffering techniques in hot spot crash analysis and other transportation safety analysis studies. This study demonstrates that including this additional factor develops a more robust picture of the safety of a particular roadway segment and highlight those crashes more heavily that are more likely associated with the target segment than others.

6.3.2 Impact of EPDO Calculation Method

As previously mentioned, the Massachusetts Department of Transportation now uses a different EPDO weighting method in their resource allocation and analysis approach that weights all fatal and injury crash types together to avoid only “chasing fatal crashes” (MassDOT Highway Division, 2020). The commonly used “cost” EPDO method is more commonly used throughout the United States for resource allocation purposes (American Association of State Highway and Transportation Officials, 2010). As previously mentioned, all independent data was scaled to be of the same scale prior to model development. Thus, all coefficient results represent their relative impact on safety compared to all other variables. The results show that the curve radius variable coefficients were larger in the case of the weighting factor EPDO method models than the cost EPDO method models. This suggests that the radius of a curve makes a smaller impact on the occurrence of fatal crashes than other crash severity outcomes. This was also the case for the number of lanes variable as it was found to make a greater impact in the weighting factor EPDO method models than the cost models. Additional differences can be inferred from the results in Table 6.4 and Table 6.5 by comparing the relative magnitude of the variable coefficient results.

Overall, the RSME results of the models using these two methods demonstrate that the use of the weighting factor EPDO method produces stronger safety models for horizontal curves than the cost EPDO method. This suggests that the use of the weighting factor EPDO method over the cost EPDO method captures the original idea of the Massachusetts Department of Transportation: the difference between a fatal outcome and a serious/possibility serious crash outcome may sometimes be a single minor factor and indistinguishable in practice (MassDOT Highway Division, 2020), especially in terms of environmental characteristics. Given the stronger model outcome using the weighting factor EPDO method, future practice and research should consider using this method for large-scale safety analysis and additionally consider separate strategies to identify the potentially non-environmental characteristics that may separate the occurrence of a fatal crash and a serious or possibly serious injury crash case.

Table 6.4. Summary of model results.

<i>Distance factor</i>	Weighting Factor		EPDO Method		Cost		EPDO Method	
	None ¹	Linear ²	Exponential ³	None	Linear	Exponential	None	Exponential
Intercept	-11.359	-13.802	-11.747	-18.698	-15.917	-15.752	-	-
Average Annual Daily Traffic (AADT)	172.922	102.606	131.142	127.734	76.733	88.540	-	-
Curve radius	79.807	103.395	99.802	61.776	59.367	59.134	-	-
Speed limit	-41.561	-36.999	-40.836	-26.497	-22.688	-22.588	-	-
Number of lanes in both directions	17.261	21.620	20.707	7.423	5.764	6.218	-	-
Functional Interstate (Reference)	-	-	-	-	-	-	-	-
Class	0	0	0	0	0	0	-	-
Principal arterial	0	0	0	0	0	0	-	-
Rural minor arterial or urban principal arterial	3.673	6.101	5.103	1.453	1.921	1.589	-	-
Urban minor arterial or rural major collector	-8.258	-5.659	-7.056	-8.908	-6.958	-7.342	-	-
Urban collector or rural minor collector	0	0	0	0	0	0	-	-
Local	0	0	0	0	0	0	-	-
Structural Good (Reference)	-	-	-	-	-	-	-	-
Condition	0	0	0	0	0	0	-	-
Fair	0	0	0	0	0	0	-	-
Deficient	-10.604	-11.922	-11.526	-12.421	-12.124	-12.239	-	-
Intolerable	0	0	0	0	0	0	-	-
Level (Reference)	-	-	-	-	-	-	-	-
Rolling	-2.182	-1.913	-2.070	-4.256	-4.177	-4.230	-	-
None (Reference)	-	-	-	-	-	-	-	-
Curbed	14.536	7.247	10.444	6.426	2.629	3.847	-	-
Positive barrier - Unspecified	0	0	0	4.890	3.800	4.018	-	-
Unprotected	0	0	0	0	0	0	-	-
Positive barrier - Semi-Rigid	10.316	1.460	5.238	8.284	2.748	4.101	-	-
Positive barrier - Rigid	0	0	0	0	0	0	-	-

¹Refers EPDO values within 300 ft (91.44 m) buffer without weighting based on distance to curve

²Refers EPDO values weighted with distance factor using Equation 6.1

³Refers EPDO values weighted with distance factor using Equation 6.2

Table 6.5. Summary of RSME model results.

<i>Distance factor</i>	Weighting Factor		EPDO Method		Cost		EPDO Method	
	None	Linear	Exponential	None	Linear	Exponential	None	Linear
RMSE of Train (80%)	45.41561	42.207	43.68221	52.59705	44.95775	45.00826		
RMSE of Test (20%)	46.51003	40.90558	42.79941	54.72887	46.25682	46.46568		

6.3.3 Horizontal Curve Safety Implications

A need exists to investigate the appropriate countermeasures to place at the most safety-critical horizontal curve locations. An application of the resulting algorithms to all curves in Massachusetts would present the most safety-critical horizontal curves in the Commonwealth, regardless of whether a crash has yet to occur at any particular location to date or not, as the value is based upon environmental characteristics. On their own, the model results also present the more influential and less influential characteristics that potentially lead to higher severity crashes at higher rates, and therefore, what countermeasures may make a larger impact on safety. While the takeaway of what characteristics impact the safety of a curve more than others depends upon the EPDO method applied, some results across all models were similar in value. To begin, curve segments on rural minor arterials or urban principal arterials were found to be less safe than those on urban minor arterials, rural major collectors, and interstates. Curve segments in deficient structural condition, compared to good condition, were found to be safer. This is likely because drivers are generally likely to drive more carefully on road segments in very poor condition, a manifestation of the theory of risk homeostasis. Risk homeostasis is a theory that suggests that all people adjust their behavior in response to their desired level of perceived risk (Wilde, 1982; Taylor, 1964). At any moment in time, Wilde (1982) suggests a road user perceives a certain level of subjective risk and compares it with the level that they would like to accept, or their “target risk.” If the level of risk is perceived to be higher or lower than their target level of risk, the individual will attempt to eliminate this discrepancy. In the case of deficient pavement conditions, the risk could be perceived as higher than in good pavement conditions.

Risk homeostasis may be the same reason that curve segments with a curbed median were found to be less safe than those without a median. The perceived safety of curbed

medians may increase driver confidence, but may not equivalently increase the actual safety of the conditions to match with their confidence. This results align with previous research by Meesit et al. (2020) that found that driving stress decreases as median width increases. To increase safety on curve segments with curbed medians, countermeasures related to traffic calming may be successful at lowering driver confidence, such herringbone pavement markings or converging chevrons (Hallmark, 2013; Awan et al., 2019).

An increase in AADT was found to lead to less safe curve segments, and as presented by the magnitude of the coefficient compared to other variable coefficients, AADT makes a larger impact on safety than all other environmental factors. This result is intuitive as exposure may increase risk and aligns with previous literature (e.g., Shirani-bidabadi et al. (2020); Elvik et al. (2019); Dong et al. (2015)). Following the AADT variable, the results demonstrate across all models that the curve radius was the second most influential environmental factor in influencing the safety of curve segments. A larger radius was found to lead to less safe curve segments. Previous research has found that curves with smaller radii have been found to be less safe per mile or per kilometer (Elvik, 2013, 2019); however, studies that have come to this finding are additionally considering the length of the curve in their analysis. As the radius is a result of the deflection angle and curve length, these studies actually appear to be investigating the impact of the deflection angle of a curve rather than the radius. As the length of each curve was not included in this study, the result presents the impact of the radius alone. It was found that larger radii are less safe than short radii conditions. Previous research has also demonstrated that crash frequency increases proportionally with the radius due to length considerations when the deflection angle is the same (Hauer, 1999). Future research should consider the various impacts that different radii and deflection angles have on curve safety. Further, future research should

investigate if curve safety should be investigated as a crash per traffic volume per mile or kilometer rate or as a crash per traffic volume rate only in the resource allocation process.

The speed limit of a curve segment was found to be the third most influential factor, and thus, countermeasures pertaining to speed should be considered at a higher level of priority. Higher speed limits resulted in higher levels of safety. This is likely due to the conditions of lower speed limit locations compared to the high speed limit locations. Curves on high speed limit roadways (such as interstates) are designed so drivers do not have to slow their speed to safely maneuver the curve. However, on lower speed limit roadways, curves are often designed to only accommodate speeds much lower than the posted speed limit with the use of posted advisory speeds. Research has shown that drivers more often select higher speeds, or relatively higher speeds, at lower speed limits compared to higher speed limits (Anastasopoulos and Mannering, 2016; Mannering, 2009). Countermeasures to create safer environments lower speed limit conditions on curve segments include rumble strips and chevron signs (Albin et al., 2016; Montella, 2009). Finally, it was found that additional lanes in both directions decreased curve segment safety. This finding aligns with previous research and is likely associated with the traffic-operation effects associated with multi-lane facilities, such as changing lanes and traffic weaving (Kononov et al., 2008; Milton and Mannering, 1998; Abdel-Aty and Radwan, 2000).

6.4 Conclusions

In the transportation safety field, there remains a lack of consensus regarding the optimal method for locating high crash locations. The purpose of this study was to investigate two critical components within the commonly used high risk crash location identification analysis method that are not yet agreed upon: 1) the optimal proximity calculation technique and 2) the optimal equivalent property damage calculation technique using an

application of a novel horizontal curve dataset in Massachusetts. The results demonstrate that the use of a linear distance weighting factor, such as presented in Equation 6.1, used in conjunction with the buffering technique as well as a less precise EPDO weighting factor method results in more robust safety analysis outcomes. This illustrates that it is meaningful to weigh crashes that are closer to target road segments more heavily as they are more likely to be associated with that particular target segment. Further, and in particular, the findings illustrate that use of the less precise weighting factor EPDO method developed and used by MassDOT Highway Division (2020) produces stronger safety models than the commonly used cost EPDO method (American Association of State Highway and Transportation Officials, 2010). This demonstrates that the use of a less precise EPDO weighting factor method creates a more robust picture of safety as sometimes crash severity outcomes can be a single minor factor and indistinguishable in meaning when used in practice. Thus, an EPDO weight factor method that lumps all injury and fatal crashes into a single factor is an optimal method to use in practice and in research in large-scale safety analyses.

There were several noteworthy findings that can assist in the determination of horizontal curve countermeasure selection in future practice and research. One stand-out finding was the impact of the curve radius, as a higher curve radius was found to be less safe than a lower curve radius. This is contrary to previous findings in literature (Elvik, 2019). However, what is often not discussed in these studies is that the curve length is included as a factor, and therefore, curves with a smaller radius are less safe per distance traveled than curves with a larger radius. Thus, this “radius” factor that these studies are discussing is rather the curve deflection angle rather than the radius itself, as the radius is made up of the deflection angle and the curve length. Future research should consider this difference and determine which method is more beneficial to use when it comes to resource allocation methods.

The contributions of this study are the development of an optimal proximity calculation method and EPDO calculation method that can be immediately applied by federal and regional agencies. The developed optimal methodological techniques can also be directly applied to any dataset and/or geometric safety analysis, such as for vertical curves or intersections. Overall, the improved results have the potential to improve hot spot identification and resource allocation at both the federal and regional levels by employing models that more accurately link specific crash segments with contributing crash characteristics.

6.4.1 Limitations

It is important to note the limitations of this research to consider in future studies. First, it is noted that crash locations are not always accurate due to human error and/or equipment failure (Imprialou and Quddus, 2019). Additionally, while filing all crashes that exceed specific thresholds in Massachusetts is required by law, crash reporting is not always done, nor are all crashes always submitted to the Registry of Motor Vehicles in Massachusetts by local police departments (MassDOT Highway Division, 2020). This should be considered when considering the results of this study, and others including road crash data in the United States. Finally, additional distance weighting factor methods and EPDO methods should be considered in future research to determine if other methods are more optimal than those presented in this study.

CHAPTER 7

CONCLUSIONS, PRACTICAL IMPLICATIONS, AND FUTURE EXTENSIONS

Equitable mobility safety continues to be a serious issue throughout the globe. At the same time, proven safety measures have been developed to increase the safety on all roadways, but are not implemented on a grand scale due to lack of resources, inefficiencies, and inequities. As these changes are not made, traffic deaths and serious injuries continue to occur on roadways throughout the world. With the aim to save lives through a more efficient use of resources, this research investigated multiple methods of efficient resource allocation at the local and state level based on surface transportation risk. This Chapter presents the conclusions, contributions, practical implications, and future extensions of this research.

This Chapter is organized into three sections. Section 7.1 discusses the conclusions from this dissertation. Section 7.3 describes the practical implications of the contributions of this research. The conclusions of the research hypotheses are presented in Section 7.2. Finally, Section 7.4 describes the specific contributions of this dissertation and Section 7.5 describes how this research can be extended in future work.

7.1 Conclusions

Allocating resources based on safety risk at multiple funding levels was shown in this research to result in a more equitable and safety-beneficial outcome for all roadway users. Better methods to determine where and how resources should be funded to benefit

the safety of all roadway users were uncovered. The results of Chapters 3 and 4 inform resource allocation policies and practices to create more equitable safety systematically, while Chapters 5 and 6 demonstrate specific methods that can be used to prioritize safety at specific locations once resources have been allocated to specific regions. The following section describes these connections and each Chapter's findings in more detail.

At the municipal level, in Chapter 3, this research found that there are clear municipal highway expenditure rate differences between varying population groups when socio-demographic, socio-economic, and environmental factors are taken into account. Municipalities that have higher poverty levels experience a lower highway expenditure rate per local mile. Further, municipalities located in remote areas far from large metropolitan regions experience a disproportionately lower highway expenditure rate per local mile. These findings indicated the need to consider social differences in systematic funding methods for equitable accessibility and road safety at the local road level. Thus, this research was taken a step further in Chapter 4 to investigate if there was a direct link at the municipal level between the efficiency of spending to improve safety depending upon different environmental characteristics, socio-economic characteristics, and municipal government composition. This research concluded that additional funding and/or support is necessary to achieve the same level of safety depending on the type of environment. Thus, environmental characteristics are critical when considering the allocation of resources for safety purposes. Overall, both Chapter 3 and Chapter 4 indicated there is a need to consider the racial profile of a population, remoteness of a community, and access of resources for a municipal government in funding algorithms to achieve an equitable level of safety in all communities. Further, at the municipal level, Chapter 4 revealed that the way funding is spent by municipalities impacts the safety of a community. This includes that road safety audits (RSAs) can offer significant safety benefits if done on a regular basis.

Resource allocation that impacts the safety of a community does not only occur at the municipal level. This dissertation investigated an optimal way for regions to fund location-specific road safety improvements through a developed reproducible geospatial methodological approach. Chapter 5 describes the development of a safety tool that can be applied for any target location type illustrated through an application with horizontal curve data. The use of this method allows for the identification of the most high-risk target segments and assists in the countermeasure selection process, specifically for specific investment needs. For the application in this research, region-specific conditions were found to result in different horizontal curve safety outcomes, highlighting the importance of developing region-specific safety analysis studies.

Region-specific safety analyses, and transportation geospatial analyses in general, require the use of commonly-applied methods that lack consensus amongst professionals. The methods applied in Chapter 5 are useful for widespread use by even those who are non-technical professionals. However, identifying the best method is necessary to explore for more robust results by technical experts and researchers. Specifically, there lacks a consensus of the optimal safety analysis methodological techniques to locate high-crash locations. This impacts the ability for regional officials and transportation professionals to use their limited resources to increase the safety throughout a region by actually targeting the locations with the highest level of risk. Thus, Chapter 6 investigated the optimal approaches to two critical components of this process: the optimal proximity calculation technique and the optimal equivalent property damage calculation technique. An approach using horizontal curve data was applied; however, the methodological approach could be reproduced with any target location or region. This research revealed that the use of a linear distance weighting factor (presented in Equation 6.1), in conjunction with the buffering technique as well as a less precise EPDO weighting factor method results in more

robust analysis outcomes. The less precise weighting factor method combines all injury and fatal crashes into a single factor, thus weighting crashes that cause harm more evenly. Using this developed method, several findings pertaining to horizontal curve safety impacts were revealed, including the finding that a higher horizontal curve radius is less safe than a lower curve radius.

7.2 Conclusions of Research Hypotheses

This dissertation was directed at addressing the research hypotheses presented in Chapter 1. This section discusses the research findings that apply to each hypothesis.

1. *Municipal roadway funds are issued disproportionately depending on the socio-demographic and socio-economic makeup of a given region. Municipalities that are less impoverished, are less racially diverse, are closer to urbanized areas, and have an older population receive more municipal roadway funding.*

The research in Chapter 3 found that municipal roadway funds are indeed issued by state agencies disproportionately using the socio-demographic and socio-economic characteristics of a municipality based on town data in New York and Massachusetts. Specifically, municipalities that were less impoverished, closer to urbanized areas, and had a larger older population were found to receive more municipal roadway funding, as hypothesized. However, the study results were inconclusive as to whether or not racial diversity of a municipality was a contributing factor. Based on this research and the review of current literature pertaining to equity in transportation and resource allocation, there is a need to conduct additional research on racial disparities from a highway funding perspective, especially in terms of municipal mobility where community needs must be considered at a higher level.

2. *There is a direct connection between the organization structure of a municipal government and socio-demographic characteristics of a region and their ability to efficiently use local highway funding to improve roadway safety. Specifically, the presence of specific municipal staff with a lower level of education and regions that are more rural and more racially diverse are correlated with inefficiencies in spending towards local road safety.*

The research in Chapter 4 revealed that there is a direct connection between the organizational structure of a municipal government and its ability to efficiently use funding to improve roadway safety. However, the results were found to be different for different regions in some instances. Having an engineer on municipal staff resulted in a higher level of efficiency in Massachusetts and a lower efficiency in New York. The same was found for having a highway engineer on staff in New York, while it was insignificant in Massachusetts. The results also indicated that support from county highway departments and hiring a consultant are associated with a higher efficiency towards safer local roads in New York. In Massachusetts, hiring a consultant did not have a significant impact. At the same time, working with a local Regional Planning Organization in Massachusetts had a negative impact on efficiency. Municipal staff composition was identified as a significant factor that impacted efficiency, with a larger staff being associated with a higher efficiency in both regions. Finally, Road Safety Audits were found to lead to higher efficiency in both states and having a civil engineering degree (or equivalent) was significantly associated with a higher efficiency in New York only. Overall, it is noted that differences between Massachusetts and New York were found in the results, likely due their different funding structures of municipalities.

A relationship between the socio-demographic characteristics of a region and its efficiency was found as well. Rural regions were found to have less efficient spending, as

did regions with lower proportions of white residents. These characteristics must then be considered in the current funding algorithms to ensure needed support is provided to specific communities to achieve the same level of safety regardless of their socio-demographic makeup.

3. *Safety issues are heightened on horizontal curve segments and geospatial tool development is not well documented in current literature. A methodology to create a comprehensive statewide horizontal curve safety tool can be developed and implemented for a given region, streamlining the safety improvement process.*

The research in Chapter 5 found that safety issues are indeed heightened on horizontal curve segments compared to tangent segments. Thus, there is a need to consider different countermeasures and safety considerations on horizontal curves compared to tangent segments. The developed methodology to create a horizontal curve safety tool was showcased using data from two states in the United States. The implementation of this tool leads to a streamlined safety improvement process, as hypothesized, as it directly highlights the horizontal curves that are most likely to have substantive safety issues into the future based on previous crash data. Additionally, the contributing factors that lead to higher severity crashes at specific curves are included in the tool, allowing countermeasure selection to be a more streamlined, direct process. Curves with specific safety issues can also be identified in a faster manner. The methodology presented in this dissertation of this tool can be used for the development and implementation of geospatial safety tools for any region.

4. *There remains a lack of consensus among safety practitioners and researchers as to the optimal method for locating these high-risk locations. A proximity technique that weights crashes more heavily based on their distance to a target roadway segment*

and less specific crash severity weighting method provides optimal results compared to other commonly used approaches.

The research in Chapter 6 concluded that a proximity technique that weights crashes more heavily based on their distance to a target road segment is a more optimal method than the traditional buffer-only crash proximity techniques used in hot spot analysis. This finding indicates that it is meaningful to weigh crashes that are closer to target road segments more heavily as they are more likely to be associated with that particular target segment. Additionally, the use of a crash severity weighting method which combines injury and fatal crashes rather than separates them was indeed shown to have more optimal results than the use of the traditional equivalent property damage calculation method. Combining fatal and injury crashes into a single factor, while weighing all other crash types at a lower level, resulted in stronger model output, indicating that this method is more beneficial in high-risk crash analyses. Further, the difference between fatal and serious or possibly serious injury crash outcomes may sometimes be a single minor factor, such as the time to necessary and specific medical care following a crash, that is indistinguishable in practice to overcome.

7.3 Practical Implications

The results of this research have numerous practical implications for transportation practitioners, policymakers, officials, and researchers. To begin, several of the methodological developments in this dissertation can be directly applied in practice to equitably improve safety through informed resource allocation practices. When combined, the methods presented in this research can impact the regional safety from a myriad of perspectives. Funding for transportation flows from state and local regions to both to specific projects and systematically to be spent on a variety of needs at the local level to improve safety.

This dissertation connects both of these funding mechanisms and allocation processes. The disproportionate nature of municipal highway funding revealed in Chapter 3 presented the importance of considering socio-demographic and socio-economic characteristics at the systematic funding level. This can be further investigated using the data envelopment analysis (DEA) method, which was found to be an advantageous analysis method at determining the efficiency of spending habits at the local level to improve safety. The methodology of using the DEA method described in Chapter 4 can be reproduced by any region to determine how they can more efficiently use their spending or distribute funding to result in the best safety outcome. Then, the methodological location-specific funding approach described in Chapter 5 combined with the weighting methods in Chapter 6 to determine where and how location-specific funding should be spent for the most beneficial safety outcomes once it is at the local or regional level, as informed by the results in Chapter 3 and Chapter 4. This methodology can be applied for horizontal curves and/or other target location types depending upon the needs and interests of the region.

Several of the results revealed in this dissertation could directly impact the policies and practices of transportation professionals to create a safer and more equitable roadway system. The algorithms that are used by state and/or regional agencies to distribute funding to municipalities were found to not be equitable in their current state. Municipalities with high poverty levels, a smaller proportion of older residents, a percentage of an older population, and in a less remote region were all characteristics that individually resulted in a higher spending transportation spending rate per local mile than municipalities with the opposite characteristics. Thus, it is critical that state agencies and other funding agencies consider environmental, socio-economic, and socio-demographic factors in their funding algorithms to ensure that funding is equitably distributed. More specifically, it is important that these elements be formalized into a more systemic resource allocation process for

funding at the local level. Additionally, these disparities were found to exist in regards to the efficiency of municipalities in their spending of to increase safety. Municipalities with specific characteristics, such as being located in an urban area or having a larger percentage of white residents, were found to be more efficient in terms of roadway safety than their counterparts. Further, certain spending habits by municipalities, such as towards RSAs, resulted in safer roads. Overall, as previously stated, the results presented in Chapter 4 can be directly applied to both the allocation level and the spending level of government agency to increase safety for municipal roads.

7.4 Research Contributions

The contributions of this research fill gaps in current literature related to safety, equity, and resource allocation. These contributions include both methodological and practical contributions and can be summarized as follows:

1. Assessment of the municipal socio-economic and socio-demographic characteristics relationship with municipal transportation funding.
2. Safety and efficiency assessment of municipal roadways on the basis of municipal educational, monetary, and staffing resources.
3. Assessment of the data envelopment analysis method for use in transportation efficiency analyses at the local level.
4. Development geospatial safety tool developmental methodology for use by regional and state highway officials.
5. Assessment of region-specific horizontal curve factors that impact safety.

6. Development of improved methodological approaches in high-risk crash safety analyses.

7.5 Future Extensions

The research this dissertation focused on can be extended in many ways. This includes region-specific extensions to the methodological applications of this research as well as extensions to the research topics of equity, resource allocation, and safety in transportation in general. The following section describes potential future research work that should be considered to expand upon the results, methods, and conclusions of this dissertation.

7.5.1 Systematic Analyses

Throughout the research in Chapter 3 and Chapter 4, only specific socio-economic, socio-demographic, and environmental characteristics were selected and considered to narrow the scope of this research. Local tax rates and land use factors should be included in future studies. Additionally, equity considerations/factors (i.e., air quality, noise, walkability, etc.) were not considered in this research and should be included in future systematic municipal research pertaining to equity, resource allocation, and safety. These specific disparities are critical to consider as the impact of climate change continues to threaten communities throughout the globe. A sensitivity analysis of that includes different factors to investigate whether some should be included or not in funding algorithms should be explored to see how they may (or may not) influence the outcome of the DEA results towards a more equitable result. International data should additionally be included in future studies, as this research only investigated these relationships within the United States, to understand in what ways this is a global problem and how it can be addressed in different regions. Further, an investigation into the use of whether centerlane miles or lane miles are

more appropriate for modeling of resource allocation at the local level should be explored, as well as the development of a weighting method that considers both at once.

This dissertation did not investigate the explicit reasons for the revealed disparities found in Chapter 3 and Chapter 4. Investigations into the “why” of these results should be considered in future work to solve the root of equity and safety issues directly in the future. The impact of declining versus growing regions, both economically and by population, should be included in future research as well to better consider future impacts, rather than only current. An evaluation of the impact of long-term planning on safety should also be performed and input from additional and diverse interviews of local highway and state highway officials should be considered.

Analyses in the future should expand upon the impacts of different funding sources on local road safety and efficiency in spending, which was not investigated in this research. More specifically, federal and/or state capital investments and other types of funding that may impact the level of safety within a community should be included in future studies to uncover additional relationships that should be considered in state and regional resource allocation algorithms. This research also did not account for how local highway funding was used and how each investment was allocated. This is important to consider when assessing the equity of investments.

Finally, municipalities and municipal roads were chosen as the level of analyses in this dissertation in terms of systematic safety and resource allocation as they are vulnerable to safety issues. However, municipalities can often be comprised of very heterogeneous populations with widely varying socio-economic status and socio-demographic characteristics. Thus, future research should consider smaller blockgroups and regions of towns to capture differences across these populations. Additionally, the investigation of larger regions may reveal disparities that are not yet known to decision makers that should be considered.

7.5.2 Location-Specific Analyses

Throughout the research in Chapter 5 and Chapter 6, crash location data was directly use for analysis purposes. However, crash locations are not always accurate due to human error and/or equipment failure. Future extensions of this research should investigate the impact of crash location accuracy on the development and employment of the horizontal curve safety tool and developed crash analysis techniques. The impact of missing crash data overall should also be considered in future research, as well as expanding the employment of the methodology to new regions. For example, the employment of both methodologies in Chapter 5 and Chapter 6 should be done in an international context in the future to investigate how these methodologies may change depending on the data available and contexts of the research. The inclusion of the cost/benefit of specific countermeasures should be included in future work to be able to provide specific recommendations based on the available resources for a given region.

Additional infrastructure data should be considered in future safety studies to investigate their impact on building a safety tool and improved safety analysis techniques, including warning signage and speed data. This data was not extensively available for the study regions at the time of this research. As available geolocated infrastructure data becomes available, this research should be expanded upon to hone into the safety impacts of different environmental and structural variables at horizontal curve segments and other target locations. Additional distance weighting factor methods and EPDO methods should be considered in future research to determine if others are more optimal than those presented in this research. Finally, the creation of specific buffer distances based on land use (for example, rural versus suburban regions) should also be explored, as the influential safety area of a curve or other focus roadway locations, may differ for different regions.

APPENDIX A

NEW YORK AND MASSACHUSETTS MUNICIPAL SURVEYS AND CORRESPONDENCE

Municipal Government Survey - Traffic & Highway Staff

The purpose of this twelve question survey is to obtain municipal information regarding traffic and highway staff throughout New York State.

Government Level

Village

Town

City

Other

Municipality Name

County Name

Does your municipality have a town/city/village engineer on staff?

Yes

No

Does your municipality have a town/village/city traffic or highway engineer on staff?

Yes
No

Please select all that are applicable to your municipality:

Has own Transportation Committee or Board (non-safety specific, e.g. the [Town of Penfield](#))
Has own Traffic Safety Committee or Board (e.g. the [Town of Guilderland](#) and the [Town of Amherst](#))
Have a Traffic Department (separate from the Highway Department)
None of the above

Has your municipality received assistance from your County Highway Department or County Engineer for assisting on a highway or transportation-related project or issue on a local roadway under your jurisdiction in the last 3 years?

Yes
No
Unsure

Has your municipality hired a consultant for a transportation/highway/traffic project in the last 3 years?

Yes
No
Unsure

How many full time highway/maintenance staff members does your municipality have on staff?

- 0
- 1 to 2
- 3 to 5
- 5 to 10
- 10 to 15
- 15 to 25
- 25+

Does your Highway Superintendent (or primary highway department official) have a college degree in any of the following?

- Civil Engineering
- Planning
- Engineering (other)

Other, related to traffic/engineering:

None of the above pertains

Does anyone on your current municipal staff have a Civil Engineering (or equivalent) degree?

Yes, their title is:

- No
- Unsure

Has your municipality conducted or been a part of a Road Safety Audit (RSA) in the last 3 years?

- Yes
- No
- Unsure

If we may have any clarification questions, could we contact you? If so, please provide your name and contact information below.

Thank you for your time. Should you have any questions regarding this questionnaire or regarding this work, please contact Alyssa Ryan or Michael Knodler. We would be happy to provide any additional information.

Alyssa Ryan, alyssaryan@umass.edu, (315) 276-5045
Michael Knodler, mknodler@umass.edu

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Survey of NYS Town Superintendents of Highways

1 message

Alyssa Ryan <alyssaryan@umass.edu>

Mon, Dec 16, 2019 at 4:46 PM

Dear New York State Town Superintendents of Highways and Staff,

I am writing to request your participation in a brief, 12 question survey related to your town highway and traffic staff. I have been in communication with the Association of Towns and Cornell Local Roads Program to formulate and send out this survey to all Towns within New York State.

This survey aims to obtain this information to understand various relationships related to government size, resources, and safety within a municipality for New York State and Massachusetts. For full background on the purpose of this survey, please see the attached letter.

The survey can be accessed through the following link. Please click or copy and paste the following into your web browser for access:

https://umassamherst.co1.qualtrics.com/jfe/form/SV_bQT7yRrQzLpI9eZ

Your participation will remain anonymous, unless you choose to provide your contact information. However, this is not required.

Thank you for your time and assistance. If you have any questions regarding this research/survey, or would prefer to provide your answers via email, please contact me at alyssaryan@umass.edu, (315) 276-5045, or Michael Knodler at mknodler@umass.edu.

Sincerely,

Alyssa Ryan
Civil & Environmental Engineering
University of Massachusetts Amherst

--

Alyssa Ryan
University of Massachusetts Amherst
Ph.D. Student, Civil Engineering
(315) 276-5045 | [LinkedIn](#)

 **Survey Cover Letter_12_2019.pdf**
16K

Alyssa Ryan
University of Massachusetts Amherst
34 Marston Hall
Amherst, MA 01003
(315) 276-5045
alyssaryan@umass.edu

December 16, 2019

Dear New York State Town Superintendents of Highways,

This letter provides background of the survey, which can be found [here](#).

In the United States, the fatal crash risk is 2.1 times higher in rural areas than urban areas and 20% of fatalities in rural areas occur on local roadways. In urban areas, this value is 14%. My research work aims to address this disparity, focusing on rural versus urban transportation safety, and more specifically, ways in which roadway safety can, and is, addressed as the local level.

With the goal of investigating the relationship between crash volumes/crash severity on local roadways with experience/resources, this survey aims to gather information of traffic and highway staff throughout New York State municipal governments, with a focus on gathering information directly from Towns. This will allow an understanding to be built of how safety may be related to experience type, background, resources, and staff numbers at a local level. This in turn will allow for an understanding of how resources, staff, etc. play a role in the transportation safety of a community at a local level, including those that may make the greatest impact. In the end, this information will help local governments realize where their resources may be best used towards creating a safer roadway environment for their community, as well as inform the state government as to which types of towns/municipalities may require additional support/resources to reach their transportation safety goals.

I am seeking to gather information from all 932 towns within New York State. I would be thankful for as much support as you may be able to offer towards that goal. I am also collecting the same information for all towns within the Commonwealth of Massachusetts.

All those who take this survey will remain anonymous, unless they choose to provide their contact information at the end of the survey for clarification purposes. Note that this is not required.

Thank you for your assistance and time. Please do not hesitate to contact me or Michael Knodler (mknodler@umass.edu) with any questions regarding this survey and/or research.

Sincerely,
Alyssa Ryan
Ph.D. Student, Department of Civil and Environmental Engineering
University of Massachusetts Amherst

Survey of NYS Towns - Highways

Alyssa Ryan <alyssaryan@umass.edu>
To: Alyssa Ryan <alyssaryan@umass.edu>
Cc: Michael Knodler <mknodler@umass.edu>

Tue, Mar 10, 2020 at 3:19 PM

Dear NYS Municipal Staff Members and Officials,

I am writing to follow up on a request to ask for your participation in a brief, 12 question survey related to your town highway and traffic staff. I have been in communication with the Association of Towns and Cornell Local Roads Program to formulate and send out [this survey](#) to all Towns within New York State. We are following up on those municipalities who have not yet responded since initially sending this survey in December 2019.

This survey aims to obtain this information to understand various relationships related to government size, resources, and safety within a municipality for New York State and Massachusetts. For full background on the purpose of this survey, please see the attached letter.

The survey can be accessed through the following link. Please click or copy and paste the following into your web browser for access:

https://umassamherst.co1.qualtrics.com/jfe/form/SV_bQT7yRrqzLpl9eZ

Your participation will remain anonymous, unless you choose to provide your contact information. However, this is not required.

Thank you for your time and assistance. If you have any questions regarding this research/survey, or would prefer to provide your answers via email, please contact me at alyssaryan@umass.edu, (315) 276-5045, or Michael Knodler at mknodler@umass.edu.

Sincerely,

Alyssa Ryan
Civil & Environmental Engineering
University of Massachusetts Amherst

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Alyssa Ryan
University of Massachusetts Amherst
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 **Survey Cover Letter_2020_NYS.pdf**
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Alyssa Ryan
University of Massachusetts Amherst
34 Marston Hall
Amherst, MA 01003
(315) 276-5045
alyssaryan@umass.edu

March 10, 2020

Dear New York State Municipal Staff Members and Officials,

This letter provides background of the survey, which can be found [here](#).

In the United States, the fatal crash risk is 2.1 times higher in rural areas than urban areas and 20% of fatalities in rural areas occur on local roadways. In urban areas, this value is 14%. My research work aims to address this disparity, focusing on rural versus urban transportation safety, and more specifically, ways in which roadway safety can, and is, addressed as the local level.

With the goal of investigating the relationship between crash volumes/crash severity on local roadways with experience/resources, this survey aims to gather information of traffic and highway staff throughout New York State municipal governments, with a focus on gathering information directly from Towns. This will allow an understanding to be built of how safety may be related to experience type, background, resources, and staff numbers at a local level. This in turn will allow for an understanding of how resources, staff, etc. play a role in the transportation safety of a community at a local level, including those that may make the greatest impact. In the end, this information will help local governments realize where their resources may be best used towards creating a safer roadway environment for their community, as well as inform the state government as to which types of towns/municipalities may require additional support/resources to reach their transportation safety goals.

I am seeking to gather information from all 932 towns within New York State. I would be thankful for as much support as you may be able to offer towards that goal. I am also collecting the same information for all towns within the Commonwealth of Massachusetts.

All those who take this survey will remain anonymous, unless they choose to provide their contact information at the end of the survey for clarification purposes. Note that this is not required.

Thank you for your assistance and time. Please do not hesitate to contact me or Michael Knodler (mknodler@umass.edu) with any questions regarding this survey and/or research.

Sincerely,
Alyssa Ryan
Ph.D. Student, Department of Civil and Environmental Engineering
University of Massachusetts Amherst

MA Municipal Government Survey - Traffic & Highway Staff

The purpose of this twelve question survey is to obtain municipal information regarding traffic and highway staff throughout the Commonwealth of Massachusetts.

Government Level

Town

City

Other

Municipality Name

County Name

Does your municipality have a town/city engineer on staff?

Yes

No

Does your municipality have a town/city traffic or highway engineer on staff?

Yes

No

Please select all that are applicable to your municipality:

Has own Transportation Committee or Board (non-safety specific, e.g. the [Town of Arlington](#))

Has own Traffic Safety Committee or Board (e.g. the [Town of Hanover](#) and the [Town of Chatham](#))

Have a Traffic Department (separate from the Highway Department)

None of the above

Has your municipality received assistance from your Regional Planning Agency on a highway or transportation-related project or issue on a local roadway under your jurisdiction in the last 3 years?

Yes

No

Unsure

Has your municipality hired a consultant for a transportation/highway/traffic project in the last 3 years?

Yes

No

Unsure

How many full time highway/maintenance staff members does your municipality have on staff?

0

1 to 2

3 to 5

5 to 10

10 to 15

15 to 25

25+

Does your Director of Public Works (or primary highway department official) have a college degree in any of the following?

Civil Engineering

Planning

Engineering (other)

Other, related to traffic/engineering:

None of the above pertains

Does anyone on your current municipal staff have a Civil Engineering (or equivalent) degree?

Yes, their title is:

No

Unsure

Has your municipality conducted or been a part of a Road Safety Audit (RSA) in the last 3 years?

Yes

No

Unsure

If we may have any clarification questions, could we contact you? If so, please provide your name and contact information below.

Thank you for your time. Should you have any questions regarding this questionnaire or regarding this work, please contact Alyssa Ryan or Michael Knodler. We would be happy to provide any additional information.

Alyssa Ryan, alyssaryan@umass.edu, (315) 276-5045
Michael Knodler, mknodler@umass.edu

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TEST: Survey of MA Municipal Highway Staff

3 messages

Aldo Villani <avillani@engin.umass.edu>
To: Alyssa Ryan <alyssaryan@umass.edu>

Wed, Feb 12, 2020 at 5:49 PM

Dear Massachusetts Municipal Staff,

I am writing to request your participation in a brief, 12 question survey related to your town or city highway and traffic staff. A similar survey has recently been sent out to all Towns within New York State in conjunction with the Association of Towns and Cornell Local Roads Program.

This survey aims to obtain information to understand various relationships related to government size, resources, and safety within a municipality for New York State and Massachusetts. For full background on the purpose of this survey please [click here](#).

The survey can be accessed through the following link. Please click or copy and paste the following into your web browser for access:

https://umassamherst.co1.qualtrics.com/jfe/form/SV_8dLBogFeRdFSHA1

Your participation will remain anonymous, unless you choose to provide your contact information. However, this is not required.

Thank you for your time and assistance. If you have any questions regarding this research/survey, or would prefer to provide your answers via email, please contact me at alyssaryan@umass.edu, (315) 276-5045, or Michael Knodler at mknodler@umass.edu.

Sincerely,

Alyssa Ryan
Civil & Environmental Engineering
University of Massachusetts Amherst

Tue, May 5, 2020 at 3:15 PM

From: UMass Transportation Center <admin@umasstransportationcenter.org>
Sent: Tuesday, May 5, 2020 3:13 PM
To: Aldo Villani
Subject: Survey of MA Municipal Highway Staff (TEST)

Dear Massachusetts Municipal Staff,

I am writing to request your participation in a brief, 12 question survey related to your town or city highway and traffic staff. This survey was first sent out in February 2020. If you have already completed this survey, thank you for taking the time to do so and I apologize for the duplicate message.

This survey aims to obtain this information to understand various relationships related to government size, resources, and safety within a municipality for New York State and Massachusetts. For a full background on the purpose of this survey, [please click here](#).

The survey can be accessed through the following [link](#). Please click or copy and paste the following into your web browser for access:

https://umassamherst.co1.qualtrics.com/jfe/form/SV_8dLBogFeRdFSHA1

Your participation will remain anonymous, unless you choose to provide your contact information. However, this is not required.

Thank you for your time and assistance. If you have any questions regarding this research/survey, or would prefer to provide your answers via email, please contact me at alyssaryan@umass.edu, (315) 276-5045, or Michael Knodler at mknodler@umass.edu.

Sincerely,

Alyssa Ryan
Civil & Environmental Engineering
University of Massachusetts Amherst

Alyssa Ryan
University of Massachusetts Amherst
34 Marston Hall
Amherst, MA 01003
(315) 276-5045
alyssaryan@umass.edu

January 2020

Dear Massachusetts Municipal Staff,

This letter provides background of the survey, which can be found [here](#).

In the United States, the fatal crash risk is 2.1 times higher in rural areas than urban areas and 20% of fatalities in rural areas occur on local roadways. In urban areas, this value is 14%. My research work aims to address this disparity, focusing on rural versus urban transportation safety, and more specifically, ways in which roadway safety can, and is, addressed as the local level.

With the goal of investigating the relationship between crash volumes/crash severity on local roadways with experience/resources, this survey aims to gather information of traffic and highway staff throughout Massachusetts municipal governments, with a focus on gathering information directly from Towns. This will allow an understanding to be built of how safety may be related to experience type, background, resources, and staff numbers at a local level. This in turn will allow for an understanding of how resources, staff, etc. play a role in the transportation safety of a community at a local level, including those that may make the greatest impact. In the end, this information will help local governments realize where their resources may be best used towards creating a safer roadway environment for their community, as well as inform the state government as to which types of towns/municipalities may require additional support/resources to reach their transportation safety goals.

I am seeking to gather information from all towns within Massachusetts. I would be thankful for as much support as you may be able to offer towards that goal. I am also collecting the same information for all towns within New York State.

All those who take this survey will remain anonymous, unless they choose to provide their contact information at the end of the survey for clarification purposes. Note that this is not required.

Thank you for your assistance and time. Please do not hesitate to contact me or Michael Knodler (mknodler@umass.edu) with any questions regarding this survey and/or research.

Sincerely,
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