Heterogeneous Data Uncertainties in Risk Management of a Multiscale Transportation Program

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Abstract

Access management, which systematically limits opportunities for egress and ingress of vehicles to highway lanes, is critical to protect trillions of dollars of current investment in transportation. While access management can be effective to avoid crashes, reduce travel times, and increase route capacities, the literature suggests a need for metrics to guide investments in resource allocation across large networks at several time horizons and geographic scales. This dissertation describes a decision aid to support a multiscale transportation access management program via a risk-cost-benefit tradeoff analysis with heterogeneous sources of data and expertise, addressing incomplete or partially relevant information on regions, decision criteria, crash rates, travel speeds, road condition, project costs, and other factors. The approach quantifies safety improvement, travel-time savings, and costs of access management through functional relationships of input parameters including crash rates, corridor access point densities, and traffic volumes. Parameter uncertainties, which vary across regions and time horizons, are addressed via numerical interval analyses. The integration of methods is demonstrated for 6,000 highway miles of a 43,000 square-mile region and its several sub-regions. The demonstration prioritizes route segments that would benefit from risk assessment and risk management, including (i) right of way purchases, (ii) restriction of access points, (iii) new alignments, (iv) developer proffers, (v) further data collection, (vi) further expert elicitation, (vii) etc. The philosophy of approach is generally applicable to address uncertainties of heterogeneous data in resource allocation and decision making for multiscale systems.

Keywords: Risk analysis, cost-benefit analysis, corridor management, transportation safety, uncertainty analysis, multicriteria analysis, systems evaluation, resource allocation, priority setting, data uncertainties

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Notation

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average daily traffic (vehicles per day)
ALDOT	Alabama Department of Transportation
B/C	Benefit-to-cost
CMF	Crash Modification Factor
CPM	Crash Prediction Module
DOT	Department of Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GIS	Geographic Information System
HCM	Highway Capacity Manual
HSM	Highway Safety Manual
IHSDM	Interactive Highway Safety Design Model
ISO	International Organization for Standardization
ITF	International Transport Forum
ITS	Intelligent Transportation Systems
MCDA	Multicriteria decision analysis
MIDOT	Michigan Department of Transportation

MNDOT	Minnesota Department of Transportation
NCHRP	National Cooperative Highway Research Program
NYSDOT	New York State Department of Transportation
OHDOT	Ohio Department of Transportation
ORDOT	Oregon Department of Transportation
SI	Safety Index
SMS	Statewide Mobility System consisting of six thousand miles of multimodal corridor in the Commonwealth of Virginia
SPF	Safety Performance Function
SRA	Society of Risk Analysis
TDM	Travel Demand Management
TPRAC	Transportation Planning Research Advisory Committee
TRB	Transportation Research Board
TXDOT	Texas Department of Transportation
VCTIR	Virginia Center for Transportation Innovation and Research
VDOT	Virginia Department of Transportation
VMT	Vehicle miles traveled
WW2	World War II
D	Travel time delay index
I	Access related crash intensity
L	Length of corridor segment (miles)
N	Number of access points

S	Posted speed (miles per hour)
T	Average daily traffic (vehicles per day)
V	Value of travel time ($ per hour)
β	Average cost per crash avoided ($ per crash avoided)
Δ	Crash reduction factor
C_{PE}	Preliminary engineering cost
C_{RW}	Right-of-way acquisition cost
C_{CN}	Construction cost
C_{PM}	Preservation and maintenance cost
C_{Total}	Total project cost
Ψ_T	B/C ratio (for travel-time savings)
Ψ_S	B/C ratio (for safety improvement)
Ψ	B/C ratio (for travel-time savings and safety improvement jointly)
B_T	Travel time savings benefits of access management
B_S	Safety improvement benefits of access management

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1 Introduction

1.1 Chapter overview

This chapter will introduce the dissertation, which is a study of advanced methods for addressing data and parameter uncertainties in risk-based access management for multiscale infrastructure corridors. The sections of this chapter are organized as follows: (i) Section 1.2 will describe the motivation of this study, (ii) Section 1.3 will describe the purpose and scope, (iii) Section 1.4 will describe the organization of the dissertation, and (iv) Section 1.5 will provide a chapter summary.

1.2 Motivation

During the Virginia 2014 General Assembly session, the 72nd Governor of Virginia, the Honorable Terry McAuliffe, highlights issues and the future opportunities related to transportation in a letter to all Virginia state employees (the entire letter is provided in its entirety in Appendix A). He states "*I strongly supported and worked with House and Senate leaders on legislation that outlines a transparent, data-driven process for evaluating new transportation projects. House Bill 2 is a landmark piece of legislation that will play a pivotal role in determining how we spend transportation dollars. We want to guarantee that Virginia's taxpayers are getting the best value for their money."*. This calls for the appropriate use of data-driven approaches to select future transportation projects and investments.

In particular, access management has been cost-effective to reduce travel times and improve safety by limiting the available entrances and exits of highways. A typical finding is that most of crashes occur when a vehicle is turning into or out of an intersection and that effective access management of corridors can reduce crashes. About 50% of all crashes are intersection-related and a high percentage of fatal and injury crashes occur at intersections (U.S. FHWA 2009). The various studies have shown that the increase in the number of access points translates into higher accident rates (Gluck et al. 1999). At the same time, access management has been shown to have a positive impact on travel-time savings (Marek 2011; Kirk et al. 2006; U.S. FHWA 2003a). As vehicles are enabled to travel nearer to posted speed on roads when access is well managed, higher access point densities are associated to reductions in free-flow speed (Gluck et al. 1999).

A typical focus of access management is minimizing or managing the number of conflict points (U.S. FHWA 2013b). Addressing access points through planning, design, and operations can increase roadway capacity, reduce crashes, and shorten travel time, with minimal disruption to accessibility. Gluck and Lorenz (2010) enumerate some widely used access management techniques to improve transportation operations and safety. The U.S. FHWA (2003a) describes a typical set of access management techniques, including access spacing, driveway spacing, sage turning lanes, median treatments, right-of-way management, etc. The use of these techniques results in safer and more efficient travel along highway systems and preserves the benefits of investment in the transportation infrastructure; however, a principled macro-level plan can help to ensure the high returns on investment, since public agencies have limited resources for planning, with constraints of budget, human resources, facilities, etc. Typically micro-level studies cannot be afforded for estimating potential benefits and costs of addressing each access point on major corridors. To prioritize investigative and implementation resources, decision makers need to screen, benchmark, and prioritize across their large-scale distributed highway networks. In highway decision making, cost-benefit analysis considers the benefits and costs that would be influenced by a potential improvement to the current status of a transportation facility (U.S. FHWA 2003b). As cost-benefit analysis can increase transparency and accountability for use of public funds, e.g., comparing the engineering and construction and eventually lifecycle costs with the future benefits associated to transportation projects, there is a need to develop a general approach to priority setting among needs for transportation access management program via a cost-benefit analysis.

1.3 Purpose and scope

This dissertation develops and illustrates a data-driven framework to prioritize locations for highway access management. Access management, as a multiscale transportation program, balances land and economic development with maintaining road system in terms of safety, capacities, travel speeds, environmental impacts, etc. The approach is to build on cost-benefit analysis and multi-criteria tradeoff analysis under uncertainties to support corridor access management plans and prioritizations. The approach combines data-driven quantitative analysis with modeling and expertise of transportation professionals, to represent the benefits and costs of access management program, to prioritize various access management projects, and to address heterogeneous sources of data and model uncertainties.

Particularly this dissertation will deliver: (i) uncertainty quantification of costs, benefits, and cost-benefit ratio, combined to a tradeoff analysis of safety and mobility metrics, (ii) safety metrics among other performance (return on investment) considerations that include benefit-to-cost (B/C) ratio and travel-time savings, (iii) resource allocation to project portfolios with metrics/estimations that have unknown joint probability distributions, in part because large data arrive from heterogeneous experts, agencies, measurements, databases, etc., and (iv) an inclusive and balanced consideration of benefits in several dimensions, including safety, mobility, and potentially others (environment, economic, etc.).

An integration of the methods will be demonstrated in case studies of multiscale transportation systems, more specifically, a 6,000 miles (9,000 kilometers) transportation corridor network called the Virginia Statewide Mobility System (SMS). The demonstration suggests how the developed methods advance existing resource allocation and risk management approaches of public agencies to make decisions in transportation planning and engineering.

1.4 Organization of dissertation

The organization of this dissertation proposal is as follows.

Chapter 2 describes the background and literature review related to transportation access management, corridor risk management, cost-benefit analysis, and multicriteria decision analysis under uncertainties.

Chapter 3 describes the details of the methodology and presents a data-driven approach of corridor access management with risk-cost-benefit analysis from a perspective of *safety improvement*. Case studies of a multiscale transportation system are shown in this chapter.

Chapter 4 develops a similar method from a complementary perspective of *travel-time savings*. Case studies of a multiscale transportation system are shown in this chapter as well.

Chapter 5 fulfills a need to integrate the above perspectives, *safety improvement and travel-time savings*. Case studies of a multiscale transportation system are shown in this chapter as well.

Chapter 6 discusses several topics related with the introduced analytical framework and the case studies.

Chapter 7 provides a summary of the dissertation and describes its several contributions to the risk analysis and systems analysis in support of transportation access management, and suggests opportunities for future work.

Figure 1 and Figure 2 provide a summary of the approach of this dissertation. The approach builds on selected knowledge from the fields of systems engineering, risk analysis, multicriteria tradeoff analysis, cost-benefit analysis, uncertainty analysis, etc. The approach includes several parts: problem definition and literature review; data collection; costs and benefits modeling from alternative perspectives; demonstrations; and issues for implementation.

1.5 Chapter Summary

This chapter described the motivation, purpose, and organization of the dissertation. Section 1.2 described the motivation of this study. Section 1.3 described the purpose and scope. Section 1.4 described the organization of this dissertation.

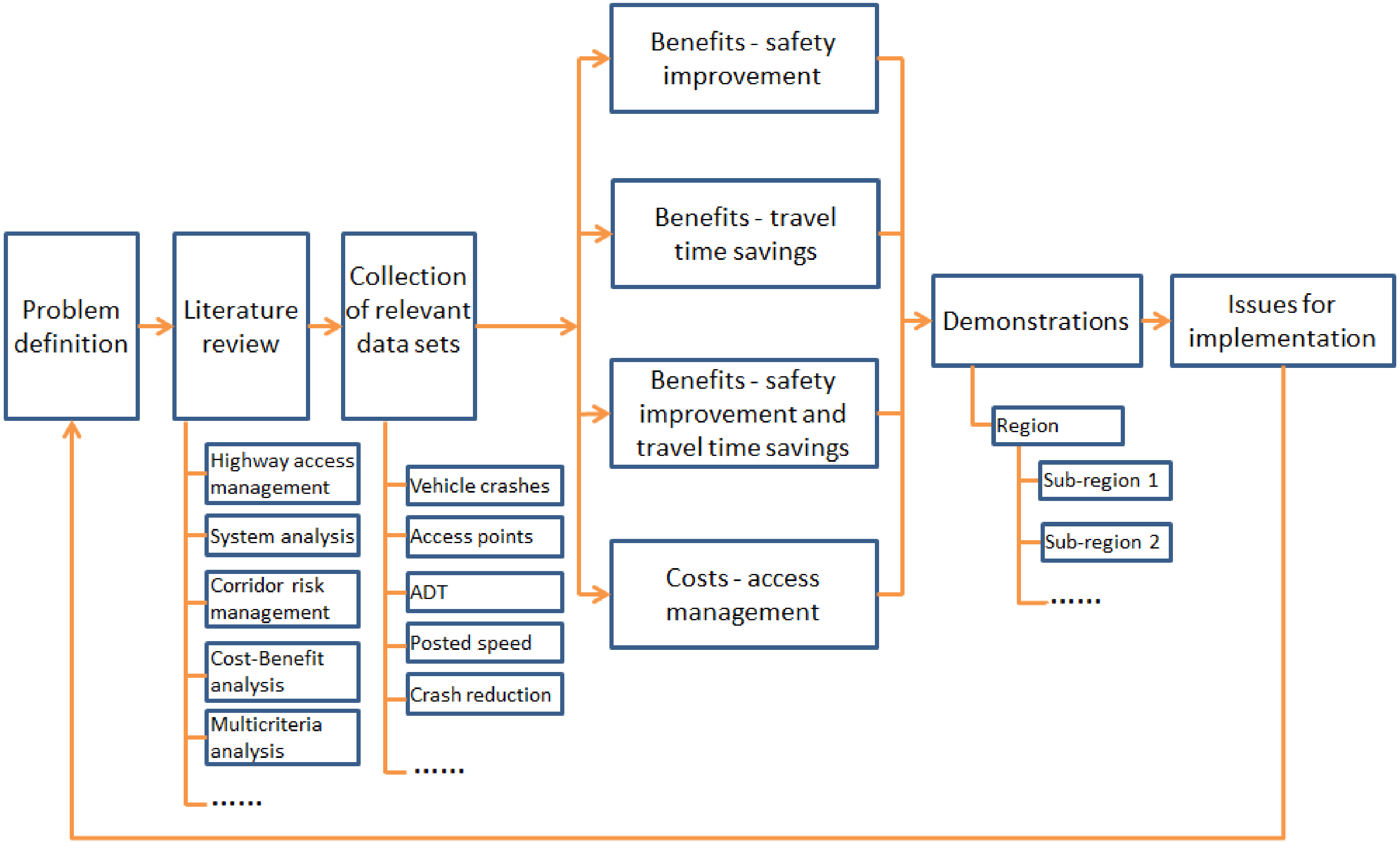

Figure 1. Technical approach of this dissertation to address heterogeneous data uncertainties in risk management of a multiscale transportation program

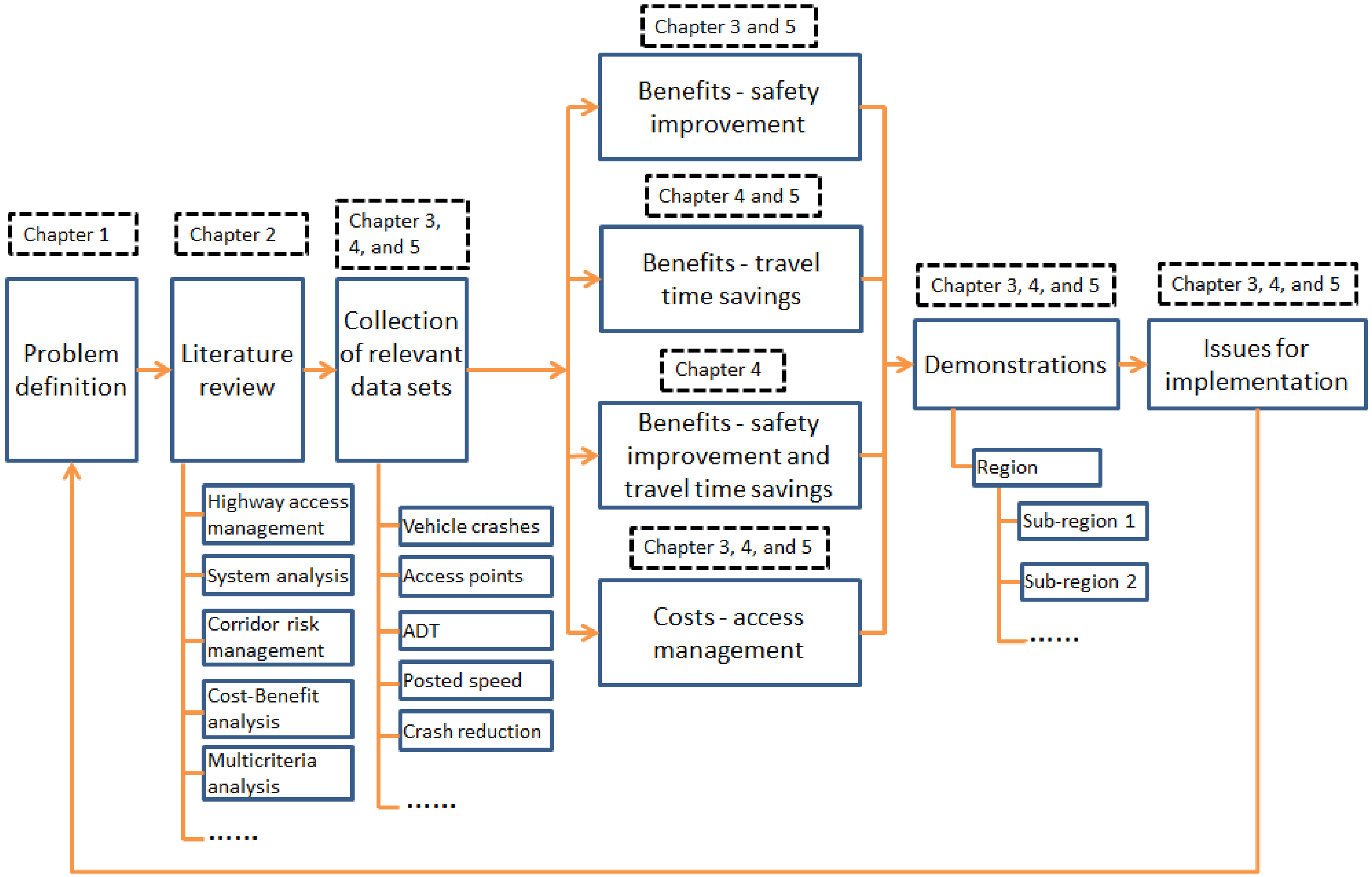

Figure 2. Technical approach of this dissertation to address heterogeneous data uncertainties in risk management of a multiscale transportation program, with particular Chapters identified

2 Background

2.1 Chapter overview

This chapter will describe literature and practice that support the need of access management programs, and the use of cost-benefit analysis, uncertainty analysis, and multicriteria decision analysis in similar contexts. There are particular needs and opportunities where access management can be assisted by an integration of systems and risk analysis, including multicriteria analysis and the quantification of benefits and costs, even with significant data and parameter uncertainties. The sections of this chapter are organized as follows: (i) Section 2.2 will describe literature related to practice and needs of transportation access management, (ii) Section 2.3 will describe literature related to corridor risk assessment and management, (iii) Section 2.4 will describe literature related to cost-benefit analysis for resource allocation, (iv) Section 2.5 will describe literature related to multicriteria decision analysis under uncertainties, and (v) Section 2.6 will provide a chapter summary.

2.2 Practice and needs of transportation access management

Access management is at the junction of land-use planning policies and traffic management and it provides a way to balance the trade-offs between land access and through-traffic mobility functions. The most important benefits of access management are to smooth the traffic movement, reduce crashes, fewer vehicle conflicts (U.S. FHWA 2003a). To insure that streets and highways operate safely and efficiently, the access to and from neighboring properties must be well managed. Schultz et al. (2010) investigate the relationship between numerous physical roadway characteristics and safety and identify several characteristics, including access density, are positively correlated with crash rates. Gluck et al. (1999) find that an increase from 10 to 20 access points per mile would increase crash rates by toughly 30 percent, and enumerate various access management techniques and their impacts. Too many access connections is a recipe for congestion on transportation network and the access management can help to relief congestion and maintain desired travel speed (Mark 2011). The HCM shows that the access points density besides other factors can reduce the free-flow speed and the typical reduction in free-flow speed is about 0.25 mile per hour per access point (U.S. National Research Council 2010). Also the travel time delay will results more fuel consumption and vehicle emissions.

Roadway access management is defined in the TRB 2003 *Access Management Manual* (U.S. National Research Council 2003) as follows: *The systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway. It also involves roadway design applications, such as median treatments and auxiliary lanes, and the appropriate spacing of traffic signals. The purpose of access management is to provide vehicular access to land development in a manner that preserves the safety and efficiency of the transportation system.* Based on studies of Williams and Levinson (2008), the formal development of access management begins around 1980 and during the last few decades, the concept of access management has gained broad acceptance and grown dramatically. About two thirds of the U.S. 50 states have a formal access management and remaining states manage the access informally in normal operations, and the access management among all states is conducted in multiple levels, such as drive-way permit level, corridor level, project level, and statewide level (Gluck and Lorenz 2010). The local and state government can use a set of access management techniques to control access to highways, major arterials, and other roadways, and then maintain a safe and efficient use of the transportation network. The typical access management techniques include: (i) access spacing, (ii) driveway spacing, (iii) sage turning lanes, (iv) median treatments, (v) right-of-way management, (vi) etc. (U.S. FHWA 2003a). Gluck and Lorenz (2010) summarize the state of practice with respect to highway access management, which can be found in NCHRP synthesis 404. In the synthesis, they examine how various agencies have acted on the access management program, what the obstacles to the action are, and how to improve the implementation of access management treatments and strategies. Marek (2011) describes that access management is a systemic control of transportation access pattern to integrate the planning and engineering control and land use decisions, provides vast information on access management techniques, together with information on how access management programs can be effectively developed and administered. Many U.S. States also have their own state-wide access management manual to set out standards for managing access to and from state roads and highways (Jones et al. 2014; MNDOT 2014; Maryland State Highway Administration 2014; Marek 2011; OHDOT 2001, etc.).

Access management projects are implemented by transportation agencies and the choice of techniques for a specific corridor segment is based on its geometry and traffic characteristics (U.S. FHWA 2003a). However, public agencies have limited resources for planning activities and typically cannot conduct locally specific access management modeling and data collection for all roadway segments of large-scale systems. To allocate resources and prioritize locations for access management investigations, transportation agencies will need to screen and benchmark needs across their large-scale highway transportation networks, possibly with simplified predictive models and with sparse data on local characteristics. Plazak and Souleyrette (2002) describe a process to identify high-priority corridors for access management near large urban areas in Iowa. They assign high priority to the routes based on a corridor ranking system that utilizes several different factors, including the proportion of access-related crashes, the crash rate, crash severity, etc. Schultz and Braley (2007) develop a prioritization method to select arterial road segments that would most benefit from access management. They find that the lack of access management, such as high access density, has a positive correlation with crash rates and apply decision trees to evaluate the needs for access management on a given roadway segment. Both the above effects primarily consider the needs or potential benefits of corridor access management to prioritize the locations while giving no or lesser attention to the costs of access management. Furthermore, previous efforts have only emphasized the safety benefits when prioritizing and screening access management projects, though travel-time savings is another principal benefit of an access management project (MNDOT 2013; TRB Transportation Economics Committee 2013). There is thus a gap in literature: how to determine whether the access management project is warranted based on both the benefits (including the consideration of safety, mobility, capacity, etc.) and costs, as transportation agencies want to increase objectivity and accountability for use of public funds.

2.3 Corridor risk assessment and management

The applicability of risk assessment and management methods to address transportation access management is an important consideration in this dissertation. It is helpful to understand the tradeoffs among costs, benefits, risks, and opportunities in order to support resource allocation for the protection of transportation and other infrastructure corridors.

Particular to corridor risk management, the transportation agencies and planners must address the multidimensional risks on various time horizons and geographic scales. Linthicum and Lambert (2010) demonstrate an approach to assess the relative risk of land development adjacent to infrastructure corridors and prioritize corridor sections for risk management by utilizing expert elicitation and geographic data. However, they only describe a single forecast method without any decision alternatives or resources allocation and fail to address multiple and diverse stakeholder interests. In order to study the infrastructure vulnerability and prioritization, Thekdi and Lambert (2012) describe a layering of risk models to identify and prioritize infrastructure components that are candidates for undergoing significant changes resulting from land development. Lambert et al. (2011) integrate several risk and reliability models to predict land development and suggest priorities for risk management. They suggest where to fund specific access management activities to minimize regret or excess cost. Lambert et al. (2012) describe several approaches to forecast land volatility and corridor development, understand how land development can influence transportation improvements, and prioritize the funding allocations to maximize the beneficial effects of land development.

In the domain of transportation access management, the risk assessment and management should anticipate the influence of land-use development on the highway access, and should support stakeholders and agencies to make effective and feasible decisions for preserving the functionality and accessibility of transportation network. Risk assessment methodology focuses on the three questions: what can go wrong, what are the likelihoods, and what are the consequences (Kaplan and Garrick 1981). *What can go wrong* addresses the safety and congestion concerns resulting from uncontrolled access on transportation corridors. *What are the likelihoods*, the primary focus of this dissertation, suggests a quantification of the needs and prioritizations of access management across the infrastructure corridor segments. *What are the consequences* refers to the costs and risks of traffic congestion, vehicle crashes, right of way acquisition, retrofits, rezoning, and others on the unmanaged transportation corridor. Risk management introduces three additional questions: what can be done, what are the trade-offs, and what are the impacts of current decisions to future options (Haimes 2009). *What can be done* refers to the implementation of the access management engineering designs, such as closing curbs and crossovers, adding parallel service roads, etc. *What are the trade-offs* addresses trade-offs among all cost, benefits, and risks. *What are the impacts* addresses the impacts of current decisions on access management in response to future conditions.

Risk is often defined as the measure of the probability and severity of adverse effects (Lowrance 1976). Recently, the ISO (2009) redefines the risk as the “effect of uncertainty on objectives”. In this definition, the “risk” is no longer “chance or probability of loss”, but “the effect of uncertainty on objectives”, thus cause the word “risk” to refer to positive possibilities as well as negative ones. Among many notable definitions of risk, Lambert (2013, 2012, and 2011) describes the risk as “the influence of scenarios on priorities”. Martinez et al. (2011) apply a multiple criteria decision analysis to prioritize investment portfolios in capacity expansion and energy security while principally studying the robustness of the prioritization to multiple uncertain and emergent scenarios. Lambert et al. (2012) address scenarios uncertainties of emergent conditions by formulating a scenario-informed multicriteria approach to prioritize major project investments for infrastructure development subject to deep and nonprobabilistic uncertainties. Karvetski and Lambert (2012) describe a framework for evaluating the deep uncertainties that most influence a priority-setting among investment in large-scale systems with a demonstration in reengineering of an energy system.

The priority setting of thousands of access management projects under different scenarios is investigated in this dissertation, since decision makers in public sector must allocate scarce resources and prioritize the access management projects in a strategic way. The effect of various scenarios, such as multidimensional perspectives, diverse parameter of benefits and costs, multiple private and public stakeholders, etc., on priority setting among investment and the future needs for access management in multiscale systems with thousands of unequal length corridor sections is demonstrated via a risk-cost-benefit analysis.

2.4 Cost-benefit analysis for resource allocation

Cost-benefit analysis can help project managers to allocate resources for further investigation through modeling, data collection, and expert elicitation. Cost-benefit analysis considers and estimates the equivalent monetary value of the benefits and costs of the projects to establish whether they are worthwhile. It has been widely used to evaluate and select among competing projects in economic terms when an agency is operating under budget constraints. Cost-benefit analysis and project selection are described by Stokey and Zeckhauser (1978) and Adler and Posner (2001). Farrow (2004) addresses cost-benefit analysis and decision making with uncertainties. Hokstad and Steiro (2006) integrate cost-benefit analysis with risk management, where the benefits are in terms of risk reduction. Merrifield (1997) discusses sensitivity analysis for cost-benefit analysis.

Particularly in highway decision making, cost-benefit analysis attempts to capture all benefits and costs accruing to society from a project or course of action, regardless of which particular party realizes the benefits or costs, or the form these benefits and costs take (U.S. FHWA 2013a). Cost-benefit analysis which considers the benefits and costs that would be influenced by a potential improvement to the current status of a transportation facility is comprehensive in scope, and it has a social perspective and focuses on monetary terms (Turnbull 2010). Agencies can use cost-benefit analysis to determine whether a project should be undertaken and what project portfolios among many competing projects should be further investigated or selected given a limited budget (U.S. FHWA 2013a). The typical costs considered in the transportation cost-benefit analysis include preliminary engineering cost, the right-of-way acquisition cost, the construction cost, and preservation and maintenance cost, while the typical benefits considered are reducing crashes, saving travel time, relieving congestion, lowering vehicle operating costs, etc. (U.S. FHWA 2013a). By using the cost-benefit analysis properly, decision makers can make efficient investment and maximize the net benefits to the public from a strategic allocation of resources. To support a comprehensive transportation policy and planning, Litman (2009) conducts a detailed study and analysis of transportation benefits and costs, and uses the best available data to develop estimates of the full costs and benefits of various forms of transport. Li and Madanu (2009) assess the impacts of risk and uncertainty in project level life-cycle benefits and costs analysis and create one stochastic optimization model for project selection in highway investment decision-making. Madanu et al. (2010) introduce an approach for project-level cost-benefit analysis of a highway intersection hardware improvement. Szimba and

Rothengatter (2012) integrate the interdependence among projects in cost-benefit analysis to select and prioritize the infrastructure projects of an investment package. However, previous studies have not succeeded in a cost-benefit analysis for highway access management projects' selection and prioritization.

On the other hand, the cost-benefit analysis fundamentally aims to discover which projects offer the best value in monetary term, though there are still some concerns and discussion about the practical cost-benefit analysis in the transportation decision making as follows: (i) what should be included in both the costs and benefits side of the analysis? and (ii) how important of the cost-benefit analysis results compared to other criteria in the decision making process? , since the value of money is only partial criterion for decision making (ITF 2011)

2.5 Multicriteria decision analysis under uncertainties

Multicriteria decision analysis (MCDA) is a philosophy to support decision making with multiple objectives or criteria in complex problems. The theoretical foundation of MCDA can be traced back to multiattribute utility theory (Keeney and Raiffa 1993) and axiom of utility measurement (von Neumann 2007), since MCDA essentially is a set of utility measurement techniques. As a result of rapid development of operations research in WW2, MCDA is used in military planning (Eckenrode 1965), and the use of MCDA to support the public and private decision making are growing quickly in numerous research and fields, such as the decision making in economics, environment, infrastructure, transportation, public policy, etc. Many review papers on the use of MCDA have been published in various applications. Romero and Rehman (1987) review 150 MCDA applications in fisheries, forestry, water, and land resources. Hayashi (2000) studies the application of MCDA in agricultural resource management from over 80 publications. Pohekar and Ramachandran (2004) present more than 90 published MCDA papers and analyze the application of various methods in sustainable energy management. Steuer and Na (2003) compile and classify 265 references of MCDA utilized to solve problems and issues in financial decision making. Kabir et al. (2013) examine and categorize about 300 published papers that report MCDA applications in infrastructure management. Agarwal et al. (2011) review about 68 research articles of MCDA techniques used for supplier evaluation and selection process.

Many literatures have proved that the MCDA is effective to support transportation and infrastructure planning and decision making, because practically the policy can barely be guided by a single objective. Zak (2011) demonstrates the application of MCDA in the public transportation and solves different decision problems in the mass transit systems. Liang and Pensomboon (2010) use MCDA approaches to aid the decisions for managing the highway slop hazard. Khademi and Sheikholeslami (2009) use the MCDA to prioritize the low-class roads for maintenance. Lambert et al. (2012) integrate the MCDA with scenario planning methods to prioritize major project investments for infrastructure development. Lambert et al. (2013) demonstrate a scenario-based MCDA framework that can assist decision makers in allocating resources to adapt transportation assets under the influence of climate change. Lu and Tolliver (2013) illustrate that the MCDA model can help the pavement management agencies to make a network-level pavement preservation planning.

However, decision making is not typically crystal clear, since many real systems have uncertainty in their nature. Zimmermann (2000) proposes a broad definition of uncertainty as: *Uncertainty implies that in a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behavior or other characteristics.* There exist two kinds of uncertainties associated with MCDA (Figueira et al. 2005): (i) internal uncertainty, which is related to decision maker's values on judgment; and (ii) external uncertainty, which is related to imperfect knowledge concerning consequence of actions. The consideration and model of uncertainties, including quantitative and qualitative, is especially critical and necessary in the decision processes. Songa et al. (2014) study the uncertainty and availability of decision weights and develop probability scoring method to solve MCDA involved multiple decision makers. Mosadeghi et al. (2013) review and explore how uncertainty analysis in the framework of MCDA can address environmental decision problems. van der Pas et al. (2010) perform MCDA in the situation of deep uncertainties to support decision making for transportation safety improvement. Karvetski et al. (2011) integrate the scenario and MCDA analysis to deal with deep uncertainties to prioritize the investments for military and industrial installations. Jeon (2010) demonstrate an incorporation of uncertainties and MCDA for choosing the most desirable alternatives in the transportation decision making.

Over the last decade, MCDA under uncertainties and cost-benefit analysis are integrated as the tool to support strategic planning. Lambert and Turley (2005) introduce a method for the allocation of localized hazard elimination funds based on multicriteria analysis and cost-benefit analysis under uncertainty by expressing the potential risk reduction (benefits) in monetary units. They illustrate how a cost-benefit analysis can be conducted for roadway lighting without knowing the precise values of parameters, which have influence on the assessment of costs and benefits. They demonstrate and apply the method, suggesting which roadway sections warrant additional lighting by quantifying the benefits and costs with interval analysis of parameter uncertainties. Lambert and Farrington (2007) apply a similar method to allocate security sensors for air contaminants. They investigate various functional forms of benefit-to-cost ratio and interpret the results via examples. Rogerson et al. (2013) apply a similar method to a runway safety program by considering several stakeholder or expert perspectives. They suggest for each of the stakeholder perspectives which of the airports should receive trainings, retrofits, or other interventions in the near term.

For the new application of evaluating and guiding an access management program, in this dissertation the cost-benefit analysis with uncertainties within the framework of multi-criteria decision analysis is used to support decision making and construct strategic plan from multiple perspectives.

2.6 Chapter summary

This chapter made a foundation for the technical parts of coming chapters by describing certain literature related to the modeling and analysis for the risk-cost-benefits of access management in the transportation engineering. Section 2.1 provided a chapter overview. Section 2.2 described literature related to the practice of access management. Section 2.3 described literature related corridor risk assessment and management. Section 2.4 described literature related to cost-benefit analysis for resources allocation. Section 2.5 described literature related to the multicriteria decision analysis with uncertainties.

3 Method phase one: Safety improvement

3.1 Chapter overview

This chapter will develop a method of identifying and prioritizing corridor sections most needing further access management investment with a focus on transportation safety. A quantitative framework will be described by introducing several assessment metrics and applying multicriteria analysis and cost-benefit analysis with parameter uncertainties. The sections of this chapter are organized as follows: (i) Section 3.2 will provide an introduction to the problem, (ii) Section 3.3 will describe the technical approach of quantification of uncertain benefits and costs, and the benefits-to-costs ratio, and compile a prioritization framework, (iii) Section 3.4 will demonstrate general methodology in more detail on a multiscale large transportation system, (iv) Section 3.5 will provide a discussion of results, and (v) Section 3.6 will provide a chapter summary. The major contributions of this chapter is to invent suitable metrics for highway access management risk-cost-benefit analysis from safety improvement perspective and a visualized multicriteria tool that enables decision makers to effectively prioritize investments along the transportation corridors.

3.2 Introduction

The efforts in this chapter develop how cost-benefit analysis with uncertain parameters can support resource allocation to safety projects or investigations in planning for access management. For the new application of evaluating and guiding an access management program, this chapter adopts general methods of Lambert and Farrington (2007, 2006) and Lambert and Turley (2005) to study alternative cost-benefit functional forms for the access management needing prioritization. The succinct purpose of this chapter is as follows: the developed approach demonstrates how the selection of high priority roadway segments for access management programs that are focused on road safety can be assisted by multicriteria analysis and the quantification of safety benefits and costs, and the resulting benefit-to-cost (B/C) ratio, in an interval analysis of the underlying parameter uncertainties.

In this chapter, access management projects with uncertainties of parameters of benefits and costs are prioritized with a combination of multicriteria analysis and cost-benefit analysis, and the form and parameters of the benefit-to-cost ratio for corridor access management are depicted. First, new metrics of crash opportunity and crash intensity as crashes per 10 million crash opportunities are introduced. Second, the parameters of the benefit-to-cost ratio and a simplified model for quantification of benefits and costs of access management are introduced. Third, the benefit-to-cost ratio in the context of a multicriteria analysis is evaluated. Last, three zones of priority - accepted, marginal, and rejected - in an x-y scatter plot of potential project locations based on the upper and lower bounds of uncertain exogenous parameters are defined. The projects located in the accepted zone have benefit-to-cost ratios greater than one. The projects located in the rejected zone have benefit-to-cost ratios that are less than one. The projects located in the marginal zone have an indeterminate inequality of benefits and costs and relative to other projects would benefit from further modeling, elicitation, and/or data collection that lead to additional precision (i.e., smaller uncertainty intervals of the underlying parameter values). Further details regarding this effort are described by Xu et al. (2014).

Priority setting recognizes that agencies are unable to analyze and develop access management options for all corridor segments because of limited resources for planning. With this method, planning agencies are supported in evaluation and selection of high priority corridor segments. The analysis will help to prioritize and screen among thousands of corridor segments for further operations/design investigation and more relevant data collection. This section thus identifies key principles, metrics, and decision and information needs that will be required, immediately followed by a practical example application to a 6,000 miles transportation network.

3.3 Quantitative metrics and approach

3.3.1 Quantifications of benefits

This section introduces a metric of crash intensity and crash reduction amenable to monetizing the potential needs and benefits of access management. The crash intensity measures the likelihood of crash per unit of exposed vehicles. The exposure measures the amount of vehicles that are subjected to that crash intensity. In many transportation literatures, the exposure is always in terms of the average daily traffic (ADT) and the crash rate, which is commonly used to evaluate the safety condition of roads and intersections, is defined as crashes per million vehicles travelled, whose calculation is relied on the information of traffic volume, the amount of crashes, and the length of corresponding roadway segment.

Although ADT is used in this chapter to measure the traffic exposure as in other places, a key interest in current research is to systematize the access policy for corridors and find a way of relating an access point inventory to the vehicular crashes. Each access point brings added potential for crashes and unmanaged access points along corridors will create more conflict points which increase the potential for crashes (U.S. FHWA, 2003a; Levinson and Gluck, 1997). The *crash opportunity* is defined to be the product of the average daily traffic and the number of access points associated with the corridor segment as follows:

$$\begin{aligned} &Crash\ Opportunity = \\ &Average\ Daily\ Traffic\ (ADT) \times Numbers \end{aligned} \tag{1}$$

The current *crash intensity* for the corridor segment expressed as crashes at access points per 10 million crash opportunities as follows:

$$
\begin{aligned}
&\textit{Access Related Crash Intensity} \\
&= \frac{\textit{Number of Crashes at Access Points per Year} \times 10^{7}}{365 \times \textit{Crash Opportunity}} \\
&= \frac{\textit{Number of Crashes at Access Points per Year} \times 10^{7}}{365 \times ADT \times \textit{Number of Access Points}}
\end{aligned} \tag{2}
$$

A crash reduction factor is used in a simplified model to estimate the potential benefits that would be influenced by access management on the highway corridor. U.S. FHWA (2013) defines the crash reduction factor as the percentage crash reduction that might be expected after implementing a given countermeasure at a specific site. The details of the crash reduction factor are described by NYSDOT (2013), Kinney (2009), MIDOT (2009), Bahar et al. (2007), Harkey (2005), and others. In the subsequent equation, the calculation of benefits focuses on safety improvement, and a crash reduction factor is used to quantify the percentage of crashes potentially avoided after implementing a typical access management. A range of values will be used to represent the variation of the estimates of the reduction factor for the typical region and its sub-regions. The benefits of access management then take the following form:

$$
\begin{aligned}
&\textit{Benefits} \\
&= \textit{Access Related Crash Intensity} \times \textit{Exposure} \\
&\quad \times \textit{Average Cost per Crash} \times \textit{Crash Reduction Factor} \\
&= \textit{Potential Crash Cost Avoided} (\$) / \textit{Access Point} / \textit{Year} = 365 \times I \times T \times \beta \times \Delta
\end{aligned} \tag{3}
$$

where *I, T, β, and Δ* described in Table 1. The crash intensity, traffic volume, and number of access points are characteristics of particular corridor sections, whereas the average cost per crash and crash reduction factor are typical of large regions rather than unique to a corridor section, as described in the next section.

3.3.2 Quantifications of costs

In this subsection, a simplified model of typical costs of access management projects is described. Access management programs are usually implemented by transportation agencies who are always seeking a cost-effective alternative. Typically, a project selection cannot be based solely on the lowest initial costs but should also account all the future costs over the project's usable life, which is the primary function of life-cycle cost analysis suggested by U.S. FHWA (2003b). Particular to transportation access management, there are numerous costs associated with life-cycle costs as other transportation engineering projects, and these costs usually fall into the following categories: preliminary engineering cost, the right-of-way acquisition cost, the construction cost, and preservation and maintenance cost. The preliminary engineering cost, which is the early stage to analyze and design work to produce construction plans, specifications, and cost estimates, includes the cost to prepare the construction documents (U.S. FHWA 2007). Preliminary engineering includes "planning to minimize the physical, social, and human environmental impacts of projects and engineering design to deliver the best alternative" (Liu et al. 2011). Preliminary engineering requires an assessment of specific design features to determine physical boundaries of the road project. The establishment of the physical footprint of a roadway facilitates the acquisition of right of way, including easements (U.S. FHWA 2007), and the cost highly depends on the location of the project. Early acquisition can result in significant cost savings and protect the right of way from development. It can be costly and time consuming to acquire right of way (Heiner and Kockelman 2005). The cost of physically implementing the project, including labor, materials, equipment, etc., is called the construction cost (U.S. FHWA 2007). The average prices of constituent items and the design characteristics of the project influence the construction cost, which tends to be the majority of the project costs. After construction, the project has maintenance costs, operations costs, and other costs to ensure its function, and these costs are called preservation and maintenance cost (FDOT 2010; King 2006). Table 2 describes each parameter of access management costs with its corresponding units.

$$C_{Total} = C_{PE} + C_{RW} + C_{CN} + C_{PM} \tag{4}$$

In this dissertation, simplifying assumptions are made that (i) these typical costs are changing linearly with the number of access points of a corridor segment and (ii) all these costs can be summed up as one term as the total costs. Estimation of preliminary engineering costs, right-of-way acquisition costs, construction costs, and preservation and maintenance costs for transportation projects is described by Liu *et al.* (2011), Zhou *et al.* (2008), U.S. FHWA (2007), Sullivan and Burris (2006), Heiner and Kockelman (2005), FDOT (1990), etc.

Table 1. Parameters for quantification of the safety benefits influenced by corridor access management

Parameter	Parameter Description	Units
I	Access related crash intensity	Crashes per 10 million crash opportunities
T	ADT	Vehicles per day
N	Number of access points	Access points
β	Average cost per crash avoided	$ per crash avoided
Δ	Crash reduction factor	Crashes avoided/current crashes

Table 2. Parameters for quantification of typical annualized costs of corridor access management

Parameter	**Parameter Description**	**Units**
C_{PE}	Preliminary engineering cost	$ per access point per year
C_{RW}	Right-of-way acquisition cost	$ per access point per year
C_{CN}	Construction cost	$ per access point per year
$C_{\mathbf{PM}}$	preservation and maintenance cost	$ per access point per year
C_{Total}	Total project cost	$ per access point per year

3.3.3 Cost-benefit analysis with uncertainties for safety improvement

This section introduces the simplified model of the benefit-to-cost ratio of typical access management projects. The purpose of this subsection is to apply the cost-benefit analysis together with a multicriteria scatter diagram to aid stakeholders to screen and prioritize the needs for further investigations of access management. A benefit-to-cost ratio is defined to be the ratio of the expected costs of vehicular crashes avoided per access point per year, as influenced by implementing typical access management techniques, to the annualized costs of projects per access point as follows:

$$\Psi_S = \frac{Benefits}{Costs} = \frac{365 \times I \times T \times \beta \times \Delta}{10^7 \times \left(C_{PE} + C_{RW} + C_{CN} + C_{PM}\right)} = \frac{365 \times I \times T \times \beta \times \Delta}{10^7 \times C_{Total}}$$
$$= \frac{Potential\ Crash\ Avoided\ (\$) / Access\ Points / Year}{Costs(\$) / Access\ Points / Year} \tag{5}$$

The benefit-to-cost ratio, Ψ_S, is the ratio of the monetary benefits to the monetary costs specifically designed for safety improvement, and the B/C ratio has been discussed in previous sections. A dimensional analysis of the benefit-to-cost ratio is provided as follows:

$$\psi_S = \frac{\left(\frac{Day}{Year}\right)\overbrace{\left(\frac{(10^7)\left(\frac{Current\ Crashes}{Year}\right)}{\left(\frac{Day}{Year}\right)\left(\frac{Vehicle}{Day}\right)(Access\ Point)}\right)}^{Crash\ Intensity}\overbrace{\left(\frac{Vehicle}{Day}\right)}^{Exposure}\overbrace{\left(\frac{Dollar}{Crashes\ Avoided}\right)}^{Avereage\ Cost\ per\ Crash}\overbrace{\left(\frac{Crashes\ Avoided}{Current\ Crashes}\right)}^{Crash\ Reduction\ Factor}}{(10^7)\underbrace{\left(\frac{Dollar}{(Access\ Point)(Year)}\right)}_{Costs\ of\ Access\ Management\ \mathrm{Pr}oject}} \tag{6}$$

The parameters β, Δ, and C_{Total} are assigned interval ranges to represent the knowledge uncertainties. In application, the literature sources and other reasonable initial estimates of the parameters (e.g., GDOT 2012; Liu et al. 2011; Madanu et al. 2010; U.S. FHWA 2007; Kirk et al. 2006; Lambert and Joshi 2006; Heiner and Kockelman 2005; FDOT 1990) are presented to highway officials of the region and sub-regions. The officials are provided opportunity to adjust the parameter upper and lower bounds to more nearly correspond with their experience particular to the region and its sub-regions. The resulting values, which derive from increased sharing of experience and knowledge, represent real-world differences in parameter bounds from region to sub-region to sub-region.

The benefit-to-cost ratio thus can be evaluated taking into account upper and lower estimates for each exogenous parameter (i.e., parameters other than T and I). An interval analysis of B/C ratio incorporated to a multicriteria evaluation of an access management program will be described on a Cartesian graph of two coordinate axes as follows. The exposure in terms of ADT is the horizontal axis of the graph, whereas the access-related crash intensity in terms of crashes at access points per 10 million crash opportunities is the vertical axis of the graph. The extreme values of each parameter other than ADT and crash intensity are used for interval calculation to generate two contours of benefit-to-cost ratio, which separate three zones in the scatterplot of the sections by vehicular exposure and current crash intensity. Because the B/C ratio is an increasing function of ADT and crash intensity, the warranted zone is above the upper contour, where the benefit-to-cost ratio exceeds one for all possible values of the uncertain parameters, the marginal zone is between the upper and lower contours, where the benefit-to-cost ratio exceeds one for some possible values of the exogenous parameters, and the unwarranted zone is below the lower contour, where the benefit-to-cost ratio does not exceed one for any possible values of exogenous parameters. If crash reduction is the major concern for access management, the corridor segments located in the warranted zone should be investigated first, the segments located in the marginal zone should be investigated second, and the segments in located in the unwarranted zone should be investigated last. The locations of upper and lower contours depend on the interval ranges of the uncertain parameters and the equation for the benefit-to-cost ratio. Adjustment of the interval ranges of parameters, which reflects the regional or sub-regional particularities, results in the shifting of these three zones. The described analysis can thus proceed without precise values of exogenous parameters and can help decision makers to prioritize needs. Policy for access management programs could focus, for example, on warranted projects, on both warranted and marginal projects, on projects of high crash intensity, on projects of high traffic exposure, and/or a combination of the above factors with other factors. The approach discussed, to be demonstrated in examples forthcoming, has the merit to bring appropriately simplified performance metrics and available objective evidence to inform the allocation of limited program resources for access management across a large scale system.

3.4 Case study on a multiscale transportation system

This section applies the above approach to an example of prioritizing needs for future investigations on corridor sections and access points that are most potentially justified by uncertain benefits and costs, with a focus on safety improvement. The access management projects screening and selecting are performed on multimodal corridors constituting a multiscale transportation network. The thousands of corridor segments with varying length with an average length of 1.4 miles were selected for prioritization for an entire region and its sub-regions. Highway corridor segments are categorized and prioritized based on important characteristics of their locations, such as rural area or urban, because the characteristics of segments in urban and rural area are significantly different, and the estimations of typical access management benefits and costs are adjusted according to the urban or rural locations of corridor segments. The approach can be easily duplicated when more detailed classification, e.g., functional classification, is needed.

The SMS, which is a 6,000 miles multimodal network, includes the highway system, critical evaluation routes, and primary routes across many localities. In the following, the example will avoid considering the interstate freeways and expressways with total length of 1,500 miles, as generally the access management techniques are not applicable to these roadway segments, whose access is strictly controlled by federal and state agencies. Diverse agency sources of quantitative and qualitative data and information are used, including roadmaps and traffic crash databases from Virginia Department of Transportation, an access points database generated specifically for this purpose from Center for Risk Management of Engineering Systems, University of Virginia (the detailed instructions for creating the inventory of access points are provided in Appendix B, and the method can be implemented for many other infrastructure networks in diverse regions.), and TIGER/line shapefiles from U.S. Census Bureau. The number of access points, the number of access-related crashes (the detailed instructions for creating the inventory of access-related crashes are provided in Appendix C, which is a repeatable process.), and the ADT for each analysis segment on the system in 2008 are collected. These data are processed to obtain the access-related crash intensity and exposure for each corridor segment. The interval ranges of the underlying parameters are assessed with the help of the engineers and planners of the regions under investigation.

3.4.1 Entire region

First, a regional database of the entire 4,500 mile corridor network is addressed. Table 3 summarizes the basic information of the network. 3,176 segments in the network belong to rural and urban areas in this regional transportation network (excluding freeways and expressways) with an average segment length of 1.4 miles. Each segment has a characterizing ADT as well.

Table 4 gives the intervals of exogenous parameters values that were set in consultation with experts and stakeholders from regional transportation agencies and were calibrated with literatures and previous studies. For example, an expert elicitation has suggested that potential costs of access management per access point per year is typically between $15,000 and $40,000 in rural areas, while that cost is typically between $40,000 and $60,000 in urban areas.

It is important to identify the segments that are most justified by cost-benefit analysis and by considering the performance metrics. As described previously, the intervals of exogenous parameters are used to generate two contours that partition the crash intensity to traffic-volume plot into the three priority zones. Figure 3 and Figure 4 provide a visualization of the cost-benefit analysis and multicriteria analysis for rural and urban corridor segments, respectively. Recall that the segments plotted below the lower contour are candidates whose benefit-to-cost ratio cannot exceed 1 for any possible value of exogenous parameters; the segments plotted above the upper contour are candidates whose benefit-to-cost ratios always exceed one for all possible values of exogenous parameters. The segments plotted between upper and lower contours are candidates whose benefit-to-cost ratios exceed 1 for some possible values of exogenous parameters. When screening and selecting the access management projects, the segments falling above the upper contour might be considered first, the segments falling between the upper and lower contours next, and the segments falling below the lower contour last. If information needs (reduction of uncertainties) were foremost for the stakeholders, those segments between the two contours might be investigated first.

Because the values and uncertainty levels differ between the rural and urban corridors, the contours and three decision zones in Figure 3 and Figure 4 are different. The counts and total length (miles) of all corridor segments falling in three decision zones are listed in Table 5. Figure 5 displays system diagram for access management project prioritization. The segments in wide hexagon line are corresponding to those located above the upper contour in the intensity and exposure plot. The segments in wide solid line are corresponding to those located between the upper and lower contours in the intensity and exposure plot. The segments in thin solid line are corresponding to those located below the lower contour in the intensity and exposure plot. The corridor segments in thin dashed line belong to freeways/expressways, and they are not included in the selection pool.

With the preceding analysis, 31 segments with a total length of 24.6 miles in the rural area and 30 segments with a total length of 15.6 miles in the urban area should draw attention and be considered first for allocating access management projects for safety improvement. In the rural area, 86% of the total length of corridor segments in the rural area and 49% of the total length of corridor segments in the urban area falling below the lower contour. These segments should be considered last, because for them, the typical access management project would be too costly relative to the potential benefits.

Table 3. Basic statistics of a 4,500 miles network of transportation corridors (excluding freeways/expressways)

	Number of segments	Total length of segments (miles)	Average length of segments (miles)
Rural	2,194	3738.7	1.7
Urban	982	578.8	0.6
Total	3,176	4317.4	1.4

Table 4. Cost-benefit function parameter bounds for access management project prioritization in a regional network of transportation corridors

Parameter	Unit	Rural		Urban	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
β	\$/crash avoided	45,000	75,000	55,000	75,000
Δ	crashes avoided/current crashes	25%	40%	15%	35%
C_{Total}	\$/access point/year	15,000	40,000	40,000	60,000

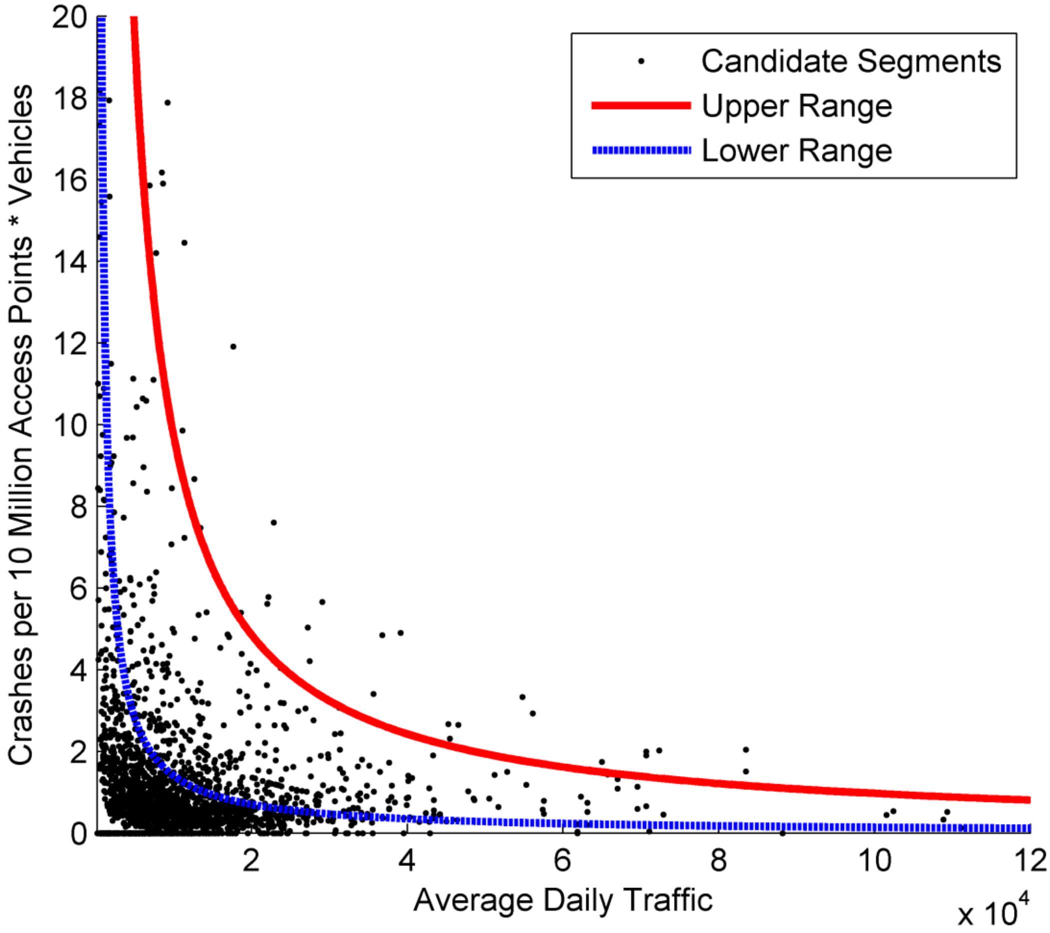

Figure 3. Example of the priority setting for a regional network of transportation corridors to contrast access-related crash intensity and traffic exposure (*rural* corridor segments)

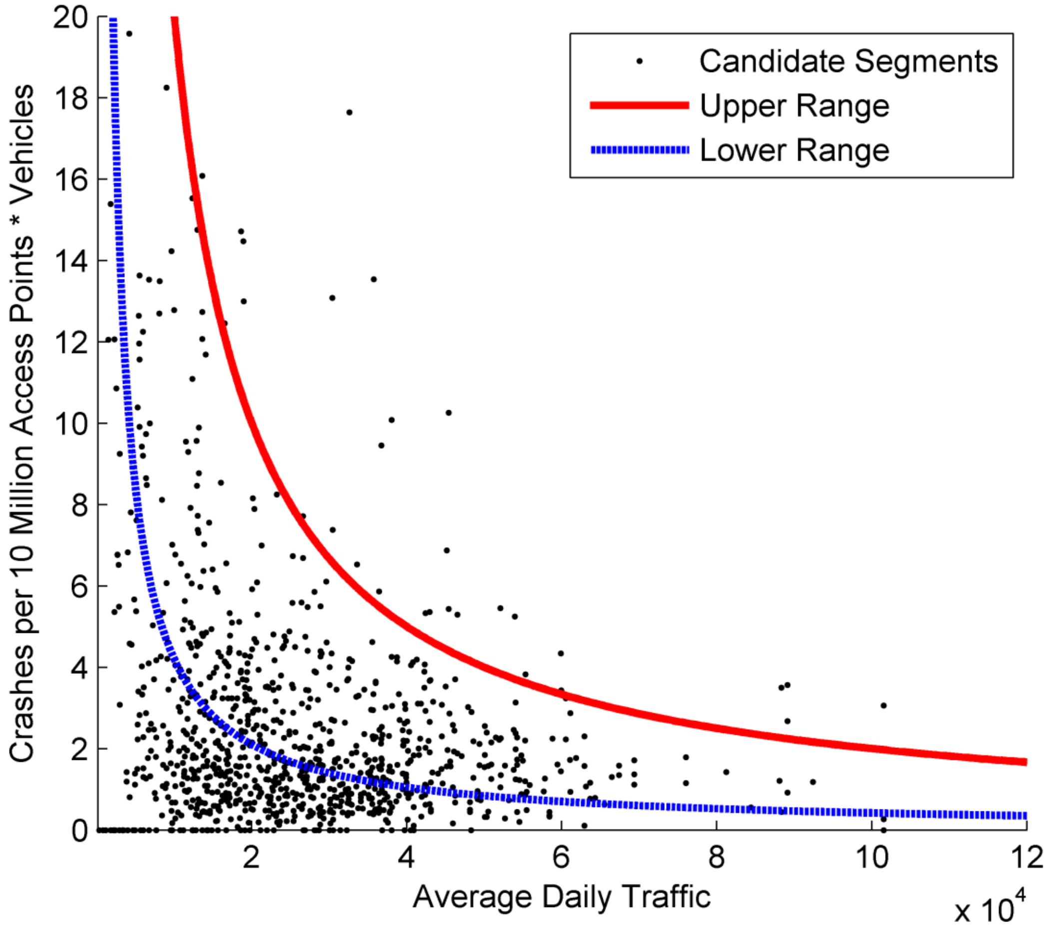

Figure 4. Example of the priority setting for a regional network of transportation corridors to contrast access-related crash intensity and traffic exposure (*urban* corridor segments)

Table 5. Number and total length (miles) of corridor segments in a regional network of corridors

Prioritization	**Rural**		**Urban**	
	Number of Segments	Total Length of Segments	Number of Segments	Total length of Segments
B/C > 1	31	24.6	30	15.6
B/C > 1 or B/C < 1	465	517.0	445	280.5
B/C < 1	1698	3197.1	507	282.6

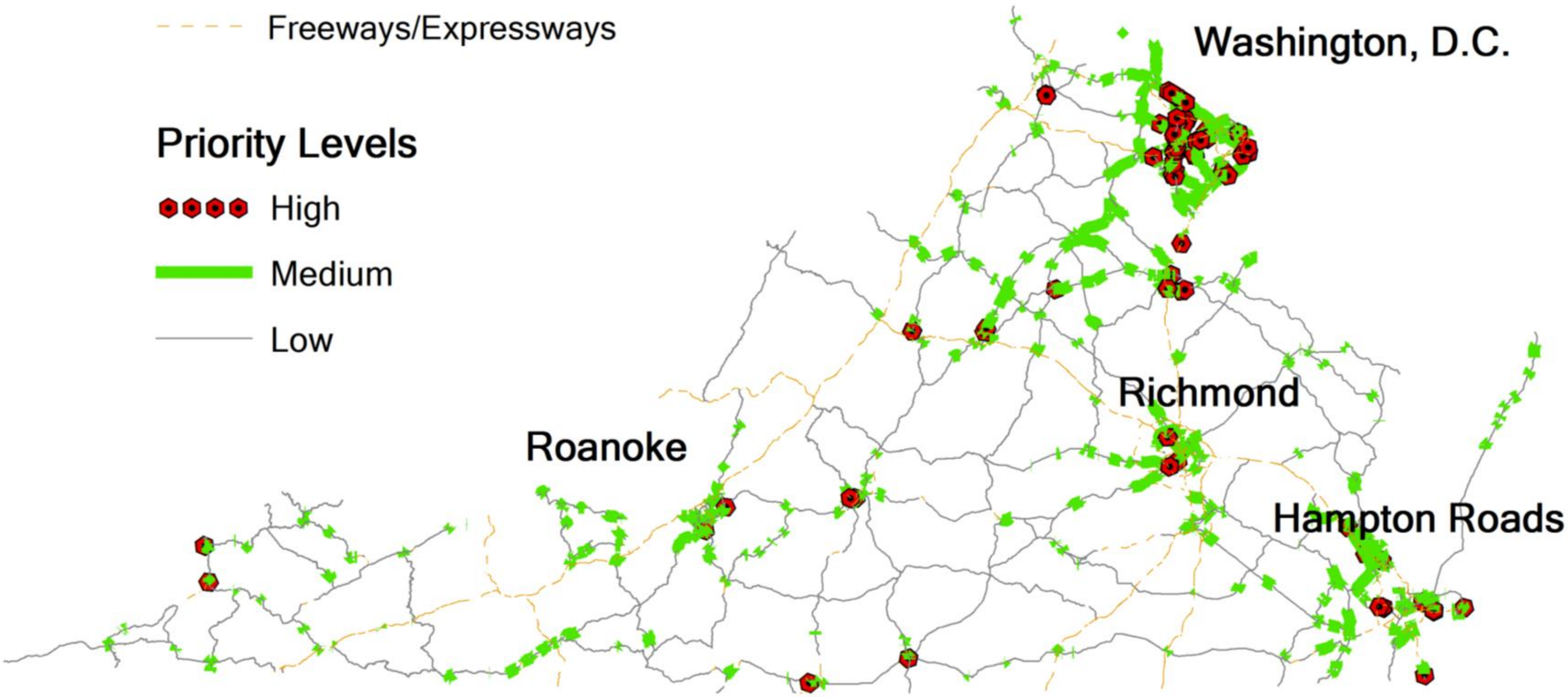

Figure 5. A 6,000 miles regional network of transportation corridors needing a policy for access management

3.4.2 Sub-regions

In addition to the study of the entire region transportation network, similar prioritization methods are applied to Virginia SMS corridor segments in Hampton Roads (Sub-region 1) and Richmond Planning Districts (Sub-region 2) and found policies of access management for them. Tables 6 and 7 provide several overview statistics of transportation corridors in the two sub-regions.

Tables 8 and 9 give the intervals of value of the parameters for Sub-regions 1 and 2, respectively. The stakeholders and experts are allowed different views on values and uncertainties of exogenous parameters among different planning districts because the estimation of benefits and costs of projects varies from region to region. For example, for the crash reduction factor, the stakeholders or experts describe that the percentage of crashes to be avoided by way of implementing the access management will range from 30% to 45% for corridor segments in rural areas in Sub-region 1, whereas they do not expect a high reduction factor in Sub-region 2, with an interval of 25% to 35%. The cost-benefit analyses for sub-region 1 and sub-region 2 in the urban area and the rural area are described in Figs. 6-9. Tables 10 and 11 give the number and total length (in miles) of corridor segments falling in three decision zones for Sub-regions 1 and 2.

For access management in the rural areas of Sub-region 1, eight segments with a total length of 4.6 miles should receive the investigative resources first, whereas 116 segments with total length 179.1 miles should be addressed last, because these projects are too costly relative to the potential benefits. By comparing crash-intensity and traffic-exposure scatter plots, it is clear that the parameter values and levels of uncertainties have significant impacts on screening and selecting projects. A higher value for parameter C_{Total} and a lower value for the parameter β would likely result in a fewer number of segments falling above the upper contour. Figures 10 and 11 provide maps for the results from these two sub-regions for the prioritization of future access management investigations, including locality specific modeling, expert elicitation, and data collection.

Table 12 provides a sample of the qualitative results of this approach. The table describes the corridor segments with various levels of priority, the uncertainties of the parameters, the upper and lower contours on a plot of crash intensity (crashes per crash opportunity) and exposure (ADT), and the benefit-to-cost ratio. Only a few corridor segments have high priorities, which suggests the immediate focus of a resource allocation strategy. The degrees of the uncertainties are reflected as the interval ranges of parameters that influence benefits and costs. The larger intervals imply greater uncertainties. The positions of the upper and lower contours on the crash-intensity and exposure plot depend on the extreme values of the intervals.

Table 6. Statistics of the network of corridors in the *Sub-region 1*

	Number of segments	Total Length (miles)	Average length (miles)
Rural	171	225.4	1.3
Urban	254	151.4	0.6
Total	425	376.8	0.9

Table 7. Statistics of the network of corridors in the *Sub-region 2*

	Number of segments	Total Length (miles)	Average length (miles)
Rural	83	121.9	1.5
Urban	109	70.9	0.7
Total	192	192.8	1.0

Table 8. Cost-benefit function parameter bounds for access management prioritization in *Sub-region 1*

Parameter	**Units**	**Rural**		**Urban**	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
β	$/crash avoided	40,000	65,000	55,000	70,000
Δ	crashes avoided/current crashes	30%	45%	20%	35%
C_{total}	$/access point/year	20,000	35,000	35,000	50,000

Table 9. Cost-benefit function parameter bounds for access management prioritization in *Sub-region 2*

Parameter	**Units**	**Rural**		**Urban**	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
β	$/crash avoided	50,000	70,000	60,000	70,000
Δ	crashes avoided/current crashes	25%	35%	20%	30%
C_{total}	$/access point/year	15,000	25,000	50,000	60,000

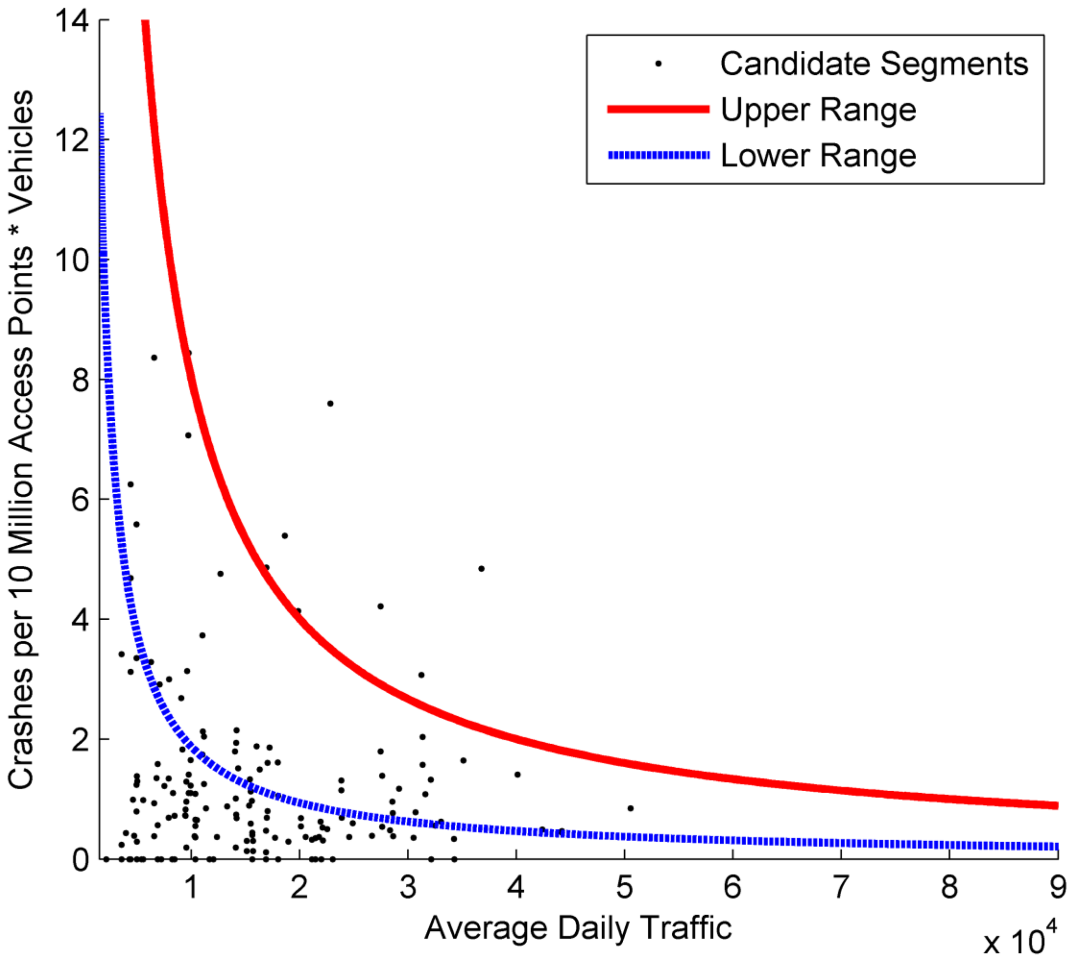

Figure 6. Case study of the priority setting for *Sub-region 1* to contrast access-related crash intensity and traffic exposure (*rural* corridor segments)

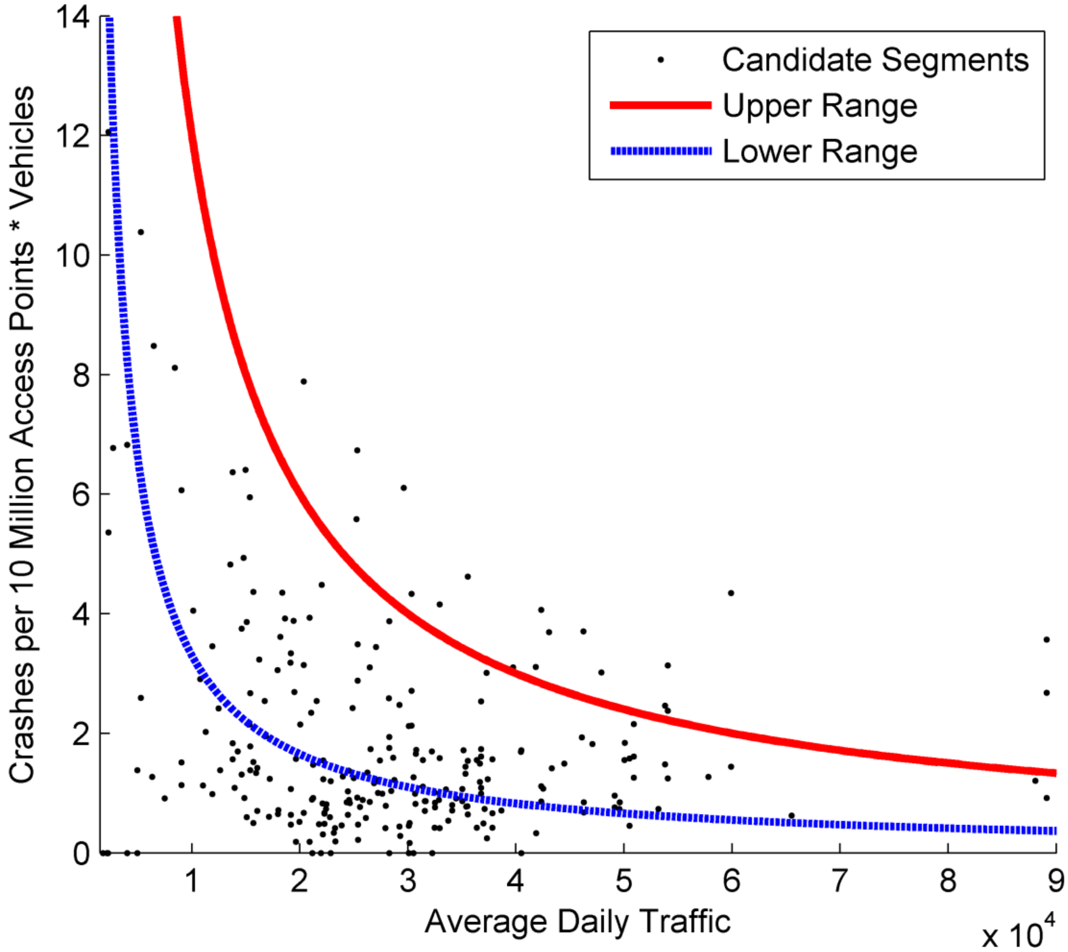

Figure 7. Case study of the priority setting for *Sub-region 1* to contrast access-related crash intensity and traffic exposure (*urban* corridor segments)

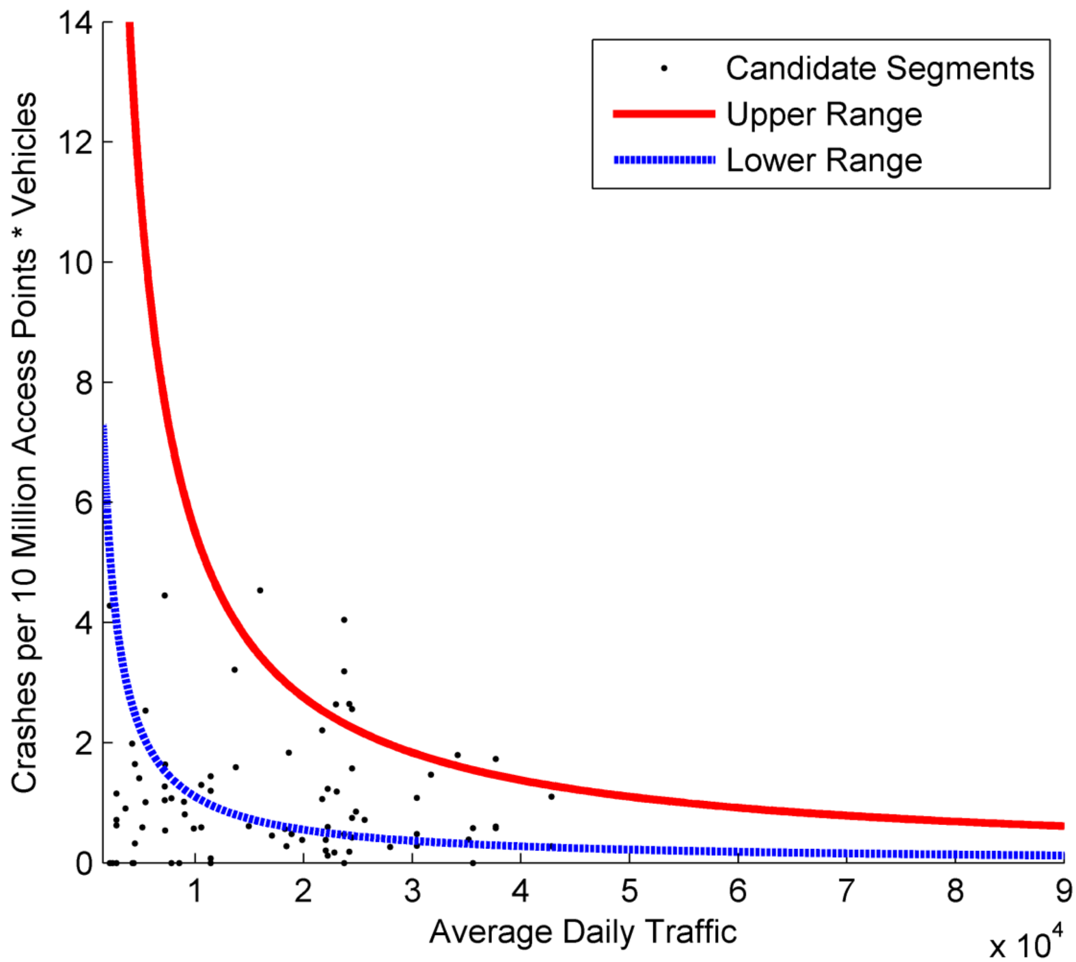

Figure 8. Case study of the priority setting for *Sub-region 2* to contrast access-related crash intensity and traffic exposure (*rural* corridor segments)

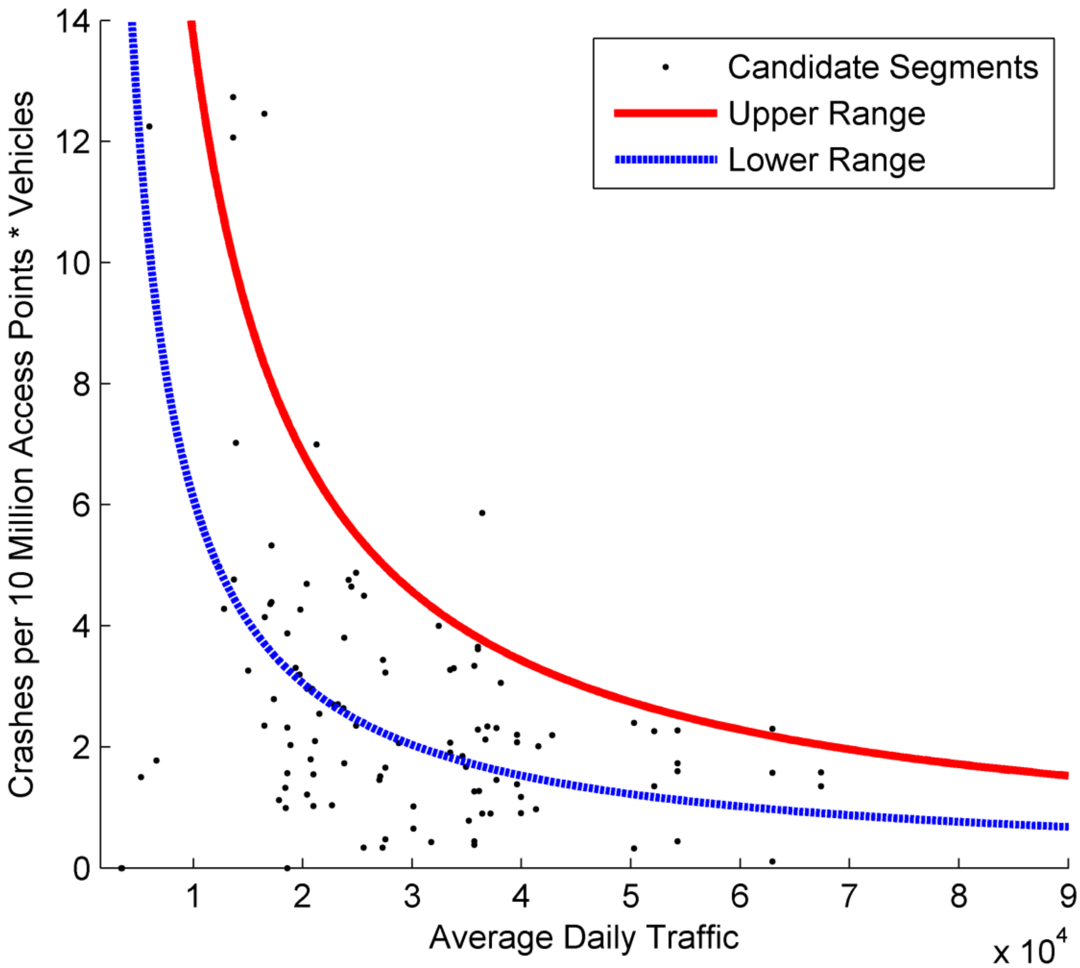

Figure 9. Case study of the priority setting for *Sub-region 2* to contrast access-related crash intensity and traffic exposure (*urban* corridor segments)

Table 10. Number and total length (miles) of corridor segments in *Sub-region 1*

Prioritization Level	Rural		Urban	
	Number of Segments	Total Length of Segments	Number of Segments	Total Length of Segments
B/C > 1	8	4.6	18	9.1
B/C > 1 or B/C < 1	47	41.8	93	54.4
B/C < 1	116	179.1	143	87.9

Table 11. Number and total length (miles) of corridor segments in *Sub-region 2*

Prioritization Level	Rural		Urban	
	Number of Segments	Total Length of Segments	Number of Segments	Total Length of Segments
B/C > 1	7	7.8	7	1.9
B/C > 1 or B/C < 1	28	29.6	51	33.8
B/C < 1	46	84.5	51	35.2

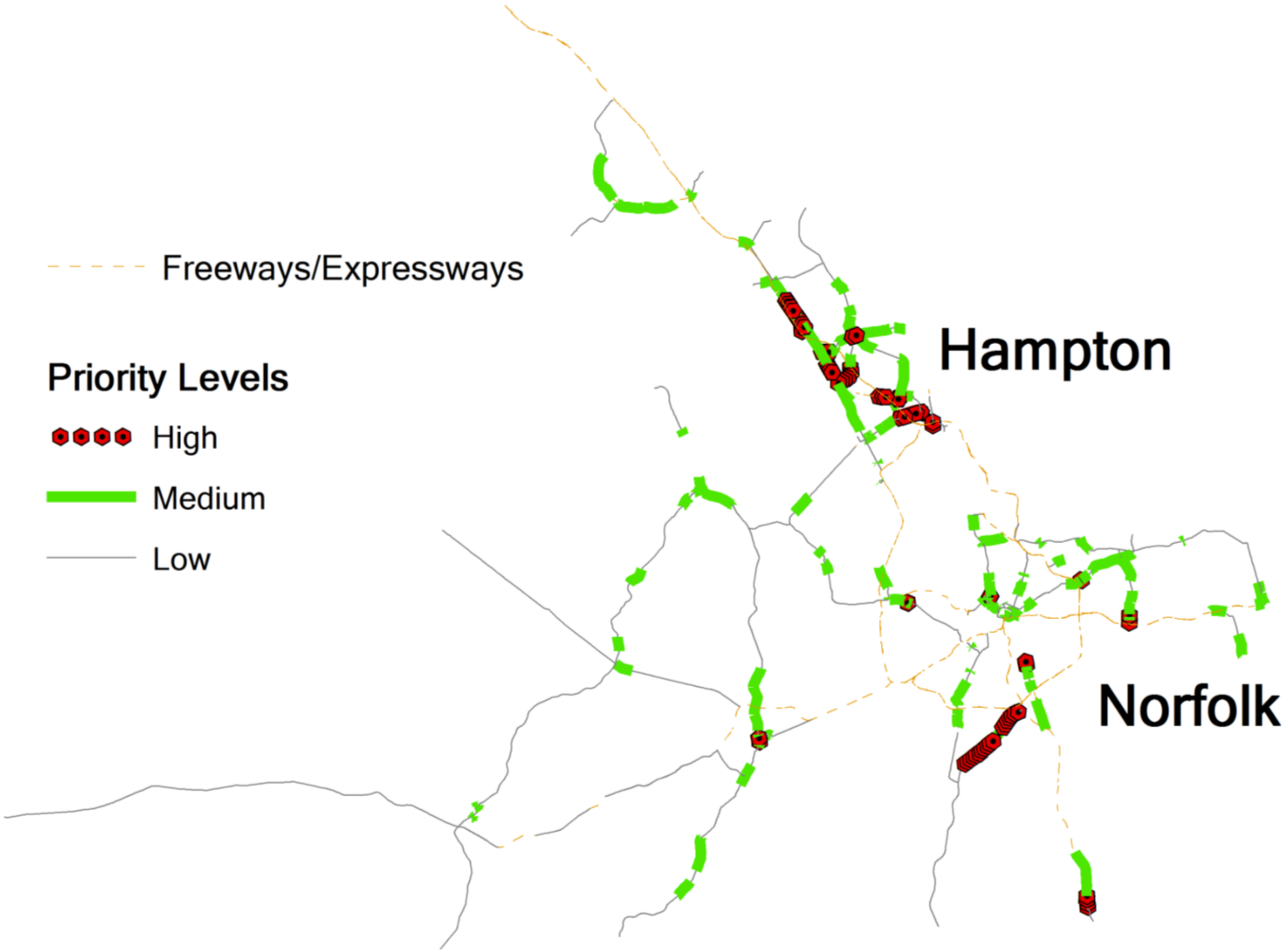

Figure 10. Transportation corridor network of the *Sub-region 1* for prioritizing access management projects

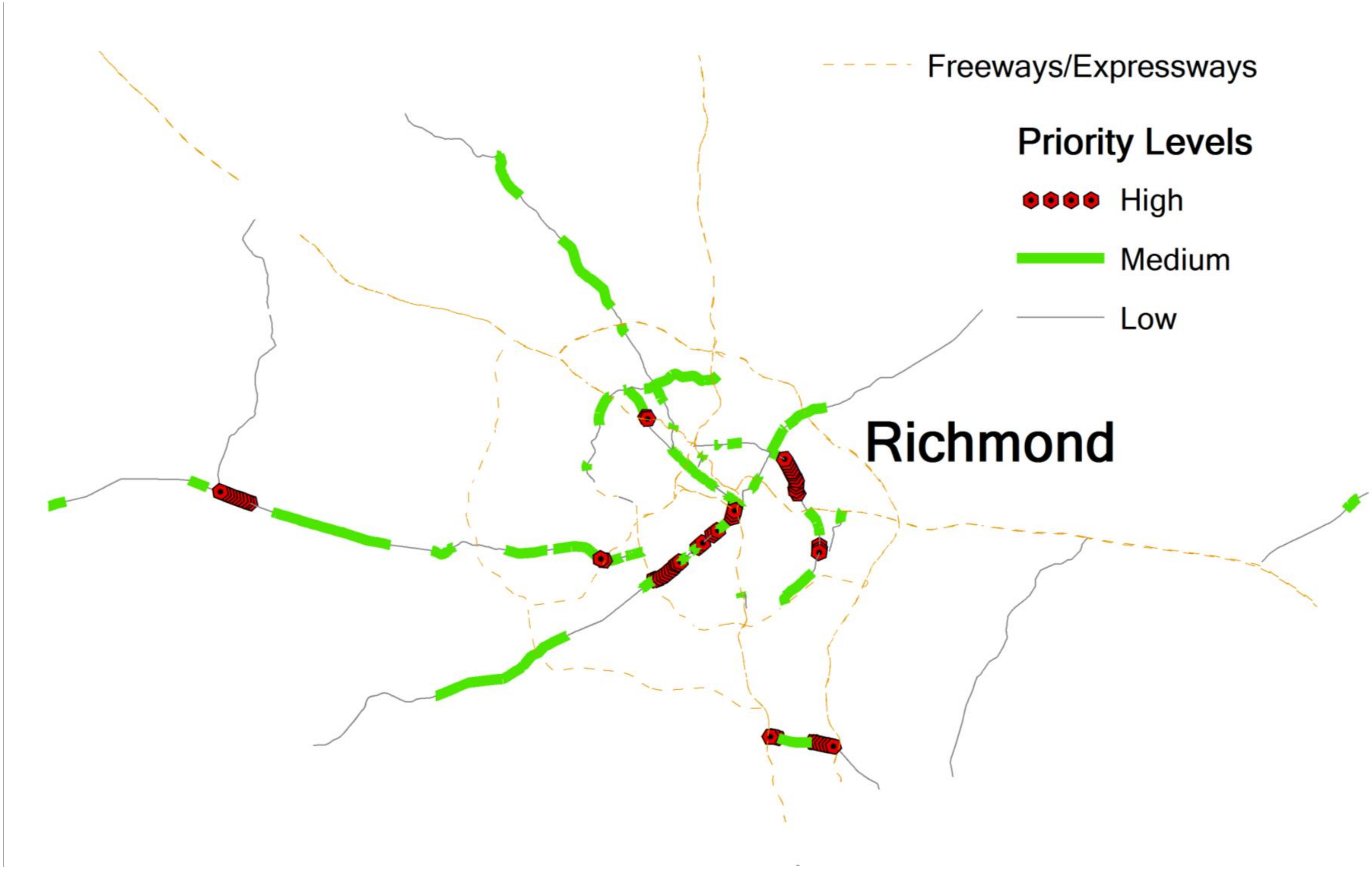

Figure 11. Transportation corridor network of the *Sub-region 2* for prioritizing access management projects

Table 12. Sample of qualitative results of access management safety program evaluation with uncertain parameters

Type of Result	***Description***	***Entire region***	***Sub-region 1***	***Sub-region 2***
Corridor segments with high priorities	Segments with benefit-to-cost ratio greater than 1, which are the small components of the transportation network	Relatively few segments (2% of all segments with total length of 40.2 miles), most of them in the northeast	Relative few segments (6% of all segments with total length of 13.7 miles)	Relatively few segments (7% of all segments with total length of 9.7 miles)
Corridor segments with medium or low priorities	Segments with benefit-to-cost ratio less than 1, which are the large components of the transportation network	Relatively many segments (98% of all segments with total length of 4277.2 miles)	Relatively many segments (94% of all segments with total length of 363.2 miles)	Relatively many segments (93% segments with total length of 183.1 miles)
Uncertainties of the parameters	Degree of uncertainties reflected as the range of parameters, which varies among different locations of corridors	Intervals of exogenous parameters are larger than those of the *Sub-region 1* or *Sub-region 2*	Intervals of exogenous parameters are larger than those of the *Sub-region 2*	[see comment at left]
Upper and lower contours	Positions of upper and lower contours are sensitive to the bounds of each of the uncertain parameters	Contours of the B/C ration are relatively more separated than those of the *Sub-region* 1 or the *Sub-region* 2	Contours are relatively more separated than those of the *Sub-region 2*	[see comment at left]

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3.5 Discussion

In future applications, one might consider that the vehicle traffic volumes on the inner lanes are not relevant to access-related crashes and that using all-lane ADT would bias the estimate of the access related crash intensity. In such case, it might be preferable to use only the outmost-lane traffic volumes for the calculations of crash intensities. Moreover, recent studies have shown how a safety index (SI) can be used as a disaggregated approach to gauge relative safety performance of a highway intersection (Cafiso et al. 2006; Lamm et al. 2006; Montella 2005; De Leur and Sayed 2002). An SI approach might be integrated to our methods to handle crash occurrences with geometric design, traffic, safety hardware (signs, signals, lighting, pavement markings, guiderails, crash cushions, etc.), driver behavior, and potential for safety improvements (PSI) quantitatively (Madanu et al. 2010). The analysis might also be extended across the facility service life cycle (Li et al. 2009).

Nevertheless, for an access management program, the crash intensity and traffic exposure are typically identified as competing dimensions in a resource allocation, and they are natural candidates to influence the assessments of relative benefits and costs. In this chapter, a quantitative cost-benefit analysis under uncertainties is introduced directly to reconcile trade-offs between traffic exposure and crash intensity and screen and prioritize among many thousands of road sections for which additional data, elicitations, and modeling might be needed for oversight of an access management program from the safety improvement perspective. The method is demonstrated for transportation networks of an entire region (a U.S. state) and two of its sub-regions. Measures of the crash intensity and traffic exposure are defined with regards to the corridor segment location. The crash reduction factor, average costs per crash, and access management project costs, are presented as uncertain exogenous parameters that influence the evaluation of costs and benefits at each location. Various ranges of parameters for each region and sub-region are identified respectively and used in the example. Numerical interval analysis is applied to proceed without precise knowledge of underlying parameters and an appropriately simplified evidence-based approach is developed to help screen corridor access management project. Highway sections, that are of high, medium, and low priority, are identified based on whether the condition of the benefit-to-cost ratio can plausibly exceed one. The key innovation of this chapter is to integrate uncertain costs, benefits, and other evidence of the efficacy of distributing access management, supporting decision makers to screen and prioritize roadway segments for performing additional investigations. The philosophy of approach is transferable to other topics in transportation safety and security where limited resources are to be allocated for project investigations across a large scale system.

Last but not least, access points are typically driveways, intersections, and interchanges (Lambert et al. 2011; Fiol et al. 2012). Various types of access points may have different influences on the performance of corridor. For example, the closure of major intersections should improve traffic flow and reduce crashes on the highway much more than that of driveways in most cases. However, in this dissertation, the courting process of access points does not distinguish different types of access points.

3.6 Chapter summary

This chapter developed a method of identifying and prioritizing corridor sections most needing further access management investment with a focus on safety. A quantitative framework was described by introducing several assessment metrics and applying multicriteria analysis and cost-benefit analysis with parameter uncertainties. Section 3.2 provided an introduction to the problem and methods of this chapter. Section 3.3 described the technical approach of quantification of uncertain benefits and costs, and the benefits-to-costs ratio, and compiles a prioritization framework. Section 3.4 demonstrated general methodology in more detail on a multiscale large transportation system. Section 3.5 provided a discussion of the results. Section 3.6 provided a chapter summary. The major contributions of this chapter is to invent suitable metrics for highway access management risk-cost-benefit analysis from safety improvement perspective and a visualized multicriteria tool that enables decision makers to effectively prioritize investments along the transportation system.

4 Method phase two: Travel-time savings

4.1 Chapter overview

This chapter will develop a method of identifying and prioritizing corridor sections most needing further access management investment with a focus on travel-time savings. A quantitative framework will be described by introducing several assessment metrics and applying multicriteria analysis and cost-benefit analysis with parameter uncertainties. The sections of this chapter are organized as follows: (i) Section 4.2 will provide an introduction to the problem, (ii) Section 4.3 will describe the technical approach of quantification of uncertain benefits and costs and the benefits-to-costs ratio, and compile a prioritization framework, (iii) Section 4.4 will demonstrate general methodology in more detail on a multiscale large transportation system, (iv) Section 4.5 will provide a discussion of the results, and (v) Section 4.6 will provide a chapter summary. The major contribution of this chapter is to develop a similar method from a complementary perspective of travel-time savings.

4.2 Introduction

For the new application of evaluating and guiding an access management program, this chapter extends analytical methods described in Chapter 3 and describes the screening among many thousands of miles of road sections where additional data, elicitation, and modeling can legitimize an access management program that is focused on travel time (delay). The scope of this chapter is an agency program focused on reducing travel time (delay), and this chapter demonstrates how the selection of high-priority roadway segments for access management can be assisted by a multicriteria analysis, the quantification of surrogates for travel time benefits and costs, and a simplified model of the benefit-to-cost ratio with interval analysis of parameter uncertainties.

For corridor access management program, there is a natural tradeoff or competition in the program between addressing sections with high traffic volumes and addressing sections with severe travel time delay. In this chapter, access management projects with uncertainties of parameters of benefits and costs are prioritized with a coordination of multicriteria analysis and cost-benefit analysis with a focus on travel-time savings. This section describes the form and parameters of a simplified benefit-to-cost ratio. First, current travel delay as hours per access point per vehicle along a corridor segment is introduced and formalized. Second, a quantification of benefits and typical costs of access management and the parameters of benefit-to-cost ratio are described. Third, the benefits and costs are integrated to evaluate the benefit-to-cost ratio in the context of a multicriteria analysis. Similar to chapter 3, an evidence diagram is introduced with two contours separating three zones (high, medium, and low) of priority in a scatterplot of two key state variables of corridor sections: (i) the exposed population in terms of vehicles per day and (ii) the intensity of the current travel delay in terms of hours of delay per access point per vehicle. The high-priority zone is above the upper contour, where the benefit-to-cost ratio exceeds one for all possible values of the uncertain parameters; the medium-priority zone is between the upper and lower contours, where the benefit-to-cost ratio exceeds one for some possible values of the exogenous parameters; the low-priority zone is below the lower contour, where the benefit-to-cost ratio does not exceed one for any possible values of exogenous parameters. Further details regarding this effort are described by Xu and Lambert (2013a).

Priority setting in this context acknowledges that agencies are unable to analyze and develop access management options for all individual corridor segments due to constrained resources modeling, elicitation, and data collection. With this method, when travel-time savings is the major concern, the corridor segments located in the high priority zone should be considered and selected for investigation first. Such investigation might include design and operations studies for the near network of a prioritized corridor segment. A cost-benefit analysis is thus described to prioritize and screen among thousands of corridor segments. The section thus identifies key principles, metrics, and decision and information needs that will be required. Immediately following will be a practical demonstration with a 6,000 miles of corridor in a multiscale network.

4.3 Quantitative metrics and approach

4.3.1 Quantifications of benefits

This section introduces the travel time delay index, amenable to monetizing the potential needs and benefits of access management from time-saving perspective. The current travel time delay index for exposed vehicles measures the delay hours per access point per vehicle.

The exposure measures the amount of vehicles that are subjected to that travel time delay index. In the transportation literature, the population exposure is often quantified as the ADT, which is adopted as the exposure term in this method.

A key interest is to systematize the access policy for corridors and find a way of relating an access point inventory to the travel time delay. The HCM (U.S. National Research Council 2010) describes a model for computing the free-flow speed for multilane highways, and the adjustment factors used in the equations show that the access point density besides other factors can reduce the free-flow speed. The magnitude of the adjustment by access point density is listed in Table 13. In this simplified planning level model, for every 10 access points per mile, the travel speed will be reduced by 2.5 miles/hour.

The difference of posted speed and impaired speed on the arterials, rather than the free-flow speed, is used to generate a surrogate for the actual travel time delay. This simplified model assumes that the reduction in free-flow speed depends on the access point density of a corridor segment linearly. Thus, *the current delay hours per vehicle* along a corridor segment is defined to be the travel time delay due the existing access points for a single vehicle as follows.

$$Travel\ Time\ Delay = \frac{Length\ of\ Roadway\ Segment}{Posted\ Speed - 0.25 \times \frac{Number\ of\ Access\ Points}{Length\ of\ Roadway\ Segment}} - \frac{Length\ of\ Roadway\ Segment}{Posted\ Speed} \tag{7}$$

For the access point density in Equation 7, the access density used in the calculation is the minimum of 40 access points per mile and the actual density, which is consistent with Table 13 and the HCM (U.S. National Research Council 2010). To normalize the travel delay hours along a corridor segment with variant number of access points, the average delay hours per access points for a single vehicle is defined as the travel time delay index as follows.

$$\begin{aligned} D &= Travel\ Time\ Delay\ Index = The\ Current\ Delay\ Hours\ per\ Vehicle\ per\ Access\ Point \\ &= \frac{Travel\ Time\ Delay}{Number\ of\ Access\ Points} \\ &= \frac{\frac{Length\ of\ Roadway\ Segment}{Posted\ Speed - 0.25 \times \frac{Number\ of\ Access\ Points}{Length\ of\ Roadway\ Segment}} - \frac{Length\ of\ Roadway\ Segment}{Posted\ Speed}}{Number\ of\ Access\ Points} \end{aligned} \tag{8}$$

The simplified benefits calculation focuses on the reducible delay time. The travel time delay index is used to quantify the number of hours saved per access point for a single vehicle that might be expected after implementing a typical access management at a specific site. That is, the greater is the current delay (attributable through the HCM (U.S. National Research Council 2010) - derived calculation to access point density), the greater is the potential benefit delay reduction of treating the access points into the future.

In 1997, the U.S. DOT published its first guidance on the subject of valuing delay and time savings (U.S. DOT 2011). Many DOTs and other governmental agencies design actions and projects to benefit travelers by reducing the time spent in traveling. The details about the evaluation of travel time are described by Victoria Transport Policy Institute (2013), ORDOT (2011), Perk et al. (2011), U.S. DOT (2011), Concas and Kolpakov (2009), Corotis (2007), Kirk et al. (2006), and Lambert and Joshi (2006). Thus, the value of time is used with the travel time delay index to compare the time savings benefits of access management projects to the costs. Below, a range of parameter values will be used to represent the variation of the estimates of the value of time across the typical options. The benefit of access management from a time savings perspective then takes the following form.

$$\begin{aligned}
&\mathit{Benefits} \\
&= \mathit{Travel\ Time\ Delay\ Index} \times \mathit{Exposure} \times \mathit{Value\ of\ Travel\ Time} \\
&= D \times T \times V \times 365 \\
&= \frac{\dfrac{L}{S - 0.25 \times N / L} - \dfrac{L}{S}}{N} \times T \times V \times 365 \\
&= \mathit{Potential\ Time\ Savings}(\$) / \mathit{Access\ Point} / \mathit{Year}
\end{aligned} \tag{9}$$

where *D, T, V, L, N, and S* are described by Table 14. The number of access points, length of corridor segment, posted speed, and traffic volume are characteristics of particular corridor sections, while the value of time is typical of large regions rather than unique to a corridor section, as described in the next section.

Table 13. Adjustment for access points density on multilane highways

Access points per mile	Reduction in free-flow speed (mile/h)
0	0.0
10	2.5
20	5.0
30	7.5
40 or more	10.0

Source: HCM (U.S. National Research Council 2010)

Table 14. Parameters for quantification of travel-time savings benefits of corridor access management

Parameter	Parameter Description	Units
D	Travel time delay index	Hours per access point per vehicle
T	ADT	Vehicles per day
V	Value of travel time	$ per hour
L	Length of corridor segment	Miles
N	Number of access points	Access points
S	Posted speed	Miles per hour

4.3.2 Quantifications of costs

The quantification of access management costs in this section is same as that discussed in Chapter Section 3.3.2. The total cost, C_{Total} and the assumptions about the costs will be reused in this section.

4.3.3 Cost-benefit analysis with uncertainties for travel-time savings

This subsection introduces a benefit-to-cost ratio of typical access management projects from travel-time savings perspective. The purpose of this subsection is to apply a cost-benefit analysis together with a multicriteria scatter diagram to aid stakeholders to screen and prioritize the needs for future investigations in access management from travel time saving perspective. A benefit-to-cost ratio is defined to be the ratio of the potential travel-time savings per access point per year (realizable by implementing typical access management techniques) to the annualized costs of access management projects per access point as follows.

$$\Psi_T = \frac{Benefits}{Costs} = \frac{D \times T \times V \times 365}{C_{PE} + C_{RW} + C_{CN} + C_{LC}} = \frac{\dfrac{\dfrac{L}{S - 0.25 \times N / L} - \dfrac{L}{S}}{N} \times T \times V \times 365}{C_{Total}}$$

$$= \frac{Potential\ Travel\ Time\ Savings(\$) / Access\ Point / Year}{Costs(\$) / Access\ Point / Year}$$

(10)

The Ψ_T, defined as the benefit-to-cost ratio, is the ratio of the monetary benefits to the monetary costs for travel-time savings, which was defined for the corridor access management in previous sections. A dimensional analysis of the benefit-to-cost ratio is provided as follows:

$$\psi_T = \frac{\overbrace{\left(\frac{\dfrac{\dfrac{Mile}{\dfrac{Mile}{Hour} - \dfrac{\dfrac{Mile}{Hour}}{\dfrac{Access\ Point}{Mile}} \times \dfrac{Access\ Point}{Mile}} - \dfrac{Mile}{\dfrac{Mile}{Hour}}}{}}{Access\ Point \times Vehicle} \right)}^{Travel\ Time\ Delay\ Index} \overbrace{\left(\frac{Vehicle}{Day}\right)}^{Exposure} \overbrace{\left(\frac{Dollar}{Hour}\right)}^{Value\ of\ Time} \left(\frac{Day}{year}\right)}{\underbrace{\left(\frac{Dollar}{(Access\ Point)(Year)}\right)}_{Costs\ of\ Access\ Management\ Project}} \tag{11}$$

The parameters V and C_{Total} are assigned interval ranges to represent the knowledge uncertainties of their potential values. In this framework, experts and stakeholders from transportation agencies will assess the uncertainties of each parameter and define the interval ranges. Nevertheless, these ranges are not solely expert based, and they can be calibrated by referring to standards of other agencies (e.g., State DOTs, U.S. DOT, etc.) or related studies (e.g., Liu et al. 2011; Perk et al. 2011; Concas and Kolpakov 2009; Zhou et al. 2008).

For a candidate segment of interest, the interval range of potential values for each of the exogenous parameters is estimated and calibrated for a region and its sub-regions, i.e., parameters other than D (travel time delay index) and T (average daily traffic). An interval analysis, where the uncertain parameters are described by an upper and lower bound, of benefit-to-cost ratio incorporated to multicriteria evaluation of an access management program is described on two coordinate axes as follows. The exposure in terms of ADT is the horizontal axis of the graph. The travel time delay index in terms of current delay hours per access point per vehicle is the vertical axis of the graph. The uncertainties of the parameters other than ADT and travel time delay index are used to generate the contours of benefit-to-cost ratio equal to one. For a benefit-to-cost ratio equal to one, the extreme values of the interval calculation generate two contours separating three zones. The upper contour reflects the "pessimistic" situation, the ratio of minimum possible benefits to maximal possible costs equals to one, while the lower contour reflects the "optimistic" situation, the ratio of maximum possible benefits to minimum possible costs equals to one. Since the benefit-to-cost ratio, Ψ, is an increasing function of ADT (vehicles per day) and travel time delay index (delay per access point per vehicle), the projects with benefit-to-cost ratio > 1 falling above the upper contour (in the high-priority zone) should be prioritized to receive further investigations and/or show the most value of additional information and modeling. The corridor segments with benefit-to-cost ratio < 1 falling below the lower contour (in the low-priority zone) should not be recommended for further investigations. The segments that fall between the upper and lower contours (in the medium-priority zone) have an indeterminate inequality of benefits and costs, and further evidence might be needed to suggest the cost efficiency of access management. The locations of upper and lower contours depend on the interval ranges of the uncertain parameters and the equation for the benefit-to-cost ratio. Adjustment of the interval ranges of parameters, which reflects the regional or sub-regional particularities, results in shifting of these three zones. The above priority setting analysis can thus proceed without precise values of exogenous parameters and can help decision makers to prioritize needs for corridor access management including monetized benefits and costs along with metrics of potential travel-time savings and traffic exposure. Policy for access management design investigations could focus, for example, on projects according to their respective zones, on projects of longer travel time delays, of high traffic exposure, and/or a combination of the above factors with other factors.

The above approach, to be demonstrated in the examples forthcoming, brings performance metrics and available objective evidence to screen thousands of miles of corridor section for sections that warrant a design/operations investigation. Once corridor sections of particular interest are identified, which is the focus of this chapter, the variety of design and operation techniques, including dynamic access management, might be considered for the corridor segments. The upcoming examples will reveal how the method overcomes a challenge of sparse data and the infeasibility of using sophisticated existing network models that have been developed for design/operations studies of local networks.

4.4 Case study of a multiscale transportation system

The above approach is applied to the SMS, which has been introduced in previous sections. The stakeholders can use above method to screen and select the access management projects from travel-time savings perspective. As in Chapter Section 3.4, the prioritization will be performed on the entire regions and its sub-regions, and the analysis is applied to corridor segments in rural and urban areas respectively. Diverse databases discussed in Chapter Section 3.4 are utilized to obtain the travel time delay index and traffic exposure for various roadway segments.

The values of time and typical access management costs are shown as ranges of average values corresponding to a regional or sub-regional analysis. These interval ranges reflecting the uncertainty interval for each of the region, and two sub-regions are assessed with help of the engineers and planners of the regions under investigation. Cost-benefit analysis with uncertainties described next can help decision makers to prioritize the uses of the limited investigative resources.

4.4.1 Entire region

The basic information of the network of 4,500 miles of corridor (excluding freeways/expressways) in the entire region can be found in Table 3.

Table 15 gives the intervals of exogenous parameters values, which were set in consultation with experts and stakeholders from regional transportation agencies with calibration with other agencies and the related literature, as described above. For example, an expert elicitation has suggested that potential costs of access management per access point per year is typically between $15,000 and $40,000 in rural areas, while that cost is typically between $40,000 and $60,000 in urban areas.

It is important to identify the segments that are most justified by cost-benefit analysis, by considering the performance metrics. As described above, the intervals of exogenous parameters are used to generate two contours, which partition the curprent travel time delay to traffic volume plot into three decision zones.

Figure 12 and Figure 13 provide a description of the cost-benefit analysis and multicriteria analysis for rural and urban corridor segments, respectively. Recall that the segments plotted below the lower contour are candidates whose benefit-to-cost ratio cannot exceed one for any possible value of exogenous parameters, and the segments plotted above the upper contour are candidates whose benefit-to-cost ratios always exceed one for all possible values of exogenous parameters. The segments plotted between upper and lower contours are candidates whose benefit-to-cost ratios exceed one for some possible values of exogenous parameters. When screening and selecting the access management projects for future investigation of design alternatives, the segments falling above the upper contour might be considered first, the segments falling between the upper and lower contours next, and the segments falling below the lower contour last. If information needs (reduction of uncertainties) are foremost for the stakeholders, those segments between the two contours might be investigated first.

The counts and total length (with percentage of totals) of all corridor segments falling in three zones of priority are described by Table 16. Figure 14 displays system diagram for access management project prioritization. The segments in red are corresponding to those located above the upper contour in the potential travel-time savings and traffic exposure plot. The segments in blue are corresponding to those located between the upper and lower contours in the plot. The segments in gray are corresponding to those located below the lower contour in the plot. The corridor segments in orange belong to freeways/expressways, and they are not placed in the selection pool.

Based on above analysis, 35 segments with total length of 28.2 miles in the rural area and 64 segments with total length of 25.1 miles in the urban area should draw attention and be considered first for allocating access management projects for travel-time savings. 80% of the total length of corridor segments in rural area and 35% of the total length of corridor segments in urban area fall below the lower contour. These segments should be considered last, because for them, the typical access management project would be too costly relative to the potential benefits from travel-time savings perspective.

Table 15. Cost-benefit function parameter bounds for access management projects prioritization in a regional network of transportation corridors

Parameter	Units	Rural		Urban	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
V	$/hour	15	30	15	30
C_{Total}	$/access point/year	15,000	40,000	40,000	60,000

Table 16. Number and total length (miles) of corridor segments in a regional network of transportation corridors

Prioritization Levels	Rural		Urban	
	Number of Segments	Total Length of Segments	Number of Segments	Total length of Segments
B/C > 1	35	28.2	64	25.1
B/C > 1 or B/C < 1	645	700.9	553	349.2
B/C < 1	1514	3009.6	365	204.4

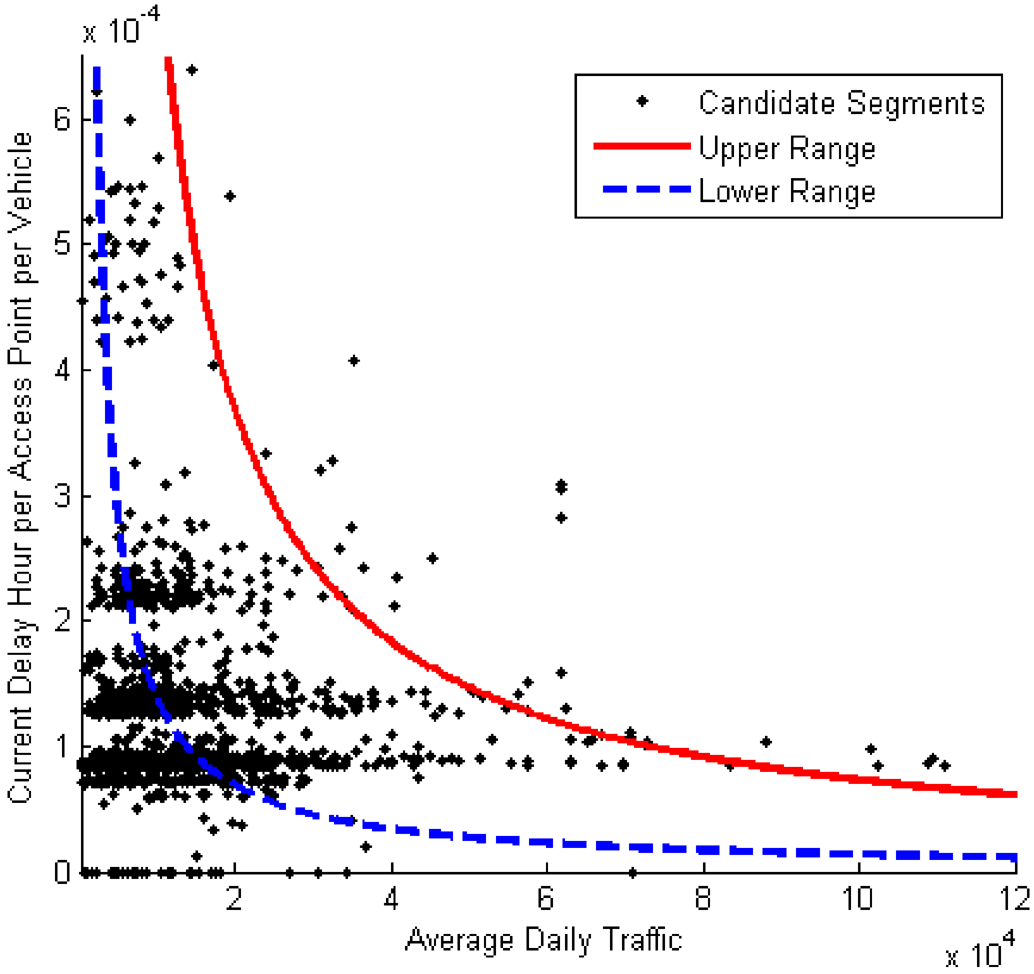

Figure 12. Example of the priority setting for a regional network of transportation corridors to contrast potential time savings and traffic exposure, *rural* corridor segments

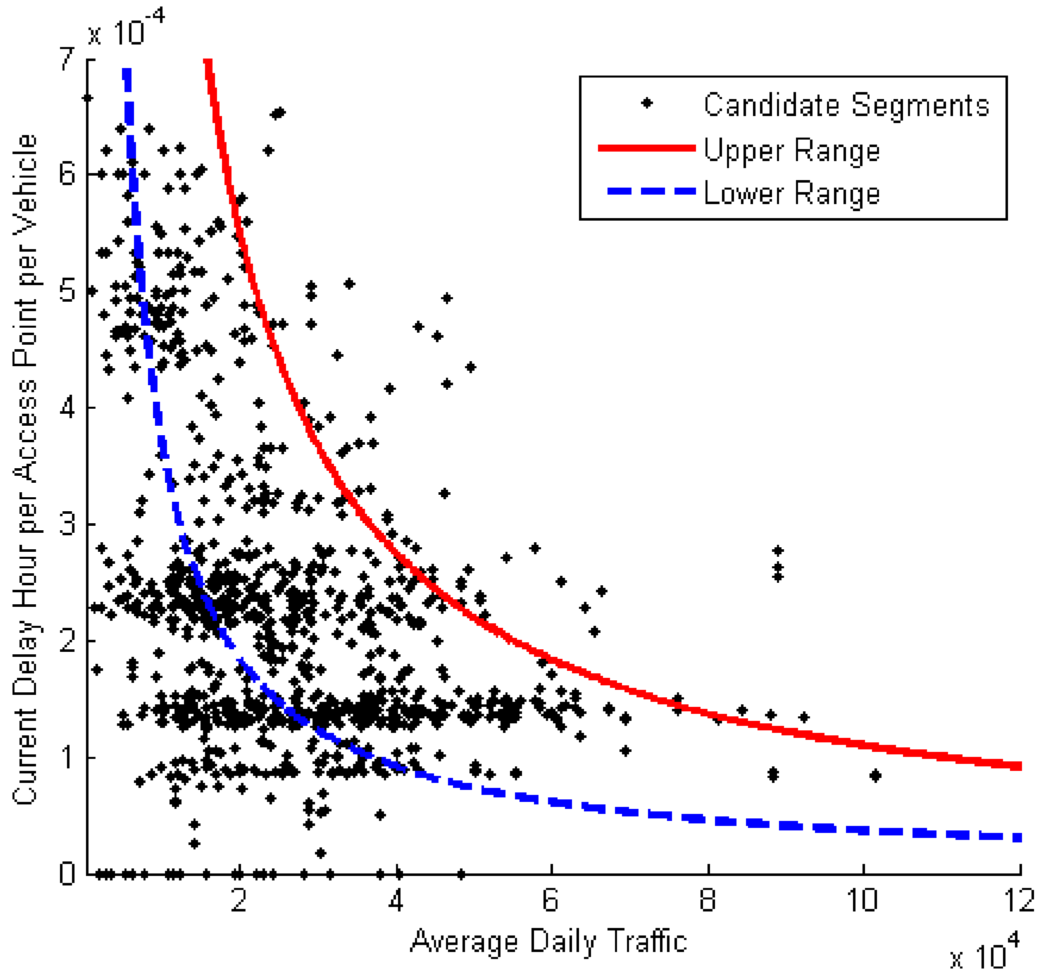

Figure 13. Example of the priority setting for a regional network of transportation corridors to contrast potential time savings and traffic exposure, *urban* corridor segments

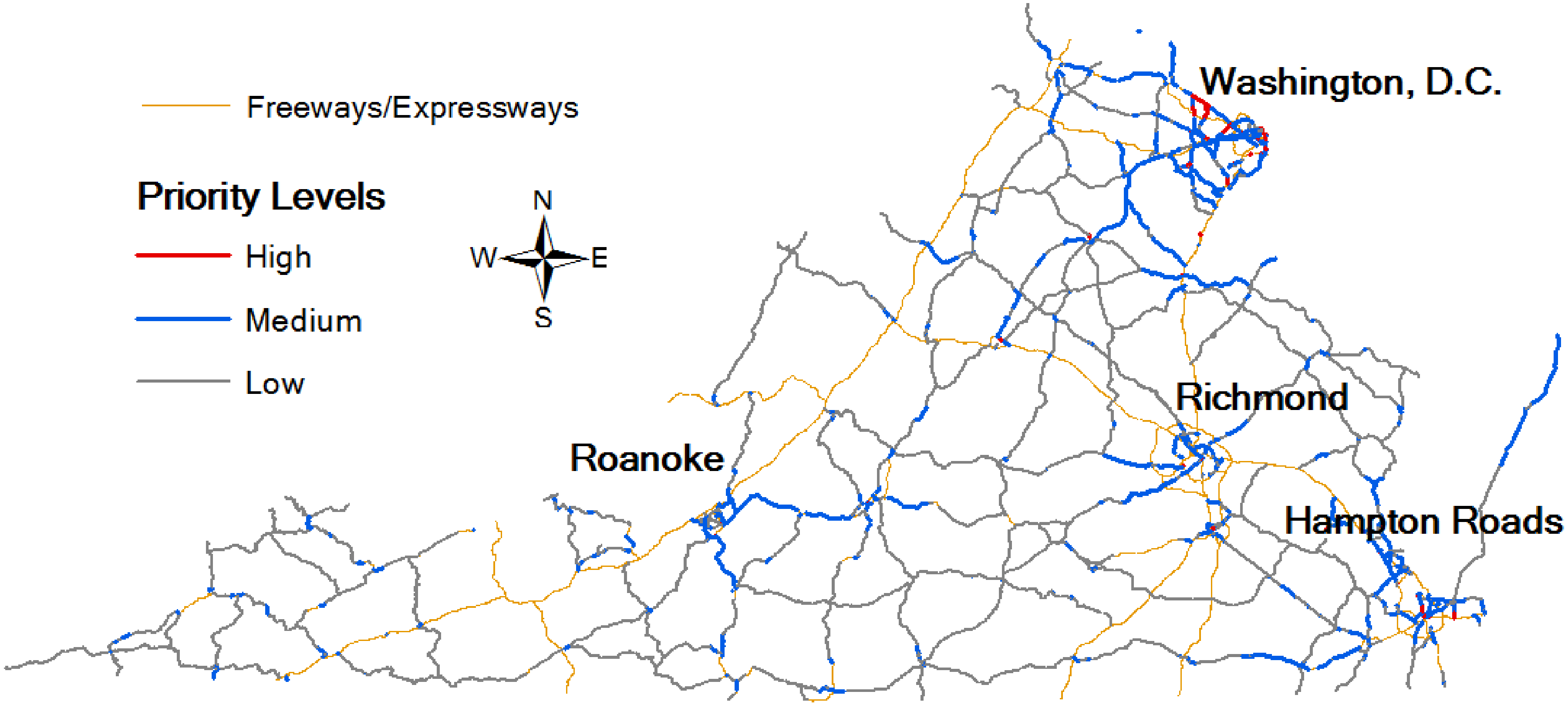

Figure 14. A 6,000 miles regional network of transportation corridors that will benefit from access management

4.4.2 Sub-regions

This prioritization method is applied to corridor segments in Hampton Roads and Richmond Planning Districts, which are referred as sub-region 1 and sub-region 2. The policies of access management for them are figured out to aid decision making. The basic information of corridor segments in such two sub-regions can be found in Chapter Section 3.4.2.

Tables 17 and 18 give the intervals of value of the parameters for the sub-region 1 and sub-region 2, respectively. The stakeholders and experts are allowed different views on values and uncertainties of exogenous parameters among different planning districts, since the estimation of benefits and costs of projects varies from sub-region to sub-region. For example, the stakeholders or experts estimate the value of time range from \$15/h to \$25/h in both rural and urban areas in sub-region 1, while they do expect a high value of time in sub-region 2, with an interval of \$20/h - \$30/h.

Table 17. Cost-benefit function parameter bounds for access management projects prioritization in *Sub-region 1*

Parameter	Unit	Rural		Urban	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
$\boldsymbol{V}$	\$/hour	15	25	15	25
C_{Total}	\$/access point/year	20,000	35,000	35,000	50,000

Table 18. Cost-benefit function parameter bounds for access management projects prioritization in *Sub-region 2*

Parameter	Unit	Rural		Urban	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
$\boldsymbol{V}$	\$/hour	20	30	20	30
C_{Total}	\$/access point/year	15,000	25,000	50,000	60,000

Tables 19 and 20 give the number and total length (miles) of corridor segments falling in three decision zones for sub-regions 1 and 2. Figures 15-18 describe the integrated cost-benefit analysis and multicriteria analysis for rural and urban corridor segments, respectively, in each of the two sub-regions.

For access management in the rural areas of sub-region 1, 7 segments with total length of 4.0 miles should receive the funding and resources first, because these projects are beneficial, while 120 segments with total length 188.3 miles should be addressed last, because these projects are too costly relative to the potential benefits. By comparing potential time savings and traffic exposure scatter plots, it is clear that the parameters values and levels of uncertainties have significant impacts on screening and selecting projects. A higher value for parameter C_{Total} and a lower value for the parameter V would likely result in a fewer number of segments falling above the upper contour. Figures 19 and 20 provide maps for the results from these two sub-regions for the prioritization of access management projects.

Table 21 provides a sample of the qualitative results. The table describes the corridor segments with various levels of priority, the uncertainties of the parameters, the upper and lower contours on a plot of potential time savings (current delay hours per access point per vehicle) and exposure (ADT), and the benefit-to-cost ratio.

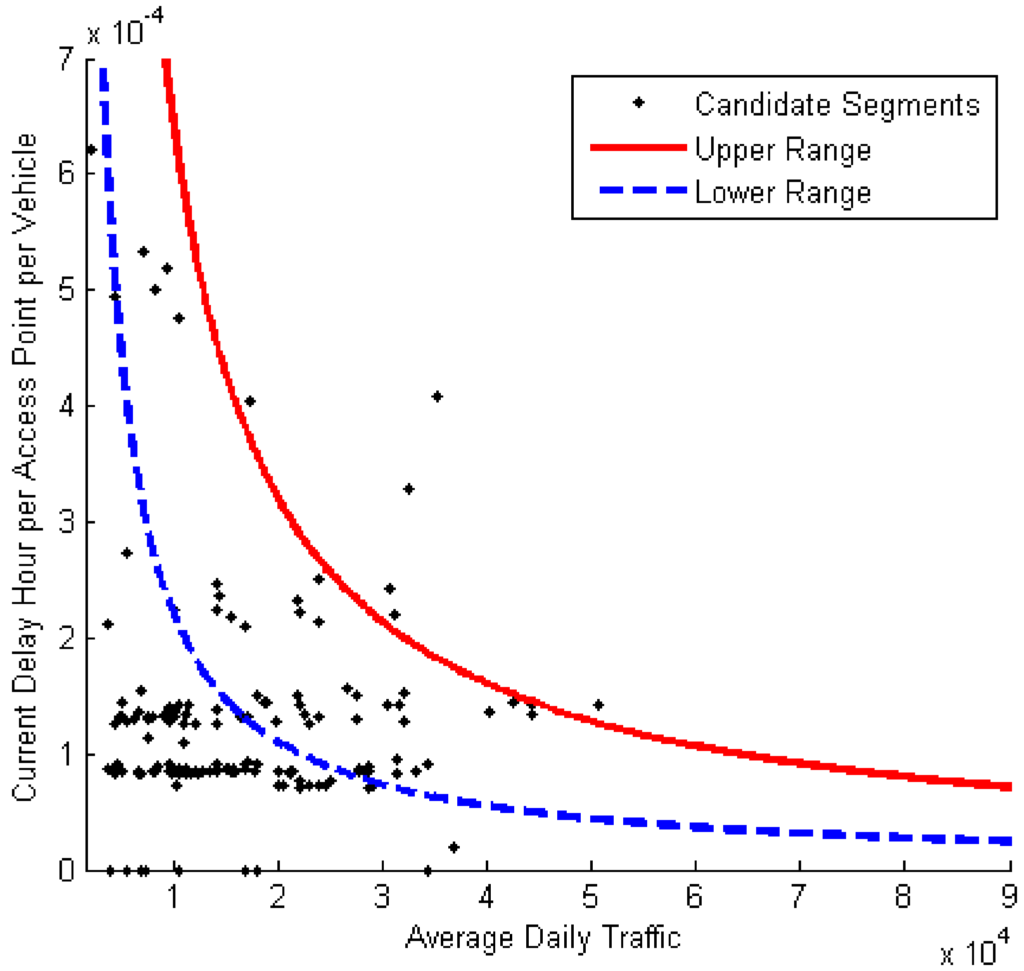

Figure 15. Case study of the priority setting for *Sub-region 1* to contrast potential time savings and traffic exposure, *rural* corridor segments

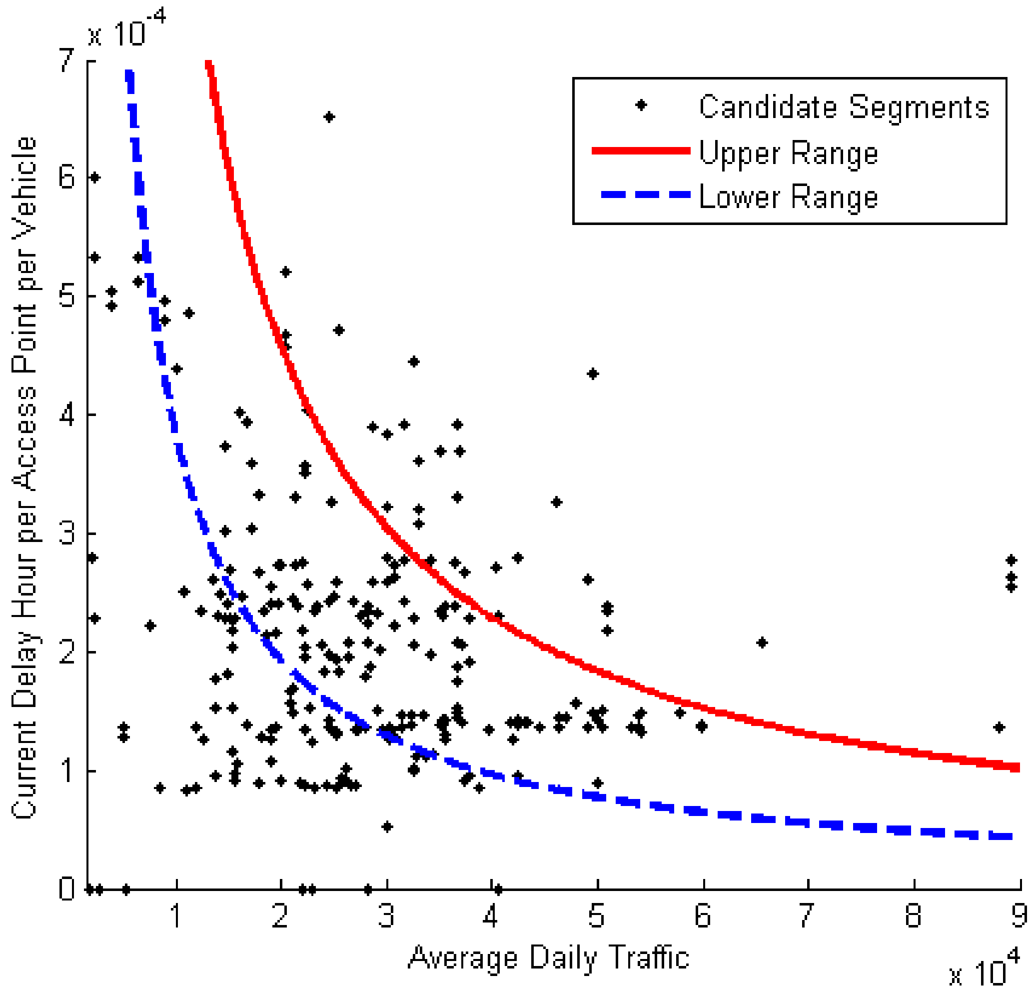

Figure 16. Case study of the priority setting for *Sub-region 1* to contrast potential time savings and traffic exposure, *urban* corridor segments

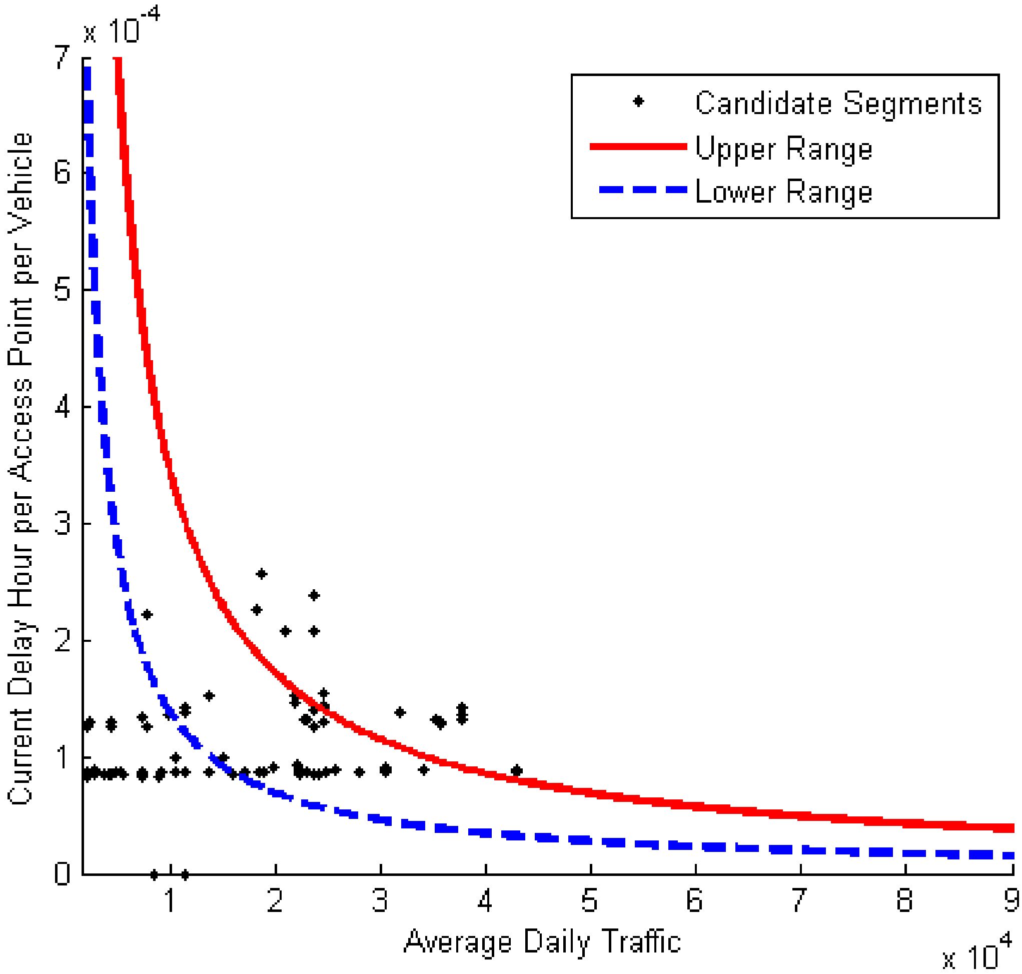

Figure 17. Case study of the priority setting for *Sub-region 2* to contrast potential time savings and traffic exposure, *rural* corridor segments

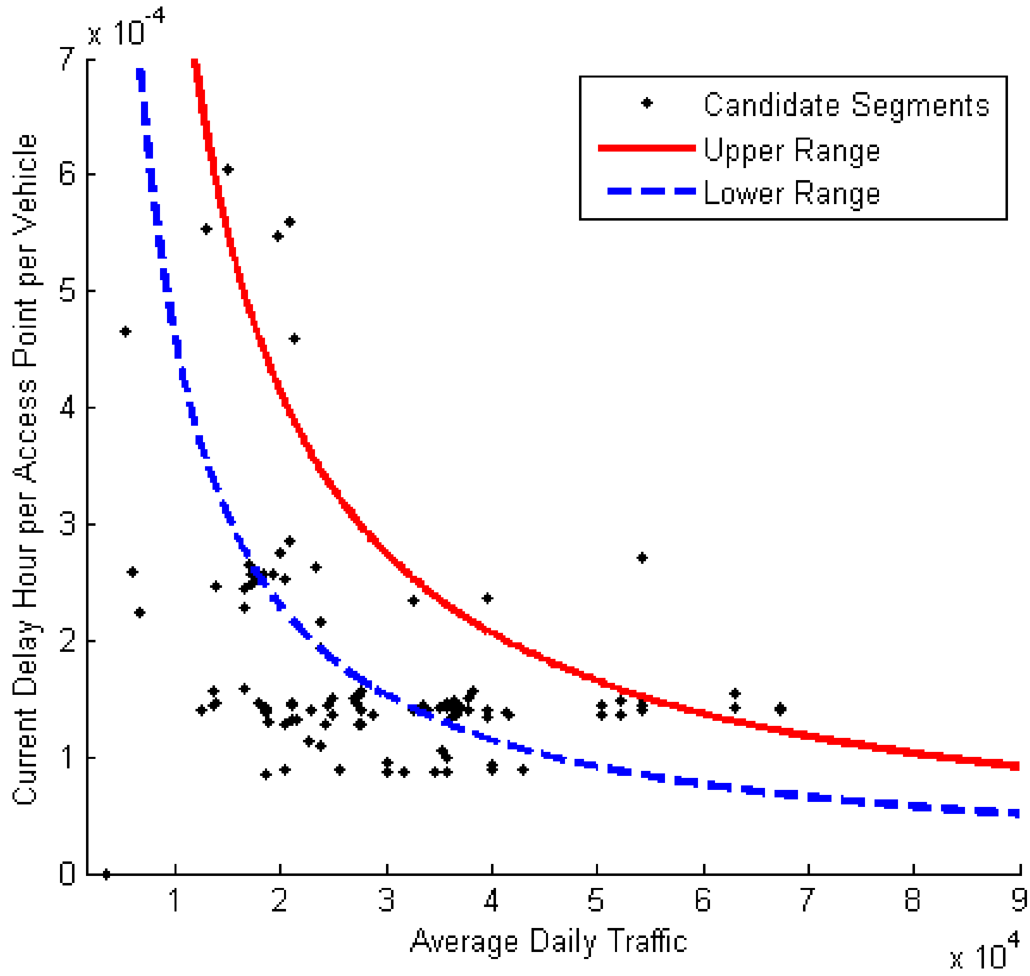

Figure 18. Case study of the priority setting for *Sub-region 2* to contrast potential time savings and traffic exposure, *urban* corridor segments

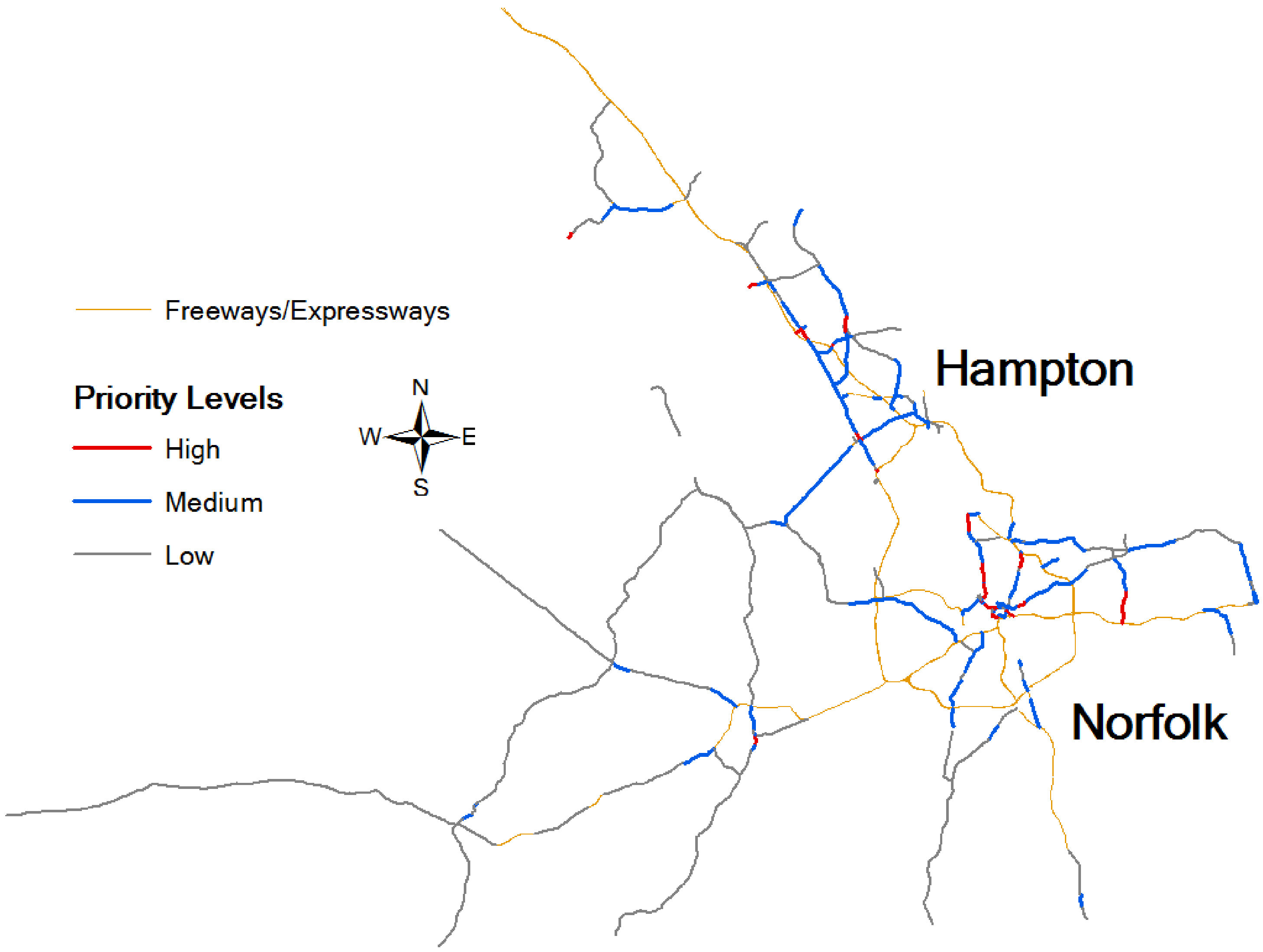

Figure 19. Transportation corridor network of the *Sub-region 1* for prioritizing access management projects

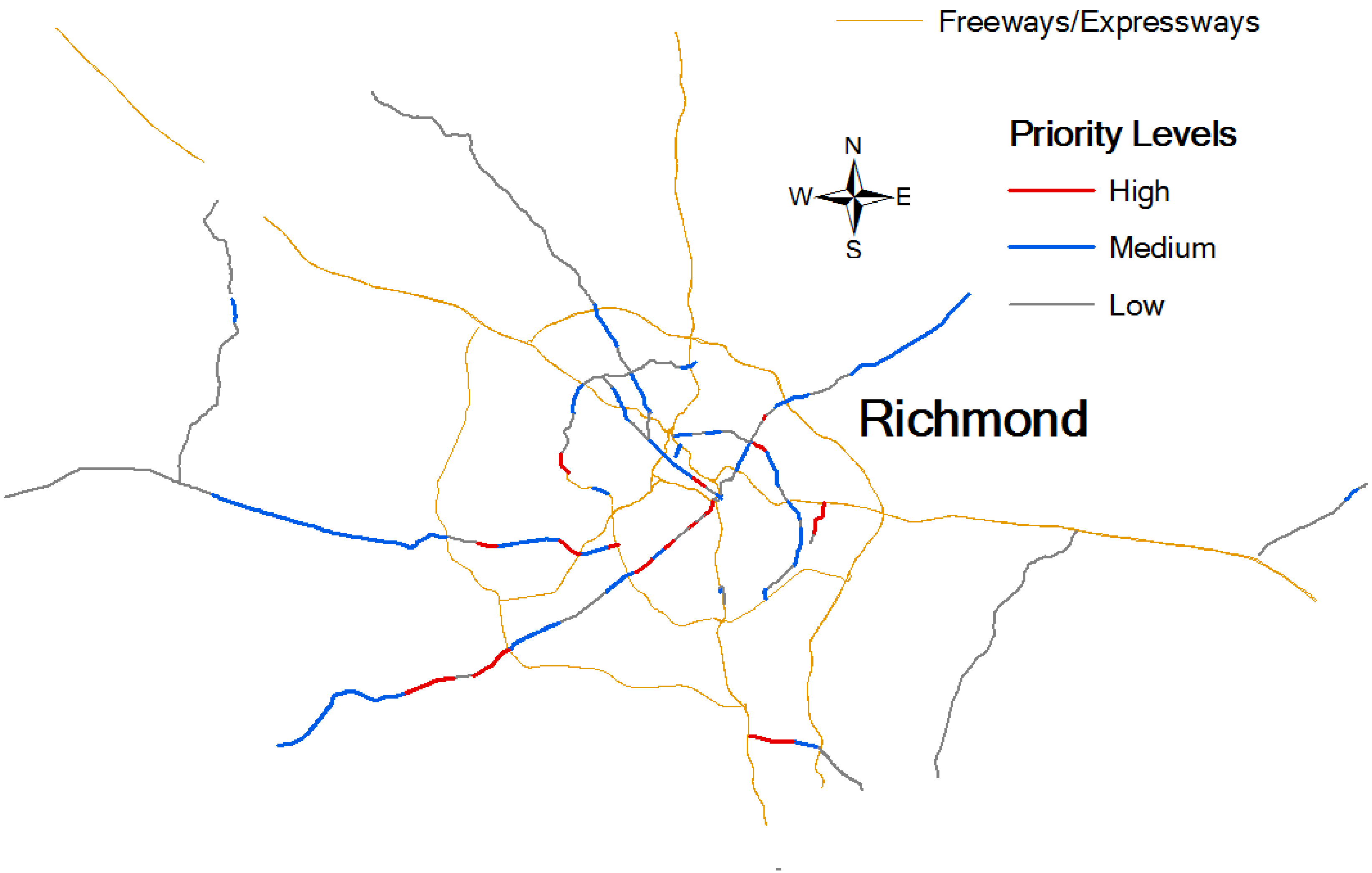

Figure 20. Transportation corridor network of the *Sub-region 2* for prioritizing access management projects

Table 19. Number and total length (miles) of corridor segments in *Sub-region 1*

Prioritization Level	**Rural**		**Urban**	
	Number of Segments	Total Length of Segments	Number of Segments	Total Length of Segments
B/C > 1	7	4.0	34	12.1
B/C > 1 or B/C < 1	44	33.1	132	80.9
B/C < 1	120	188.3	88	58.4

Table 20. Number and total length (miles) of corridor segments in the *Sub-region 2*

Prioritization Level	**Rural**		**Urban**	
	Number of Segments	Total Length of Segments	Number of Segments	Total Length of Segments
B/C > 1	17	11.1	11	7.0
B/C > 1 or B/C < 1	32	40.9	40	27.2
B/C < 1	34	69.9	58	36.8

Table 21. Sample of qualitative results of access management program evaluation with uncertain parameters

Type of Result	*Description*	*Entire region*	*Sub-region 1*	*Sub-region 2*
Corridor segments with high priorities	Segments with benefit-to-cost ratio greater than 1, which are the small components of the transportation network	Relatively few segments (3% segments with total length of 53.3 miles), most of them in the northeast	Relative few segments (10% segments with total length of 16.1 miles)	Relatively few segments (15% segments with total length of 18.1 miles)
Corridor segments with medium or low priorities	Segments with benefit-to-cost ratio less than 1, which are the large components of the transportation network	Relatively many segments (97% segments with total length of 4264.1 miles)	Relatively many segments (90% segments with total length of 360.7 miles)	Relatively many segments (85% segments with total length of 174.8 miles)
Uncertainties of the parameters	Degree of uncertainties reflected as the range of parameters, which varies among different locations of corridors	Intervals of exogenous parameters are larger than those of the *Sub-region* 1 or *Sub-region 2*	Intervals of exogenous parameters are larger than those of the *Sub-region 2*	[see comment at left]
Upper and lower contours	Positions of upper and lower contours are sensitive to the bounds of each of the uncertain parameters	Contours of the B/C ration are relatively more separated than those of the sub-region 1 or the *Sub-region 2*	Contours are relatively more separated than those of the *Sub-region 2*	[see comment at left]

4.5 Discussion

The scope of this approach is a larger corridor management problem, including corridor risk management, solely focused on “travel time (delay)”. The present efforts address a particular concern within access management, namely the filtering among thousands of 0.5-2 miles sections where additional preliminary investigation should be undertaken, other than attempt to advance the state of the art in travel delay estimation (e.g., as needed for comparing designs or otherwise making an analysis of a local network). The proposed metric uses the difference in posted speed and impaired speed (on the arterials), rather than using free-flow speed, to estimate the travel time delay. The state-of-the-practice model appropriately does not consider that free-flow speed could be less than the posted speed, as appropriate for prescreening, that is, the approach of interest here. Furthermore, in this study, the needed result for transportation agencies is a prioritization of corridor segments on which an investigation of network effects, etc., can be explored. Design and operations models would be used at that time. The surrogate metrics of delay are appropriate and necessary for large-scale systems and limited resources for investigation of design alternatives.

A possible concern is that the number of access points is used to normalize the travel time delay along a specific corridor segment. This recommended metric is consonant with approaches in risk analysis across disciplines, which contrast the level of exposed population (ADT) with the level of hazard intensity (delay per access point per vehicle). Since the only delay being considered in this chapter is attributable to access point density, the recommended metric of intensity is appropriate and even eases the job of the analyst in presenting the case for access management with managers for safety, economics, preservation, emergencies, etc. The metric of travel time delay index is thus grounded in principles of risk assessment and risk management, and is furthermore useful in framing the problem of transportation access management at hand. Another potential concern is the comprehensiveness of our multicriteria analysis. The benefits of access management are comprehensive and multicriteria in nature, i.e., travel time, safety, accessibility, economic development, etc., though the scope of this paper is a program focused solely on “travel time (delay)”. The effort identifies two key competing criteria provides them for support of decision-making; more specifically, there is a tradeoff or competition in the access management program in treating sections with, in one dimension, high traffic volumes (ADT) and sections with, in another dimension, high intensity of delay per access point per vehicle. Additionally, uncertainty also plays a major role in our model, and the intervals of parameters is used as simple treatments of uncertainty, while many treatments of uncertainty (e.g., probabilistic, fuzzy, Dempster Shafer, scenario, etc.) are available. The interval analysis makes a simple and practical choice to use upper and lower bounds on the parameter values elicited from experts. A sophisticated treatment of this uncertainty would bely the aim of this proposed method, which is to suggest where new investigation is needed across a large-scale system.

Last but not least, a reader might believe that rural segments are not congested and expect that segments most needing access management are located in urbanized areas, and thus that it is redundant to include the corridor segments in rural area for access management program evaluation. Indeed, rural segments are of high concern to planners since their time horizon is 10 - 20 years. To not protect a rural segment (with right-of-way acquisition, development restrictions, and others) is a typical regret of planners once the development is sure to occur or has already occurred. The protection of urbanized segments is more often regret than a feasible alternative. Nevertheless, there are some urban segments worthy of consideration by the filtering analysis for planning.

Nevertheless, various studies have suggested that an increase in access points can be associated with a longer travel time delay. For an access management program, the route mobility and traffic exposures are typically identified as competing dimensions in a resource allocation. These two objectives are placed on orthogonal axes as discussed above to reconcile tradeoffs and highlight the fact that a severe travel time delay on a corridor segment with a small number of average daily traffic is proportionally more significant than a mild travel time delay on a corridor segment with a large number of average daily traffic. The approach in this chapter uses simplified models and the best available data/evidence in supporting decision-making and offers a basis in evidence to help prioritize corridor access management.

The approach has aimed at *planning* wherein many billions of dollars of future regret may come about on thousands of miles of corridor, as distinguished from *design and operations*. The selection is not to fund the projects, rather to perform additional investigation of whether it is plausible that benefits exceed costs, or if additional precision of the benefits or cost estimates is otherwise of interest. The efforts address how to allocate scarce resources for modeling studies associated with an access management program. The innovation of this chapter is to enable access management planning to proceed with sparse data and appropriately simplified models on a large scale of thousands of miles of arterial corridors (and many thousands of miles of adjacent network). Another innovation is in the identification of metrics of *intensity* and *exposure* for this topic.

4.6 Chapter summary

This chapter developed a method of identifying and prioritizing corridor sections most needing further access management investment with a focus on travel-time savings. A quantitative framework was described by introducing several assessment metrics and applying multicriteria analysis and cost-benefit analysis with parameter uncertainties. Section 4.2 provided an introduction to the problem. Section 4.3 described the technical approach of quantification of uncertain benefits and costs, and the benefits-to-costs ratio, and compiled a prioritization framework. Section 4.4 demonstrated general methodology in more detail on a multiscale large transportation system. Section 4.5 provided a discussion of the results. Section 4.6 provided a chapter summary. The major contribution of this chapter is to develop a similar method from a complementary perspective of travel-time savings.

5 Method phase three: Safety improvement and travel-time savings

5.1 Chapter overview

This chapter will develop a risk-cost-benefit analysis jointly from the perspectives of safety and congestion, and demonstrate the innovation in application to priority-setting in access management. A quantitative framework will be described by introducing several assessment metrics and applying multicriteria and cost-benefit analysis with parameter and data uncertainties. The sections of this chapter are organized as follows: (i) Section 5.2 will provide an introduction to the problem, (ii) Section 5.3 will describe the technical approach of quantification of uncertain benefits and costs, and the benefits-to-costs ratio, and compile a prioritization framework, (iii) Section 5.4 will demonstrate general methodology in more detail on a multiscale large transportation system, (iv) Section 5.5 will provide a discussion of the results, and (v) Section 5.6 will provide a chapter summary. The major contribution of this chapter is to adopt interval analysis of parameter uncertainties for multicriteria risk-cost-benefit analysis with diverse sources of data and elicitation uncertainties, and fulfill a need to integrate the above perspectives, safety improvement and travel-time savings.

5.2 Introduction

For the new application of evaluating and guiding an access management program, this chapter will extend analytical methods in chapters 3 and 4. Usually no single model or perspective is sufficient for complex decision and risk problems (Haimes 2009). For example, public agencies cannot always know preference rankings of transportation projects from several perspectives, such as travel-time savings, safety improvement, roadway capacity increment, etc. Typically, diverse source of data and expertise are elicited to support risk-cost-benefit analysis by agencies. In these situations, it is common to have missing, partially relevant, and imprecise data on key parameters of a priority-setting model.This chapter demonstrates general lessons from how prioritization of resources for transportation access management programs can proceed with imprecise or partially relevant data of underlying parameters, including crash rates, travel speeds, time-savings and crash-reduction factors, and related costs.

Xu et al. (2014) and Xu and Lambert (2013a) addressed safety and congestion separately, neglecting to integrate the several perspectives and to treat the uncertainties of underlying data and parameters. This chapter will thus develop a risk-cost-benefit analysis jointly from the perspectives of safety and congestion, and demonstrate the innovation in application to priority-setting in access management. The chapter will describe the functional forms and parameters of a benefit-to-cost (B/C) ratio that is able to accommodate several perspectives jointly, with appropriate attention to the underlying data and elicitation uncertainties.

Hazard intensity indicates the potential harm per unit of exposed population. Population exposure indicates the size of the population that is subject that harm. Higher densities (per mile) of access points are associated to reductions in free-flow speed and increases in vehicular crash rates. To initiate the cost-benefit analysis in access management, first the hazard intensity is defined as the access point density, and the population exposure is in terms of ADT, which has been widely used in risk and transportation literature. They are often identified as potentially competing dimensions in a resource allocation in the access management program. Next quantifications of benefits and costs of access management and the parameters of B/C ratios from time savings and safety improvement perspectives are described sequentially, amenable to monetizing the potential needs of access management. Last the measure of intensity and exposure with other parameters as the B/C ratio are integrated in the context of a multicriteria analysis, which is assessed and investigated in details subsequently. An evidence diagram is used with two contours separating three tiers (high, medium, and low) of priority in a scatterplot of two key state variables of corridor sections: (i) traffic volume (vehicles per day), and (ii) access point density (access points per mile). The high-priority is above the upper contour, where the B/C ratio exceeds one for all possible values of uncertain parameters; the medium-priority is between upper and lower contours, where the B/C ratio exceeds one for some possible values of the exogenous parameters; the low-priority is below the lower contour, where the B/C ratio does not exceed one for any possible values of exogenous parameters. To account for several perspectives on the benefits and costs assessment, the B/C ratio is evaluated taking into account parameter intervals for safety improvement and travel-time savings.

The forthcoming analysis helps to prioritize and screen among thousands of corridor segments for further operations/design investigation and relevant data collection and elicitation of experts from different perspectives, such as travel-time savings, crash reduction, etc. The analysis identifies principles, models, metrics, and information needs. Immediately following will be a practical example with a 6,000 miles transportation network on a geographic region of 43,000 square miles.

5.3 Quantitative metrics and approach

5.3.1 Quantification of benefits – travel-time savings

This section will relate access points to travel delays. The HCM (U.S. National Research Council 2010) describes the access point density adjustment factor in a model of estimating free-flow speed for multilane highways. Table 13 in Chapter 4 shows the magnitude of the adjustment of the free-flow speed by access point density.

In our planning-level model, the difference of free-flow speed and impaired speed on the corridors is used to measure the travel time delay. This simplified model assumes that the reduction in free-flow speed depends on the access point density of a corridor segment linearly. Thus, the current delay hours per vehicle along a corridor segment is defined as the travel time delay for a single vehicle due to existing access points as follows.

$$\begin{aligned} &\mathit{Travel\ Time\ Delay} \\ &= \frac{\mathit{Length\ of\ Roadway\ Segment}}{\mathit{Free\ Flow\ Speed} - 0.25 \times \mathit{Access\ Point\ Density}} - \frac{\mathit{Length\ of\ Roadway\ Segment}}{\mathit{Free\ Flow\ Speed}} \\ &= \frac{\mathit{Length\ of\ Roadway\ Segment}}{\mathit{Free\ Flow\ Speed} - 0.25 \times \dfrac{\mathit{Number\ of\ Access\ Points}}{\mathit{Length\ of\ Roadway\ Segment}}} - \frac{\mathit{Length\ of\ Roadway\ Segment}}{\mathit{Free\ Flow\ Speed}} \end{aligned} \tag{12}$$

In application, the minimum of 40 access points per mile and the actual density is used as the access point density in Equation 1, which is consistent with Table 13 from HCM (2010).

To normalize the travel delay hours along a corridor segment with various lengths, the average delay hours per mile for a single vehicle is defined as the *travel time delay index* as follows:

$$
\begin{aligned}
I &= Travel\ Time\ Delay\ Index = The\ Current\ Delay\ Hours\ per\ Vehicle\ per\ Mile \\
&= \frac{Travel\ Time\ Delay}{Length\ of\ Roadway\ Segment} \\
&= \frac{\dfrac{Length\ of\ Roadway\ Segment}{Free\ Flow\ Speed - 0.25 \times \dfrac{Number\ of\ Access\ Points}{Length\ of\ Roadway\ Segment}} - \dfrac{Length\ of\ Roadway\ Segment}{Free\ Flow\ Speed}}{Length\ of\ Roadway\ Segment} \\
&= \frac{1}{Free\ Flow\ Speed - 0.25 \times \dfrac{Number\ of\ Access\ Points}{Length\ of\ Roadway\ Segment}} - \frac{1}{Free\ Flow\ Speed}
\end{aligned}
\tag{13}
$$

The *travel time delay index* is used to quantify time saved per mile for a single vehicle that might be expected after implementing a typical access management along a specific corridor segment. That is, the greater is the current delay, the greater is the potential benefit (delay reduction) of treating the access points into the future. To quantify the equivalent monetary value of travel-time savings, the *value of travel time* is used with the *travel time delay index*, and the estimates of the *value of travel time* have been discussed in Chapter 4.

The benefits calculation in Equation 14 focuses on the reducible delay time. T, *V*, *L*, *N*, and *F* are explained by Table 22. As described in the forthcoming section, the number of access points, length of corridor segment, and traffic volume are characteristics of particular corridor sections, while the value of travel time and free-flow speed are typical of large regions rather than unique to a corridor section.

$$
\begin{aligned}
B_T &= Travel\ Time\ Savings\ Benefits \\
&= Travel\ Time\ Delay\ Index \times Traffic\ Exposure \times Value\ of\ Time \\
&= I \times T \times V \times 365 \qquad (14) \\
&= \left(\frac{1}{F - 0.25 \times N/L} - \frac{1}{F} \right) \times T \times V \times 365 \\
&= Potential\ Time\ Savings(\$)/Mile/Year
\end{aligned}
$$

Table 22. Summary of key parameters for quantification of the potential benefits (travel-time savings) of corridor access management

Parameter	Parameter Description	Units
I	Travel time delay index	Hours per mile per vehicle
T	ADT	Vehicles per day
V	Value of travel time	$ per hour
L	Length of corridor segment	Miles
N	Number of access points	Access points
F	Free-flow speed	Miles per hour

5.3.2 Quantification of benefits – safety improvement

This section will relate access points to corridor safety. We use the metric of *crash intensity*, which is first introduced for measuring the likelihood of crashes per unit of exposed vehicles by Xu et al. (2014), and a *crash reduction factor* to monetize the potential benefits of access management. The current *crash intensity* for the corridor segment expressed as the number of intersection-related crashes per 10 million *crash opportunities*, which is defined as the product of the average daily traffic and the number of access points, is as follows.

$$\begin{aligned}
&Access\ Related\ Crash\ Intensity \\
&= \frac{Number\ of\ Crashes\ at\ Access\ Points\ per\ Year \times 10^7}{365 \times Crash\ Opportunity} \\
&= \frac{Number\ of\ Crashes\ at\ Access\ Points\ per\ Year \times 10^7}{365 \times ADT \times Number\ of\ Access\ Points}
\end{aligned} \qquad (15)$$

Since an effective access management strategy can improve the corridor safety performance, below the calculation of benefits focuses on safety improvement and a *crash reduction factor* is used to quantify the percentage of crashes potentially avoided after implementing typical access management techniques. Crash costs is included in the quantification of expected access management benefits in this paper, as crash costs are always used to allocate highway safety resources among programs, to evaluate proposed safety regulations, and to convince policymakers that safety programs are beneficial. Furthermore, to account the traffic *exposure* (ADT) measuring the number of vehicles that are daily subjected to that *crash intensity*, the normalized (by length) benefit of access management from safety improvement perspective then takes the following form, where *R*, *T*, *D, β,* and *Δ* are described by Table 23. In Equation 16, the traffic volume, access point density, and length of roadway segment are characteristics of particular corridor sections, while crash intensity, crash costs, and crash reduction factor are typical of large regions rather than unique to a corridor section.

$$
\begin{aligned}
&B_S = Safety\ Improvement\ Benefits = \\
&= \left(\begin{aligned} &Crash\ Intensity \times Exposure \times Number\ of\ \ Access\ Points \\ &\times Average\ Cost\ \ per\ Crash \times Crash\ Reduction\ Factor \end{aligned} \right) \Big/ Length\ of\ \ Roadway\ Segment \\
&= \left(\begin{aligned} &Crash\ Intensity \times Exposure \times Length\ of\ \ Roadway\ Segment \\ &\times Access\ Point\ Density \times Average\ Cost\ \ per\ Crash \times Crash\ Reduction\ Factor \end{aligned} \right) \Big/ Length\ of\ \ Roadway\ Segment \\
&= 365 \times R \times T \times D \times \beta \times \Delta \\
&= Potential\ Crash\ Avoided\ (\$) / Mile / Year
\end{aligned}
$$

(16)

Table 23. Summary of key parameters for quantification of the potential benefits (safety improvement) of corridor access management

Parameter	Parameter Description	Units
R	Access related crash intensity	Access related crashes per 10 million vehicle access points passed
T	ADT	Vehicles per day
D	Access points density	Access points per mile
β	Average cost per crash avoided	$ per crash avoided
Δ	Crash reduction factor	Crashes avoided/current crashes

5.3.3 Quantification of costs

The quantification of access management costs in this section is quite similar to that discussed in Chapter Sections 3.3.2 and 4.3.2. However, to incorporate with the new measures of benefits above and find the B/C ratio used to select projects, several changes have been made to the access management costs accordingly. The unit of project costs in this chapter is $/mile/year as shown in Table 24. It is assumed that preliminary engineering costs (C_{PE}), right-of-way acquisition costs (C_{RW}), construction costs (C_{CN}), and preservation and maintenance costs (C_{PM}) of access management projects are changing linearly with the length of a corridor segment and all these costs can be summed up as the total costs (C_{Total}). Details of the cost elicitations are provided in Chapter 3.

Table 24. Parameters for quantification of typical annualized costs of access management

Parameter	Parameter Description	Unit
C_{PE}	Preliminary engineering cost	\$ per mile per year
C_{RW}	Right-of-way acquisition cost	\$ per mile per year
C_{CN}	Construction cost	\$ per mile per year
C_{PM}	Preservation and maintenance cost	\$ per mile per year
C_{Total}	Total project cost	\$ per mile per year

5.3.4 Cost-benefit analysis with uncertainties for safety improvement and travel-time savings

When allocating funds and other resources, stakeholders and analysts seek to filter among many competing needs with different level of benefits. This subsection describes a diagram of the candidate corridor segments, which helps to identify segments that are most beneficial for travel-time savings or safety improvement. Candidate segments, which are under consideration for implementation of access management techniques, are evaluated using a cost-benefit analysis adapted from Xu and Lambert (2013a) and Xu et al. (2014).

For highway access management, as the access point density and average daily traffic are identified as potentially competing dimensions in a resource allocation, a tradeoff diagram is effective to relate the *traffic exposure* in terms of ADT to the *hazard intensity* in terms of access point density. A need for access management located in one zone of such a graph represents a low-exposure and low-hazard situation. A need located in another zone represents a high-exposure and high-hazard situation. Cost-benefit analysis will be adapted to distinguish several zones of such a graph in this paper. A benefit-to-cost (B/C) ratio is defined to be the ratio of the expected annual benefits to costs. As described above, the benefits of access management are in terms of travel-time savings and safety improvement. Thus, three related analyses (the benefits of travel-time savings, the benefits of safety improvement, and the benefits of travel-time savings and safety improvement jointly) in Equations 17, 18, and 19 are used for obtaining a comprehensive prioritization policy for access management.

The B/C ratio of travel-time savings benefits to the total costs is defined as follows:

$$
\begin{aligned}
\psi_T &= \frac{Benefits_{Travel\ Time\ Savings}}{Costs} = \frac{B_T}{Costs} \\
&= \frac{I \times T \times V \times 365}{C_{PE} + C_{RW} + C_{CN} + C_{PM}} = \frac{\left(\frac{1}{F - 0.25 \times N/L} - \frac{1}{F}\right) \times T \times V \times 365}{C_{Total}} \\
&= \frac{\left(\frac{1}{F - 0.25 \times D} - \frac{1}{F}\right) \times T \times V \times 365}{C_{Total}} = \frac{Potential\ Travel\ Time\ Savings(\$)/Mile/Year}{Costs(\$)/Mile/Year}
\end{aligned}
\tag{17}
$$

The B/C ratio of safety improvement benefits to the total costs is defined as follows:

$$
\begin{aligned}
\psi_S &== \frac{Benefits_{Safety\ Improvement}}{Costs} = \frac{B_S}{Costs} \\
&= \frac{365 \times R \times T \times D \times \beta \times \Delta}{10^7 \times \left(C_{PE} + C_{RW} + C_{CN} + C_{PM}\right)} = \frac{365 \times R \times T \times D \times \beta \times \Delta}{10^7 \times C_{Total}} \\
&= \frac{Potential\ Crash\ Avoided(\$)/Mile/Year}{Total\ Costs(\$)/Mile/Year}
\end{aligned}
\tag{18}
$$

The B/C ratio of benefits of travel-time savings and safety improvement jointly to the total costs has the following form:

$$\begin{aligned}
\psi &= \frac{Benefits_{Safety\ Improvement} + Benefits_{Travel\ Time\ Saving}}{Costs} = \frac{B_S + B_T}{C_{PE} + C_{RW} + C_{CN} + C_{PM}} \\
&= \frac{365\times R\times T\times D\times \beta\times \Delta + \left(\frac{1}{F-0.25\times D} - \frac{1}{F}\right)\times T\times V\times 365\times 10^7}{10^7\times C_{Total}} \\
&= \frac{365\times R\times T\times D\times \beta\times \Delta + \left(\frac{0.25\times D}{F-0.25\times D}\right)\times \frac{1}{F}\times T\times V\times 365\times 10^7}{10^7\times C_{Total}} \\
&= \frac{365\times T\times \left(D\times R\times \beta\times \Delta + \left(\frac{0.25\times D}{F-0.25\times D}\right)\times \frac{1}{F}\times V\times 10^7\right)}{10^7\times C_{Total}} \\
&= \frac{Total\ Benefits(\$)/Mile/Year}{Total\ Costs(\$)/Mile/Year}
\end{aligned} \tag{19}$$

In Equations 17, 18, and 19, Ψ_T, Ψ_S, and Ψ are defined as benefit-to-cost ratios, and dimensional analyses of benefit-to-cost ratios, Ψ_T *and* Ψ_S, are provided in Equations 20 and 21 respectively.

For a road segment of interest, an interval range of potential values for each of the exogenous parameters is estimated, i.e., parameters other than access point density and average daily traffic. The interval analysis is undertaken for the parameters and not for the location-specific variables. In this framework, diverse experts/stakeholders from transportation agencies representing several professional disciplines assess the uncertainties of each parameter and define the interval ranges. These elicitations are calibrated by referring to industry standards, handbooks, and manuals. The interval analysis, where the uncertain parameters are described by an upper and lower bounds, of B/C ratio incorporated to a multicriteria evaluation of an access management program will be described on a diagram of two coordinate axes. The *traffic exposure* in terms of ADT increases along the horizontal axis, while the *hazard intensity* in terms of access point density increases along the vertical axis.

Setting the benefit-to-cost ratio (Ψ_T, Ψ_S, or Ψ) equal to one, the extreme values of the interval evaluation generate two contours separating three tiers of priority : (1) *high*, whose needs have *exposure* and *intensity* such that the B/C ratio exceeds 1.0 for all possible values of the exogenous parameters, (2) *medium*, whose needs are such that the B/C ratio exceeds 1.0 for some possible values of exogenous parameters, (3) *low*, whose needs are such that B/C ratio does not exceed 1.0 for any possible values of the exogenous parameters. Access management is thus distinguished in this diagram by their position in terms of *exposure* and *intensity* relative to the zones. The candidate segments falling below the lower contour (low priority) should not be recommended for further investment. The segments between the upper and lower contours (medium priority) have an indeterminate inequality of benefits and costs, and further elicitations and/or data collection might be useful to suggest the cost-efficiency. The segments falling above the upper contour (high priority) should be prioritized first to receive further resources and investigations, because they are most economically justified by the cost-benefit analysis. Furthermore, adjusting of the ranges of exogenous parameters shifts the decision zones in response to local and regional particularities.

With the above method, a cost-benefit evaluation can thus proceed without precise knowledge of the exogenous parameters. A diagram of needs contrasting *intensity* and *exposure* makes it possible to interpret the relative priorities, without excluding non-quantified considerations. The above approach, to be demonstrated in examples forthcoming, brings performance metrics and available objective evidence to inform the allocation of limited resources for access management across a large-scale infrastructure system, all the while accounting for diverse quality and nature of elicitations, data, and the associated parameter values.

$$\frac{\overbrace{\left(\frac{\dfrac{1}{\dfrac{Mile}{Hour}-\dfrac{\dfrac{Mile}{Hour}}{\dfrac{Access\ Point}{Mile}}\times\dfrac{Access\ Point}{Mile}}-\dfrac{1}{\dfrac{Mile}{Hour}}}{Vehicle}\right)}^{Travel\ Time\ Delay\ Index}\overbrace{\left(\frac{Vehicle}{Day}\right)}^{Traffic\ Exposure}\overbrace{\left(\frac{Dollar}{Hour}\right)}^{Value\ of\ Travel\ Time}\left(\frac{Day}{year}\right)}{\underbrace{\left(\frac{Dollar}{(Mile)(Year)}\right)}_{Costs\ of\ \ Access\ Management\ Project}} \tag{20}$$

$$\frac{\left(\frac{Day}{Year}\right)\overbrace{\left(\frac{\left(10^{7}\right)\left(\dfrac{Current\ Crashes}{Year}\right)}{\left(\dfrac{Day}{Year}\right)\left(\dfrac{Vehicle}{Day}\right)\left(Access\ Point\right)}\right)}^{Crash\ Intensity}\overbrace{\left(\frac{Vehicle}{Day}\right)}^{Traffic\ Exposure}\overbrace{\left(\frac{Access\ Point}{Mile}\right)}^{Access\ Point\ Density}\overbrace{\left(\frac{Dollar}{Crashes\ Avoided}\right)}^{Crash\ Cost}\overbrace{\left(\frac{Crashes\ Avoided}{Current\ Crashes}\right)}^{Crash\ Reduction\ Factor}}{\left(10^{7}\right)\underbrace{\left(\frac{Dollar}{(Mile)(Year)}\right)}_{Total\ Cost\ of\ \ Access\ Management\ Project}} \tag{21}$$

5.4 Case study on a multiscale transportation system

This section applies the above method to prioritize needs for corridor access management on 6,000 mile of arterials. Prioritization is performed on all roadway sections in rural and urban areas respectively belonging to the SMS, which is a 6,000 miles multimodal network, includes the highway system, critical evacuation routes, and primary routes spanning many localities with over eleven million in resident population. In the following, our examples avoid considering the interstate freeways/expressways with a total length of 1,500 miles, since generally the access management programs are not applicable to limited-access segments whose access is already controlled by federal and state agencies. The number of crashes, access points density, average daily traffic, posed-speed, etc. for each corridor section are collected from diverse data sources, which have been discussed in Chapter Section 3.4. Ranges of average values of exogenous parameters corresponding to a regional or sub-regional analysis are used for interval analysis, including the free-flow speed, access-related crash intensity, crash cost, crash reduction factor, value of travel time, access management costs, etc.

5.4.1 Entire region

First a regional database of the entire 4,500 miles road network, which does not include freeways/expressways segments, is addressed. Table 3 in Chapter Section 3.4.1 describes key characteristics of the transportation network in the region.

To account for uncertainties of benefits and costs, we allow the experts/stakeholders upper and lower bounds on each of F, R, β, Δ, V, and C_{Total}. Thus, the parameter F may assume an interval of (40-mile/hour, 60-mile/hour) in rural areas and (35-mile/hour, 50-mile/hour) in urban areas, indicating that experts/stakeholders assert for this region that the average free-flow speed on SMS in rural areas lies between 40-mile per hour and 60-mile per hour, while the average free-flow speed in urban areas lies between 35-mile per hour and 50-mile per hour. Furthermore, this also represents that they have more uncertainties in the free-flow speed in rural areas than that in urban areas, and typically the average free-flow speed in rural areas is higher than that in urban areas. Table 25 describes upper and lowers bounds of the exogenous parameters, which are set in consultation with experts/stakeholders from regional transportation and other agencies, and calibrated with related literatures and studies.

Table 25. Cost-benefit function parameter bounds for prioritization of needs for access management in a regional network of transportation corridors

Parameter	**Unit**	**Rural**		**Urban**	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
F	Miles/hour	65	95	55	80
R	Access related crashed per 10 million vehicle access points passed	0.25	1.4	0.85	3.30
β	$ /crash	60,000	80,000	65,000	90,000
Δ	Crashes avoided/current crashes	40%	65%	30%	60%
V	$/hour	15	30	20	35
C_{Total}	$/mile/year	100,000	500,000	5500,00	1,200,000

It is important to identify the segments that are most justified by cost-benefit analysis, as well as by considering the performance metrics. As described above, the stakeholders/experts-elicited upper and lower range values are used to generate two contours, which partition the access point density to traffic volume plot into three priority zones, and examine the competing dimensions of the hazard intensity and traffic exposure for each corridor segment. As discussed in previous chapters, segments falling above the upper contour should be prioritized to receive investigation and investment resources. Segments falling below the lower contour are not recommended for allocating resources in considering only the economic issues. For other segments between upper and lower contours, further evidence might be needed to determine the potential cost-efficiency of access management investment.

Recall that we have three B/C ratios – Ψ_S , Ψ_T, and Ψ, and for each B/C ratio, the interval of the exogenous parameters are used to build two contours which are superimposed on a scatterplot of *intensity* and *exposure*. Figure 21 (the scatterplot in log scale) provides a visualization of the cost-benefit analysis and multicriteria analysis for corridor segments belonging to rural and urban areas. Because the range values and uncertainty levels differ between rural and urban areas, places of upper and lower contours are different in Fig. 21. The crossing of contours in the scatterplot suggests conditions under which particular projects would be justified by one B/C criterion and fail to be justified by another criterion. For example in Figure 21, several projects are located above the red dashed line, however are below the blue dashed line. This implies that the associated B/C ratio is surely less than 1 from the travel-time-savings perspective, while the B/C ratio could be greater than 1 (depending on uncertain parameter values) from the safety improvement perspective. The counts and total length of all corridor segments falling in three priority zones for Ψ_T, Ψ_S, and Ψ are listed in Table 26 and Table 27. Fig. 22 shows the legend for all intensity and exposure plots in this chapter and Fig. 23 displays system diagrams for access management projects prioritization based on the evaluation of Ψ_T, Ψ_S, and Ψ. The sample Matlab code used to generate the scatterplot and decision contours are shown in Appendix D.

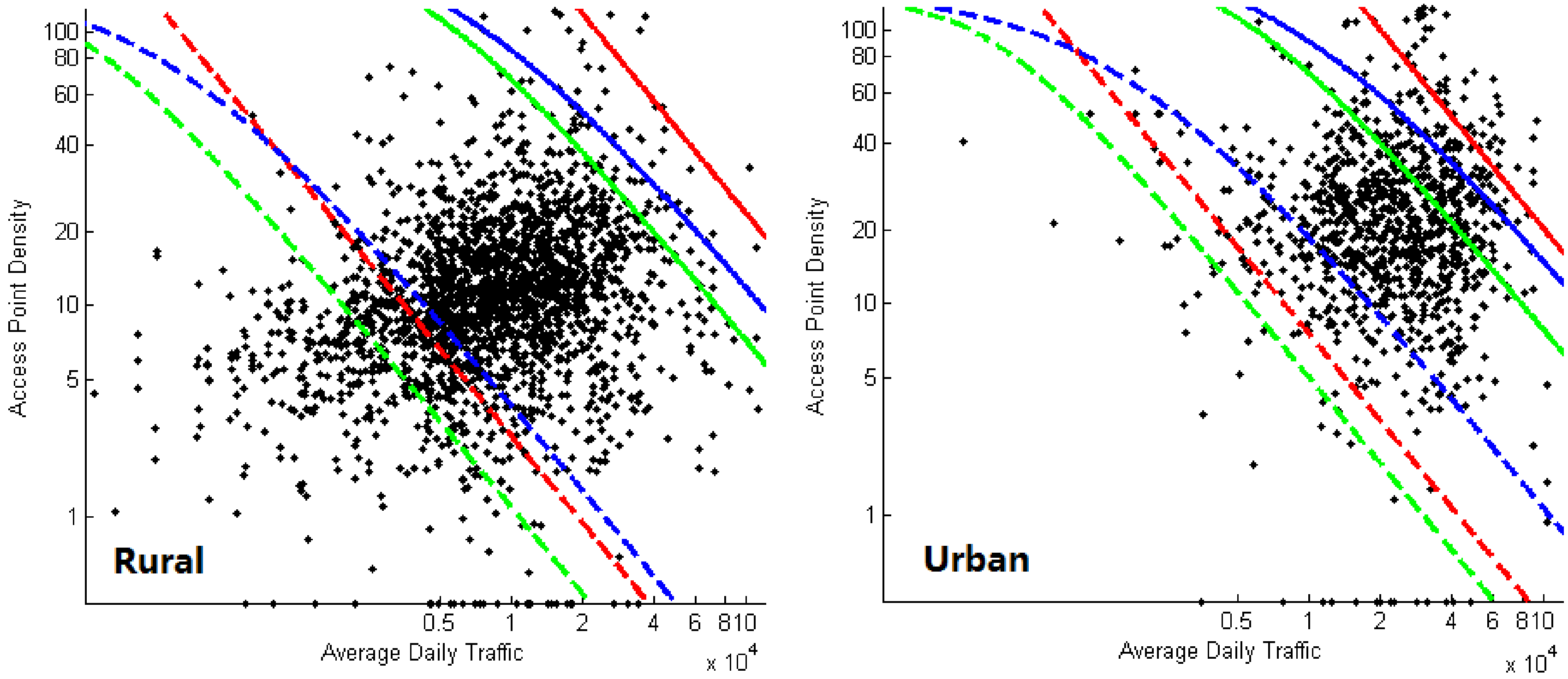

Figure 21. Example of the priority setting for the region of the case study to contrast access point density and traffic exposure (Figure is in log scale and using the Figure 22 as the legend.)

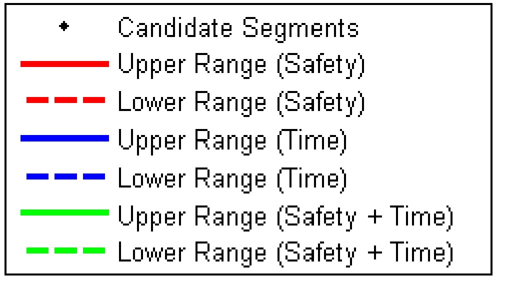

Figure 22. The legend for the access point density and traffic exposure diagrams of this Chapter

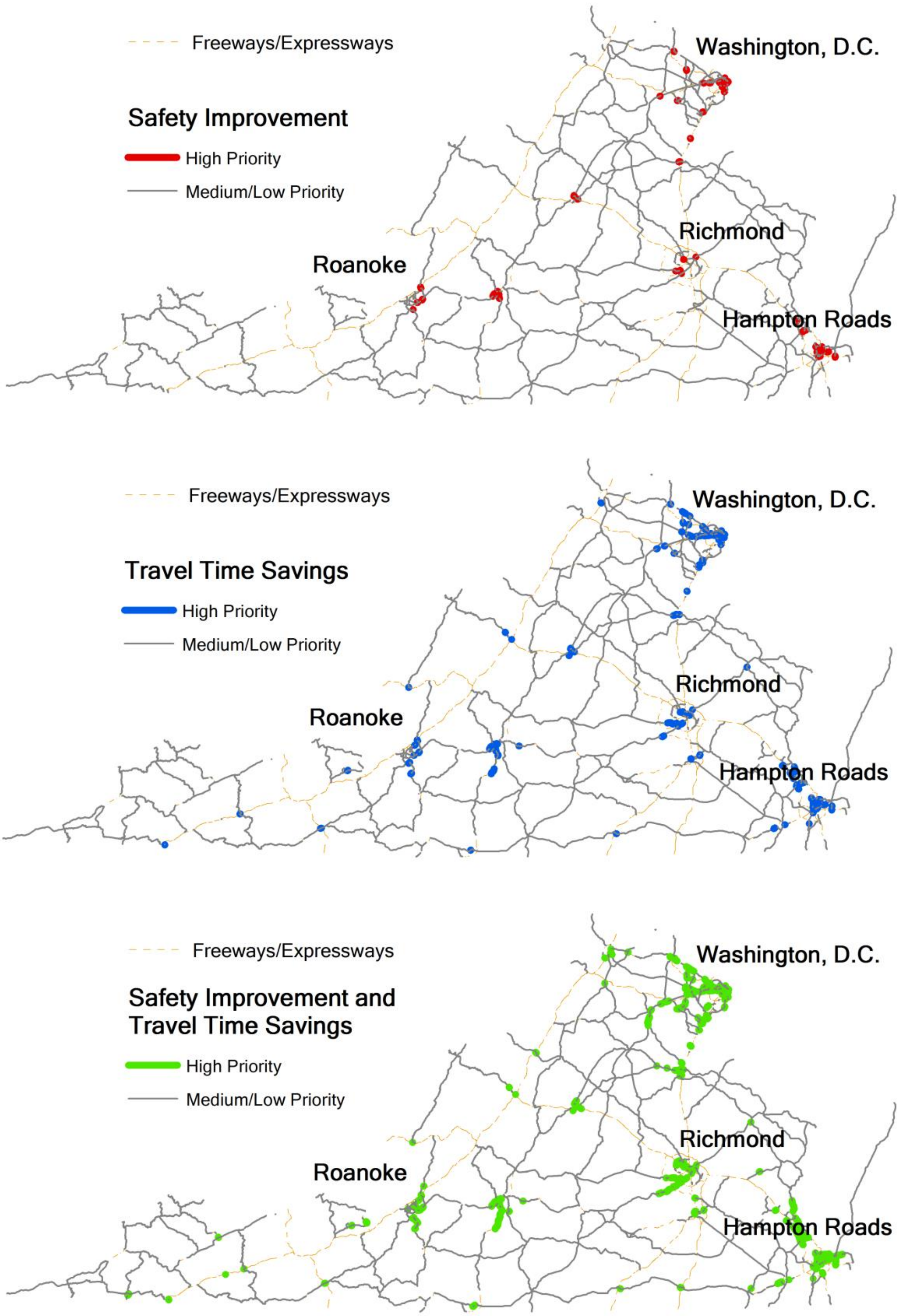

Figure 23. Several tiers of priority for the region of the case study

Table 26. Number of corridor segments in a regional network of transportation corridors

Cost-to-benefit ratio	Rural			Urban		
	Ψ_S	Ψ_T	Ψ	Ψ_S	Ψ_T	Ψ
B/C > 1	5	35	75	51	105	255
B/C > 1 or B/C < 1	1682	1437	1812	877	710	692
B/C < 1	507	722	307	54	167	35

Table 27. Total length (in miles) of corridor segments in a regional network of transportation corridors

Cost-to-benefit ratio	Rural			Urban		
	Ψ_S	Ψ_T	Ψ	Ψ_S	Ψ_T	Ψ
B/C > 1	0.8	13.7	42.5	13.0	39.6	131.5
B/C > 1 or B/C < 1	2523.1	2080.1	2912.5	537.5	454.7	428.8
B/C < 1	1191.6	1621.7	760.4	24.6	80.9	14.9

5.4.2 Sub-regions

In addition to the study of the entire region, the prioritization methods are applied to the Virginia SMS corridor in Hampton Roads Planning District (sub-region 1) and Richmond Planning District (sub-region 2) and find particular decision policies for them. Several overview characteristics of corridor segments in these two sub-regions are provided in Tables 6 and 7 in Chapter Section 3.4.2.

Similar to previous study of the entire region, the interval estimation will be performed on all exogenous parameters. Furthermore, the stakeholders/experts are allowed different views on value uncertainties of exogenous parameters between these two planning districts, since the estimation of benefits and costs vary from sub-region to sub-region. Tables 28 and 29 describe the upper and lower bounds on parameters of costs and benefits of access management for sub-region 1 and sub-region 2 respectively, whose assessments rely on their own special transportation and construction conditions. For instance, for the crash reduction factor in rural areas, the stakeholders/experts describe that the percentage of crashes to be avoided by way of implementing the access management will range from 45% to 70% for sub-region 1, while they do anticipate a lower reduction percentage in sub-region 2, with an interval of 30% to 60%.

Table 28. Cost-benefit function parameter bounds for prioritization of needs for access management in a network of transportation corridors in *sub-region 1*

Parameter	**Unit**	**Rural**		**Urban**	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
F	Miles/hour	40	55	35	50
R	Access related crashed per 10 million vehicle access points passed	0.4	1.5	0.8	2.5
β	$ /crash	65,000	85,000	60,000	95,000
Δ	Crashes avoided/current crashes	45%	70%	35%	65%
V	$/hour	15	35	20	40
C_{Total}	$/mile/year	200,000	600,000	700,000	1,200,000

Table 29. Cost-benefit function parameter bounds for prioritization of needs for access management in a network of transportation corridors in *sub-region 2*

Parameter	**Unit**	**Rural**		**Urban**	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
$\boldsymbol{F}$	Miles/hour	35	55	35	50
$\boldsymbol{R}$	Access related crashed per 10 million vehicle access points passed	0.3	1.5	1.3	3.5
$\boldsymbol{\beta}$	$ /crash	45,000	75,000	65,000	90,000
$\boldsymbol{\Delta}$	Crashes avoided/current crashes	30%	60%	25%	55%
$\boldsymbol{V}$	$/hour	15	35	15	40
$\boldsymbol{C_{Total}}$	$/mile/year	100,000	450,000	600,000	1,100,000

Then the evaluation proceeds by using the above interval ranges of uncertainties related to the benefit-to-cost ratio. As above, the cost/benefit contours are used to identify corridor segments where the benefits of an access management project outweigh the costs, segments where the benefits of a access management project does not outweigh the costs, and segments where the relationship is inconclusive.

The cost-benefit analysis for Ψ_S, Ψ_T, and Ψ in sub-region 1 is described in Fig. 24 (scatterplot in log scale), and that for sub-region 2 is displayed in Fig. 25 (scatterplot in log scale). For both sub-regions only a few corridor segments have high priorities and this suggests the immediate focus of a resource allocation strategy. Tables 30, 31, 32, and 33 provide the qualitative results of this approach, which describe the number and total length of corridor segments falling in three priority zones for sub-regions 1 and 2 according to particular interval ranges of each exogenous parameter and benefit-to-cost function. E.g., in sub-region 1 if both the safety improvement and travel-time savings are major concerns for access management program, 113 segments with total length of 56.8 miles should receive the investigative resources first, while 36 segments with total length 52.5 miles should be addressed last, because access management projects on these 36 segments are too costly relative to the potential benefits (safety improvement and travel-time savings jointly). For sub-region 2, 49 segments with a total length of 27.5 miles should receive the investigative resources first, while 8 segments with total length 12.1 miles should be addressed last. Figures 26 and 27 provide diagrams from these two sub-regions for the prioritization of future access management investment, including closing access points, acquiring right of way, collecting additional data, making new alignments, etc.

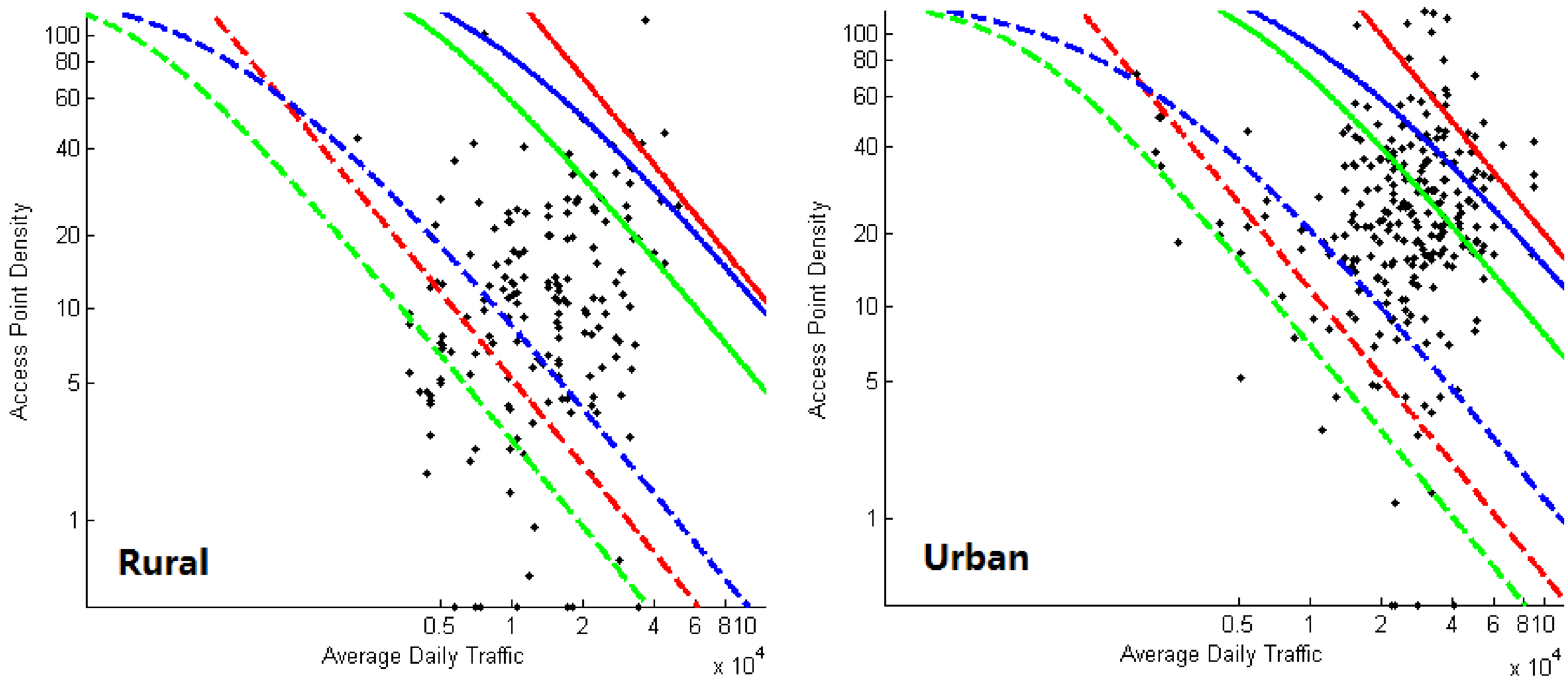

Figure 24. Example of the priority setting for *sub-region 1* to contrast access point density and traffic exposure (Figure is in log scale and using the Figure 22 as the legend.)

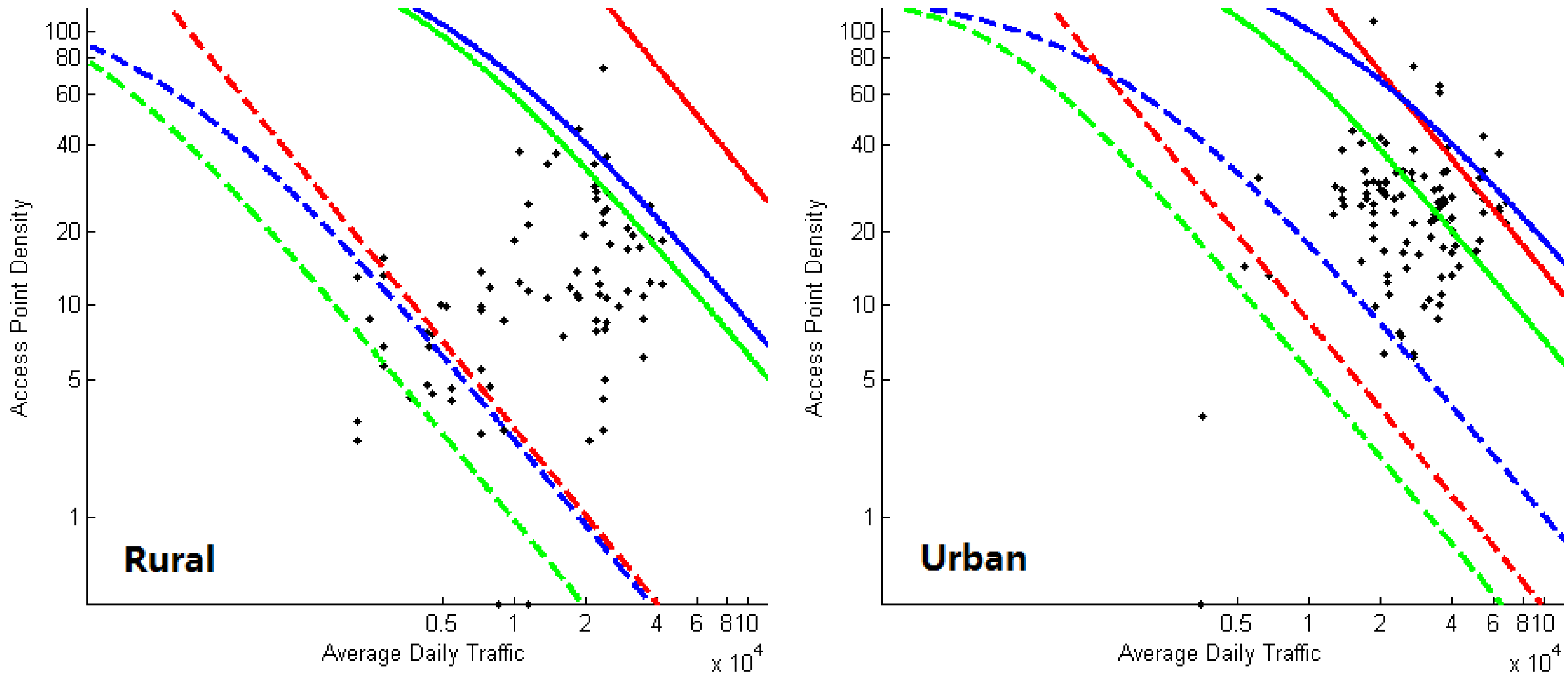

Figure 25. Example of the priority setting for *sub-region 2* to contrast access point density and traffic exposure (Figure is in log scale and using the Figure 22 as the legend.)

Table 30. Number of corridor segments in *sub-region 1*

Cost-to-benefit ratio	Rural			Urban		
	Ψ_S	Ψ_T	Ψ	Ψ_S	Ψ_T	Ψ
B/C > 1	4	7	20	19	40	93
B/C > 1 or B/C < 1	127	107	126	210	173	150
B/C < 1	40	57	25	25	41	11

Table 31. Total length (in miles) of corridor segments in *sub-region 1*

Cost-to-benefit ratio	Rural			Urban		
	Ψ_S	Ψ_T	Ψ	Ψ_S	Ψ_T	Ψ
B/C > 1	0.4	1.9	9.8	3.9	13.6	47.0
B/C > 1 or B/C < 1	143.7	117.6	172.2	130.9	111.9	93.0
B/C < 1	79.9	104.5	42.1	15.7	24.9	10.4

Table 32. Number of corridor segments in *sub-region 2*

Cost-to-benefit ratio	**Rural**			**Urban**		
	Ψ_S	Ψ_T	Ψ	Ψ_S	Ψ_T	Ψ
B/C > 1	0	4	7	13	9	42
B/C > 1 or B/C < 1	64	63	70	92	95	65
B/C < 1	19	16	6	4	5	2

Table 33. Total length (in miles) of corridor segments in *sub-region 2*

Cost-to-benefit ratio	**Rural**			**Urban**		
	Ψ_S	Ψ_T	Ψ	Ψ_S	Ψ_T	Ψ
B/C > 1	0.0	0.9	3.7	5.8	1.4	23.8
B/C > 1 or B/C < 1	79.8	83.8	106.3	62.7	66.4	45.8
B/C < 1	41.4	36.5	11.2	2.0	2.7	0.9

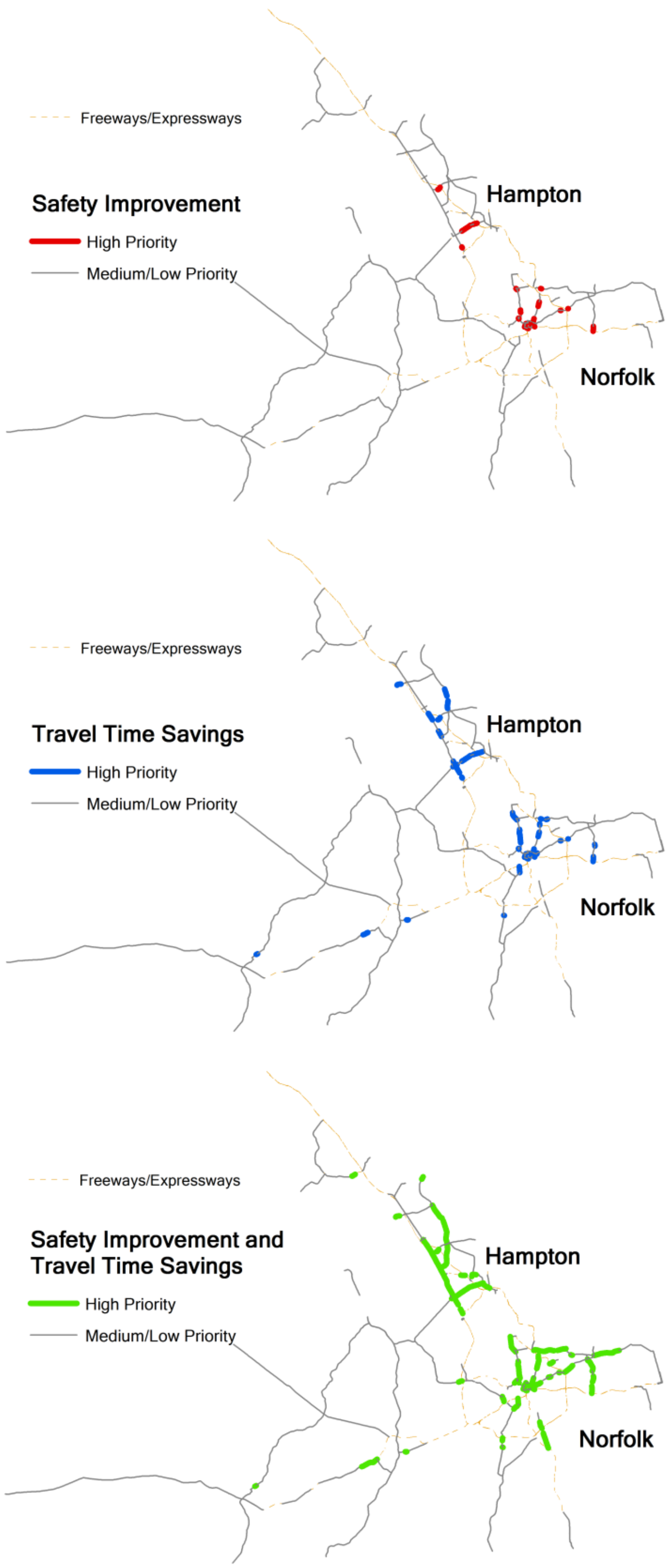

Figure 26. Several tiers of priority for the *sub-region 1*

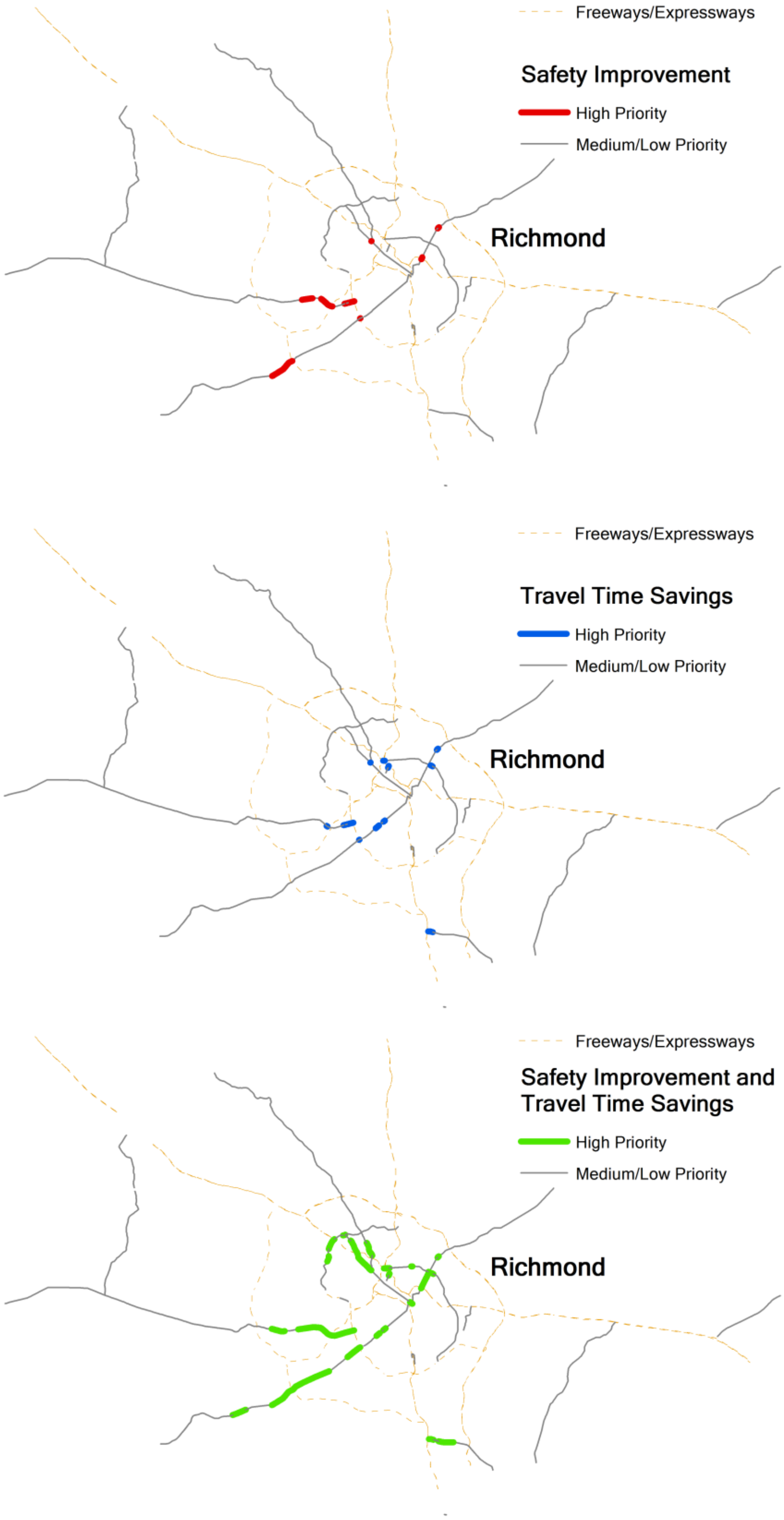

Figure 27. Several tiers of priority for the *sub-region 2*

Table 34 presents a sample of the qualitative results of this approach. The table describes the corridor segments with various levels of priority, the uncertainties of the parameters, the upper and lower contours in a plot of hazard *intensity* and traffic *exposure*, the benefit-to-cost ratio, etc.

Table 34. Sample of the qualitative results of the example, with implications for expert elicitations and data collection

Type of findings	*Sample of findings*
Uncertainties of the parameters	Degree of uncertainties is reflected in the uncertainty ranges of parameters, which varies across locations of corridors.
Positions of upper and lower contours	The positions are sensitive to uncertainty ranges of each of the parameters.
Shape of upper and lower contours	The shapes depend on the forms of benefit-cost functions (b/c ratios).
Corridor segments with high priorities	Segments with benefit-to-cost ratio greater than 1, which are fewer. The joint-benefits perspective has more high-prioritized corridor sections than either single perspective (safety or travel time).
Corridor segments with medium/low priorities	Segments with benefit-to-cost ratio less than 1, which are greater in number. The joint-benefits perspective has fewer low-prioritized corridor sections than either single perspective.

5.5 Discussion

The efforts in this chapter have demonstrated how resource allocation decisions can be supported by applying interval analysis (of uncertainties) to estimate of risk-reduction and other benefits that originate from heterogeneous sources of expertise. Furthermore, interval analysis is applied where there is imprecise knowledge of underlying parameters of a resource allocation to balance safety and other metrics, as it is recognized that a conventional method for propagating error or uncertainty in arithmetic calculation is interval analysis.

The approach in this chapter is complementary and consistent with the philosophy of multiobjective combinatorial optimization in Figure 28. The entries in parentheses are not demonstrated in this chapter, and are recommended for future work depending on the needs of the application at hand. The maximization of possibility of B/C ratio exceeding one is demonstrated in the tradeoff chart contours. The several pairs of contours are generated based on safety benefits alone, travel-time benefits alone, and safety and travel-time benefits added together.

In summary, this approach to risk-cost-benefit analysis with uncertain parameters should be of fundamental interest across applications of risk analysis, including engineering, health, environment, policy, economic development, etc. Multicriteria risk analysis (where safety or risk criteria are balanced among other objectives including cost and performance) and cost-benefit analysis (where monetization benefits and costs makes possible various measures of economic efficiency and effectiveness) do not typically meet. An innovation of this effort is how to feature the uncertainty (intervals) of a benefit-cost analysis within a context of a multicriteria risk-cost-benefit tradeoff analysis. The approach and its visual tool allow for the two perspectives (tradeoff analysis and B/C ratio) to complement one another. Furthermore, this chapter describes that the application of this method and its visual tool is quite compelling to allocate resources in such a way to avoid regret around the planning of infrastructure corridors where crash avoidance is among several other concerns for system evaluation.

Nonetheless, the contribution of the chapter has been to adopt interval analysis of parameter uncertainties for multicriteria risk-cost-benefit analysis with diverse sources of data and elicitation uncertainties. First, the urgency to allocate planning and investigative resources to highway segments and to consider safety and congestion mitigation along with other types of benefits is addressed. A multicriteria analysis and cost-benefit analysis are introduced together to risk assessment and management, in part by applying interval uncertainties where there is imprecise knowledge to underlying parameters. Consistent with diverse applications of risk analysis, the multicriteria analysis contrasts the *hazard intensity* with the *population exposure* in the evaluation of various benefits and costs. Second, measures of hazard *intensity* in forms of access point density and population *exposure* in forms of average daily traffic are identified, as well as other parameters that influence assessments of benefits and costs in access management. A quantitative cost-benefit analysis under uncertainties is introduced directly to reconcile trade-offs between *intensity* and *exposure* with respect to the corridor segment location, and prioritize among many thousands of road sections for which additional data, elicitations, and modeling might be useful for evaluation of an access management program from multiple perspectives, including travel-time savings and safety improvement. The method is demonstrated with transportation networks of an entire region (a U.S. state) and two of its sub-regions by introducing different benefit-to-cost functions (Ψ_S, Ψ_T, and Ψ) and characterizing various ranges of exogenous parameters for each region and sub-regions. Highway sections that are of high, medium, and low priority for access management from different perspectives are identified, which are recognized based on whether the condition of the benefit-to-cost ratio can plausibly exceed one.

$$\underset{\substack{\text{Portfolio of projects;}\\ \text{Data collection;}\\ \text{Expert elicitation}}}{Max}\begin{cases} \text{Safety improvement} \\ \text{Travel - time savings} \\ (\text{Economic}) \\ (\text{Environmental}) \\ (\text{Others}) \\ \text{Possibility that } b/c \geq 1 \\ \qquad\qquad \text{Safety} \\ \qquad\qquad \text{Travel time} \\ \qquad\qquad \text{Safety + travel time} \\ \qquad\qquad (\text{Others}) \end{cases}$$

$$\text{Subject to fiscal and program constraints}$$

Figure 28. A multiobjective combinatorial optimization problem for risk management of a multiscale transportation access management program

5.6 Chapter summary

This chapter developed a risk-cost-benefit analysis jointly from the perspectives of safety and congestion, and demonstrated the innovation in application to priority-setting in access management. A quantitative framework was described by introducing several assessment metrics and applying multicriteria and cost-benefit analysis with parameter and data uncertainties. Section 5.2 provided an introduction to the problem and methods of this chapter. Section 5.3 described the technical approach of quantification of uncertain benefits and costs, and the benefits-to-costs ratio, and compiles a prioritization framework. Section 5.4 demonstrated general methodology in more detail on a multiscale large transportation system. Section 5.5 provided a discussion of the results. Section 5.6 provided a chapter summary. The major contribution of this chapter is to adopt interval analysis of parameter uncertainties for multicriteria risk-cost-benefit analysis with diverse sources of data and elicitation uncertainties, and fulfill a need to integrate the above perspectives, safety improvement and travel-time savings.

6 Discussion

6.1 Chapter Overview

This chapter will assemble and analyze various commentaries on the quantitative framework and case studies. Several concerns with the metrics and integrated methods have already been discussed in Chapter Sections 3.5, 4.5, and 5.5. The sections of this chapter are organized as follows: (i) Section 6.2 will describe alternative statistical modeling and other data-driven techniques for evaluating and predicting the safety and travel time performance of highway corridor, (ii) Section 6.3 will review and discuss the related practice on safety and travel time evaluation and modeling in the traffic/transportation engineering, (iii) Section 6.4 will describe a sensitivity analysis of the risk-cost-benefit functions by illustrating how each uncertain parameter influences prioritization policies and discussing the implications of changing the form the risk-cost-benefit functions from linear to non-linear, and (iv) Section 6.5 will provide a chapter summary.

6.2 The prediction of highway safety and travel time performance

This section discusses the evaluation and prediction of highway safety and travel time performance in a data-rich environment. In order to conduct risk-cost-benefit analysis for highway access management, heterogeneous datasets are utilized to generate unique suitable metrics and quantify the safety and travel time performance of corridor section in this dissertation. However, safety and travel time performance evaluation and prediction in this dissertation are simplified for allocating investigative resources and for preliminary highway decision making and access management project selection (e.g. the difference of free-flow speed and impaired speed is used to evaluate the congestion on the arterials.). Statistical modeling for highway safety and travel time performance is out of the scope of this dissertation. It is addressed by others in the literature as described below.

Due to the popularity of intelligent transportation systems (ITS), more and more gathered information and data give people remarkable opportunities to analyze and management transportation information, and discover deeper information hiding in the database. In this section, some effective data-driven approaches and models that predict and measure highway safety and congestion are discussed. Although discovering new prediction and evaluation methods is not the concentration of current efforts, upcoming discussed methods are certainly beneficial for the risk-cost-benefit analysis. E.g., for the risk-cost-benefit analysis discussed in this dissertation, the predicted crashes based on roadway features of individual corridor segment could be used to quantify the crash intensity, and the forecasted traffic volume can be used to in the risk exposure and severity plot.

6.2.1 Traffic crash prediction

Traffic crash is a major public safety issue, though safety improvement has been made through roadway design and operations in recent years. Many statistical and quantitative models are investigated in order to discover relationships among roadway features and safety for preventing future crashes and reducing loss. Almost all studies of how crash related to roadway features results in the study of prediction of occurrence of crashes on highway corridors. For example, the Highway Safety Manual (HSM) uses crash modification factors (CMFs) derived from the statistical modeling of safety effects of geometric design elements to predict the safety performance for highway with various conditions (more details about the HSM will be discussed in the Chapter Section 6.3).

Developing of sound statistical models for analyzing transportation crashes is very important. Zeeger and Deacon (1986) study the data from a few U.S. states and examine the relationship between certain types of crashes and roadway features. After analyzing different combination of thirty-four variables, they find a few best factors to predict the number of crashes, such as average daily traffic, lane width, width of paved and unpaved shoulder, average roadside hazard rating, terrain type, etc. Although their model is some of the first research in predicting crashes, it is not ready for the practical use. To find a more accurate model to estimate the number of crashes, Miaou and Lum (1993) try four predictive models in predicting the track crashes by using the data from the Highway Safety Information System (HSIS): (i) additive regression model, (ii) multiplicative linear regression model, (iii) Poisson regression model with an exponential rate function, and (iv) Poisson regression model with a non-exponential rate function. They find that Poisson regression model outperform linear regression model because of the nature of crashes, which are distinct and rare events and whose count are non-negative numbers. Miaou and Lum (1993) realize that

Poisson regression models may overestimate or underestimate the likelihood of crashes if the accident data is significantly overdispersed relative to its mean. The research of Poisson regression models to study the crash data can be found in a lot of literature (Abdel-Aty and Pemmanaboina 2005; Kumara and Chin 2005; Daniel and Chien 2004). Shankar et al. (1995) use Negative Binomial (NB) regression model to exam how roadway geometric and environmental factors can affect the occurrence of crashes and compare the NB regression model with the Poisson regression. Many other applications of NB regression in the traffic crashes analysis are used to address transportation safety concerns (Miaou 2001; Zegeer et al.2001; Vogt 1999). Because crash data often exhibit over-dispersion (Park and Lord 2009), there has been considerable interest and study in approaches that allow for excessive zeroes, such as zero-inflated Poisson (ZIP), zero-inflated negative binomial (ZINB), and other zero-inflated count regression models (Qin et al 2004; Kumara and Chin 2003; Lee and Mannering 2002). Lord et al. (2005) review the most commonly count data regression models in crash modeling and prediction, including Poisson, binomial, NB, ZIP and ZINB models, and multinomial probability models, and provide the guidance on how to select appropriate models under different saturations.

Besides above discussed parametric probabilistic count data regression models, numerous advanced data mining and machine learning approaches have been conducted to increase the accuracy of crash prediction. In this direction, several researchers have explored Artificial Neural Networks (ANN) (Xie et al. 2007; Chang 2005; Abdelwahab and Abdel-Aty 2002), Generalized Additive Models (Li et al. 2011; Xie and Zhang 2008), Quintile regression (QR) (Wu et al. 2014; Qin and Reyes 2011; Qin et al. 2010), Bayesian Methods (Ma et al. 2008; Miaou and Song 2005; Pawlovich et al. 2006; Washington and Oh 2006), etc. in traffic safety studies.

6.2.2 Travel time prediction

The travel time prediction is another appealing research area, as the travel time information is of interest to both road users and transportation agencies. In this dissertation the travel time is calculated by using the travel distance divided by the moving speed for estimating the potential travel time savings that can be expected from good access management strategies. However, there are various models developed during past decades for more accurate travel time prediction, especially when the corridor network has been integrated with many intelligent transportation systems (ITS) and more real-time and historical traffic and road information are readily available.

Typically the travel time prediction models require historical traffic data. Van Arem et al (1997) use autoregressive integrated moving average (ARIMA) models to predict the travel time in general traffic conditions; however, they find that the ARIMA model is applicable to normal traffic congestion, but shows larger deviations in non-recurring congestion. To address the viability of the time series data, Tsekeris and Stathopoulos (2006) investigate an autoregressive heteroscedastic model referred as ARFIMA-FIAPARCH, which incorporates fractionally integrated components in both the conditional mean and the conditional variance equations, and they find that ARFIMA-FIAPARCH can improve the accuracy of predicated volatility and outperform the generalized autoregressive conditional heteroscedasticity (ARIMA-GARCH) model when it is used to provide short-term traffic volatility forecasts. Cetin and Comert (2006) apply regime switching approaches to short-term traffic flow predictions by monitoring and updating the mean of the process. Vlahogianni et al. (2006) identify the overall nonlinearity and non-stationarity in univariate series of traffic volume, and point out that ARIMA model and other linear approaches may not be appropriate for the data with high short-term fluctuation. Yeon et al. (2008) use Discrete Time Markov Chains (DTMC) where the states correspond to the existing link traffic conditions to estimate travel time on a highway. Innamaa (2005) employs the feedforward multilayer perception neural network to investigate the predictability of travel time. van Hinsbergen et al. (2009) combine neural networks in a committee using Bayesian inference theory for a short-time travel prediction, and their approach allows for accurate estimation of confidence interval for the prediction. Besides above discussed approaches, the other most applied types of traffic prediction models are multivariate time-series forecasting (Stathopoulos and Karlaftis 2003), Kalman filtering (Wang and Papageorgiou 2005; Chien and Kuchipudi 2003; Chen and Chien 2001), nearest neighbor methods (Clark 2003; Smith and Demetsky 1996), linear weighted regression (Zhong et al. 2005), support vector regression (Wu et al. 2004), Bayesian models (Wang et al. 2014; Fei et al. 2011; Park and Lee 2004), etc. Nevertheless, all above discussed techniques typically fall into either paramedic or nonparametric statistical methods, which reveal the travel time prediction mechanisms and help practitioners and researchers understanding how variety of factors can affect the traffic flow in transportation network.

6.3 The safety and travel time performance of a transportation system

The previous section discusses the statistical modeling in the transportation safety and travel time evaluation and prediction, and the related practices are presented in this section. Moreover, there might be some gap between the planning strategy (project prioritization and resource allocation) addressed in this dissertation and the considerations of safety and travel time savings from the view of traffic and transportation engineering. In part this gap is explained by the scope of this dissertation being a large-scale corridor access management problem, including corridor risk management and cost-benefit analysis for highway decision making and project planning, rather than engineering analysis. This section discusses the safety and travel time savings practice in traffic/transportation engineering.

6.3.1 Highway safety

The highway transportation system can be broken down into three broad categories: the driver; the vehicle; and the road and its environment, and vehicular crashes are generally a consequence of one or combination of those elements (Mearkle 2009). The road accident results serious social and anatomic problems, and in order to improve the safety performance of the transportation systems, public agencies always prefer to design a better system by improving the part of the systems that can be controlled, such as roads and vehicles, other than road users and weather. From the perspective of highway safety designers or engineers, it is critical to understand what the significant road characterizes that contributes to vascular crashes and how to model them to evaluate the roadway safety performance. In recent years, more and more emphasis has been placed on the improving the highway safety in transportation planning, design, and operations decision makings. Many geometric features of a road influence its safety performance. The relationship between characteristics of roadways and traffic accidents can be classified into cross-section effects and alignment effects (Mohammed 2013). The cross-section effects are typically includes the following parameters: (i) lane width, (ii) number of lanes, (iii) shoulder width and type, (iv) median width and type, (v) climbing lanes, (vi) access density, (vii) median barrier, and (viii) etc. While the alignment effects are typically includes: (i) curve radius, (ii) curvature change rate, (iii) superelevation, (iv) transition curve, (v) sight distance, (vi) gradients, (vii) crest curves, (viii) sag curves, and (ix) etc.

To estimate the number of crashes on road segments and intersections and evaluate the relationship between the roadway features and its safety performance, the Highway Safety Manual (HSM) provided by the American Association of State Highway and Transportation Officials (AASHTO) describes a set of analytical tools and techniques (U.S. National Research Council et al. 2010). Furthermore, as a companion to the HSM, the U.S. FHWA develops a crash-prediction module (CPM) in the interactive highway safety design model (IHSDM) to provide quantitative crash prediction algorithms for estimating the frequency and severity of crashes on a highway, e.g. rural-lane and multilane highway, and urban and suburban arterial, by using geometric design and traffic characteristics. The above literature enables highway engineers to quantitatively predict the highway safety performance based on underlying factors or characteristics if they are known. The HSM describes fundamental concepts for understanding of crashes and crashes modeling. Two principle features in the HSM prediction algorithm are safety performance functions (SPFs) and crash modification factors (CMFs). The SPFs are regression equations that estimate the predicted number of total crashes for base conditions based on the crash history of roadways with similar attributes (e.g., two-lane rural highway). The SPFs are different depending on the type of roadway segments and intersection. In the base condition, the independent variables in SPFs for a two-lane rural highway are average daily traffic and length of highway corridor as shown in Equation 22.

$$N_{spf\ rs} = ADT \times L \times 365 \times 10^{-6} \times e^{(-0.312)} \quad (22)$$

Where $N_{spf\ rs}$ is the estimated total crash frequency for roadway segment base conditions, ADT is the average daily traffic (vehicles per day), and L is the length of a highway segment (miles).

Since the SPFs is designed by using base conditions for roadway segments. To apply SPFs to other corridor segment with non-base condition, the crash prediction yielded by the SPFs must be modified to account for possible differences that may exist across various roadway classes that have different geometric features. As shown in Equation 23, The CMFs are multiplicative factors used to adjust the base crash frequency for the effect of various geometric and traffic control conditions, which vary form the base conditions in the SPFs.

$$N_{predicted\ rs} = N_{spf\ rs} \times C_r \times \prod_{i=1}^{n} CMF_i \quad (23)$$

Where $N_{predicted\ rs}$ is the estimated total crash frequency for roadway segment, C_r is the calibration factor for the highway with specific local conditions, and CMFs are the accident modification factors for non-base condition highway segments. The CMFs for different geometric conditions of a location can be found in HSM and the typical CMFs consideration includes lane width, shoulder width and type, horizontal curve, grades, driveway density, centerline rumble strips, passing lanes, two-way left-turn lanes, roadside design, lighting, automated speed enforcement, etc. More details of CMFs can be found in the HSM and crash modification factors clearinghouse (http://www.cmfclearinghouse.org/).

Among these factors causing accident risk in highway transportation system and influencing the highway safety performance, the access density and traffic conflicting points on the highway system draw massive attention from traffic engineers and practitioners, because conflicting traffic flows are inherent problems at intersections, driveways, and railroad crossings, and intersection is one of the most common place for fatal accidents. E.g., the National Highway Traffic Safety Administration (NHTSA) estimates that about 41% of the traffic crashes are intersection or intersection-related crashes. The HSM offers methods to predicted crash frequency for each segment and intersection, and detailed multiple-vehicle intersection-related crashes prediction process can be found in the HSM chapter 12, which is designed for urban and suburban arterial. The equations show that for all kinds of crashes, such as total crashes, fatal and injury crashes, and property-damage-only crashes, the SPFs for intersection-related collisions depend on average daily traffic volume on both major and minor roads, and the type of the intersection (three-Leg Intersections with Minor-Road Stop Control (3ST), Three-Leg Signalized Intersections (3SG), Four-Leg Intersections with Minor-Road Stop Control (4ST), Four-Leg Signalized intersections (4SG)). Many recent studies and research of CMFs of access points density and the prediction of crash related crashes can be found in the crash modification factors clearinghouse.

In this dissertation, a quantitative decision framework supporting highway access management program is invented. In order to solve this practical problem and simplify the planning process, it is assumed that there is a linear relationship between access points and ADT and crashes, although the SPFs in the HSM and the crash modification factors clearinghouse show that there is a nonlinear relationship between crashes and ADT and the relationship varies by facility types, and the CMFs for reducing access point density is also a nonlinear function of ADT. Nevertheless, present efforts address a particular concern that how to screen and prioritize thousands of corridor segments for an access management program, not investigate the quantitative relationship among ADT, access point density, and number of crashes in the traffic engineering. However, the SPFs and CMPs, especially the estimations and standard errors for the CMFs for reducing access point density that can be found in crash modification factors clearinghouse, is used to bound parameters in the cost-benefit function used in current efforts, such as the crashes reduction factor. Future efforts might make more use of the HSM that advocates for nonlinear relationships between crashes and access-point densities.

6.3.2 Travel time savings

The travel time is defined as the time spent when a traveler displaces between two locations. In the transportation network, the travel time can be decomposed to free flow time and additional time (Carrion and Levinson 2012). The free flow time is the amount of time the driver spends in driving from starting point to destination without encountering any traffic congestion. The additional time is the increase of travel time due to the variation of traffic conditions. As the congestion have negative impact on the life quality, energy consumption, and environment protection, many transportation engineer and planners have developed a variety of strategies to deal with congestion and support effective transportation system. Some fundamentals of traffic congestion and traffic flow theory are discussed by Daganzo (1997). However, due to the nature of these variations and the dynamic of traffic condition, it is always challenging to provide an accurate prediction of travel time on a specific highway section.

Nevertheless, many efforts have been made to address congestion and save travel time during past , e.g., multimodal approach to bottleneck removal project in Virginia, integrated congestion relief strategies in Wisconsin, Statewide Traffic Incident Management in Maryland, etc. (U.S. FHWA 2014). According to U.S. FHWA (2014), the efforts are in three general categories as follows.

- Adding more capacity: Increasing the number and size of highways and providing transit and freight rail service. Adding more lanes to existing highways and building new ones has been the traditional response to congestion.
- Operating existing capacity more efficiently: Getting more out of what we have. The operational improvement is dealing with how to more effectively use current road system, rather than building more infrastructures. Another key understanding of operational

projects on current road systems is to consider the return on investment, which is another central consideration in this dissertation through cost-benefit analysis.

- Encouraging travel and land use patterns that use the system in less congestion producing ways: Travel Demand Management (TDM), Non-Automotive Travel Modes, and Land Use Management. These methods focus on how to manage the demand of highway travel and land development.

The additional travel time due to the extensive number of access points on the highway corridor has been the foremost consideration, as it has been generally shown that more access points can reduce the free-flow speed and people always would like to reduce the travel time and would rather do something else, other than traveling. As a means of operational improvement, access management is one among other approaches to control the access to highway system and improve the efficiency and reliability of the transportation network. This dissertation has offered a framework for how to select and prioritize thousands of competing access management projects for travel time savings and traffic congestion relief.

6.4 Parameter sensitivity analysis and non-linear deviation of the cost-benefit function

This section investigates how each of the uncertain parameters might influence decision policies and prioritization through a sensitivity analysis, and discusses the implications of possible non-linear deviations of the presently linear risk-cost-benefit functions.

6.4.1 Example of sensitivity analysis of cost-benefit function

A parameter sensitivity analysis can make cost-benefit analysis much more informative, discourage abuse, and make inadvertent bias more transparent (Merrifield 1997). Moreover, the sensitivity analysis can be used to assess the model assumptions. Especially, for the cost-benefit analysis, the assumptions and inputs can affect the benefits and costs estimates and the selection of profitable projects, therefore it is important to conduct sensitivity analysis, i.e., to demonstrate how the final B/C ratio changes if costs or benefits increased or decreased by certain percentage. In this dissertation, the uncertainty plays an important role in the cost-benefit analysis, by conducting sensitivity analysis and dealing with these uncertainties, the decision makers can compare the prioritization lists for various alternatives, examine the possibility that a project will have positive net benefits, and find the most sensitive input for further study. So this section inspects how the B/C ratios and decision contours varying according to different values of inputs and how the uncertain parameters influence the magnitude of benefits and costs. The B/C ratios for safety improvement and travel time savings in the Chapter Section 5.3.4 are used for illustration, and the similar analysis can be extended to other cost-benefit functions.

6.4.1.1 Cost-benefit function for safety improvement

There are five uncertain inputs, R, β, Δ, and C_{Total} in the cost-benefit function for safety improvement in Chapter Section 5.3.4. Table 25 with the interval range of each parameter has been set up for the risk-cost-benefit analysis for the entire region. The following three scenarios are considered for examining how each parameter can influence the B/C ratio evaluation.

- Scenario 1: the crash intensity, R, has growth of 10 percent, and no growth in other inputs
- Scenario 2: the crash reduction factor, Δ, has growth of 10 percent, and no growth in other inputs
- Scenario 3: the cost of crash, β, has growth of 10 percent, and no growth in other inputs

The cost-benefit analysis is repeated for transportation network in entire region (rural part) multiple times and the decision contours on the risk-cost-benefit plot (in log scale) are shown in Figures 29, 30, and 31 for each scenario respectively (red lines are drawn under the original scenario and cyan lines are drawn under the new scenario). Although ranges and uncertainties of each parameter differ among three scenarios, the locations and shapes of upper and lower contours are exactly same across all three figures, which implies that the B/C ratio is same sensitive to all uncertain parameters in this case. The reason behind this phenomenon is that a linear relationship exists between the benefits and the parameters, and the same percentage growth of each parameter will cause the same percentage change of B/C ratio. Furthermore, for all three scenarios, it can be observed that more candidate segments have B/C ratio greater than one for sure and less candidate segments have B/C ratio less than one for sure because of the growth of net benefits under the new scenario.

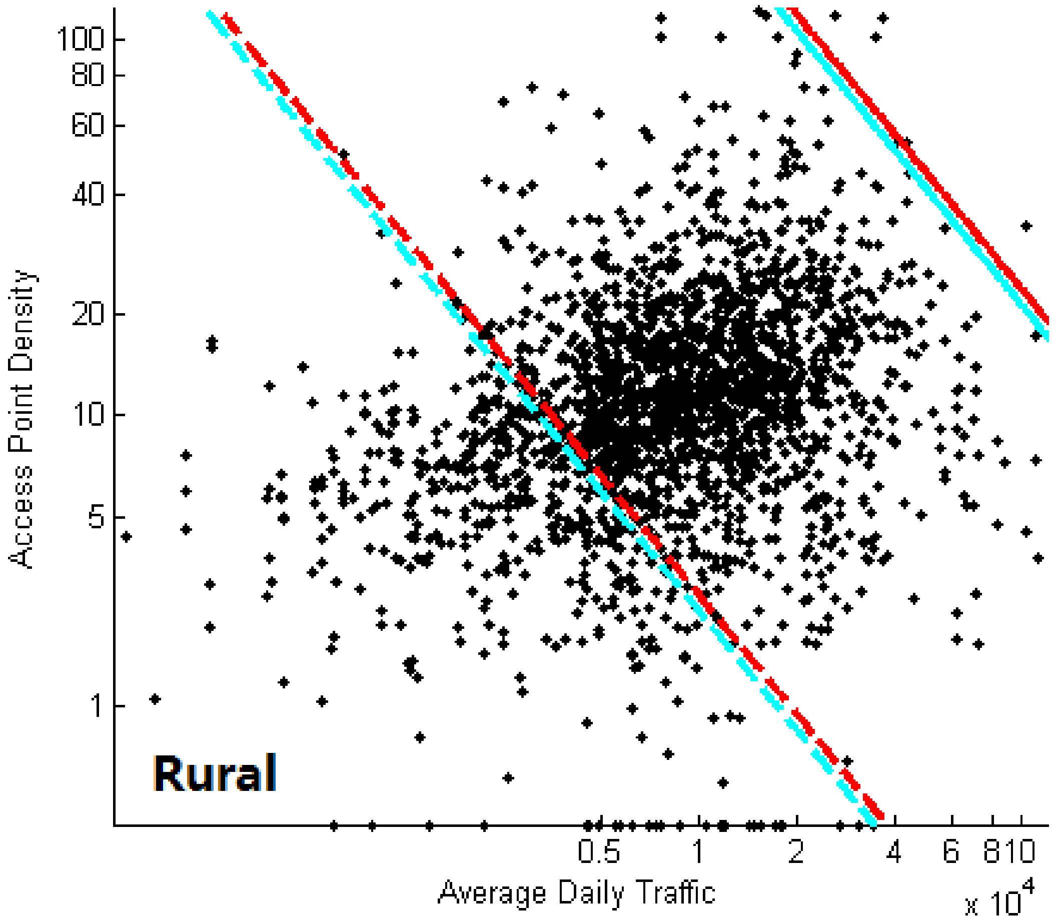

Figure 29. Example of the priority setting for entire region (rural) of the case study if the crash intensity, *R*, has growth of 10 percent, and no growth in other inputs

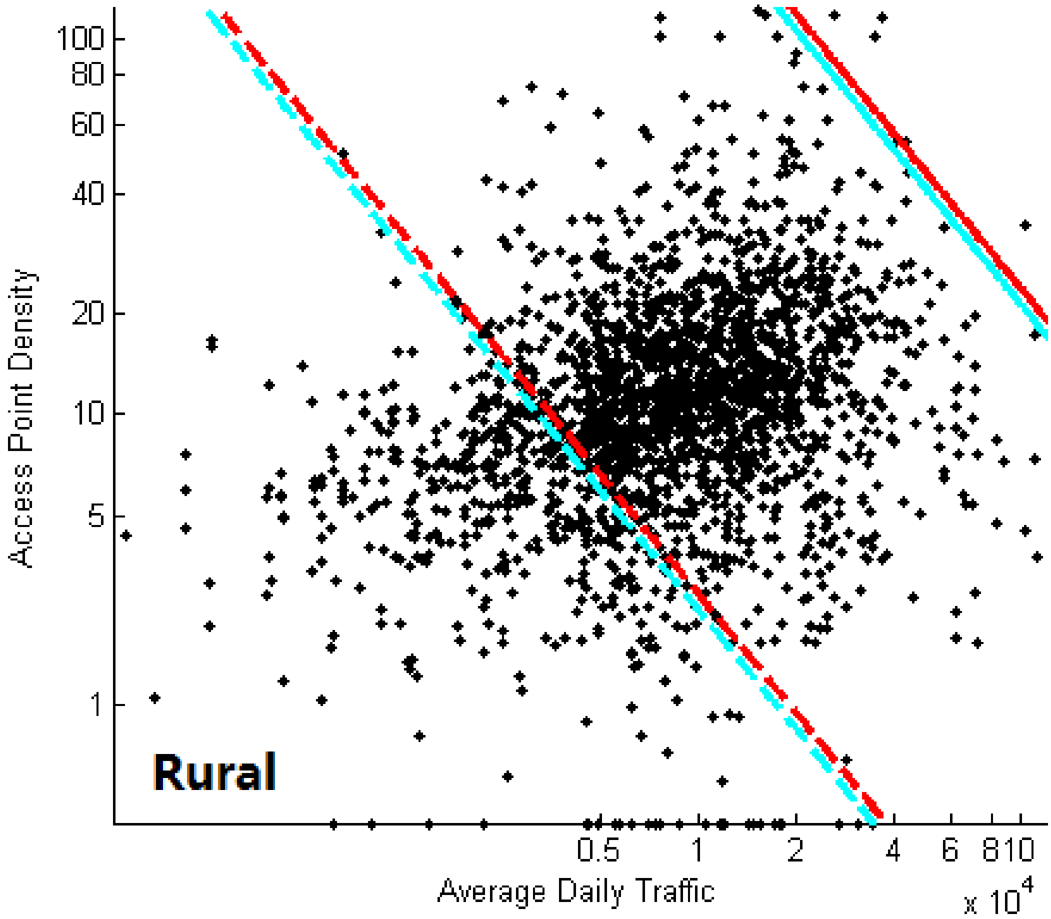

Figure 30. Example of the priority setting for entire region (rural) of the case study if the crash reduction factor, *Δ*, has growth of 10 percent, and no growth in other inputs

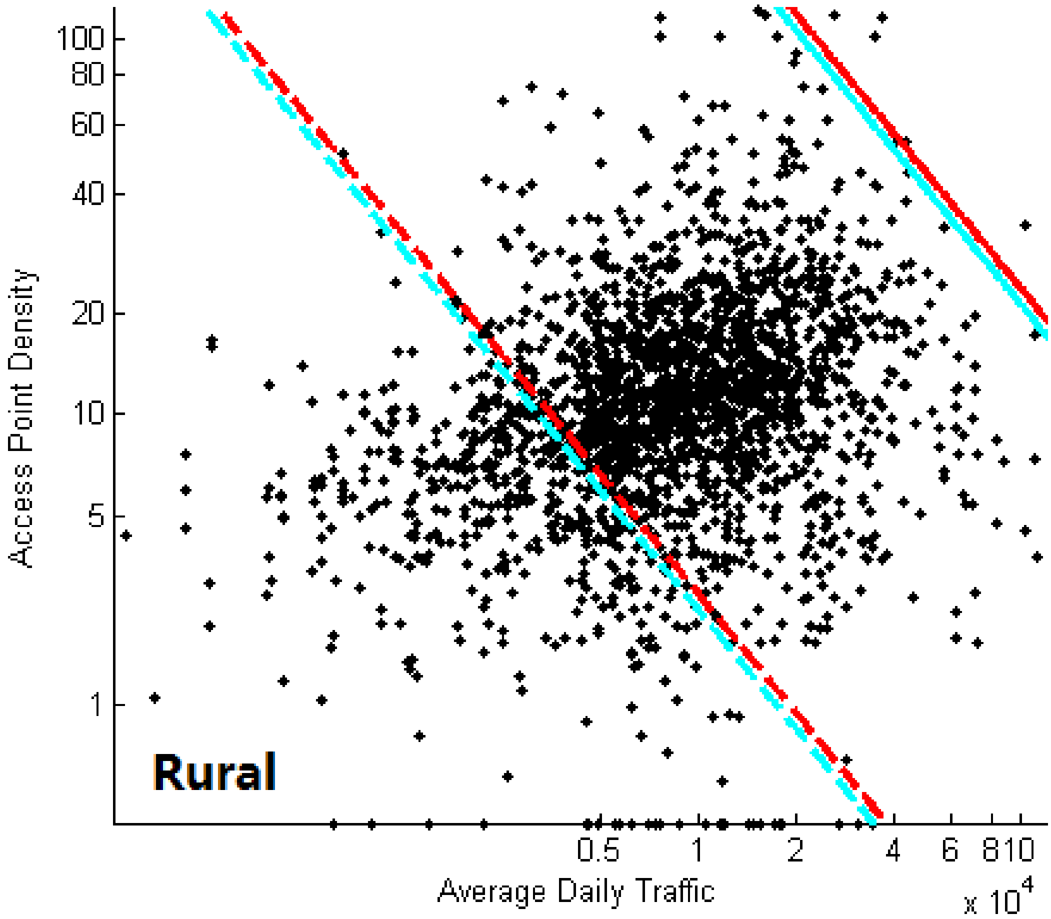

Figure 31. Example of the priority setting for entire region (rural) of the case study if the cost of crash, β, has growth of 10 percent, and no growth in other inputs

6.4.1.2 Cost-benefit function for travel-time savings

Similar parameter sensitivities are performed on the travel time savings cost-benefit function below. There are two uncertain inputs, *F* and *V*, in the cost-benefit function. The following scenarios are considered for the sensitivity analysis.

- Scenario 1: the free-flow speed, *F*, has growth of 10 percent, and no growth in other inputs

- Scenario 2: the value of travel time, *V*, has growth of 10 percent, and no growth in other inputs

Figures 32 and 33 display the risk exposure and intensity plot (in log scale) with decision contours for each scenario respectively. The relative locations and shapes of decision contours are dissimilar under two scenarios, since in the cost-benefit function for travel time savings there is a linear relationship between the benefits and value of travel time, but not between the benefits and the free-flow speed. Moreover, if the free-flow speed, *F*, increases 10 percent, fewer candidate segments have B/C ratio greater than one for sure and more candidate segments have B/C ratio less than one for sure. On the other hand, if the value of travel time, *V*, increases 10 percent, more candidate segments have B/C ratio greater than one for sure and less candidate segments have B/C ratio less than one for sure. In this case the B/C ratio is more sensitive to the free-flow speed estimate and it might be worthwhile to do further study to refine the free-flow speed estimate if there are resource constraints.

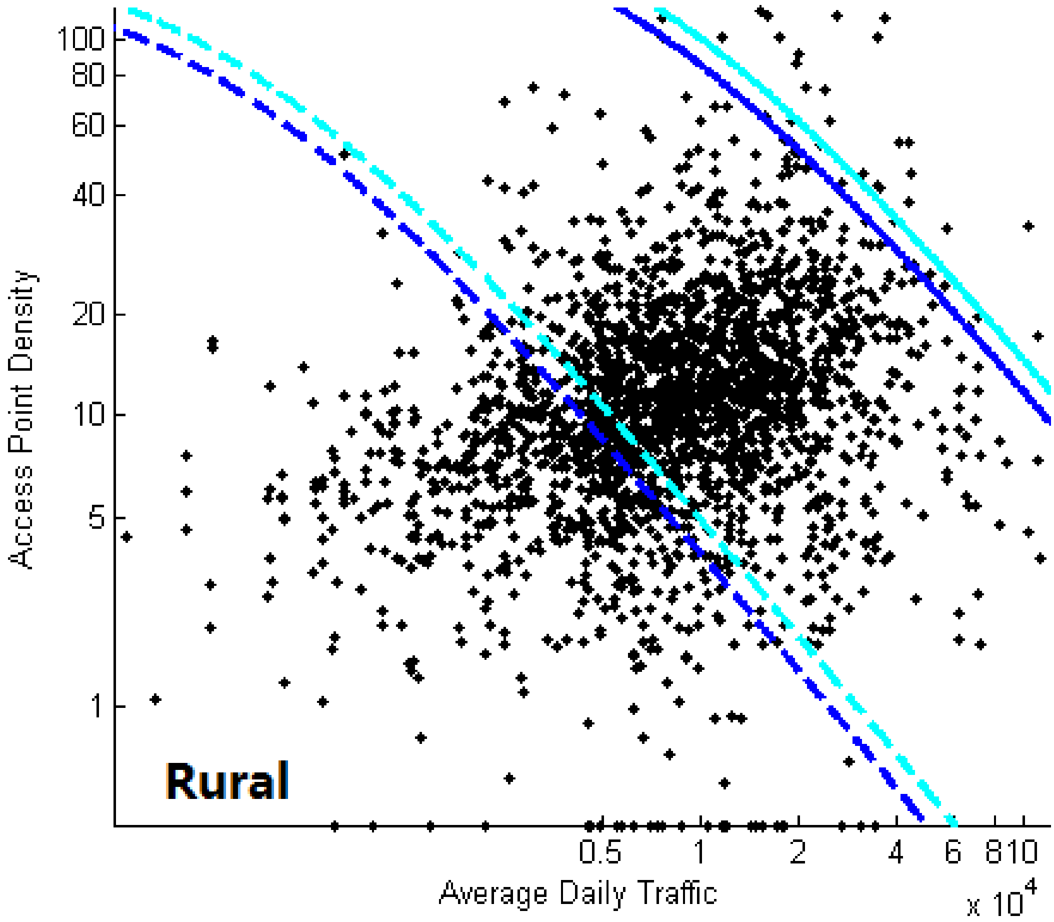

Figure 32. Example of the priority setting for entire region (rural) of the case study if the free flow speed, *F*, has growth of 10 percent, and no growth in other inputs

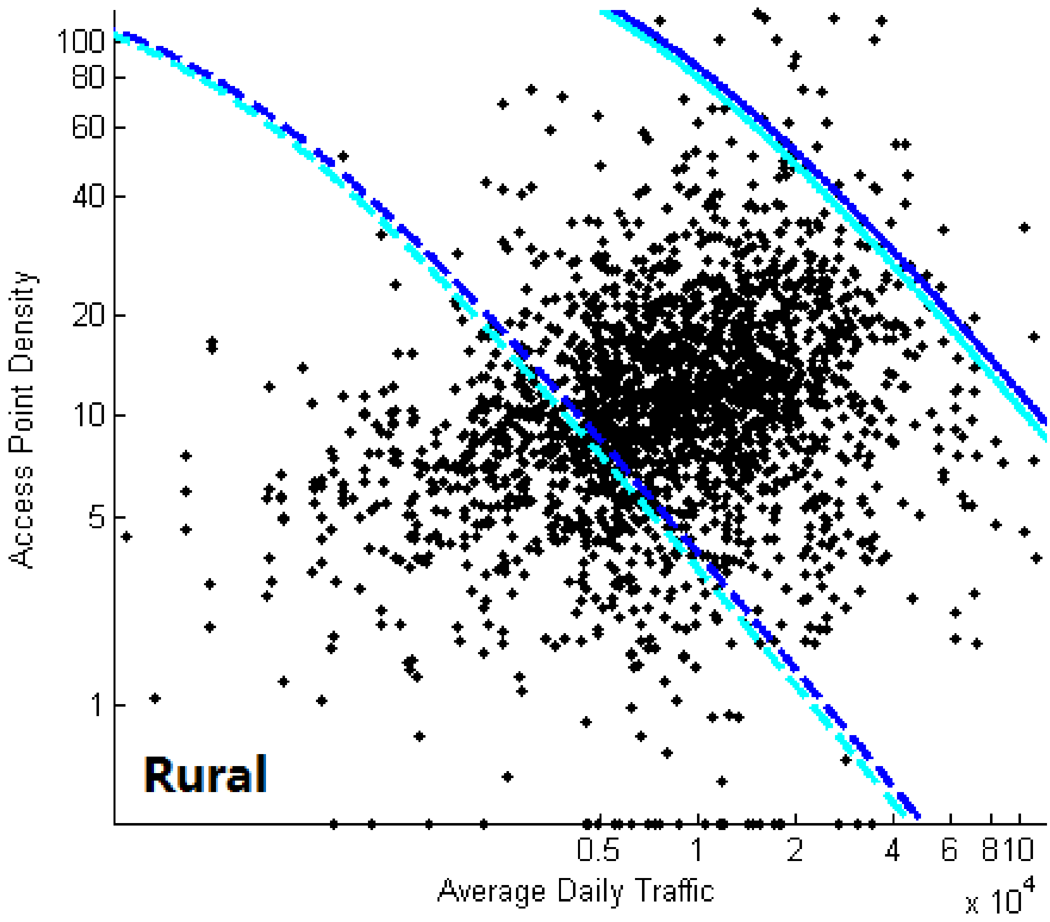

Figure 33. Example of the priority setting for entire region (rural) of the case study if the value of travel time, *V*, has growth of 10 percent, and no growth in other inputs

6.4.2 Deviation of cost-benefit function

This section of discussion is dedicated to understanding different forms of the cost-benefit function that could be used to combine the risk and cost-benefit analysis for decision makings in the projects prioritization and resources allocation. Most of the information in this section is either taken directly, or indirectly, from related studies by Lambert and Farrington (2007) and the master thesis of Farrington (2006). Therefore, although repeated citations will not be used, it should be assumed that all the information in this section is adapted from the above literature unless otherwise noted.

Lambert and Farrington (2007) and Farrington (2006) investigate how various cost-benefit functions in elementary and deviated forms can influence the prioritization of project candidates and demonstrate the results on the risk-cost-benefit coordinate graph. The elementary cost-benefit function defined by them assumes that a linear relationship exists between the benefits and the parameters. The cost-benefit function for safety improvement used in Chapter 5 happens to have the same assumptions and is in a very similar form. Therefore the discussion and review of this previous work provide more thorough understanding of present effort.

Their research investigates six different functional forms of the cost-benefit function for prioritizing the location of chemical, biological, and/or radiological (CBR) sensor for hazard protection. Similar to current studies, they identify the measures of hazard intensity and population exposure as well as parameters that influence assessments of benefits and costs. More specifically, *the risk-reduction factor*, *the vulnerability factor*, and *the risk avoided per exposed person* are introduced as parameters that influence assessments of risks, benefits, and costs as shown in Equation 24.

$$\Psi = \frac{\rho\Lambda\Gamma\Phi\Delta}{\Pi_f} \quad (24)$$

Where ρ is hazard *intensity*, Λ is population *exposure*, Γ is attack vulnerability, Φ is the risk-reduction factor, Δ is the risk avoided per exposed person in dollars, and Π_f is the annual cost for a sensor (the context of this formulation can be found in the original literatures). Moreover, five extended form of the cost-benefit function that are applicable under different assumptions and scenarios are identified as (i) constant benefit, which extends the elementary cost-benefit function by an addition of a constant benefit in the numerator; (ii) exponential intensity or exposure, This subsection introduces the exponential intensity or exposure cost-benefit function, which extends the elementary cost-benefit function by an intensity or exposure variable in the denominator raised to a power; (iii) variable costs as a function of exposure or intensity, which extends the elementary cost-benefit function by an additional cost variable as a function of exposure or intensity; (iv) external source of funding for threshold values of intensity, which considers that an external source of funding exists if intensity is above a threshold value; (v) variable costs as a function of threshold values of exposure, which considers that variable costs related to exposure thresholds exist in addition to fixed costs. Table 35 lists the formula and key assumption of each cost-benefit function for each investigation. They find that each functional form generates unique decision contours on the risk intensity and exposure plot, and therefore the prioritization levels for each project /location candidates under each cost-benefit function are varying. For example, Figure 34 shows the cost-benefit decision contours and prioritization zones when variable costs as a function of threshold values of exposure, and the sharp dips in the contours occur in Figure 34 is because of the variable costs associated with threshold values of exposure. More detailed cost-benefit analysis and cost-benefit contours associated with different forms of cost-benefit functions can be found in the original literature (Lambert and Farrington 2007; Farrington 2006).

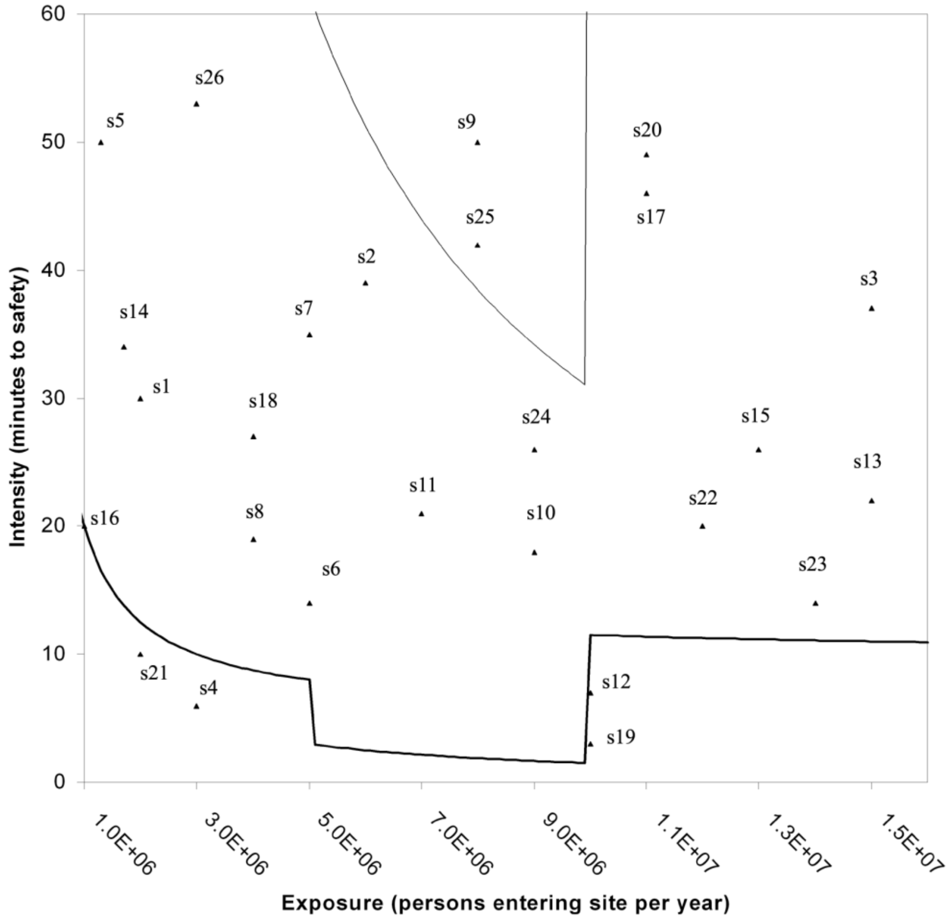

Figure 34. Application of the variable costs as a function of threshold values of exposure cost-benefit function (source: Farrington 2006)

Cost-benefit function	Parameters	Assumptions
$\Psi = \frac{\rho\Lambda\Gamma\Phi\Delta}{\Pi}$	ρ: Hazard *intensity*, Λ: Population *exposure* Γ : Vulnerability Φ: Risk-reduction factor Δ: Risk avoided Π_f: Fixed annual cost	There is a linear relationship between the benefits, variables and the parameters
$\Psi = \frac{(\rho\Lambda\Gamma\Phi\Delta)+\varepsilon}{\Pi}$	ε: Constant benefits	Each site selected realizes a benefit that is in addition and unrelated to the other variables and parameters
$\Psi = \frac{\rho^x\Lambda^y\Gamma\Phi\Delta\varpi}{\Pi}$	x: Intensity exponent y: Exposure exponent ω: Correction factor	The benefits of a sensor placement are a function of the exponential intensity and/or exponential exposure
$\Psi = \frac{\rho\Lambda\Gamma\Phi\Delta}{\Pi_f + \Pi_v}$	Π_f: Fixed annual cost Π_v: Variable annual cost	There is an additional cost associated with each unit of intensity and/or exposure
$\Psi = \frac{\rho\Lambda\Gamma\Phi\Delta}{\sum_{i=1}^{n}\Pi_i I_{\{\rho\in\rho_i\}}}$	Π_i: Sensor costs I: Indicator variables	Different sensor costs exist for different ranges of intensity
$\Psi = \frac{\rho\Lambda\Gamma\Phi\Delta}{\Pi_f + \Pi_v}$	Π_f: Fixed annual cost Π_v: Variable annual cost	Different sensor costs exist for different ranges of exposure

Table 35: Summary of six cost-benefit function investigation (adapted from: Lambert and Farrington 2007)

The above studies by Lambert and Farrington (2007) and Farrington (2006) describe the results for the cost-benefit function taxonomy for the risk-based resources allocation. In their taxonomy, the shapes and locations of the decision contours on the risk exposure and intensity plot distinguish different forms of cost-benefit function. Moreover, the priority level of each location varies across the several assumptions of non-linear form of the cost-benefit functions.

6.5 Chapter Summary

In this chapter, several concerns about the developed methodology and case studies were explored based on the comments from journal-article peer reviewers and the PhD advisory committee. Section 6.2 described statistical and other data-driven modeling and techniques for evaluating and predicting the safety and travel time performance of highway corridor. Section 6.3 reviewed and discussed the safety and travel time evaluation and modeling practice in the traffic/transportation engineering. Section 6.4 explored further considerations of risk-cost-benefit functions by illustrating how each uncertain parameter influences prioritization policies, and discussing possible non-linear deviations from the linear risk-cost-benefit functions used in the previous chapters. Section 6.5 provided a chapter summary.

7 Summary and conclusion

7.1 Chapter overview

This chapter will describe the conclusions and contributions of this dissertation. The sections of this chapter are organized as follows: (i) Section 7.2 will provide a summary of the dissertation, (ii) Section 7.3 will detail contributions of this effort to systems engineering and risk management literature, (iii) Section 7.4 will describe opportunities for future, and (iv) Section 7.5 will provide the conclusion of this dissertation.

7.2 Summary of dissertation

This dissertation has developed a framework for allocating resources and prioritizing transportation access management projects under data and parameter uncertainties. The general requirements of the study called for the appropriate use of evidence in prioritizing sections of transportation network and addressing the uncertainties in evidence that are influential to the risk-cost-benefit analysis of access management projects across multiscale systems. The uncertainties of such systems, which require consideration of both measurement data and model parameters in the evaluation of typical costs and benefits of access management projects, are multi-dimensional. The uncertainties considered in this dissertation include:

- *Metric/evaluation uncertainty* as shown in Figure 35: In this dissertation, the risk-cost-benefit analysis contrasts the *hazard intensity* with the *population exposure* in the evaluation of various benefits and costs. Although *population exposure* in a highway transportation program is typically in terms of average daily traffic, the metric of *hazard intensity* varies depending on practical needs and circumstances. For example, to evaluate the hazard intensity, the access point density is used in Chapter 5 as shown Figure 35 (left), while the travel time delay index is used in Chapter 4 as shown Figure 35 (right).

- *Data uncertainty* as shown in Figure 36: For every corridor segment candidate, the associated *hazard intensity* and *population exposure* are not perfectly known, which means there are uncertainties along the x-axis and y-axis in the contrast plot. For example, the vehicular crashes in the year of 2008 are used to quantify the *crash intensity*; however, the *crash intensity* is dynamic and the crash amount is changing over time.

- *Parameter uncertainty* as shown in Figure 37: Several parameters are used to quantify the benefits and costs of access management projects. In this framework, the interval analysis of benefits and costs describes parameter uncertainties and generates decision contours around three zones of priority. Degree of uncertainties is reflected as the range of parameters and the distance between upper and lower contours on the *hazard intensity* and the *population* *exposure* plot. The uncertain parameters in this dissertation include but not limits to crash reduction factor, costs per crash avoided, value of travel time, free-flow speed, and crashes per crash opportunity.

- *Model uncertainty* as shown in Figure 38: The model uncertainty is another significant consideration throughout the dissertation. The position and shape of the decision contours are very sensitive to the model and its corresponding interval bounds of each of the uncertain parameters. Different models are crucial in the decision making process, as no single perspective can solve complex decision making problem. In the transportation program, the public agencies need to understand how perspectives or scenarios can influence the prioritization and selection of projects and investment. In this dissertation, travel-time savings, safety improvement, and travel-time savings and safety improvement jointly are three major concerns in the transportation access management.

- *Decision uncertainty* as shown in Figure 39: In the *hazard intensity* and the *population exposure* plot, two decision contours separate three decision zones with high, medium, and low priorities. The decision makers can select different candidate segments to allocate corresponding limited resources, since their needs are various across three decision zones. For example, all corridor segments (represented by triangles) in high priority zone are most needful of immediate access management and investment; corridor segments (represented by square) in a medium priority zone are most need additional data, expert elicitations, and uncertainty reduction; and corridor segments (represented by circle) in low priority zone needs are most needful of proactive access management planning and protection.

- *Region Uncertainty* as shown in Figure 40: This dissertation describes a decision making process for a multiscale transportation program, which is demonstrated with a 6,000 miles of corridor. The interval range of each exogenous parameter varies from region to region. To reconcile the region uncertainty, the decision approach in this dissertation allows stakeholders and decision makers to have different views on the value of each parameter among different regions. For instance, the Figure 40 displays two *hazard intensity* and the *population exposure* plots specifically designed for two different regions.

Thus, the current effort considers quantifications of costs and benefits, diverse perspectives, multiple criteria, evaluation of tradeoffs among criteria, etc. under multi-dimensional uncertainties in the prioritization of transportation programs. The application of the approaches screens and prioritizes corridor sections for oversight of an access management program from several perspectives, such as travel-time savings, safety improvement, and travel-time savings and safety improvement jointly. The integration of uncertain costs, benefits, and other evidence of the productivity of distributing limited resources is applicable to protecting and maintaining the mobility, safety, and efficiency of transportation network.

The risk-cost-benefit tradeoff analysis that is developed in this dissertation is in general useful to justify investments in risk management when diverse sources of data, experts, and stakeholders are involved. The analysis suggests how comparing prioritizations that result from varying perspectives, of safety and/or travel time with associated data, model, and parameter uncertainties, is useful to a complex decision-making problem. The lessons learned are applicable to a variety of large-scale systems where limited resources are to be allocated and distributed, and where expert elicitations and data uncertainties are of diverse types. The adoption of interval analysis is not a rejection of probabilistic methods, rather a recognition that such methods would entail significant limiting or unacceptable assumptions of statistical independence (and/or conditional dependence) of experts and datasets, and/or infeasible data collection and elicitations. The approach is flexible and adapt to various data sets. The framework has been transferred to transportation planners for future use in the field.

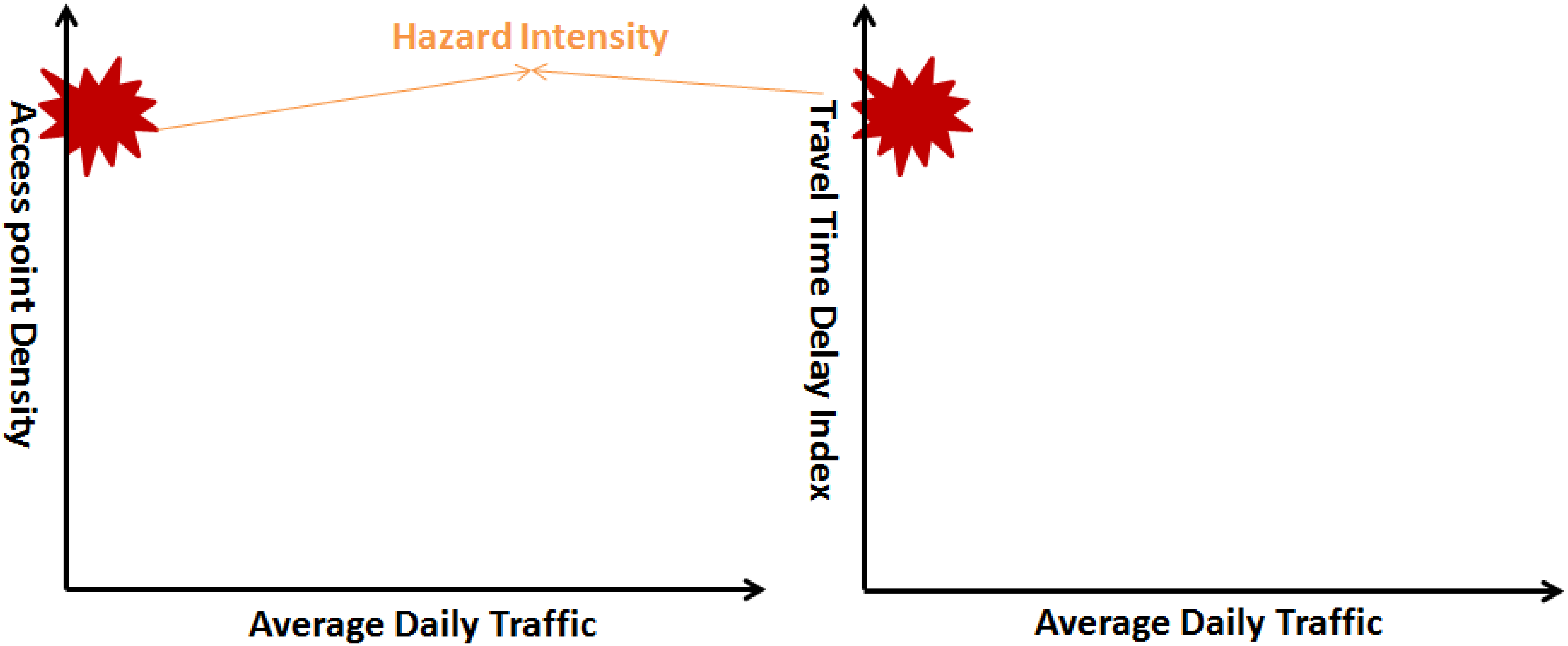

Figure 35. *Metric/evaluation* uncertainty, wherein the choice of evaluation metrics has a significant influence to the allocation of resources

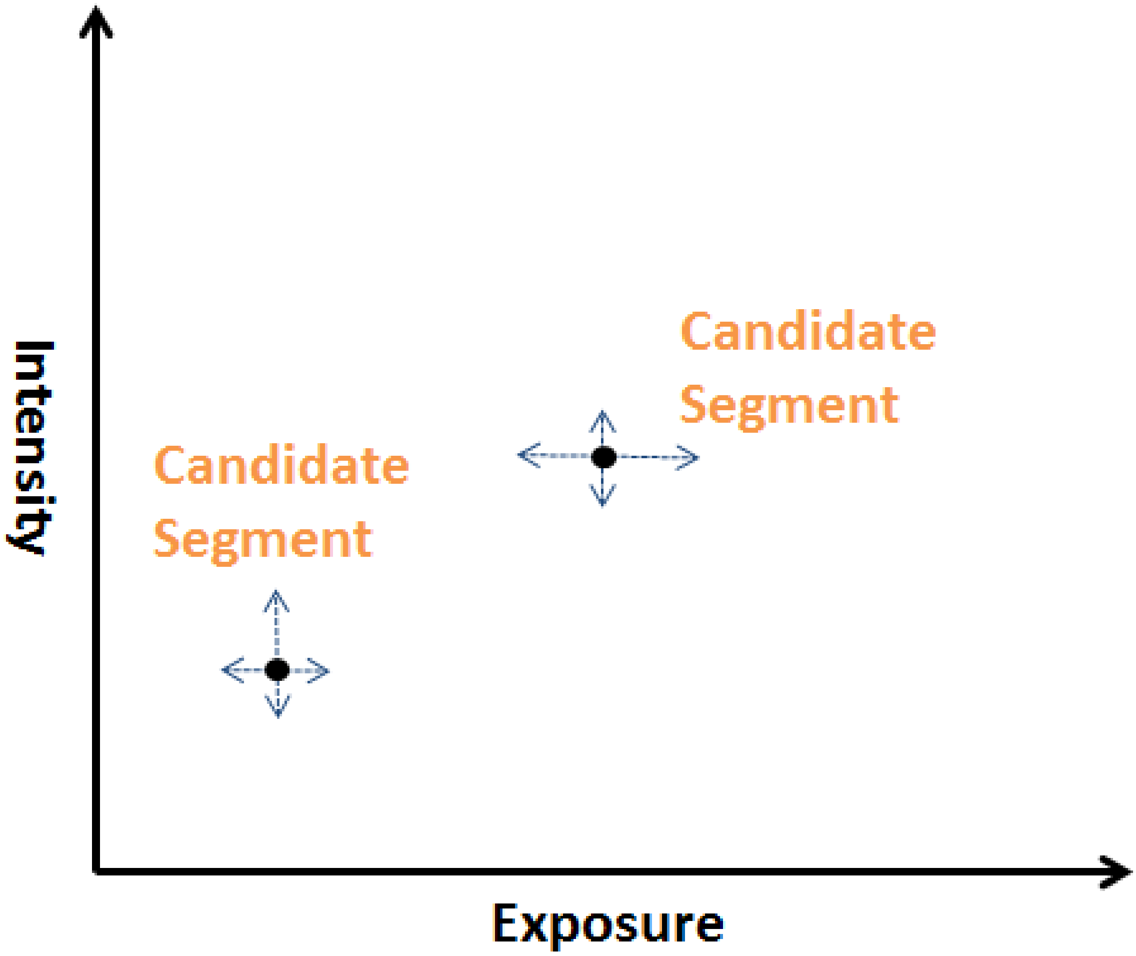

Figure 36. *Data/measurement* uncertainty arising from measurement error and evolution of local conditions with time and seasons

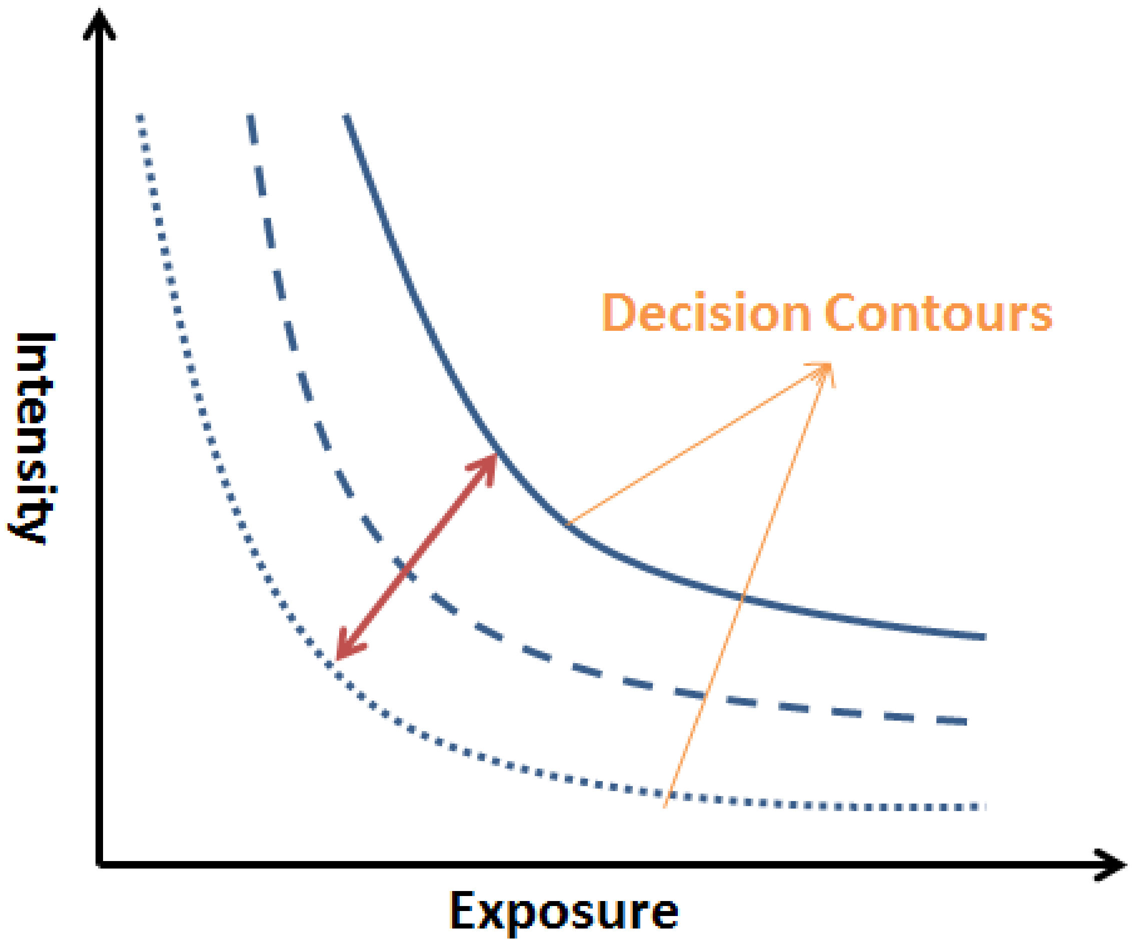

Figure 37. *Parameter* uncertainty, which is an influence of expert elicitation and estimation of modeling parameters

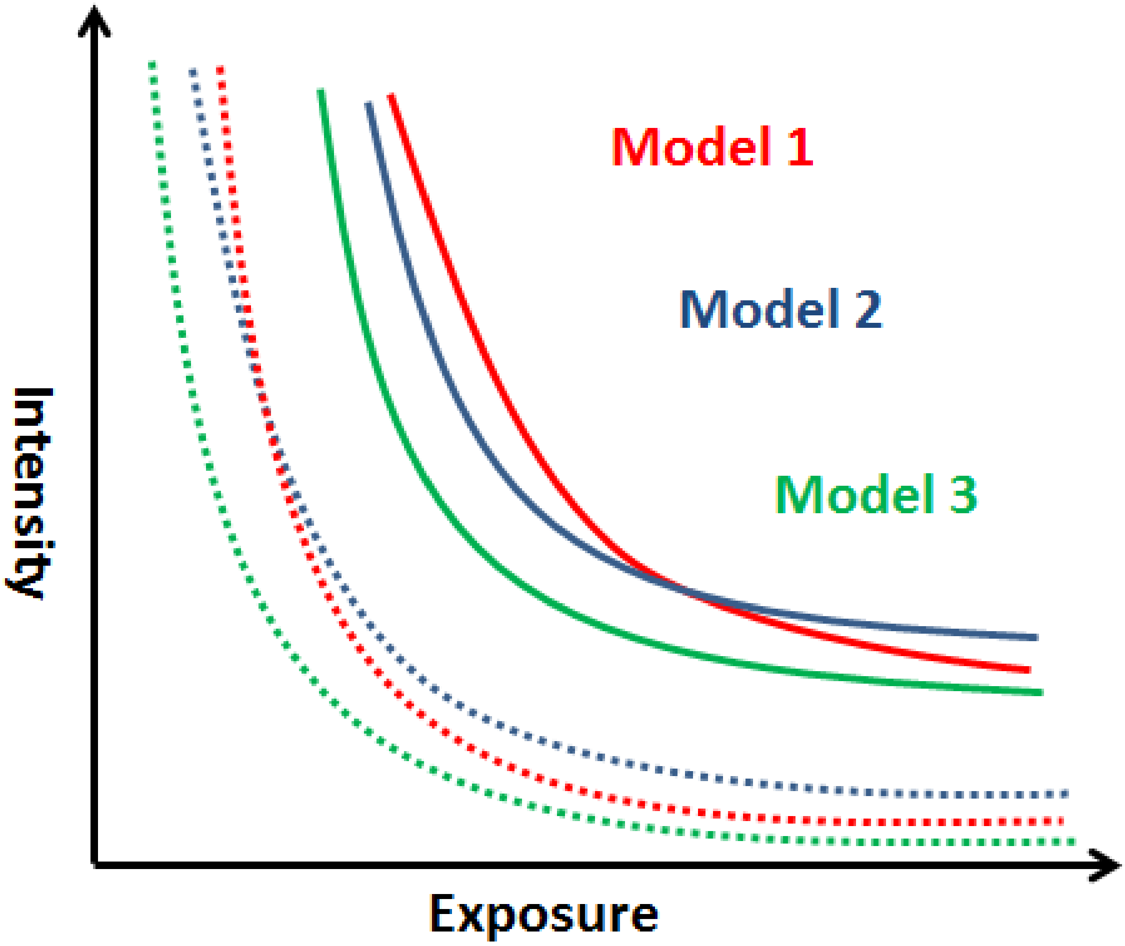

Figure 38. *Model* uncertainty, which manifests in the current effort in a choice to include safety, travel-time, and other categories of benefits

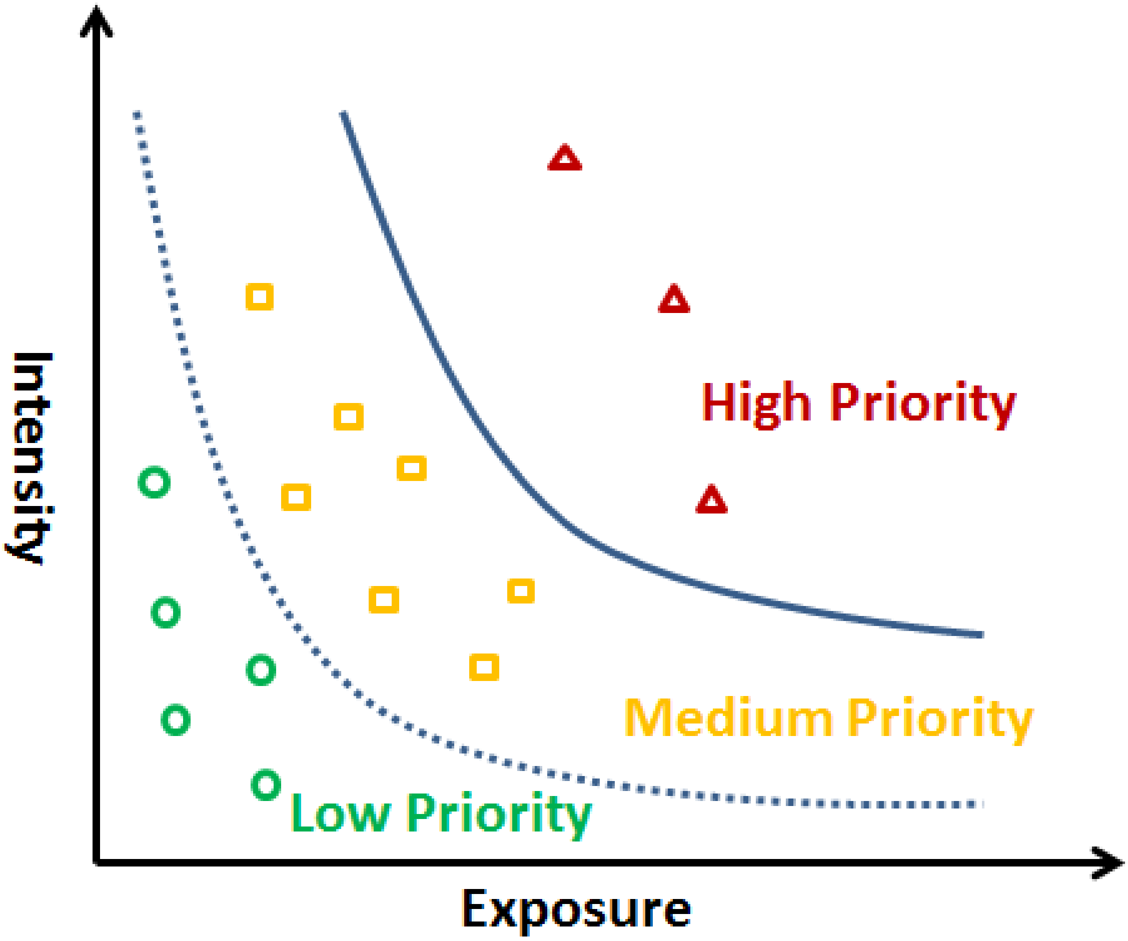

Figure 39. *Decision* uncertainty, which recognizes decision needs for ruling out next steps for particular road sections (low priority), collecting more data and elicitations for others (medium priority), and taking immediate remedial action for others (high priority)

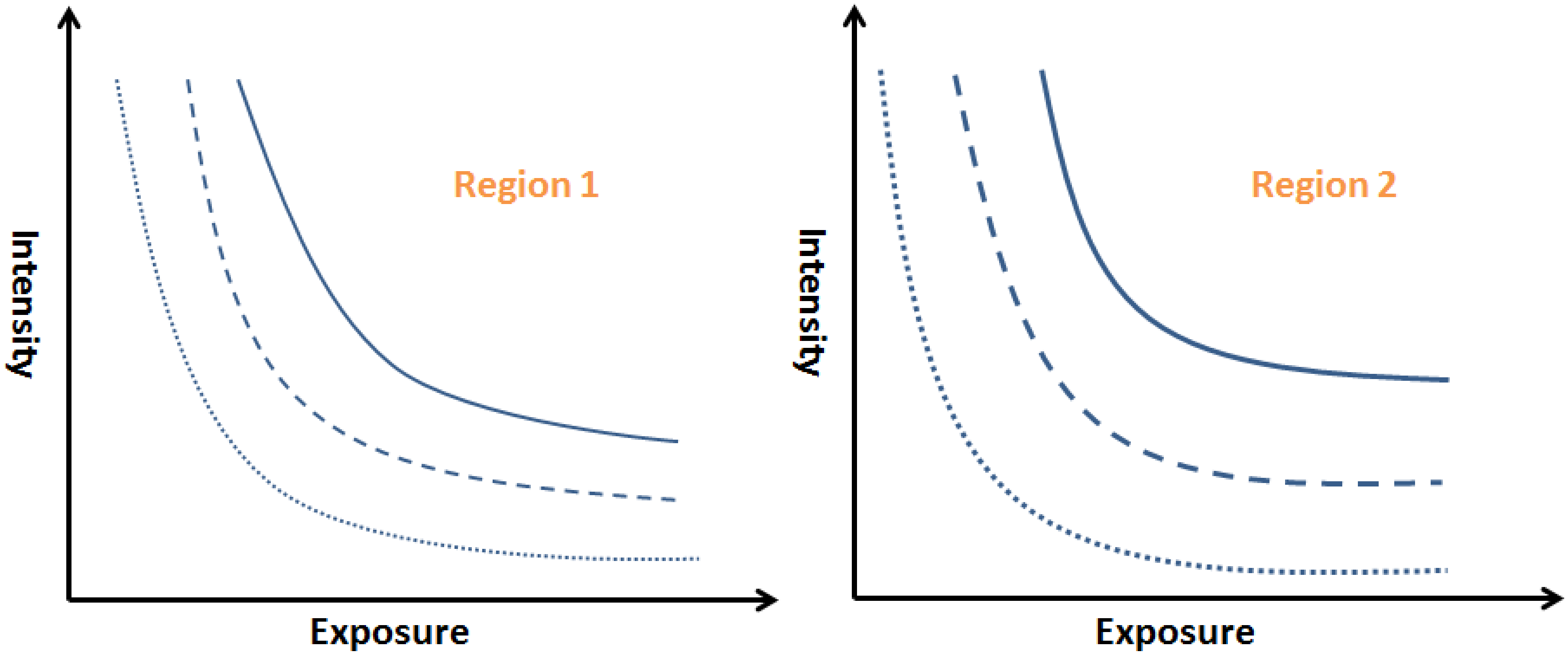

Figure 40. *Region/location* uncertainty, which recognizes that local conditions matter to the costs of remedial actions and other factors

7.3 Contributions

This dissertation summarizes theory, methodology, and application disseminated in the literature (Xu and Lambert 2014; Xu et al. 2014; Xu and Lambert 2013a) and conference presentations (Lambert et al. 2014; Xu and Lambert, 2013b; Thekdi et al. 2012; Watson et al. 2012). Appendix E provides milestones of the research effort demonstrated in this dissertation.

There are several theoretical and methodological contributions of this research as follows:

- ***Contribution 1:*** Provided a framework of develop supporting methodologies for cost-benefit analysis, especially for infrastructure corridor access management field. The efforts provide methodologies to quantify the benefits and costs of typical access management program and allow stakeholders to justify which corridor segments are most beneficial compared to the costs and prioritize the projects. This contribution is described by the Chapter Sections 3.3, 3.4, 4.3, 4.4, 5.3, and 5.4.

- ***Contribution 2:*** Integrated a cost-benefit analysis with multicriteria analysis in order for decision makers to assess how priorities changes as a result of various access point density and average daily traffic of corridor segments when considering a access management program. This contribution is described by the Chapter Sections 3.3, 3.4, 4.3, 4.4, 5.3, and 5.4.

- ***Contribution 3:*** Incorporated multiple perspectives to account for variations in benefits and risks of regions and their diverse features and stakeholders. The decision makers can compare and explore the impacts of prioritization across several perspectives. Integrating these viewpoints into a single decision-aiding toll can inform a variety of decision makers. This contribution is described by the Chapter Sections 5.3 and 5.4.

- ***Contribution 4:*** Used interval analysis of uncertainties for decision makers to address data and model uncertainties and conduct cost-benefit analysis without knowing the precise values of exogenous parameters, which is a typical challenge encountered in real engineering problems. The interval ranges reflect the uncertainty levels of data and parameters. This contribution is described by the Chapter Sections 3.3, 3.4, 4.3, 4.4, 5.3, and 5.4.

- ***Contribution 5:*** Provided decision support for transportation agencies to preserve the functionality and accessibility of transportation network in response to future conditions, since the agencies can prioritize project investments with transparency and accountability for the expected return on the investment. The approach is transferable to other topics in transportation safety and mobility where there is a need for limited resources to be allocated across a large multiscale system. This contribution is described by the Chapter Sections 3.4, 4.4, and 5.4.

- ***Contribution 6:*** Identified and created various suitable metrics for measuring the roadway performance and quantifying of benefits and costs in the domain of highway access management. The metrics include delay hours, travel time delay index, crash opportunity, access related crash intensity, etc. These metrics are notable for two reasons. First, they can be used to evaluate the potential benefits that can be expected after implementing a set of typical access management techniques for individual corridor sections. Second, they offer an efficient and critical way to relate and contrast the access point density and average daily traffic, which are typically identified as competing dimensions in an access management resource allocation. This contribution is described by the Chapter Sections 3.3, 3.4, 4.3, 4.4, 5.3, and 5.4.

- ***Contribution 7:*** Built case studies that use multicriteria risk-cost-benefit analysis for screening and prioritizing the transportation access management projects for Virginia Statewide Mobility System. This contribution enables access management planning to proceed without precise knowledge of data and model parameters on a large scale of thousands of miles of arterial corridors. Furthermore, this contribution shows how various perspectives can influence the selection of access management projects with high, medium, and low priorities. This contribution is described by the Chapter Sections 3.4, 4.4, and 5.4.

- ***Contribution 8:*** Developed, documented, and demonstrated an access-point (road layer) sampling process. The methods resulted in the spatial marking of about 50,000 access points over 6,000 miles of critical transportation corridors (SMS) in the Commonwealth of Virginia. The method can be implemented for diverse regions and infrastructure. This contribution is described by the Chapter Section 3.4 and the Appendix B.

- ***Contribution 9:*** Developed, documented, and demonstrated of an access-related vehicular crashes sampling process. The methods resulted in the spatial marking of about 40,000 traffic crashes/accidents in 2008 on 6,000 miles of critical transportation corridors (SMS) in the Commonwealth of Virginia. The method can be implemented for diverse regions and transportation networks. This contribution is described by the Chapter Section 3.4 and the Appendix C.

7.4 Future work

This section will describe several research opportunities that are grounded on the philosophy, methods, and results of this dissertation.

- ***Additional perspectives:*** As discussed in the chapters 3, 4, and 5, the major benefits of highway access management are safety improvement and travel time delay reductions. They are crucial when decision makers consider the investment of public fund. However, no single perspective is sufficient for a complex systems analysis (see, e.g., Haimes 2009), and furthermore, additional perspectives, such as mobility and capacity increases, reduced vehicle operating costs, emissions-avoided, etc., are helpful to account for variations in benefits of diverse stakeholders. Although a key challenge needing more investigation is how to quantify these typical benefits in multiple dimensions and correlate them with the access point density, comparing and exploring the impacts of these prioritizations across the more perspectives are suggested to constitute a fuller multicriteria analysis.

- ***Quantification of costs and benefits:*** Future research may investigate the form of benefit-cost functions, since the shapes of upper and lower decision contours in the scatterplot are determined by the form of B/C ratio. In this dissertation, several innovative metrics are discussed and used for risk-cost-benefit analysis for access management. The metrics provide the foundation for screening and prioritizing the projects, but it cannot be guaranteed that they are the best available measurement suitable for the risk management in the access management. Future work might focus on creating or discovering new metrics to integrate the multicriteria analysis, risk analysis, and cost-benefit analysis.

- ***Uncertainties of data and parameters:*** Although the analytical framework introduced in this dissertation overcomes the uncertainties issues of data and parameters in the decision making process, the project prioritization and selection still rely on precise numerical intervals. Another area of future work is to inspect the uncertainty intervals of particular exogenous parameters because the benefit-to-cost ratio and two decision contours in the *hazard intensity* and *population* diagrams depend on extreme values of each parameter.

Improved estimates of the ranges of parameter values would result to increased trustworthiness and replicability of the analysis.

7.5 Conclusion

The dissertation has contributed to the protection of transportation systems and risk-cost-benefit analysis of highway access management program in the following respects - incorporating diverse sets of data and expert evidence, quantifying the costs and benefits of access management projects, addressing the imprecise knowledge to underlying parameters and data, supporting multicriteria decision making, and validating model on a multiscale transportation systems. The results will be useful to benefit highway access management in the following respects: evaluating uncertain benefits and costs, prioritizing the access management resources allocation, and identifying where the corridor sections are most needing further access management investigation and investment. The approach ought to be of interest to analysts, planners, policymakers, and stakeholders who apply heterogeneous data and expertise to decision making.

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Appendix A: Message from the 72nd Governor of Virginia

Commonwealth of Virginia

Office of Governor Terry McAuliffe

March 13, 2014

Dear Fellow State Employees:

Last Saturday, we concluded the regular session of the 2014 General Assembly. Together, we tackled issues related to economic development, the Standards of Learning tests, transportation, public safety, and veterans' issues. I am proud of what we have achieved and have been very impressed by the hard work and dedication of our entire state workforce. We have made important strides for Virginia families, but more work needs to be done. Below is an outline of some of our key accomplishments.

The Economy

Growing Virginia businesses and bringing new ones to the Commonwealth is my top priority as Governor. I strongly supported legislation that increases the cap on research and development tax credits. This legislation enhances Virginia's business climate and builds on the strong presence of thriving, innovative companies in the Commonwealth. In addition, I worked hard to secure critical increases for the motion picture production tax credit. This increase is critical for the film industry in Virginia as tax credits provide continuity to potential film clients for long range planning. We are well positioned to continue our success for attracting films and television series with this enhanced economic development tool.

Working with a bipartisan team in both chambers, I was pleased to see the swift passage of my first introduced bill in the legislature, Senate Bill 673. This legislation allows the City of Bristol to use a portion of the state sales tax to help with a major retail development area for the region. The legislation is essential to the continued progress of this important project, which was approved by the 2012 General Assembly. I am pleased to help this project move forward, which represents a significant local investment and will create an estimated 2,000 local jobs.

Education

Education is another area in which we are working hard to make important strides. As many of you know, Virginia's Standards of Learning (SOL) program is not meeting the needs of our students, parents and teachers. Therefore, SOL reform was a main priority for my administration this General Assembly Session. We worked with legislators from both parties, stakeholders and education experts to begin making progress on the important work of reforming and strengthening our standardized testing system.

House Bill 930 will reduce the number of SOL assessments from 22 to 17 for elementary and middle school students. This legislation empowers teachers to utilize class time in a way that promotes innovative knowledge. This bill also creates the Standards of Learning Innovation Committee which will bring together legislators and stakeholders to review current SOL guidelines and recommend best practices to ensure that Virginia's testing structure prepares our students to compete globally in the 21st century.

Transportation

With respect to transportation, I strongly supported and worked with House and Senate leaders on legislation that outlines a transparent, data-driven process for evaluating new transportation projects. House Bill 2 is a landmark piece of legislation that will play a pivotal role in determining how we spend transportation dollars. We want to guarantee that Virginia's taxpayers are getting the best value for their money. In addition, I look forward to signing Senate Bill 156, which encourages the use of E-Z Pass transponders and eliminates unnecessary fees on Virginia's toll roads.

Public Safety

I have already signed legislation that transfers the responsibility for overseeing and coordinating efforts to strengthen homeland security from the Secretary of Veterans Affairs and Homeland Security to the Secretary of Public Safety. This reorganization resulted from a 2013 report by the Joint Legislative Audit and Review Commission on homeland security and preparedness. This important change will make sure that the Commonwealth can effectively and efficiently coordinate preparedness efforts.

Veterans

I am honored to have worked with the General Assembly to move Virginia forward this session in promoting veterans and their families. Senate Bill 18 will improve financial security for military families by providing unemployment compensation to military spouses who leave their job to accompany their active duty spouse to a new military duty assignment in Virginia. More than half of active duty service members are married and spouse employment is a key income source for many military families. I strongly supported this legislation and look forward to signing it when it gets to my desk.

Closing the Health Care Coverage Gap

As you know, we still do not have a budget, which is why I have called the House and Senate back for a Special Session commencing on March 24, 2014. My intention is for this session to last for three weeks, and it is my hope that the House and Senate will resolve their outstanding budget issues during this time. By reaching an agreement that will close the healthcare coverage gap, more than 400,000 Virginians will have access to the healthcare they desperately need and Virginia will draw down federal dollars that our citizens have already sent to Washington. Over the next several weeks, I will continue to travel across the state to hear from patients, health care providers, and local residents about how this important issue is affecting their lives.

Lastly, I want you to know that I am committed to passing a budget as swiftly as possible. I recognize that not having a budget creates uncertainty, and I will do my best to bring legislators together so we can find common ground and do what is best for Virginia families.

Please know how much I appreciate and value your service as employees of Virginia State government. During my first two months in office, I have had the opportunity to visit with many of you and look forward to working with you to create a stronger, more prosperous Virginia.

Thank you for your continued service to the Commonwealth and its citizens.

Sincerely,

Governor Terry McAuliffe

Appendix B: Map layer sampling method for characterizing SMS corridor access points

The following methodology is for access point inventory along selected Virginia transportation corridors. A repeatable method is developed for collecting, cleansing, and analyzing data on access points on a statewide scale. The databases used in this method include VDOT's SMS road layer files and U.S. Census layer files for all roads in Virginia. The automated access points sampling and identification is based on ArcGIS, which is a geographic information system (GIS) for working with maps and geographic information. The methodology is not designed with the goal of being perfectly accurate and can be applied to any statewide mobility system. However, the produced results can be used to identify locations or corridor segments that may need further inspection for various purposes in the transportation engineering, especially for transportation access management. By comparing with previous access point sampling method (Thekdi, 2012), which is a manual visual identification process, the current approach is much more efficient, while retaining satisfactory accuracy. Below are detailed procedures on how to carry out this methodology.

Acquisition of the Data

1. Data are readily available, such as from U.S. Census Bureau 2011 TIGER/Line® road shapefiles (http://www.census.gov/geo/maps-data/data/tiger-line.html) as shown in Figure 41.

2. Select "FTP site" download option

3. Use FTP client (such as FileZilla) to download all VA road shapefiles simultaneously

4. Extract all zipped files with zip utility (7-Zip)

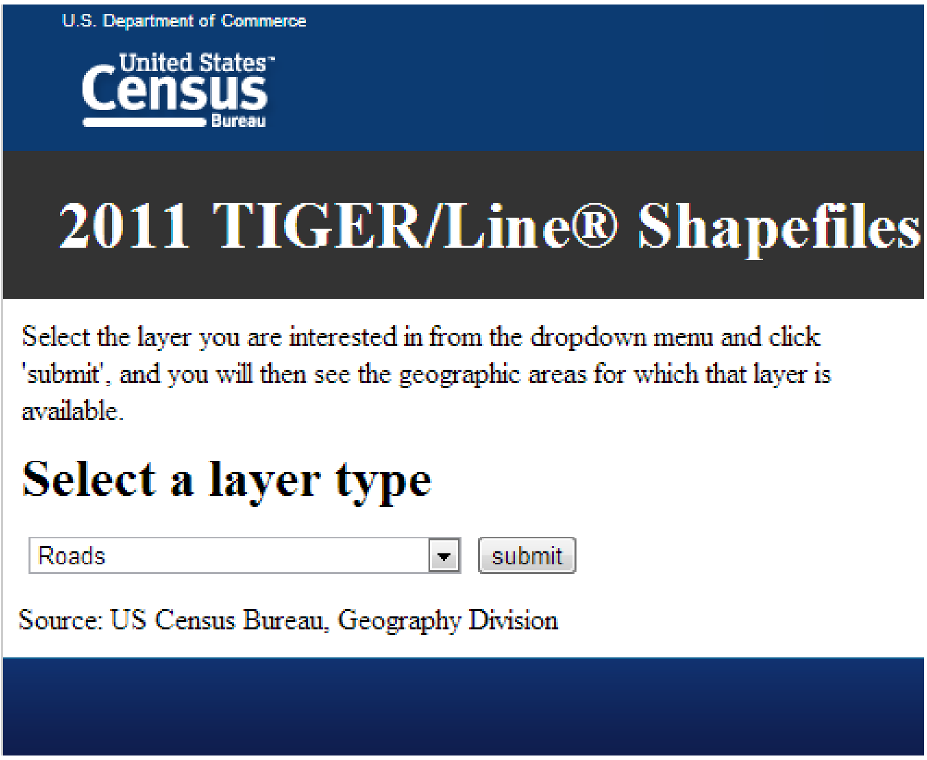

Figure 41. 2011 TIGER/Line shapefile (source: U.S. Census Bureau)

Sampling procedure

1. Import all shapefiles into ArcMap

2. Combine all road shapefiles into one shapefile for entire state. Figure 42 shows the diagram of all roads in Virginia and Figure 43 displays the database having all roads information.

3. Select Catalog on the right hand side and navigate to Intersect tool as shown in Figure 44

   - Catalog-> Toolboxes-> System Toolboxes-> Analysis Tools-> Overlay-> Intersect

4. Select appropriate shapefile as the input feature

5. Change output type to point and wait for ArcGIS to construct intersection shapefile

6. Add latitude and longitude as attributes to intersection shapefile

7. Remove duplicated points

   - Dissolve points with equal latitude and longitude coordinates to remove duplicates using a projection

8. Save completed shapefile

   - Figure 45 provides an example of access points/intersections marking.

   - Figure 46 shows the access points database with detailed latitude and longitude of each intersection.

9. Select SMS intersections

   - Select points within 30 meter radius buffer of the SMS corridor centerlines using select by Location. The SMS corridor database is shown in Figure 47.

     - selection-> select by location-> choose selection method as "select feature from"-> choose target layer as the intersections map layer and source layer as the SMS map layer -> apply 30 meters as a search distance

   - The Figure 48 shows a sample access points (SMS intersections) identification result. In Figure 48, green outlined corridor represents SMS corridor; black line corridor represents other corridor; green dot represents intersection on SMS; and black dot represents intersection off SMS.

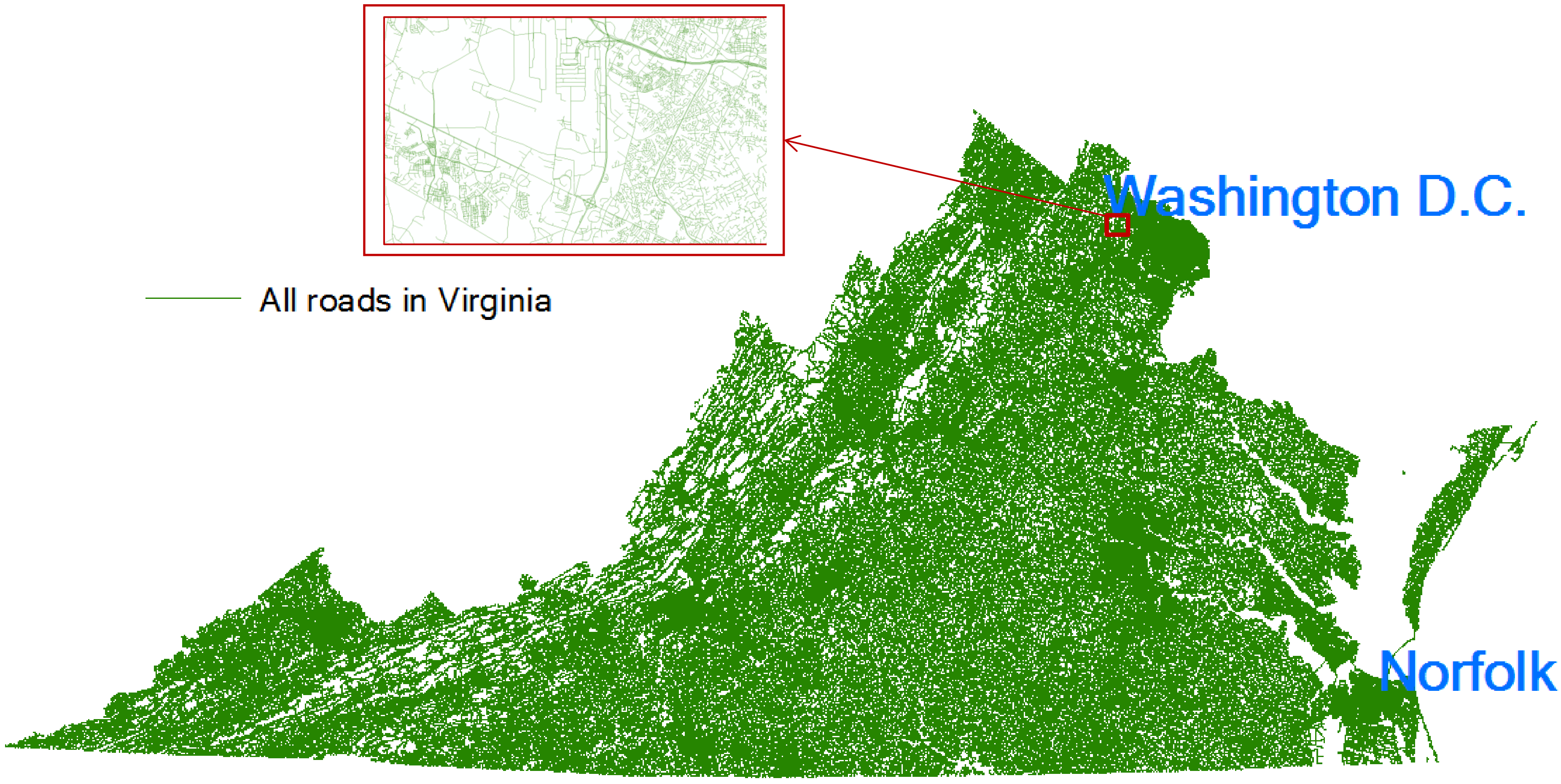

Figure 42. All roads in the state of Virginia

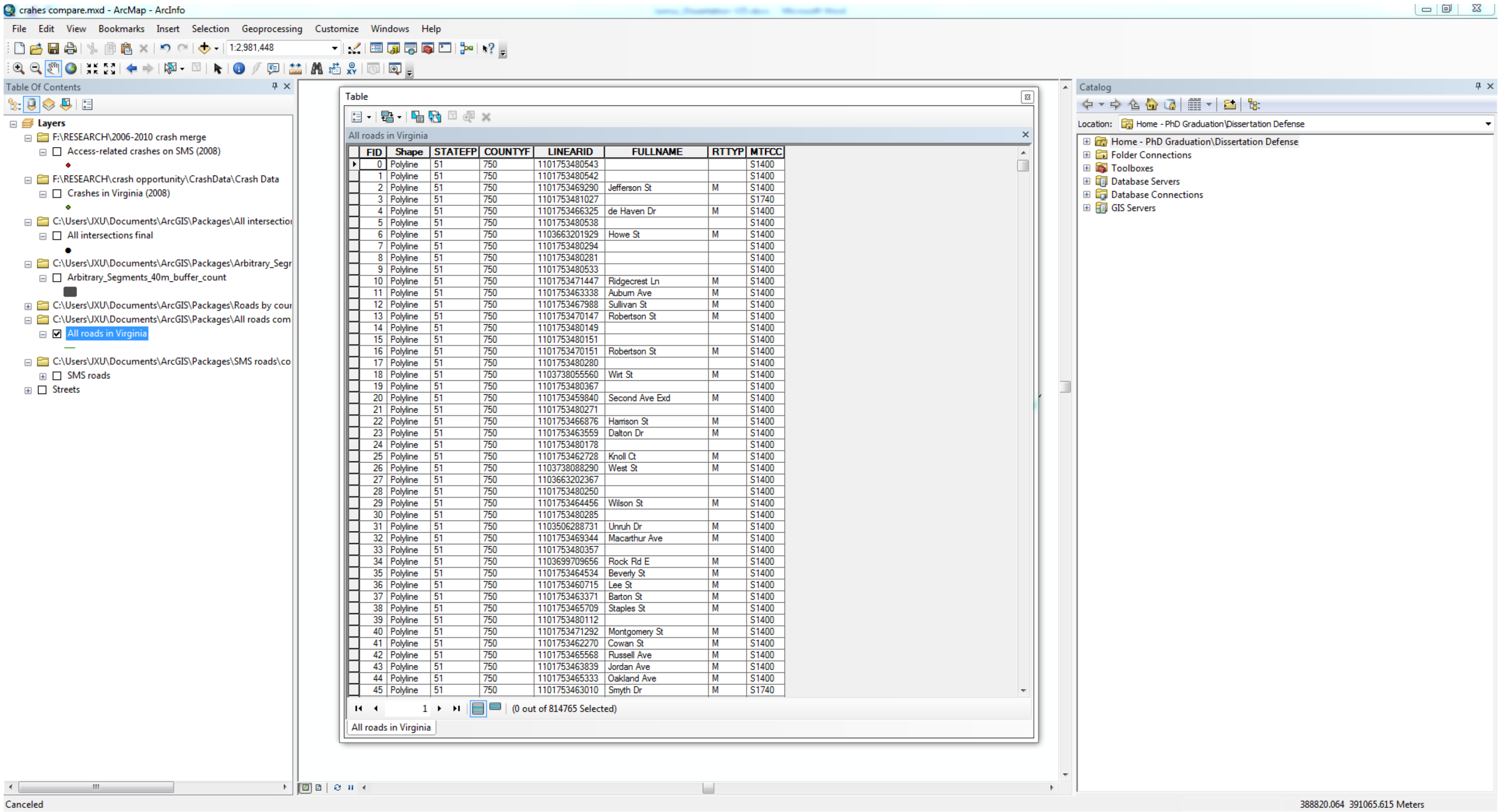

Figure 43. The database of all roads in Virginia

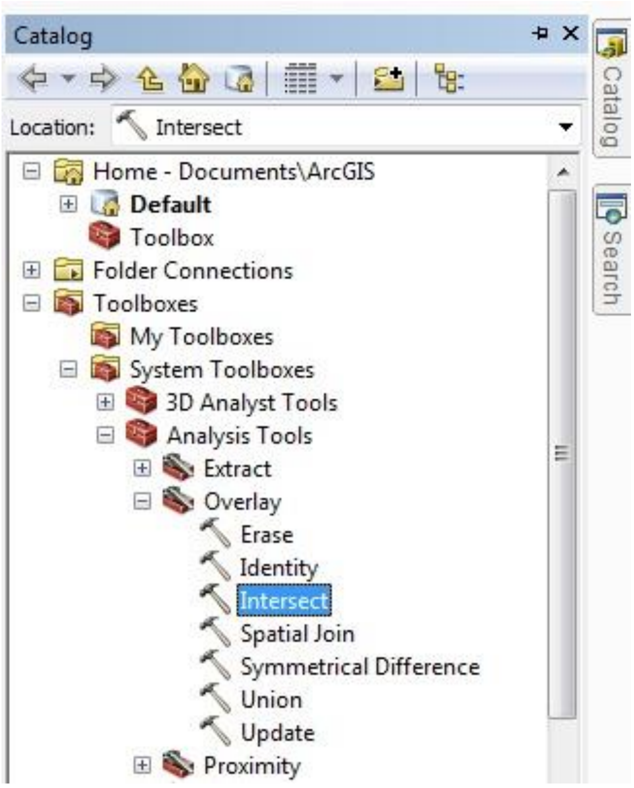

Figure 44. ArcGIS Catalog “Intersection”

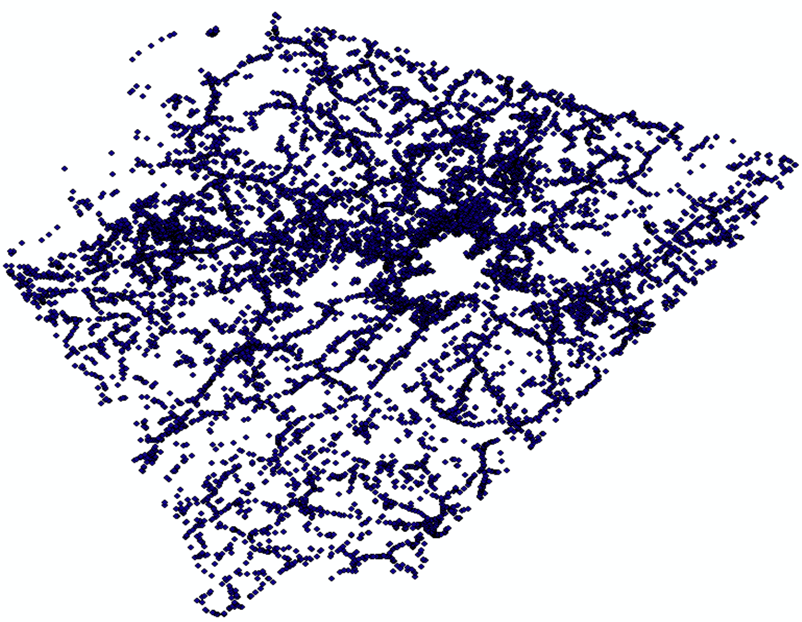

Figure 45. Access points/intersections marking in Albemarle County in Virginia

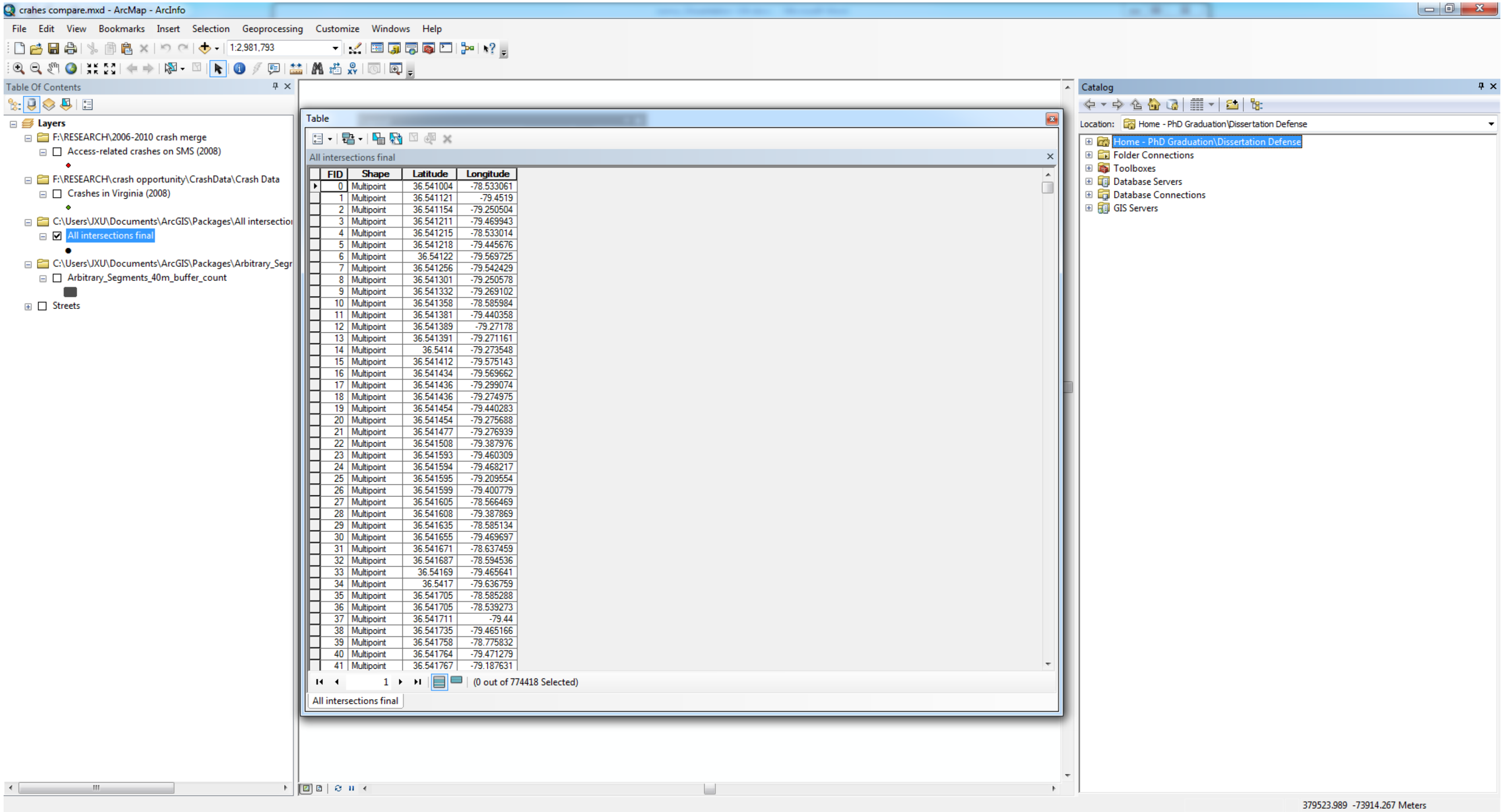

Figure 46. Access points database with latitude and longitude

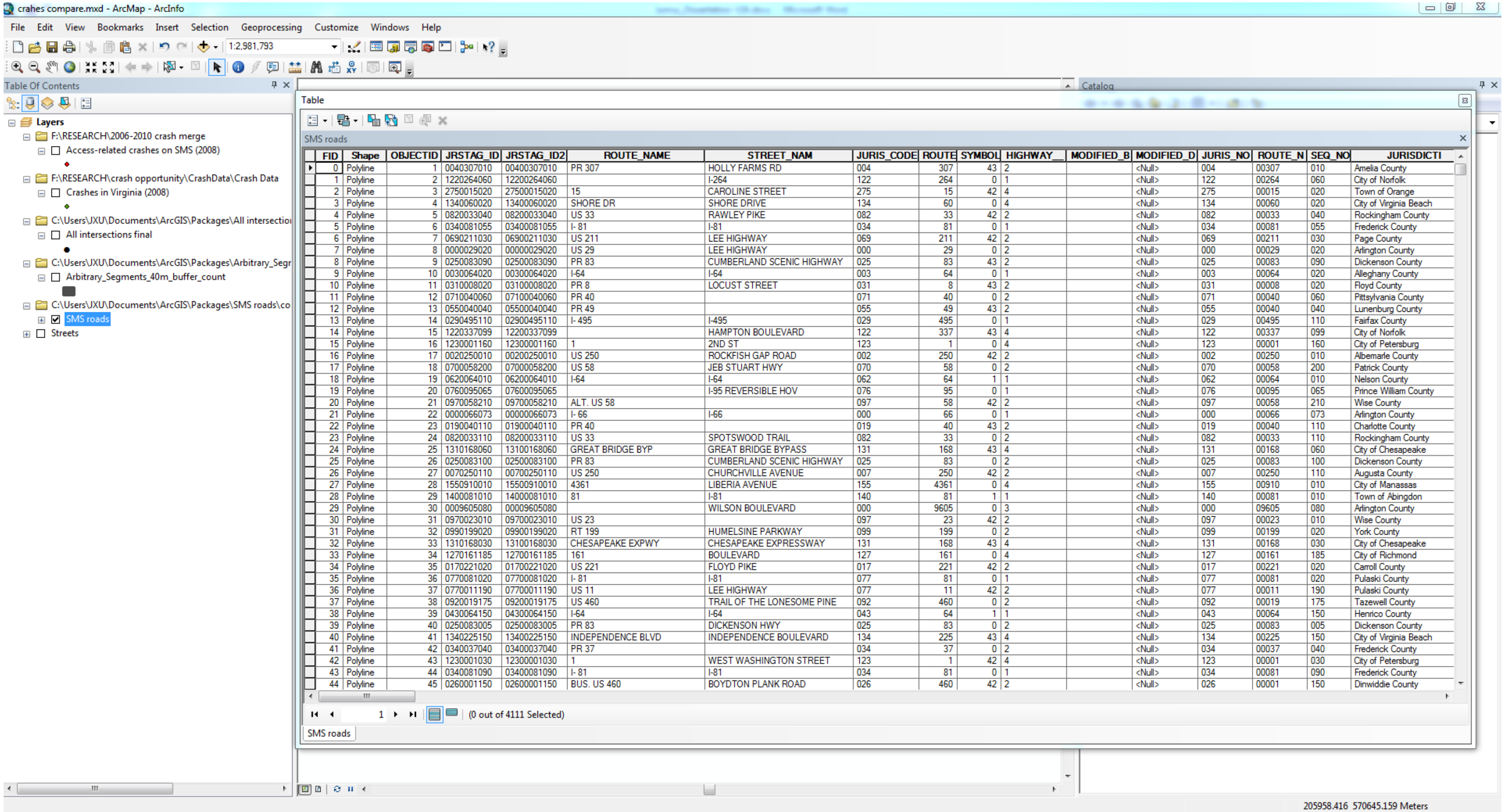

Figure 47. SMS database with detailed information of corridor segments with arbitrary length

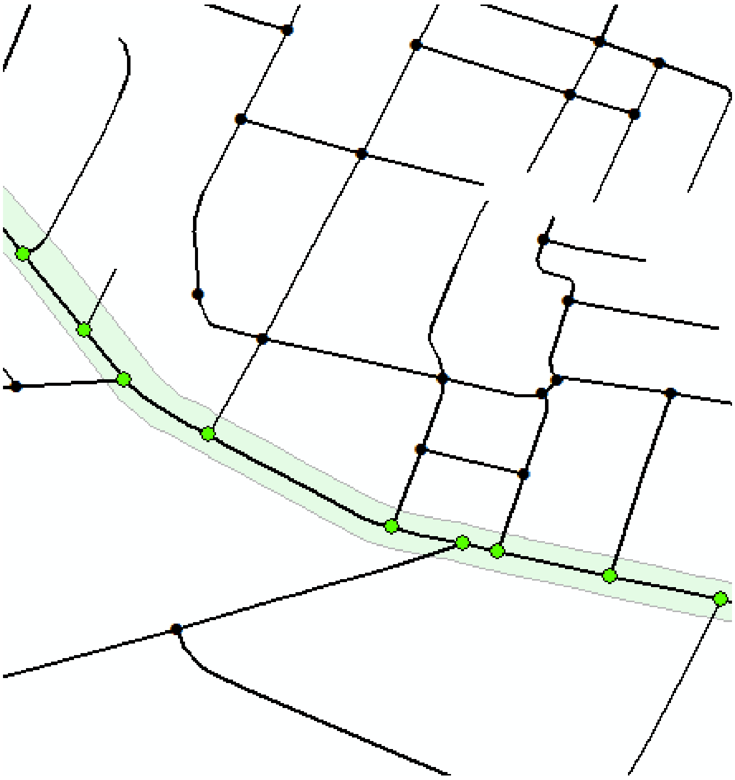

Figure 48. A sample SMS intersections/access points identification result

Limitations of Methodology

This methodology is developed under the requirement that it is able to be quickly and automatically implemented without intensive human resources. As a result of this, the method shows the following limitations in nature:

1. Identification errors

   - False positives - identifies intersections that do not exist, e.g. road layer sampling method over counts access points on multi-lane highways, such as overpasses, On/off ramps, etc.

- False negatives - does not identify real access points likely due to undercounting of driveways and side roads in rural areas.

2. Buffer method to find intersections

Create 30 meter "buffer" area around SMS roads and count any intersections within 30 meter buffer of SMS road, which will inflate or deflate the intersection counts on multi-lane road due to the racial nature of the buffer (points from the intersecting road are captured near the intersection).

The Figure 49 provides an example of access points sampling errors.

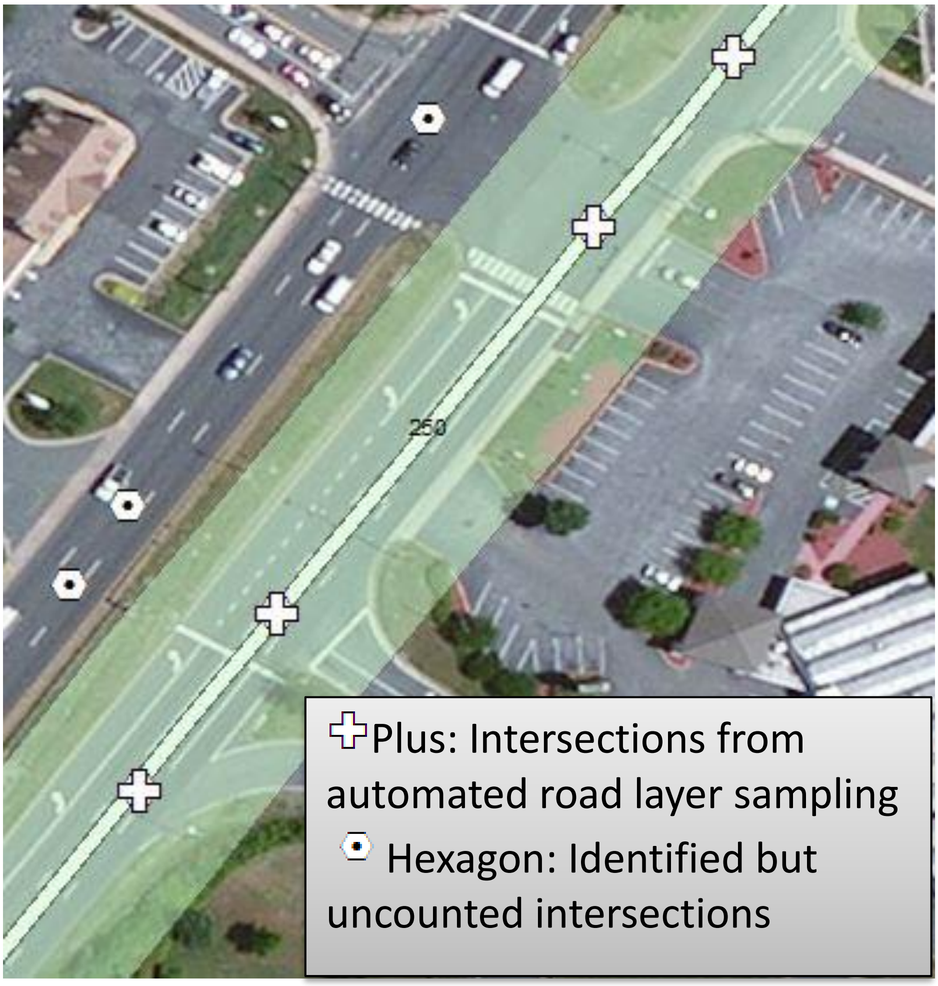

Figure 49. An example of the limitation of map layer sampling method

Appendix C: Map layer sampling method for quantifying access related traffic crashes

The following method is used for quantifying access related crashes on selected Virginia transportation corridors. A repeatable method is developed for identifying and counting access related vehicular crashes. The software used is ArcGIS. The map layers used in this method include Virginia traffic crash (2008) and Virginia SMS access points inventory map layer files. The method can be applied to any other transportation network for locating and quantifying access related traffic crashes. Note that this methodology is not developed with the goal of being 100% accurate, and the fundamental assumption is that all crashes within 300 feet radius of access point are access related. Below are detailed procedures on how to carry out this methodology.

Loading in the Data

1. Open ArcMap and create a new map

2. Click “Add Data” button

3. Select and import appropriate road database/network files

   - To demonstrate the methodology on the Virginia SMS, Virginia traffic crashes (2008) , and SMS access point inventory map layer files are added by using the “Add Data” button

4. Ensure all data layers use the same coordinate system

Identifying Procedure

1. Create a buffer around each access point using the buffer function from the ArcToolbox window and save the new shape file

    - Input Features should be the previously imported - Virginia SMS access points inventory map layer files

    - Output Feature will be a new shape file

    - Specify the desired radius of the buffer in the linear unit field – in this case 300 feet is chosen

2. Filter out all access related vehicular crashes into a new layer

    - Select Catalog on the right hand side and navigate to Intersect tool

        - Catalog-> Toolboxes-> System Toolboxes-> Analysis Tools-> Overlay-> Intersect

    - Select appropriate shapefile as the input feature

        - New buffer shape file created in above step and Virginia traffic crash (2008) map layer files

    - Change output type to point and wait for ArcGIS to construct intersection shapefile

    - Output feature will be a new shape file, which is a desired access related traffic crashes map layer. Figure 50 provides an example of the result and show all access related crashes in a specific small region.

- Figure 51 shows a contrast the crashes in the entire Virginia and access-related crashes on SMS in the year of 2008

- Figure 52 displays the database of access-related crashes on SMS in the year of 2008

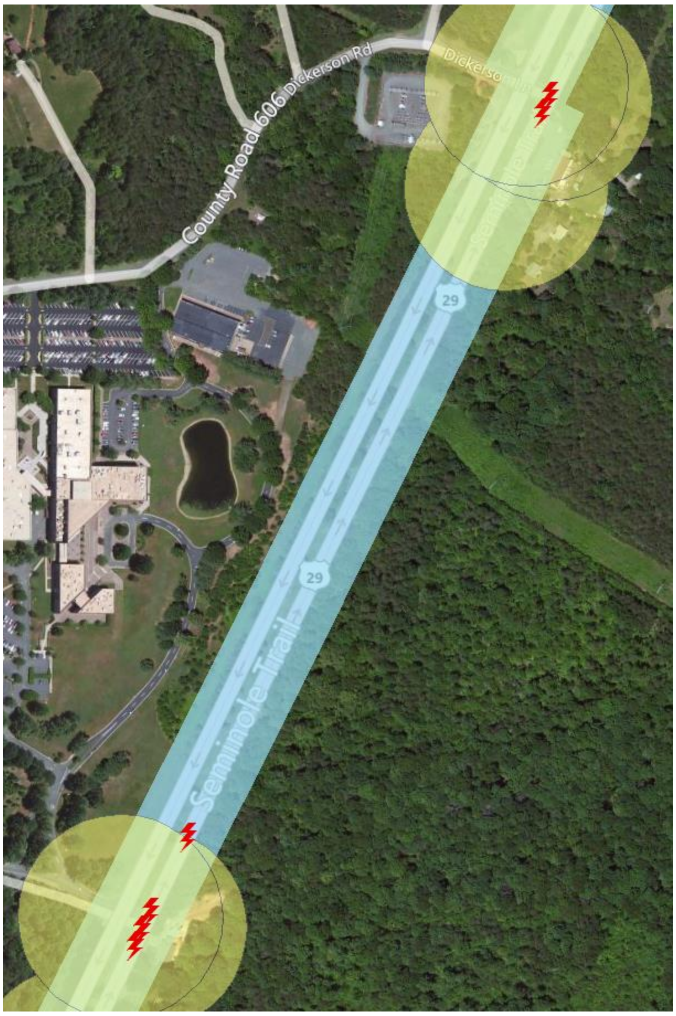

Figure 50. An example of map layer sampling method for quantifying access related traffic crashes

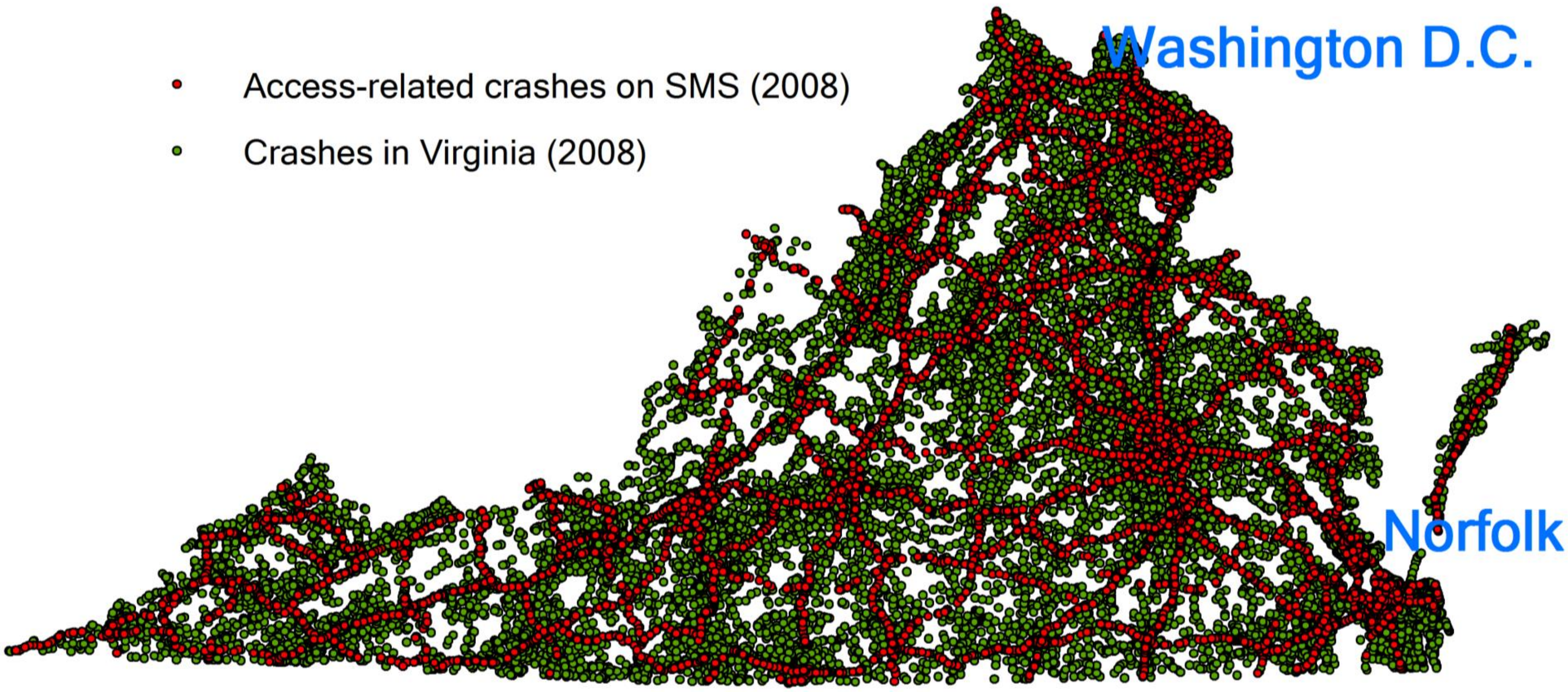

Figure 51. All Virginia vehicular crashes and access-related crashes on SMS in 2008

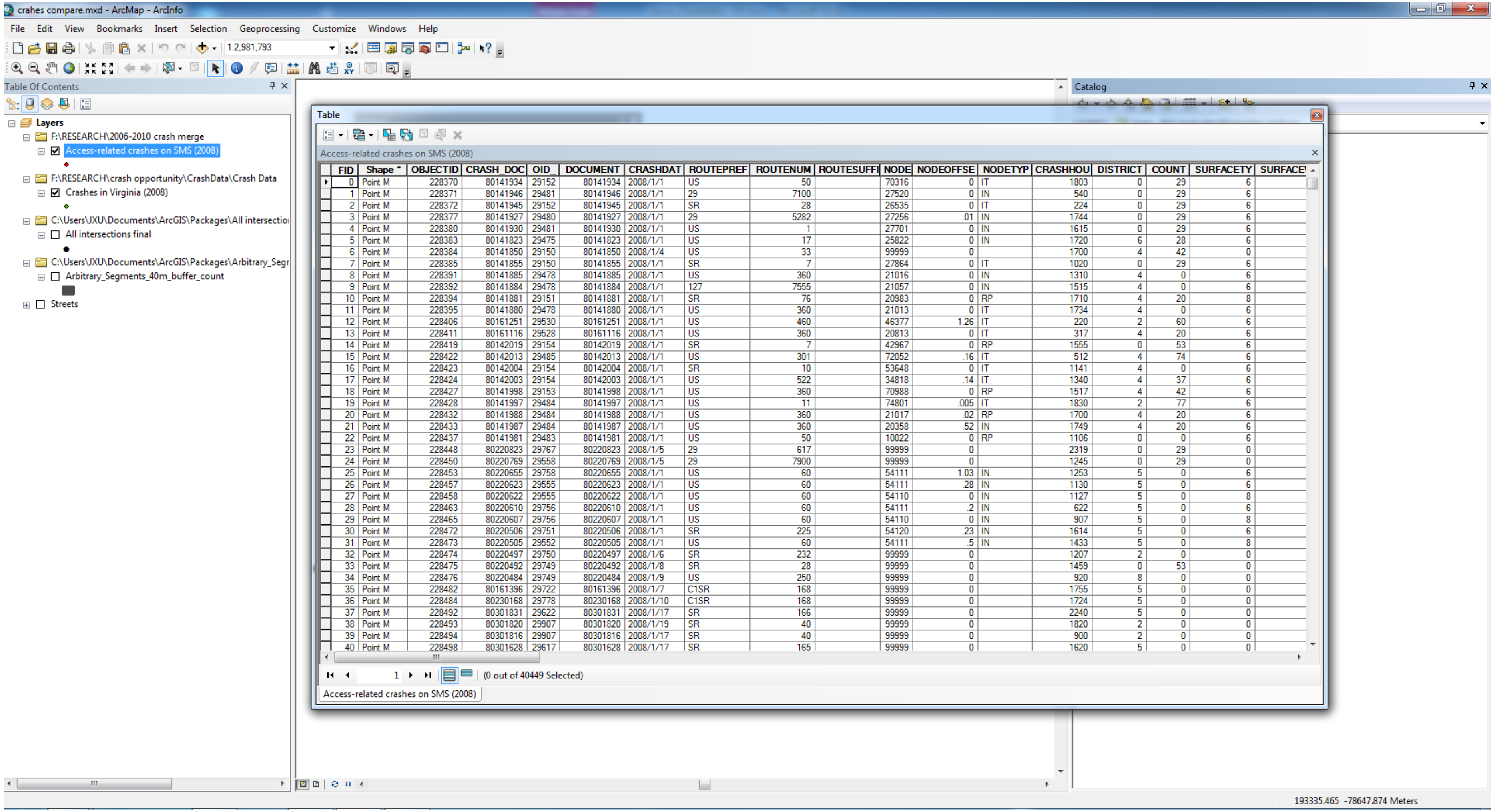

Figure 52. Database of access-related crashes on SMS in the year of 2008

Appendix D: Matlab sample code for generating decision contours in the *hazard intensity* and *population* diagram

The following matlab code is used to generate the hazard intensity and population diagram and decision contours for all SMS rural candidate segments in the entire region in Chapter 5. Similar codes can be written for all candidate segments in other entire regions and sub-regions.

```
% load the data from external file.
data = xlsread('C:\Users\JXU\Dropbox\BC paper\Add B_C analysis - new -
new\Clean_Rural_analysis_RawData.xlsx','Sheet1');


% log transformation.
accessDensity = log(data(:,6)+1);
ADT = log(data(:,8)+1);

% generate the hazard intensity and population diagram
figure()
scatter(ADT,accessDensity,'.','black');

range = log([150,12*10^4,0,120]+1);
axis(range);

% relabel xtick
xtick=log([0.5 1 2 4 6 8 10]*10^4 +1);
xtick = round(xtick * 10) / 10;
set(gca,'xtick',xtick);

% relabel ytick
ytick = log([1 5 10 20 40 60 80 100]+1);
ytick = round(ytick * 10)/10;
set(gca,'ytick',ytick);
set(gca,'yticklabel',{'1','5','10','20','40','60','80','100'});



set(gca,'xticklabel',{'0.5','1','2','4','6','8','10'});
```

```
% generate the decision contours
hold on
upper1=ezplot('365*exp(x)*exp(y)*0.25*60000*0.40-500000*10^7',range);
set(upper1,'LineStyle','-','color','r','LineWidth',2.5);

lower1=ezplot('365*exp(x)*exp(y)*1.4*80000*0.65-100000*10^7',range);
set(lower1,'LineStyle','- -','color','r','LineWidth',2.5);

upper2=ezplot('365*exp(x)*(0.25*exp(y)/(60*(60-0.25*exp(y))))*15-500000',range);
set(upper2,'LineStyle','-','color','blue','LineWidth',2.5);

lower2=ezplot('365*exp(x)*(0.25*exp(y)/(40*(40-0.25*exp(y))))*35-100000',range);
set(lower2,'LineStyle','- -','color','blue','LineWidth',2.5);

upper3=ezplot('365*exp(x)*exp(y)*0.25*60000*0.40+365*exp(x)*(0.25*exp(y)/(60*(60-0.2
5*exp(y))))*15*10^7-500000*10^7',range);
set(upper3,'LineStyle','-','color','g','LineWidth',2.5);

lower3=ezplot('365*exp(x)*exp(y)*1.4*80000*0.65+365*exp(x)*(0.25*exp(y)/(40*(40-0.25
*exp(y))))*35*10^7-100000*10^7',range);
set(lower3,'LineStyle','- -','color','green','LineWidth',2.5);

hold off
```

Appendix E: Milestones of the research effort

Milestone	Date
Arrive to Ph.D. program in Systems Engineering at UVa	08/2010
Presentation at TPRAC meeting	12/2011
Presentation at VDOT, Richmond VA	03/2012
Ph.D comprehensive examination	04/2012
Presentation at 2012 IEEE SIEDS conference	04/2012
Presentation at TPRAC meeting	05/2012
Presentation at Virginia GIS conference	09/2012
Presentation at TPRAC meeting	10/2012
Presentation at TPRAC meeting	04/2013
Ph.D. dissertation proposal	06/2013
Paper accepted to *Environment Systems and Decisions*	07/2013
Paper accepted to *ASCE Journal of Transportation Engineering*	09/2013
Paper submitted to *Risk Analysis*	10/2013
Presentation at TPRAC meeting	11/2013
Presentation at 2013 SRA annual meeting	12/2013
Presentation at VDOT, Staunton VA	01/2014
Responded to favorable reviews of *Risk Analysis* submitted paper	01/2014
Presentation at VDOT, Richmond VA	02/2014
Presentation at VDOT, Richmond VA	04/2014
Ph.D. dissertation defense	04/2014