Applied Research and Innovation Branch

EXPLICIT CONSIDERATION OF SAFETY IN THE TRANSPORTATION PLANNING PROCESS

Jake Kononov, PE, PhD, DiExSys

Richard G. Sarchet, PE, DiExSys

Elliot Sulsky, PE, Felsburg Holt & Ullevig

Kelly Leadbetter, AICP, Felsburg Holt & Ullevig

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This report develops a methodology for the Explicit Consideration of Safety in the Transportation Planning Process by focusing on science-based and data-driven project selection, which considers susceptibility to cost-effective correction rather than simply observed frequency and severity of crashes. Only a very small percentage of projects (4 percent or less in Colorado) are exclusively safety motivated and funded. Most projects are aimed at some combination of mobility, pavement preservation, maintenance, improved air quality, operations as well as safety. Safety consideration is present explicitly or implicitly in most transportation infrastructure projects and the challenge is to bring safety to a common denominator with other goals of the project. The actual planning process is influenced not only by scientifically estimated objective benefits and costs, but also by the availability of funding, political climate, and other intangible factors. Nevertheless, with all other things being equal, the proposed methodology provides a quantitative framework for decision makers in selecting and ranking transportation projects.</td></tr>
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Study Panel Members

Aaron Willis – Colorado Department of Transportation

Bill Haas – Federal Highway Administration

Charles Meyer – Colorado Department of Transportation

David Reeves – Colorado Department of Transportation

David Swenka – Colorado Department of Transportation

Jason Wallis – Colorado Department of Transportation

Lisa Streisfeld – Colorado Department of Transportation

Michelle Scheuerman – Colorado Department of Transportation

EXECUTIVE SUMMARY

The Colorado-specific safety knowledge base, developed and effectively applied in the design process at CDOT, is not yet used to inform the planning process. This report transfers the use of these Colorado-specific, predictive and diagnostic tools to the transportation planning process. It develops a proposed methodology for the Explicit Consideration of Safety in the Transportation Planning Process by focusing on science-based and data-driven project selection, which considers susceptibility to cost-effective correction, rather than simply observed frequency and severity of crashes.

This methodology will aid in ranking and prioritizing safety aspects of projects in concert with other attributes, such as mobility, air quality, noise, etc. It effectively translates state-of-the-art safety analysis techniques into an applied, practical methodology that transportation planners and practicing engineers can use.

Only a very small percentage of projects (4 percent or less in Colorado) are exclusively safety motivated and funded. Most projects are aimed at some combination of mobility, pavement preservation, maintenance, improved air quality, operations as well as safety. Safety consideration is present, explicitly or implicitly, in most transportation infrastructure projects, and the challenge is to bring safety to a common denominator with the other goals of the projects. The concept of a Life Preservation Effectiveness score, introduced in this study, provides planners with this capability. It reflects how much safety benefit, expressed in dollars, can be derived per unit of expenditure. If the same approach is adapted to other important project goals, then each project within a planning region can be effectively compared with others, on the merits of its combined, total benefit.

The actual planning process is influenced not only by scientifically estimated objective benefits and costs, but also by the availability of funding, political climate, and other intangible factors. Nevertheless, with all other things being equal, the proposed methodology provides a quantitative framework to assist decision-makers in selecting and ranking transportation projects.

Implementation

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TABLE OF CONTENTS

List of Figures

List of Tables

List of Acronyms and Abbreviations

3C	Continuous, Cooperative, and Comprehensive
AADT	Annual Average Daily Traffic
acc/mvmt	Accidents per million vehicle miles traveled
ADT	Average daily traffic
CDOT	Colorado Department of Transportation
CMF	Crash modification factor
CRF	Crash reduction factor
CSS	Context sensitive solutions
CURE	Cumulative Residuals
DOT	Department of Transportation
DRCOG	Denver Regional Council of Governments
EB	Empirical Bayes
FAT	Fatal
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
ft.	feet
FTA	Federal Transit Administration
GLM	Generalized Linear Model
GVMPO	Grand Valley Metropolitan Planning Organization
HSM	Highway Safety Manual
INJ	Injury
ITE	Institute of Transportation Engineers
LOSS	Level of Service of Safety
LPE	Life Preservation Effectiveness
LRTP	Long range transportation plan
m	meter
mi.	mile
MAP-21	Moving Ahead for Progress in the 21st Century Act
MPO	Metropolitan Planning Organizations (MPOs)

NFRMPO	North Front Range Metropolitan Planning Organization
PACOG	Pueblo Area Council of Governments
PDO	Property damage only
PPACG	Pikes Peak Area Council of Governments
PUC	Public Utilities Commission
RTM	Regression to the Mean
RTP	Regional transportation plan
SafeTREC	Safe Transportation Research and Education Center
SCP	Safety Conscious Planning
SEMCOG	Southeast Michigan Council of Governments
SPF	Safety performance functions
TDM	Transportation Demand Management
TIP	Transportation improvement program
TPR	Transportation planning region
TRB	Transportation Research Board
TSP	Transportation Safety Planning
VMT	Vehicle miles traveled
VZS	Vision Zero Suite

INTRODUCTION

The Colorado Department of Transportation (CDOT) is the nation's leader in addressing safety during the design process; in contrast to design, consideration of safety during the planning cycle is largely qualitative, influenced by intuition and groupthink. Daniel Kahneman (1)(*Judgment under Uncertainty, Heuristics and Biases*, Cambridge University Press, 1974), a 2002 Nobel Prize winner in behavioral economics, has conclusively proven that intuitive statistical inferences or judgments made by the economists, physicians, and other professionals although are generally useful, are sometimes biased, and lead to severe and systematic errors. Kahneman showed that a simple algorithm developed by professionals outperforms professional judgments made by the same professionals. The authors believe that it is also true in planning road safety improvements. The current Colorado planning process does not take advantage of the latest safety analysis methodologies and the existing Colorado-specific predictive and diagnostic tools. The Moving Ahead for Progress in the 21st Century Act (MAP-21) emphasizes a data-driven, strategic approach to improving highway safety on all public roads by focusing on performance. Our approach to meeting the goal outlined in this report was to develop a methodology for the Explicit Consideration of Safety in the Transportation Planning Process by focusing on science-based and data driven project selection, which would consider susceptibility to cost-effective correction rather than simply observed frequency and severity of crashes. This methodology will aid in ranking and prioritizing safety aspects of projects in concert with other attributes, such as mobility, environment, etc. It effectively translates state-of-the-art safety analysis techniques into applied practical methodology that transportation planners and practicing engineers can use. Consensus building and negotiations between CDOT and its planning partners are central to the current transportation planning process. It is likely to remain so in the foreseeable future. This methodology aims to inform this safety planning debate by considering safety explicitly and quantitatively using Colorado-specific predictive and diagnostic tools. Incorporating such methodology into the Colorado transportation planning process is expected to maximize crash reduction in the climate of constrained resources. This report consists of the following parts:

- Literature Review
- Safety within Colorado Metropolitan Planning Organizations
- How to Measure Safety
- How to Discern the Nature of the Safety Problem

- New Methodology and the Role of Observational Before and After Studies
- How to Rank Future Safety Benefits of Projects
- How to Bring Safety to a Common Denominator with Other Project Goals
- Financial Calculus of Safety Improvements

LITERATURE REVIEW

MAP-21 emphasizes a data-driven, strategic approach to improving highway safety on all public roads that focuses on performance. It establishes a performance goal to achieve a significant reduction in traffic fatalities and injuries. What would be considered significant, however, has not yet been defined, and the path for getting there is not clearly mapped out. In general, CDOT, along with many other states, has adopted a Moving Toward Zero Death initiative. How to make significant progress toward this lofty goal, however, is not altogether clear at present. To better understand how best to incorporate explicit consideration of safety in the planning process, we conducted a review of extant literature in the United States and abroad. This review is organized in three broad categories of studies:

- Studies related to Safety Conscious Planning (SCP)
- Studies related to selected geometric design and traffic operations elements that influence safety in the planning process
- Studies of safety policy issues in other countries

The review of each category of studies will be organized in chronological order. Following this study-by-study review, we summarize the findings. We will also examine and summarize current practices of considering safety among Colorado's Metropolitan Planning Organizations (MPOs).

Studies Related to Safety Conscious Planning (SCP)

1 1942 As early as 1942, Sir Alker Tripp, a former commissioner of Scotland Yard and an authority on town planning, reflected, "Any town so planned that its citizens are killed and injured in vast numbers, is obviously an ill-planned town".[1]

2 2002 In 2002, AECOM Consulting Transportation Group, Federal Highway Administration (FHWA), and Federal Transit Administration (FTA) jointly published a report on "Considering Safety in the Transportation Planning Process."[2] The report examined the integration of safety into the transportation planning process. It recognizes that safety is an essential part of transportation and needs to be considered by all agencies involved, including state departments of transportation, metropolitan planning organizations, transit agencies, local governments, special districts, and non-profit organizations. Improving the safety of the transportation network requires an active, conscious approach to monitoring the transportation system for safety problems and anticipating problems before they occur. This report focused on incorporating safety into the transportation planning process for the multimodal transportation system and on providing planners with information and techniques to better understand the role of safety within this process.

This report represents the initial conceptual effort on including safety in the planning process.

3 2003 In "Proactive Approach to Safety Planning,"[3] Petzold makes a strong case for SCP. He observes that highway safety is a serious public health issue in the United States. In 2001, more than 3 million injuries and 42,000 fatalities occurred on U.S. roads. In all, 6 million crashes in 2001 resulted in an estimated financial loss of $230 billion to America. FHWA is dedicated to saving lives and believes that safety-conscious planning is the starting place and a key component of a safer transportation system. This article provides an overview of how the FHWA's focus has shifted from increasing capacity and reducing traffic congestion to placing a greater emphasis on reducing traffic fatalities by means of SCP strategies.

This early work by Petzold recognizes a need to address safety in the planning process.

4 2003 Hoffman and Epstein in their 2003 ITE paper[4] state that although safety is often listed as a goal, specific strategies to increase safety are seldom included in statewide and metropolitan planning processes. They further outline strategies that include the following: (1) Making safety an explicit priority within the transportation planning process. This means that safety is given equal weight with congestion relief and environmental protection in the decision-making process at the project, corridor and system levels. (2) Proactive, as well as reactive, strategies for addressing safety. The safety impacts of future transportation investments are assessed and addressed. (3) Integrating safety into long-range transportation plans and shorter-range metropolitan and statewide Transportation Improvement Programs. This paper described early efforts to organize the Federal SCP initiative, its accomplishments over two years, the results of the first national leadership conference, a national action plan for SCP, and what's next.

Hoffman's and Epstein's call to value safety as much as congestion relief is important; their work in organizing Federal SCP initiatives was also a step in the right direction.

5 2004 In her 2004 article, **"**Planning It Safe to Prevent Traffic Deaths and Injury,"[5] Susan Herbel discusses the concept of SCP and the efforts underway to explain and implement the SCP process. The Transportation Equity Act requires that every statewide and metropolitan planning process consider projects and strategies that will increase the safety and security of the transportation system. SCP implies a proactive approach to the prevention of accidents and unsafe transportation conditions by establishing inherently safe transportation networks. Although SCP protocols are still being developed, there must be close collaboration between a wide-reaching group of stakeholders to anticipate and prevent road accidents and unsafe conditions before they occur. To be effective, SCP must integrate planning and engineering with emergency management, enforcement and education activities.

A theme of collaboration among a wide-reaching group of stakeholders is a common thread among many researchers' approaches to effective SCP.

6 2005 Claudia Knezek, in a 2005 paper on "Local Adoption of Safety Conscious Planning through Technology Transfer,"[6] observed that SCP model, a comprehensive safety system, had been selected as the statewide network to adopt in New Jersey because it promoted the reduction of crashes that affect the security and congestion of the entire New Jersey transportation infrastructure. The intended benefit of this implementation effort was realized when funding opportunities, resources, and technical support reached county and local municipalities, where more than 60 percent of the roadway fatalities occur annually. Another gain had been the collective empowerment of a partnership being applied to resolving regional safety issues. Also, SCP facilitated the involvement of local elected officials, working together with safety professionals, to organize local safety networks within their own communities.

It is clear from this paper that safety is an important community value and that collaboration among elected officials, governments and safety professional is essential to achieve reduction in the frequency and severity of crashes. What is not clear, however, is how to achieve it.

7 2005 Michael Meyer observed that two new concepts have been introduced in transportation planning and engineering over the past 10 years: SCP and a context-sensitive solutions (CSS) approach to project development. His paper[7] examines SCP and CSS from the perspective of basic concepts and principles, and identifies issues that have served as focal points for disagreements in the past between those interested in promoting the community context and those advocating safety. Despite these disagreements, the two concepts are complementary: SCP can provide important context for CSS development efforts, and CSS provides an opportunity to consider safety, along with other community concerns in project-level planning. Because SCP and CSS both depend heavily on the participation of many stakeholders and community representatives, transportation agencies must ensure that participants representing safety and community context issues are involved so that they can contribute to the ultimate outcome of each process.

Meyer, in this paper, and other researchers emphasize the need for community and stakeholder involvement so that they can form a consensus and jointly contribute to an optimal outcome. While this is certainly important, without the understanding of the underlying relationships among safety, mobility, and community concerns, it may be difficult to forge consensus on these often emotional issues.

8 2006 Andrew Tarko, in his 2006 Transportation Research Board (TRB) paper[8], observed that the current planning practice addresses safety implicitly as a by-product of adding capacity and operational efficiency to the transportation system. SCP is a new proactive approach to the prevention of crashes based on establishing inherently safe transportation networks by integrating the consideration of safety into the transportation planning process.

Tarko's observation on the state of the current planning practice is accurate and points to a need for explicit consideration of safety in the planning process.

9 2006 R. Anderson and J. Hacker presented a paper on "Planning for Safety in the Philadelphia Region"[9] at the 2006 Institute of Transportation Engineers (ITE) Technical Conference in San Antonio, Texas. This paper addressed the steps the Delaware Valley Regional Planning Commission, a bi-state MPO for the Greater Philadelphia, Camden, Trenton area, initiated to integrate safety into the planning process. The paper also addressed the first phases in the creation of a Regional Safety Action Plan. This plan will form the basis for transportation safety projects and programs in the region. The vision and goal setting were derived from a regional, collaborative assessment, rather than from a strict "top down" or "bottom up" process. This method clarifies safety procedures and measures, permitting prioritization and integration of these features into a regional safety conscious plan. The paper focused on collaboration and the formulation of common goals and required that new partnerships be formed with a refocused emphasis on safety. It did not, however, provide a practical guide of how to achieve these goals. Collaboration and formulation of new partnerships are certainly important but not sufficient to improve safety.

10 2006 At the same conference, J. Bruff presented a paper[10] describing the experience of integrating safety into the transportation planning process in the Southeast Michigan Council of Governments (SEMCOGs). Bruff emphasized that safety is an essential part of transportation and must be considered by all agencies involved—state departments of transportation (DOTs), MPOs, transit agencies, local governments, special districts, and nonprofit organizations. He observed that improving the safety of the transportation network requires an active, conscious approach to monitoring the transportation system for safety problems, and anticipating problems before they occur. This paper addressed three principal themes to safety planning: (1) making the case for safety planning; (2) describing the work involved in safety planning; (3) identifying how safety planning can meet local needs. He concluded with apologies to Nike with a recommendation to “Just Do It.” One is hard pressed to object to anything in the paper; however, it too falls short of providing an analytical framework of how to reduce frequency and severity of crashes through the planning process.

11 2006 In a 2006 TRB paper entitled “Safety-Conscious Planning in Practice: Development of Regional Safety Planning and Policy Priorities,”[11] L. Goldman, et al., described the development of regional safety priorities in a 13-county region of New Jersey. The study, according to its authors, had three elements: a data-driven, collaborative assessment of priority multimodal safety needs throughout the region; recommended applications of engineering, enforcement, and educational countermeasures; and development of project concepts for advancement through the MPO planning process. Active meaningful interagency and public input was integral in all these steps. The authors concluded that the development of a regional safety priorities study does not represent a one-time effort but is a first step toward improving how safety considerations are integrated into the planning process. Since the study’s conclusion, recommended improvements at three locations have been funded for construction and several more are under consideration.

One might expect, or at least hope, that a major 13-county safety study would yield a greater output of specific projects.

12 2006 TRB sponsored the 10th National Conference on Planning for Small and Medium-Sized Communities, held in Nashville, Tennessee[12], in 2006, which concluded the following about SCP. Transportation planners usually are not trained to do safety analysis, and MPOs for small and medium sized areas often do not have adequate manpower and other resources needed to carry out a comprehensive safety program. Therefore, MPOs need to examine thoroughly the scope of safety planning and the analytical tools that may be needed. Conference proceedings also recognized that crash prediction models currently available for safety analysis are difficult to use for long-range planning involving future highway networks because planners do not make forecasts of the values of the variables commonly used in these models.

13 2007 A. Hadayeghi, et al., in "Safety Prediction Models in Urban Transportation Planning Applications,[13] observed that urban transportation planning has traditionally focused on capacity and congestion issues, with some attention paid to operation and management. In contrast, road safety has received little attention in the planning process. The objective of this research study was to develop a series of zonal-level collision prediction models that are consistent with conventional models commonly used for urban transportation planning. A generalized linear regression modeling approach, with the assumption of a negative binomial error structure, was used to explore relationships between collision frequency in a planning zone and some explanatory variables, such as traffic intensity, socioeconomic and demographic factors, land use, and traffic demand measures.

The zonal approach to safety management has some potential for future applications; however, when taking into consideration the state of the practice and the state of the art, as well as data availability, this approach is not currently feasible. Additionally, at this time, project development from the safety standpoint is done at the project or corridor level after the network is examined.

14 2007 Kononov, Allery, and Znamenacek presented a "Case History of Applying Safety-Conscious Methods by the Colorado DOT."[14] They revisited the problem of using crash rates and described a two-phased process used to evaluate the safety impacts of multiple design alternatives. The evaluation process was based on the available safety performance functions (SPFs), calibrated specifically for urban freeways, in concert with diagnostic investigations, and pattern recognition analysis. This work provided a useful blueprint of how Colorado methodology can be developed.

15 2007 Tarko, et al.,[15] developed a methodology for SCP in Indiana based on existing SPFs. Following evaluation of the performance of the functions developed for regions other than Indiana, Tarko observed that only full recalibration, which is, in fact, equivalent to developing their own models, gives a chance of obtaining a useful prediction tool for Indiana conditions.

Availability of Colorado-specific SPFs provides an opportunity for development of a Colorado data-driven methodology.

16 2008 D. Gaines and M. Meyer examined the challenges of SCP in midsized metropolitan areas[16]. The national survey and case studies focused on long-range planning, data collection, human resources, technical analysis, and collaboration aspects of SCP, as applied today. Identified challenges included conflicting organizational cultures, limited staff, and limited technical tools. Gaines and Meyer observed that institutional and technical issues faced by midsized MPOs can be overcome by identifying a safety champion in the management ranks, encouraging state DOTs to provide midsized MPOs with more tools and training in SCP, promoting a stronger relationship between the Governor's safety representative and the MPO, and creating a more comprehensive forum for collaboration among safety professionals.

In this study, as in many others, the emphasis was on the organizational structure, not a specific methodology that can be learned and applied. It is a good place to start but not a road map to the goal.

17 2009 According to Ida van Schalkwyk[17], National Cooperative Highway Research Program (NCHRP) Project 8-44(2) "Transportation Safety Planning: Forecasting the Safety Impacts in Socio-Demographic Changes and Safety Countermeasures" aimed at developing a robust, defensible, and accurate analytical set of algorithms to forecast the safety impacts of engineering and behavioral countermeasures at the planning level. It also intended to develop user-friendly software, compatible to the extent possible with planning-level data inputs, to incorporate the analytical procedures for forecasting safety. Since that time, the project has been completed; however, its implementation into practice ran into difficulties. Safe Transportation Research and Education Center (SafeTREC) at the University of California, Berkley concluded that the initial phase of the NCHRP 8-44 resulted in the development of an analytical core in the form of a forecasting tool. However, it did not address a sufficient variety of conditions, and it was currently not user-friendly. **Figure 1** provides a conceptual illustration of the idea behind PLANSAFE.

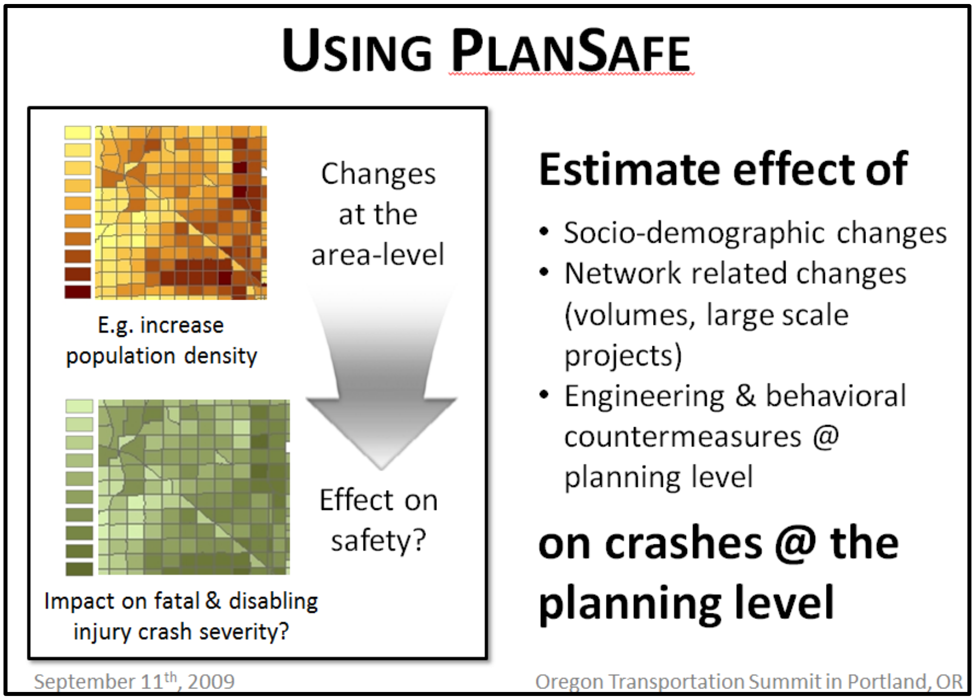

Figure 1. PLANSAFE Conceptual Illustration

At first glance, the idea of the macroscopic, zonal, multivariate crash prediction models has certain intellectual appeal; however, from the practical standpoint, its use at present appears premature. Once certain zones are predicted to have increases in frequency and severity of crashes, the planners should have requisite knowledge of how effective and how cost-effective various countermeasures are at the macroscopic level. This knowledge is currently neither reliable nor available. Even at the microscopic level, researchers still debate the fundamental relationships between safety and other input variables, such as degree of congestion, number of lanes, lane width, etc. Additionally, input variables to generate such complex models are not readily available, and modeling is too complex to be performed by the average MPO. There is currently no evidence that these macroscopic models have been effectively used to make decisions leading to safety improvements.

18 2015 The recent NCHRP Report 811, by Cambridge Systematics[18], defines the institutionalization of safety as a composite of seven principles. These principles, collectively known as the Transportation Safety Planning (TSP) Framework, were developed based on literature review, practitioner outreach surveys, interviews and workshops. The principles are as follows:

1. Ensure DOT and MPO committees, policy boards, and other planning structures include safety expertise (e.g., safety professionals, practitioners, and stakeholders) or discuss transportation safety topics;
2. Collect and analyze crash and road data for identifying and prioritizing safety issues, projects, and programs;
3. Define and include transportation safety in the vision, goals, and objectives;
4. Integrate safety performance measures into the agency's overall performance management system;
5. Incorporate transportation safety issues, such as pedestrian and bicycle safety, safe mobility for older citizens, and transit safety, in planning programs and documents;
6. Establish safety as a decision factor to prioritize and allocate funds to safety issues, projects, and programs; and
7. Implement a monitoring system to track the transportation system's safety performance and regularly evaluate the performance of safety programs and policies.

The TSP Framework includes sound principles; it focuses on organizational aspects of SCP without providing substantive and detailed guidance of how safety planning should be done. It implies that requisite safety expertise exists among practitioners and stakeholders and safety will be adequately addressed only if they (safety practitioners and stakeholders) are involved with boards and planning structures and have access to data.

19 2015 At the recent International Conference on Transportation, in Athens, Greece, Todd Litman presented a paper on the safety benefits of effective Transportation Demand Management (TDM).[19] Research described in this paper indicates that vehicle-travel reduction strategies, such as improved public transit services, transport pricing reforms and smart growth development policies, can provide large traffic safety benefits: residents of more multimodal communities have about a fifth the per capita traffic casualty rate as automobile-oriented communities. These considerations are important to keep in mind when there are opportunities to influence the process of town planning.

Studies Related to Selected Geometric Design and Traffic Operations Elements that Influence Safety in the Planning Process

1 2012 H. Isebrands and S. Hallmark examined the safety performance of roundabouts in their 2012 award-winning TRB Paper entitled "Statistical Analysis and Development of Crash Prediction Model for Roundabouts on High-Speed Rural Roadways."[20] They observed that roundabouts have proven to be effective in urban and suburban environments in the United States, but little has been reported on the effectiveness of roundabouts in rural environments on high-speed roadways. This research was the first comprehensive look at roundabouts in a rural environment with high-speed approaches. Nineteen intersections had ample comprehensive crash data to be evaluated and analyzed for safety performance. The findings validated the hypothesis that roundabouts in a rural environment, as well as roundabouts in urban and suburban environments, outperformed other intersection safety improvements. A before-and-after crash analysis was conducted for the 19 intersections by using a negative binomial regression model. Results showed statistically significant reductions for the total number of crashes (63 percent) and injury crashes (88 percent) when roundabouts were implemented. A before-and-after Empirical Bayes (EB) estimation was also conducted, and the results were consistent, indicating a 62 percent to 67 percent reduction in total crashes and an 85 percent to 87 percent reduction in injury crashes at these rural intersections. Furthermore, results showed that injury-producing crash types, such as the angle crash, were reduced by 91 percent, which was statistically significant. Finally, this research produced crash prediction models at the planning level, for total and injury crashes, at rural roundabouts on high-speed roadways. This supplements the models produced in NCHRP Report 572: "Roundabouts in the United States" and reported in the AASHTO *Highway Safety Manual*.

Such significant reductions in the frequency and severity of crashes resulting from converting intersections to roundabouts should be noticed and should influence planning and design policies at the DOTs as well as at cities and counties.

2 2015 A recent study by Canadian researcher Dewan Maud Karim[21] addresses the relationship between safety and the lane width. Karim observes that, of all street design elements, no other has evoked as much bafflement, incredulity and conjecture as the safer range of travel lane width. Traditional traffic engineers argue wider lanes are safer. Supporters of the livable street concept passionately promote the safety benefits of a relatively narrower lane width. Recent claims are emerging in favor of the livable street approach. However, neither side has yet produced any empirical evidence that links crash frequency or severity to lane width. This paper attempted to address this disquieting quandary. Extensive literature review, both academic and project reports or articles, has been conducted to examine recent claims, to outline an emerging scientific perspective, and to provide an important logical platform for this research. To examine the relationship between lane width and crash rates, this study used two existing crash databases from Tokyo and Toronto, originally collected as part of a greater effort to investigate the occurrence mechanism for vehicle-to-vehicle side-impact crashes at signalized intersections. Five novel but identical evidences are discovered for both cities. Both narrow (less than 2.8m [9.2 ft.]) and wide (over 3.1~3.2m) (10.17 to 10.50 ft.) lanes have proven to increase crash risks with equal magnitude. Safety benefits bottom out around 3.1m (for Tokyo) and 3.2m (for Toronto). Beyond the “safety valley curve,” wider lanes (wider than 3.3m) adversely affect overall side-impact collisions (**Figure 2**).

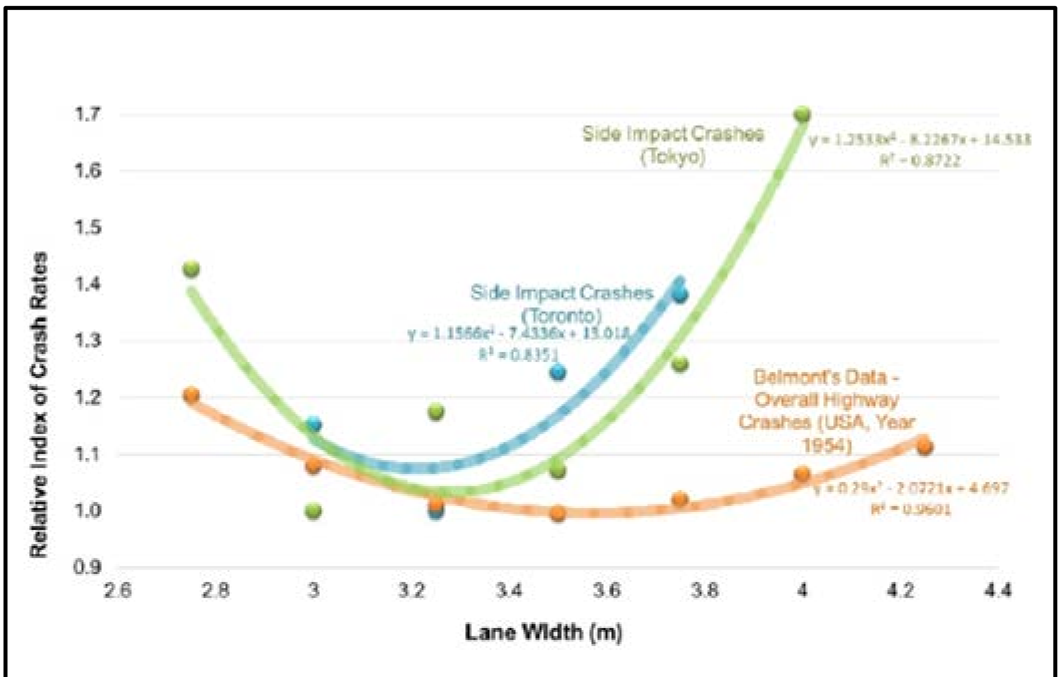

Figure 2. Lane Width and Crash Rates, from “Narrower Lanes, Safer Streets”

Secondly, among the types of crashes, right-turn crashes are relatively sensitive to lane width, while the safer range of lane width is relatively narrower for right-angle and left-turn crashes. Thirdly, the lateral displacement of driving maneuvers or oscillations stays within a narrow range (0.2m from bottom of safety curve), implying that humans display a surprisingly narrow “safety comfort zone” while trying to achieve a dynamic equilibrium status within the travel lane width. Fourthly, the capacity of narrower lanes is higher. No difference on safety and large vehicle carrying capacity is observed between narrower and wider lanes. Pedestrian volume declines as lanes widen, and intersections with narrower lanes provide the highest capacity for bicycles. Finally, wider lanes (over 3.3~3.4m) (10.82 to 11.15 ft.), the predominant practice of Toronto regions, are associated with 33 percent higher impact speed rates and higher crash rates, despite higher traffic volumes and one-sixth the population than that of Tokyo. Dewan concludes that given that the empirical evidence favors “narrower is safer”; the “wider is safer” approach based on personal or intuitional opinion should be discarded. The findings acknowledge that the street environment impacts human behavior and that narrower lanes in urban areas result in less aggressive driving and more ability to slow or stop a vehicle over a short distance to avoid collision. Street designers can use the “unused space” to provide an enhanced public realm, including cycling facilities and wider sidewalks, or to save money on the asphalt not used by motorists.

Karim’s study provides a clear and well-substantiated narrative of how he reached his conclusions. The dataset used included 190 intersections in Tokyo and 70 intersections in Toronto, which is sufficiently large. Even though safety researchers today do not view the use of linear regression as the most appropriate methodology, Karim’s findings may well be valid.

3 2012 Bonneson, et al., found in the “Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges,” NCHRP Project 17-45[22] that crash frequency is *lower* on freeways with many lanes than it is on freeways with few lanes (**Figure 3**).

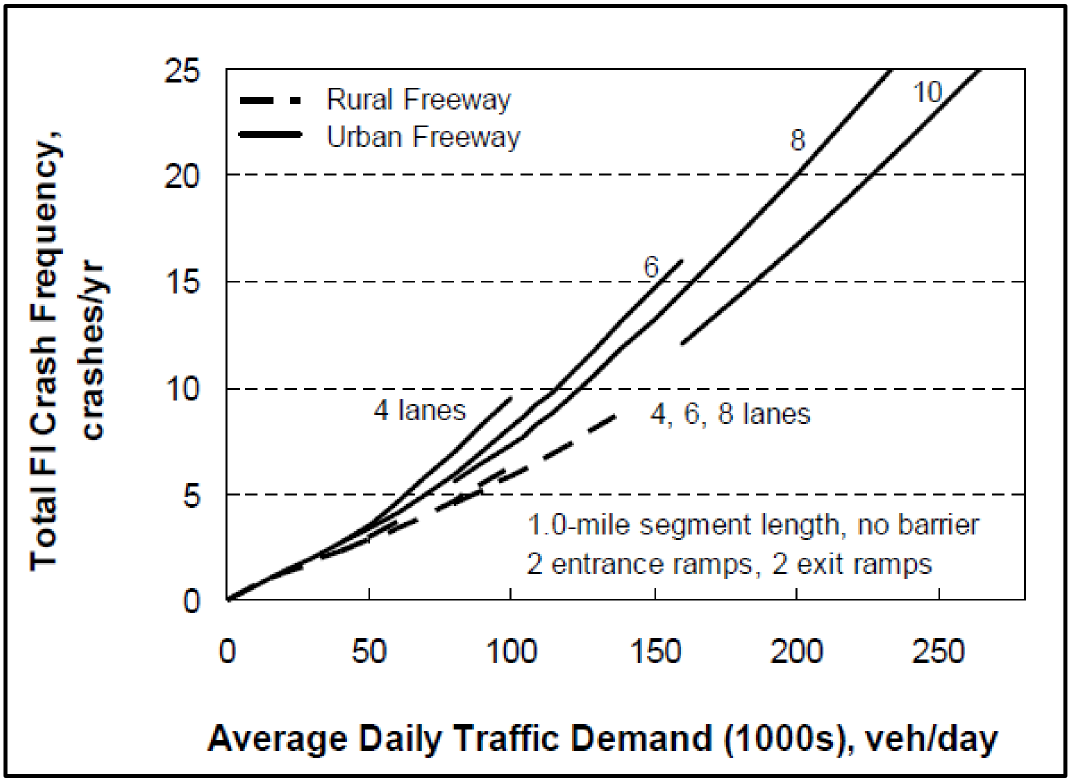

Figure 3. Crash Frequency by Volume and Number of Lanes, from Bonneson, et al.

The Bonneson, et al., models indicate that an urban six-lane freeway segment has about 7 percent fewer crashes than an urban four-lane segment and that a rural six-lane segment has about 3 percent fewer crashes than an urban four-lane segment. These trends are counter to those found when comparing the crash rates in **Table A**, also from Bonneson, which indicates that crash rate is *higher* on freeways with many lanes. Bonneson concludes that these crash rate trends reflect the fact that the proportion of barrier along a freeway segment typically increases (and the lateral clearance decreases) with an increase in the number of lanes. According to Bonneson, the proposed predictive models account for the influence of barrier presence and lateral clearance and, therefore, more accurately indicate provide a more accurate indication of the relationship between number of lanes and crash frequency.

Table A. Crash Rates Summary for Freeway Segments with Different Number of Lanes, from Bonneson, et al.

State	Area Type	Through Lanes	Exposure,[1] mvm	FI Crashes / 3 years[4]					Crash Rate, cr/mvm
				Multiple-Vehicle[2]	Single-Vehicle	Ramp Entrance[3]	Ramp Exit[3]	Total	
Calif-ornia	Rural	4	1,927	108	165	33	20	326	0.17
		6	3,271	223	229	22	25	499	0.15
		8	4,004	222	269	21	15	527	0.13
	Urban	4	1,819	193	128	48	8	377	0.21
		6	4,560	641	428	141	54	1,264	0.28
		8	4,057	782	274	125	44	1,225	0.30
		10	3,873	888	235	112	39	1,274	0.33
		Overall:	23,511	3,057	1,728	502	205	5,492	0.23
Maine	Rural	4	2,506	154	229	10	8	401	0.16
		6	446	25	16	2	0	43	0.10
		8							
	Urban	4	1,050	88	80	14	11	193	0.18
		6	31	5	3	3	2	13	0.42
		8	17	6	4	0	1	11	0.63
		10							
		Overall:	4,051	278	332	29	22	661	0.16
Wash-ington	Rural	4	1,954	64	179	4	2	249	0.13
		6	3,332	184	189	15	6	394	0.12
		8							
	Urban	4	1,358	175	108	17	9	309	0.23
		6	2,259	301	136	15	10	462	0.20
		8	2,301	594	115	83	22	814	0.35
		10							
		Overall:	11,203	1,318	727	134	49	2,228	0.20
All states	Rural	4	6,387	326	573	47	30	976	0.15
		6	7,050	432	434	39	31	936	0.13
		8	4,004	222	269	21	15	527	0.13
	Urban	4	4,227	456	316	79	28	879	0.21
		6	6,850	947	567	159	66	1,739	0.25
		8	6,375	1,382	393	208	67	2,050	0.32
		10	3,873	888	235	112	39	1,274	0.33
		Overall:	38,765	4,653	2,787	665	276	8,381	0.22
All states, excluding speed-change lane-related crashes	Rural	4	6,387	326	573			899	0.14
		6	7,050	432	434			866	0.12
		8	4,004	222	269			491	0.12
	Urban	4	4,227	456	316			772	0.18
		6	6,850	947	567			1,514	0.22
		8	6,375	1,382	393			1,775	0.28
		10	3,873	888	235			1,123	0.29
		Overall:	38,765	4,653	2,787			7,440	0.19

Others dispute whether this assertion is accurate. It is possible that conclusions in Bonneson et al., are an artifact of how the model was developed (by mixing data from Main and California with Washington and choosing inflexible functional form), not a reflection of a physical phenomenon.

4 2008 In their 2008 TRB paper entitled "Relationships Between Safety and Both Congestion and Number of Lanes on Urban Freeways,"[23] Kononov, Bailey, and Allery found that comparing slopes of SPFs for different numbers of lanes suggests that adding lanes on urban freeways initially results in safety improvement, which diminishes as congestion increases. Once traffic demand goes up, the slope of the SPF, described by its first derivative, becomes steeper, and accidents increase at a faster rate with Annual Average Daily Traffic (AADT) than would be expected from a freeway with fewer lanes. This is found to be true for total, injury, and fatal crashes. While more research in this area is needed, this phenomenon may possibly be explained as follows: As the number of lanes increases, the opportunities for conflicts related to lane changes also go up. Furthermore, the increased maneuverability associated with the availability of more lanes tends to increase the average traffic speed and the speed differential. **Figure 4** provides a conceptual illustration of this phenomenon.

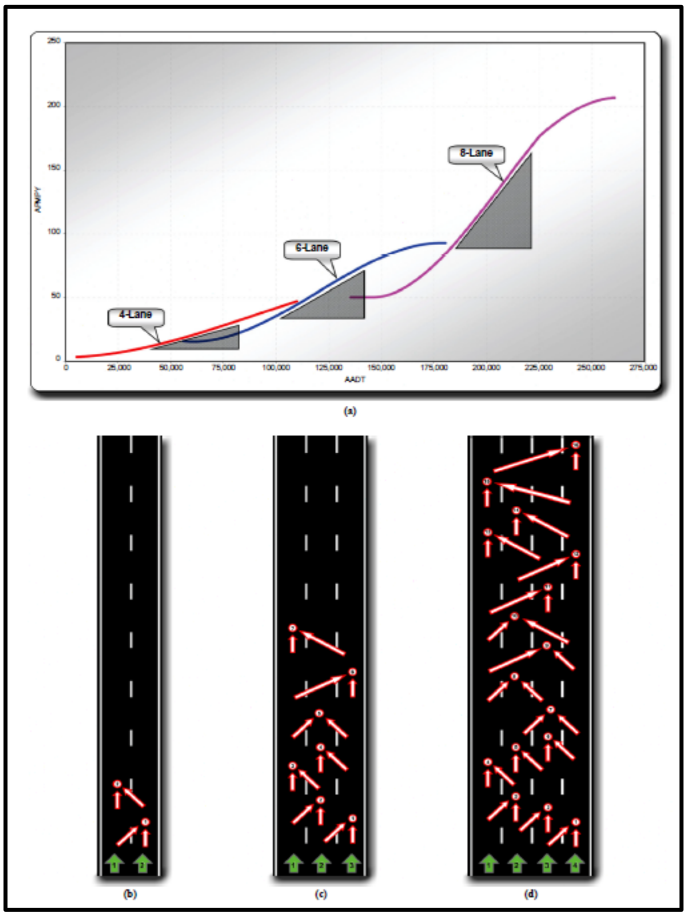

Figure 4. Safety, Number of Lanes, and Number of Conflict Opportunities, from Kononov, et al.

Studies of Safety Planning Policy Issues in Other Countries

1 2011 In TRB Special Report 300, "Achieving Traffic Safety Goals in the United States—Lessons from Other Nations."[24] the authors observe that, in recent decades, nearly every high-income country has made more rapid progress than the United States has in reducing the frequency of road traffic deaths and the rate of deaths per kilometer of vehicle travel. As a result, the United States can no longer claim to rank high in road safety by world standards. The United States is missing significant opportunities to reduce traffic fatalities and injuries. The experiences of other high-income nations and of the U.S. states with the best improvement records indicate the benefits from more rigorous safety programs. Most high-income countries are reducing traffic fatalities and fatality rates (per kilometer of travel) faster than is the United States, and several countries that experienced higher fatality rates 20 years ago, now are below the U.S. rate. From 1995 to 2009, annual traffic fatalities declined by 52 percent in France, 39 percent in the United Kingdom, 25 percent in Australia, and 50 percent in total in 15 high-income countries (excluding the United States) for which long-term fatality and traffic data are available, but by only 19 percent in the United States. The experience of these benchmark nations indicates that the successful national programs function effectively at three levels of activity:

1. **Management and planning**: Transportation, public safety, and public health administrators systematically measure progress toward quantitative objectives, direct resources to the most cost-effective uses, and communicate with the public and elected officials to maintain their support.
2. **Technical implementation of specific countermeasures**: A range of measures is used to regulate driver behavior, maintain effective emergency response, and ensure safe design and maintenance of roads. The techniques are generally of proven high effectiveness and often intensively applied.
3. **Political support and leadership**: Commitment of elected officials ensures that resources are provided, administrators are held accountable for results of safety initiatives, and system users are held accountable for compliance with laws.

CDOT's adoption of the Moving Toward Zero Death initiative is an important step; however, the question of how to make further significant progress in this direction is not known.

2 2013 J. Luoma and M. Sivak in "Why Is Road Safety in the U.S. not on Par with Sweden, the U.K., and the Netherlands? Lessons to be Learned"[25], compared safety and related factors in the United States with those in Sweden, the United Kingdom, and the Netherlands, to identify actions most likely to produce casualty reductions in the United States. Their main recommendations included the following: (1) lower states' blood alcohol content limits and introduce effective random breath testing; (2) reexamine the current speed-limit policies and improve speed enforcement; (3) implement primary seat-belt-wearing laws in each state that would cover both front and rear occupants, and reward vehicle manufacturers for installation of advanced seat-belt reminders; (4) reconsider road-safety target setting so that the focus is on reducing fatalities, not on reducing fatality rate per distance driven; and (5) consider new strategies to reduce vehicle distance driven.

3 2012 According to a fact sheet titled, "Background of the Five Sustainable Safety Principles,"[26] put out by the Dutch Institute for Road Safety Research (SWOV), the concept of sustainable safety was conceived, developed and implemented in the Netherlands in the nineties. It is based on the following five principles listed in **Table B**:

Table B. Description of the 5 Sustainable Safety Principles, from SWOV Website

Sustainable Safety Principle	Description
Functionality of roads	Monofunctionality of roads as either through roads, distributor roads, or access roads in a hierarchically structured road network
Homogeneity of mass and/or speed and direction	Equality of speed, direction, and mass at moderate and high speeds
Predictability of road course and road user behaviour by a recognizable road design	Road environment and road user behaviour that support road user expectations through consistency and continuity of road design
Forgivingness of the environment and of road users	Injury limitation through a forgiving road environment and anticipation of road user behaviour
State awareness by the road user	Ability to assess one's capacity to handle the driving task

The background and content of these principles are briefly discussed below.

Functionality. Roads have two functions: conveyance and access. According to the Dutch principle of Functionality, roads ideally should fulfill one single function and be as monofunctional as possible. The Dutch Functionality principle is akin to the U.S. concept of functional class and related access control principles. The Dutch, however, extended this concept far beyond U.S. practices in ensuring that roads are as monofunctional as practical. All road authorities in the Netherlands have now categorized the Dutch road network "on paper" in the framework of sustainable safety. They have begun to actively reorganize the roads according to their functional and operational requirements. How much progress has been achieved toward monofunctional roads in Holland, however, is not entirely clear. On the other hand, it is not always possible or acceptable to meet these monofunctional requirements for all roads, without radical changes.

Homogeneity. The sustainable safety vision takes "man as a measure of all things" as a starting point and its purpose is to prevent (serious) crashes and, when this is not possible, to limit the consequences of crashes (reduction of injury severity). In a crash, human's physical vulnerability comes into play. Injury is the result of a combination of released kinetic energy (mass x speed^2), biomechanical properties of the human body, and the physical protection that the vehicle offers its occupants. The homogeneity principle in practical terms means the following.

If road users/vehicles with large mass differences use *the same* traffic space, *the speeds should be so low* that the most vulnerable road users and transport modes come out of a crash without any severe injuries. In an ideal situation, this is achieved by mandating low speeds through the road infrastructure, not by appealing to the road users' individual choices.

At locations where traffic uses *high speeds*, different types of road users and road users driving in different directions should be *physically separated* from each other as much as possible and road users should be *protected* by their vehicle. That way, conflicts leading to severe injury are prevented. SWOV developed the following safe speed table (**Table C**) in the framework of sustainable safety principles.

Table C. Sustainable Safety Safe Speed Table

Road types in combination with permitted road users	Safe speed (km/h)
Roads with possible conflicts between cars and unprotected road users	30
Intersections with possible transverse conflicts between cars	50
Roads with possible frontal conflicts between cars	70
Roads with no possible frontal or transverse conflicts between road users	≥100

Predictability. One of the sustainable safety principles is that a road should have a recognizable design and a predictable alignment. If this is the case, then road users know how they are expected to behave and what they can expect from other road users so that crashes may be prevented. For roads to be recognizable, it is important not only to distinguish *between* road categories but also to have uniformity *within* categories.

The principle of predictability is based on the idea that human errors and the resulting crashes can be prevented by providing a road environment that is predictable by means of a recognizable road design and predictable alignment. The road features should tell the road user immediately what road type he is driving on, which driving behavior is expected of him and other road users, and which other types of road users he can meet. In the ideal case, the road should be self-explaining as much as possible. This makes the traffic system more predictable, and indecisive behavior and crashes as a result of that may be prevented.

The Dutch concepts of predictability and recognizable road design resonate with the U.S. concepts of driver expectancy and design consistency. In the Netherlands, however, these concepts are applied more rigorously and consistently, and with good results.

Forgivingness. In addition to functionality and homogeneity, *physical forgivingness* is also an important factor in preventing injury, even if the infrastructure did not give rise to the crash. Forgiving surroundings ensure that the physical consequences of errors remain limited. This is particularly important in traffic situations where people drive fast.

This concept is similar to the U.S. concepts of forgiving roadside and clear zone. They are similarly applied in the United States; however, the concepts of functionality, homogeneity, and predictability applied in concert with forgiveness are producing better results in the Netherlands.

State Awareness. *State awareness* means knowing one's capabilities. More formally, it is the degree of concurrence between one's own perception of one's task capability and what it really is—how good does someone think she is and how good she is in reality? The more perceptions match reality, the better the state awareness. In turn, *task capability* is the sum of the road user's driving skill and fitness to drive. *Driving skill* is the result of learning and gaining experience and is related to vehicle control and traffic insight. *Fitness to drive* is related to the temporary and permanent physical and mental state of the road user—is he healthy, well rested, attentive, and not under the influence of alcohol, drugs or medication? *Risk awareness* means knowing how dangerous the traffic situation is in which you find yourself. It is also called hazard perception. In formal terms, risk awareness is the degree of concurrence between the perceived task demands and the real ones—how dangerous does someone think it is and how dangerous is it really? The more they coincide, the better the risk awareness.

In brief, *calibration* is adapting the traffic task based on a comparison of the estimated task difficulty (how difficult is the task and how good am I?) with a reference value. This is based on many processes, including state awareness and risk awareness. In the first instance, road users—consciously or unconsciously—assess their own task capability (state awareness) and the task demands; that is, the complexity and/or hazards of the traffic task (risk awareness). The difference between the perceived task capability and the perceived task demands corresponds with the task difficulty. If you believe that you are more than a match for the task, you will find the task relatively easy—the task difficulty is low. On the other hand, if the task demands more from you than you think you can cope with, you will find the task (too) difficult.

Currently, not enough is known about how good the state and risk awareness and calibration of road users is. Almost all the research carried out in this field focuses on young, novice drivers. That research provides cautious suggestions regarding measures that could be successful in improving the state awareness, risk awareness, and calibration of road users; however, more knowledge is required.

CHAPTER 1 – SAFETY WITHIN COLORADO METROPOLITAN PLANNING ORGANIZATIONS

The five MPOs in Colorado include Denver Regional Council of Governments (DRCOG), Grand Valley MPO (GVMPO), North Front Range MPO (NFRMPO), Pueblo Area Council of Governments (PACOG), and Pikes Peak Area Council of Governments (PPACG).

Each MPO develops its transportation plans and programs using the "3C" (continuous, cooperative, and comprehensive) planning process, as required by FHWA 23 Code of Federal Regulations (CFR) § 450.306 and FTA in 23 CFR § 613.100. MAP-21 legislation, adopted July 6, 2012, is the comprehensive federal legislation addressing surface transportation that guides the long-range planning process. MAP-21 contains eight factors addressed by the 3C metropolitan transportation planning process. The second factor is to increase the safety of the transportation system for all motorized and non-motorized users. However, the degree to which safety is addressed in this comprehensive process varies. This review of the way in which safety is incorporated in this comprehensive process focuses on two of the main MPO plans: the regional transportation plans (RTPs) and the Transportation Improvement Programs (TIPs).

Denver Regional Council of Governments (DRCOG)

Regional Transportation Plan. DRCOG's 2040 Fiscally Constrained RTP, adopted on February 18, 2015, is based on the goals and policy direction of Metro Vision 2035, along with input received so far for Metro Vision 2040. The process for selecting regionally significant roadway capacity projects used updated Metro Vision-based criteria adopted by the DRCOG Board in April 2014.

The 2040 RTP classifies transportation projects into two broad categories: those that are regionally significant (for air quality conformity purposes) and those that are not. Regionally significant projects are major roadway, interchange, and rapid transit projects that significantly change the capacity of the transportation network. The selection process for regionally significant projects classifies the projects as roadway, interchange, or rapid transit capacity projects.

Regionally significant projects: The regionally significant roadway capacity projects are evaluated based on 10 metrics, one of which is a safety measure. The measure is based on a weighted crash rate (crashes per vehicle miles traveled [VMT]). The most recent three years of crash data are used. The maximum number of points possible for the safety criteria is 8 out of 100. Crashes involving injuries and fatalities are factored by 5. Eight points are awarded to the top 10 percent of projects with the highest values, and 4 points are awarded to the next 15 percent of projects. The maximum score for projects is 100 points.

Non-regionally significant projects: All roadway capacity projects and roadway operational improvement projects can receive a maximum of 7 points (toward a maximum total of 100) for crash reduction. This is based on the project's estimated crash reduction and weighted crash rate. Roadway reconstruction projects can receive a maximum of 5 points (toward a maximum total of 100) for crash reduction. This is based on the project's estimated crash reduction and weighted crash rate. Transit passenger facilities projects do not explicitly include safety evaluation criteria. Bicycle/Pedestrian Projects can receive a maximum of 12 points (toward a maximum total of 100) under the safety evaluation criteria based on the anticipated improvement of existing safety problems related to crash history and other measures such as facility lighting.

Transportation Improvement Program. DRCOG's 2016–2021 TIP was adopted on April 15, 2015. The development of the TIP was guided by the *Policy on Transportation Improvement Program Preparation*. This policy includes roadway crash reduction (safety) criteria as a part of the evaluation. Safety is incorporated through the crash reduction evaluation criteria required for all roadway projects. The evaluation considers the current annualized weighted crash rate per 1,000 average daily traffic (ADT) and/or the estimated reduction in the number of crashes.

For the crash rate computation, the applicant is required to provide the roadway data (crash reduction computation area length and ADT) and the number of crashes over the three most recent years. The applicant is then asked to estimate the potential reduction in the number of crashes from the project. The estimates are used to determine levels (low, medium, high) of improvement to award crash reduction points for project selection and prioritization.

Grand Valley Metropolitan Planning Organization (GVMPO)

Regional Transportation Plan. The Grand Valley 2040 RTP Update, adopted on December 15, 2014, is the region's first performance-based plan. The first regional goal for 2040 is to improve roadway safety for all travelers. Chapter 7, Regional Roadways, summarizes safety trends in the region, including the number of crashes and the severity of crashes. The data are aggregated to identify high-frequency crash locations and to better understand contributing factors. These hot spots are then prioritized when allocating state and federal safety improvement funding.

To prioritize future alternatives, a subcommittee of the 2040 Steering Committee considered the implementation timeframe, benefits, and performance impacts of proposed transportation projects. This group included representatives from local governments in the region, CDOT, and staff of the MPO. This group evaluated performance data for each project, including safety data. For safety, the criterion is identified as, "high crash volume/rate intersection, locally identified hotspot, adds or improves safety features." Two performance measures were associated with the safety goal: (1) fatality and serious injury rate per 100 million VMT, and (2) five-year average annual reduction in fatalities and serious injuries.

Transportation Improvement Program. The GVMPO's 2016–2019 TIP, adopted on April 27, 2015, implements those needed improvements identified in the MPO's adopted RTP, described above. This 2040 planning effort considers more than 70 project and corridor alternatives. The TIP does not include any additional evaluation criteria beyond what exists in the RTP.

North Front Range Metropolitan Planning Organization (NFRMPO)

Regional Transportation Plan. NFRMPO's 2040 RTP, adopted in September 2014, is guided by a value statement. The value statement, "We seek to provide a multi-modal transportation system that is safe, as well as socially and environmentally sensitive for all users that protects and enhances the region's quality of life and economic vitality," mentions safety first. The value statement is supported by four main MPO goals that are in-line with national goals from FHWA. Goal 2, Mobility, is to, "Provide a transportation system that moves people and goods safely, efficiently, and reliably." This goal is further supported by objectives. Objective 4, to reduce the number of severe traffic crashes, is supported by a performance measure and a target, as shown in **Table D**.

Table D. NFRMPO Goal 2

Goal	Objective	Performance Measure	Target
Provide a transportation system that moves people and goods safely, efficiently, and reliably	Reduce the number of severe traffic crashes	Five-year rolling average of injury and fatal crashes	No increase in crashes

Transportation Improvement Program. The NFRMPO's FY2018–2021 TIP was released to the public on December 1, 2016. The applicant is required to complete an application form, detailing the 2040 Regionally Significant Corridor and how the project fits within the 2040 NFRMPO RTP Corridor Vision. The applicant is also required to identify the anticipated impact the project will have on the MPO goal(s) and performance measure(s), using data, if possible. The scoring criteria include the following categories: safety, mobility, system preservation, and partnerships. The applicant should include the total number of accidents (separated by severity), time period of accident data (at least three years), source of the data, and the facility ADT. The applicant is also required to "describe the type of accidents that are occurring (rear-end, broadside etc.) and to what extent the project will address these issues."

Pueblo Area Council of Governments (PACOG)

Long Range Transportation Plan. PACOG's 2035 Long Range Transportation Plan (LRTP), adopted on January 24, 2008, relies on CDOT's crash records to identify locations of high crash rates relative to the number of vehicles entering intersections. The LRTP concludes that, "Improvements to these intersections should lower the number of crashes and have the greatest benefit for overall system safety." The LRTP relies heavily on CDOT's FY 2010 Problem Identification Report. The LRTP does not indicate additional methodology applied to the selection and prioritization of projects.

Transportation Improvement Program. The 2016–2019 TIP was adopted on February 24, 2011. The TIP does not provide detailed information on the selection and prioritization of projects.

Pikes Peak Area Council of Governments (PPACG)

Regional Transportation Plan. PPACG's RTP, completed in January 2012, uses a framework called Safety Conscious Planning, which integrates safety concerns into all planning levels. Crash data are the cornerstone of PPACG's regional safety planning. The data come from accident records and include the type of accident; severity of the accident (such as fatal, injury, and property damage only); location of the crash; weather conditions; and other specifics.

The factors used to analyze crashes include the total number, the total number of fatal and injury accidents, the total crash exposure rate (a comparison between the number of crashes and the traffic volume), the injury and fatality exposure rate (an indication of the severity of crashes on given roads), and a weighted hazard index, which shows which roadways and intersections have the most severe crashes using a weighted calculation. These factors are used to rank the safety performance and develop a ranked list of projects.

Transportation Improvement Program. The 2016–2019 TIP is PPACG's current TIP. No new projects have been added to the TIP since the 2013–2018 TIP. PPACG's TIP prioritization is a result of the weighted calculation from the RTP. To monitor progress in implementing the MPO's RTP, PPACG staff evaluate each project's ability to fulfill RTP goals. The evaluation criteria provide a series of yes/no questions that indicate how the proposed project will incorporate the goals of the MPO's RTP.

Recent Developments. In 2016 PPACG deployed Vision Zero Suite (VZS) software, which uses Colorado-specific predictive and diagnostic tools. Its systematic use at PPACG is expected to maximize crash reduction within constraints of available budgets.

MPO Summary

Each MPO recognizes the importance of safety in some capacity. However, each MPO takes a different approach to determine safety issues and safety improvements for inclusion in the TIP, as shown in **Table E**.

Table E. MPOs Consideration of Safety Summary

MPO	Existing Safety in the RTP	Safety Considerations in the TIP
DRCOG	Crashes per VMT, weighting crashes involving injuries and fatalities	Applicants are required to provide roadway crash reduction estimates based on project type and ADT
GVMPO	Number and severity of crashes to determine hot spots	Steering Committee evaluated performance data for each project, including safety
NFRMPO	Five-year rolling average of injury and fatal crashes; target is no increase in crashes	Applicants are required to describe the types of accidents that are occurring and to what extent the project will address these issues
PACOG	Crash rates relative to the number of vehicles	Undefined methodology for selection and prioritization based on safety
PPACG	Number of crashes, including severity, and a weighted hazard index	PPACG's staff evaluates each project based on a series of yes/no questions

Safety Planning within CDOT

CDOT oversees the statewide planning process for several modes of transportation, such as freight, transit, bicycle and pedestrian, and rail. The following summarizes the way in which safety is incorporated into these modal plans.

CDOT Statewide Transportation Plan. The CDOT Statewide Transportation Plan is a long-range performance-based plan that was completed in March 2015. A guiding vision of the plan is the incorporation of safety in all areas. According to the plan, CDOT applies data-driven processes to reduce crashes and education strategies to modify driver behavior to help move Colorado toward zero deaths.

- **The safety goal of the plan**: Move Colorado toward zero deaths by reducing traffic-related deaths and serious injuries.
- **Safety objective**: Reduce the number and rate of all transportation fatalities and serious injuries, the economic impact of crashes, and the number of bicyclist and pedestrian fatalities and serious injuries.
- **Performance measures**:
  - Number of fatalities
  - Fatalities per VMT
  - Number of serious injuries
  - Serious injuries per VMT
  - Economic impact of crashes
  - Number of bicyclist and pedestrian fatalities involving motorized vehicles
  - Number of bicyclist and pedestrian serious injuries involving motorized vehicles

The plan quantifies safety improvement as a decrease in traffic fatalities and serious injuries. Over the past decade, Colorado has seen a steady decrease in traffic fatalities (from 742 in 2002 to 472 in 2012) and serious injuries (from 5,014 in 2002 to 3,242 in 2012). This is despite the fact that both population and total VMT have increased during the same period of time.

The Statewide Plan identifies investment needs by category, one of which is safety. The plan assumes that safety is generally enhanced with every project. The safety category of investment needs includes education and targeted safety focused projects such as rail crossings and safety hot spots. The plan calls for $1.2 billion needed from 2016 to 2025 and more than $1.6 billion needed from 2026 to 2040 to meet these needs; however, funding challenges exist. CDOT's investment strategy includes safety. Safety will be considered in every project type and will be addressed not only through targeted safety investment programs (such as HSIP and FASTER Safety) but through all programs and projects.

The plan calls for strategic statewide actions to achieve the goals. For CDOT to achieve the safety goal, CDOT will focus targeted safety investments and strategies on eight emphasis areas: aging road users, bicyclists and pedestrians, data, impaired driving, infrastructure, motorcyclists, occupant protection, and young drivers. CDOT plans to improve crash data collection and accessibility, while implementing safety programs and initiatives, using proven behavioral countermeasures, technology or design to reduce crashes on all roads.

CDOT gathers input from 10 rural Transportation Planning Regions (TPRs) to develop RTPs for each. These RTPs are later incorporated into the Statewide Transportation Plan. Each TPR has different needs, priorities, and strategies for the future; however, the approach to understanding existing safety and determining future safety projects is consistent among every TPR. Each RTP includes a crash rate (per million VMT) for the Region and determines whether this crash rate is above or below the statewide average (1.70 crashes per million VMT). The RTPs also identify the most prominent crash types in each Region. The RTPs qualitatively determine that safety is important, but the RTPs do not explicitly explain the methodology for project prioritization when it comes to safety.

CDOT State Highway Freight Plan. CDOT finalized the Colorado State Highway Freight Plan in July 2015. CDOT's first goal when it comes to freight is to "improve the safety of the Colorado Freight System." CDOT's Freight Plan cites the statewide goal of "Moving Towards Zero Deaths" and recognizes that it will be necessary to coordinate efforts along the Freight Corridors for this goal to be achieved.

Crash data of Freight Corridor segments were analyzed to compare crash rates (crashes per million VMT) of trucks to crash rates for all vehicle types from 2008–2012. The percent difference was calculated between the general crash rate and the truck crash rate. Most crash rates were negative numbers, indicating that truck crash rates are mostly lower than the overall crash rate for all vehicle types. However, the analyses identified a few segments of Freight Corridors where the truck crash rates were higher than the overall crash rate. CDOT intends to focus on the segments with relatively higher truck crash rates. According to the plan, CDOT is working to obtain additional data to assess the causes of these increased crash levels. The type of additional data was not identified.

The Freight Plan identifies several freight policy strategies, many of which have a primary goal area of safety. For example, one strategy is "targeted crash type mitigation." CDOT will continue to analyze crash data to identify types and trends, better understand the causes of specific crash types, and develop programs to inform all drivers of ways to avoid the most common types of truck crashes, such as sideswipes and rear-end collisions. This strategy aligns with the Colorado Strategic Highway Safety Plan's overall vision to reach zero deaths.

CDOT Statewide Transit Plan. The Statewide Transit Plan, completed in March 2015, notes that Colorado's transportation planning is consistent with federal planning regulations and calls for a multimodal transportation plan that enhances the safety of the system. Safety and security are identified as goals of the plan. The goal and supporting objectives are to "create a transit system in which travelers feel safe and secure and in which transit facilities are protected by supporting and implementing strategies that help agencies maintain safer fleets, facilities, and service, and provide guidance on safety and security measures for transit systems."

Two implementation actions are associated with this goal. The first is that, "Pending guidance from FTA, CDOT will assist all agencies in developing a safety and security plan consistent with FTA requirements." The target is 100 percent of grantees by 2017. The second implementation action is that, "CDOT will work with transit providers to implement measures that improve the safety and security of those using public transit." The first associated performance measure is 0 fatalities involving transit vehicles per 100,000 transit vehicle miles. The second associated performance measure aims for 65 percent or higher of vehicles in rural Colorado transit fleets in fair, good, or excellent condition (per FTA definitions).

CDOT Bicycle and Pedestrian Plan. The first-ever Statewide Bicycle and Pedestrian Plan was adopted in October 2012 with an amendment made in June 2015. The Bicycle and Pedestrian Plan recognizes that, "while overall crash volumes could be used to measure the success of safety programs, the raw number of crashes or fatalities may not tell the complete story of pedestrian and bicycle safety." The plan proposes using the following data as a baseline for evaluating crash reduction strategies: lighting conditions, month of year, crash fault (motorist versus bicyclist/pedestrian), sex of the bicyclist or pedestrian involved, and age of the bicyclist or pedestrian involved.

The Bicycle and Pedestrian Plan starts by establishing existing conditions. According to the plan, Colorado's overall fatality rate is 0.94 fatalities/100,000 population. For bicycle crashes, the fatality rate is 1.51 fatalities/100,000 population. Because the actual number of pedestrian or bicycle miles traveled may not be directly correlated to population, some care must be taken when using this rate as a basis of comparison. The Bicycle and Pedestrian Plan recognizes that the crash rate (typically fatalities per 100,000 population) is an incomplete metric for safety. The Bicycle and Pedestrian Plan cites the need for a detailed database of crash records and crash reports to provide specific baseline data with respect to the temporal, demographic, and causal factors associated with pedestrian and bicycle crashes. The results of such data and analysis could be used to identify specific measures that could be taken to reduce pedestrian and bicycle crashes.

The Bicycle and Pedestrian Plan establishes goals and investment decision criteria as well as associated performance measures. The first goal and investment decision criterion is enhancing safety by reducing crash rates or the potential threat of crashes. The performance measure associated with this goal is the degree to which the project would result in safety improvement as quantified by FHWA's Crash Modification Factors. The project's ability to reduce the crash rate or the potential threat of crashes then receives a score between 0 and 10. A project applicant would likely be expected to provide historic crash data, along with a description of the postulated crash reduction that would result from project implementation.

CDOT Freight and Passenger Rail Plan. The Freight and Passenger Rail Plan was completed in March 2012, shortly after the creation of the Division of Transit and Rail within CDOT. Goal #2 is to provide for the safety of people, infrastructure, and goods. The plan includes six general objectives to support Goal #2, all of which are qualitative objectives.

The Freight and Passenger Rail Plan includes a summary of the rail incidents in Colorado reported to the Federal Railroad Administration (FRA) from 2003 to 2010. Rail safety is summarized by two rail safety categories: rail equipment incidents and highway/rail crossing incidents. According to the plan, the total number of incidents reported in 2010 was almost 42 percent lower than the number reported in 2003, and it was nearly 53 percent lower than the highest amount reported in 2006. The analysis also includes the severity of incidents from 2008 to 2010. More than half of these incidents, 63 percent, resulted in property damage only, whereas 20 percent resulted in injuries and 17 percent resulted in fatalities. The plan identifies at-grade highway/rail crossings as a critical factor in the safe operation of the rail system and the highway network in Colorado.

CDOT's Safety and Traffic Engineering Branch manages the prioritization of rail crossings for assignment of safety funding under the Federal Aid Section 130 Railroad/Highway Safety Program. Section 130 provides funds for highway/railroad grade crossing safety improvements, such as signing, pavement markings, active warning devices, illumination, and crossing surface repair. Section 130 projects are identified and prioritized based on an accident prediction analysis using a hazard index. The CDOT Safety and Traffic Engineering Branch, Railroad Program, administers the Section 130 program and is the point of contact with railroads, the Public Utilities Commission (PUC), and local agencies on all CDOT/railroad contracts. The plan does not include the accident prediction analysis.

CDOT Summary. Each CDOT plan highlights the importance of safety. However, the way in which safety issues and solutions are incorporated varies, as shown in **Table F**.

Table F. CDOT Consideration of Safety in Planning Summary

Plan	Safety in the Plan
Statewide Transportation Plan	• Quantitative performance measures
Regional Transportation Plans for TPRs	• Quantitative measures such as crashes per VMT • Qualitative evaluation to determine the high priority corridors
State Highway Freight Plan	• Quantitative approach to existing truck crashes per million VMT
Statewide Transit Plan	• Quantitative goals for achieving a safer system
Bicycle and Pedestrian Plan	• Quantitative determination of existing fatality rate • Quantitative evaluation based on FHWA's Crash Modification Factors to determine crash reduction
Freight and Passenger Rail Plan	• Projects identified and prioritized based on an accident prediction analysis using a hazard index

CHAPTER 2 – SUMMARY OF CURRENT PRACTICES

Most current research efforts considering safety in the planning process fall short of providing a clear blueprint to follow in Colorado.

The methodology of developing area-wide safety models is too esoteric and complex to apply to safety decision-making in a DOT or MPO environment.

Most research in SCP focuses only on organizational aspects of the process without providing substantive guidance of how planning should be done. It implies that requisite safety expertise exists among practitioners and stakeholders and if only they (safety practitioners and stakeholders) would get involved with planning boards and MPOs, and have access to data, safety will be adequately addressed. Unfortunately, the analytical framework necessary for effective and rational safety planning is a missing link in the process. As a result, it is difficult to build consensus among CDOT and its planning partners around a rational plan that would lead to safety improvement.

The science-based safety knowledge base, developed in the design process at CDOT, is not yet used to inform the planning process.

What is known about the relationships between safety and congestion, lane width and safety, number of lanes and safety, traffic control and safety has little connection to the current planning process.

AASHTO *Highway Safety Manual* (HSM) is not currently referenced for work of the MPOs in safety arena.

European and Australian successes in safety improvement are well documented and are based on lowering speed limits, automating speed enforcement, and having mandatory seat belt and helmet laws in place. Because these ideas are radical by U.S. standards, the Safe System Approach in the Netherlands, Australia, and New Zeeland is not currently transferable to the United States for political reasons.

The U.S./CDOT approach currently focuses on Moving Toward Zero Death initiatives; however, what we are prepared to do to get there is not yet clear. It is challenging to confront politically sensitive issues head on and our resources are limited. CDOT has one advantage over other DOTs, however. It has developed and applied a Colorado-specific Safety Knowledge base consisting of predictive and diagnostic tools to scope all projects for many years. This effort is strongly correlated with the significant fatal crash reduction between 2002 AND 2010 (**Figure 5**). Additionally, a 2014 TRB paper by K.F. Wu, et al.,[27] shows that Colorado was effective in its efforts to improve safety and compares favorably with other states (**Figure 6**). K.F. Wu, et al., attributes this success to advanced methodology and data quality. This methodology has not yet been incorporated into the planning process in Colorado, and we hope to accomplish the transfer through this research project.

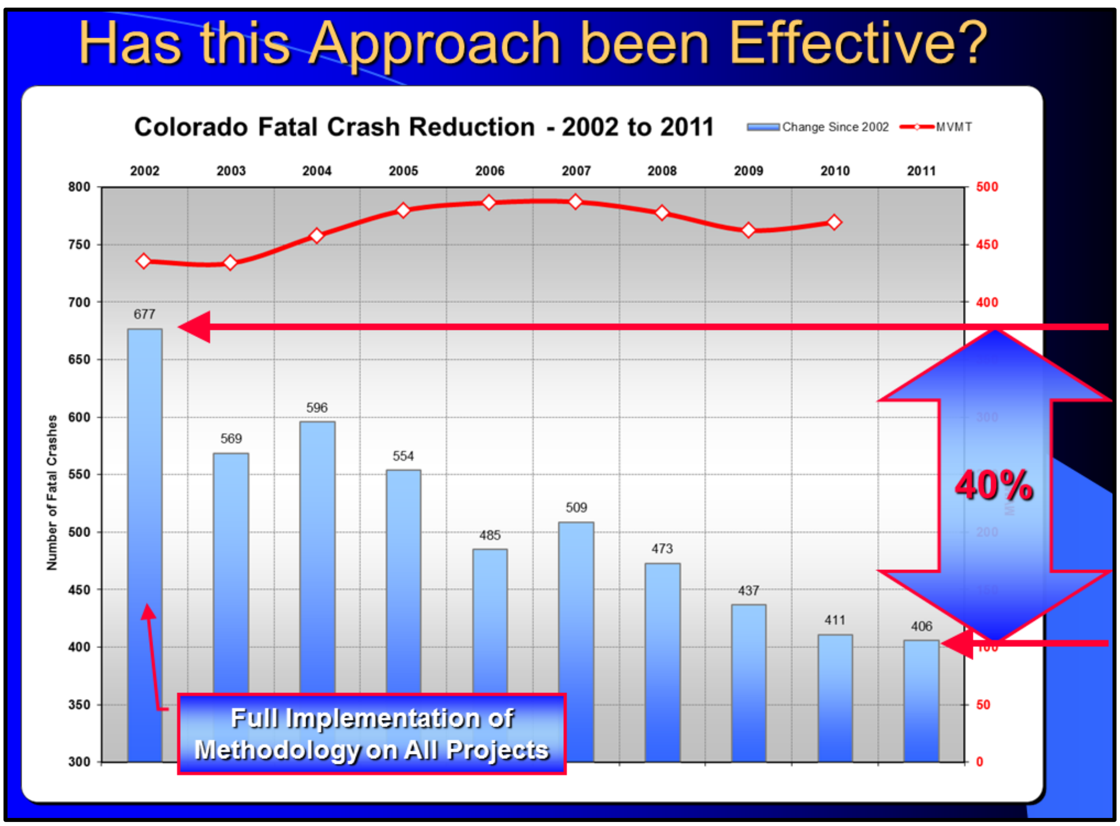

Figure 5. Fatal Crash Reduction in Colorado, 2002–2010

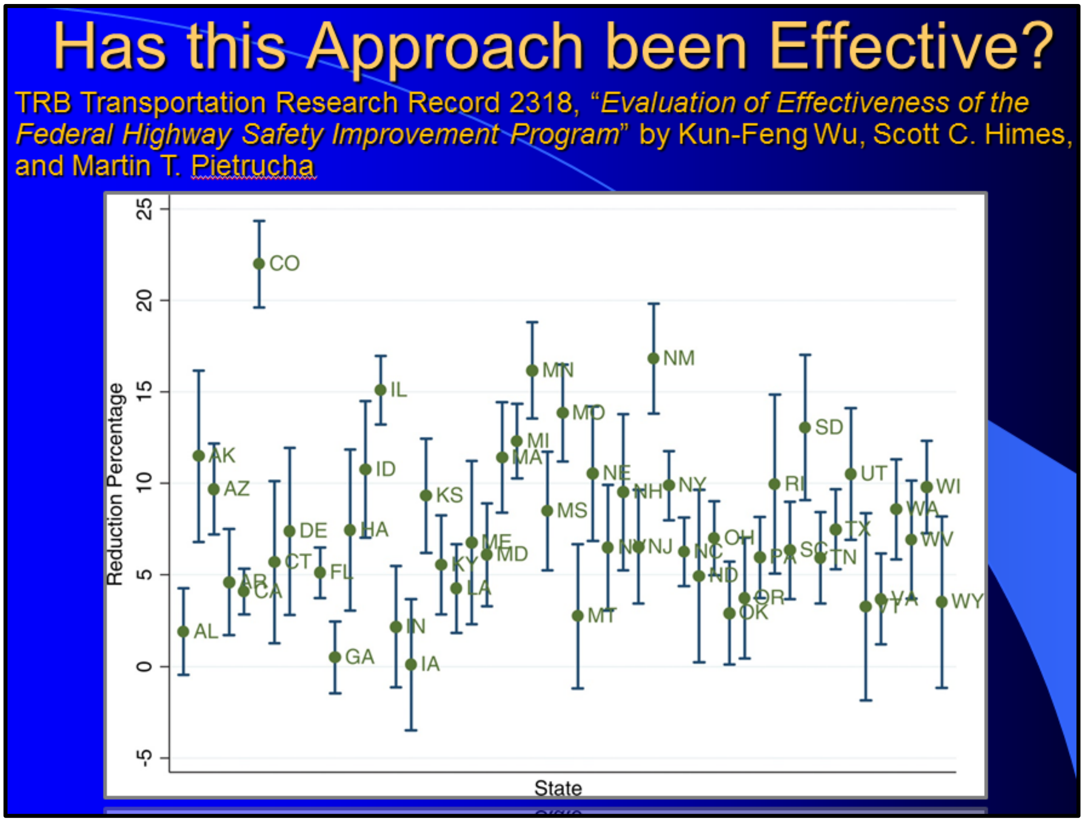

Figure 6. Fatal Crash Reduction in Colorado Compared with Other States from Wu, et al.

CHAPTER 3 – HOW TO MEASURE SAFETY?

When a group of doctors is presented with a patient's vital signs, results of a blood test, a cardiogram, and an x-ray, they generally will be able to agree whether they are examining a sick or a well patient. In contrast, when a group of transportation engineers and planners is presented with crash data, traffic volume, traffic control and geometric design data for a specific segment or an intersection, they will not be able to form a consensus on the safety performance of the transportation facility in question. Over the last 6 years, during training classes on the HSM methodology, the authors have frequently conducted an informal psychological experiment designed to test the ability of transportation engineers and planners to judge the presence of a safety problem at a transportation facility. The participants were presented with crash data, traffic volume, traffic control and geometric design data for several segments and intersections with known safety performance, and asked to characterize their performance as average, better than average or worse than average. The groups were *always* divided in their opinions, and often, the majority judged safety performance of facilities incorrectly. Despite many years of modern road building, the transportation planners and engineers, until recently, lacked a definitive frame of reference on how to assess and describe the magnitude of the safety problem.

Problems with Using Accident Rate

Although AASHTO published the HSM in 2010, many jurisdictions continue to use accident rate as a measure of safety. The following two examples illustrate problems inherent in using accident rates. The concept of a rate assumes that it (rate) remains constant across the range of traffic exposure. This often conflicts with empirical evidence. The first example shows a circumstance when accident rate is declining with congestion and the second one shows the opposite.

Example 1. A section of a two-lane, rural mountainous highway in Colorado (SH 119) (**Figure 7**) exhibited the following accident history and accident rates during a study period from 1988 through 1995 over 5.85 mi (**Table G**). In 1992, the mountain town of Black Hawk opened gambling casinos, and virtually overnight the traffic volume on the highway section quadrupled. The accident rates for each year, measured in accidents per million VMT (acc/mvmt), are computed below, and the results are shown in **Table G**.

$$accident\ rate = \frac{(\#\text{accidents}\ )\ (1{,}000{,}000)}{365\,\frac{\text{days}}{\text{year}}\,(\text{AADT})\ 5.85\ \text{miles}}$$

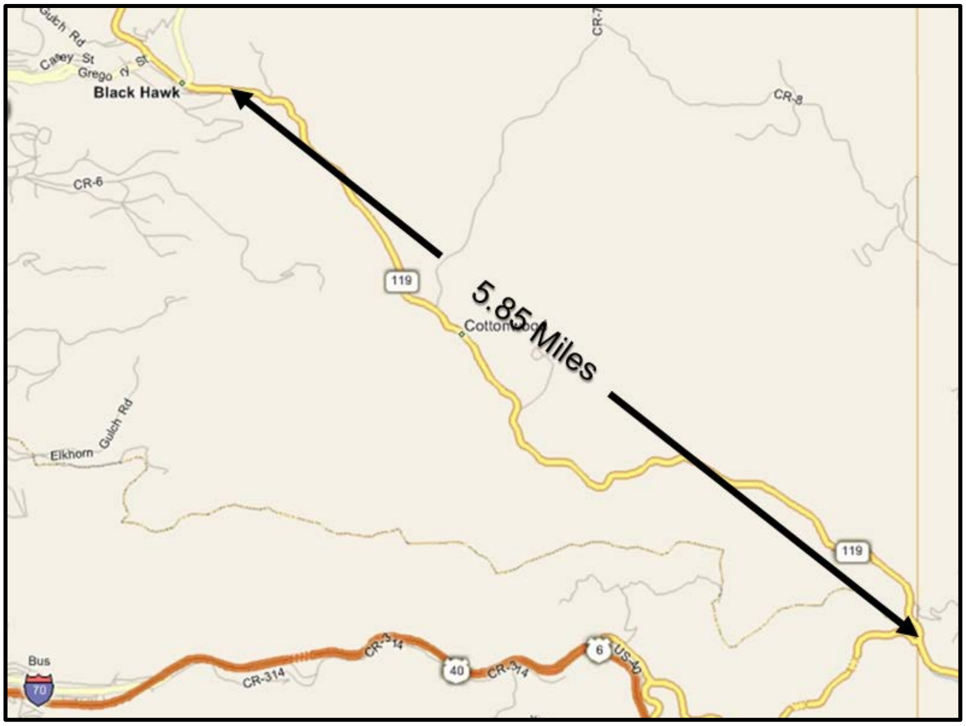

Figure 7. SH 119

Table G. Accident History and Rates, SH 119 1988–1995

Year	No. of Accidents	AADT	Rate	Avg. Rate
Before gambling				
1988	13	2,900	2.11	2.28
1989	11	2,900	1.79	
1990	13	3,050	2.01	
1991	23	3,400	3.19	
After gambling				
1992	30	10,618	1.33	1.24
1993	30	13,200	1.07	
1994	36	14,300	1.19	
1995	40	13,900	1.36	

During the four-year period before the opening of the casinos, the average accident rate was 2.28 acc/mvmt. The following four years, after legalization of gambling in this town, the accident rate was reduced by almost 50 percent. The alignment and typical section of the highway did not change with the introduction of gambling, yet by measuring safety with accident rates it could be surmised that following the opening of the casinos, safety on the same highway improved by 50 percent. Further, it is of interest to note that following gambling, the proportion of accidents in one direction that involved alcohol (returning home after gambling) increased 500 percent. This finding begs the question: Are drinking and driving in concert with gambling good for safety? Probably not, but if accident rates are used as a measuring device, one would have to conclude that they are. This example shows that the accident rate significantly declined with an increase in AADT. A possible explanation for this increase may be the fact that a high degree of congestion, the presence of buses, and the lack of passing opportunities on a 6% grade have naturally resulted in very low speeds, which influenced safety performance.

Example 2. Example 2 examines changes in accident rates on C-470 between Platte Canyon and I-25 (**Figure 8)** over a period of 15 years. In 1990 C-470 carried an AADT of 36,010, and by 2004 the AADT more than doubled. **Table H** summarizes changes in total and injury crash rates that occurred on C-470 over the study period.

Figure 8. C-470 Location Map

Table H. Changes in Crash Rate on C-470 Over Time

1990	2004
AADT = 36,000 VPD	AADT = 77,682 VPD
Total Accident Rate = 0.41 ACC/MVMT	Total Accident Rate=1.00 ACC/MVMT
Injury Accident Rate = 0.18 ACC/MVMT	Injury Accident Rate = 0.29 ACC/MVMT

Even though all elements of geometric design of C-470 met and exceeded standards in the *AASHTO Policy on Geometric Design*, its safety has significantly deteriorated with the increase in congestion. Its total crash rate increased by 146 percent (0.41 to 1.00), and its injury crash rate by 60 percent (0.18 to 0.29). The rising crash rates are likely caused by compression of traffic flow without a notable reduction in speed: resultant headways are so small that drivers find it difficult or impossible to compensate for errors and avoid crashes.

Example 1 and Example 2 together provide compelling evidence that accident rate changes with AADT. To understand how the crash rate is changing, we need to determine a relationship between safety and traffic exposure. This relationship is known as a Safety Performance Function (SPF), and it is unique for each facility type.

Safety Performance Functions

SPFs are accident prediction models that generally relate traffic exposure measured in AADT to safety measured in the number of accidents over a unit of time. CDOT has developed SPFs for most transportation facilities in Colorado, now available to CDOT's planning partners at: https://www.codot.gov/library/traffic/traffic-manuals-guidelines/safety-crash-data/safety-analysis-information.

A brief description of how SPFs were developed follows.

Dataset Preparation. Dataset preparation used the CDOT accident database. Accident history for each facility was prepared over the period of five years (1/1/2010 to 12/31/2014) for segments and (1/1/2000 to 12/31/2004) for intersections. AADT for each roadway segment was entered into the same dataset for segments models. For freeways, all the interchange-related accidents, including accidents that occurred on ramps and crossroads, were removed from the accident database before fitting the model. The reason for removing ramp and cross road accidents was to isolate mainline-only crashes, required for the development of Freeway SPFs. On rural arterial roads, the dataset was prepared in a similar fashion, except that intersection-related accidents were removed before fitting the model. Isolating approximately 250 ft. on both sides of rural intersections is a conservative measure, but it will ensure that intersection-related conflicts will not pollute the dataset consisting of non-intersection-related accidents and road segments. Datasets for the development of intersection SPFs for each intersection type were compiled by collecting crashes coded as at intersection, and intersection-related, and linking them with mainline and side-road AADT for each intersection. More recent Colorado intersection SPFs covering the 2011 to 2015 timeframe are currently under development and expected to become available early in 2018.

Choice of the Model Form, Model Fitting and Goodness of Fit. The SPF is developed by modeling annual crash counts at a population of facilities as a function of the traffic at the facilities. Based on substantial empirical evidence derived from observing safety performance of various segments and intersections as well as the work of other researchers (Hauer[28]), Sigmoidal and Hoerl functions were used to represent the underlying relationships between safety and exposure. Sigmoidal and Hoerl functions are both flexible nonlinear models (Kononov, et al.[29]); they lend themselves well to capturing the overall shape of observed data for the segments and intersections. The general model forms of Sigmoidal and Hoerl functions used in SPF development are provided below:

$E(y) = l\left(\beta_0 + \frac{\beta_1}{1+\beta_2(x^{-\beta_3})}\right)$, Sigmoidal Function for Segment SPFs

$E(y) = l\beta_0(x)^{\beta_1}\exp(\beta_2 x)$, Hoerl Function for Segment SPFs

Where:

$E(y)$ – Number of crashes expected to occur annually on a road segment

x – Segment AADT

l – Segment Length

β – Model Parameters

$E(x_1, x_2) = \beta_0 + \frac{\beta_1}{(1+\beta_2 {x_1}^{-\beta_3})(1+\beta_4 {x_2}^{-\beta_5})}$, Sigmoidal Function for Intersection SPFs

$E(x_1, x_2) = \beta_0 \left({x_1}^{\beta_1}\right)\left({x_2}^{\beta_2}\right)(e^{\beta_3 x_1})$, Hoerl Function for Intersection SPFs

Where:

$E(x_1, x_2)$ – Number of crashes expected to occur at an intersection given the values of x_1 and x_2

x_1 – AADT Major Road

x_2 – AADT Side Road

β – Model Parameters

All the datasets exhibited over-dispersion. Consequently, the annual accident counts were modeled by Negative Binomial distributions with a dispersion parameter α and expected values as shown above. In the case of the Hoerl distribution, the resulting model is a Generalized Linear Model (GLM) having AADT and the log of AADT as predictors and a log link function. Obtaining maximum likelihood estimates for α and β by maximizing the log-likelihood of the data over β and α is computationally convenient. Details are shown below.

$E(y) = \mu$

$Var(y) = \mu(1 + \alpha\mu) = \mu + \alpha\mu^2 > \mu$, thus, the standard deviation of y is $\sqrt{\mu + \alpha\mu^2}$

$L(\mu, \alpha) = \prod_{i=1}^{n} \frac{\Gamma(\alpha^{-1}+y_i)}{\Gamma(\alpha^{-1})y_i!} \left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right)^{y_i} \left(\frac{1}{1+\alpha\mu_i}\right)^{\alpha^{-1}}$

$\ln\left(L(\mu, \alpha)\right) = \sum_{i=1}^{n} \ln\left(\frac{\Gamma(\alpha^{-1}+y_i)}{\Gamma(\alpha^{-1})y_i!}\right) + y_i \ln\left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right) + \alpha^{-1} \ln\left(\frac{1}{1+\alpha\mu_i}\right)$

Where:

y – Vector of random variables modeling annual accident counts on segments or intersections

μ – Expected values of y, estimated by the SPF

y_i – Observed number of accidents on a segment or intersection over one year, a sample from the i^{th} component of y.

α – Scalar over-dispersion parameter

$L(\mu, \alpha)$ – Negative Binomial likelihood function

Γ – Gamma Function

The quality of fit was confirmed with the Cumulative Residuals (CURE) method described in Hauer and Bamfo[30]. The CURE method displays visually how well the fitted model function describes the dataset. To generate a CURE plot, sites are sorted by their average AADT. Then, for each site, the residual (observed accidents – predicted accidents) is computed. The k^{th} cumulative residual is calculated by summing first k residuals. The cumulative residuals are plotted against the corresponding AADT. Because of the random nature of accident counts, the cumulative residual line represents a so-called "random walk." For a model that fits well in all ranges of AADT, the cumulative residual plot should oscillate around zero. If the cumulative residual value steadily increases within a range of values of the independent variable, then, within that range, the model predicts fewer accidents than have been observed. Similarly, a decreasing cumulative residual line indicates that, in that range, fewer accidents have been observed than are predicted by the model. The cumulative residual line for a model that fits the data well should lie largely within two standard deviations of a theoretical random walk. Failure to do so indicates the presence of outliers or signifies an ill-fitting model. For instance, **Figures 9 and 10** show CURE plots reflecting a well-fitting model relating total and injury crashes for major road AADT for the Colorado urban divided, signalized, 4-leg intersections. SPF Model parameters are as follows:

$$E(x_1, x_2) = \beta_0\left({x_1}^{\beta_1}\right)\left({x_2}^{\beta_2}\right)\left(e^{\beta_3 x_1}\right)$$

Frequency SPF Model	*Severity SPF Model*
β_0 *= 2.6 x 10*$^{-8}$	β_0*=1.04 x 10*$^{-9}$
β_1 *= 1.581*	β_1 *= 1.8508*
β_2 *= 0.4985*	β_1 *= 0.4547*
β_3 *= -2.585 x 10*$^{-5}$	β_3 *= -3.74 x 10*$^{-5}$
α_f*= 0.1343 (Over-dispersion)*	α_s*= 0.1546 (Over-dispersion)*

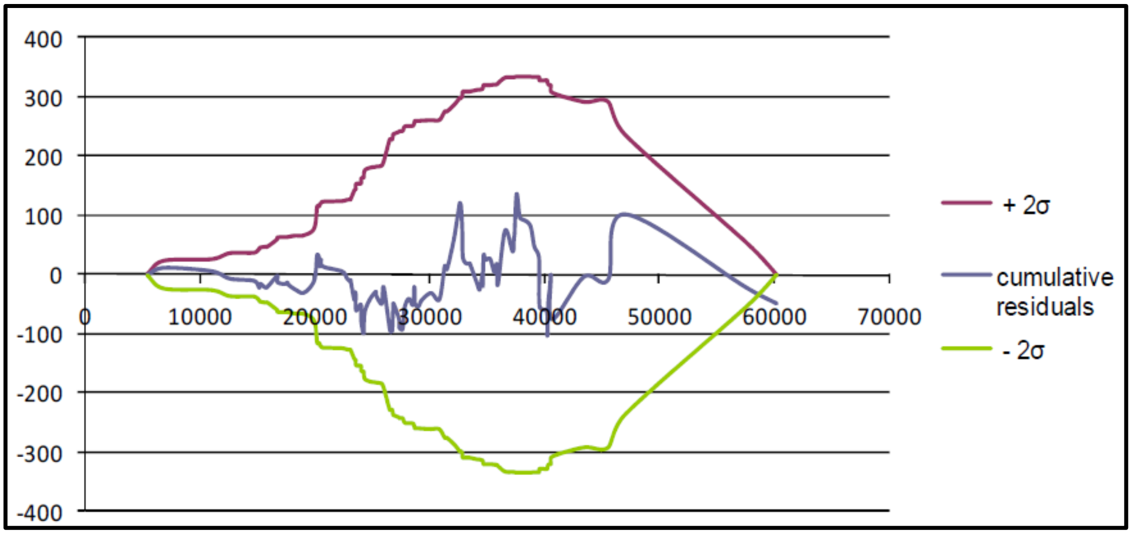

Figure 9. Cure Plot Intersection Frequency SPF Main Line AADT

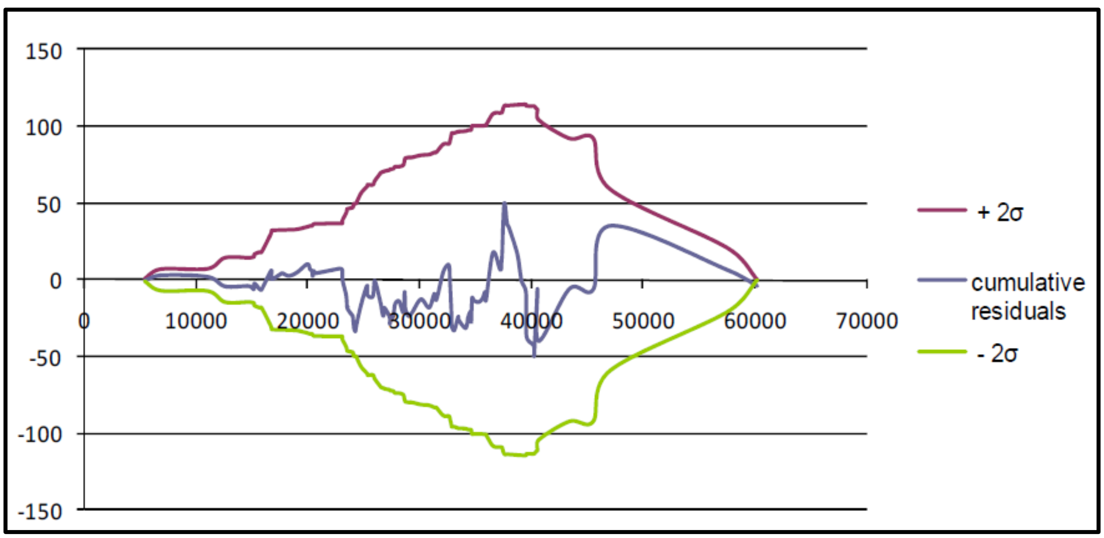

Figure 10. Cure Plot Intersection Severity SPF Main Line AADT

Correcting for the Regression to the Mean Bias. The best guess about the future is usually obtained by computing the average of past events. In road safety, the average of several years of crash history of a highway segment or of an intersection provides an estimate of what is likely to be observed in the future. The precision of this estimate, however, can be improved on by correcting it for the Regression to the Mean (RTM) bias. RTM phenomenon reflects the tendency for random events, such as vehicle crashes, to move toward the average during an experiment, or over time. For instance, if a segment or an intersection exhibits unusually high or unusually low crash frequency in a particular year, because of RTM, we need to be aware that over the long run its true average is closer to the mean representing safety performance of similar facilities. The existence of the RTM bias has long been recognized and is now effectively addressed by using the Empirical Bayes (EB) method[31]. Using the EB method is particularly effective when it takes a long time for a few accidents to occur, as is often the case on Colorado rural roads.

The EB method for estimating safety increases the precision of estimation and corrects for the regression to the mean bias. It is based on combining the information contained in accident counts (known as crash history) with the information contained in knowing the safety of similar entities. The information about safety of similar entities is brought into the EB procedure by the SPF. To illustrate the application of the EB method, let's examine safety performance of a segment of SH 491B milepost (MP) 67.58 to MP 69.60 over a period of five years (1/1/2010 to 12/31/2014).

Observed 5-year average accident severity (injury and fatal crashes) η = 0.495 acc/mile per year.

Expected severity μ = 0.19 acc/mile per year, predicted by the SPF

Over-dispersion parameter α = 0.42, estimated from the SPF

Number of years of crash history n = 5

$$\text{Weight (W)} = \frac{1}{1+(\mu \times n)\alpha} = \frac{1}{1+(0.19 \times 5)0.42} = 0.72$$

EB Corrected Estimate = W x μ + (1-W) x η =

= 0.72 x 0.19 + (1.00-0.72) x 0.495 = 0.275 acc/mile per year

Figure 11 shows the SPF predicted mean, the observed five-year average, and the EB estimate that reflects correction for the RTM bias. After correcting for RTM bias, safety performance of SH 491B between MP 67.58 and MP 69.60 is well above the mean and suggests high to moderate potential for crash reduction.

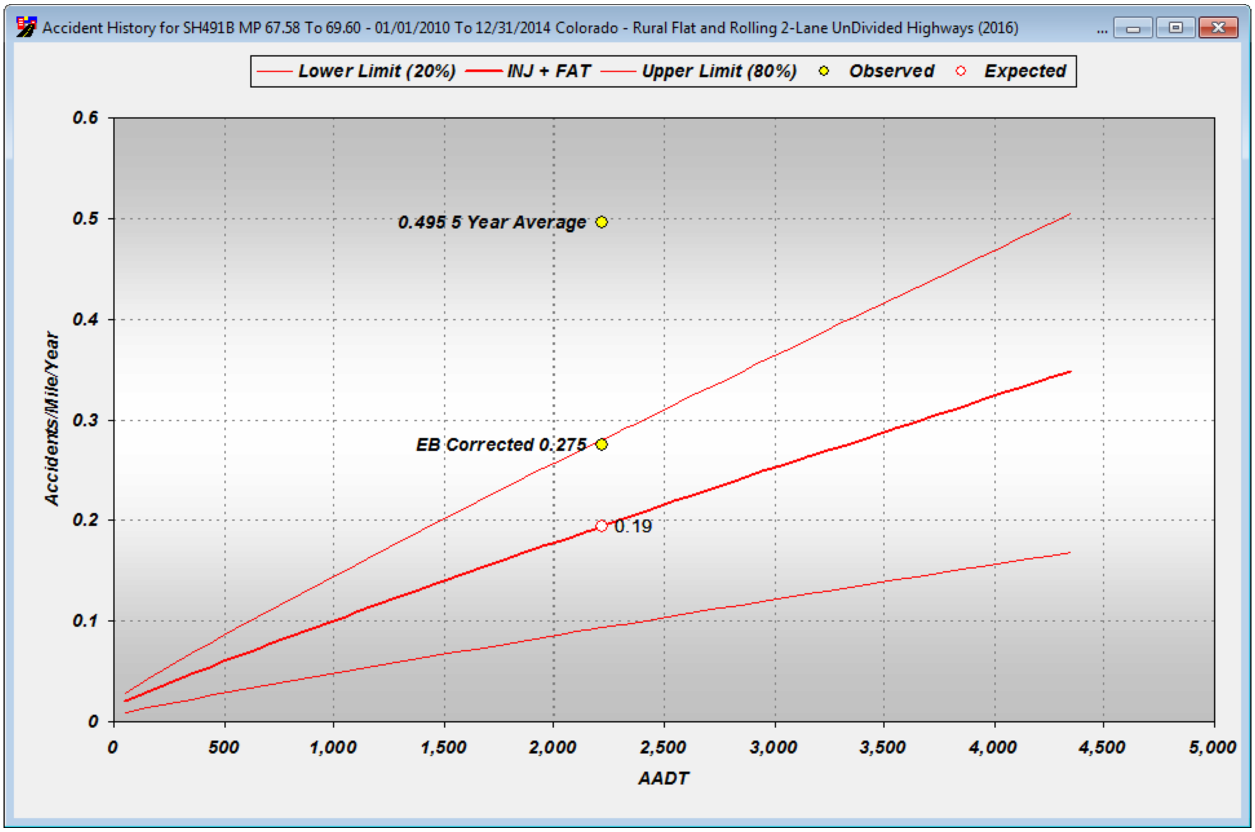

Figure 11. EB Estimate and SPF

Correcting for RTM is useful because it improves precision of our estimate of safety performance of existing facilities during the transportation planning process. It is especially critical when the mean is small, less than 1 for instance; however, when the means are large, correcting for the RTM may not be sufficiently significant to influence the decisions in the planning phase of project development.

Level of Service of Safety (LOSS)

Concept Description. Development of the SPF lends itself well to the conceptual formulation of the Level of Service of Safety (LOSS). The concept of LOSS uses quantitative assessment and qualitative description to characterize the safety of a roadway segment, in reference to its expected performance and severity. If the level of safety predicted by the SPF will represent a normal or an expected number of accidents at a specific level of AADT, then the degree of deviation from the norm can be stratified to represent specific levels of safety.

- LOSS I – Indicates low potential for crash reduction
- LOSS II – Indicates low to moderate potential for crash reduction
- LOSS III – Indicates moderate to high potential for crash reduction
- LOSS IV – Indicates high potential for crash reduction

The gradual increase in the degree of deviation of the LOSS boundary line from the fitted model mean reflects the observed increase of variability in the number of accidents as AADT increases. The delineated boundary lines represent 20^{th} and 80^{th} percentiles of the SPF population. Selection of the 20^{th} and 80^{th} percentiles is made to identify roadway segments with some potential for crash reduction or to recognize a particularly good performance.

Introduction of the LOSS concept enables transportation engineers to do the following:

- Quantitatively assess and qualitatively describe the degree of safety or un-safety of a roadway segment.
- Effectively communicate the magnitude of the safety problem to other professionals, elected officials, members of the media, and law enforcement officials.
- Bring the perception of roadway safety in line with the reality of safety performance for a specific facility.
- Provide a frame of reference for decision making on non-safety motivated projects (resurfacing or reconstruction, for instance).
- Provide a frame of reference from a safety perspective for planning major corridor improvements.

LOSS reflects how the roadway segment is performing regarding its expected accident frequency and severity at a specific level of AADT. It provides only an accident frequency and severity comparison with the expected norm. It does not, however, provide any information related to the nature of the safety problem itself. If a safety problem is present, LOSS will describe its magnitude only from a frequency and severity standpoint. The nature of the problem is determined through diagnostic analysis, using Direct Diagnostics and Pattern Recognition techniques[32].

Calibration of the Level of Service of Safety (LOSS) Boundaries. SPF is initially calibrated using original data that are over-dispersed and well described by the Negative Binomial distribution. In the process of calibration, the over-dispersion parameter is estimated from the data and establishes a "link" function between the population's mean and its standard deviation. The relationship between standard deviation and the mean is described as follows:

$$\sigma = \sqrt{\mu + \alpha\mu^2}$$

Where:

μ – Expected frequency predicted by the SPF

α – Over-dispersion parameter estimated from the SPF

Over-dispersion is typical in the accident data; however, when the magnitude of the problem is assessed, it is important to correct observed crash frequency for the regression to the mean bias using the EB procedure. The EB method for estimating safety increases the precision of estimation. It is based on combining the information contained in accident counts (known crash history) with the information contained in knowing the safety of similar entities. The information about safety of similar entities is brought into the EB procedure by the mean (μ) of the SPF. When an individual site is examined in the LOSS framework, it is corrected for the RTM bias; therefore, it is appropriate to compare its degree of deviation from the mean using the distribution reflecting the EB corrected population. When safety performance of all segments in the dataset is corrected for the RTM bias using the EB procedure, the resulting population will naturally have a smaller variance than before correction. EB corrected population is described by the Gamma distribution where the relationship between the mean and standard deviation is as follows:

$$\sigma = \sqrt{\alpha\mu^2}$$

LOSS boundaries are then calibrated by computing the 20th and the 80th percentiles using the Gamma Distribution Probability Density Function below[33]:

$$f(\mu) = \frac{a^b \mu^{b-1} e^{-a\mu}}{\Gamma(b)}$$

where:

μ – the mean

b – dispersion parameter estimated from the regression

a – b/μ

Γ – Gamma Function

Figure 12 graphs SPF and LOSS for total crashes, and **Figure 13** for Injury and Fatal Crashes only for Colorado 4-Lane Divided Highways.

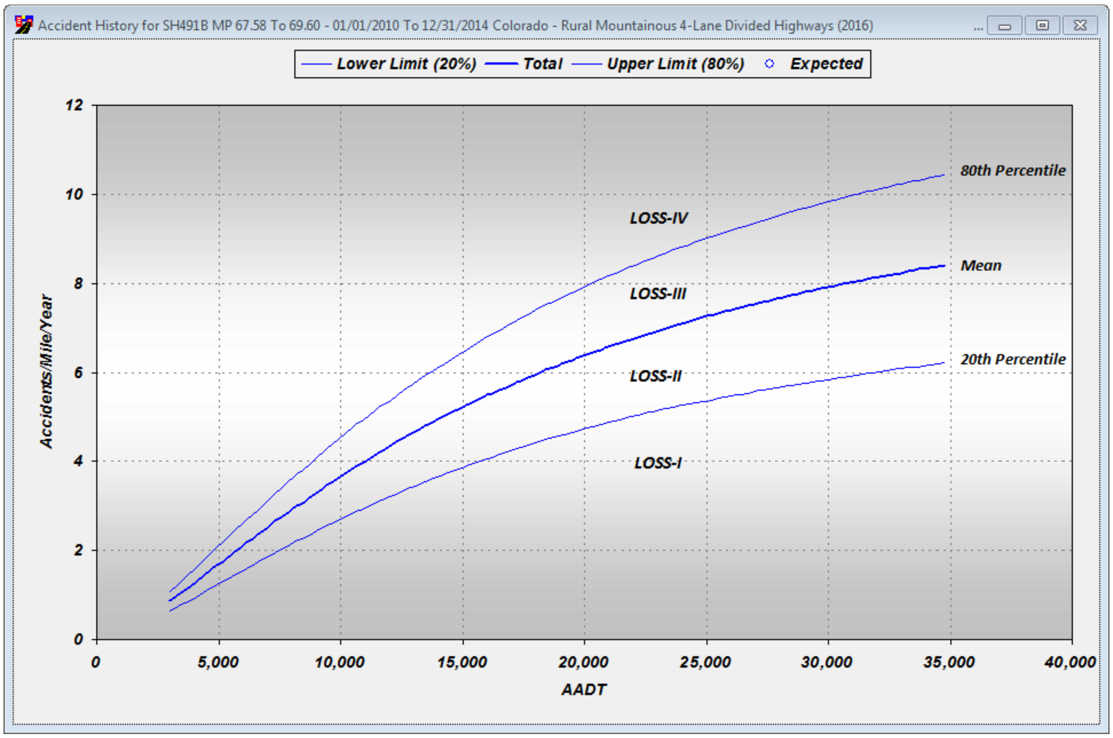

Figure 12. SPF Total Rural Mountainous 4-Lane Divided Highways

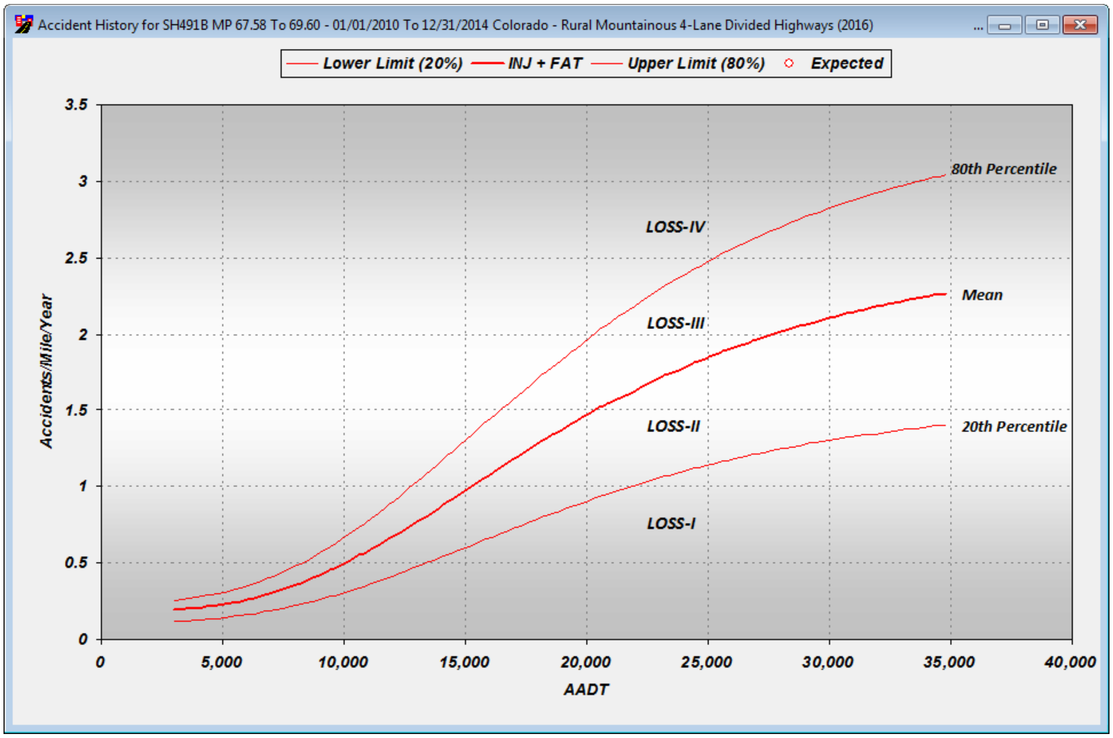

Figure 13. SPF Injury + Fatal Rural Mountainous 4-Lane Divided Highways

CHAPTER 4 – HOW TO DISCERN THE NATURE OF THE SAFETY PROBLEM

Detection of an accident pattern suggests the presence of an element, or elements, in the roadway environment, which triggered a deviation from a random statistical process in the direction of reduced safety. Identification of such an element provides a critical clue to accident causality. Existence of accident patterns susceptible to correction may, or may not, be accompanied by the overrepresentation in accident frequency reflected by the SPFs. In fact, it can be said that the detection of accident patterns provides a more direct link to the development of the countermeasure strategy than a mere increase in accident frequency. While LOSS provides a means of assessing the magnitude of the safety problem, diagnostic examination aids in assessing its nature. During in-depth safety studies of Colorado segments and intersections, a comprehensive methodology was developed to conduct diagnostic analysis of safety problems for different classes of roads in various Colorado environments. Direct diagnostics methods and a pattern recognition algorithm are described by Kononov[34]. Because traffic accidents can be viewed as random Bernoulli trials, it is possible to detect deviations from the random statistical process by computing the observed cumulative probability for each normative parameter.

To illustrate the use of the diagnostic methodology, we will examine Colorado SH 82 between MP 27.26 and MP 29.50. Within study limits, SH 82 is a 4-Lane Divided Highway in rolling terrain. SPF analysis shows elevated frequency of crashes reflected by the LOSS IV (**Figure 14**). Direct diagnostic analysis shows that the number of fixed object crashes is highly abnormal. Sixty-six (66) out of 94 crashes (70.21 percent) (**Figure 15**) involved striking a fixed object, when the average for Rural 4-Lane Divided Highways in Colorado is only 32.89 percent. All the Colorado diagnostic norms are now available at:

https://www.codot.gov/library/traffic/traffic-manuals-guidelines/safety-crash-data/safety-analysis-information.

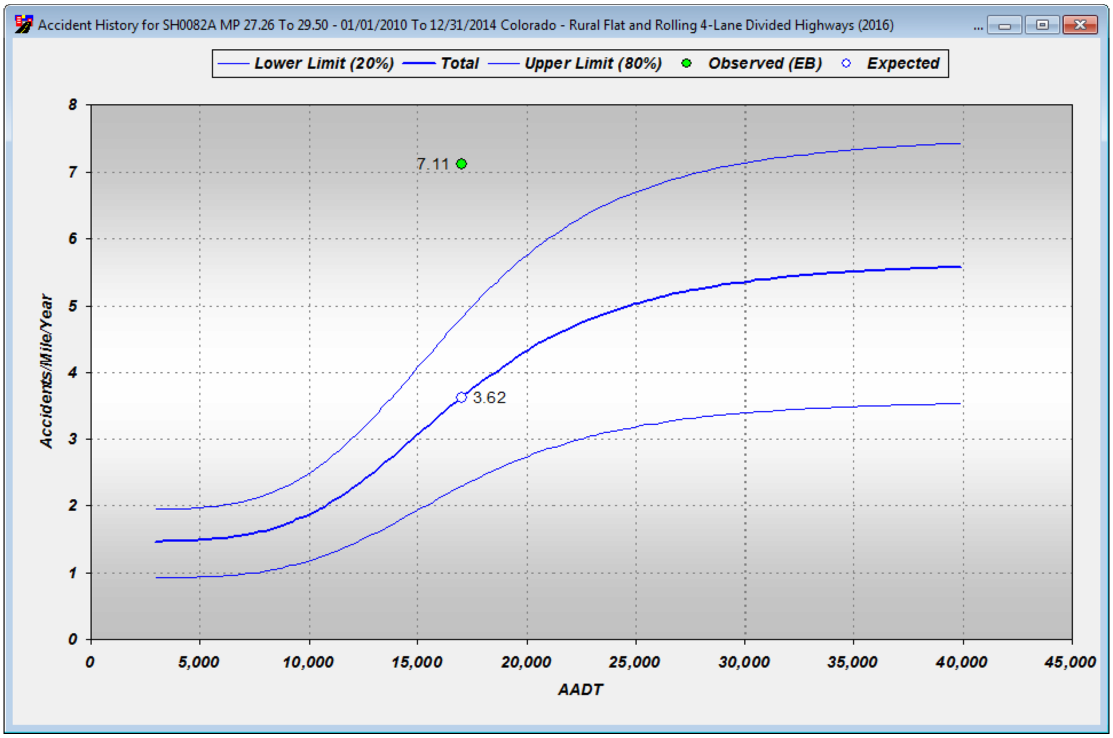

Figure 14. EB Corrected SPF Total SH 82A MP 27.26-MP 29.50

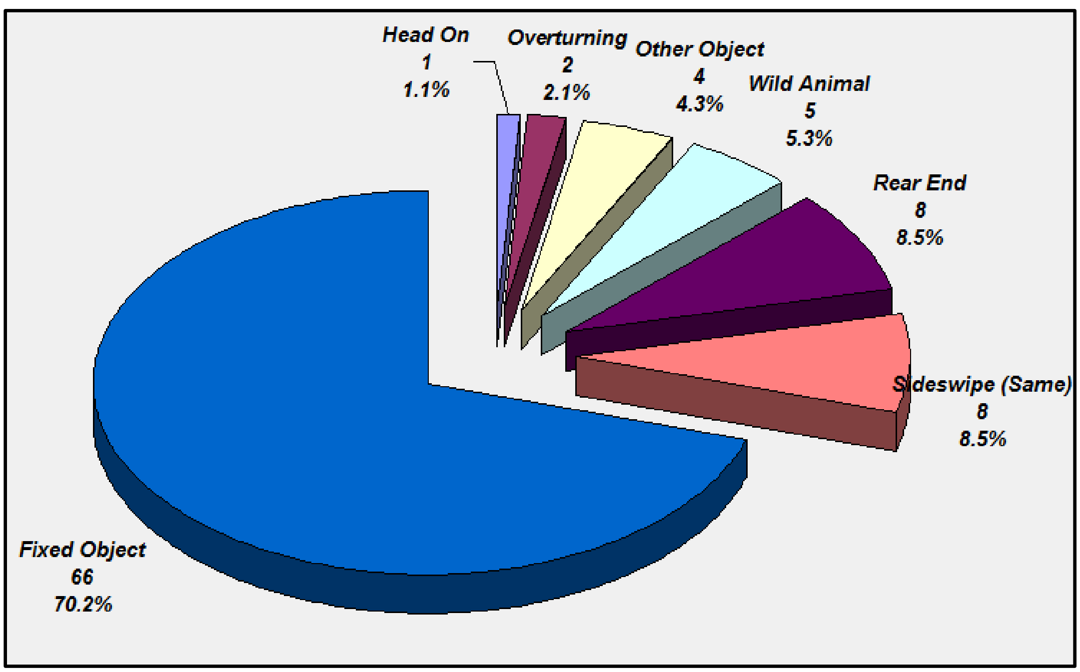

Figure 15. SH 82A MP 27.26-MP 29.50 Distribution of Crashes by Type

$$P(X \le x) = B(x, n, p) = \sum_{i=0}^{x} \frac{n!}{(n-i)!\,i!} p^{i}(1-p)^{n-i}$$

Where:
n – Total number of crashes (94)

x – Number of fixed object crashes (66)

p – Expected % of fixed object crashes based on statewide statistics (32.89%)

$P(X \le 66, n=94, p=32.89\%) = 1$

This computation can be easily performed using the BINOM.DIST statistical function available in Microsoft Excel (**Figure 16**).

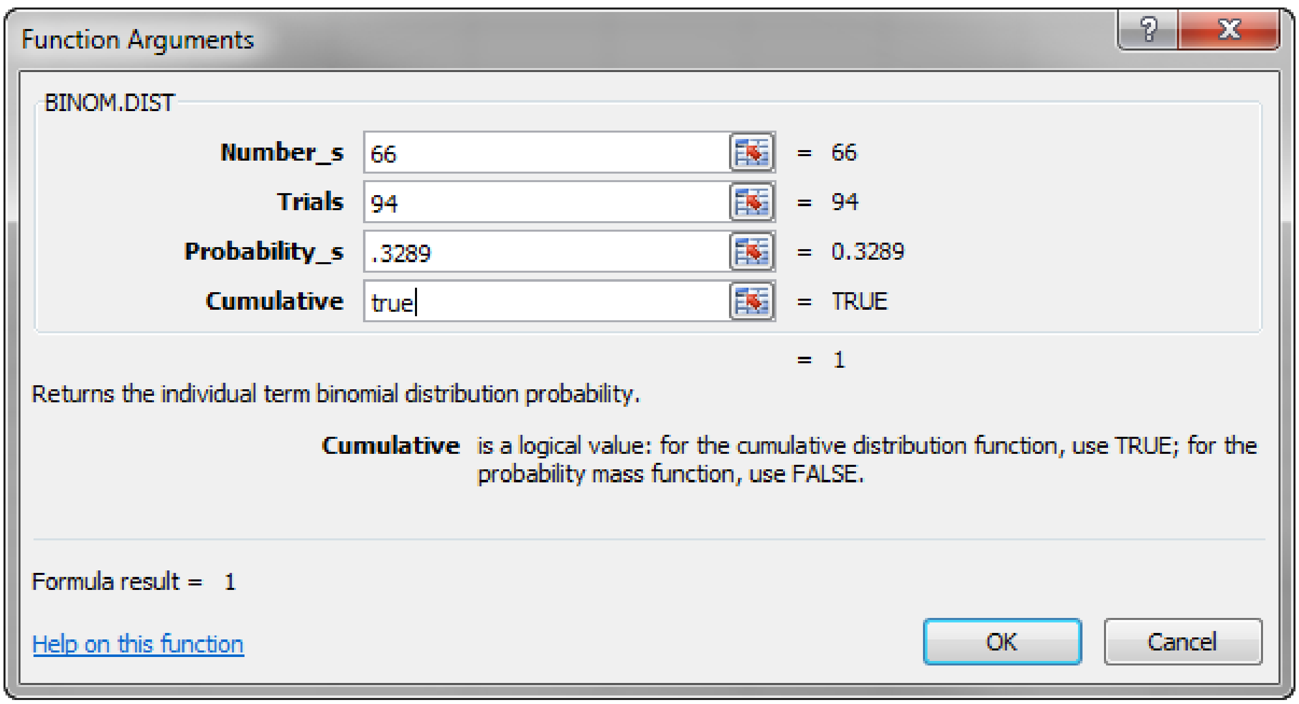

Figure 16. BINOM.DIST Function from MS Excel

Such a high cumulative probability of observing 66 or fewer fixed object crashes out of 94 total accidents suggests that an elevated frequency of crashes may be attributed to the fixed object crash pattern. Potential countermeasures may include improved signing and delineation, shoulder widening or realignment depending on the site-specific geometric characteristics.

CHAPTER 5 – NEW METHODOLOGY AND THE ROLE OF OBSERVATIONAL BEFORE AND AFTER STUDIES

One of the main sources of factual knowledge about the effect of highway and traffic engineering measures are the "observational before and after studies." The term observational, in this context, distinguishes between a randomized experiment designed to answer a research question, and observing the safety consequences of some treatment that has been constructed for purposes other than answering a research question. The results of the observational before and after studies are expressed and quantified by the Crash Reduction Factors (CRF) or Crash Modification Factors (CMF). A CRF is an estimate of the change in crashes after the implementation of a countermeasure, and a CMF = 1-CRF. CRF/CMFs can be incorporated into the new procedure for considering safety explicitly in the planning process. The most complete, credible and comprehensive source of CRFs/CMFs is the FHWA CMF Clearing House, at www.cmfclearinghouse.org. It contains more than 5,000 CMFs and provides the star quality rating for each reflecting the quality or confidence in the results of the study producing the CMF. The star rating is based on a scale of 1 to 5, with 5 indicating the highest or most reliable rating. To evaluate the effectiveness of the proposed procedure, we will compare the observed changes over time in safety performance at selected locations with changes predicted by the CMFs. Initially three case histories will be examined to demonstrate application of CRF/CMFs in the proposed new safety planning methodology:

1. Improvements of the Urban Signalized Intersection at SH 83 (Leetsdale) and Quebec
2. Improvements of the Urban Signalized Intersection at SH 30 (Havana) and Mississippi
3. Improvements on the Rural 2 Lane State Highway, SH 133 MP 46.00 to MP 51.50

In the process of quantifying safety benefits of proposed improvements, we will use the monetary values assigned to crashes by severity by the National Safety Council, which are updated periodically. The current (2015) values are:

- Property Damage Only (PDO) = $9,300
- Injury (INJ) = $80,700
- Fatal (FAT) = $1,500,000

Case History 1

- Location – SH 83 (Leetsdale) MP 74.89 to MP 74.95 at Quebec (**Figure 17**).
- Proposed improvements included signal rebuild, including fully protected left turns.

Figure 17. Leetsdale Drive at Quebec Street

- Before Period 2000–2003 and After Period 2005–2008 (1 year in between for construction)
- Crash history in the four years of the Before Period (2000–2003):
  - 117 PDO
  - 46 INJ
  - 0 FAT
- Observed crash pattern in the Before Period – Approach Turn – 45 Crashes (29 PDO and 16 INJ)
- Crash history in the four years of the After Period (2005–2008):
  - 91 PDO
  - 25 INJ
  - 0 FAT

- Observed crash patterns in the After Period – None, Approach Turn – 6 Crashes (5 PDO and 1 INJ)
- Estimation of benefits related to the reduction in Approach Turn Crashes (Life Cycle 20 years)
  - INJ 16 -1 = 15 INJ crashes prevented in 4 years = (93.75% Reduction) = (3.75 crashes per year) → Life Cycle Benefit = 3.75 ($80,700) (20 years) = $6,052,500
  - PDO 29 – 5 = 24 PDO crashes prevented in 4 years = (82.76% Reduction) = (6.00 crashes per year) → Life Cycle Benefit = 6.00 ($9,300) (20 years) = $1,116,000
- Total benefit over the life cycle is $6,052,000 + $1,116,00 = $7,168,500 based on observed crash reduction. According to the FHWA clearing house, expected CRF is 90% for INJ and 90% for PDO. If expected CRFs are used to estimate future safety benefit, the benefits are as follows:
  - INJ, $\frac{16\ crashes\ (0.9)}{4\ years}$ 20 years ($80,700) = $5,810,400
  - PDO, $\frac{29\ crashes\ (0.9)}{4\ years}$ 20 years ($9,300) = $1,213,650
- Total life cycle benefit estimated using CRFs = $5,810,400 + $1,213,650 = $7,024,050

Safety benefits derived from observed changes in safety performance expressed in dollars ($7,168,500) are close to the benefits predicted by using CRF ($7,024,050), which suggests that using CRF to estimate safety benefits in the planning process has the potential to be effective. It enables planners to anticipate and quantify safety benefits correctly when projects are contemplated and selected.

From the standpoint of overall safety performance, it is also of interest to note that it changed from LOSS IV (High Potential for Crash Reduction) in the Before Period, to the low range of LOSS III (Moderate to High Potential for Crash Reduction) in the After Period, for all crashes (**Figure 18**). For injury and fatal crashes, safety performance changed from LOSS IV in the Before Period, to LOSS II (Low to Moderate Potential for Crash Reduction) in the After Period (**Figure 19**). This significant change in safety performance provides an important frame of reference and shows that rebuilding this signal and changing its left turn phasing was effective from a safety standpoint.

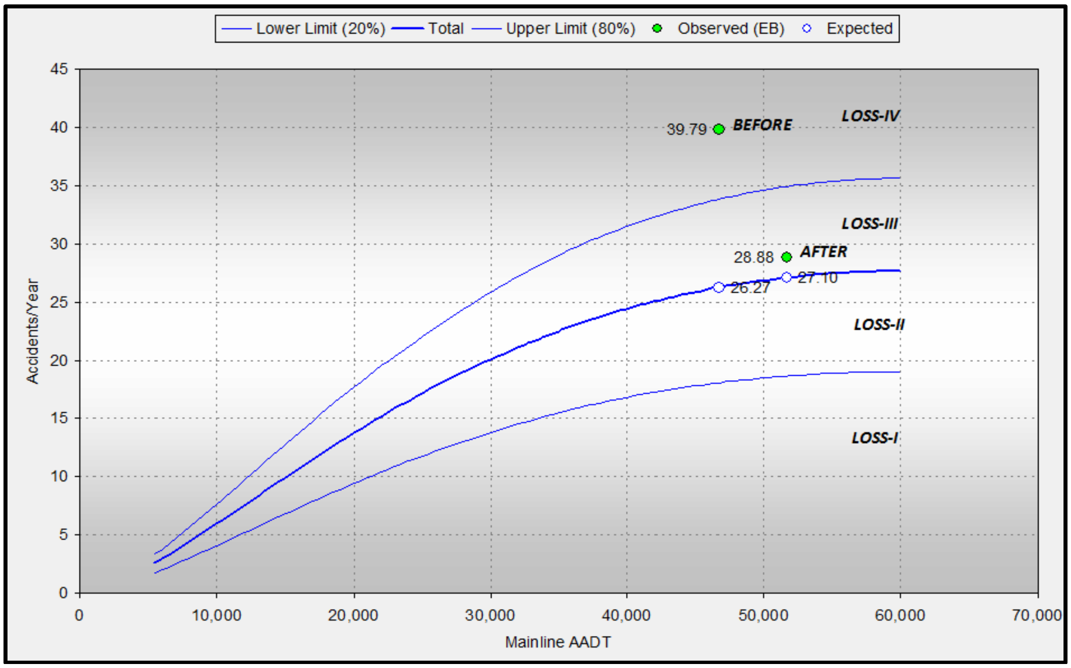

Figure 18. SH 83 at Quebec SPF EB Corrected Frequency Graph Before and After

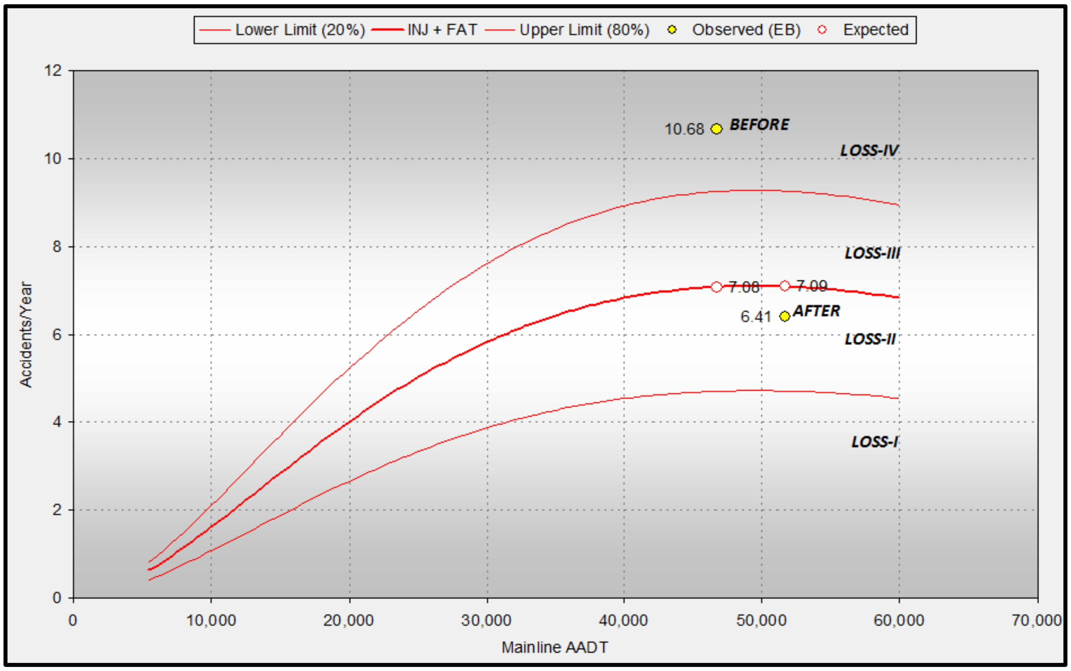

Figure 19. SH 83 at Quebec SPF EB Corrected Severity Graph Before and After

Case History 2

- Location SH 30 (Havana) MP 5.76 to MP 5.82 at Mississippi (**Figure 20**)
- Proposed improvements included signal rebuild, protected left turn phasing on all approaches, and minor geometric improvements to improve operations

Figure 20. Mississippi Avenue at Havana Street

- Before Period 2002–2004 and After Period 2006–2008 (1 year in between for construction)
- Crash history in the three years of the Before Period (2002–2004)
  - 82 PDO
  - 52 INJ
  - 0 FAT
- Observed crash pattern in the Before Period also – Approach Turn – 53 Crashes (28 PDO and 25 INJ)
- Crash history in the three years of the After Period (2006–2008)
  - 59 PDO
  - 13 INJ
  - 0 FAT

- Observed crash patterns in the After Period – None, Approach Turn – 5 Crashes (4 PDO and 1 INJ)
- Estimation of benefits related to the reduction in Approach Turn Crashes (Life Cycle 20 years)
    - INJ 25 – 1 = 24 INJ crashes prevented in 3 years = (96% Reduction) = (8 crashes per year) → Life Cycle Benefit = (8) ($80,700)(20 years) = $12,912,000.
    - PDO 28 – 4 = 24 PDO crashes prevented in 3 years = (85.71% Reduction) = (8 crashes per year) → Life Cycle Benefit = (8) ($9,300) (20 years) = $1,488,000
- Total benefit over the life cycle is $12,912,000 + $1,488,000 = $14,400,000 based on observed crash reduction.
- If expected CRFs from the FHWA clearing house are used (90% reduction for INJ and 90% for PDO) to estimate future safety benefits, they can be computed as follows:
    - INJ $\frac{25\ crashes\ (0.9)}{3\ years}$ 20 years ($80,700) = $11,620,800
    - PDO $\frac{28\ crashes\ (0.9)}{3\ years}$ 20 years ($9,300) = $1,562,400
- Total life cycle benefit estimated using the FHWA Clearing House CRF = $11,620,800 + $1,562,400 = $13,183,200

In this case, as in the previous example, the safety benefits derived from observed changes in safety performance expressed in dollars ($14,400,000) are close to the benefits predicted by using the FHWA Clearing House CRF ($13,183,200), which further supports the view that using CRF to estimate safety benefits in the planning process has the potential to be effective. When overall safety performance is examined, we can observe that frequency, as well as severity, improved from the LOSS IV (High Potential for Crash Reduction) in the Before Period to the LOSS I (Low Potential for Crash Reduction) in the After Period (**Figure 21 and Figure 22)**.

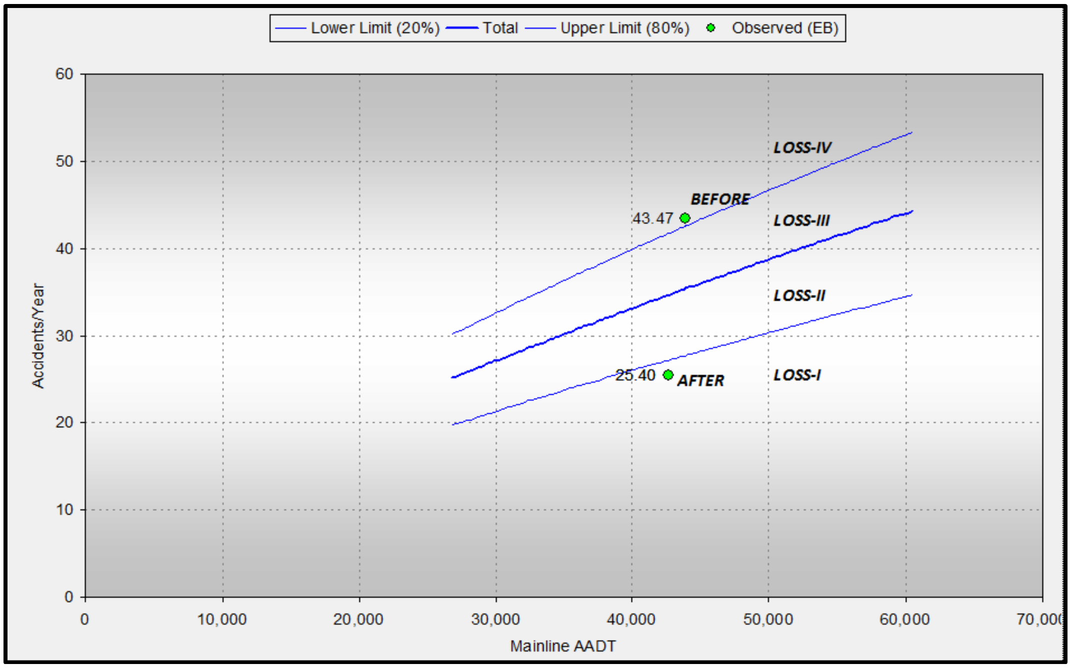

Figure 21. SH 30 at Mississippi SPF EB Corrected Frequency Graph Before and After

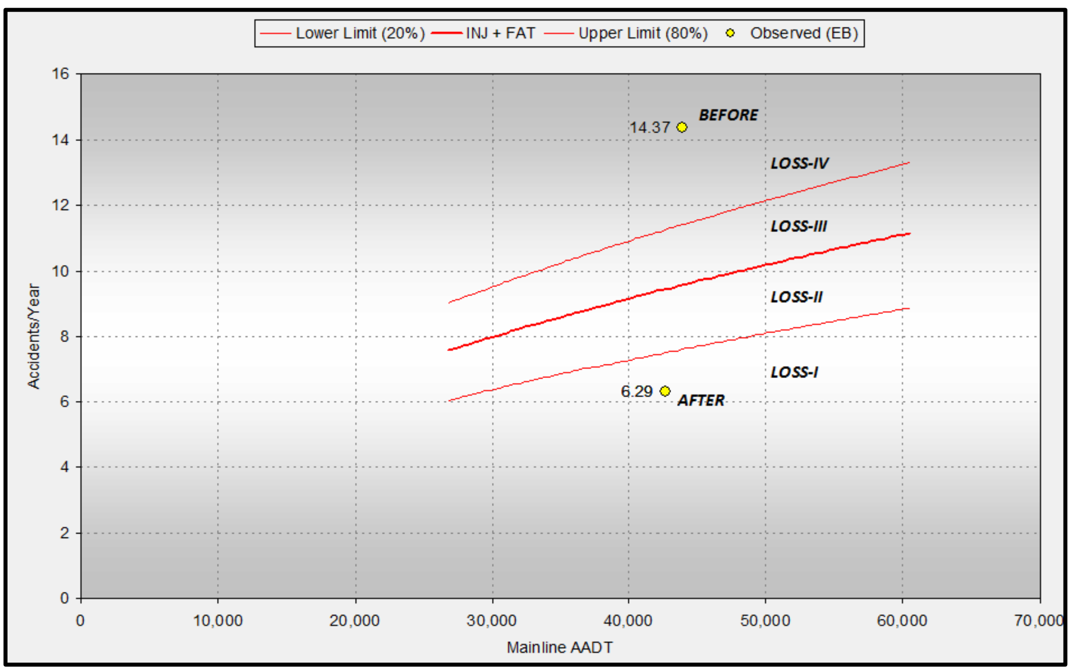

Figure 22. SH 30 at Mississippi SPF EB Corrected Severity Graph Before and After

Case History 3

- Location SH 133 MP 46.00 to MP 51.50, McClure Pass (**Figure 23**)
- Improvements included construction of new guardrail to reduce roadway departure crashes.

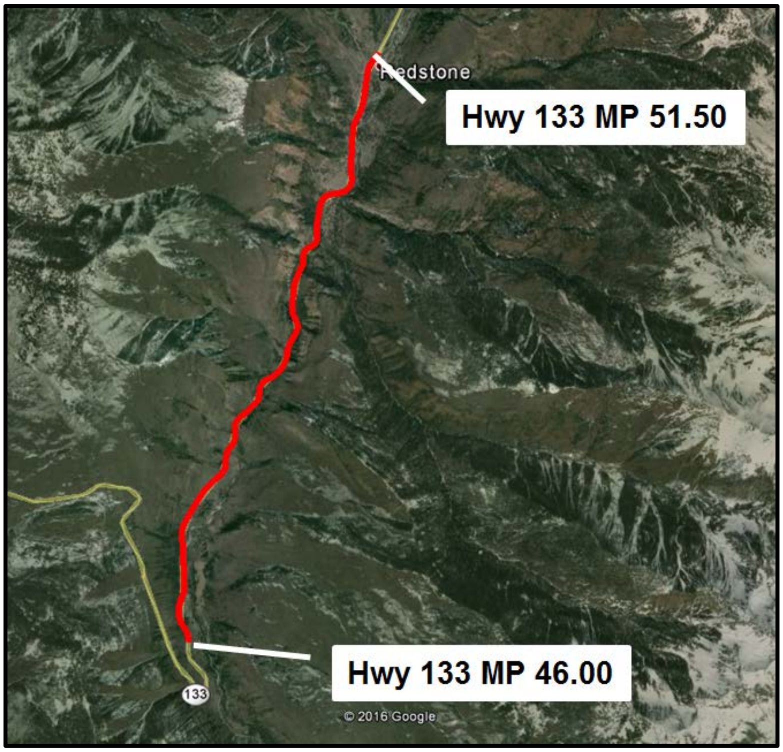

Figure 23. SH 133 McClure Pass

- Before Period 2002–2006 and After Period 2009–2013 (Construction took place in two phases over a period of two years)
- Crash history in the five years of the Before Period (2002–2006)
  - PDO 17
  - INJ 7
  - FAT 3
- Relevant observed crash patterns in the Before Period – Off Road, Single Vehicle, and Fixed Objects
- Crashes susceptible to correction through guardrail construction in the Before Period – Overturning and Fixed Objects (excluding guardrail) – 10 PDO, 6 INJ, and 3 FAT

- Crash history in the five years of the After Period (2009–2013)
    - PDO 11
    - INJ 0
    - FAT 1
- Relevant crashes in the After Period – 6 PDO, 0 INJ, and 1 FAT
- Estimation of benefits of reduction in Overturning and Fixed Object Crashes related to guardrail construction (Life Cycle 20 years)
    - INJ 6 – 0 = 6 INJ crashes prevented in 5 years = (100% Reduction) = (1.20 crashes per year) → Life Cycle Benefit = (1.20) ($80,700) (20 years) = $1,936,800
    - FAT 3 -1 = 2 FAT crashes prevented in 5 years = (67% reduction) = (0.40 crashes per year) → Life Cycle Benefit = (0.40) ($1,500,000) (20) = $12,000,000
    - PDO 10 – 6 = 4 PDO crashes prevented in 5 years = (40% reduction) = (0.80 crashes per year) → Life Cycle Benefit = (0.80) ($9,300) (20) = $148,800
- Total benefit over the life cycle is $1,936,800 + $12,000,000 + $148,800 = $14,085,600 based on observed crash reduction.
- If expected CRFs from the FHWA clearing house are used (40% reduction for INJ, 60% for FAT and 20% for PDO) to estimate future safety benefits, they can be computed as follows:
    - INJ $\frac{6\ crashes\ (0.4)}{5\ years}$ 20 years ($80,700) = $774,720
    - FAT $\frac{3\ crashes\ (0.60)}{5\ years}$ 20 years ($1,500,000) = $10,800,000
    - PDO $\frac{10\ crashes\ (0.2)}{5\ years}$ 20 years ($9,300) = $74,400
- Total life cycle benefit estimated using the FHWA Clearing House CRF = $774,720 + $10,800,000 + $74,400 = $11,649,200

In this case, observed benefit is somewhat higher than predicted using CMF; nevertheless, the CMF prediction represents a reasonable estimate of what to expect following deployment of guardrail and would be considered conservative for this site.

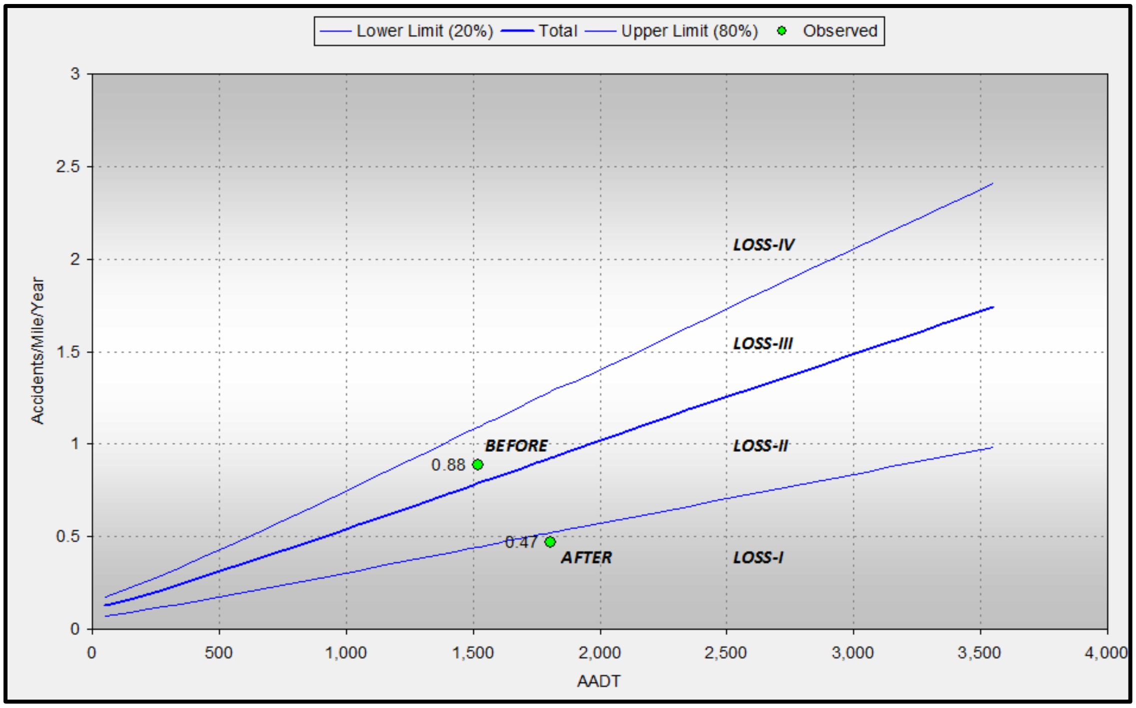

Figure 24. SH 133 MP 46.00–51.50 SPF EB Corrected Frequency Graph Before and After

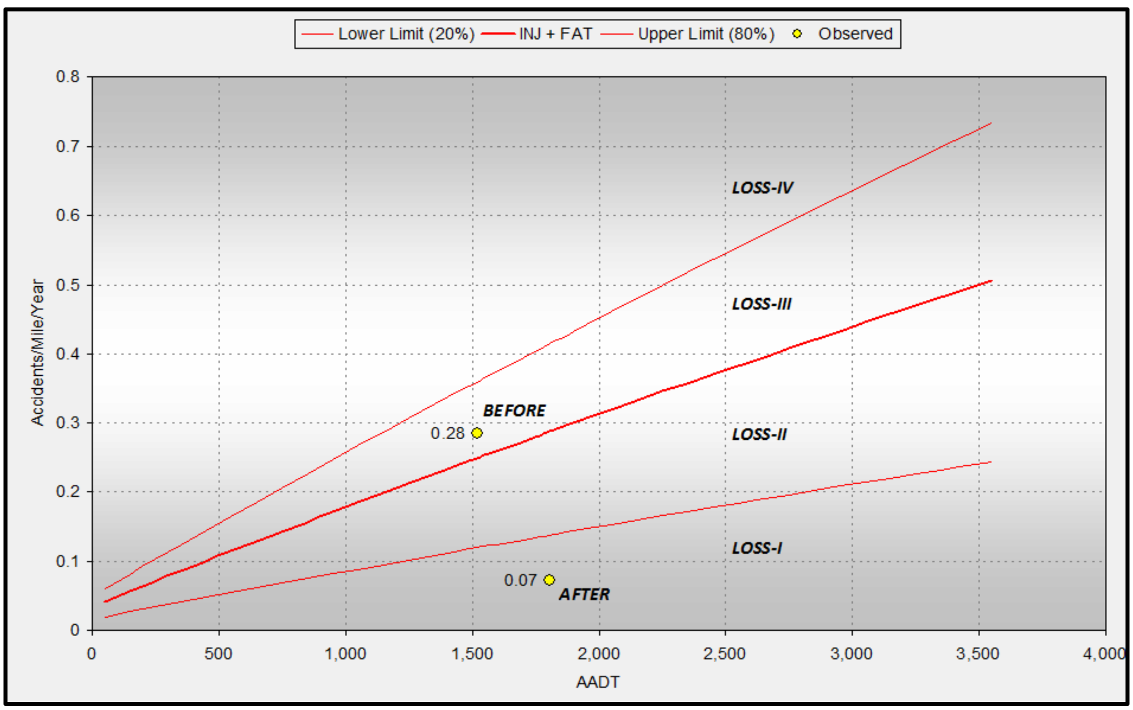

Figure 25. SH 133 MP 46.00–51.50 SPF EB Corrected Severity Graph Before and After

Overall safety performance of SH 133 MP 46.00 to MP 51.50 has changed from the low range of LOSS III (Moderate to High Potential for Crash Reduction) to LOSS I (Low Potential for Crash Reduction) from both frequency and severity standpoints. It is of interest to know that in the Before Period the segment performed close to normal, yet a correctly diagnosed pattern of roadway departure crashes led to a highly effective countermeasure; in this case, construction of guardrail. This demonstrates that the key to effective safety planning is the ability to discern the nature of the problem through diagnostic analysis, which provides an important clue to the development of effective countermeasures.

Case History Conclusions

Examination of these before and after case histories suggests that using the reliable CRF/CMFs will lead to effective estimation of future safety benefits. Although the CRF/CMFs contain some inherent degree of uncertainty, they represent the best science-based estimate of what will happen after construction and should be viewed as a standard tool for SCP. Using SPFs provides a frame of reference for the assessment of the magnitude of the safety problem; however, diagnostic examination leads to the selection of an appropriate countermeasure and its related CRF/CMF.

CHAPTER 6 – HOW TO RANK FUTURE SAFETY BENEFITS OF PROJECTS

Chapter 5 described how to quantify future safety benefits of a project by using CRF/CMFs once the nature of the problem has been identified. This chapter will address how to rank safety components of different projects in such a way that projects with the most cost-effective safety scope are assigned the highest score. Cost-effectiveness will be measured by how many crashes can be prevented, expressed in dollars per unit of investment into construction of safety improvements. To explore how this can be done, we will use the three case histories already examined and add two others involving urban freeway corridors where the improvements are not yet constructed. We will then consider a methodology of how best to rank these five (5) projects from a safety standpoint using diagnostic methodology and the CRFs. The two additional locations are:

- Case History 4, I-25 in Pueblo, MP 96.00 to MP 100.00
- Case History 5, I-70 in Grand Junction, MP 28.00 to MP 32.00

Case History 4

I-25 in Pueblo, MP 96.00 to MP 100.00 (**Figure 26**)

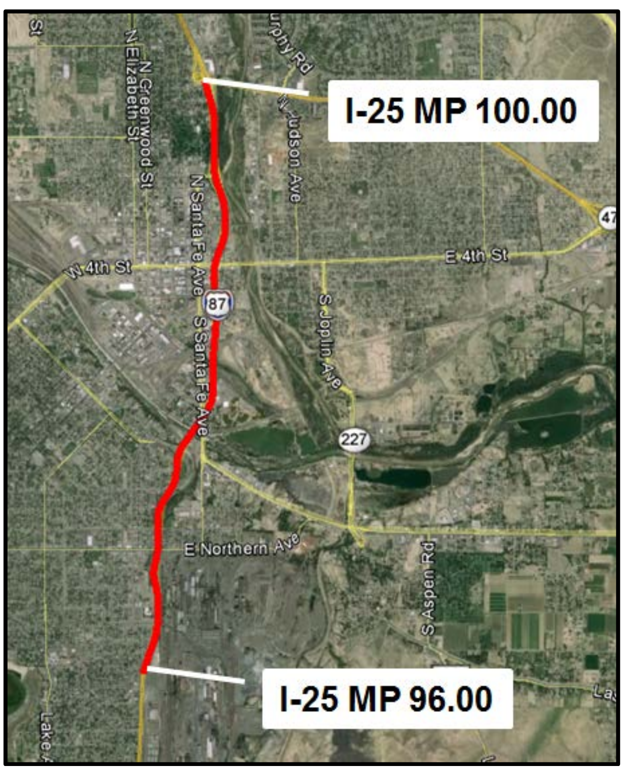

Figure 26. I-25 in Pueblo

- Crash history over a five-year period 2010–2014
  - PDO 400
  - INJ 183
  - FAT 4
- Safety performance during the study period was at LOSS IV from the frequency and severity standpoints, reflecting high potential for crash reduction (**Figure 27 and Figure 28**).
- Observed crash patterns that may susceptible to correction are:
  - Overturn and Fixed Objects
  - Rear end and Sideswipe Same Direction
  - Run Off Road

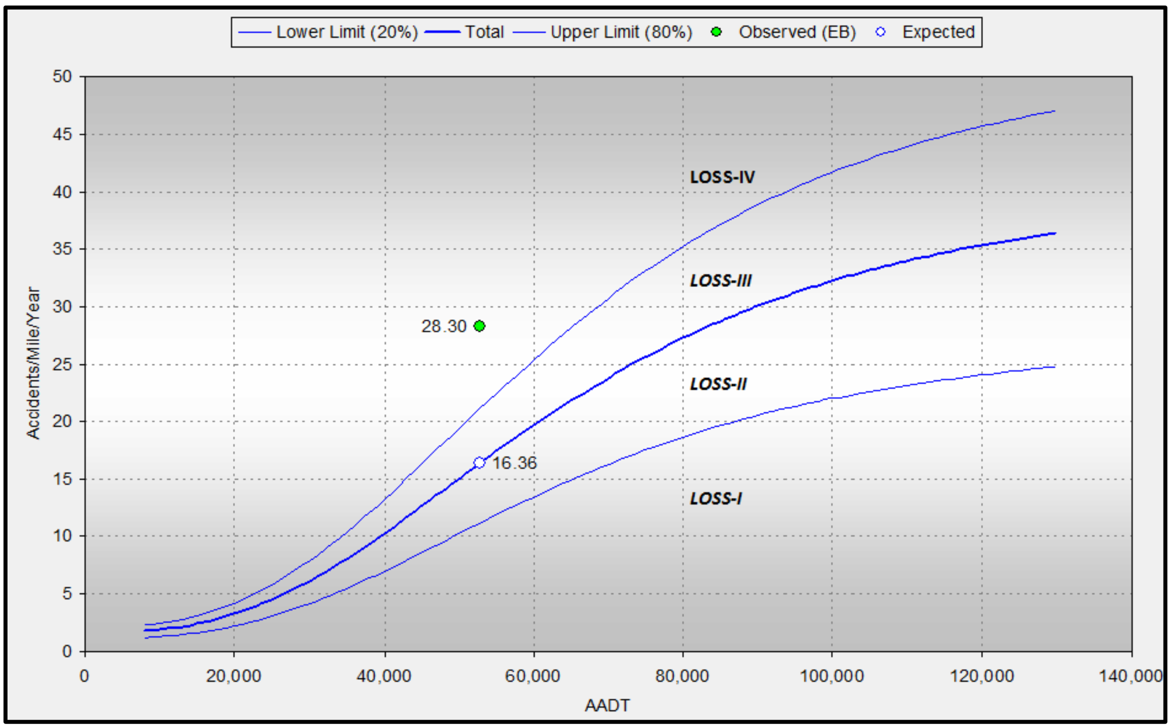

Figure 27. I-25 MP 96.00-100.00 SPF EB Corrected Frequency Graph

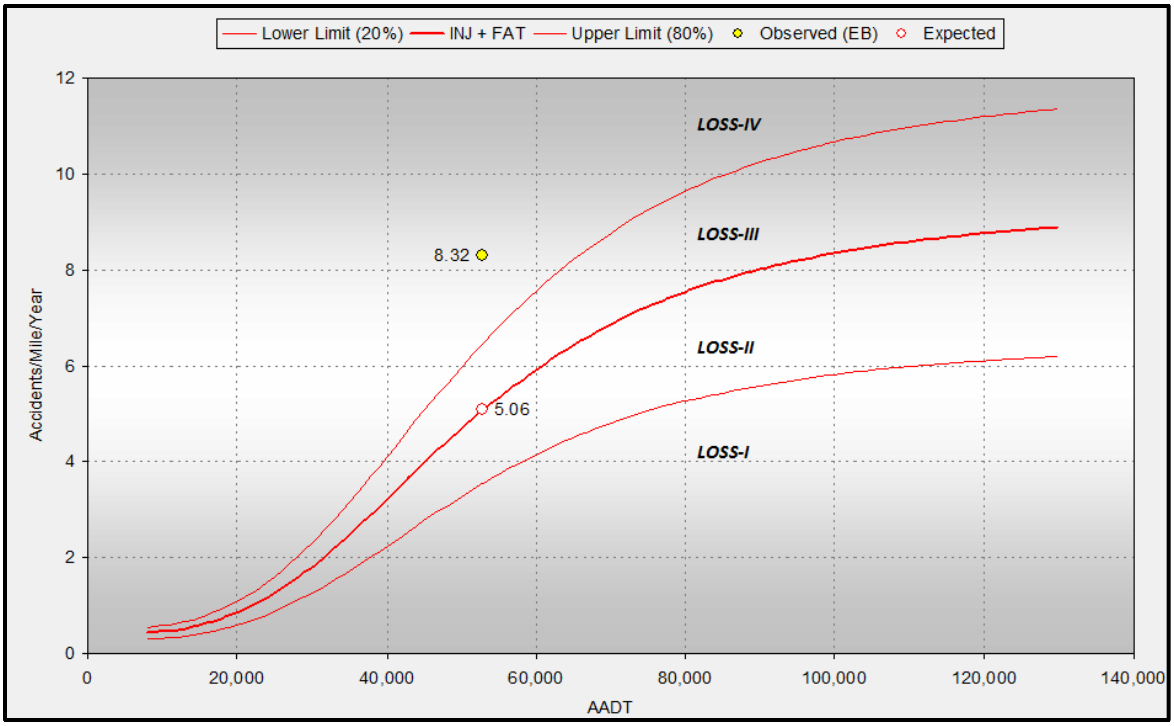

Figure 28. I-25 MP 96.00-100.00 SPF EB Corrected Severity Graph

- Overturn and Fixed Objects
  - PDO 180
  - INJ 91
  - FAT 3

Shoulder widening is generally considered an effective countermeasure to reduce overturning and fixed object crashes. CRF for shoulder widening is 20% for PDO, INJ, and FAT and the life cycle of improvement is 20 years. Total safety benefit can be estimated as follows:

$$\frac{180\ \text{PDO}(0.2)(\$9{,}300) + 91\ \text{INJ}(0.2)(\$80{,}700) + 3\ \text{FAT}(0.2)(\$1{,}500{,}000)}{5\ \text{years}}\ 20 years$$

$$= \$10{,}814{,}160$$

- Rear End and Sideswipe Same Direction
  - PDO 192
  - INJ 83
  - FAT 0

Rear end and Sideswipe Same Direction crashes on an urban freeway corridor can be reduced by increasing interchange spacing and metering on-ramps. Related CRF is 30% for PDO, INJ, and FAT and the life cycle of improvement is 20 years. Total safety benefit can be estimated as follows:

$$\frac{192 \text{ PDO}(0.3)(\$9{,}300) + 83 \text{ INJ}(0.3)(\$80{,}700)}{5 \text{ years}}\, 20 years = \$10{,}180{,}444$$

- Run Off Road Crashes
  - PDO 180
  - INJ 87
  - FAT 2

Crashes involving running off the road are susceptible to correction through realignment. Related CRF is 35% for PDO, INJ, and FAT and the life cycle of improvement is 20 years. Total safety benefit can be estimated as follows:

$$\frac{180 \text{ PDO}(0.35)(\$9{,}300) + 87 \text{ INJ}(0.35)(\$80{,}700) + 2 \text{ FAT}(0.35)(\$1{,}500{,}000)}{5 \text{ years}}\, 20 years$$
$$= \$16{,}372{,}860$$

Total life cycle benefit estimated using the FHWA Clearing House CRF = \$10,814,160 + \$10,180,444 + \$16,372,860 = \$37,367,464

Case History 5

I-70 in Grand Junction, MP 28.00 to MP 32.00 (**Figure 29**)

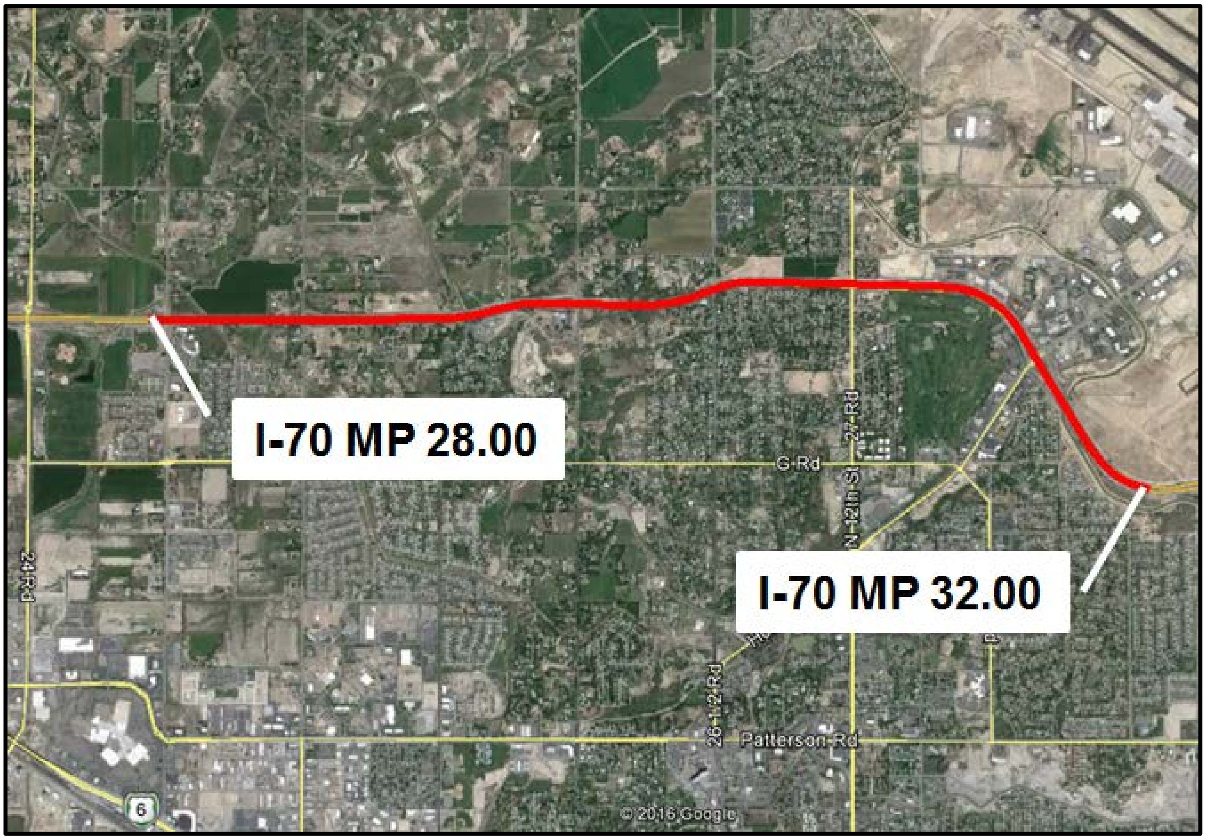

Figure 29. I-70 in Grand Junction

- Crash history over a five-year period, 2010–2014
  - PDO 58
  - INJ 31
  - FAT 2
- Safety performance during the study period was in the low range of LOSS IV from the frequency and severity standpoints, reflecting a high potential for crash reduction (**Figure 30 and Figure 31**).
- Observed crash patterns that may be susceptible to correction are:
  - Overturning
  - Fixed object crashes not involving collisions with an existing barrier or a bridge rail

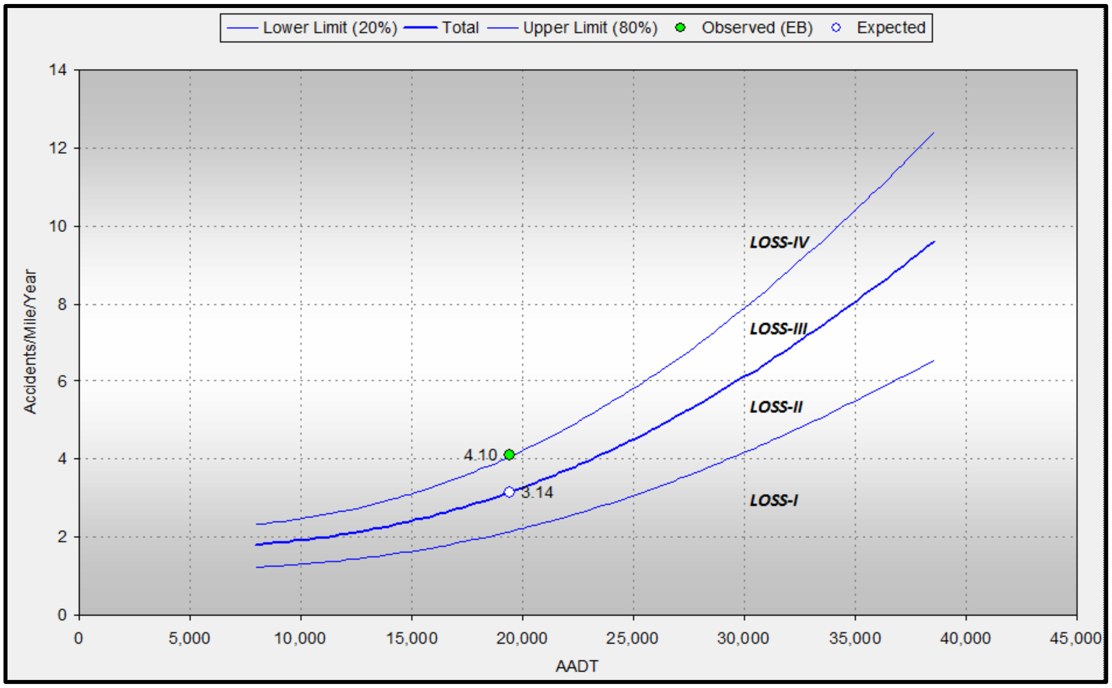

Figure 30. I-70 MP 28.00-32.00 SPF EB Corrected Frequency Graph

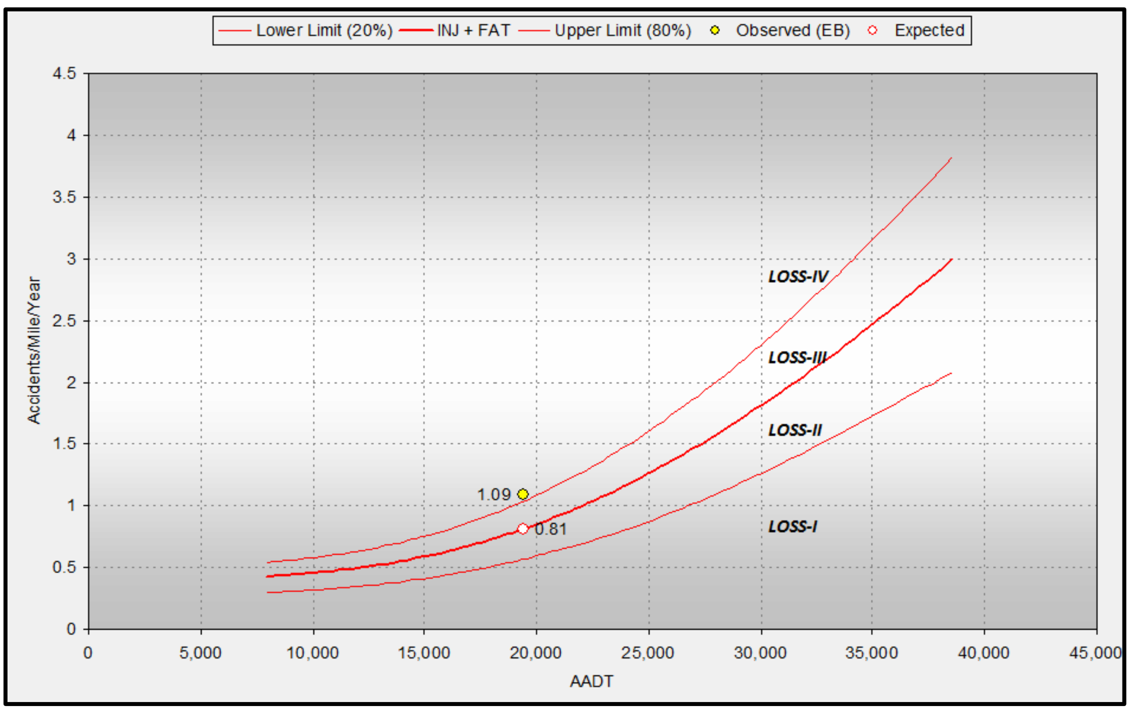

Figure 31. I-70 MP 28.00-32.00 SPF EB Corrected Severity Graph

- Overturning and fixed object crashes not involving collisions with an existing barrier or a bridge rail
  - PDO 19
  - INJ 20
  - FAT 1

In this case shoulders are already of standard width. To address identified problems, construction of a median barrier and additional guardrail are expected to be effective countermeasures with CRF of 20% for PDO, 40% for INJ, and 60% for FAT crashes with the life cycle of improvement of 20 years. Total safety benefit can be estimated as follows:

$$\frac{19 \text{ PDO}(0.20)(\$9{,}300) + 20 \text{ INJ}(0.40)(\$80{,}700) + 1 \text{ FAT}(0.60)(\$1{,}500{,}000)}{5 \text{ years}}\ 20 years$$

$$= \$6{,}323{,}760$$

Case History Summary

Now that safety benefits have been quantified for five projects, we are able to compare them to each other from the safety standpoint and rank them by the amount of expected safety improvement expressed in dollars (**Table I**).

Table I. Ranked by Benefit

Ranking	Project Name	Benefit	% of Max	LOSS Total	LOSS, I+F
1	I-25 in Pueblo	$37,367,464	100%	IV	IV
2	Havana and Mississippi	$13,183,200	35%	IV	IV
3	McClure Pass	$11,649,200	31%	III	III
4	Leetsdale and Quebec	$7,024,050	19%	IV	IV
5	I-70 in Grand Junction	$6,323,760	17%	IV	IV

These projects are different in scope and located in different environments, yet using this methodology, we can evaluate and rank their respective safety benefits quantitatively, which is important in the planning process. Among the five projects under consideration, major urban freeway corridor improvements on I-25 in Pueblo are expected to produce the largest safety benefits of $37,367,464 derived over the life cycle of 20 years. Guardrail construction on I-70 in Grand Junction is expected to yield the lowest at $6,323,760 over the same time period. Even though freeway corridor improvements in Pueblo are expected to produce the largest safety benefit, it does not necessarily mean that they will produce the largest benefit per unit of resources required to construct the improvements. The guiding principle behind effective highway safety management is that the money goes where it achieves the greatest safety effect. To evaluate the cost-effectiveness of each project, we will now consider the cost of these improvements, as well as the benefits of crash reduction. The estimate of the expected cost at the planning phase is inherently preliminary; nevertheless, it provides a way to inform the decision-making process on potential cost-effectiveness of project selection from the safety standpoint. **Table J** provides the cost of construction and safety benefit of the five projects examined previously.

Table J. Safety Benefits and Construction Costs

Ranking	Project Name	Safety Benefit	Construction Cost	LOSS Total	LOSS, I+F
1	I 25 in Pueblo	$37,367,464	$400,000,000	IV	IV
2	Havana and Mississippi	$13,183,200	$1,000,000	IV	IV
3	McClure Pass	$11,649,200	$700,000	III	III
4	Leetsdale and Quebec	$7,024,050	$450,000	IV	IV
5	I 70 in Grand Junction	$6,323,760	$900,000	IV	IV

One possible way to develop a scoring methodology of safety components is to a develop a ranking system based on computing how much safety benefit can be derived for every $1,000 of construction. For instance, for Leetsdale and Quebec, with a safety benefit of $7,024,050 and a cost of construction of $450,000, this score can be computed as follows:

$$\frac{7{,}024{,}050(1{,}000)}{450{,}000} = 15{,}609$$

Considering that CDOT is now Moving Toward Zero Death, it may be appropriate to name this score a Life Preservation Effectiveness (LPE) score. The higher the LPE score, the greater the effect on crash reduction for every $1,000 spent on construction. **Table K** lists these same projects ranked by their LPE scores. The project with the highest LPE score among the five we examined is the construction of guardrail on McClure Pass. Even though I-25 in Pueblo is expected to produce the greatest safety benefits, its LPE is the lowest, reflecting the fact that it will produce the lowest crash reduction per dollar spent on construction. Among the five projects, McClure Pass had the best LOSS, emphasizing the fact that the presence of crash patterns susceptible to cost-effective correction may or may not accompanied by elevated frequency and severity of crashes. LOSS provides a quantitative assessment of the magnitude of the problem; diagnostics, however, provide a more direct link to understanding crash causality and subsequent development of the countermeasures.

Table K. Life Preservation Effectiveness Score Ranking

Ranking	Project Name	LPE Score	Safety Benefit	Construction Cost	LOSS Total	LOSS, I+F
1	McClure Pass	16,642	$11,649,200	$700,000	III	III
2	Leetsdale and Quebec	15,609	$7,024,050	$450,000	IV	IV
3	Havana and Mississippi	13,183	$13,183,200	$1,000,000	IV	IV
4	I-70 in Grand Junction	7,026	$6,323,760	$900,000	IV	IV
5	I-25 in Pueblo	93	$37,367,464	$400,000,000	IV	IV

CHAPTER 7 – HOW TO BRING SAFETY TO A COMMON DENOMINATOR WITH OTHER PROJECT GOALS

As stated previously, this research project focuses on developing a methodology for explicit and effective consideration of safety in the planning process. It is important to note, however, that only a small percentage of projects (4 percent or less in Colorado) are exclusively safety motivated and funded. Most projects are aimed at mobility, pavement preservation, maintenance, improved air quality, operations, in addition to safety. Safety consideration is present explicitly or implicitly in most transportation infrastructure projects and the question becomes how to bring safety to a common denominator with other project goals. The concept of a LPE score provides planners with this capability. It reflects how many safety benefits can be derived per unit of expenditure, and if the same approach is adapted to other important project goals, then each project within a planning region can be effectively compared with others on the merits of its combined benefit.

Assuming that mobility and air quality benefits can be expressed in dollars, similar to the way safety benefit was handled earlier, let's examine a hypothetical example. Major Corridor Project A, with construction cost of $900,000,000, is projected to have the following benefits expressed in dollars over its life cycle:

- Safety = $180,000,000
- Mobility = $420,000,000
- Air Quality = $50,000,000

Major Corridor Project B, with construction cost of $410,000,000, is expected to produce a different set of benefits over its life cycle listed below:

- Safety = $120,000,000
- Mobility = $360,000
- Air Quality = $80,000,000

A composite benefit consisting of per unit of investment in safety, mobility and air quality can be computed as follows:

$$\text{Composite Benefit Project A} = \frac{(180{,}000{,}000+420{,}000{,}000+120{,}000{,}000)(1{,}000)}{900{,}000{,}000} = 800$$

$$\text{Composite Benefit Project B} = \frac{(120{,}000{,}000+360{,}000{,}000+80{,}000{,}000)(1{,}000)}{410{,}000{,}000} = 1{,}366$$

Based on the above analysis, Corridor Project B is expected to produce a higher benefit per unit of investment than Corridor Project A. As such, it should be given a higher priority ranking in the planning process. It is important to acknowledge that the actual planning process is influenced by not only scientifically estimated objective benefits and costs, but also the availability of funding, political climate, and other intangible factors. Nevertheless, with all other things being equal, the proposed methodology provides a quantitative framework for decision makers in selecting and ranking transportation projects.

CHAPTER 8 – FINANCIAL CALCULUS OF CRASH REDUCTION

In 2015, CDOT adopted the Moving Colorado Toward Zero Deaths (TZD) initiative, which states as its goal the intention to significantly reduce fatal crashes in the State of Colorado at some future date. To be effective, a safety plan should link expenditures and expected safety improvement outcomes, recognizing that some degree of uncertainty may exist about the magnitude of actual crash reductions, cost of construction, and traffic exposure.

The question then becomes how much money does it cost to prevent one traffic fatality per year? With this information in hand, it would become possible to develop a financial plan aimed at an accepted annual fatal crash reduction. According to the National Safety Council 2015 update, the cost of a fatality is about $1,500,000.

For simplicity sake, let’s dispense with interest rate and the annual increase in VMT for now. If we construct a highway safety improvement project that prevents one fatality per year over its service life of 10 years, we will then realize a societal benefit of $15,000,000 (cost of 10 prevented fatalities) over a 10-year period. It is important to note that the benefit only begins once the improvement has been constructed.

If we select projects in such a way that following construction we can observe a benefit/cost ratio (B/C) of 3, then the cost of this improvement should be $5,000,000 spent in year one. In other words, a one-time cost of $5,000,000 in construction will prevent one fatality per year for 10 years.

$(\$1{,}500{,}000\ x\ 10\ Years)/3 = \$5{,}000{,}000$

If our goal is to prevent 10 percent of fatalities per year on our road toward zero death and there are 500 highway fatalities per year in Colorado, to achieve the 10 percent reduction goal, we need to prevent 50 fatalities annually:

10% (500) = 50 fatalities

Considering that it costs \$5,000,000 to prevent one fatality per year, it will take \$5,000,000 x 50 = \$250,000,000 to prevent the 10 percent of fatalities annually.

This would be a good place to note that CDOT's Annual HSIP budget is only around \$40,000,000.

It seems apparent that a 10 percent reduction in fatalities annually is not within our grasp. Let's go through the same exercise and estimate how much it would take to achieve 5 percent fatality reduction annually. Obviously to achieve 5 percent fatal crash would cost half as much.

\$125,000,000, which is about 10 percent of CDOT's budget

Is it reasonable to expect to be able to spend 10 percent of CDOT's budget on safety? This is not an easy question to answer, even in the climate of the Toward Zero Death initiative. Clearly, the expenditure of \$117,500,000 annually is well beyond current annual HSIP; however, each construction project presents an opportunity for cost-effective safety improvements that are consistent with the intent of the project scope. When all branches of CDOT and its planning partners are working toward achieving the important and ambitious goal of reducing 5 percent of the fatalities annually, achieving this goal can become a reality. For instance, scheduled maintenance, pavement preservation, rehabilitation, reconstruction, major widening, realignment projects, pedestrian and bicycle improvements, police enforcement, and education all have the significant potential to reduce crashes, within constraints of available budgets, when this potential and needs are identified at the planning phase. The data-driven approach to solving safety problems presented in this report is based on Colorado-specific predictive and diagnostic tools. These analytical tools are intended to be used in providing safety decision support analysis, not only on safety motivated projects identified in HSIP, but on *all* projects planned in Colorado.

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