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Evaluating Benefits of Stratifying Cost of Injuries by Severity in CDOT Benefit-Cost Analysis

Gillian McCarthy, P.E., DiExSys
Jake Kononov, Ph.D., P.E., DiExSys

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16. Abstract

The aim of this study was to investigate whether stratifying the degree of injury by severity and assigning specific dollar costs to each severity level would enhance the quality of project selection. The results strongly suggest a distinction between a composite and a stratified approach in allocating injury crash costs within a Benefit Cost Analysis (BCA). Additionally, the study evaluates various options and proposes recommendations for a suitable value to represent the worth of a statistical life in BCA for highway safety projects. The key finding of the report is that adopting a stratified approach for assigning injury crash costs facilitates a more sensitive and comprehensive BCA. This, in turn, promotes more effective resource allocation through improved project selection and contributes to the overarching objective of enhancing highway safety.

Implementation:
Building upon the study's findings, the Colorado Department of Transportation (CDOT) has decided to incorporate the stratification of injury severity in the BCA process for prioritizing project selection. This procedural shift in BCA may potentially redirect additional resources towards rural projects where higher levels of crash severity are observed or those projects with a history of crashes involving vulnerable road users.

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Executive Summary

The aim of this study was to determine whether stratifying the degree of injury by severity and assigning specific dollar amounts to each severity level would enhance the quality of project selection and, consequently, road safety in Colorado. The research commences with a review of existing literature on benefit-cost analysis (BCA) in highway safety. The literature review has identified current challenges to BCA as a tool, including the inconsistencies in the nationally recognized value of a statistical life (VSL). Despite its challenges, however, it is generally accepted that a data-driven approach, such as BCA, should be employed in resource allocation to enhance safety on the nation's roads. While crash cost estimate sources generally align across states, there is significant variability in the employed injury level scales, as well as in the conversion and adaptation between these scales, and in the weighting of injury levels. The importance of resolving the impact of the injury level scale on crash cost estimation has been recognized as beneficial nationally in terms of safety BCA.

Subsequent to the literature review, an examination of the cost of injuries occurring in various facilities and environments in Colorado was conducted. This examination involved statistical testing to determine whether there is a distinction between the current composite injury cost approach to BCA employed by CDOT and a stratified approach to assigning injury costs. The results of this examination strongly reject the null hypothesis across all categories at the 99% confidence interval. This analysis suggests that the severity of injuries resulting from crashes varies depending on the environment, type of facility, crash type, and level of congestion. We recommend that these differences be systematically quantified and considered to inform BCA and be incorporated into resource allocation decisions. The key finding of the report is that implementing a stratified approach for assigning injury crash costs facilitates a more sensitive and comprehensive BCA. Its implementation may potentially redirect additional resources towards rural projects where higher levels of crash severity are observed or those with a history of crashes involving vulnerable road users.

With regard to the VSL which could be incorporated into BCA we recommend that CDOT adopt the average economic cost value set by the National Safety Council ($1,750,000 in $2020). While this is not a perfect solution to a complex and sensitive issue, it is a sensible and rational one that ensures the cost of a fatal injury crash, a tragic but random and generally rare event is within the same order of magnitude as other crash levels, thus preventing skewed outcomes that would make resource allocation less effective. Ultimately, a more sensitive data-driven approach will enhance the quality of project selection and road safety in Colorado.

Implementation Strategy

To implement the findings of this report into CDOT’s procedures and methodology it is expected that safety management software used by CDOT to conduct BCA will be modified to use stratified cost of injuries and VSL recommended in this report.

Chapter 1 – Introduction and Literature Review

It is generally accepted that a data-driven approach should be used in deciding how best to allocate resources to improve safety on nation's roads. Cost-benefit analysis is one such data-driven tool which assists decision making when it comes to safety projects. The definition and cost of serious injuries is one critical data component in the cost-benefit analysis. Limited resources and competing needs, dictate that funding must be optimized and allocated to safety projects in a way that is most cost-effective. To better understand the current practices in cost-benefit analysis of highway safety projects, and the potential benefits of stratifying the cost of an injury crash by degree of severity, we undertook a review of extant literature on the topic of cost-benefit analysis as it relates to highway safety and of the current practices across 10 state jurisdictions. The review is organized into two parts:

- An examination of extant literature related to cost-benefit analysis for highway safety and
- A summary of the practices in the state DOTs of Alabama, California, Louisiana, Montana, Oklahoma, Oregon, South Dakota, Texas, Washington, and Wyoming.

The review of literature and a state-by-state summary of current practices will be followed by a brief summary of our findings.

Literature on the Topic of Cost-Benefit Analysis related to Highway Safety

Elvik, R. *How to Trade Safety Against Cost, Time and Other Impacts of Road Safety* (2019)

In a recent paper in *Accident Analysis and Prevention* Elvik discusses the necessity of making decisions, compromises, and trade-offs when it comes to formal policy analysis and asserts that the way in which these are achieved does not have to be fixed in the method of converting everything into monetary terms. While he recognizes the attraction of Cost-Benefit Analysis (CBA) in finding the right balance between safety and other objectives, he argues it "cannot deliver what it promises." Elvik goes on to more closely evaluate CBA as it relates to road safety.

CBA and Road Safety

Elvik argues one shortcoming of CBA is the controversial converting of life and limb to a monetary value to compare objectives, criticizing the uncertainty and wide variability of this value to date, highlighting a failure to converge on a single acceptable value. According to Elvik the resulting "rough estimates" provide cause to doubt the justifiability and the assumptions that went into obtaining values, did they ever reflect public preference? As such, Elvik rejects valuation studies. Elvik illustrates by example that as the value of a fatality increased, the optimal number of reduced fatalities increased, as did the cost of the budget required to achieve the reduction. He states the value placed on a road fatality therefore "makes a big difference with respect to how much government ought to spend on road safety according to cost-benefit analysis and how far down this will bring the number of fatalities."

Other Options

Elvik compares multicriteria analysis (MCA) and CBA. MCA uses a hierarchy and relative scoring mechanism. He asserts MCA is more flexible than CBA because it can include criteria which are not economic to begin with (such as life and limb), allows for doubt, and allows a budget to be the binding constraint, so it can tell when something becomes too expensive. There are few applications to date in road safety. Elvik provokes some thought, proposing any technique of policy analysis which involves public or policy maker input which is solicited by analysts is at risk of the analyst influencing the results.

Elvik considers the health life-cycle approach which utilizes estimates of 'Disability Adjusted Life Years' (DALYs) which, we are told are less variable than the value of a fatality. Elvik admires the factual nature of this approach, removing the need to monetize value judgments, and that DALY scores of severe and lifelong impairments tend to resemble one another across studies, (unlike the value of a life lost), as well as the visual expression of the approach, allowing easy depiction of uncertainty and overall contribution of criterion. This approach would seem attractive in that it removes the value or preference judgments made by analysts.

Elvik discusses his own prior research and that of Furberg et al. involving the health life-cycle approach in regard to road safety. His argument in favor of the approach is supported if we agree with his perspective that selecting positive changes in DALYs to estimate the impact of a measure is a good thing by the reasoning that reducing DALYs is equivalent to shortening lifespan and reducing a health state. Elvik asserts that road safety measures ranked by gains in DALYs could be an alternative to CBA in supporting policy setting. There is an argument however, that although a health life-cycle approach presents facts, the decision on which facts to present is based on values. Elvik's counterargument is that the impacts of road safety expressed as DALYs should be less controversial than a monetary amount assigned to the value of a fatality.

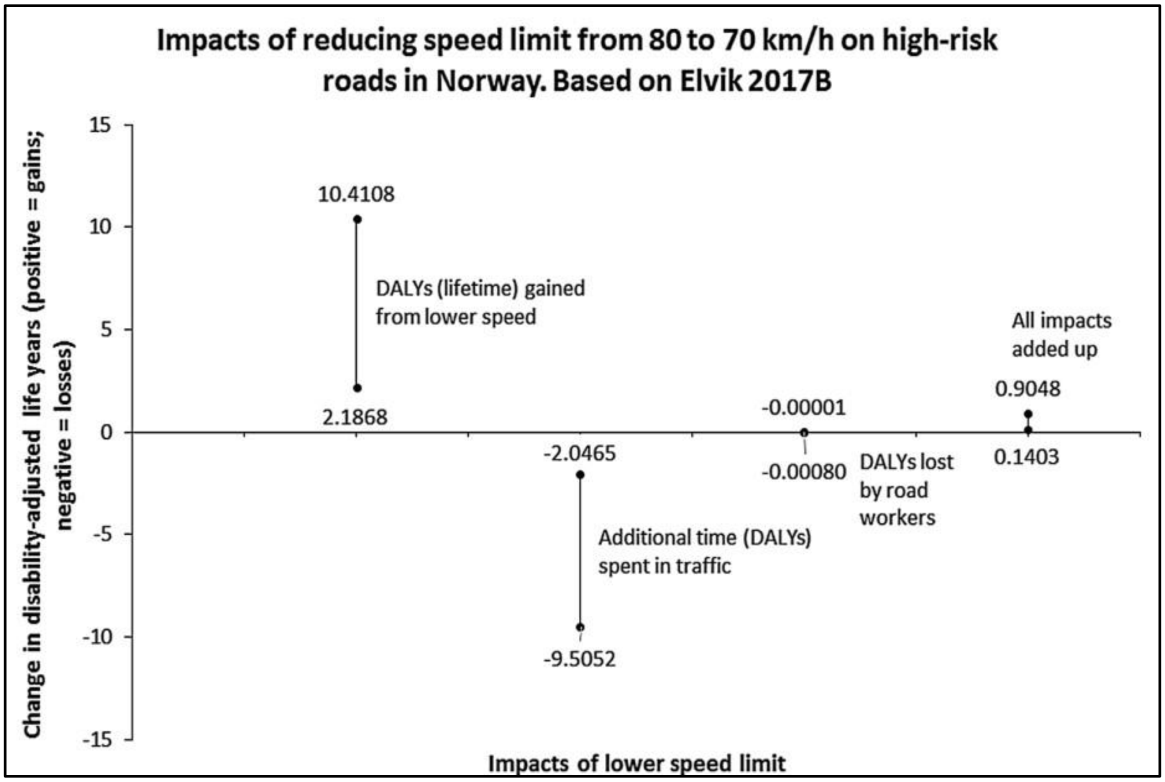

Figure 1.1: Elvik, Health Life-Cycle Approach, Depiction of Changes in DALY Values

This paper considers some of the contemporary arguments against CBA and suggests a health life-cycle approach as an alternative tool for policy decision making.

Elvik, R. *The Value of Life – The Rise and Fall of a Scientific Research Program* (2016)

In 2016 the Norwegian Centre for Transport Research published a report by Elvik which is a critical assessment of the developments in the field of valuations research since the 1970s regarding the use of and methodologies behind cost-benefit analysis as a tool with which to prioritize policy objectives. Elvik asserts that improved road safety has a monetary value to society, based on the valuation of a statistical life, a valuation which has increased in variability over time. In the report, Elvik assesses various common approaches to the valuation of a life such as the willingness-to-pay approach and the QALY scale. The QALY (Quality Adjusted Life Year) while not entirely dissimilar to the AASHTO KABCO scale in terms of injury severity is not recommended by Elvik as a basis for valuation of safety when it comes to injury types due to the variation between the methods of obtaining a QALY value, which result in inconsistent and non-identical values.

This work recognizes that life must have an explicit monetary value to make trade-offs between objectives, and that uniformity of that value is important and assists in comparing objectives and prioritizing resources.

Harmon et al. *Crash Costs for Highway Safety Analysis*. (2018)

In 2018 the FHWA published a guide on the use of crash unit costs in highway safety analysis, which synthesized current practices in 42 states responding to a survey questionnaire on crash unit cost estimation, and summarized the issues related to cost estimation and application. The guide points to advantages of nationalizing a set of crash costs such as consistency in decision making. The "great disparity" between the crash unit costs employed across the states is highlighted here.

The guide makes a distinction between tangible crash costs, quantified economically, and intangible costs, such as pain and suffering, which are more difficult to quantify economically, but suggests using Quality Adjusted Life Years (QALY) assists in this quantification. It outlines the development of crash cost scales by FHWA, AASHTO, NHTSA and the National Safety Council, in which comprehensive (tangible plus intangible) crash costs are used but does not consider if the QALY crash unit costs, which have been derived from a 'willingness-to-pay' approach, might already include consideration a person has given to lost wages, etc. and in that sense might be a doubling up of crash cost estimates.

The guide informs us that 72% of the 42 respondent states use either crash cost values from the HSM, injury costs published by the NSC or guidance on the VSL published by the U.S. DOT. A summary of crash costs across 33 states was included in the guide (see below), some states could not be included due to omissions in data provided.

Severity	Minimum Cost	Mean Cost	Maximum Cost
K	$190,200	$4,288,422	$10,100,000
A	$89,200	$781,094	$3,300,000
B	$0	$174,335	$955,500
C	$0	$98,188	$955,500
O	$0	$10,582	$42,298

Figure 1.2: Harmon et al. Crash Unit Cost Summary of 33 States

About a third of respondent states reported using values directly from those sources mentioned above, while just under half reported adapting those cost values in some way. About two thirds of states responding use crash unit costs and 14% use person-injury costs, with 20% using both. Most respondents, 61% appear to use comprehensive crash costs with just over 20% using only economic costs and under 20% using both. Clearly procedures across the states have a wide range of variability. Another source of variability is that some states translate values between different injury level scales, while some do not employ a conversion and apply costs from one scale to injury levels from another.

The guide discusses the weighting of crash costs as part of cost estimation, a practice followed by most respondents. Approaches vary so much so that some states obtain values which represent combined severities, others which represent omitted severities and other values which are adjusted by preference. The guide stresses the importance of using accurate estimates for crash unit costs and recommends the costs of all crash severities and types be used in CBA. The guide also advocates that crash unit costs be applied to the number of crashes and person-injury unit costs be applied to the number of people involved in the crash.

The guide makes three assertions with importance to our review: firstly as crash costs vary more by severity than type, it is more important to account for severity as part of a BCA than for type; secondly that analysts performing BCA should adjust for crash costs between jurisdictions (states) such as cost of living, income levels, medical costs etc., when possible; thirdly "reconciling the impact of injury scale on crash cost is an important consideration for future crash cost estimates and for safety analysis in general."

Hauer, E. *Can One Estimate the Value of Life or is it Better to be Dead Than Stuck in Traffic?* (1994)

In an article in *Transportation Research Part A: Policy and Practice*, Hauer addresses the question of whether a computation is the best way to give legitimacy to policy decisions made on behalf of the public which involve a risk to life. Hauer uses a paper by McGee et al. from 1989 providing guidance on replacement of "STOP" signs at intersections by "YIELD" signs to make the point that by assessing the assigned monetized value of a life against the value of time (in terms of delays) in $/hr, there comes a point at which the monetized value of time lost in traffic delays at the intersection over several years is more than the monetized value of an average life lost (estimated at 37.3 years in the guidance), implying then the delay loss is worth more than the value of the life . Unsurprisingly people find this unsettling. However, he asserts that "we must accept that in decisions made on behalf of a public, the use of a finite value of life is legitimate" to permit functionality of governance and decision making, even if the idea does not sit well with us all.

The main body of Hauer's work focuses on the shortcomings of different approaches to the valuation of life and of risk assessments in both ideology and methodology. Hauer recognizes the difficulties in assigning a value to life: the subjective nature of the exercise, lack of consistency and reliability of inputs. For example, in terms of the revealed preferences economic method, we cannot expect people to have a preference when "one of the prospects involves one's own death." Therefore, basing the value of a life on what people say or how they choose is not especially useful for decision making.

Hauer emphasizes the problem in the traditional valuation approaches, that is the variability in people's beliefs, and the difficulty discerning between conclusions based on "uninformed opinions," or "guesses" and those based on "sound information" and "reflection." Hauer concludes with the assertion that there is not a benefit to having a common value of life across all domains unless certain conditions are met:

1. If budgeted money can get to the agency that can save a life at the lowest cost, then there is a value in declaring the lowest cost at which a life can be saved. This is independent of the value of a life.
2. All agencies' budgets are adjusted so that the cost of saving a life is the same in each agency and does not exceed a common value, in which case a common value of life based on revealed preferences is acceptable.

Hauer, E. *Computing What the Public Wants: Some Issues in Road Safety Cost-Benefit Analysis* (2010)

In this article published in 2011 in *Accident Analysis and Prevention*, Hauer argues that the cost-benefit analysis as a tool used to justify how public money is spent is flawed. He focuses on three aspects to those flaws: the wide variation in the value of a statistical life which is employed; the premises behind CBA are based in circumstances which are difficult to apply to road safety; the use of present values based on discounted future lives and time.

Hauer argues that with specific regard to road safety, the CBA computation involves questionable values (time savings are valued too highly against life) and a debatable method (discounting is diminishing the value of future lives, causing a bias against decisions for investment in road safety). Hauer asserts that the latter suggests "a statistical life lost next year has now less value than a statistical life lost this year."

Variation in the Value of a Statistical Life (VSL)

Hauer establishes that VSL estimates vary widely across research and outlines the evolution of DOT policy guidelines regarding VSL. He criticizes "meta-analysis" as a way to make estimates, which could be said to be essentially finding the median of a large, dispersed data set. His paper asserts that the VSL "depends on various factors some of which pertain to the state of the world" and expresses the idea of each intervention having its own VSL. Hauer claims decisions guided by a CBA will only maximize welfare if the VSL used in each reflects the specifics of the intervention at which the CBA is aimed.

Consistency between VSL and Value of Time (VOT)

The paper indicates that a road safety CBA must be able to compare money, time, freedom, and safety, and to do so must have a framework for an "exchange rate" between one and the other. Hauer discusses the U.S. DOT values of time. He reasserts the argument in his previous paper, regarding the absurdity of how the value of a life year can equal the value of delay time. Hauer states that the VSL and VOT recommended by guidelines are mutually inconsistent and that using inconsistent values of time and life ends up favoring time saving interventions at the expense of life. The computation only results in sensible decisions if the "unit values for life, injury and time are in the correct ballpark."

Discounting

Hauer outlines variability to the selection of discount rates and criticizes conversion of the expected VSL to present value by discounting, as devaluing a future life. Hauer explains how using an inappropriate discount rate, can lead to elevation of some projects while diminishing others. One can agree that consistent use of inappropriate discount rates leads to unreliable CBA conclusions. The overarching theme is reflected by the question, is it right to discount time and life? The other flaw Hauer draws attention to is that the VOT and the VSL change proportionally with income, which itself tends to increase over time. Hauer concludes with questioning the fairness in discounting methods and if concepts which are more ethical and political in nature should be a part of economics, essentially asserting the rationale used for discounting goods and services can't be applied to time and life.

This work highlights that there is a lack of consensus on the VSL, which means that guidance on their use could be inaccurate and result in consistently poor decisions. However, CBA as a tool need not be discarded but should be thoroughly tested to see if it provides what the public would choose in a given situation, otherwise it needs repairing.

Hauer, E. *Cost-Effectiveness in Road Safety – When is it a Way Out?* (2011)

In his 2011 Transportation Research Board (TRB) paper, Hauer lays out the fundamental difference between a Cost Effectiveness Analysis (CEA) and a Cost Benefit Analysis (CBA), that is that the latter must convert lives and injuries into dollars for means of comparison and the former must not, making it attractive. Hauer acknowledges some of the commonly discussed deficiencies around the CBA, which can cause misleading results. Regarding the CEA, Hauer's view is that if a safety measure can be expressed by one figure accurately and with legitimacy, it can be used to rank options, but under two conditions:

1. The countermeasures being assessed are expected to save accidents of the same severity or one countermeasure is superior to the other on all severity scores and
2. There is no question as to whether spending of funds on the best option is justified.

As these conditions are rarely met, he explores if compromises can be made to both.

The first anomaly he discusses it that single value indexing, that is assigning weights to each severity level (PDO, Injury, Fatality) to compare how many of accident type X are equal to one accident type Y. Hauer discusses the procedure across several different states as well as within the National Highway Traffic Safety Administration (NHTSA). Pointing at NHTSA's weighting procedure, (a ratio of injuries to fatalities then expressed as a percentage cost per 'equivalent life saved') Hauer asserts integrated weighting or indexing, has not removed the translation of life and limb into a dollar amount, it has just veiled the process. Therefore, this procedure has not really moved away from the problems surrounding assigning a value to a statistical life. Hauer summarizes in order for a CEA to be workable it must employ an acceptable set of weights, which cannot be done without assigning a monetary value to life and limb and states of health, making its initial attractive characteristic redundant.

Hauer questions justification of spending as it relates to CEA. He illustrates his argument by way of example: if an amount X is deemed justifiable expenditure on a certain safety measure because of its cost-effectiveness ratio, then any other measure with a smaller price tag and cost-effectiveness ratio could be said to be automatically justifiable. The point is well made and because cost-effectiveness ratios vary widely, where the bar for justification lies at any time is not clear. Hauer concludes the question will always return to how much the greater public would be willing to spend to reduce the chance of death or injury on the road, and so the applicability of the CEA cannot be expanded.

This work asserts that unless a safety benefit can be expressed by a single number and there is no question if the expenditure is justified, then a CBA, rather than a CEA, is the only way to go, and we must consider the difficult task of assigning a dollar amount to life and limb.

Heath, J. *The Machinery of Government* (2020)

In his recent book, "The Machinery of Government," Heath dedicates a chapter to a discussion on the utilization of a cost benefit analysis as a means to decide on the "provision of public good" . The chapter generally defends-CBA as a tool to resolve collective problems. Heath makes the point that using money as a metric of value in a CBA is not merely for economics, but it ensures equality, by comparing apples to apples, so to speak.

Heath discusses use of CBA in a road safety policy-making scenario, emphasizing the goal of resource optimization for maximum return. He discusses contemporary arguments around the topic of morality when it comes to the valuation of life.

This work emphasizes that the value of a CBA is dependent on the quality of the inputs used for the analysis and the valuation of a life is a controversial feature of CBA but also a necessary feature.

National Academies of Science, Engineering and Medicine. *Development of a Comprehensive Approach for Serious Traffic Injury Measurement and Reporting Systems* (2021)

A recent report published by the National Academies of Sciences, Engineering and Medicine recognizing the goals of MAP-21 provides a guide to states for the development of measures of serious injury crashes. The report emphasizes the importance in consistently defining what is classed as a serious injury and states the definition should be based on medical diagnosis rather than definitions obtained through police reports.

The report provides a critical review of current common injury coding practices and systems across the states [KABCO, AIS (abbreviated injury scale) and SCD-CM (international classification of disease, clinical modification)]. Perhaps one of the expected critiques is the current anomaly with the commonly used KABCO system in transportation safety: the definitions for A/B/C level injury coding differ across the states. However, despite this failing, only the KABCO systems has readily available data for severity ranking metrics.

The conclusion and advice in the Academies' report is that a serious injury should be defined as that which falls into the category of MAIS level-3 and above. The Maximum Abbreviated Injury Scale (MAIS) characterizes injury types and is an anatomically based way of ranking injury severity. Ranking goes from level-1 to level-6, with level-1 being minor injuries and level-6 being maximal injury, it is generally accepted that MAIS level-3 is the cutoff for what is considered serious injury. The report asks the obvious question, if most states are using KABCO based definitions why not use 'A' as the standard measure of serious injury? The argument is that it may demotivate implementation of data linkage and introduce biased results. The report cites studies which point to variability in the use of the KABCO scale geographically, due to overestimation, underestimation, and misrepresentation of serious injuries. The Academies' report asserts that these failings could lead to "suboptimal allocation of countermeasures to prevent serious injuries" and instead proposes an interim solution: set MAIS 3+ as target definition for serious injuries and use existing data to estimate the number of serious injuries based on MAIS 3+ definition.

The major assertion of this report is that the most complete long-term solution for measuring serious injury is to link crash data to medical outcome data at a state level, to improve performance measures and meet the goals of MAP-21. This could be achieved for example by way of hospital discharge databases being used to count the number of serious injuries in a crash or taking samples of hospital records for crash subsets. The outcome would be the ability to evaluate roadway performance through the linkage of serious injury crashes and facility, crash, and vehicle types, as well as driver behavior.

As part of the report several surveys across the states were taken to get a better picture of current practices and those planned for future implementation. The results indicated that most states use a probabilistic linkage approach through a Crash Outcome Data Evaluation System (CODES) program, which identifies which cases in paired data sets refer to the same person, even if there is no personal identifier. Feedback from the 42 respondents showed that 41 states measure serious injuries as part of their transportation safety improvements. Thirty-three of 42 respondents use injury coding language like KABCO, others use unique definitions. Furthermore, results indicated that presently, most respondents are in the process of, or are planning to link crash data to hospital discharge data, about two thirds link or plan to link to EMS data, while under half link or plan to link to emergency department data. Unsurprisingly, about 90% link to roadway inventory databases, generally by direct deterministic means (using individual identifiers that can be matched among combined data sets).

The report's findings indicate that challenges to achieving data linkage sooner are mainly funding, confidentiality and data usage restrictions, as well as software/hardware infrastructure.

It is certainly agreeable that a more complete solution to measuring and recording serious injury crashes will better support the accuracy of inputs to the cost-benefit analysis. It seems there is promise to the roadmap that the Academies lay out in this report, with North Carolina showing success in developing an annually updated linked crash-EMS statewide database. While linkages like this are occurring in many states, they are still probabilistic. At present several states are implementing pilot programs to test crash-to-EMS linkage processes that are not probabilistic.

Summary of Practices Across 10 State Departments of Transportation

Alabama Department of Transportation

The state of Alabama uses the KABCO scale outlined in the AASHTO Highway Safety Manual (HSM). Crash costs are based on those in the HSM and updated to more current estimates using a 3% growth rate. Alabama stratifies by degree of injury but combines Fatal (K), Disabling (A) and Evident Injury (B) crashes under a single value as part of its benefit-cost calculations, so that differentiation is made only between Possible Injury and all other levels of injury/fatality. The societal cost of crashes as assigned and implemented by the state of Alabama is shown below.

Table 1.1: Alabama DOT Stratified Crash Costs ($2015)

Crash Type	Value ($2015)
FAT/Disabling INJ/Evident INJ (K/A/B)	$239,292
Possible INJ (C)	$67,915
PDO (O)	$11,193

California Department of Transportation (CALTRANS)

The state of California uses crash cost estimates based on the values set out in the Highway Safety Manual first edition and adjusts them to reflect current dollar values. The state follows the HSM procedures for cost-benefit analysis of projects. Caltrans stratifies injury costs according to both injury level and location type, in terms of intersection or roadway. The state uses the KABCO injury scale found in the HSM but combines Fatal (K) and Severe Injury (A) under a single severity level, which results in a four-tiered severity rating. The location type is differentiated only for Fatal and Severe Injury crashes, but not for other injury levels. The costs of crashes as assigned and implemented by the state of California are shown below in $2020.

Severity (S)	Crash Severity *	Location Type	Crash Cost ***
3	**Fatality and Severe Injury Combined (KA)	Signalized Intersection	$1,590,000
3		Non Signalized Intersection	$2,530,000
3		Roadway	$2,190,000
2	Evident Injury – Other Visible (B)		$142,300
1	Possible Injury–Complaint of Pain (C)		$80,900
0	Property Damage Only (O)		$13,300

Figure 1.3: California DOT Stratified Injury Costs ($2020)

Louisiana Department of Transportation and Development

The state of Louisiana stratifies its crash costs based on injury level, while using its own injury level scale with values from A through E, which assigns four injury levels, including fatal:

A – Fatal

B – Severe Injury

C – Moderate Injury

D – Complaint of Injury

E – PDO

Current crash costs were obtained from a 2016 study undertaken by the Center for Analytics and Research in Transportation Safety (formerly the Highway Safety Research Group) of Louisiana State University. Current crash costs are shown below.

Table 1.2: Louisiana DOTD Stratified Crash Costs ($2016)

Crash Type	Value ($2,016)
FAT (A)	$1,710,561
Severe INJ (B)	$489,446
Moderate INJ (C)	$173,578
Complaint INJ (D)	$58,636
PDO (E)	$24,982

Montana Department of Transportation

The state of Montana stratifies its crash costs based on five injury levels, as per the KABCO scale.

The following is an example taken from the 2018 FHWA publication, "Crash Costs for Highway Safety Analysis". The dollar year for the monetized values were unknown at the time of publication.

Table 1.3: Montana DOT Stratified Crash Costs

Crash Type	Value ($2,016)
FAT (K)	$5,628,500
Disabling INJ (A)	$298,700
Evident INJ (B)	$109,100
Possible INJ (C)	$61,600
PDO (O)	$10,000

Oklahoma Department of Transportation

The state of Oklahoma stratifies its crash costs according to injury level, with crash costs based on U.S. DOT guidance . The state equates MAIS (Maximum Abbreviated Injury Scale) scale injury severity levels set out in U.S. DOT guidance to KABCO severity levels and in this way uses the injury unit costs as the crash unit costs. The values in the MAIS scale are derived from the value of a statistical life which is adjusted annually for changes in prices and incomes and published by the DOT.

The stratified injury costs based on monetized $2016, as used by Oklahoma DOT are shown below.

MAIS	KABCO	Comprehensive Crash Unit Cost
MAIS 6	K	$9,600,000
MAIS 4	A	$2,553,600
MAIS 2	B	$451,200
MAIS 1	C	$28,800
MAIS 0	O	$4,200

Figure 1.4: Oklahoma DOT Stratified Injury Crash Costs ($2016)

Oregon Department of Transportation

The state of Oregon bases its crash costs on the 'cost-of-crash' values and procedures outlined in the first edition of Highway Safety Manual Appendix 4.A and adjusts them annually. Oregon uses the most characteristics out of the states reviewed in stratifying its crash costs for cost-benefit analysis, doing so by a combination of injury level, facility type and location (see below), using the KABCO severity level scale. The state combines injury levels as follows:

- Fatal (K) and Serious (A)
- Moderate (B) and Minor (C)
- PDO (O)

However, for pedestrian and bicycle projects as part of the ARTS program, Oregon uses a cost-effectiveness analysis to prioritize projects based on changes to crash frequency. A cost-effectiveness-index (CEI) estimates the cost to reduce one crash, the lower the index value, the higher the project is prioritized .

The costs of injuries stratified by severity, facility and location type used by the state are depicted below, shown in $2019.

Comprehensive Economic Value per Crash [2,3]		
Highway Type	Urban	Rural
PDO		
All facilities	$21,800	$21,800
Moderate (Injury B) and Minor (Injury C) Injury		
Interstate	$77,800	$89,200
Other State Highway	$80,800	$91,900
Off System	$81,300	$93,200
Fatal and Serious (Injury A) Injury		
Interstate	$1,530,000	$2,260,000
Other State Highway	$1,490,000	$2,140,000
Off System	$1,110,000	$1,940,000

Figure 1.5: Oregon DOT Stratified Injury Costs ($2019)

South Dakota Department of Transportation

The state of South Dakota does not stratify crash costs based on injury level, rather it differentiates between injury and non-injury crashes. As such, it combines Fatal and all other injury level crashes (K/A/B/C) under one cost and PDO under another.

Table 1.4: South Dakota DOT Crash Costs ($2013)

Crash Type	Value ($2013)
Fatal and All other Injury (K/A/B/C)	$374,724
PDO (O)	$17,528

Texas Department of Transportation

The state of Texas uses a Safety Improvement Index (SII) to perform cost-benefit analysis of proposed projects. The SII is a "ratio of the annual savings in preventable crash costs that have occurred at a location to the cost of constructing the proposed improvement." A project with an index value greater than 1.0 is considered cost-effective. The SII stratifies costs by injury level based on the KABCO scale, focusing only on injury levels K, A and B. Texas does not evaluate crashes at injury level C (Minor) and O (PDO). Injury levels are stratified as follows:

- Fatal (K) and Incapacitating (A)
- Non-Incapacitating (B)

Crash costs are based on figures released by the National Safety Council (See **Table 1.5**).

Table 1.5: National Safety Council, Average Comprehensive Cost by Injury Severity, 2020

Crash Type	Value ($)
Death	$11,449,000
Disabling	$1,252,000
Evident	$345,000
Possible injury	$160,000
No injury observed	$52,700

The crash unit cost values are weighted by repeating a number of steps using the most recent three years of crash data. For incapacitating injuries, for example, the process would be as follows:

1. Obtain total number of incapacitating injuries over the past three years.
2. Obtain the total number of injuries of all severities, including no injuries, in those incapacitating crashes from step one.
3. For each injury type in the incapacitating injury level crashes, multiply by its corresponding level injury unit cost.
4. Add together the cost of all injuries and non-injuries in incapacitating injury level crashes, divide this number by the total number of incapacitating injuries which produces the average incapacitating crash unit cost.

The above steps are repeated for fatal in non-incapacitating injury crashes. A weighted average of fatal and incapacitating injury crash costs is obtained by "multiplying each average crash unit cost by the ratio of fatal crashes among all fatal and incapacitating injury crashes, and the same for incapacitating injury crashes, and summing the result" .

The 2020 cost of injuries stratified by severity used by the state are depicted below and were obtained from the TXDOT SII Calculator .

Table 1.6: Texas DOT Stratified Crash Costs (2021)

Crash Type	Cost ($)
FAT (K) & Incapacitating INJ (A)	$3,700,000
Non-Incapacitating INJ (B)	$520,000

Washington State Department of Transportation

The state of Washington stratifies its crash costs based on KABCO injury levels. In doing so, the state combines Fatal and Disabling injuries stratifying as follows:

- Fatal (K) and Disabling Injury (A)
- Evident Injury (B)
- Possible Injury (C)
- PDO (O)

The societal cost of a crash is based on figures released by the FHWA and the National Highway Traffic Safety Administration (NHTSA) and adjusted periodically as needed to account for inflation.

The 2010 stratified crash costs implemented by WSDOT are shown below.

Table 1.7: Washington State DOT Stratified Crash Costs (2010)

Crash Type	Value
FAT (A) & Disabling INJ (A)	$2,900,00
Evident INJ (B)	$155,000
Possible INJ (C)	$60,000
PDO (O)	$10,000

Wyoming Department of Transportation

The state of Wyoming uses the KABCO injury level scale to stratify its crash costs. Wyoming stratifies injury severity levels into three categories as follows:

- Critical (K/A: Fatal and Incapacitating Injury)
- Serious (B/C: Non-Incapacitating and Possible Injury)
- Damage (O/U: No Injury and Unknown)

Crash costs are developed based on the U.S. DOT Value of a Statistical Life (VSL) for a fatal injury. The state uses weighting factors which it applies to the VSL to weight costs based on severity. The state adjusts figures annually based on updated VSL numbers released by the U.S. DOT.

The weighting process Wyoming employs involves three steps:

1. A "translator table" from TIGER BCA Resource Guide is used to convert VSL injury costs into KABCO crash costs.
2. KABCO crash costs are combined into severity weighted crash costs values (Critical, Serious, Damage).
3. The severity weighted crash costs are adjusted annually for inflation as recommended by the U.S.DOT.

2013 crash costs as used by Wyoming DOT are shown below.

Severity	Comprehensive Crash Unit Cost
K/A	$2,237,000
B/C	$98,000
O	$39,000

Figure 1.6: Wyoming DOT Stratified Crash Costs ($2013)

Summary of Findings

Cost-Benefit Analysis is widely accepted as one of the most common methods used in decision making around policy objectives in order to prioritize measures and allocate funding. The CBA is commonly criticized for the ethically controversial need to assign a monetary value to life and limb, as well as the historical lack of convergence on a singular value across studies and in application for the value of a statistical life (VSL). Another area of concern around the valuation of life and limb which goes into the CBA is the methodology behind the valuations research which supports it, which is frequently cited as being too subjective, with unreliable and inconsistent inputs. It's commonly agreed upon that the value of a CBA is dependent on the quality of the inputs used for the analysis. There is consensus that placing a value on a life lost is necessary in order to make trade-offs and that a lack of a uniform value is problematic.

Some alternatives to the CBA are Multicriteria Analysis and the Health-Life Cycle Approach, however the former has not been applied in many instances related to road safety to date and the latter is not without questions around its suitability and has not been widely accepted to date regarding road safety. The consensus appears to be that the CBA analysis has its flaws as a tool and may require some updating, particularly around the valuation of life, it remains however a widely accepted tool for decision making. The common question being asked in all of this is how much the public is willing to spend on safety measures to reduce the risk of life and limb on the road?

The most commonly used scale in transportation safety is the KABCO injury level scale as outlined in the AASHTO Highway Safety Manual. Nine out of the ten states reviewed use injury designations based on the KABCO scale, Louisiana however has developed its own injury level scales. However, an anomaly with the KABCO system is the definitions for A/B/C level injury coding differs across the states, with stratification of injury levels across the states varying widely. Additionally, several states combine other higher injury levels with the fatal injury level. South Dakota is different in that it only makes a distinction between all injury level crashes, including fatal, and property damage only crashes.

The VSL employed by states is generally obtained from sources such as the U.S. DOT, FHWA, the AASHTO HSM, the National Safety Council and/or the National Highway Traffic Safety Administration (NHTSA). Except in the case of Louisiana where costs in that state were determined from independent research. The VSL assigned at the Fatality level also dramatically varies from as low as $239,292 ($2015) in Alabama, to as high as $9,600,000 ($2016) in Oklahoma. In order to compare the cost of crash severities (PDO, Injury and Fatality), many states use a weighting or weighted indexing procedure.

A recent report by the National Academies has asserted that the definition of an injury crash should be based on what are medically diagnosed terms rather than in what is obtained from crash reports. The report advises the long-term solution for measuring serious injury is to link crash data to medical outcome data at a state level by way of a statewide integrated database.

While sources used for crash cost estimates might in general align across the states, there is wide ranging variability in injury level scales employed, and in conversion and adaptation between scales, as well as in the weighting of injury levels. The importance of resolving the impact of injury level scale on the estimation of crash costs has been recognized as nationally beneficial in terms of safety BCA.

Chapter 2 – Examination of the Changes in the Cost of Injury Level Crashes As Influenced By Factors Such as Environment, Facility Type and Crash Type

The principal question behind this research is whether injury costs vary as factors such as environment, facility type and crash type differ, and if stratifying the cost of an injury crash by degree of injury i.e., severity, to reflect these variations will lead to improved project selection and ultimately road safety in the state of Colorado. In order to answer that question, it is necessary to examine more deeply the relationship between injury and cost. This section of the report discusses the results of an examination of the changes in the cost of injury crashes across different environments, facilities and crash types on Colorado roads.

Method

A study period of ten years, 2010-2019, was chosen for the analysis. In order to ensure sufficient sample size, facility types were selected for analysis which were well represented in terms of crash volume, i.e., those facilities which experienced a high number of crashes over the ten-year period.

For each facility type the injury crash listings for the ten-year study period were used to determine the average cost of an injury crash on that facility type. Crash listings include a breakdown of injury levels for each individual crash based on the KABCO injury level scale. The levels of interest were C (level 2 injury), B (level 3 injury) and A (level 4 injury). For example, an individual injury crash may have one level-C injury and two level-B injuries occurring. At the same time, a fatal crash, in addition to recording a fatality, may also have had injuries recorded as part of the crash, these injuries were also accounted for.

Identifying a Difference in Injury Crash Cost

To serve as an initial indication as to whether there is a difference in the cost of an injury crash when factors such as facility type, environment and crash type vary, the mean cost of an injury crash was determined for the I-25 and I-70 facilities in Colorado, in rural and in urban environments and compared. Both facilities are freeway facilities which are well represented in terms of crash history. This was achieved by firstly using the most current KABCO societal and human capital costs for crashes (**Table 2.1**), to calculate the cost of all injuries which occurred on those freeways over the study period. (CDOT currently uses a combined cost of $106,100 for an Injury level crash which is based on the KABCO stratified costs).

Table 2.1: KABCO Societal & Human Capital Costs 2021

Crash Severity	2001 Human Capital Cost	2001 Comprehensive Society Cost	2021 CPI – Adjusted Human Capital Cost	2021 ECI – Adjusted Comprehensive Society Cost
Fatal (K)	$ 1,245,600	$ 4,008,900	**$ 1,906,200**	$ 6,638,100
Disabling Injury (A)	$ 111,400	$ 216,000	$ 170,500	**$ 349,600**
Evident Injury (B)	$ 41,900	$ 79,000	$ 64,100	**$ 127,600**
Possible Injury (C)	$ 28,400	$ 44,900	$ 43,500	**$71,800**
PDO (O)	$ 6,400	$ 7,400	$ 9,800	**$ 11,500**

The cost of every injury crash which was recorded on the I-25 and I-70 freeways during the study period was obtained by multiplying the number of injuries occurring under each injury level, by the associated cost for each injury level, for each individual crash as follows:

1. Number of 'Disabling Injury' (A – level 4) injuries recorded as part of the crash multiplied by $349,600.
2. Number of 'Evident Injury' (B – level 3) injuries recorded as part of the crash multiplied by $127,600.
3. Number of 'Possible Injury' (C – level 2) injuries recorded as part of the crash multiplied by $71,800.

For example, on interstate I-25 between mile point 1.00 and mile point 2.00, where the interstate is classified as being in a rural environment, there were 23 injury crashes recorded over the ten-year study period (see **Table 2.2**).

Table 2.2: Crashes Occurring on Rural I-25 MP 1.00-2.00, 2010-19

	Hwy	MP	date	severity	injlevel_2	injlevel_3	injlevel_4
#1	25A	1.1	6/26/10	INJ	1	0	0
#2	25A	1.3	3/19/10	INJ	1	1	0
#3	25A	1.9	3/26/10	INJ	0	1	0
#4	25A	1.9	3/26/10	INJ	2	0	0
#5	25A	1	1/31/11	INJ	1	0	0
#6	25A	1.2	4/1/11	INJ	0	2	0
#7	25A	1.9	10/14/12	FAT	1	2	0
#8	25A	1.6	12/22/14	INJ	3	1	0
#9	25A	1	4/7/15	INJ	0	1	0
#10	25A	1.1	8/8/15	INJ	0	1	0
#11	25A	1.4	12/2/16	INJ	1	0	0
#12	25A	1.4	11/25/16	INJ	0	1	0
#13	25A	1.7	4/27/16	INJ	0	0	1
#14	25A	1.9	3/27/16	INJ	1	0	0
#15	25A	2	10/13/16	INJ	1	0	0
#16	25A	1.5	5/27/17	INJ	1	0	0
#17	25A	1.9	7/29/17	INJ	3	0	0
#18	25A	1.1	2/24/18	INJ	1	0	0
#19	25A	1.6	5/14/18	INJ	2	0	0
#20	25A	1.8	6/20/18	INJ	0	0	1
#21	25A	1.9	8/31/18	INJ	0	1	2
#22	25A	1.67	2/23/19	INJ	0	0	1
#23	25A	1.5	8/1/19	INJ	1	0	0

In this brief example, the cost of each injury crash would have been calculated as follows:

Table 2.3: Cost Calculations for Injury Crashes, Rural I-25 MP 1.00-2.00, 2010-19

	injlevel_2	injlevel_3	injlevel_4	
#1 =	1*$71,800			=$71,800
#2 =	1*$71,800 +	1*$127,600		=$199,400
#3 =		1*$127,600		=$127,600
#4 =	2*$71,800			=$143,600
#5 =	1*$71,800			=$71,800
#6 =		2*$127,600		=$255200
#7 =	1*$71,800 +	2*$127,600		=$327,000
#8 =	3*$71,800 +	1*$127,600		=$343,000
#9 =		1*$127,600		=$127,600
#10 =		1*$127,600		=$127,600
#11 =	1*$71,800			=$71,800
#12 =		1*$127,600		=$127,600
#13 =			1*$349,600	=$349,600
#14 =	1*$71,800			=$71,800
#15 =	1*$71,800			=$71,800
#16 =	1*$71,800			=$71,800
#17 =	3*$71,800			=$215,400
#18 =	1*$71,800			=$71,800
#19 =	2*$71,800			=$143,600
#20 =			1*$349,600	=$349,600
#21 =		1*$127,600 +	2*$349,600	=$826,800
#22 =			1*$349,600	=$349,600
#23 =	1*$71,800			=$71,800

In this way the total cost for an injury crash, and subsequently for all injury crashes which occurred on these freeways in urban and rural environments over the study period was ascertained. The total cost of all injury crashes was then divided by the number of crashes involved. The resultant provided the average cost of an injury crash occurring on the urban I-25 and I-70 facilities and on the rural I-25 and I-70 facilities over the study period.

The same method was used to obtain the average cost for an injury crash of a specific crash type on these freeways by focusing only on crashes of a certain type within the crash history listings. In this case, the average cost of an injury guard rail crash was compared with that of an injury rear end crash on I-25 and I-70 between rural and urban environments.

The initial indications from this raw analysis showed that the average cost of an injury crash changes as factors such as facility type, environment, and crash type change. **Table 2.4** following, shows the differences in the average cost of an injury crash for the combined I-25 and

I-70 facilities (i.e. freeway facilities) between an urban and rural environment and between the crash types of guard rail and rear end collisions. Evidently the average cost is not the same in all situations.

Table 2.4: Differences in Average Cost of an Injury Crash across Urban and Rural Freeways

	Average Cost of an Injury Crash	**Average cost of a *Guard Rail* Injury Crash**	**Average Cost of a *Rear End* Injury Crash**
Urban Freeways	Total # of Injury Crashes: 17,984 Total Cost of Injury Crashes: $2,609,700,00.00 Average Cost: **$145,112.32**	Total # of Injury Crashes: 964 Total Cost of Injury Crashes: $138,872,200.00 Average Cost: **$144,058.30**	Total # of Injury Crashes: 10,025 Total Cost of Injury Crashes: $1,344,842,200.00 Average Cost: **$134,148.85**
Rural Freeways	Total # of Injury Crashes: 8,026 Total Cost of Injury Crashes: $1,347,705,200.00 Average Cost: **$167,917.42**	Total # of Injury Crashes: 733 Total Cost of Injury Crashes: $116,725,000.00 Average Cost: **$159,242.84**	Total # of Injury Crashes: 2,596 Total Cost of Injury Crashes: $411,851,000.00 Average Cost: **$158,648.31**

The section following addresses the question of whether the differences observed in the average cost of an injury crash across various facilities, environments and crash types are statistically significant.

Statistical Analysis – Paired t-tests

Following the initial indication of noticeable differences in the cost of an injury crash between urban freeway facilities versus rural freeway facilities, and between injury crash types in those environments, the next step involved the expansion of the analysis to include additional facilities and crash types across the rural and urban environments. The facilities and crash types selected for analysis were, as outlined previously, those which are well represented in terms of crash history, and therefore sample size. The complete list of categories in terms of facility type and crash type which were selected for analysis and comparison of injury crash costs are listed in **Figure 2.1**.

1. Rural Freeways versus Urban Freeways
2. Rural 4-lane Arterials versus Urban 4-lane Arterials
3. Urban versus Rural Intersection Rear-End on Arterials
4. Urban versus Rural Fixed Object (non-intersection) on Arterials
5. Urban Arterials Intersection Broadside versus Intersection Rear-End
6. Urban Arterials Intersection Approach Turn versus Intersection Sideswipe Same Direction
7. Urban Arterials Intersection Approach Turn versus Intersection Rear-End

Figure 2.1: Categories of Facility and/or Crash Type Selected for Statistical Analysis

The categories selected, in addition to being well represented in terms of crash volume and history, demonstrate variability in facility type, environment and crash type.

The calculation process outlined previously implementing the KABCO injury level scale with societal and human capital costs, was repeated to determine the cost of each injury crash recorded over the study period for those crashes of interest categorized in **Figure 2.1** above. To determine if the differences observed in the average cost of an injury crash across these varying facility types, environments and crash types were statistically significant, two types of t-test were performed: a paired two-sample means t-test and; a two-sample assuming unequal variances t-test. These statistical functions are incorporated under the DATA ANALYSIS tool available on Microsoft Excel (**Figure 2.2**).

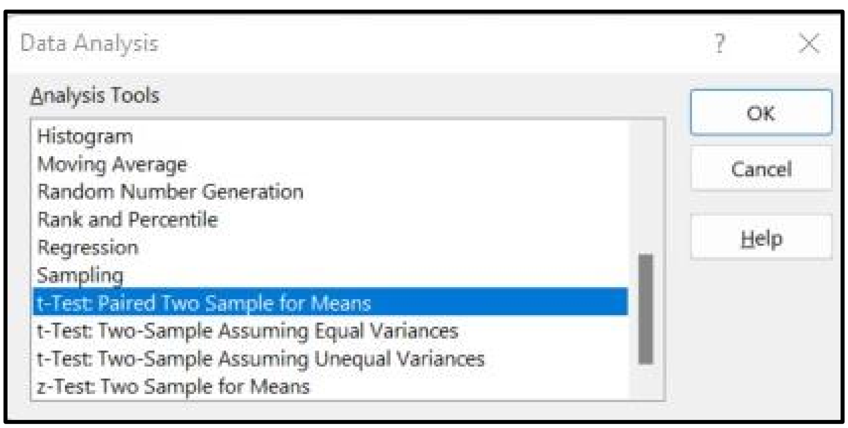

Figure 2.2: Data Analysis Statistical Tools from MS Excel

Both the paired sample means t-test and the two-sample unequal variances t-test can be easily computed using the statistical functions provided by MS Excel. Using an example to illustrate and referring to **Figure 2.3**, comparing injury crashes on urban 4-lane arterials with injury crashes on rural 4-lane arterials, the "Variable-1" range included the calculated cost of each injury crash on all urban 4-lane arterials for the study period, while the "Variable-2" range included the calculated cost of each injury crash on all rural 4-lane arterials. In concert with **Figure 2.3**, a snapshot of the list of urban and rural 4-lane arterial injury crashes which were analyzed is provided in **Figure 2.4**.

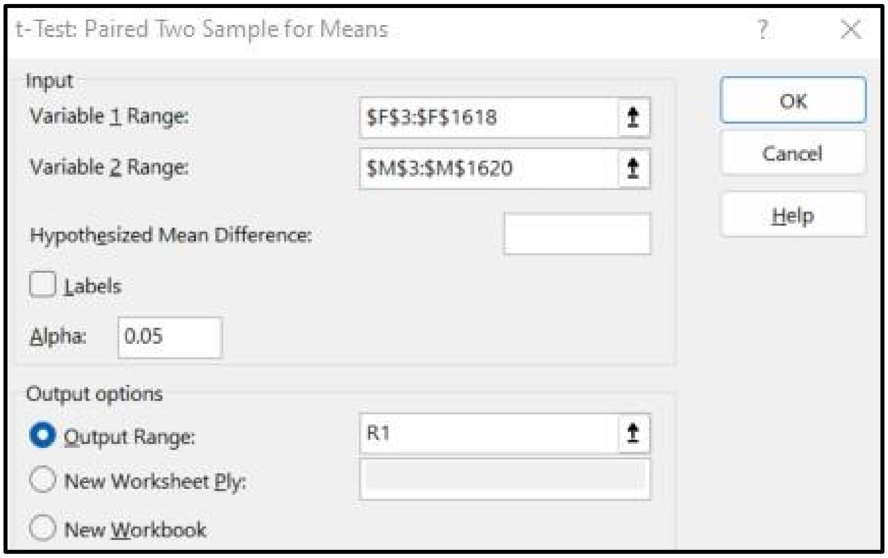

Figure 2.3: A Paired Sample Means t-Test Statistical Analysis Tool from MS Excel

A	B	C	D	E	F	G	H	I	J	K	L	M
Urban 4-lane Arterials [UF4DH, UF4UH, UM4DH, UM4UH, UR4DH, UR4UH]							Rural 4-lane Arterials [RF4DH, RF4UH, RM4DH, RM4UH, RR4DH, RR4UH]					
rte	mp	injlevel_2	injlevel_3	injlevel_4	Cost		rte	mp	injlevel_2	injlevel_3	injlevel_4	Cost
105A	4.9	4	0	0	$ 287,200.00		119A	6	1	0	3	$ 1,120,600.00
105A	5.1	1	0	0	$ 71,800.00		119A	6.1	1	0	0	$ 71,800.00
105A	5.26	1	0	0	$ 71,800.00		119A	6.1	1	0	0	$ 71,800.00
287Z	0.06	1	0	0	$ 71,800.00		52B	88.2	0	1	0	$ 127,600.00
75B	5.38	0	1	0	$ 127,600.00		52B	88.4	2	0	0	$ 143,600.00
105A	4.98	1	0	0	$ 71,800.00		119A	6.5	0	1	0	$ 127,600.00
128B	12.18	1	2	0	$ 327,000.00		121B	0.11	0	1	0	$ 127,600.00
128B	12.21	1	0	0	$ 71,800.00		92A	2.55	0	0	1	$ 349,600.00
128B	12.21	1	0	0	$ 71,800.00		92A	2.6	0	1	1	$ 477,200.00
78A	33.2	1	0	0	$ 71,800.00		92A	3.5	1	0	0	$ 71,800.00
105A	4.73	1	0	0	$ 71,800.00		92A	3.8	0	1	0	$ 127,600.00

Figure 2.4: Snapshot of Cost Calculations for Urban & Rural 4-ln Arterials Injury Crashes used for t-Testing

For both the paired sample means t-test and the two-sample unequal variance t-test, an alpha level of 0.01 was selected. For each category listed in **Figure 2.1** once the injury crash costs over the study period were calculated, data sets were implemented to perform the statistical t-tests to determine if there are statistically significant differences in the mean cost of an injury level crash across the sample of categorized facilities and crash types selected.

Assumptions on the data sets and samples were as follows:

- The samples are independent and identically distributed.
- The samples are sufficiently large enough to follow an approximately normal distribution.
- There are unequal variances between samples.

For the purposes of this analysis, Variable-1 and Variable-2 are both the sum of the individual costs of each injury crash for the facility or crash type in question. The Null Hypothesis indicates that the difference in the means for each data set is not statistically significant. Rejection of the Null Hypothesis (i.e. adoption of the Alternative Hypothesis), indicates that the difference in the means for each data set is observed to be statistically significant. The selected alpha level of 0.01 indicates a 99% confidence interval in the observed results of the t-tests.

- Null Hypothesis: assumes that there is no difference in the mean cost of an injury crash between samples.
- Alternative Hypothesis: assumes there is a statistically significant difference between the mean cost of an injury crash across samples (rejection of null hypothesis).

A p-value (P(T<=t) one tail and P(T<=t) two tail) of less than 0.01 in this case would indicate the null hypothesis should be rejected.

Findings Across Varied Environments, Facility Types & Crash Types

For each of the categories analyzed as listed in **Figure 2.1**, the comparisons by way of both the paired sample means t-test and the two-sample unequal variance t-test, indicated a strong rejection of the null hypothesis across all categories and across both types of statistical t-tests at the 99% confidence interval. The results of t-tests performed for each category tested are provided in **Tables 2.5-2.11** following.

Table 2.5: t-Test Results: Urban Freeway Crashes vs. Rural Freeway Crashes (I-25, I-70)

t-Test: Paired Two Sample for Means	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$130,914	$168,402
Variance	1.34E+10	4.74E+10
Observations	2297	2297
Pearson Correlation	-0.021897267	
Hypothesized Mean Difference	0	
df	2296	
t Stat	-7.218E+00	
P(T<=t) one-tail	**3.557E-13**	
t Critical one-tail	2.328E+00	
P(T<=t) two-tail	**7.113E-13**	
t Critical two-tail	2.578E+00	
t-Test: Two-Sample Assuming Unequal Variances	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$135,455	$168,402
Variance	1.41E+10	4.74E+10
Observations	3507	2297
Hypothesized Mean Difference	0	
df	3199	
t Stat	-6.634075877	
P(T<=t) one-tail	**1.910E-11**	
t Critical one-tail	2.328E+00	
P(T<=t) two-tail	**3.820E-11**	
t Critical two-tail	2.577E+00	

Table 2.6: t-Test Results: Urban 4-ln Arterial Crashes Vs. Rural 4-ln Arterial Crashes

t-Test: Paired Two Sample for Means	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$139,150	$165,482
Variance	1.43E+10	2.22E+10
Observations	1618	1618
Pearson Correlation	-0.008180547	
Hypothesized Mean Difference	0	
df	1617	
t Stat	-5.524E+00	
P(T<=t) one-tail	**1.928E-08**	
t Critical one-tail	2.329E+00	
P(T<=t) two-tail	**3.856E-08**	
t Critical two-tail	2.579E+00	

t-Test: Two-Sample Assuming Unequal Variances	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$140,564	$165,483
Variance	1.60E+10	2.22E+10
Observations	7954	1618
Hypothesized Mean Difference	0	
df	2116	
t Stat	-6.282E+00	
P(T<=t) one-tail	**2.019E-10**	
t Critical one-tail	2.328E+00	
P(T<=t) two-tail	**4.037E-10**	
t Critical two-tail	2.578E+00	

Table 2.7: t-Test Results: Urban Arterial Intersection Rear-End Crashes Vs. Rural Arterial Intersection Rear-End Crashes

t-Test: Paired Two Sample for Means	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$115,534	$151,690
Variance	6.63E+09	1.86E+10
Observations	773	773
Pearson Correlation	0.009815756	
Hypothesized Mean Difference	0	
df	772	
t Stat	-6.355E+00	
P(T<=t) one-tail	**1.783E-10**	
t Critical one-tail	2.331E+00	
P(T<=t) two-tail	**3.566E-10**	
t Critical two-tail	2.582E+00	
t-Test: Two-Sample Assuming Unequal Variances	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$114,136	$151,690
Variance	7.47E+09	1.86E+10
Observations	11536	773
Hypothesized Mean Difference	0	
df	814	
t Stat	-7.552E+00	
P(T<=t) one-tail	**5.758E-14**	
t Critical one-tail	2.331E+00	
P(T<=t) two-tail	**1.152E-13**	
t Critical two-tail	2.582E+00	

Table 2.8: T-Test Results: Urban Arterial Fixed Object Crashes (non-intersection Vs. Rural Arterial Fixed Object Crashes (non-intersection)

t-Test: Paired Two Sample for Means	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$156,900	$171,791
Variance	1.93E+10	4.50E+10
Observations	1776	1776
Pearson Correlation	0.018193812	
Hypothesized Mean Difference	0	
df	1775	
t Stat	-2.495E+00	
P(T<=t) one-tail	**6.343E-03**	
t Critical one-tail	2.328E+00	
P(T<=t) two-tail	**1.269E-02**	
t Critical two-tail	2.579E+00	

t-Test: Two-Sample Assuming Unequal Variances	**Urban**	**Rural**
	Variable 1	Variable 2
Mean	$156,900	$166,820
Variance	1.93E+10	2.86E+10
Observations	1776	5637
Hypothesized Mean Difference	0	
df	3568	
t Stat	-2.483E+00	
P(T<=t) one-tail	**6.532E-03**	
t Critical one-tail	2.327E+00	
P(T<=t) two-tail	**1.306E-02**	
t Critical two-tail	2.577E+00	

Table 2.9: T-Test Results: Intersection Broadside Vs. Rear-End Crashes on Urban Arterials

t-Test: Paired Two Sample for Means	**Broadside**	**Rear-End**
	Variable 1	Variable 2
Mean	$161,834	$113,929
Variance	2.29E+10	7.24E+09
Observations	6552	6552
Pearson Correlation	-0.030485247	
Hypothesized Mean Difference	0	
df	6551	
t Stat	22.05330947	
P(T<=t) one-tail	**2.508E-104**	
t Critical one-tail	2.327E+00	
P(T<=t) two-tail	**5.015E-104**	
t Critical two-tail	2.577E+00	

t-Test: Two-Sample Assuming Unequal Variances	**Broadside**	**Rear-End**
	Variable 1	Variable 2
Mean	$161,834	$114,136
Variance	2.29E+10	7.47E+09
Observations	6552	11536
Hypothesized Mean Difference	0	
df	9027	
t Stat	23.44017222	
P(T<=t) one-tail	**2.650E-118**	
t Critical one-tail	2.327E+00	
P(T<=t) two-tail	**5.301E-118**	
t Critical two-tail	2.576E+00	

Table 2.10: t-Test Results: Intersection Approach Turn Vs. Intersection Sideswipe Same Direction Crashes on Urban Arterials

t-Test: Paired Two Sample for Means	**Approach Turn**	**Sideswipe Same Direction**
	Variable 1	Variable 2
Mean	$174,390	$124,966
Variance	2.25E+10	1.05E+10
Observations	794	794
Pearson Correlation	0.018541982	
Hypothesized Mean Difference	0	
df	793	
t Stat	7.724831143	
P(T<=t) one-tail	**1.691E-14**	
t Critical one-tail	2.331E+00	
P(T<=t) two-tail	**3.383E-14**	
t Critical two-tail	2.582E+00	
t-Test: Two-Sample Assuming Unequal Variances	**Approach Turn**	**Sideswipe Same Direction**
	Variable 1	Variable 2
Mean	$173,825	$124,966
Variance	2.44E+10	1.05E+10
Observations	7047	794
Hypothesized Mean Difference	0	
df	1251	
t Stat	11.93674966	
P(T<=t) one-tail	**1.748E-31**	
t Critical one-tail	2.329E+00	
P(T<=t) two-tail	**3.497E-31**	
t Critical two-tail	2.580E+00	

Table 2.11: T-Test Results: Approach Turn Crashes Vs. Rear-End Crashes on Urban Arterials

t-Test: Paired Two Sample for Means	**Approach Turn**	**Rear-End**
	Variable 1	Variable 2
Mean	$173,825	$113,966
Variance	2.44E+10	7.35E+09
Observations	7047	7047
Pearson Correlation	-0.005200008	
Hypothesized Mean Difference	0	
df	7046	
t Stat	28.1201378	
P(T<=t) one-tail	**2.734E-165**	
t Critical one-tail	2.327E+00	
P(T<=t) two-tail	**5.468E-165**	
t Critical two-tail	2.577E+00	

t-Test: Two-Sample Assuming Unequal Variances	**Approach Turn**	**Rear-End**
	Variable 1	Variable 2
Mean	$173,825	$114,136
Variance	2.44E+10	7.47E+09
Observations	7047	11536
Hypothesized Mean Difference	0	
df	9715	
t Stat	29.42408819	
P(T<=t) one-tail	**1.147E-182**	
t Critical one-tail	2.327E+00	
P(T<=t) two-tail	**2.294E-182**	
t Critical two-tail	2.576E+00	

The results depicted in **Tables 2.5-2.11** show that even for this analysis which includes just a proportion of all facility and crash types which might have been tested for comparison, the outcome is strongly and consistently the rejection of the null hypothesis. In other words, results indicate that there are statistically significant differences in the mean cost of an injury crash as factors such as facility type, environment and crash type vary. At the 99% confidence interval it can be inferred that results would be the same were additional facilities, environmental factors and crash types subjected to testing.

Because the crash costs determined in the analysis were at the individual crash level, which is stratified into crash levels A, B, and C, we can conclude that the observed differences across data sets demonstrate there is a direct relationship between the degree of injury (severity) and the average cost of an injury crash occurred on different facilities in different environment.

Figure 2.5 through **Figure 2.24** show the distribution of injury crashes by levels A, B and C, or 'Disabling Injury,' 'Evident Injury' and 'Possible Injury,' respectively, for each category of facility and/or crash type selected for statistical analysis which was listed in **Figure 2.1**. The data shows that the proportional distribution of severity varies from one facility, environment and/or crash type to the next.

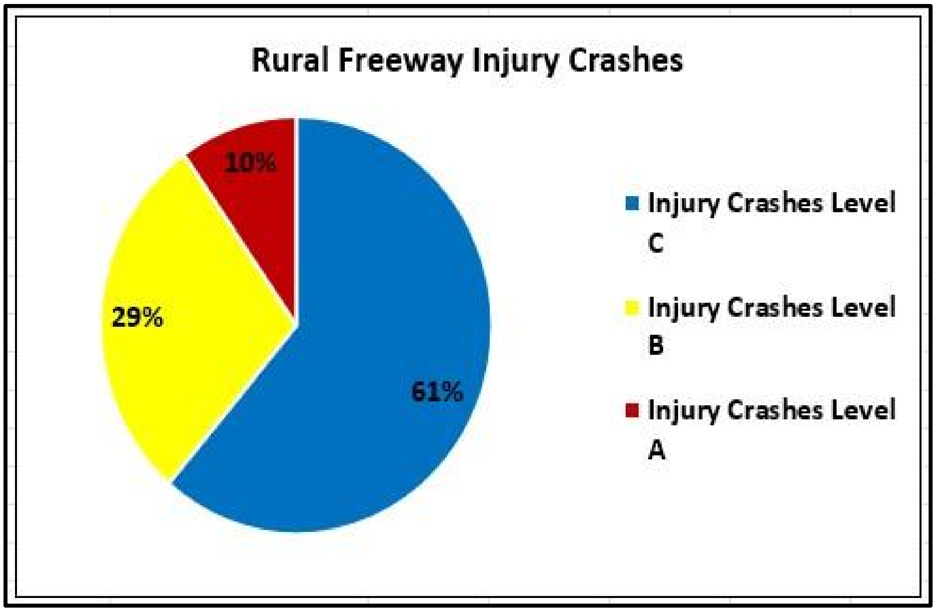

Figure 2.5: Rural Freeway Distribution of Severity of Injury Crashes

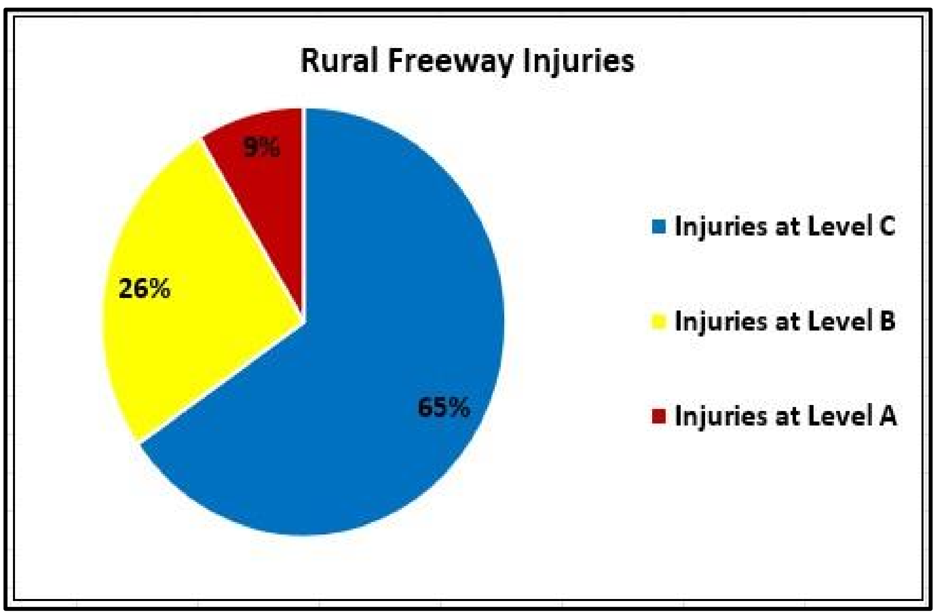

Figure 2.6: Rural Freeway Distribution of Severity of Injuries

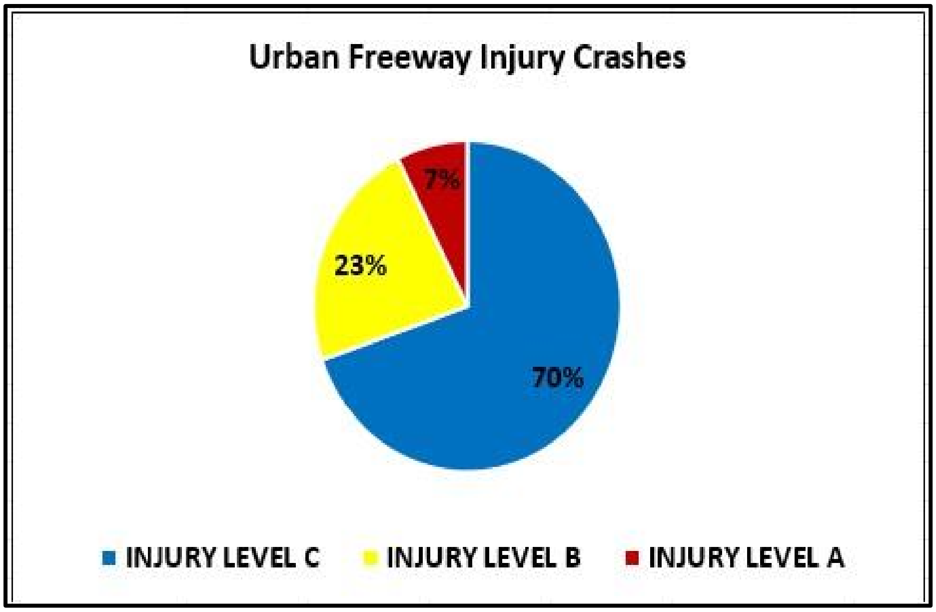

Figure 2.7: Urban Freeway Distribution of Severity of Injury Crashes

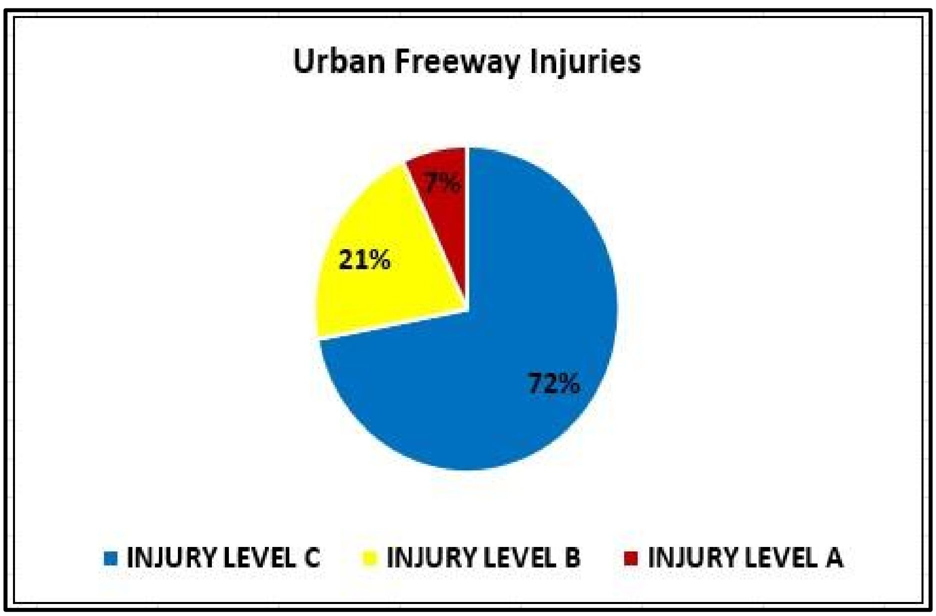

Figure 2.8: Urban Freeway Distribution of Severity of Injuries

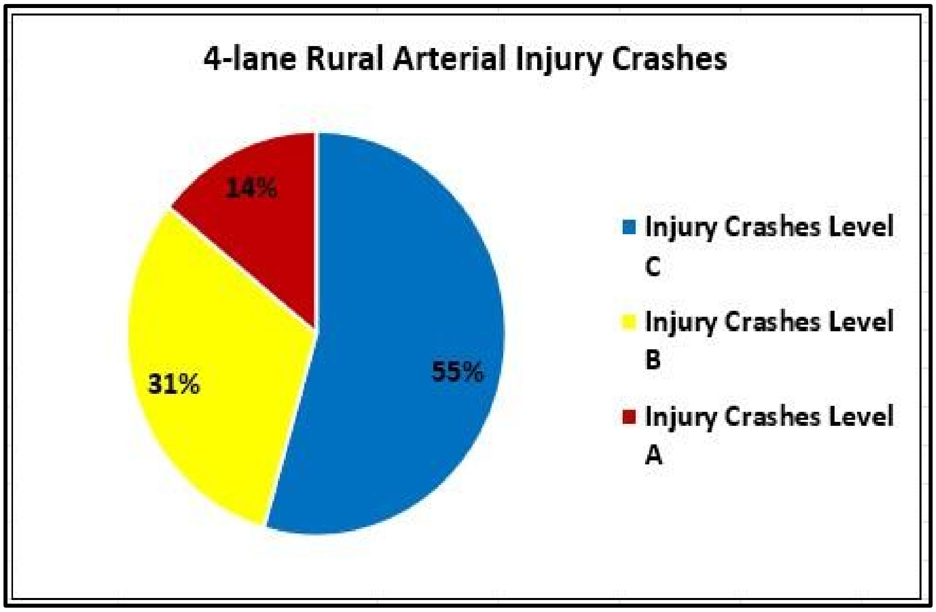

Figure 2.9: Rural 4-ln Arterial Distribution of Severity of Injury Crashes

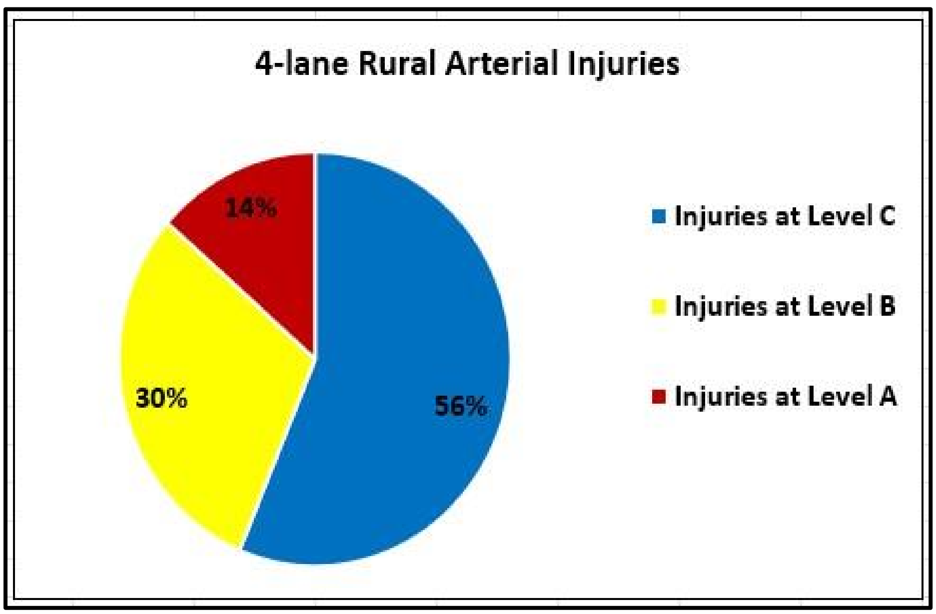

Figure 2.10: Rural 4-ln Arterial Distribution of Severity of Injuries

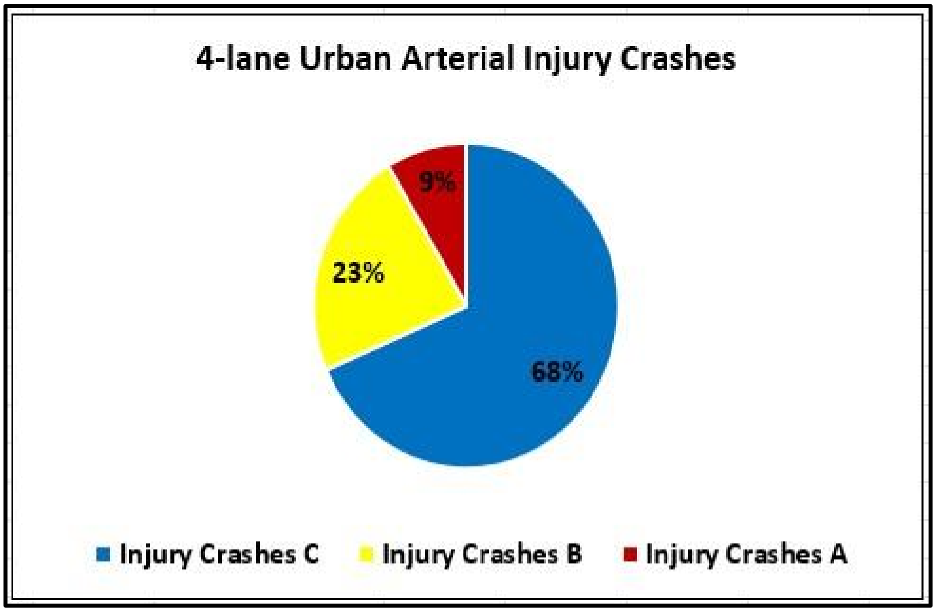

Figure 2.11: Urban 4-ln Arterial Distribution of Severity of Injury Crashes

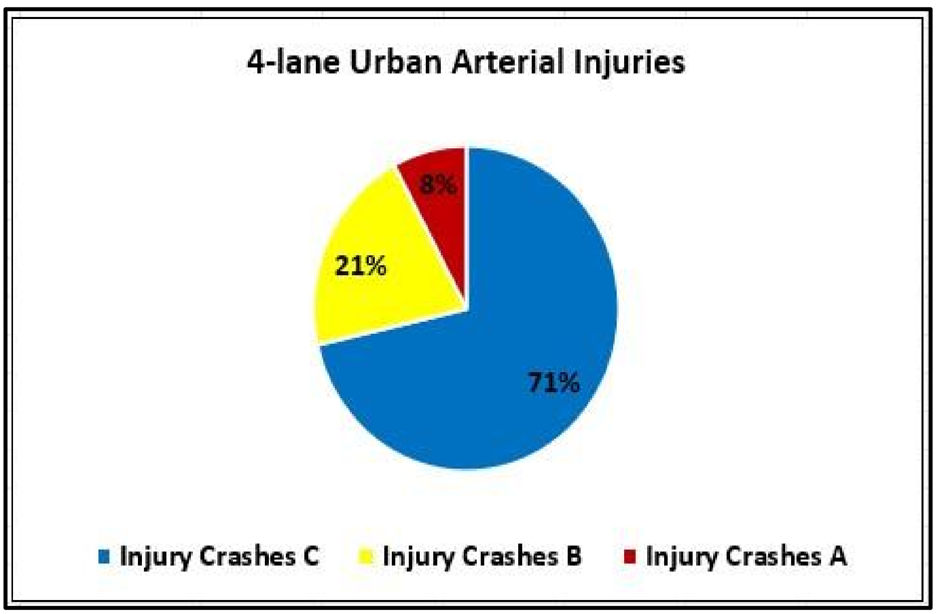

Figure 2.12: Urban 4-ln Arterial Distribution of Severity of Injuries

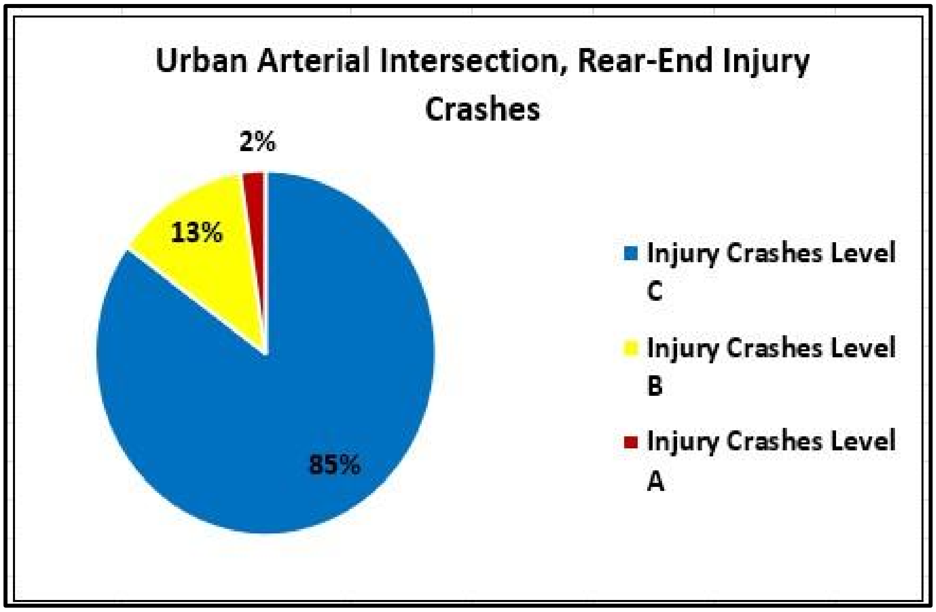

Figure 2.13: Urban Arterial Intersection, Distribution of Rear-End Injury Crash Severity

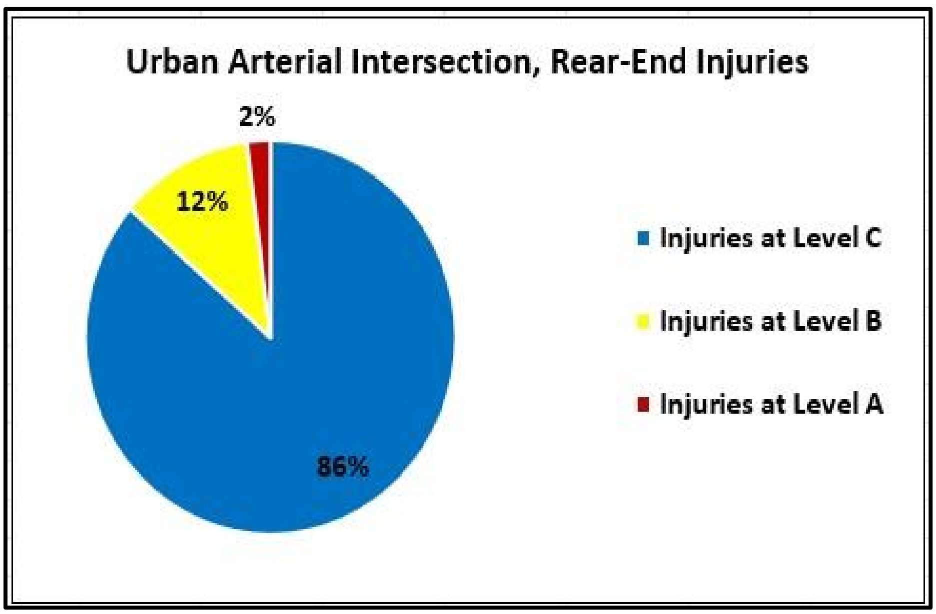

Figure 2.14: Urban Arterial Intersection, Distribution of Severity of Rear-End Injuries

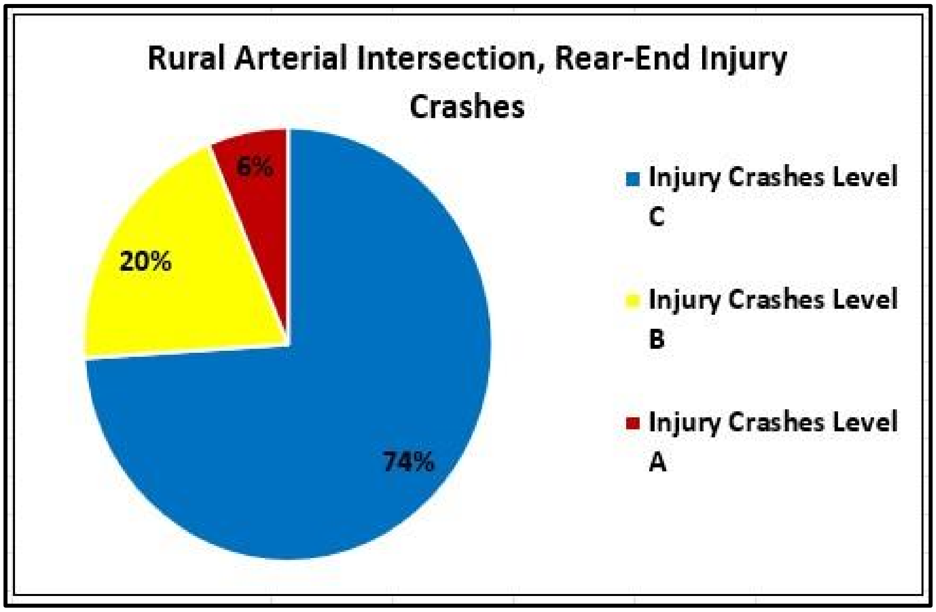

Figure 2.15: Rural Arterial Intersection Distribution of Rear-End Injury Crash Severity

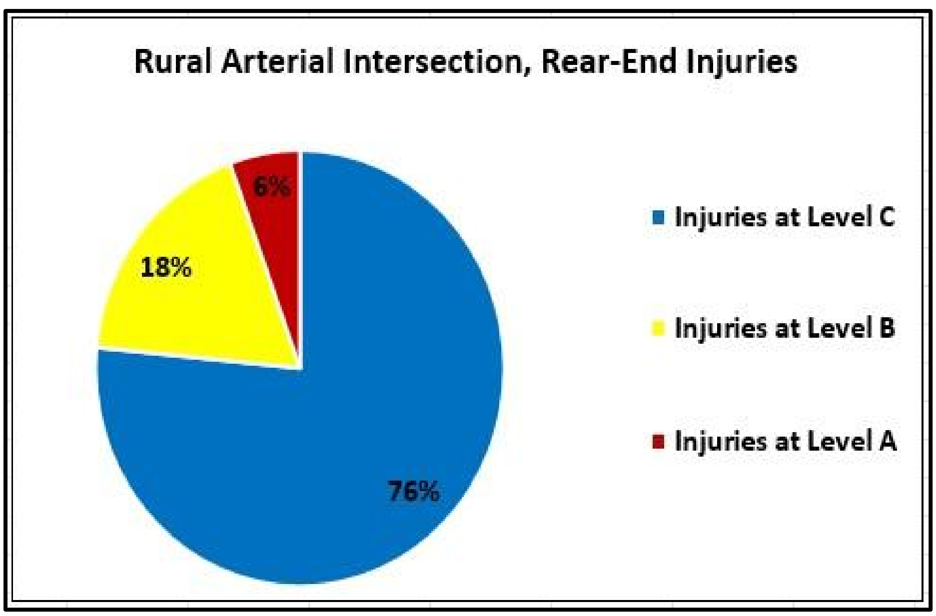

Figure 2.16: Rural Arterial Intersection Distribution of Severity of Rear-End Injuries

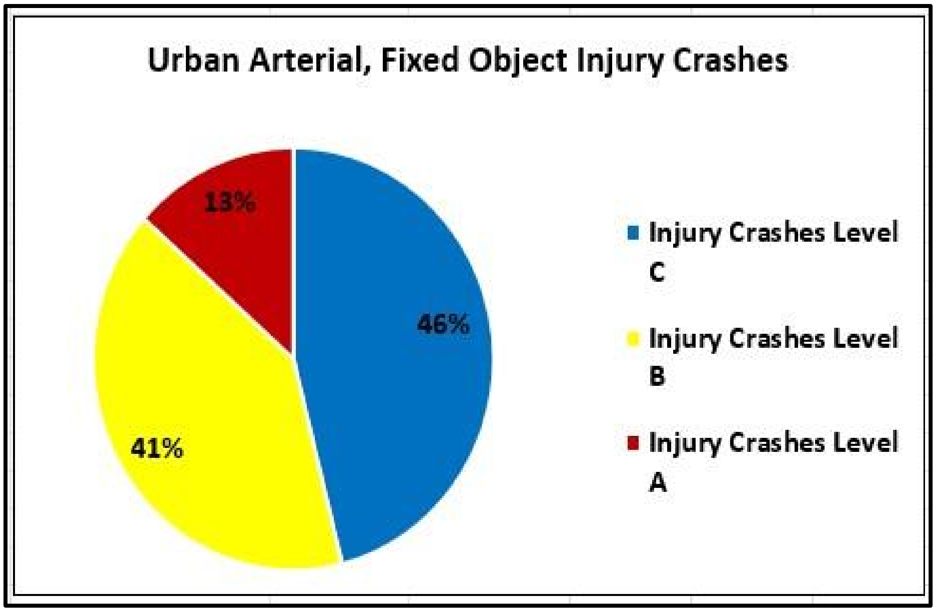

Figure 2.17: Urban Arterial Distribution of Fixed Object Injury Crash Severity

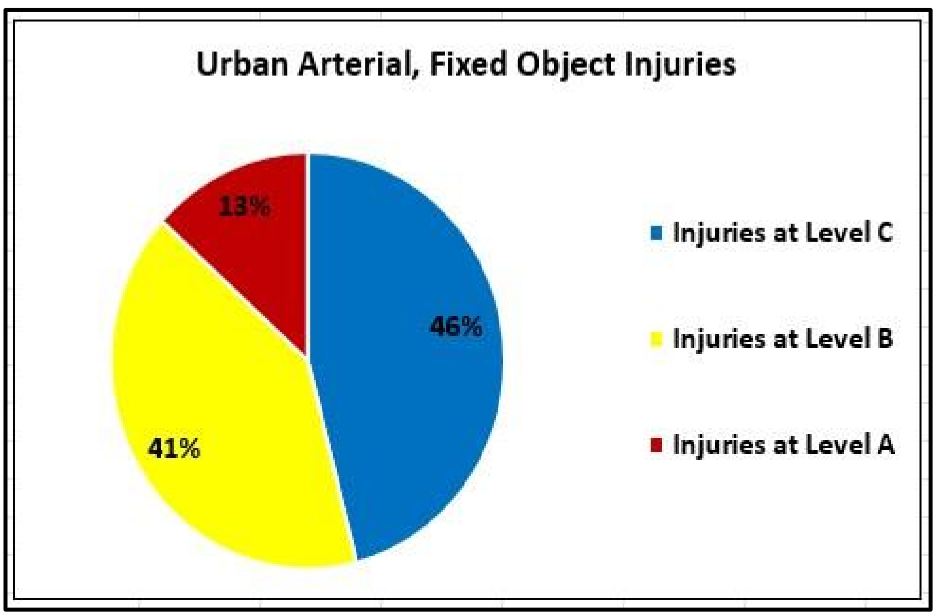

Figure 2.18: Urban Arterial Distribution of Severity of Fixed Object Injuries

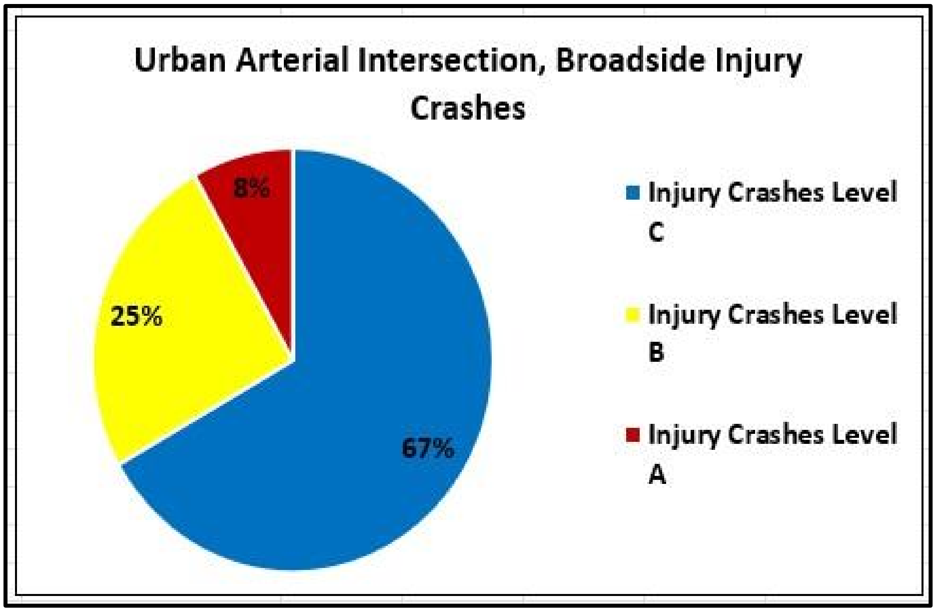

Figure 2.19: Urban Arterial Intersection Distribution of Broadside Injury Crash Severity

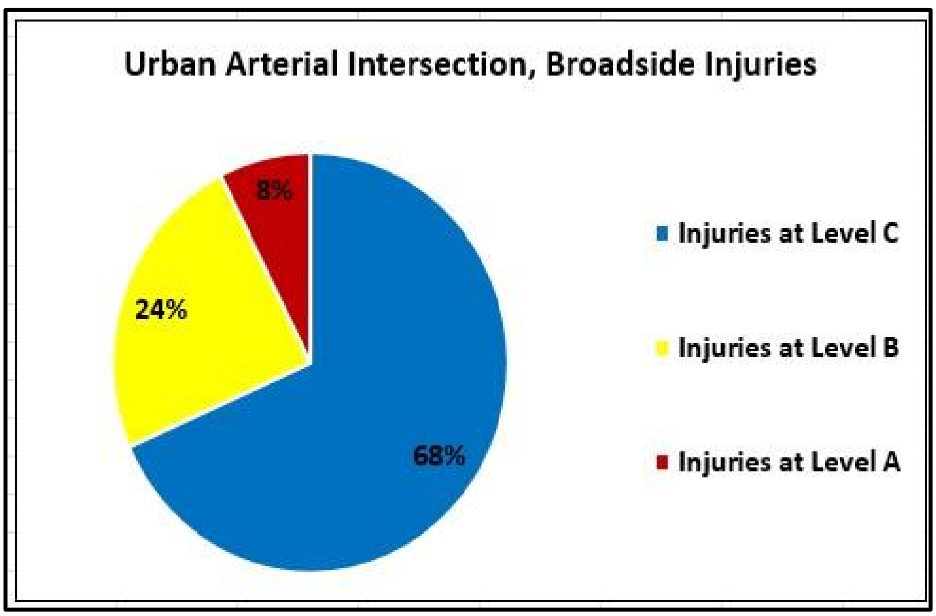

Figure 2.20: Urban Arterial Intersection Distribution of Severity of Broadside Injuries

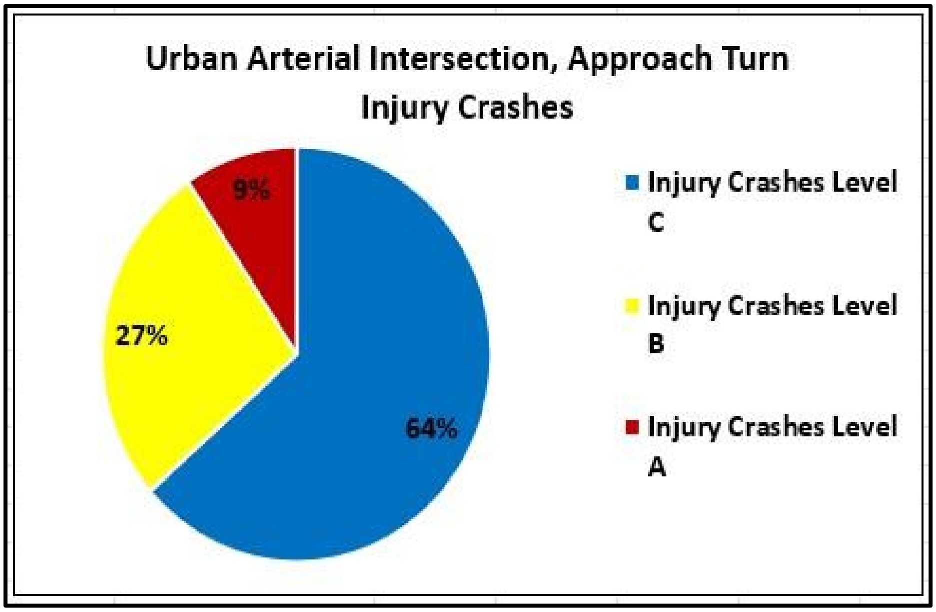

Figure 2.21: Urban Arterial Intersection Distribution of Approach Turn Injury Crash Severity

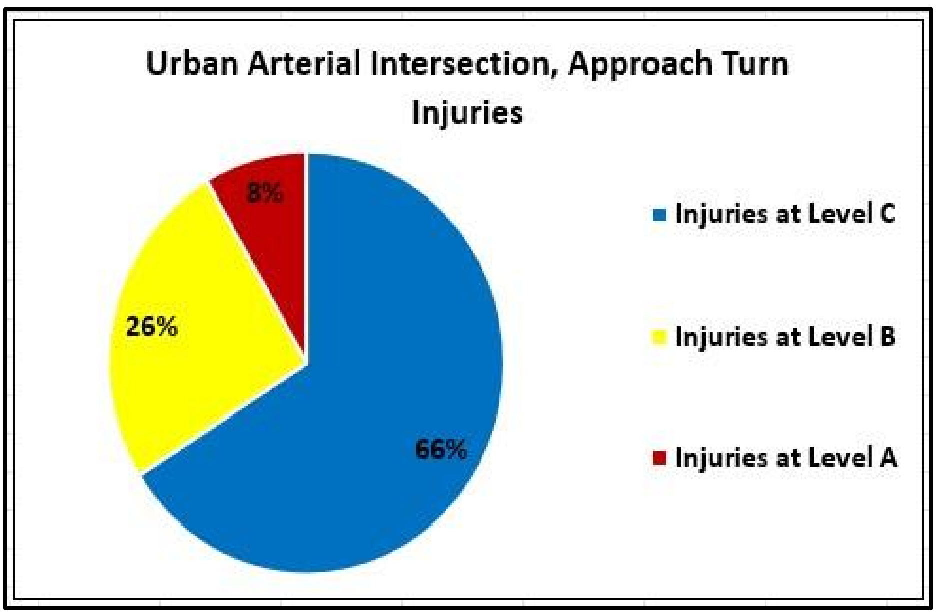

Figure 2.22: Urban Arterial Intersection Distribution of Severity of Approach Turn Injuries

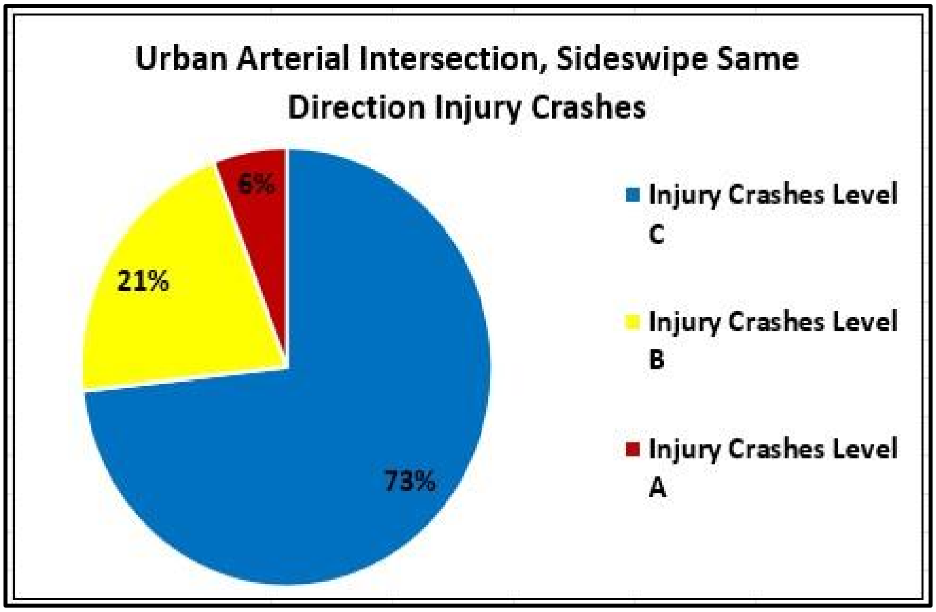

Figure 2.23: Urban Arterial Intersection Distribution of Sideswipe Same Direction Injury Crash Severity

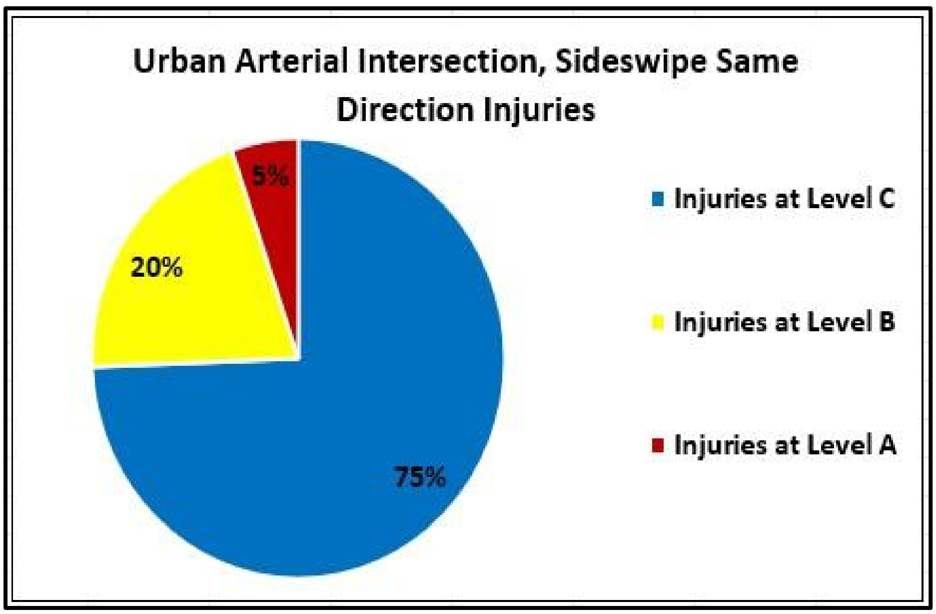

Figure 2.24: Urban Arterial Intersection Distribution of Severity of Sideswipe Same Direction Injuries

Another interesting observation which can be made based on the categories of crashes analyzed here, is that results suggest crashes on rural facilities have higher mean injury crash costs than do those on urban facilities. The implications of these findings may potentially shift additional budgetary resources towards more rural environments because of the increased severity of crashes experienced there.

Implications and Sample Case Studies

As discussed above, the findings of this research indicate a direct relationship between the degree of injury and the average cost of an injury crash. One significant implication of this finding could be the shifting of economic resources towards rural safety projects where crashes experienced are typically more severe. In light of this, several case examples are provided following, in which the differences in benefit-cost outcomes are illustrated when the current composite approach to cost analysis is employed and when an approach which stratifies the cost of an injury crash by degree of injury is employed.

Example 1 – 16th Street & Havana Street, Aurora

The intersection of 16th Street and Havana Street in Aurora is a two lane stop controlled intersection in an urban environment. Broadside crashes were identified as a pattern at the intersection and in the period between June 2017 and May 2018 the intersection was modified from two-way stop controlled on 16th Street only, to all-way stop controlled including additional signing and striping.

Figure 2.25: 16th & Havana April 2015 Facing North

Figure 2.26: 16th & Havana August 2019 Facing North

In the two year period before improvements took place, (1/1/2015 – 12/31/2016), there were 42 total crashes at the intersection, including 25 property damage only (PDO) crashes, 17 Injury crashes (with 29 injuries) and no Fatal crashes (**Table 2.12**). Broadside crashes accounted for over 83% (35 crashes) of all crashes in this period, and over 94% (15 crashes) of all injury crashes and accounted for about 93% (27 injuries) of all persons injured.

Table 2.12: Crash Summary at 16th & Havana, 1/1/15 - 12/21/16

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

03/28/2023

16th — **Type:** Intersection **Details:** 16th / havana **From:** 1/1/2015 **To:** 12/31/2016

Crash Severity

By Crashes:		Number of People:	
FAT:	0	Killed:	0
INJ:	17	Injured:	29
PDO:	25		
TOTAL:	42		

Crash Location

On Road:	42
Off Road Left:	0
Off Road Right:	0
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	42

Weather Conditions

None:	25
Rain:	2
Snow/Sleet/Hail:	0
Fog:	0
Dust:	0
Wind:	0
Unknown:	15
TOTAL:	42

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	35	Embankment:	0
Head On:	0	Curb:	0
Rear End:	4	Delineator Post:	0
Sideswipe (Same):	0	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	0	Large Boulders or Rocks:	0
Overtaking Turn:	3	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	0
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		42
Concrete Barrier:	0		

Lighting Conditions

Daylight:	35
Dawn/Dusk:	2
Dark-Lighted:	5
Dark-Unlighted:	0
Unknown:	0
TOTAL:	42

Road Conditions

Dry:	39
Wet:	2
Muddy:	0
Snowy:	0
Icy:	1
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	42

Number of Vehicles

One Car:	0
Two Car:	35
Three or More:	7
Unknown:	0
TOTAL:	42

Using the existing composite injury crash approach to calculating crash costs as part of benefit-cost analysis, **Table 2.13** shows the anticipated B/C of **712.52** for the conversion to all-way stop control using an estimated cost of $10,000.

Table 2.13: Composite B/C Analysis for All-Way Stop Control at 16th & Havana, 1/1/15 - 12/31/16

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Composite BC 16th — **From:** 1/1/2015 **To:** 12/31/2016 **Street 1:** 16th **Street 2:** havana

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 25	23 :Injured C	CRF for PDO: 61%	Cost of PDO: $11,500
INJ C: 12	6 :Injured B	CRF for INJ C: 61%	Cost of INJ C: $106,100
INJ B: 5	0 :Injured A	CRF for INJ B: 61%	Cost of INJ B: $106,100
INJ A: 0	0 :Killed	CRF for INJ A: 61%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 61%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 8
			Capital Recovery Factor: 0.155
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $10000
Days: 730
Type: Convert 2-Way Stop Control to All-Way Stop Control, Signing & Striping
Notes: All Intersection & Related Crashes. CMF ID#3130
Benefit/Cost Ratio: 712.52

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Figure 2.27 shows the crashes occurring at the intersection in the before period distributed by level of severity. Injury crashes account for over 53% of all crashes with injury level C (Possible Injury) representing the largest proportion of injury crashes.

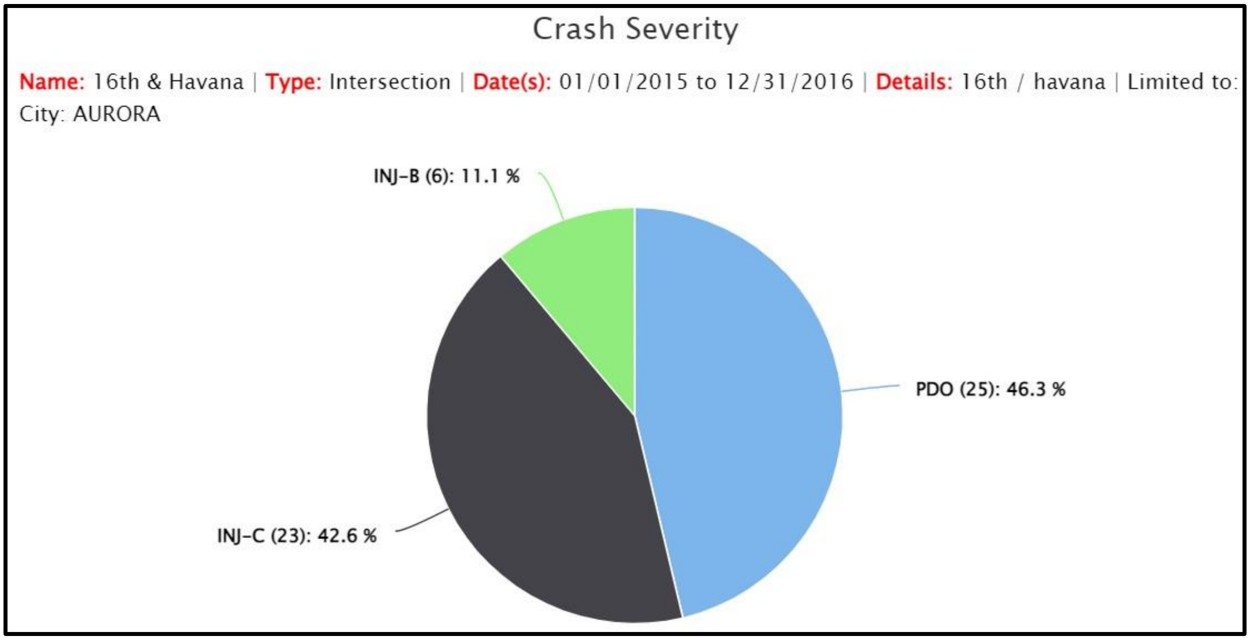

Figure 2.27: Distribution of Crash Severity at 16th & Havana, 1/01/15 – 12/31/16

If crash costs are determined based on the stratified injury levels and the benefit-cost analysis is performed using stratified injury crash costs, using the same estimated cost for improvements of $10,000, **Table 2.14** shows the anticipated B/C becomes **572.77**.

Table 2.14: Stratified B/C Analysis for All-Way Stop Control at 16th & Havana, 1/1/15-12/31/16

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Stratified BC 16th — **From:** 1/1/2015 **To:** 12/31/2016 **Street 1:** 16th **Street 2:** havana

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 25	23 :Injured C	CRF for PDO: 61%	Cost of PDO: $11,500
INJ C: 12	6 :Injured B	CRF for INJ C: 61%	Cost of INJ C: $71,800
INJ B: 5	0 :Injured A	CRF for INJ B: 61%	Cost of INJ B: $127,600
INJ A: 0	0 :Killed	CRF for INJ A: 61%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 61%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 8
			Capital Recovery Factor: 0.155
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $10000
Days: 730
Type: Convert 2-Way Stop Control to All-Way Stop Control, Signing & Striping
Notes: All Intersection & Related Crashes. CMF ID#3130
Benefit/Cost Ratio: 572.77

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

In this instance the stratified approach to B/C analysis does not provide as high a B/C ratio, however if the distribution of crash severity is considered, it is evident that the majority of crashes which occurred were PDO crashes, followed by injury level C crashes, which are the least severe of all injury crash levels. We would expect the stratified approach to calculating B/C to produce a higher B/C ratio in a situation where there were a larger proportional number of higher severity injury crashes, i.e. more crashes at level B and level A. Furthermore, while the B/C ratio resulting from the stratified analysis is lower than that resulting from the composite analysis, this does not necessarily mean that it is not as good, rather the stratified approach is providing a more precise benefit-cost analysis by including the degree of severity as part of the cost calculation, and therefore informing better decision making.

The period for analysis after improvements is the two years between 1/1/2019 – 12/31/2020. In this period there were a total of nine crashes recorded at the intersection, including eight PDO crashes and one Injury crash (with one person injured) (see **Table 2.15**). The number of Broadside crashes accounted for about 66% of all crashes (six crashes), and all six were PDO crashes.

PDO crashes fell 68% from 25 to eight in the after period, Injury level crashes fell 94% from 17 to 1, while the number of injuries fell about 97% from 29 to 1.

Table 2.15: Crash Summary at 16th & Havana, 1/1/19 – 12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

03/28/2023

16th — **Type:** Intersection **Details:** 16th / havana **From:** 1/1/2019 **To:** 12/31/2020

Crash Severity

By Crashes:		Number of People:	
FAT:	0	Killed:	0
INJ:	1	Injured:	1
PDO:	8		
TOTAL:	9		

Crash Location

On Road:	8
Off Road Left:	0
Off Road Right:	1
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	9

Weather Conditions

None:	9
Rain:	0
Snow/Sleet/Hail:	0
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	9

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	6	Embankment:	0
Head On:	0	Curb:	0
Rear End:	0	Delineator Post:	0
Sideswipe (Same):	0	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	1	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	1	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	1
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	1	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		9
Concrete Barrier:	0		

Lighting Conditions

Daylight:	7
Dawn/Dusk:	0
Dark-Lighted:	2
Dark-Unlighted:	0
Unknown:	0
TOTAL:	9

Road Conditions

Dry:	9
Wet:	0
Muddy:	0
Snowy:	0
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	9

Number of Vehicles

One Car:	1
Two Car:	8
Three or More:	0
Unknown:	0
TOTAL:	9

Figure 2.28 shows the distribution of crash severity for the after period. Most crashes were PDO crashes, while the majority of injury crashes were injury level C crashes, "Possible Injury."

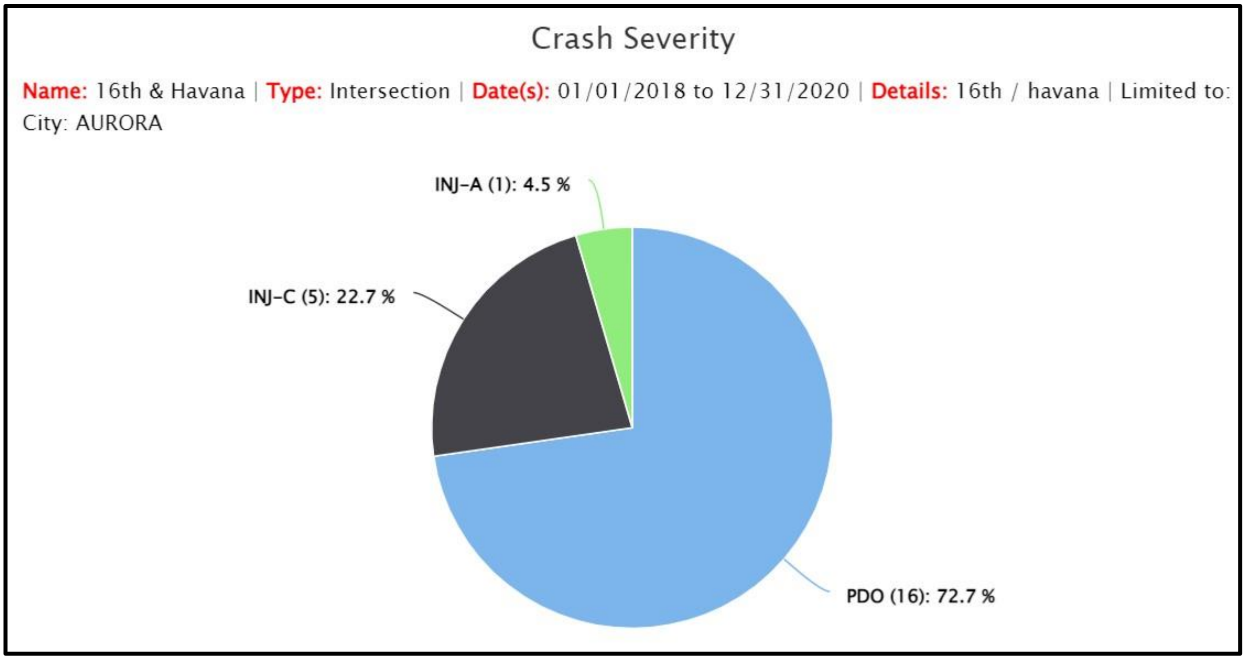

Figure 2.28: Distribution of Crash Severity at 16th & Havana, 1/1/19 – 12/31/20

The magnitude of safety problems on select highway sections and intersections can be assessed through the use of Safety Performance Function (SPF) methodology. An SPF reflects the complex relationship between exposure (measured in ADT) and the crash count for a section of roadway measured in crashes per mile per year (CPMPY) or for an intersection, measured in crashes per year. The SPF models provide an estimate for the expected crash frequency and severity for a range of ADT among similar facilities. This allows for an assessment of the magnitude of the safety problem from a frequency standpoint.

Development of the SPF lends itself well to the conceptual formulation of the Levels of Service of Safety (LOSS). The concept of level of service uses qualitative measures that characterize safety of a roadway segment in reference to its expected performance and severity. If the level of safety predicted by the SPF represents a normal or expected number of crashes at a specific level of ADT, then the degree of deviation from the normal 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

LOSS boundaries are calibrated by computing the 20th and the 80th percentiles using the Gamma Distribution Probability Density Function. Gradual change in the degree of deviation of the LOSS boundary line from the fitted model mean reflects the observed increase of variability in crashes as ADT increases. LOSS reflects how a segment of roadway or intersection is performing in regard to its expected crash frequency at a specific level of ADT.

The SPF plot for total crashes (see **Figure 2.29**) reflects an improvement in the crash record in terms of crash frequency, although it performs in the LOSS-IV category, reflecting high potential for crash reduction, in both the before and after periods. The SPF plot for fatal and injury crashes (see **Figure 2.30**) also reflects a notable improvement in the crash record in terms of severe crashes, performing in the LOSS-IV category, reflecting high potential for crash reduction, in the before period and performing in the LOSS-II category, reflecting low to moderate potential for crash reduction, in the after period. The total crash frequency rate has been reduced by about 70%, while the crash severity rate has been reduced by about 72%.

Figure 2.29: SPF Graph Total Crashes 16th & Havana, Before (1/1/15-12/31/16), After (1/1/19-12/31/20)

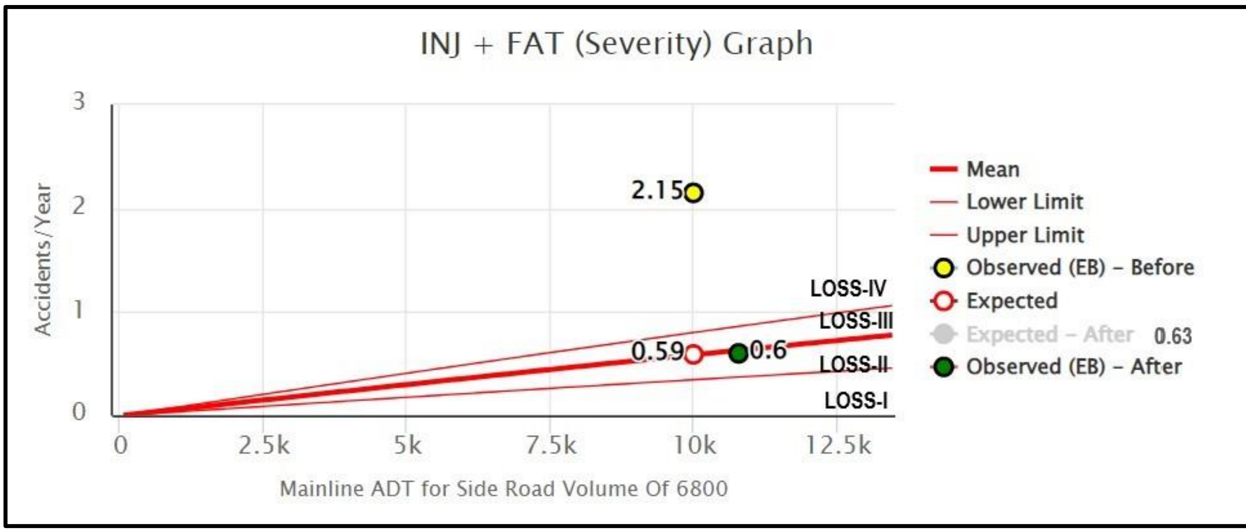

Figure 2.30: SPF Graph INJ+FAT Crashes 16th & Havana, Before (1/1/15-12/31/16), After (1/1/19-12/31/20)

Table 2.16 shows a B/C ratio of **1,104.08** based on the observed reduction in crashes between the before and after period using the composite injury cost approach. Comparatively, **Table 2.17** shows a B/C ratio of **881.85** based on observed reduction in crashes between periods using the stratified injury cost approach. As discussed previously, although the stratified approach on the surface may appear to offer not as good a B/C/ ratio, in fact what is being presented in a much more precise B/C analysis which lends itself to better informed decision making.

Table 2.16: Composite B/C Analysis for Reduction in Crashes at 16th & Havana from 1/1/15-12/31/16 to 1/1/19-12/31/20

CDOT
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Economic Analysis Report

03/28/2023

Composite BCA 16th — **From:** 1/1/2015 **To:** 12/31/2016 **Street 1:** 16th **Street 2:** havana

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 25	23 :Injured C	CRF for PDO: 68%	Cost of PDO: $11,500
INJ C: 12	6 :Injured B	CRF for INJ C: 97%	Cost of INJ C: $106,100
INJ B: 5	0 :Injured A	CRF for INJ B: 97%	Cost of INJ B: $106,100
INJ A: 0	0 :Killed	CRF for INJ A: 97%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 0%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 8
			Capital Recovery Factor: 0.155
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $10000
Days: 730
Type: Convert 2-Way to All-Way Stop Control. All Intersection & Related Crashes.
Notes: CRF based on reduction in crashes between (1/1/15-12/31/16)&(1/1/19-12/31/20)
Benefit/Cost Ratio: 1104.08

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Table 2.17: Stratified B/C Analysis for Reduction in Crashes at 16th & Havana from 1/1/15-12/31/16 to 1/1/19-12/31/20

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Stratified BCA 16th — **From:** 1/1/2015 **To:** 12/31/2016 **Street 1:** 16th **Street 2:** havana

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 25	23 :Injured C	CRF for PDO: 68%	Cost of PDO: $11,500
INJ C: 12	6 :Injured B	CRF for INJ C: 97%	Cost of INJ C: $71,800
INJ B: 5	0 :Injured A	CRF for INJ B: 97%	Cost of INJ B: $127,600
INJ A: 0	0 :Killed	CRF for INJ A: 97%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 0%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 8
			Capital Recovery Factor: 0.155
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $10000
Days: 730
Type: Convert 2-Way to All-Way Stop Control. All Intersection & Related Crashes.
Notes: CRF based on reduction in crashes between (1/1/15-12/31/16)&(1/1/19-12/31/20)
Benefit/Cost Ratio: 881.85

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 2 – US-6 and SH-139, Loma

The intersection of US-6 and SH-139 in Loma is a two-lane four-leg intersection. The intersection is located in a rural environment with a posted speed limit of 45 mph north-south, 40 mph eastbound and 55 mph westbound. Between February and July 2015 approaches to the intersection were widened, a left turn lane was added on each approach and signals were installed to address an observed broadside crash pattern.

Figure 2.31: US6 & SH139 August 2011

Figure 2.32: US6 & SH139 June 2016

In the 5-year period before construction took place, (1/1/2010 – 12/31/2014), there were 13 total crashes at the intersection, including 6 Injury crashes (with 12 injuries) and 7 PDO crashes (**Table 2.18**). Broadside crashes accounted for 92% of all crashes (12 crashes) and 100% of all Injury crashes and injuries occurring in that time.

Table 2.18: Crash Summary at US6 & SH139, 1/1/10 – 12/31/14

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

03/28/2023

US6 — **Type:** Intersection **Details:** Rt: 6 Section: A MM: [15.08 - 15.18] **From:** 1/1/2010 **To:** 12/31/2014

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	6	Injured:	12
PDO:	7		
TOTAL:	13		

Crash Location

On Road:	13
Off Road Left:	0
Off Road Right:	0
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	13

Weather Conditions

None:	13
Rain:	0
Snow/Sleet/Hail:	0
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	13

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	12	Embankment:	0
Head On:	0	Curb:	0
Rear End:	1	Delineator Post:	0
Sideswipe (Same):	0	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	0	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	0
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		13
Concrete Barrier:	0		

Lighting Conditions

Daylight:	9
Dawn/Dusk:	1
Dark-Lighted:	1
Dark-Unlighted:	2
Unknown:	0
TOTAL:	13

Road Conditions

Dry:	13
Wet:	0
Muddy:	0
Snowy:	0
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	13

Number of Vehicles

One Car:	0
Two Car:	12
Three or More:	1
Unknown:	0
TOTAL:	13

Using the existing composite injury crash approach to calculating crash costs as part of benefit-cost analysis, **Table 2.19** shows the anticipated B/C of **1.28** for intersection upgrades including lane widening, addition of left turn lanes and signal installation at US-6 and SH-139 using a project cost of $2,600,155.

Table 2.19: Composite B/C Analysis for Intersection Upgrades at US6 & SH139, 1/1/10 – 12/31/14

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Composite BCA US6 — **Loc:** 6 A **Begin:** 15.08 **End:** 15.18 **From:** 1/1/2010 **To:** 12/31/2014

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 7	7 :Injured C	CRF for PDO: 80%	Cost of PDO: $11,500
INJ C: 4	5 :Injured B	CRF for INJ C: 80%	Cost of INJ C: $106,100
INJ B: 2	0 :Injured A	CRF for INJ B: 80%	Cost of INJ B: $106,100
INJ A: 0	0 :Killed	CRF for INJ A: 80%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 80%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $2600155
Days: 1825
Type: New Signals, Lane Widening, Additional Left Turn Lane all 4 Approaches
Notes: (Composite CRF). All intersection & related crashes.
Benefit/Cost Ratio: 1.28

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Figure 2.33 shows the distribution of crashes by level of severity at the intersection in the before period. The majority of crashes at the intersection are comprised of PDO and Injury level C ("Possible Injury") crashes, with some injury level B crashes ("Evident Injury"), and no injury level A ("Incapacitating Injury") crashes.

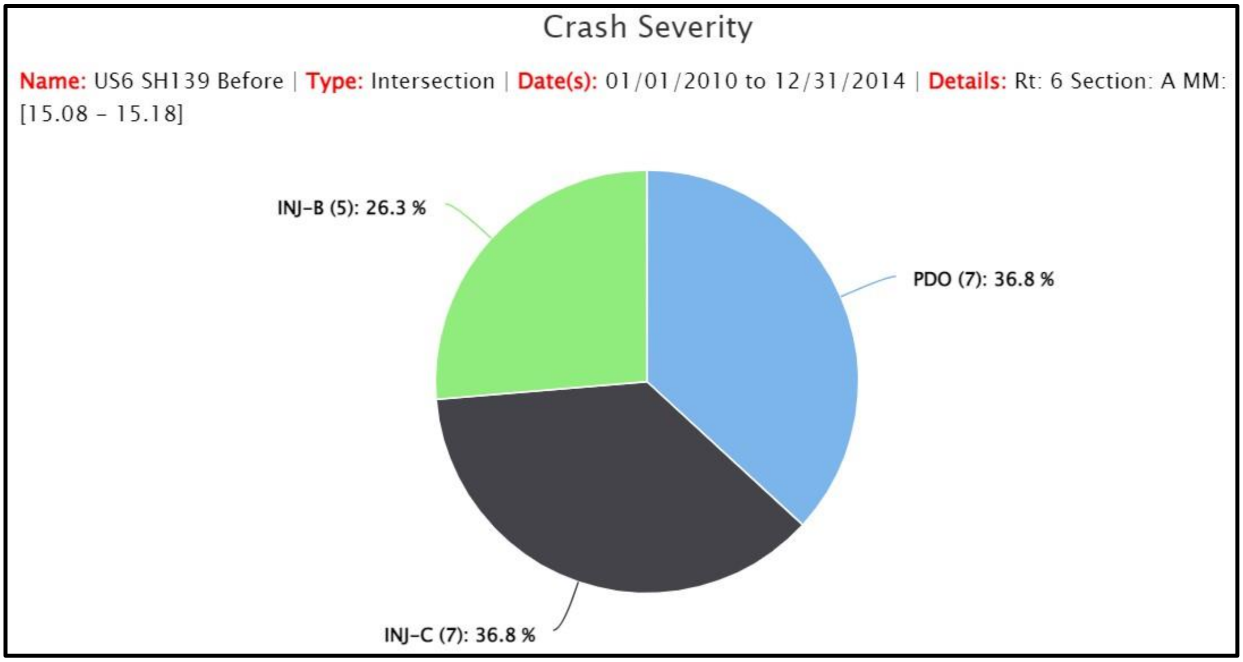

Figure 2.33: Crash Distribution by Severity at US6 & SH139, 1/1/10 – 12/31/14

If crash costs are determined based on the stratified injury levels, using the same project cost for improvements of $2,600,155, **Table 2.20** shows the anticipated B/C ratio becomes **1.15**. Similar to the previous example, the stratified approach to calculating a B/C ratio returns a smaller B/C ratio. This again reflects the sensitivity of the stratified approach to the degree of severity of the crashes, which in this case is weighted towards the lower-level injury crashes, with no crashes at the higher level 'A' present. In this way the stratified approach offers a more precise calculation.

Table 2.20: Stratified B/C Analysis for Intersection Upgrades at US6 & SH139, 1/1/10 – 12/31/14

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Stratified BCA US6 — **Loc:** 6 A **Begin:** 15.08 **End:** 15.18 **From:** 1/1/2010 **To:** 12/31/2014

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 7	7 :Injured C	CRF for PDO: 80%	Cost of PDO: $11,500
INJ C: 4	5 :Injured B	CRF for INJ C: 80%	Cost of INJ C: $71,800
INJ B: 2	0 :Injured A	CRF for INJ B: 80%	Cost of INJ B: $127,600
INJ A: 0	0 :Killed	CRF for INJ A: 80%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 80%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $2600155
Days: 1825
Type: New Signals, Lane Widening, Additional Left Turn Lane all 4 Approaches
Notes: (Composite CRF). All intersection & related crashes.
Benefit/Cost Ratio: 1.15

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

In the five-year period after improvements were made, (1/1/2016 – 12/31/2020), there were a total of six crashes recorded at the intersection, including two PDO crashes and four Injury crashes (with four people injured) (**Table 2.21**). The number of Broadside crashes accounted for 50% of all crashes and 50% of both the number of injury crashes and the number of people injured.

Table 2.21: Crash Summary at US6 & SH139, 1/1/16 – 12/31/20

CDOT
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General Summary Report

03/28/2023

US6 **Type:** Intersection **Details:** Rt: 6 Section: A MM: [15.08 - 15.18] **From:** 1/1/2016 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	4	Injured:	4
PDO:	2		
TOTAL:	6		

Crash Location

On Road:	6
Off Road Left:	0
Off Road Right:	0
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	6

Weather Conditions

None:	6
Rain:	0
Snow/Sleet/Hail:	0
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	6

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	3	Embankment:	0
Head On:	0	Curb:	0
Rear End:	0	Delineator Post:	0
Sideswipe (Same):	0	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	3	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	0
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		6
Concrete Barrier:	0		

Lighting Conditions

Daylight:	5
Dawn/Dusk:	0
Dark-Lighted:	1
Dark-Unlighted:	0
Unknown:	0
TOTAL:	6

Road Conditions

Dry:	5
Wet:	1
Muddy:	0
Snowy:	0
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	6

Number of Vehicles

One Car:	0
Two Car:	6
Three or More:	0
Unknown:	0
TOTAL:	6

Figure 2.34 shows the distribution of crashes by level of severity at the intersection in the after period. Injury crashes make up over 66% of all crashes, with all being at the injury level C ("Possible Injury") level.

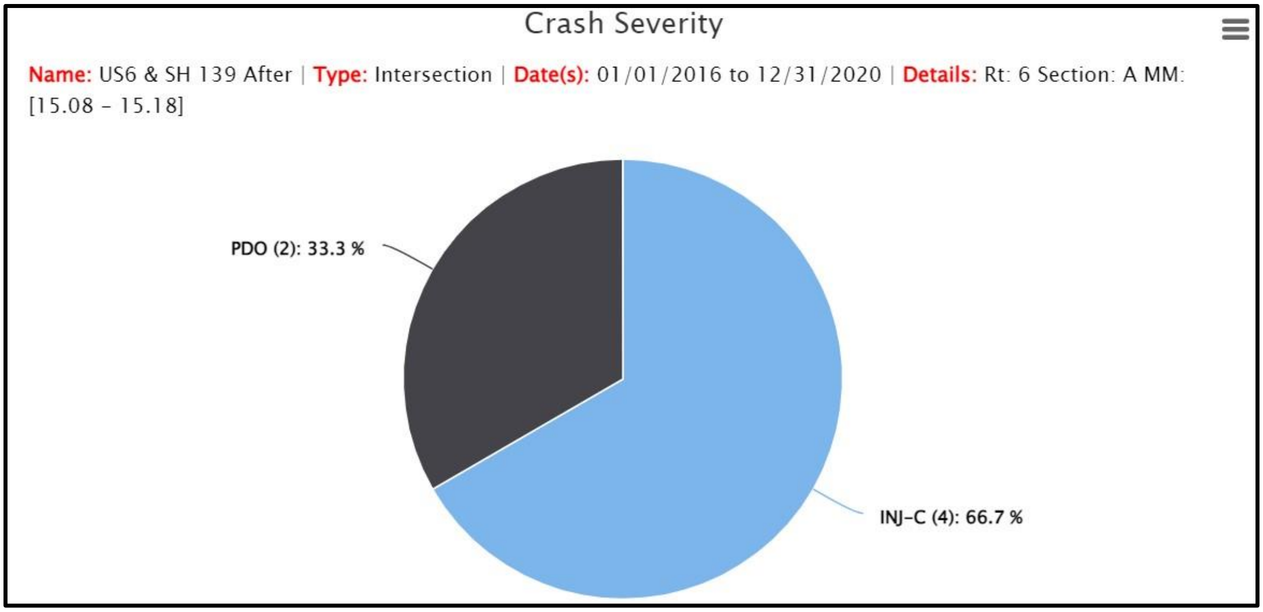

Figure 2.34: Crash Distribution by Severity at US6 & US139, 1/1/16 – 12/31/20

The SPF plot for total crashes (see **Figure 2.35**) reflects an improvement in the crash record in terms of crash frequency, although it performs in the LOSS-IV category, reflecting high potential for crash reduction, in both the before and after periods. The SPF plot for fatal and injury crashes (see **Figure 2.36**) also reflects an improvement in the crash record in terms of severe crashes, although it performs in the LOSS-IV category, reflecting high potential for crash reduction, in both the before and after periods. Total crash frequency has been reduced by about 49%. Crash severity has been reduced by about 29%.

Figure 2.35: SPF Graph Total Crashes US6 & SH139, Before (1/1/10-12/31/14), After (1/1/16-12/31/20)

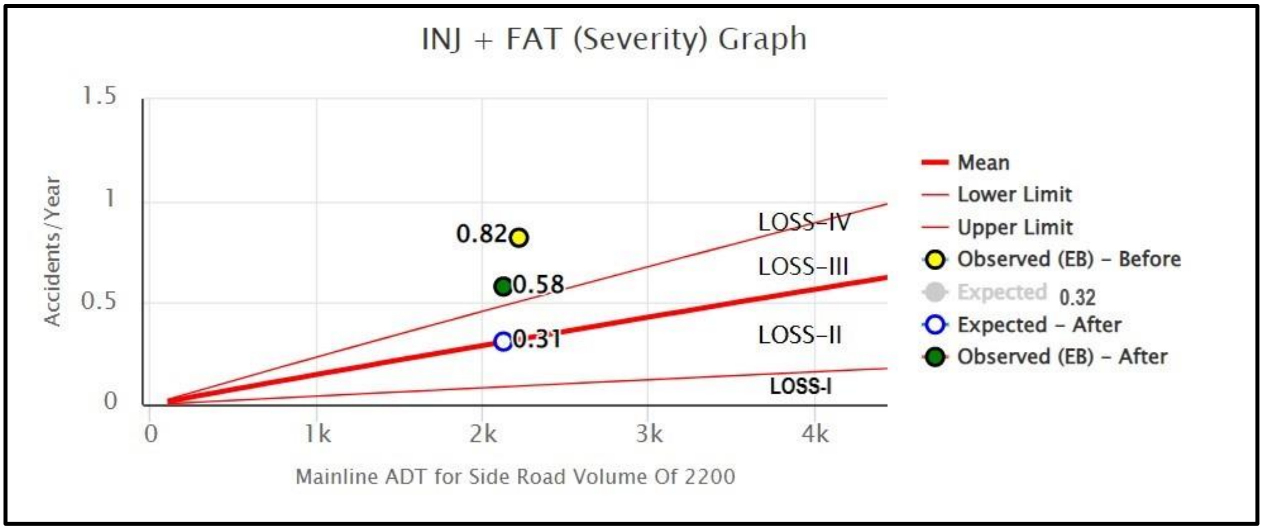

Figure 2.36: SPF Graph INJ+FAT Crashes US6 & SH139, Before (1/1/10-12/31/14), After (1/1/16-12/31/20)

PDO crashes fell about 71% from 7 in the before period to 2 in the after period, Injury level crashes fell about 33% from 6 to 4 between periods, while the number of injuries fell about 67% from 12 to 4. **Table 2.22** shows a B/C ratio of **1.07** based on the observed reduction in crashes between the before and after period using the existing composite injury cost approach.

Table 2.22: Composite B/C Analysis US6 & SH139, Before (1/1/10-12/31/14), After (1/1/16–12/31/20)

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Composite BCA US6 — **Loc:** 6 A **Begin:** 15.08 **End:** 15.18 **From:** 1/1/2010 **To:** 12/31/2014

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 7	7 :Injured C	CRF for PDO: 71%	Cost of PDO: $11,500
INJ C: 4	5 :Injured B	CRF for INJ C: 67%	Cost of INJ C: $106,100
INJ B: 2	0 :Injured A	CRF for INJ B: 67%	Cost of INJ B: $106,100
INJ A: 0	0 :Killed	CRF for INJ A: 67%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 0%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $2600155
Days: 1825
Type: New Signals, Lane Widening, Add'l LT Lane all 4 Approaches. Intersection & related crashes
Notes: CRF based on crash reduction between (1/1/10-12/31/14)&(1/1/16-12/31/20)
Benefit/Cost Ratio: 1.07

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

When the benefit-cost analysis is performed using stratified injury costs, **Table 2.23** shows a B/C ratio of **0.97** based on the observed reduction in crashes between the before and after period. Again, the stratified approach to calculating a B/C ratio returns a smaller B/C ratio, with this being a more precise calculation reflecting a greater sensitivity to the degree of severity of the crashes in the before period, which in this case is weighted more towards less severe injuries and PDO crashes.

Table 2.23: Stratified B/C Analysis US6 & SH139, Before (1/1/10-12/31/14), After (1/1/16 – 12/31/20)

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Stratified BCA US6 — **Loc:** 6 A **Begin:** 15.08 **End:** 15.18 **From:** 1/1/2010 **To:** 12/31/2014

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 7	7 :Injured C	CRF for PDO: 71%	Cost of PDO: $11,500
INJ C: 4	5 :Injured B	CRF for INJ C: 67%	Cost of INJ C: $71,800
INJ B: 2	0 :Injured A	CRF for INJ B: 67%	Cost of INJ B: $127,600
INJ A: 0	0 :Killed	CRF for INJ A: 67%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 0%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $2600155
Days: 1825
Type: New Signals, Lane Widening, Add'l LT Lane all 4 Approaches. Intersection & related crashes
Notes: (Composite CRF) based on crash reduction between (1/1/10-12/31/14)&(1/1/16-12/31/20)
Benefit/Cost Ratio: 0.97

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 3 – SH-34 and 83rd Avenue, MP 105.86-105.96, Greeley

The intersection of SH-34 and 83rd Avenue is located in a rural high-speed environment where the posted speed limit is 65mph. The intersection is a four-lane four-leg divided intersection. Broadside crashes were identified as a problem at this location and in 2017 signalization was provided at the intersection to address the problem.

Figure 2.37: SH34 & 83rd Avenue July 2012 Facing North

Figure 2.38: SH34 & 83rd Avenue July 2019 Facing North

Crash history records show that in the 3-year period before improvements took place, (1/1/2014 – 12/31/2016), there were 44 total crashes at the intersection, including 20 PDO, 24 Injury crashes (with 39 people injured), and no Fatal crashes (**Table 2.24**). Broadside crashes accounted for 77% of all crashes at the intersection, and about 92% of Injury crashes (22 crashes) and about 90% of all injuries (35 injuries).

Table 2.24: Summary of Crashes at SH34 & 83rd Ave, 1/1/14 - 12/31/16

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

03/28/2023

General Summary SH34 — **Type:** Intersection **Details:** Rt: 34 Section: A MM: [105.86 - 105.96] **From:** 1/1/2014 **To:** 12/31/2016

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	24	Injured:	39
PDO:	20		
TOTAL:	44		

Crash Location

On Road:	42
Off Road Left:	1
Off Road Right:	1
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	44

Weather Conditions

None:	38
Rain:	2
Snow/Sleet/Hail:	2
Fog:	1
Dust:	0
Wind:	1
Unknown:	0
TOTAL:	44

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	34	Embankment:	0
Head On:	0	Curb:	0
Rear End:	1	Delineator Post:	1
Sideswipe (Same):	2	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	4	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	1	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	2
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	1	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		44
Concrete Barrier:	0		

Lighting Conditions

Daylight:	31
Dawn/Dusk:	3
Dark-Lighted:	6
Dark-Unlighted:	4
Unknown:	0
TOTAL:	44

Road Conditions

Dry:	39
Wet:	2
Muddy:	0
Snowy:	2
Icy:	0
Slushy:	1
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	44

Number of Vehicles

One Car:	2
Two Car:	36
Three or More:	6
Unknown:	0
TOTAL:	44

Using the existing composite approach to calculating crash costs as part of benefit-cost analysis, **Table 2.25** shows a B/C of **52.41** for conversion to a signalized intersection using an estimated cost of $300,000. Benefit-cost analysis is based on the reduction in broadside crashes.

Table 2.25: Composite B/C Analysis for SH34 & 84th Ave, 1/1/14 – 12/31/16

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Composite BCA SH34 — **Loc:** 34 A **Begin:** 105.86 **End:** 105.96 **From:** 1/1/2014 **To:** 12/31/2016

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 12	23 :Injured C	CRF for PDO: 80%	Cost of PDO: $11,500
INJ C: 14	8 :Injured B	CRF for INJ C: 80%	Cost of INJ C: $106,100
INJ B: 5	4 :Injured A	CRF for INJ B: 80%	Cost of INJ B: $106,100
INJ A: 3	0 :Killed	CRF for INJ A: 80%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 80%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $300000
Days: 1095
Type: New Signals
Notes: Broadside Crashes Only
Benefit/Cost Ratio: 52.41

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Figure 2.39 below shows the breakdown of broadside crashes by severity at the intersection in the before period. Almost 75% of all crashes are injury level crashes, with the largest proportion of those being injury level C (“Possible Injury”) crashes, however injury level B (“Evident Injury”) is well represented there are also injury level A (“Incapacitating Injury”) crashes present.

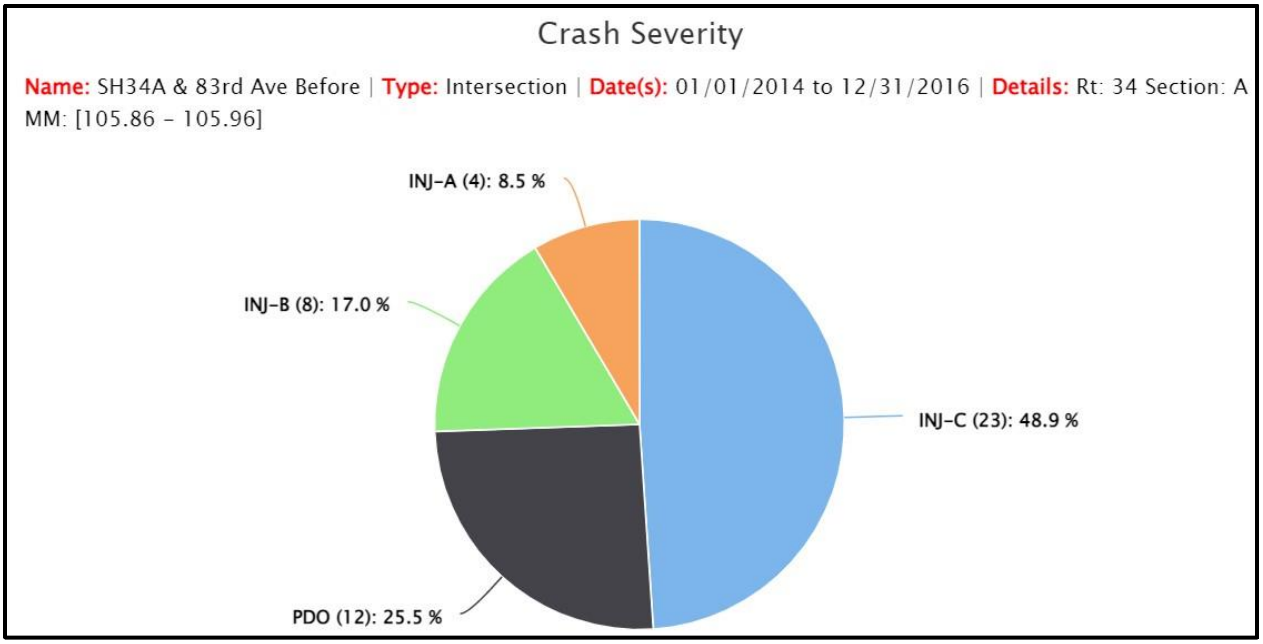

Figure 2.39: Crash Distribution by Severity at SH34 & 83rd Ave, 1/1/14 – 12/31/16

If crash costs are determined based on the stratified injury level costs, then **Table 2.26** shows the anticipated B/C ratio becomes **57.27**. This result is 9% higher than the estimated B/C ratio obtained using the traditional composite approach. Due to the predominance of injury level C crashes, this is not a dramatic difference, but it could be significant when decisions need to be made on the allocation of limited budgetary resources.

Table 2.26: Stratified B/C Analysis SH-34 & 83rd Ave, 1/1/14 – 12/31/16

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Stratified BCA SH34 — **Loc:** 34 A **Begin:** 105.86 **End:** 105.96 **From:** 1/1/2014 **To:** 12/31/2016

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 12	23 :Injured C	CRF for PDO: 80%	Cost of PDO: $11,500
INJ C: 14	8 :Injured B	CRF for INJ C: 80%	Cost of INJ C: $71,800
INJ B: 5	4 :Injured A	CRF for INJ B: 80%	Cost of INJ B: $127,600
INJ A: 3	0 :Killed	CRF for INJ A: 80%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 80%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $300000
Days: 1095
Type: New Signals
Notes: Broadside Crashes Only
Benefit/Cost Ratio: 57.27

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

In the 3-year after period (1/1/2018 – 12/31/2020), records show PDO crashes increased 10% to 22 crashes, while the number of Injury crashes fell 58% from 24 to 10 and the number of injuries fell 56% from 39 to 17, and there were no Fatal crashes (**Table 2.27**). The number of Broadside crashes fell to a total of four (12.5% of all crashes). The number of Injury level broadsides fell to three (30% of all injury crashes), while the number of people injured in broadside crashes fell to five (29% of all injuries).

Table 2.27: Summary of Crashes at SH34 & 83rd Ave, 1/1/18- 12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

03/28/2023

General Summary SH34 — **Type:** Intersection **Details:** Rt: 34 Section: A MM: [105.86 - 105.96] **From:** 1/1/2018 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	10	Injured:	17
PDO:	22		
TOTAL:	32		

Crash Location

On Road:	31
Off Road Left:	0
Off Road Right:	1
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	32

Weather Conditions

None:	30
Rain:	1
Snow/Sleet/Hail:	1
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	32

Crash Type

Overturning:	1	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	4	Embankment:	0
Head On:	0	Curb:	0
Rear End:	21	Delineator Post:	0
Sideswipe (Same):	1	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	3	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	1
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	1	Involving Other Object:	1
Bridge Rail:	0	Total Other Object:	1
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		32
Concrete Barrier:	0		

Lighting Conditions

Daylight:	22
Dawn/Dusk:	3
Dark-Lighted:	5
Dark-Unlighted:	2
Unknown:	0
TOTAL:	32

Road Conditions

Dry:	29
Wet:	2
Muddy:	0
Snowy:	1
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	32

Number of Vehicles

One Car:	2
Two Car:	23
Three or More:	7
Unknown:	0
TOTAL:	32

Figure 2.40 shows the distribution of crashes by severity in the after period at SH-34 and 83rd Avenue. The majority of crashes are PDO crashes, and injury level C crashes comprise the largest proportion of injury level crashes.

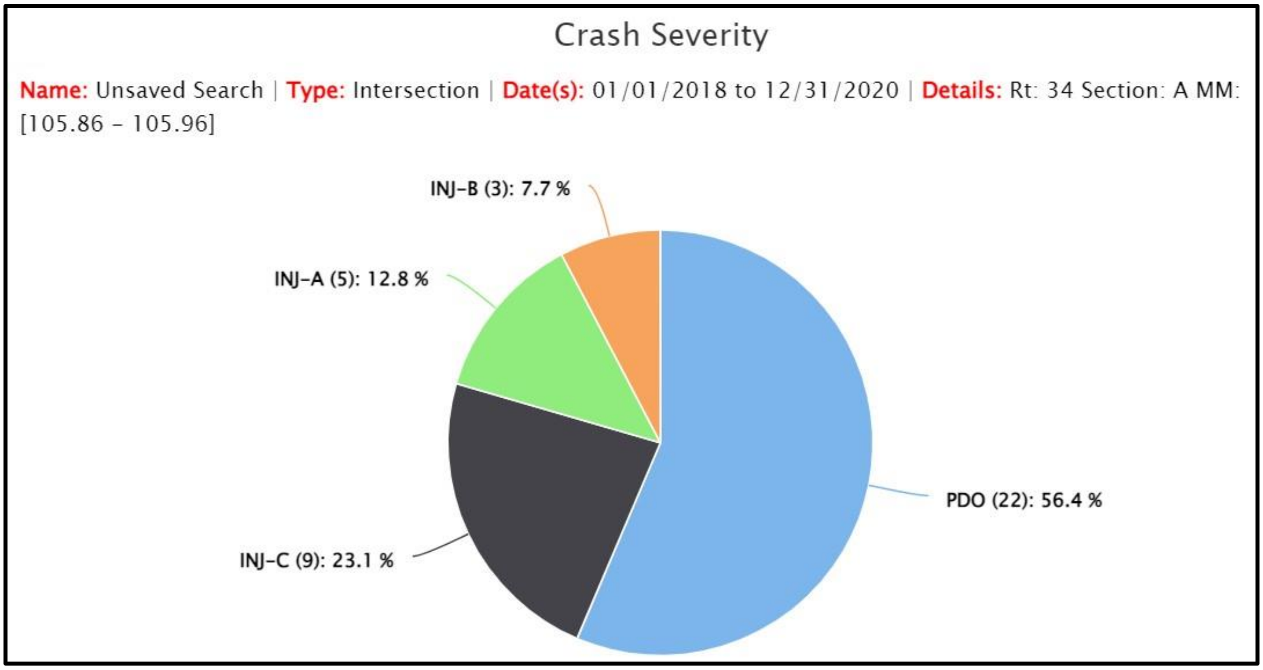

Figure 2.40: Crash Severity Distribution at SH34 & 83rd Ave, 1/1/18 – 12/31/20

The SPF plot for total crashes (see **Figure 2.41**) reflects an improvement in the crash record in terms of crash frequency, although it performs in the LOSS-IV category, reflecting high potential for crash reduction, in both the before and after periods. The SPF plot for fatal and injury crashes (see **Figure 2.42**) reflects a more notable improvement in the crash record in terms of severe crashes, although it performs in the LOSS-IV category, reflecting high potential for crash reduction, in both the before and after periods. Total crash frequency has been reduced by about 25% from what was expected if nothing had changed. Crash severity has been reduced by about 51% from what was expected if nothing had changed.

Figure 2.41: SPF Graph Total Crashes SH34 & 83rd Ave, Before (1/1/14-12/31/16), After (1/1/18-12/31/20)[1]

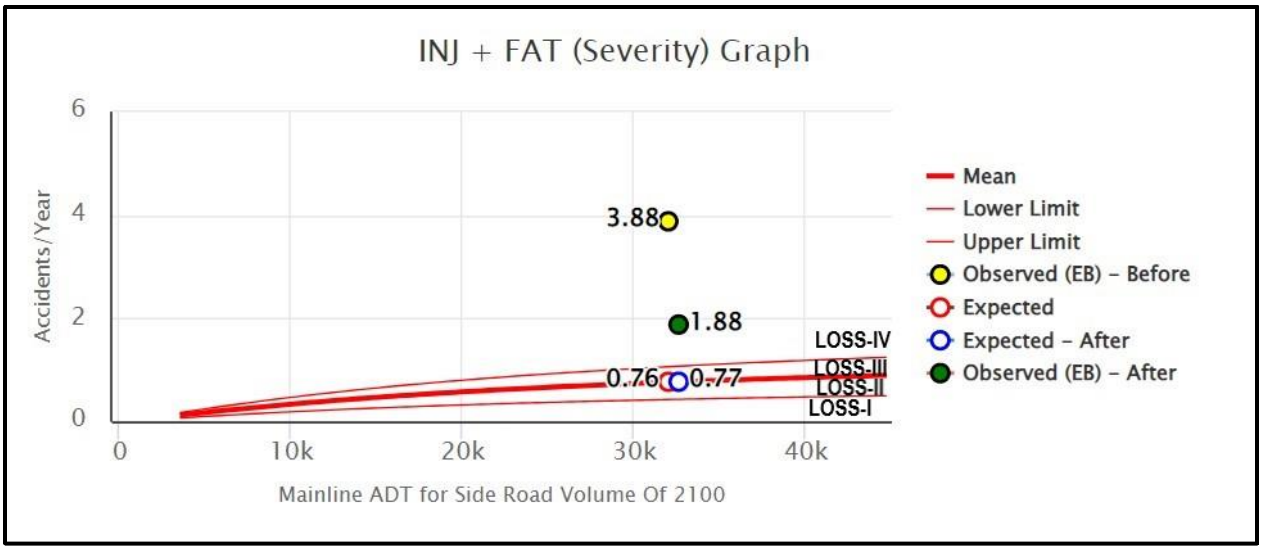

Figure 2.42: SPF Graph INJ+FAT Crashes, SH34 & 83rd Ave, Before (1/1/14-12/31/16), After (1/1/18-12/31/20)[1]

Table 2.28 shows a B/C ratio of **56.48** based on the observed reduction in crashes between the before and after period using the composite injury cost approach.

[1] SPF models have not yet been developed for Colorado Rural 4-lane 4-leg Divided Unsignalized Intersections; therefore, a proxy model of CO Urban 4-lane 4-leg Divided Unsignalized Intersections has been used which provides a close fit for illustration.

Table 2.28: Composite B/C Analysis SH-34 & 83rd Ave, Before (1/1/14-12/31/16), After (1/1/18-12/31/20)

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Composite BCA SH34 — **Loc:** 34 A **Begin:** 105.86 **End:** 105.96 **From:** 1/1/2014 **To:** 12/31/2016

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 12	23 :Injured C	CRF for PDO: 92%	Cost of PDO: $11,500
INJ C: 14	8 :Injured B	CRF for INJ C: 86%	Cost of INJ C: $106,100
INJ B: 5	4 :Injured A	CRF for INJ B: 86%	Cost of INJ B: $106,100
INJ A: 3	0 :Killed	CRF for INJ A: 86%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 0%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $300000
Days: 1095
Type: New Signals. Broadside Crashes Only.
Notes: CRF Based on BS crash reduction between (1/1/14-12/31/16)& (1/1/18-12/31/20)
Benefit/Cost Ratio: 56.48

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Table 2.29 indicates a B/C ratio of **61.71** when costs are calculated according to stratified injury level. This represents a B/C ratio approximately 9% higher than that using the composite approach. Again, this indicates the greater sensitivity of the stratified approach to the varying degree of severities of crashes in the before period, on which the B/C is based. Crashes occurring across levels C, B and A with increasing severity are accounted for more precisely with the stratified approach.

Table 2.29: Stratified B/C Analysis SH-34 & 83rd Ave, Before (1/1/14-12/31/16), After (1/1/18-12/31/20)

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/28/2023

Stratified BCA SH34 — **Loc:** 34 A **Begin:** 105.86 **End:** 105.96 **From:** 1/1/2014 **To:** 12/31/2016

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 12	23 :Injured C	CRF for PDO: 92%	Cost of PDO: $11,500
INJ C: 14	8 :Injured B	CRF for INJ C: 86%	Cost of INJ C: $71,800
INJ B: 5	4 :Injured A	CRF for INJ B: 86%	Cost of INJ B: $127,600
INJ A: 3	0 :Killed	CRF for INJ A: 86%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 0%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $300000
Days: 1095
Type: New Signals. Broadside Crashes Only.
Notes: CRF Based on BS crash reduction between (1/1/14-12/31/16)& (1/1/18-12/31/20)
Benefit/Cost Ratio: 61.71

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 4 – Dahlia Street and I-76 Frontage Road, Commerce City

The intersection of Dahlia Street and I-76 Frontage Road is a four-leg four-lane two-way stop controlled undivided intersection in an urban environment. The intersection demonstrates an Injury crash pattern, as well as a Broadside crash pattern and a pattern of crashes involving multiple vehicles. A potential solution to the crash patterns seen at this location could be a roundabout.

Figure 2.43: Dahlia Street & I-76 Frontage Road

Figure 2.44: Dahlia St. & I-76 Frontage Rd. June 2021, Facing East

Crash records indicate that in the 5-year period between 01/01/2016-12/31/2020 there were 49 crashes recorded at the intersection, including 26 PDO crashes, 23 Injury crashes (with 34 people injured) and no Fatal crashes (**Table 2.30**). Injury crashes accounted for over 46% of all crashes at the intersection. There were 38 Broadside crashes accounting for about 78% of all crashes, about 87% of all injury crashes and about 91% of all injuries.

Table 2.30: Crash Summary at Dahlia St. & I-76 Frontage Rd., 1/1/16-12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

03/31/2023

I-76 — **Type:** Intersection **Details:** i-76 / dahlia **From:** 1/1/2016 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	23	Injured:	34
PDO:	26		
TOTAL:	49		

Crash Location

On Road:	48
Off Road Left:	0
Off Road Right:	1
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	49

Weather Conditions

None:	48
Rain:	1
Snow/Sleet/Hail:	0
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	49

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	38	Embankment:	0
Head On:	0	Curb:	0
Rear End:	4	Delineator Post:	0
Sideswipe (Same):	1	Fence:	1
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	5	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	1
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		49
Concrete Barrier:	0		

Lighting Conditions

Daylight:	29
Dawn/Dusk:	6
Dark-Lighted:	6
Dark-Unlighted:	8
Unknown:	0
TOTAL:	49

Road Conditions

Dry:	49
Wet:	0
Muddy:	0
Snowy:	0
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	49

Number of Vehicles

One Car:	1
Two Car:	39
Three or More:	9
Unknown:	0
TOTAL:	49

Figure 2.45 shows the distribution of crash severity at the intersection over the five-year period. Injury level C crashes are the most predominant crash level.

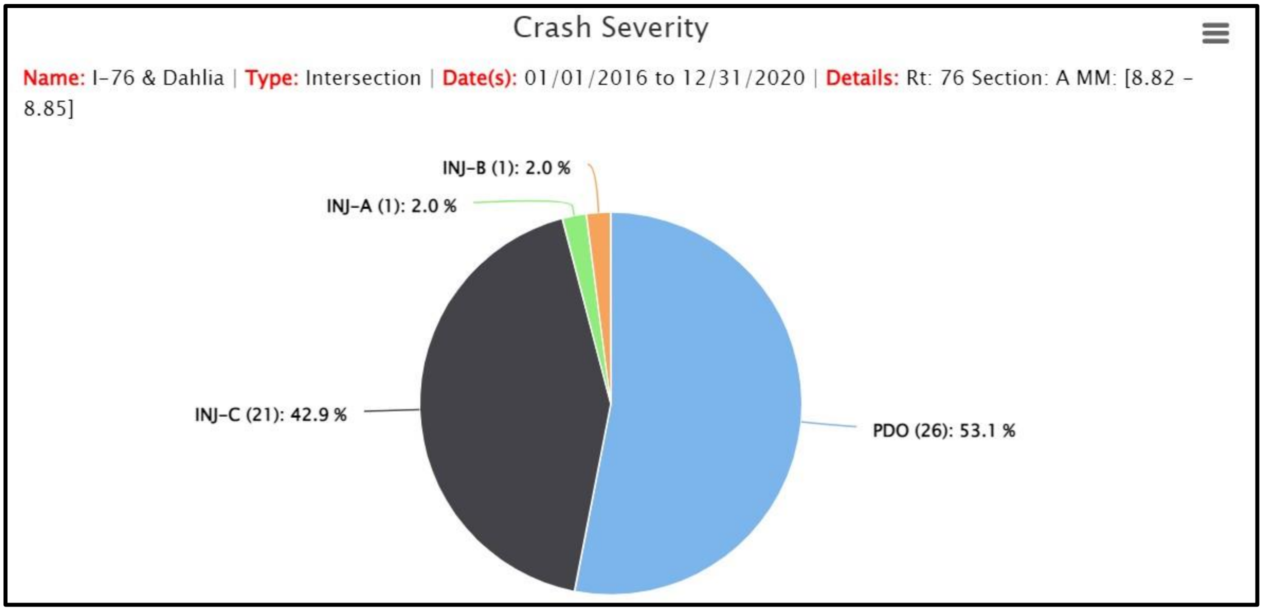

Figure 2.45: Crash Severity Distribution at Dahlia St. & I-76 Frontage Rd., 1/1/16-12/31/20

Figure 2.46 and **Figure 2.47** show the facility is operating in the LOSS-IV category from both the total crash frequency standpoint and the crash severity standpoint, reflecting high potential for crash reduction.

Figure 2.46: SPF Total Crashes at Dahlia & I-76 Frontage Rd., 1/1/16-12/31/20

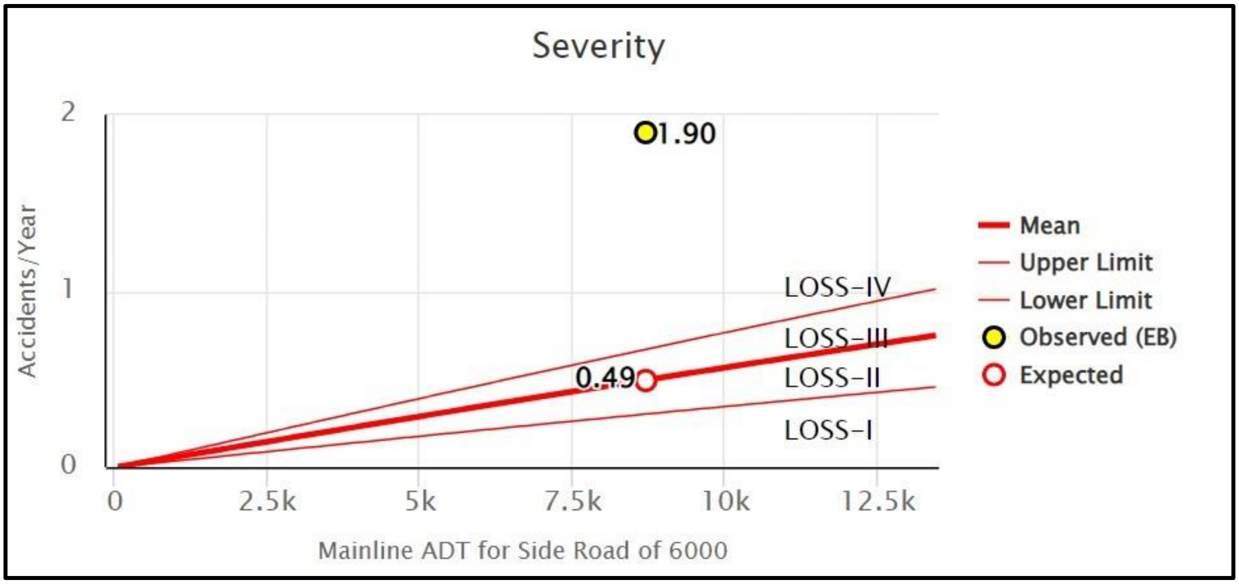

Figure 2.47: SPF INJ+FAT Crashes at Dahlia & I-76 Frontage Rd., 1/1/16-12/31/20

To address a pattern of high severity broadside crashes and crashes involving multiple vehicles at an intersection facility such as this, replacement of the intersection with a roundabout would be a suitable mitigation measure. **Table 2.31** shows a B/C ratio of **2.90** using an estimated cost of $3M for replacement of the intersection with a roundabout using the existing composite approach to injury cost.

Table 2.31: Composite B/C Analysis for Roundabout at Dahlia St. & I-76 Frontage Rd.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/31/2023

Composite BCA I-76 — **From:** 1/1/2016 **To:** 12/31/2020 **Street 1:** I-76 **Street 2:** DAHLIA

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 26	28 :Injured C	CRF for PDO: 35%	Cost of PDO: $11,500
INJ C: 21	5 :Injured B	CRF for INJ C: 76%	Cost of INJ C: $106,100
INJ B: 1	1 :Injured A	CRF for INJ B: 76%	Cost of INJ B: $106,100
INJ A: 1	0 :Killed	CRF for INJ A: 76%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 76%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $3000000
Days: 1826
Type: Replace with Roundabout
Notes: All intersection & related crashes
Benefit/Cost Ratio: 2.9

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

If stratified injury levels are used to determine costs, the stratified benefit-cost analysis in **Table 2.32** shows a B/C ratio of **2.43**. As witnessed with other case examples, the lower B/C ratio reflects the higher proportion of low severity crashes at the PDO level and injury level C which occurred.

Table 2.32: Stratified B/C Analysis for Roundabout at Dahlia St. & I-76 Frontage Rd.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

03/31/2023

Stratified BCA I-76 — **From:** 1/1/2016 **To:** 12/31/2020 **Street 1:** I-76 **Street 2:** DAHLIA

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 26	28 :Injured C	CRF for PDO: 35%	Cost of PDO: $11,500
INJ C: 21	5 :Injured B	CRF for INJ C: 76%	Cost of INJ C: $71,800
INJ B: 1	1 :Injured A	CRF for INJ B: 76%	Cost of INJ B: $127,600
INJ A: 1	0 :Killed	CRF for INJ A: 76%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 76%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $3000000
Days: 1826
Type: Replace with Roundabout
Notes: All intersection & related crashes
Benefit/Cost Ratio: 2.43

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 5 – Lookout Mountain Road (59135651A) MP 0.00-6.69, Jefferson County

Lookout Mountain Road is a two-lane rural mountainous road in Jefferson County. It has narrow shoulders and no rumble strips. Crash records for the roadway segment show crashes involving motorcycles are overrepresented at 29.4%. In the five-year period between 01/01/2016 – 12/31/2020, there were a total of nine motorcycle crashes, which included two PDO crashes and seven Injury crashes with eight people injured (**Table 2.33**). All of the motorcycle involved crashes were run off the road crash types (head-on, overturning, guard rail).

Figure 2.48: Typical Section Lookout Mountain Road, Eastbound July 2019

Table 2.33: Motorcycle Involved Crash Summary on Lookout Mountain Road, 1/1/16-12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

04/03/2023

General Summary Lookout Mountain Road — **Type:** Segment **Details:** Rt: 59135651 Section: A MM: [0 - 6.69] **From:** 1/1/2016 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	7	Injured:	8
PDO:	2		
TOTAL:	9		

Crash Location

On Road:	3
Off Road Left:	0
Off Road Right:	6
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	9

Weather Conditions

None:	8
Rain:	1
Snow/Sleet/Hail:	0
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	9

Crash Type

Overturning:	6	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	0	Embankment:	0
Head On:	1	Curb:	0
Rear End:	0	Delineator Post:	0
Sideswipe (Same):	0	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	0	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	2
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	2	**TOTAL:**	0
Cable Rail:	0		9
Concrete Barrier:	0		

Lighting Conditions

Daylight:	5
Dawn/Dusk:	4
Dark-Lighted:	0
Dark-Unlighted:	0
Unknown:	0
TOTAL:	9

Road Conditions

Dry:	8
Wet:	1
Muddy:	0
Snowy:	0
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	9

Number of Vehicles

One Car:	8
Two Car:	1
Three or More:	0
Unknown:	0
TOTAL:	9

Figure 2.49 shows the corridor SPF for the entire roadway segment from MP 0.00 to MP 6.69. The graph indicates that from MP 0.00-2.5 approximately, the roadway performs at the LOSS-II level from both the total crash frequency and the crash severity standpoint, which represents low to moderate potential for crash reduction. Between MP 2.5-6.69 however, the performance of the roadway shifts between LOSS-III and LOSS-IV from both the total crash frequency and the crash severity standpoint, representing moderate to high potential for crash reduction and high potential for crash reduction, respectively.

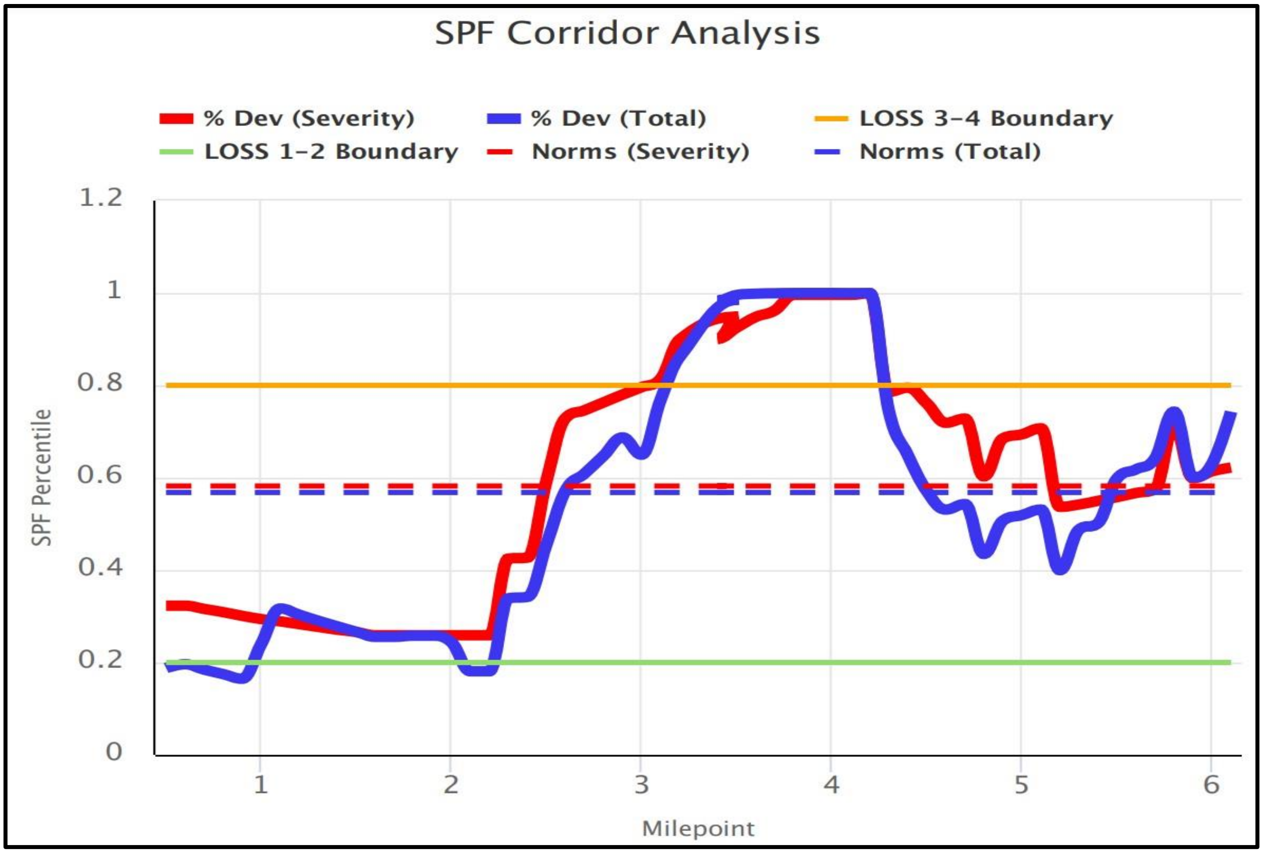

Figure 2.49: SPF Graph Total & INJ+FAT Crashes Lookout Mountain Road 1/1/16-12/31/20

Figure 2.50 shows that motorcycle involved crashes were recorded between MP 3.04 and MP 6.60. These crashes showed a pattern of single vehicle run off the road crashes.

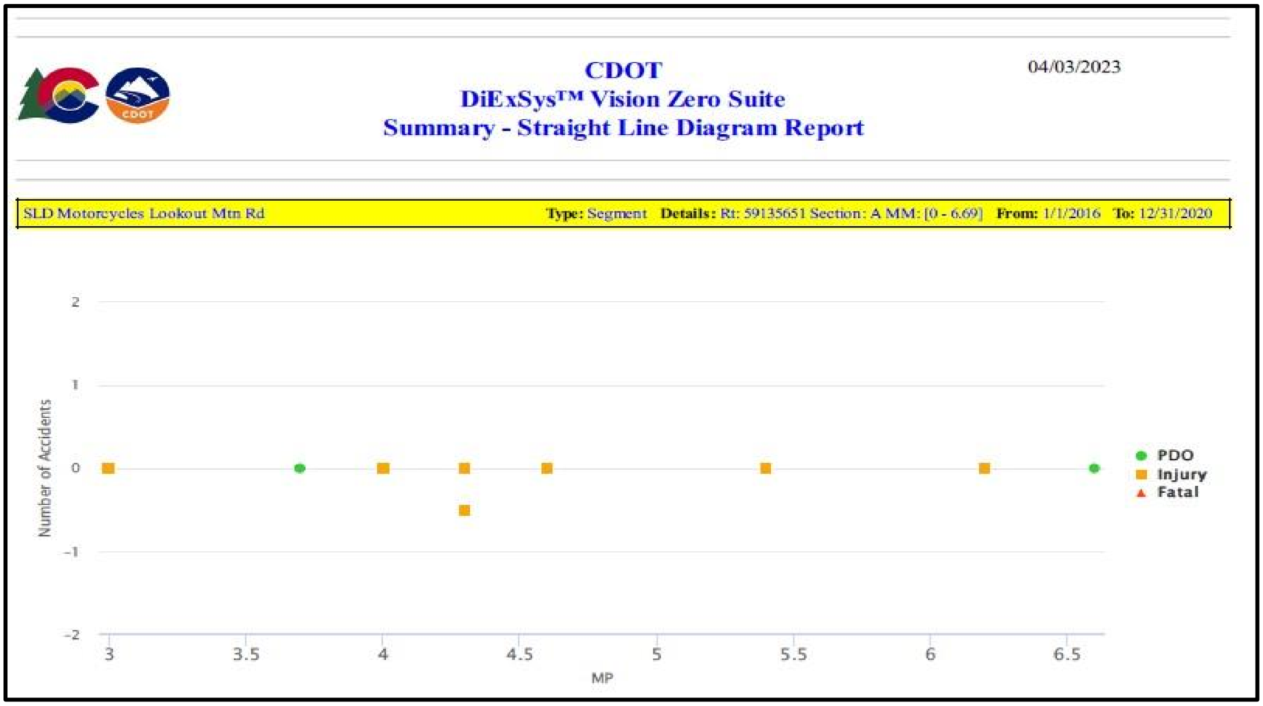

Figure 2.50: Straight Line Diagram for Motorcycle Involved Crashes Lookout Mountain Rd

A possible mitigation measure to the pattern seen here would be the placement of "MOTORCYCLES USE EXTREME CAUTION" signs with "NEXT 4 MILES" plaques at about MP 2.69 eastbound and MP 6.69 westbound.

Figure 2.51 shows the distribution of crash severity on the roadway segment over the analysis period. In this case the majority of injuries (77.7%), are at the more severe injury levels B and A, with level A ("Incapacitating Injury") making up a sizeable 33.3% of all injuries.

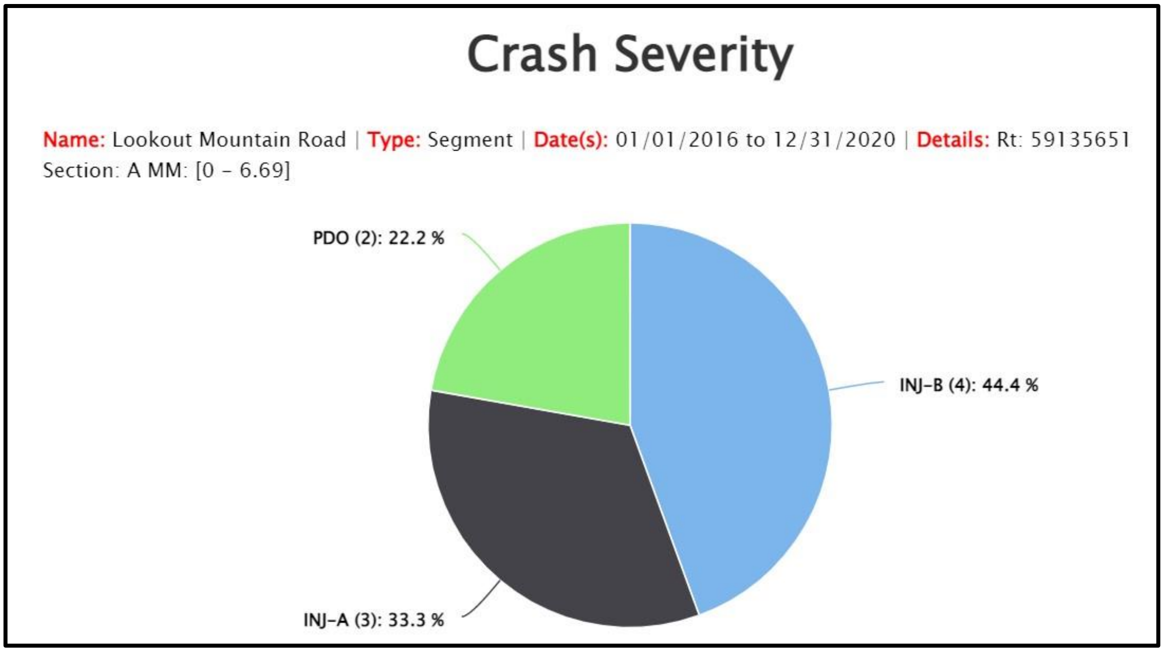

Figure 2.51: Distribution of Crash Severity Lookout Mountain Rd. 1/1/16-12/31/20

Table 2.34 shows the benefit-cost analysis for the placement of warning signs using an estimated cost of $3,000 when the composite approach to injury cost is used. The composite approach produces a B/C ratio of **62.04**.

Table 2.34: Composite B/C Analysis Lookout Mountain Rd Motorcycle Warning Signs

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Composite BCA Lookout Mtn Rd — **Loc:** 59135651 A **Begin:** 0 **End:** 6.69 **From:** 1/1/2016 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 2	0 :Injured C	CRF for PDO: 20%	Cost of PDO: $11,500
INJ C: 0	5 :Injured B	CRF for INJ C: 20%	Cost of INJ C: $106,100
INJ B: 4	3 :Injured A	CRF for INJ B: 20%	Cost of INJ B: $106,100
INJ A: 3	0 :Killed	CRF for INJ A: 20%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 20%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 6
			Capital Recovery Factor: 0.197
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $3000
Days: 1826
Type: Install MOTORCYCLES USE EXTREME CAUTION - NEXT 4 MILES Signs
Notes: Motorcycle Involved Crashes Only
Benefit/Cost Ratio: 62.04

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

If injury costs are calculated based on stratified injury levels, the benefit-cost analysis produces a B/C ratio of **121.67**, as seen in **Table 2.35**. This represents a B/C which is 96% higher, or almost double that produced using the composite approach the injury cost. In this case the sensitivity of the stratified approach to degree of severity is more evident in the benefit-cost calculation. In situations where there is a proportionately higher number of injuries at the more severe levels, such as this, we would expect a more pronounced difference between the B/C ratios calculated from the composite approach and from the stratified approach.

Table 2.35: Stratified B/C Analysis for Lookout Mountain Rd. Motorcycle Crashes

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Stratified BCA Lookout Mtn Rd — **Loc:** 59135651 A **Begin:** 0 **End:** 6.69 **From:** 1/1/2016 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 2	0 :Injured C	CRF for PDO: 20%	Cost of PDO: $11,500
INJ C: 0	5 :Injured B	CRF for INJ C: 20%	Cost of INJ C: $71,800
INJ B: 4	3 :Injured A	CRF for INJ B: 20%	Cost of INJ B: $127,600
INJ A: 3	0 :Killed	CRF for INJ A: 20%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 20%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 6
			Capital Recovery Factor: 0.197
			Annual Maintenance/Delay Cost: $0

Improvement Cost:	$3000
Days:	1826
Type:	Install MOTORCYCLES USE EXTREME CAUTION - NEXT 4 MILES Signs
Notes:	Motorcycle Involved Crashes Only
Benefit/Cost Ratio:	121.67

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 6 – US-550 MP 81-82, Ouray County

US-550 between MP 81 and MP 82 is a mountainous 2-lane undivided rural highway in Ouray County. The speed limit is 25 mph through the segment, which has narrow shoulders and centerline rumble strips. The segment is characterized by a series of curves on grade. Analysis of crash history during the five-year period between 01/01/2016 – 12/31/2020 identified a pattern of Overturning crashes along the segment. During this five-year period there were a total of eight crashes on the segment, including two PDO crashes, four Injury crashes (with five injuries) and two Fatal crashes (with two fatalities). Overturning crashes accounted for about 63% of all crashes (5 crashes), 100 % of all injury level crashes and 50% of Fatal crashes and fatalities.

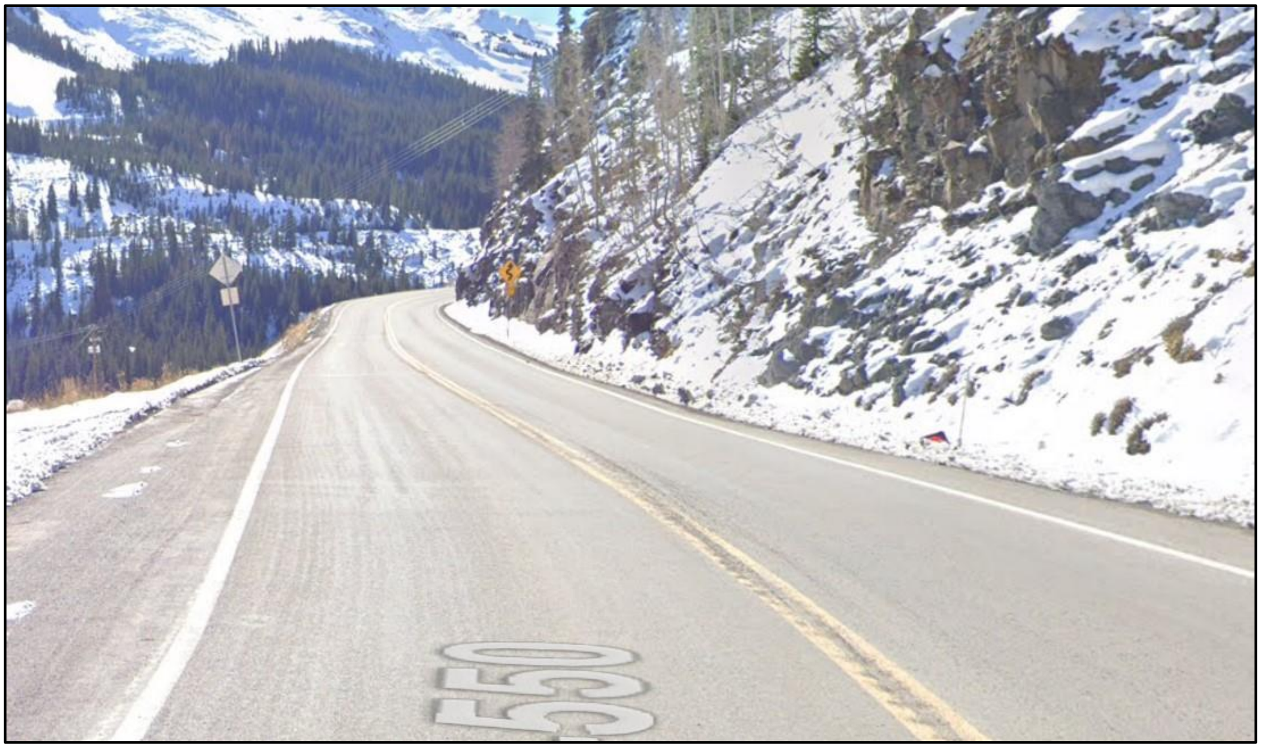

Figure 2.52: Typical Cross Section, US550 MP 81-82, Facing South Oct. 2021

Figure 2.53 shows the facility is operating at the LOSS-III level from the total crash frequency standpoint, representing moderate to high potential for crash reduction. **Figure 2.54** shows that from the crash severity standpoint, the facility is operating at the LOSS-IV level, indicating high potential for crash reduction.

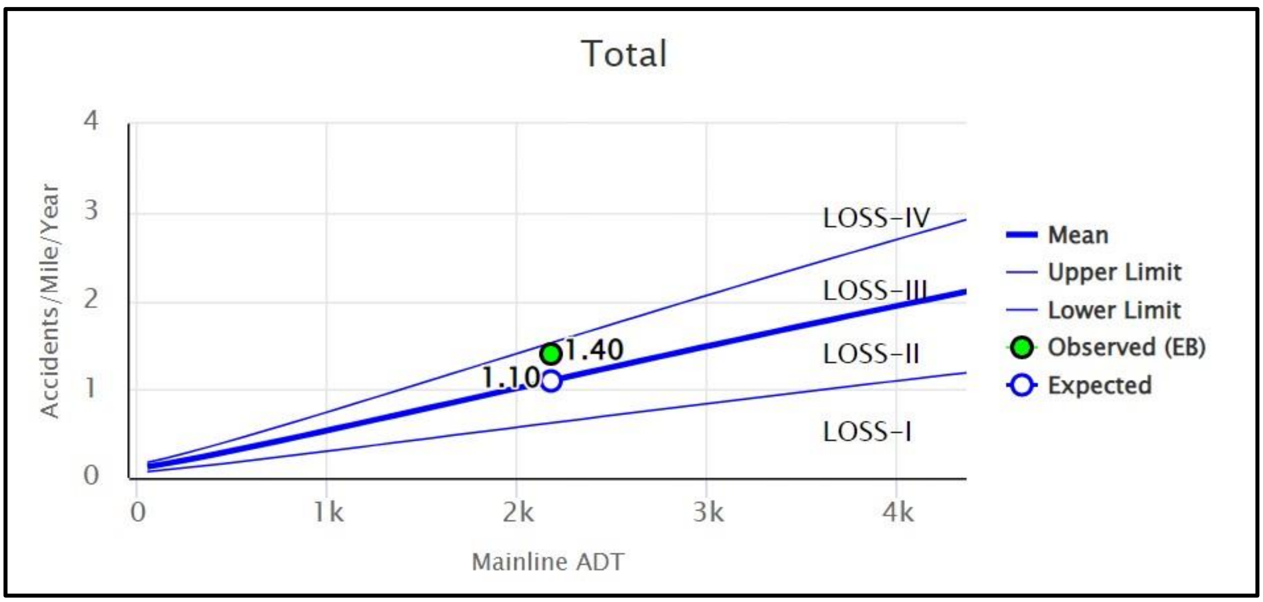

Figure 2.53: SPF Total Crashes US550 MP 81-82, 1/1/16-12/31/20

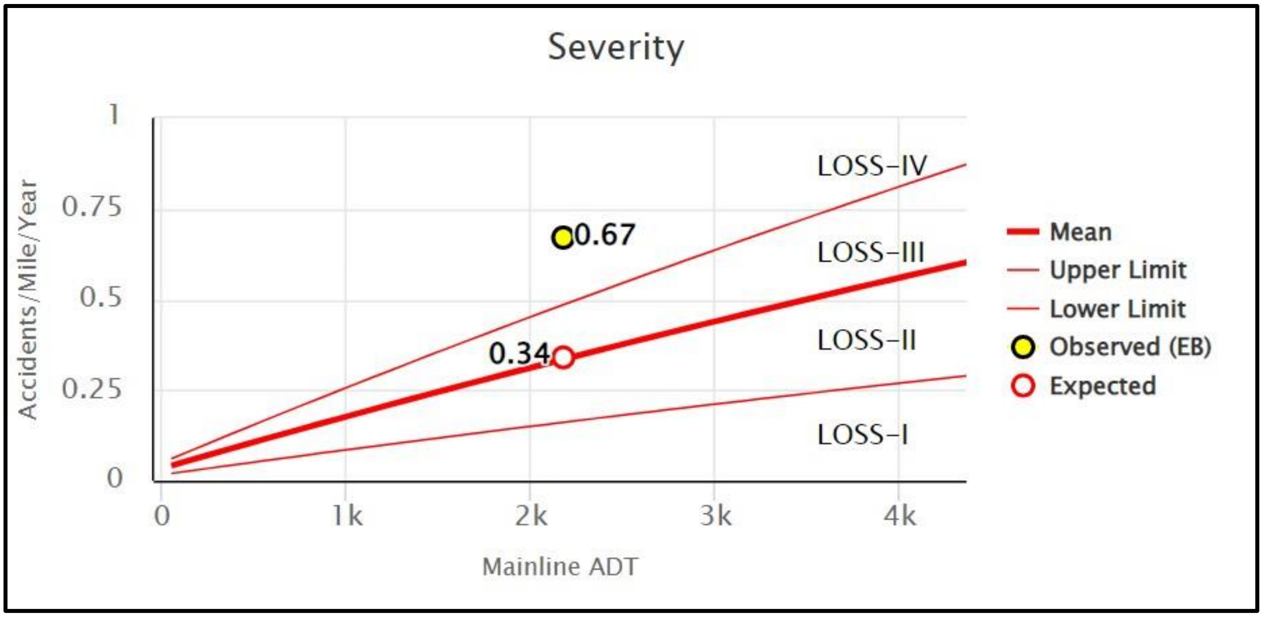

Figure 2.54: SPF INJ+FAT Crashes US550 MP 81-82, 1/1/16-12/31/20

Crash records indicate that 3 out of the 5 overturning crashes were off-right crashes, with all occurring at MP 81.5. Additionally, one of the overturning crashes was recorded as "on-road," however crash notes show that it involved a motorcycle which came to rest straddling the eastbound lane and the eastbound shoulder, and as such should be considered as an off road-right crash. The crash occurred at MP 81.7 and was an injury level B crash. In addition, one Fixed Object crash was also a run-off-the-road right crash. This brings to a total of five run-off-the-road right crashes, all of which were recorded as being located at a curve-on-grade and all were eastbound. **Figure 2.55** shows the mile point locations of these crashes.

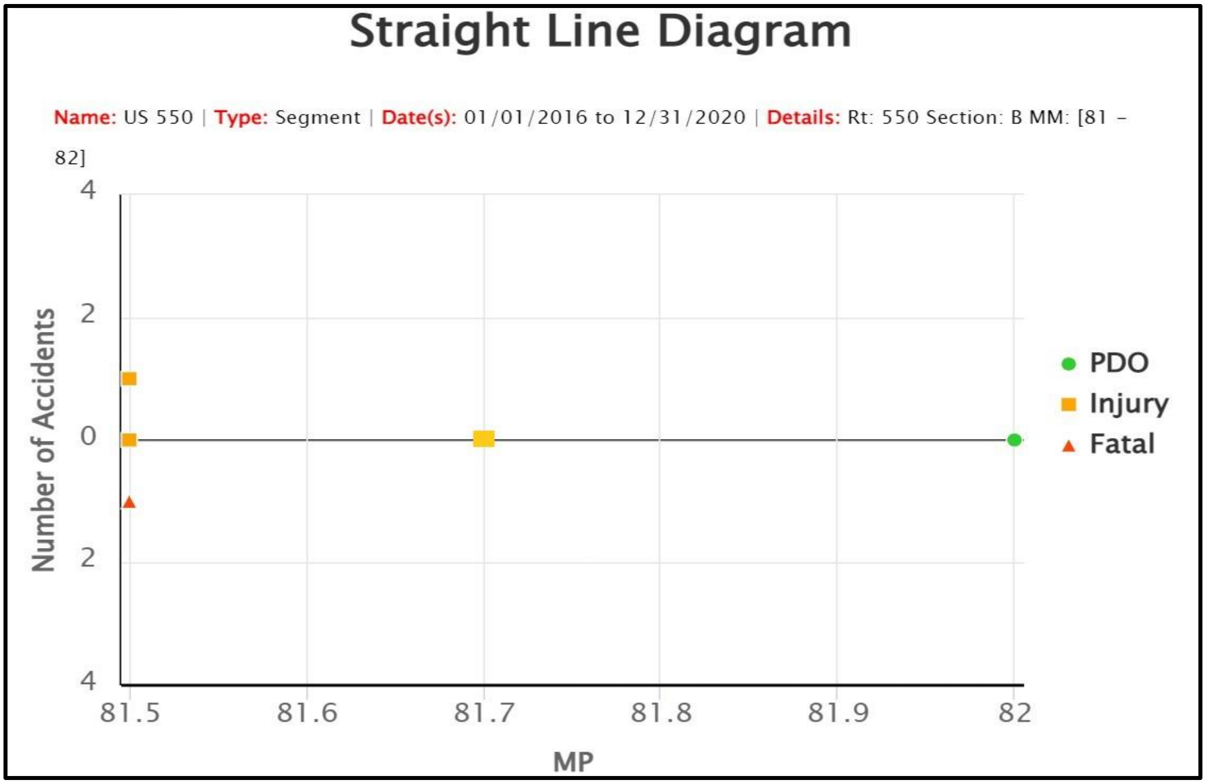

Figure 2.55: Straight Line Diagram for Run-Off-the-Road Right Crashes US550 MP 81-82

Figure 2.56 shows that severe injuries make up about 84% of all run-off-the-road right crashes on the segment, with injury level A ("Incapacitating Injury") being most heavily represented, and with one fatality included amongst those crashes.

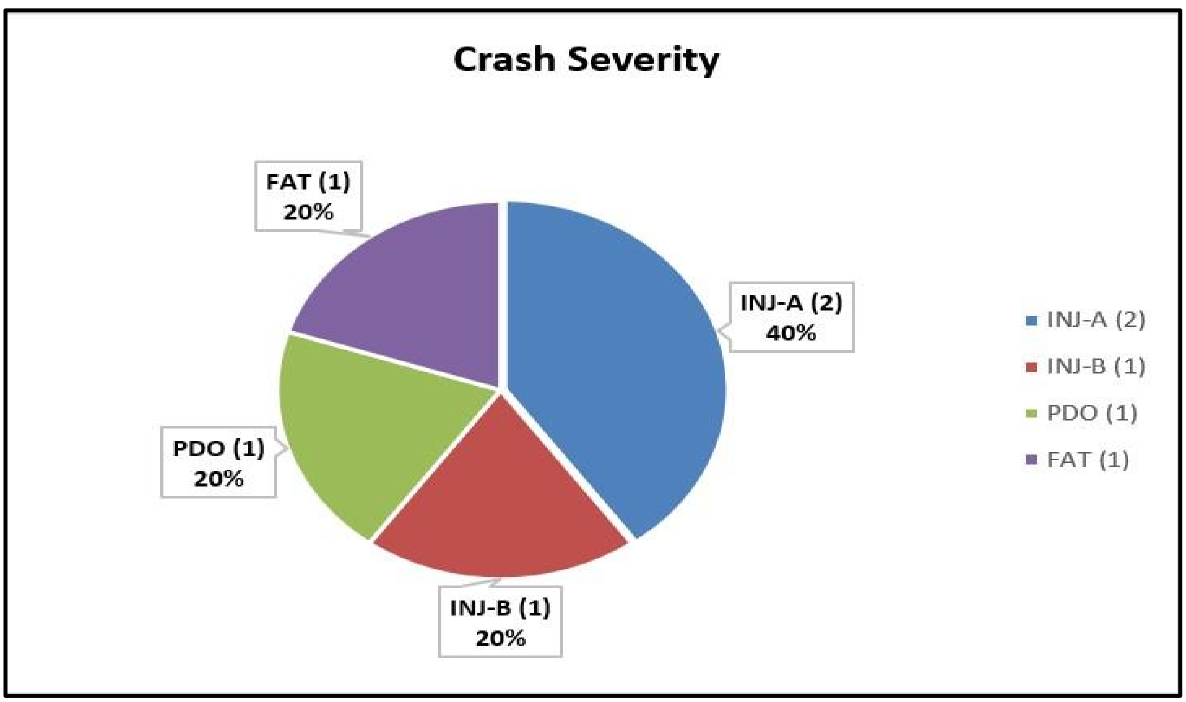

Figure 2.56: Crash Severity Distribution US550 MP 81-82 1/1/16-12/31/20

One solution to address this pattern of eastbound run-off-the-road right crashes, which includes the majority of overturning crashes, would be the installation of eastbound right side guard rail between MP 81.30-82.00. Using an estimated cost of $105,000, **Table 2.36** shows that using the existing composite approach to injury crash cost, the estimated B/C ratio is **38.28**.

Table 2.36: Composite B/C Analysis for Guardrail US550 MP 81-82

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Composite BCA US-550 — **Loc:** 550 B **Begin:** 81 **End:** 82 **From:** 1/1/2016 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 1	0 :Injured C	CRF for PDO: 0%	Cost of PDO: $11,500
INJ C: 0	1 :Injured B	CRF for INJ C: 40%	Cost of INJ C: $106,100
INJ B: 1	3 :Injured A	CRF for INJ B: 40%	Cost of INJ B: $106,100
INJ A: 2	1 :Killed	CRF for INJ A: 40%	Cost of INJ A: $106,100
FAT: 1		CRF for FAT: 60%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $105000
Days: 1826
Type: Installation of Right Side Guard Rail Eastbound
Notes: Run Off the Road Right Crashes Only
Benefit/Cost Ratio: 38.28

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

If injury costs are calculated according to stratified injury level, the benefit-cost analysis shown in **Table 2.37** indicates a B/C ratio of **47.05**. This indicates that the B/C ratio is about 23% higher when the stratified injury cost approach is implemented compared to the composite approach. This follows the trend of a higher B/C ratio being produced by the stratified approach when crashes tend to be weighted more heavily towards those of a higher degree of severity such as in this case. This further demonstrates how the stratified approach is more sensitive in this regard, and therefore more precise.

Table 2.37: Stratified B/C Analysis for Guard Rail US550 MP 81-82

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Stratified BCA US-550 — **Loc:** 550 B **Begin:** 81 **End:** 82 **From:** 1/1/2016 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 1	0 :Injured C	CRF for PDO: 0%	Cost of PDO: $11,500
INJ C: 0	1 :Injured B	CRF for INJ C: 40%	Cost of INJ C: $71,800
INJ B: 1	3 :Injured A	CRF for INJ B: 40%	Cost of INJ B: $127,600
INJ A: 2	1 :Killed	CRF for INJ A: 40%	Cost of INJ A: $349,600
FAT: 1		CRF for FAT: 60%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $105000
Days: 1826
Type: Installation of Right Side Guard Rail Eastbound
Notes: Run Off the Road Right Crashes Only
Benefit/Cost Ratio: 47.05

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 7 – SH-66 & 75th Street (MP 32.55-32.61), Boulder County

The intersection of SH-66 and 75th Street west of Longmont is a four-lane four-leg divided signalized intersection in a rural environment. The speed limit along US-66 is 50 mph. Google Street View imagery indicates that sometime between October 2019 and September 2021 (see **Figure 2.57** and **Figure 2.58**), the eastbound and westbound left turn signals were reconfigured from five-section protected/permissive to three-section Flashing Yellow Arrow (FYA) which can be useful for implementing fully protected left turns by a specific time of day, which would be an effective mitigation against approach turn crashes.

Crash records are currently available through 2020 and show that the last approach turn crash recorded was late June 2020. It is highly likely that it was around this time that the signal reconfiguration took place. When crash records for the five-year period between 1/1/2015-12/31/2019 are examined, direct diagnostics do show a pattern of both injury level crashes and approach turn crashes during this period (**Table 2.38**), as might be expected given the remediation measures taken.

Figure 2.57: Eastbound Left Turn Signals SH66 &75th Oct. 2019

Figure 2.58: Eastbound Left Turn Signals SH66 & 75th Sept. 2021

Table 2.38: Direct Diagnostics SH66 & 75th St. 1/1/15-12/31/19

CDOT
DiExSys™ Vision Zero Suite
Diagnostics Report

04/03/2023

Diagnostics SH66 — Cutoff: 5 Acc's @ 95

Category/Trait	Statewide Average %	This Location # Crashes	This Location %	Probability %
Crash Severity				
Injury (INJ)	35.11%	22	55%	99.69%
Crash Location				
On Road	94.04%	40	100%	100%
Crash Type				
Approach Turn	24.47%	21	52.5%	100%

Because crash records are available only through 2020, a comparison of before and after crash rates is not possible. However, an examination of crash records between 1/1/2015-12/31/2019 shows there were a total of 40 crashes at the intersection in this period, including 18 PDO crashes, 22 Injury crashes (with 39 injuries) and no Fatal crashes (**Table 2.39**). Approach turn crashes accounted for about 59% of injury crashes during this period (13 injury crashes) and about 59% of all injuries during this period (23 injuries).

Figure 2.59 and **Figure 2.60** show the facility is operating at the LOSS-IV level from both the total crash frequency standpoint, and the crash severity standpoint, representing high potential for crash reduction. (Because a Rural four-lane four-leg Divided Signalized intersection model is not currently available on Vision Zero Suite web application, a proxy model produced using an Urban four-lane four-leg Divided Signalized intersection as used).

Figure 2.59: SPF Total Graph for SH66 & 75th Street, 1/1/15-12/31/19

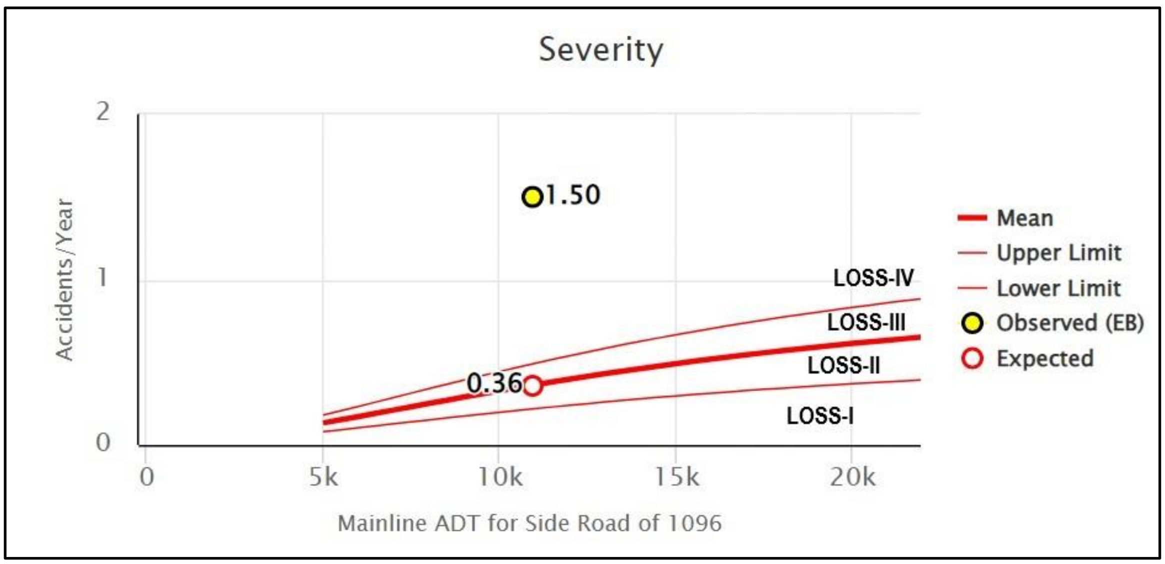

Figure 2.60: SPF INJ+FAT Graph for SH66 & 75th Street, 1/1/15-12/31/19

As might be expected given the reconfiguration, all approach turn crashes involved at-fault eastbound and westbound vehicles occurring between 7AM and 10PM. If fully protected left turns were provided between the hours of 7AM and 10PM the benefit-cost calculations can be interpreted as follows.

When the existing composite approach to injury crash costs is implemented for benefit-cost analysis, a B/C ratio of **241.44** is obtained using an estimated project cost of $16,000 (**Table 2.40**).

Table 2.39: Crash Summary SH66 & 75th Street 1/1/15-12/31/19

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

04/03/2023

Gen Summary SH66 — **Type:** Intersection **Details:** Rt: 66 Section: B MM: [32.55 - 32.61] **From:** 1/1/2015 **To:** 12/31/2019

Crash Severity

By Crashes:		Number of People:	
FAT:	0	Killed:	0
INJ:	22	Injured:	39
PDO:	18		
TOTAL:	40		

Crash Location

On Road:	40
Off Road Left:	0
Off Road Right:	0
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	40

Weather Conditions

None:	37
Rain:	0
Snow/Sleet/Hail:	3
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	40

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	4	Embankment:	0
Head On:	0	Curb:	0
Rear End:	14	Delineator Post:	0
Sideswipe (Same):	1	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	21	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	0
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace Equipment:	0
Traffic Signal Pole:	0		
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		40
Concrete Barrier:	0		

Lighting Conditions

Daylight:	36
Dawn/Dusk:	0
Dark-Lighted:	2
Dark-Unlighted:	2
Unknown:	0
TOTAL:	40

Road Conditions

Dry:	37
Wet:	2
Muddy:	0
Snowy:	1
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	40

Number of Vehicles

One Car:	0
Two Car:	36
Three or More:	4
Unknown:	0
TOTAL:	40

Table 2.40: Composite B/C Analysis SH66 & 75th Street

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Composite BCA SH66 — **Loc:** 66 B **Begin:** 32.55 **End:** 32.61 **From:** 1/1/2015 **To:** 12/31/2019

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 8	13 :Injured C	CRF for PDO: 90%	Cost of PDO: $11,500
INJ C: 5	7 :Injured B	CRF for INJ C: 90%	Cost of INJ C: $106,100
INJ B: 5	3 :Injured A	CRF for INJ B: 90%	Cost of INJ B: $106,100
INJ A: 3	0 :Killed	CRF for INJ A: 90%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 90%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $16000
Days: 1825
Type: Protected/Permissive LT to FYA Fully Protected by Time of Day Eastbound & Westbound
Notes: EB & WB Approach Turn Crashes Only
Benefit/Cost Ratio: 241.44

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Figure 2.61 shows that there is somewhat of a balance between the lower-level injuries at injury level C and the higher-level injuries at injury level B and A over the analysis period. Injuries at level B and level A comprise about 33% of injuries with level C slightly higher at about 42%.

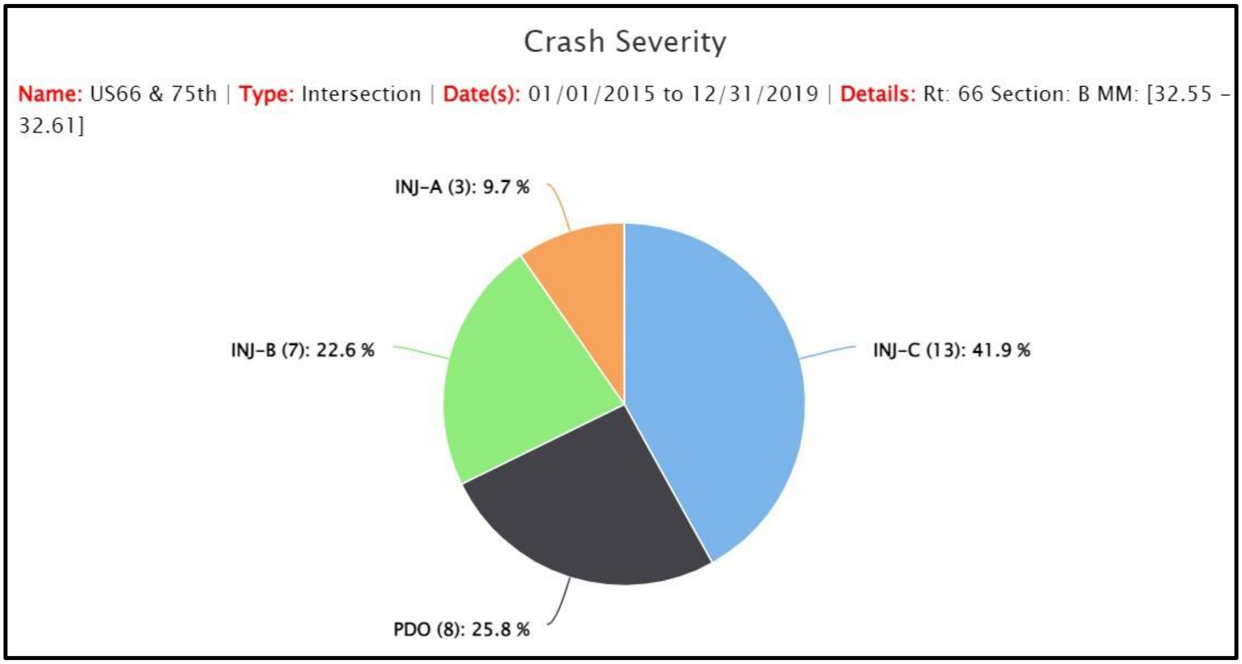

Figure 2.61: Distribution of Crashes by Severity SH66 & 75th Street

If injury crash costs are determined based on stratified injury level, the benefit-cost analysis shows a B/C ratio of **282.92** in **Table 2.41**. The B/C ratio returned using the stratified approach is approximately 17% higher than that calculated using the composite approach. The higher B/C once again reflects a higher degree of sensitivity and precision towards the degree of injury severity seen. Because higher level injuries represent a proportion of injuries close to that represented by the lower level injuries at this intersection, the benefit of providing fully protected left turns by time of day, which targets higher severity crashes, is more pronounced.

Table 2.41: Stratified B/C Analysis SH66 & 75th Street

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Stratified BCA SH66 — **Loc:** 66 B **Begin:** 32.55 **End:** 32.61 **From:** 1/1/2015 **To:** 12/31/2019

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 8	13 :Injured C	CRF for PDO: 90%	Cost of PDO: $11,500
INJ C: 5	7 :Injured B	CRF for INJ C: 90%	Cost of INJ C: $71,800
INJ B: 5	3 :Injured A	CRF for INJ B: 90%	Cost of INJ B: $127,600
INJ A: 3	0 :Killed	CRF for INJ A: 90%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 90%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $16000
Days: 1825
Type: Protected/Permissive LT to FYA Fully Protected by Time of Day Eastbound & Westbound
Notes: EB & WB Approach Turn Crashes Only
Benefit/Cost Ratio: 282.92

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 8 – US-40A MP 214-217, Grand County

SH40 MP 214-217 is a 2-lane rural undivided highway located south of Granby in Grand County. The driving environment could be described as high-speed rural, with a speed limit of 55mph between MP 214.00-214.50 and a speed limit of 65 mph between MP 214.50-217. It has 12-foot lanes and 9-foot shoulders, with no rumble strips.

Figure 2.62: US40 Typical Section, Facing North

An analysis of crash history between 1/1/16-12/31/20 shows there was a total of 40 crashes, including 27 PDO crashes, 12 Injury crashes (with 13 injuries) and 1 Fatal crash (with 1 fatality) (see **Table 2.42**). Pattern recognition shows there is a pattern of Off-Road and Fixed Object crashes as well as crashes under Snowy and Icy conditions (**Table 2.43**).

Table 2.42: Crash Summary US40 MP 214-217, 1/1/16-12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

04/03/2023

General Summary US40 — **Type:** Segment **Details:** Rt: 40 Section: A MM: [214 - 217] **From:** 1/1/2016 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	1	Killed:	1
INJ:	12	Injured:	13
PDO:	27		
TOTAL:	40		

Crash Location

On Road:	17
Off Road Left:	6
Off Road Right:	17
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	40

Weather Conditions

None:	25
Rain:	0
Snow/Sleet/Hail:	9
Fog:	0
Dust:	0
Wind:	6
Unknown:	0
TOTAL:	40

Crash Type

Overturning:	6	Bridge Abutment:	0
Other Non-Collision:	1	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	2
Broadside:	0	Embankment:	3
Head On:	1	Curb:	1
Rear End:	3	Delineator Post:	2
Sideswipe (Same):	0	Fence:	4
Sideswipe (Opposite):	2	Tree:	1
Approach Turn:	0	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	1
Domestic Animal:	0	Rocks in Roadway:	17
Wild Animal:	10	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	2	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	1	**TOTAL:**	0
Cable Rail:	0		40
Concrete Barrier:	0		

Lighting Conditions

Daylight:	22
Dawn/Dusk:	3
Dark-Lighted:	0
Dark-Unlighted:	15
Unknown:	0
TOTAL:	40

Road Conditions

Dry:	18
Wet:	0
Muddy:	0
Snowy:	3
Icy:	18
Slushy:	1
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	40

Number of Vehicles

One Car:	34
Two Car:	6
Three or More:	0
Unknown:	0
TOTAL:	40

Table 2.43: Pattern Recognition for US40 MP 214-217, 1/1/16-12/31/20

CDOT
DiExSys™ Vision Zero Suite
Diagnostics Report

04/03/2023

Diagnostics US40 | Cutoff: 5 Acc's @ 95

Category/Trait	Statewide Average %	This Location # Crashes	This Location %	Probability %
Number Of Vehicles				
Single Vehicle Accidents	73.81%	34	85%	96.97%
Crash Location				
Off Road	35.91%	23	57.5%	99.84%
Off Road Right	21.63%	17	42.5%	99.92%
Crash Type				
Total Fixed Objects	21.83%	17	42.5%	99.91%
Weather Conditions				
Snow or Sleet or Hail	12.9%	9	22.5%	97.24%
Wind	2.38%	6	15%	100%
Road Conditions				
Icy Road	13.1%	18	45%	100%

Figure 2.63 shows the facility is operating at the LOSS-II level from the total crash frequency standpoint, indicating low to moderate potential for crash reduction. While **Figure 2.64** shows the facility is operating at the LOSS-III level from the crash severity standpoint, indicating moderate to high potential for crash reduction.

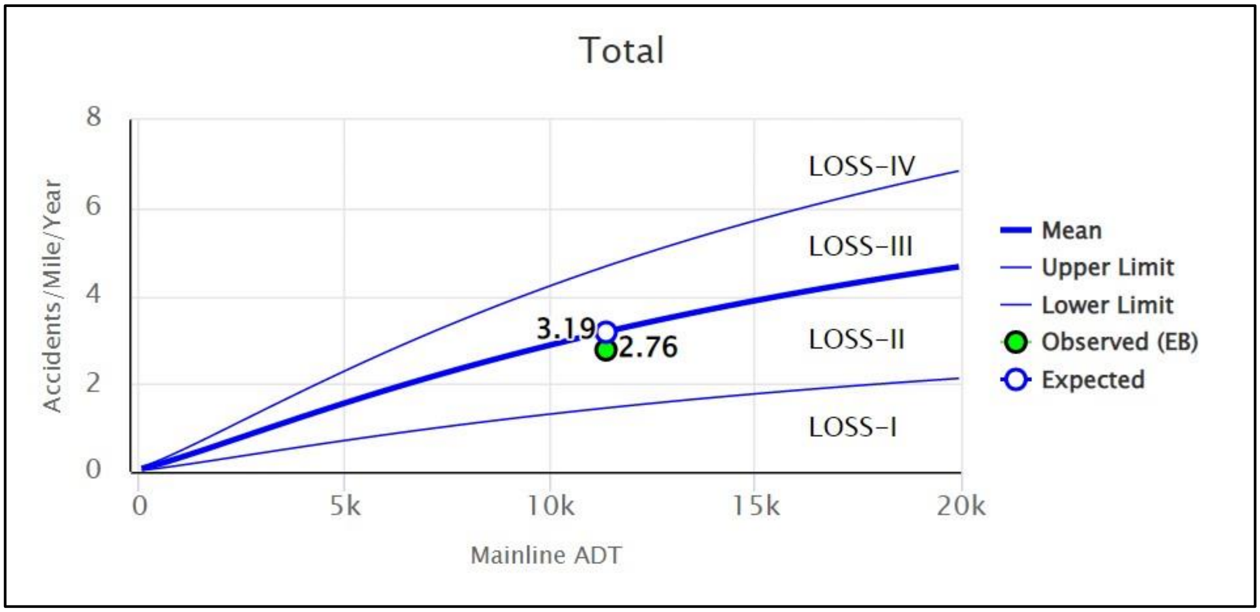

Figure 2.63: SPF Total Graph US40 MP 214-217

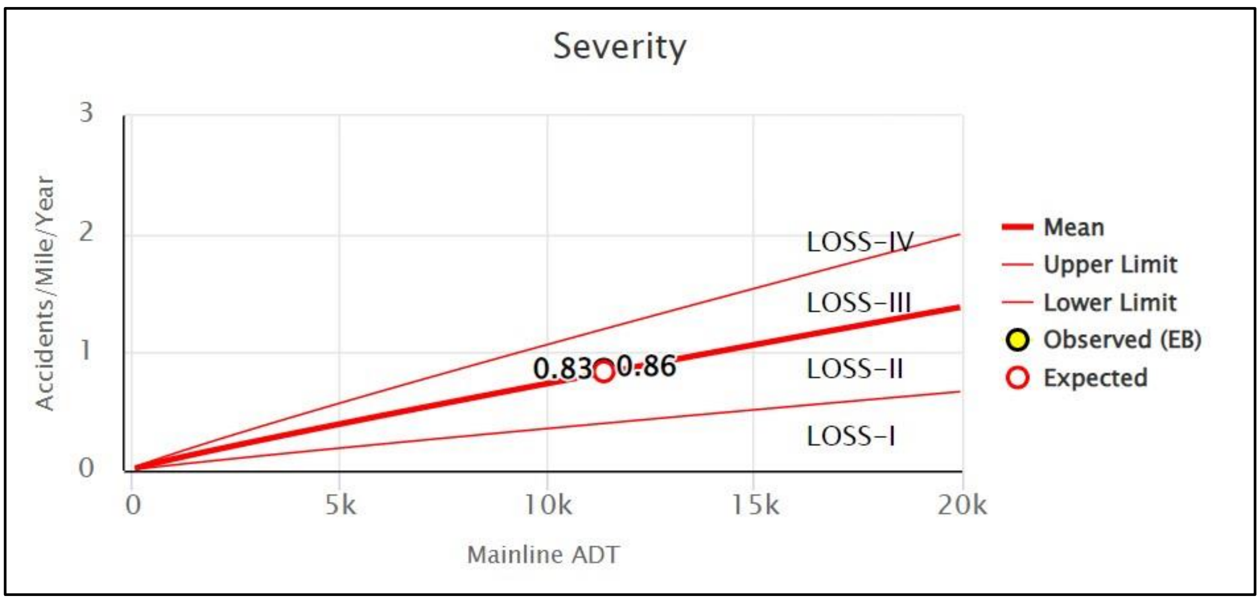

Figure 2.64: SPF INJ+FAT Graph US40 MP 214-217

As might be expected crash records show that all Fixed Object crashes were run-off-the-road crashes. There was a total of 23 run-off-the-road crashes, comprising 15 PDO crashes and 8 Injury crashes (with 8 injuries). Over 73% of roadway departure crashes were off-right crashes. A significant amount of roadway departure crashes, 74%, occurred in snowy, icy or slushy road conditions.

There were five total other crash types that occurred in snowy, icy or slushy conditions in which the crashes were on-road. These included three PDO crashes and two Injury crashes (with three injuries).

When all roadway departure crashes are considered, (74% of which were on snowy, icy or slushy roadway conditions), together with all remaining on-road crashes occurring under snowy, icy or slushy conditions, these crashes together represent 58.3% of all Injury crashes and about 62% of all injuries which occurred on the roadway segment in the 5-yr analysis period. This indicates that there is a large degree of overlap between the identified patterns of Off-Road, Fixed Object crashes and crashes occurring under snowy or icy conditions.

A suitable remediation strategy would be the installation of milled shoulder rumble strips in both directions between MP 214-217, along with increased de-icing maintenance efforts during seasons of snowfall. Because the only fatal injury which was recorded was a head-on collision, although recorded as on-road, it does represent a lane-departure crash, and as such milled centerline rumble strips would be a suitable remediation measure. Assuming an estimated cost of $22,500 and an estimated annual maintenance increase of $2,000, **Table 2.44** shows that using the traditional composite approach to injury crash cost, the expected benefit-cost ratio is **55.65**, this assumes a conservative estimate of a 15% CRF for additional de-icing efforts combined with the typical CRF of 27%/27%/27% (PDO/INJ/FAT) for combined shoulder and centerline rumble strips.

Table 2.44: Composite B/C Analysis US40 MP 214-217

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Composite BCA US40 — Loc: 40 A Begin: 214 End: 217 From: 1/1/2016 To: 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 18	9 :Injured C	CRF for PDO: 38%	Cost of PDO: $11,500
INJ C: 8	2 :Injured B	CRF for INJ C: 38%	Cost of INJ C: $106,100
INJ B: 2	0 :Injured A	CRF for INJ B: 38%	Cost of INJ B: $106,100
INJ A: 0	1 :Killed	CRF for INJ A: 38%	Cost of INJ A: $106,100
FAT: 1		CRF for FAT: 38%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $2000

Improvement Cost: $22500
Days: 1826
Type: Rumble Strips: Centerline & Shoulders. Increased seasonal de-icing efforts.
Notes: Run off the Road & Lane Departure Crashes & Crashes under Adverse Winter Road Conditions
Benefit/Cost Ratio: 55.65

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

If benefit-cost analysis is performed using the stratified costs for injury crashes, **Table 2.45** shows that the B/C ratio is about 8% lower, at **51.15**. Looking more closely at the degree of applicable injuries on this highway segment, it is evident that the majority of injury level crashes are in the less severe categories, injury level B and injury level C, with only one fatality. In this case again we see that the stratified approach is more sensitive to the injury severity and reflects that accordingly in the B/C analysis.

Table 2.45: Stratified B/C Analysis US40 MP 214-217

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/03/2023

Stratified BCA US40 — **Loc:** 40 A **Begin:** 214 **End:** 217 **From:** 1/1/2016 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 18	9 :Injured C	CRF for PDO: 38%	Cost of PDO: $11,500
INJ C: 8	2 :Injured B	CRF for INJ C: 38%	Cost of INJ C: $71,800
INJ B: 2	0 :Injured A	CRF for INJ B: 38%	Cost of INJ B: $127,600
INJ A: 0	1 :Killed	CRF for INJ A: 38%	Cost of INJ A: $349,600
FAT: 1		CRF for FAT: 38%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $2000

Improvement Cost: $22500
Days: 1826
Type: Rumble Strips: Centerline & Shoulders. Increased seasonal de-icing efforts.
Notes: Run off the Road & Lane Departure Crashes & Crashes under Adverse Winter Road Conditions
Benefit/Cost Ratio: 51.15

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Example 9 – Nevada Avenue and Platte Avenue, Colorado Springs

The intersection of Nevada Avenue and Platte Avenue in the City of Colorado Springs is a four-lane four-leg divided signalized intersection. It has dedicated left and right turn lanes northbound and southbound (**Figure 2.65**). Google Street View imagery indicates that there is a signal head provided for each thru and turn lane at the intersection, and that currently the intersection operates permissive left turns on all approaches (see example, **Figure 2.66**).

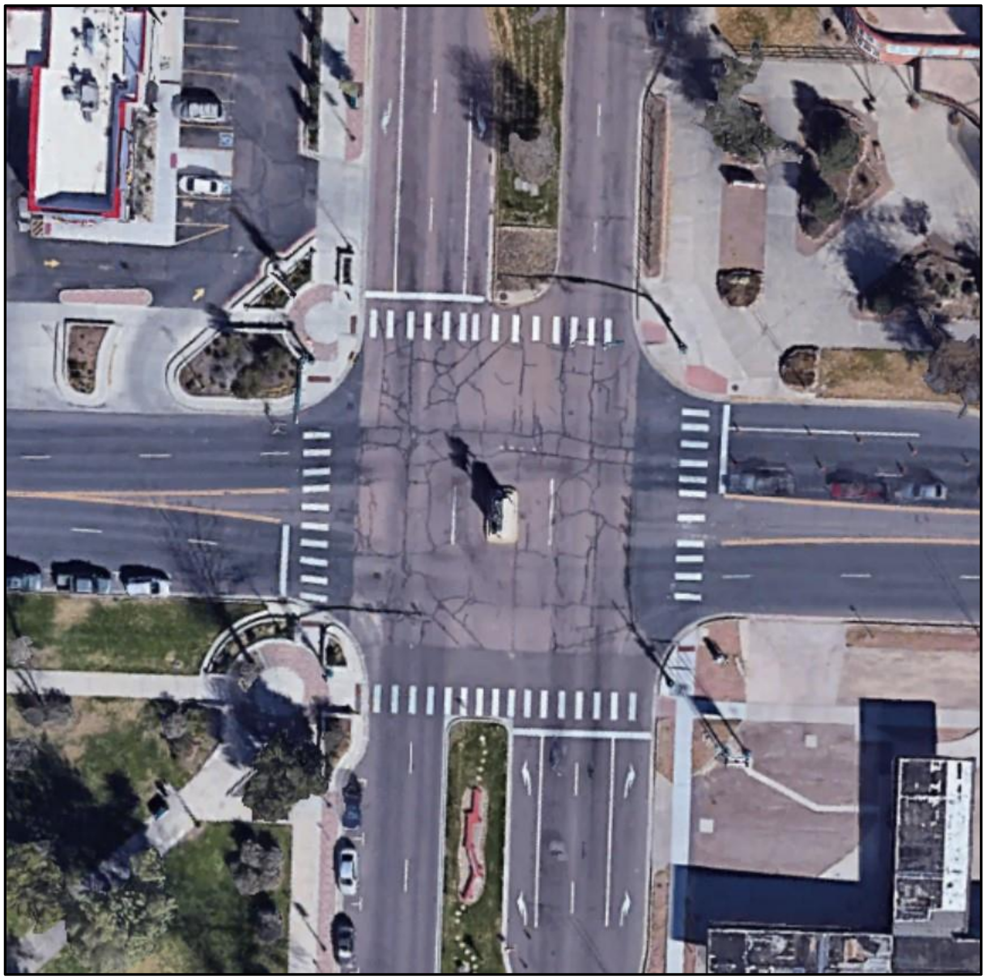

Figure 2.65: Aerial View Nevada Ave. & Platte Ave.

Figure 2.66: Nevada Ave. & Platte Ave. Facing North, June 2021

Crash history records for the 5-year period between 1/1/16-12/31/20 show that there were 60 crashes at the intersection including 35 PDO, 24 Injury (with 39 injuries) and 1 Fatal crash (with

1 fatality) (**Table 2.46**). Direct diagnostics identified a pattern of Injury and Approach Turn crashes at the intersection (see **Table 2.47**). Furthermore, there were also four Pedestrian crashes and one Bicycle crash in the analysis period, which does constitute a pattern.

Table 2.46: Crash Summary Nevada Ave. & Platte Ave., 1/1/16-12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

04/03/2023

Gen. Summary Nevada — **Type:** Intersection **Details:** nevada / platte **From:** 1/1/2016 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	1	Killed:	1
INJ:	24	Injured:	39
PDO:	35		
TOTAL:	60		

Weather Conditions

None:	56
Rain:	0
Snow/Sleet/Hail:	1
Fog:	0
Dust:	0
Wind:	0
Unknown:	3
TOTAL:	60

Lighting Conditions

Daylight:	46
Dawn/Dusk:	1
Dark-Lighted:	13
Dark-Unlighted:	0
Unknown:	0
TOTAL:	60

Road Conditions

Dry:	58
Wet:	2
Muddy:	0
Snowy:	0
Icy:	0
Slushy:	0
Foreign Material:	0
Road Treatment:	0
Unknown:	0
TOTAL:	60

Crash Location

On Road:	59
Off Road Left:	0
Off Road Right:	0
Off Road at Tee:	0
Off in Median:	1
Unknown:	0
	60

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	4	Culvert/Headwall:	0
Broadside:	8	Embankment:	0
Head On:	1	Curb:	0
Rear End:	16	Delineator Post:	0
Sideswipe (Same):	3	Fence:	0
Sideswipe (Opposite):	2	Tree:	0
Approach Turn:	24	Large Boulders or Rocks:	0
Overtaking Turn:	1	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	1	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	0
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		60
Concrete Barrier:	0		

Number of Vehicles

One Car:	0
Two Car:	55
Three or More:	5
Unknown:	0
TOTAL:	60

Table 2.47: Direct Diagnostics Nevada Ave. & Platte Ave.

CDOT
DiExSys™ Vision Zero Suite
Diagnostics Report

04/04/2023

Diagnostics Nevada — **Cutoff:** 5 Acc's @ 95

Category/Trait	Statewide Average %	This Location # Crashes	This Location %	Probability %
Crash Severity				
Injury (INJ)	28.51%	24	40%	98.03%
Crash Type				
Approach Turn	16.02%	24	40%	100%
Human Contributing Factor				
Unfamiliar with Area	3.16%	5	8.33%	98.84%

Figure 2.67 shows the facility is operating at the LOSS-III level from the total crash frequency standpoint, indicating moderate to high potential for crash reduction. While **Figure 2.68** shows the facility is operating at the LOSS-IV level from the crash severity standpoint, indicating high potential for crash reduction.

Crash records show that Approach turn crash account for 40% of all injury crashes, while Pedestrian and Bicycle crashes account for 16%. Combined this is over 50% of injury level crashes which are attributable to approach turn crashes and crashes involving pedestrian or bicycles. Additionally, 24% of injury crashes are due to Broadside crashes.

Figure 2.67: SPF Total Graph Nevada Ave. & Platte Ave.

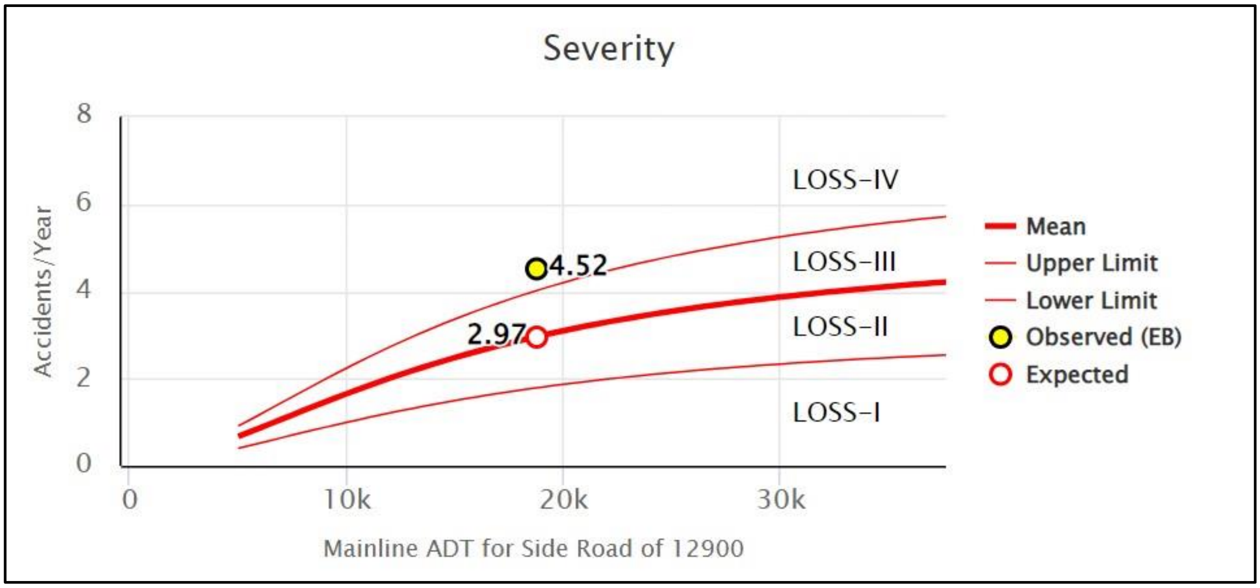

Figure 2.68: SPF INJ+FAT Graph Nevada Ave. & Platte Ave.

Crash records indicate that 80% of approach turn crashes involved eastbound or westbound left turning vehicles. **Figure 2.69** shows that with the current permissive left turn signal configuration eastbound and westbound, vehicles are forced to make a left turn with a partially obstructed view of oncoming traffic due to the presence of a large centerpiece statue in the intersection. One solution might be the removal of the statue to improve sight distance for left turning vehicles. However, even if this were achieved, approach turn crashes tend to be higher with fully permissive left turn signal configurations than those with protected/permissive configurations, and it is likely the problem would persist. A switch to protective/permissive configuration eastbound and westbound would also require the addition of a left turn lane on the eastbound and westbound approaches.

Figure 2.69: Obstructed View for Left Turns Nevada & Platte, Facing West, June 2021

If Pedestrian and Bicycle crashes are considered, crash records make it clear that all but one of these crashes involved turning movements by at-fault vehicles.

- NB vehicle making right turn conflicting with WB pedestrian. Likely a right on red movement.
- SB vehicle making a left turn conflicting with a SB pedestrian. Currently left turning vehicles on all approaches must yield to pedestrians. A left turning SB vehicle has a partially obstructed view of the SB pedestrian crossing on the east side of the intersection due to the centerpiece statue.
- NB vehicle going straight conflicting with a WB bike going straight, with the vehicle cited as being at-fault.
- WB vehicle making right turn conflicting with SB pedestrian going straight. Likely a right on red movement.
- WB vehicle making a right turn conflicting with a NB pedestrian going straight.

Three out of four pedestrian crashes involved right turning vehicles conflicting with pedestrian using the crosswalks, while one involved a left turning vehicle. As already outlined, vehicles making left turns have a partially obstructed view of the pedestrian crosswalk due to the statue. Additionally, right turning vehicles can currently make turns on red while the adjacent vehicular and pedestrian traffic has a green light and “WALK” signal. Because the pedestrian crosswalks are located at the intersection and immediately in front of the “STOP” bars vehicles making a right on red are looking left and can miss a pedestrian stepping out in front of them coming from the right and are at a high risk of hitting them due to the intersection alignment.

Broadside crashes also contributed significantly to injury crashes at the intersection. Shorter than recommended Yellow (Change) plus All-Red (Clearance) intervals are strongly correlated with broadside crashes. One solution would be review and correction of Yellow plus All-Red timings in the field for conformance with NCHRP Report 731 *Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections (2012)*.

When the patterns seen in approach turn, broadside, pedestrian and bicycle crashes are considered together, it is evident that the geometric configuration of the intersection, including the presence of a centerpiece statue and the proximity of the crosswalks and stop bars, are contributing to the patterns, and it is likely that there are signal timing issues which are also contributing to the high injury rates. An alternative which would provide a solution to all of these patterns would be the replacement of the intersection with a roundabout, which could be built to accommodate the existing statue. An urban roundabout configuration which includes pedestrian crossing which are offset from the roundabout junction, such as that seen in **Figure 2.70** would be a suitable alternative. A configuration such as this would mean that left turning vehicles have completed a turn through 90 degrees before approaching their departure lane such that they have a clear unobstructed view. Furthermore, because crosswalks are set back from the intersection, motorists can give their attention to the presence of pedestrians in the crosswalk rather than signal timing. Finally, the possibility of broadside crashes is removed.

Figure 2.70: Example of an Urban Roundabout Intersection with Pedestrian Crossings[2]

Table 2.48 shows the breakeven benefit-cost analysis for replacement of the signalized intersection with a roundabout using the traditional composite approach to injury crash costs, it

[2] http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=25 Accessed 8/8/2022

uses the conservative estimate of a single lane roundabout. The analysis shows that spending up to $10.5M would be cost-effective.

Table 2.48: Composite Breakeven B/C Analysis Nevada Ave. & Platte Ave.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/04/2023

Composite BCA Nevada — **From:** 1/1/2016 **To:** 12/31/2020 **Street 1:** nevada **Street 2:** platte

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 35	33 :Injured C	CRF for PDO: 26%	Cost of PDO: $11,500
INJ C: 20	5 :Injured B	CRF for INJ C: 55%	Cost of INJ C: $106,100
INJ B: 4	1 :Injured A	CRF for INJ B: 55%	Cost of INJ B: $106,100
INJ A: 0	1 :Killed	CRF for INJ A: 55%	Cost of INJ A: $106,100
FAT: 1		CRF for FAT: 55%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $10500000
Days: 1826
Type: Roundabout: Conversion of SIgnalized Intersection to Roundabout (Single Lane)
Notes: Intersection Related Crashes
Benefit/Cost Ratio: 1

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

In comparison, when the stratified approach to injury costs is employed, the same breakeven benefit-cost analysis shows that spending $9,224,475, an amount which is around 9.6% lower than that calculated using the composite approach, would be more cost-effective (**Table 2.49**). **Figure 2.71** shows that the majority of crashes at the intersection were either PDO crashes or less severe injury level crashes, those occurring at level C, "Possible Injury." This demonstrates the greater degree of sensitivity of the stratified approach to injury severity and consequently the more precise cost-benefit analysis afforded by the stratified approach, such that budgetary allocation could be employed more effectively.

Table 2.49: Stratified Breakeven B/C Analysis Nevada Ave. & Platte Ave.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/04/2023

Stratified BCA Nevada	**From:** 1/1/2016 **To:** 12/31/2020 **Street 1:** nevada **Street 2:** platte

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 35	33 :Injured C	CRF for PDO: 26%	Cost of PDO: $11,500
INJ C: 20	5 :Injured B	CRF for INJ C: 55%	Cost of INJ C: $71,800
INJ B: 4	1 :Injured A	CRF for INJ B: 55%	Cost of INJ B: $127,600
INJ A: 0	1 :Killed	CRF for INJ A: 55%	Cost of INJ A: $349,600
FAT: 1		CRF for FAT: 55%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 20
			Capital Recovery Factor: 0.080
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $9224475
Days: 1826
Type: Roundabout: Conversion of SIgnalized Intersection to Roundabout (Single Lane)
Notes: Intersection Related Crashes
Benefit/Cost Ratio: 1

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

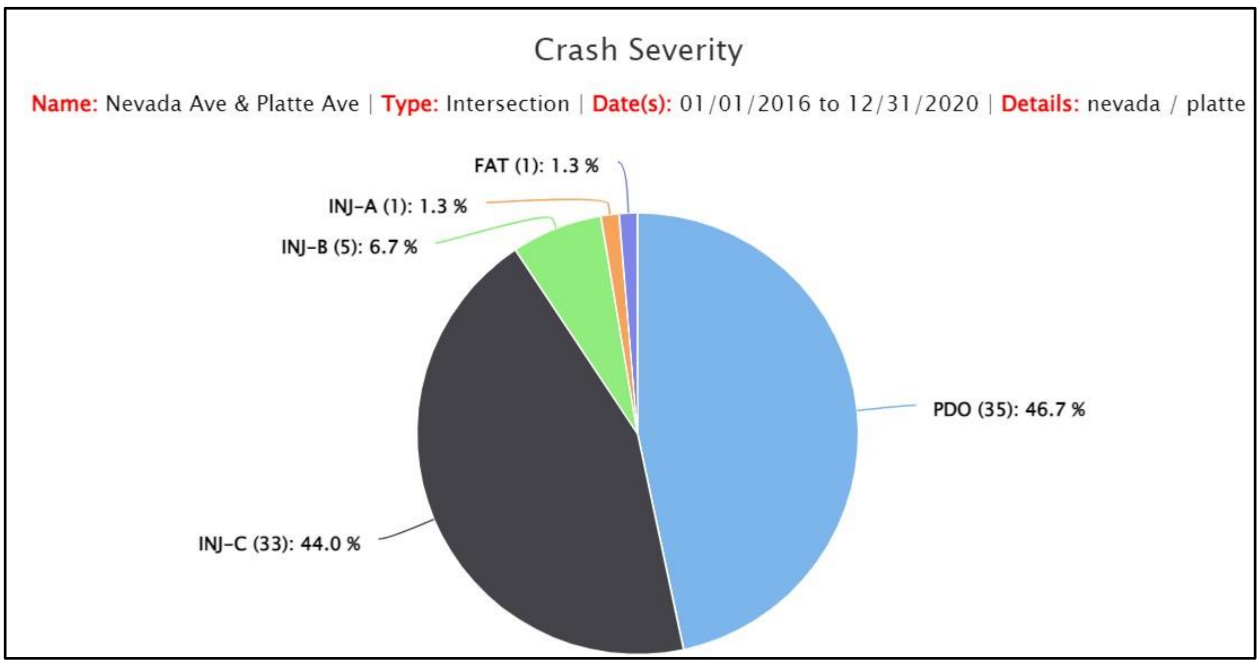

Figure 2.71: Crash Severity Distribution Nevada Ave. & Platte Ave.

Example 10 – SH21 (Powers Blvd.) MP 137.58-137.62 & Milton E. Proby Pkwy, Colorado Springs

The intersection of Powers Blvd. and Milton Proby Pkwy in Colorado Springs is an urban four-lane four-leg divided signalized intersection. It has double left turn lanes eastbound, northbound and southbound, and a single left turn lane westbound. It has channelized right turn lanes on all approaches and one signal head for each lane. Google Street View imagery indicates that the intersection has undergone a number of upgrades in recent years, one of which has been the replacement of protected/permissive left turns for eastbound and westbound traffic with fully protected left turn movements. Imagery indicates that this change took place sometime between August 2015 and July 2017 (see **Figure 2.72** and **Figure 2.73**).

Figure 2.72: Westbound Milton Proby Pkwy, Aug. 2015

Figure 2.73: Westbound Milton Proby Pkwy, July 2017

Crash history records show there were 45 total crashes in the 3-year period before upgrades to eastbound and westbound left turn signals took place (1/1/12-12/31/14). These included 24 PDO and 20 Injury (with 31 injuries) crashes and 1 Fatal crash (with 1 fatality) (**Table 2.50**).

Table 2.50: Crash Summary Powers Blvd. & Milton Proby Pkwy, 1/1/12-12/31/14

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

04/04/2023

Gen. Summary SH21 — **Type:** Intersection **Details:** Rt: 21 Section: A MM: [137.58 - 137.62] **From:** 1/1/2012 **To:** 12/31/2014

Crash Severity

By	Crashes:	Number of	People:
FAT:	1	Killed:	1
INJ:	20	Injured:	31
PDO:	24		
TOTAL:	45		

Weather Conditions

None:	42
Rain:	1
Snow/Sleet/Hail:	2
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	45

Lighting Conditions

Daylight:	20
Dawn/Dusk:	4
Dark-Lighted:	21
Dark-Unlighted:	0
Unknown:	0
TOTAL:	45

Road Conditions

Dry:	39
Wet:	3
Muddy:	0
Snowy:	0
Icy:	2
Slushy:	0
Foreign Material:	0
Road Treatment:	1
Unknown:	0
TOTAL:	45

Crash Location

On Road:	44
Off Road Left:	0
Off Road Right:	1
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	45

Crash Type

Overturning:	2	Bridge Abutment:	0
Other Non-Collision:	1	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	11	Embankment:	0
Head On:	0	Curb:	1
Rear End:	6	Delineator Post:	0
Sideswipe (Same):	6	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	18	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	0	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	1
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	0	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	0	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		45
Concrete Barrier:	0		

Number of Vehicles

One Car:	3
Two Car:	38
Three or More:	4
Unknown:	0
TOTAL:	45

Table 2.51 shows that in the three-year period prior to upgrading to fully protected left turns westbound and eastbound, there were patterns of Approach Turn and Broadside crashes at the intersection. Crash records show that almost 78% of all approach turn crashes involved eastbound and westbound at-fault vehicles. There were 14 EB and WB approach turn crashes in the before period, including 6 PDO, 7 Injury (with 9 injuries) and 1 Fatal (with 1 fatality).

In the 3-year period after the upgrades were made to EB and WB left turn signals, (1/1/18-12/31/20) crash records show the total number of crashes recorded was 33, including 25 PDO, 8

Injury (with 11 injuries) and 0 Fatal crashes (see **Table 2.52**). The number of EB and WB Approach Turn crashes fell to a total of four, and all four crashes were PDO crashes. This indicates a 33% reduction in PDO crashes and a 100% reduction in injury and fatal crashes due to EB and WB approach turn crashes. Records show that the proportion of approach turn crashes represented by EB and WB at-fault drivers fell from 78% to just over 44%.

Table 2.51: Direct Diagnostics Powers Blvd. & Milton Proby Pkwy 1/1/12-12/31/14

CDOT
DiExSys™ Vision Zero Suite
Diagnostics Report

04/04/2023

Diagnostics SH21 — **Cutoff:** 5 Acc's @ 95

Category/Trait	Statewide Average %	This Location # Crashes	This Location %	Probability %
Crash Severity				
Injury (INJ)	28.51%	20	44.44%	99.27%
Crash Type				
Broadside	14.44%	11	24.44%	97.69%
Approach Turn	16.02%	18	40%	100%
Lighting Conditions				
Dark - Lighted	22.15%	21	46.67%	99.99%
Condition Of Driver				
Alcohol	3.54%	7	15.56%	99.98%

However, despite the fall in E-W approach turn crashes following upgrade to fully protected left turns, there were still two EB and two WB at-fault approach turn crashes in the after period. In concert with this we can see that there were four NB-SB at-fault approach turn crashes in the before period and five NB-SB at-fault approach turn crashes in the after period. Approach turn crashes at signals with fully protected left turns are highly unusual and are indicative of inadequate red clearance time following protected left turns. Insufficient red clearance time for fully protected left turns can result in an approach turn crash because the next movement is the opposing thru movement.

Furthermore, as seen in the crash history, there were 11 broadsides recorded in the before period, involving at-fault vehicles in all 4 directions. In the after period, the number of broadside crashes fell to four, suggesting the conversion to fully protected left turns E-W may have had an indirect effect on these crashes.

Table 2.52: Crash Summary Powers & Milton Proby Pkwy, 1/1/18-12/31/20

CDOT
DiExSys™ Vision Zero Suite
General Summary Report

04/04/2023

Gen Summary SH21 — **Type:** Intersection **Details:** Rt: 21 Section: A MM: [137.58 - 137.62] **From:** 1/1/2018 **To:** 12/31/2020

Crash Severity

By	Crashes:	Number of	People:
FAT:	0	Killed:	0
INJ:	8	Injured:	11
PDO:	25		
TOTAL:	33		

Crash Location

On Road:	28
Off Road Left:	5
Off Road Right:	0
Off Road at Tee:	0
Off in Median:	0
Unknown:	0
	33

Weather Conditions

None:	31
Rain:	0
Snow/Sleet/Hail:	2
Fog:	0
Dust:	0
Wind:	0
Unknown:	0
TOTAL:	33

Crash Type

Overturning:	0	Bridge Abutment:	0
Other Non-Collision:	0	Column/Pier:	0
Pedestrian:	0	Culvert/Headwall:	0
Broadside:	4	Embankment:	0
Head On:	0	Curb:	2
Rear End:	9	Delineator Post:	0
Sideswipe (Same):	5	Fence:	0
Sideswipe (Opposite):	0	Tree:	0
Approach Turn:	9	Large Boulders or Rocks:	0
Overtaking Turn:	0	Barricade:	0
Parked Motor Veh:	1	Wall/Building:	0
Railway Veh:	0	Crash Cushion:	0
Bicycle:	0	Mailbox:	0
Motorized Bicycle:	0	Other Fixed Object:	0
Domestic Animal:	0	Rocks in Roadway:	5
Wild Animal:	0	Vehicle Cargo/Debris:	0
Light/Utility Pole:	2	Road Maintenace	0
Traffic Signal Pole:	0	Equipment:	0
Sign:	1	Involving Other Object:	0
Bridge Rail:	0	Total Other Object:	0
Guard Rail:	0	**TOTAL:**	0
Cable Rail:	0		33
Concrete Barrier:	0		

Lighting Conditions

Daylight:	21
Dawn/Dusk:	1
Dark-Lighted:	11
Dark-Unlighted:	0
Unknown:	0
TOTAL:	33

Road Conditions

Dry:	30
Wet:	1
Muddy:	0
Snowy:	0
Icy:	1
Slushy:	0
Foreign Material:	0
Road Treatment:	1
Unknown:	0
TOTAL:	33

Number of Vehicles

One Car:	5
Two Car:	27
Three or More:	1
Unknown:	0
TOTAL:	33

However, broadside crashes are strongly correlated with shorter than recommended intervals and all of this indicates that there may be insufficient Yellow plus All-Red signal times at the intersection, even following the E-W signal upgrades. Change and clearance intervals should be assessed in the field and corrected if found to not be in compliance with NCHRP Report 731, *Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections* (2012).

Figure 2.74 shows the SPF graph for the facility from the total crash frequency standpoint. It shows that in the three-year before period the facility performed in the high LOSS-III category, indicating moderate to high potential for crash reduction. In the three-year after period the facility still performed in the LOSS-II category, with the crash rate reducing about 23%.

Figure 2.75 shows the SPF graph for the facility from the crash severity standpoint. It shows that in the three-year before period the facility performed in the LOSS-IV category, indicating high potential for crash reduction. In the three-year after period the facility performed in the low LOSS-II category, indicating low to moderate potential for crash reduction, with the crash reducing about 51%.

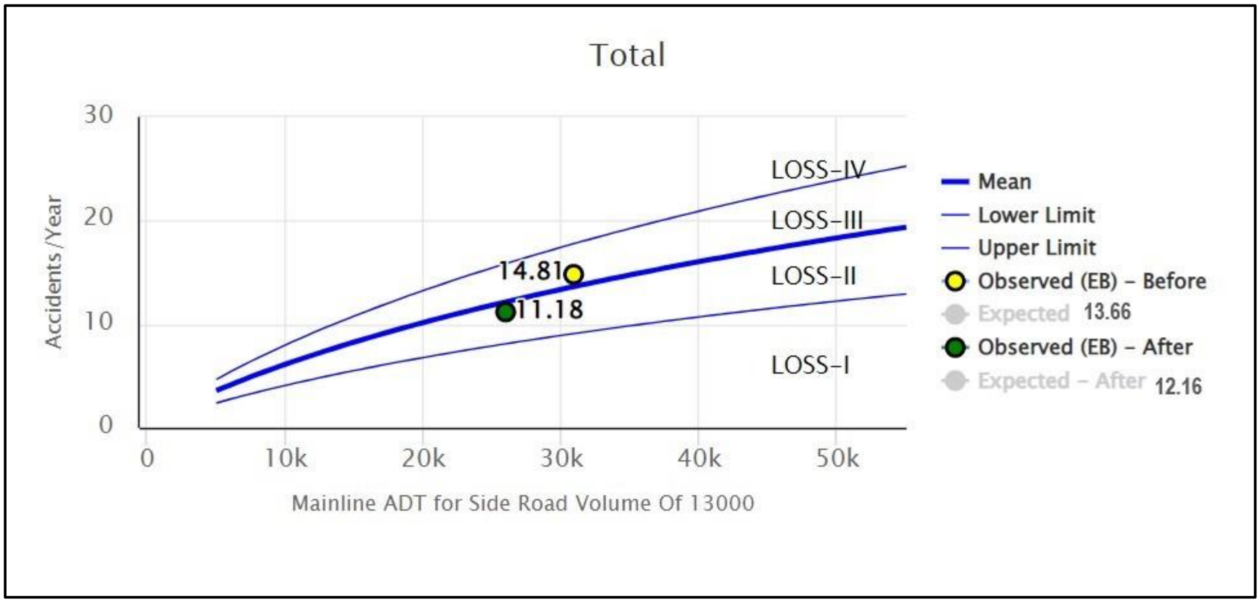

Figure 2.74: SPF Graph Total Crashes Powers Blvd. & Milton Proby Pkwy, Before (1/1/12-12/31/14), After (1/1/18-12/31/20)

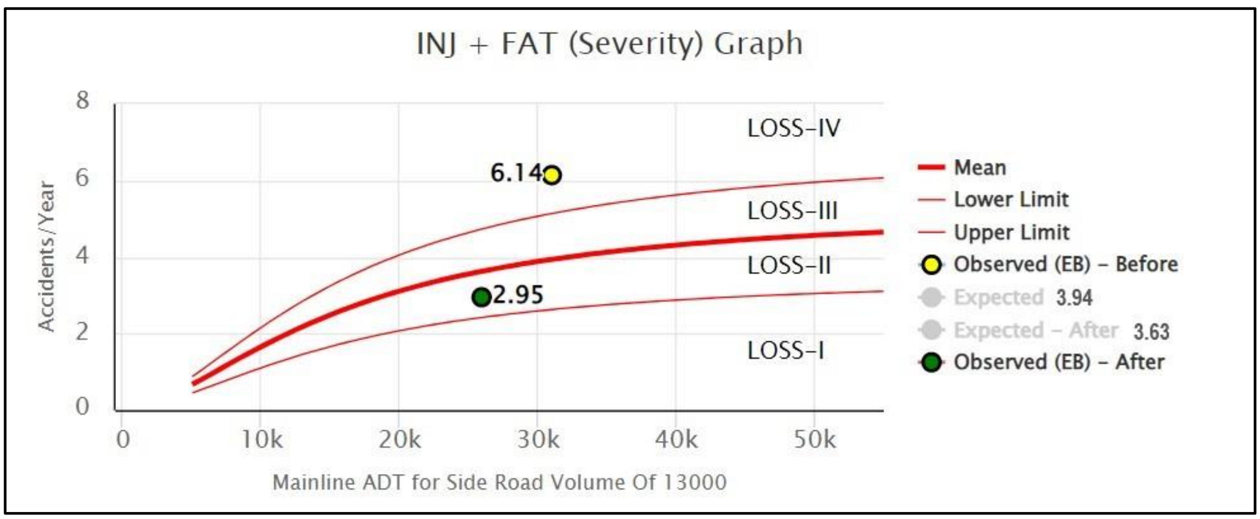

Figure 2.75: SPF Graph INJ+FAT Powers Blvd. & Milton Proby Pkwy, Before (1/1/12-12/31/14), After (1/1/18-12/31/20)

The following benefit-cost analysis focuses only changes brought about by the upgrade to fully protected left turn signals in the eastbound and westbound directions at the intersection. Using the traditional composite approach to injury cost allocation, **Table 2.53** shows the benefit-cost analysis for upgrading EB and WB protected/permitted left turn signals to fully protected left turn signals, using an estimated cost of $20,000. **Table 2.53** shows a B/C ratio of **467.29**.

Table 2.53: Composite B/C Analysis for Fully Protected Left Turns EB & WB at Powers Blvd. & Milton Proby Pkwy.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/04/2023

Composite BCA SH21 — **Loc:** 21 A **Begin:** 137.58 **End:** 137.62 **From:** 1/1/2012 **To:** 12/31/2014

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 6	7 :Injured C	CRF for PDO: 33%	Cost of PDO: $11,500
INJ C: 3	3 :Injured B	CRF for INJ C: 100%	Cost of INJ C: $106,100
INJ B: 3	3 :Injured A	CRF for INJ B: 100%	Cost of INJ B: $106,100
INJ A: 2	1 :Killed	CRF for INJ A: 100%	Cost of INJ A: $106,100
FAT: 1		CRF for FAT: 100%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $0

Improvement Cost:	$20000
Days:	1095
Type:	Signals: Fully Protected Left Turns EB & WB
Notes:	Approach Turn Crashes - EB & WB Only
Benefit/Cost Ratio:	467.29

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

If the stratified approach to injury cost allocation is used, the benefit-cost analysis (**Table 2.54**) shows a B/C ratio of **545.67** which is about 17% higher than that found using the composite approach. **Figure 2.76** shows that this intersection experienced a sizeable proportion of more severe approach turn crashes. Fatal crashes and crashes at injury level B and level A were represented in the same proportion as crashes at injury level C. This is another example of how using the stratified injury cost approach to benefit-cost analysis allows an analysis which is more sensitive in terms of the degree of severity of injuries occurring at a facility, and therefore more precise when it comes to resource allocation.

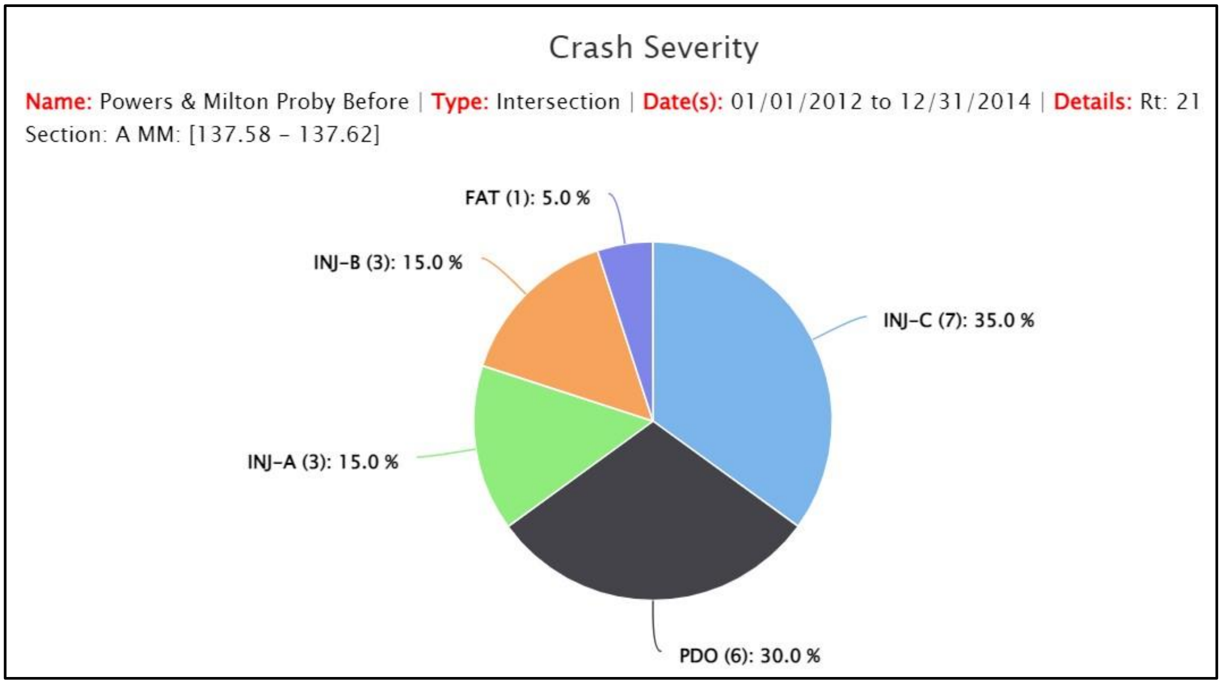

Figure 2.76: EB & WB Approach Turn Crash Severity Distribution Powers & Milton Proby

Table 2.54: Stratified B/C Analysis for Powers Blvd. & Milton Proby Pkwy.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/04/2023

Stratified BCA SH21 — **Loc:** 21 A **Begin:** 137.58 **End:** 137.62 **From:** 1/1/2012 **To:** 12/31/2014

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 6	7 :Injured C	CRF for PDO: 33%	Cost of PDO: $11,500
INJ C: 3	3 :Injured B	CRF for INJ C: 100%	Cost of INJ C: $71,800
INJ B: 3	3 :Injured A	CRF for INJ B: 100%	Cost of INJ B: $127,600
INJ A: 2	1 :Killed	CRF for INJ A: 100%	Cost of INJ A: $349,600
FAT: 1		CRF for FAT: 100%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $20000
Days: 1095
Type: Signals: Fully Protected Left Turns EB & WB
Notes: Approach Turn Crashes - EB & WB Only
Benefit/Cost Ratio: 545.67

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

Regarding broadside and approach turn crashes seen in the after period which may be related to inadequate Yellow plus All-Red intervals, **Table 2.55** shows the B/C analysis if correction of intervals at the intersection were to be performed. Using an estimated cost of $1,000, and the composite approach to injury cost allocation, a B/C ratio of **308.74** is anticipated.

Table 2.55: Composite B/C Analysis for Retiming at Powers Blvd. & Milton Proby Pkwy.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/04/2023

Composite BCA SH 21 — **Loc:** 21 A **Begin:** 137.58 **End:** 137.62 **From:** 1/1/2018 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 8	6 :Injured C	CRF for PDO: 15%	Cost of PDO: $11,500
INJ C: 5	0 :Injured B	CRF for INJ C: 15%	Cost of INJ C: $106,100
INJ B: 0	0 :Injured A	CRF for INJ B: 15%	Cost of INJ B: $106,100
INJ A: 0	0 :Killed	CRF for INJ A: 15%	Cost of INJ A: $106,100
FAT: 0		CRF for FAT: 15%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $1000
Days: 1095
Type: Review & Correction of Yellow+All-Red Timing Intervals
Notes: Broadside & Approach Turn Crashes Only
Benefit/Cost Ratio: 308.74

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

In comparison, if the benefit-cost analysis for correction of intervals in performed using the stratified approach to injury costs, **Table 2.56** indicates a B/C ratio of **221.54** is anticipated. This is about 28% lower than that obtained using the composite approach. When the distribution of crash severity of broadside and approach turn crashes which were used for the B/C analysis are considered, it is clear the majority of crashes are PDO and all injury crashes are at the lowest injury level, C. (**Figure 2.77**).

This serves as a final example as to how the stratified injury cost approach to benefit-cost analysis is more sensitive to degree of severity of injuries and therefore more precise when it comes to the benefits realized. A more sensitive and precise method of benefit-cost analysis supports more informed decision making and more targeted resource allocation.

Table 2.56: Stratified B/C Analysis for Retiming at Powers Blvd. & Milton Proby Pkwy.

CDOT
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/04/2023

Stratified BCA SH 21 | **Loc:** 21 A **Begin:** 137.58 **End:** 137.62 **From:** 1/1/2018 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes		Projected Crashes and Reduction Factors	Other Information
PDO: 8	6 :Injured C	CRF for PDO: 15%	Cost of PDO: $11,500
INJ C: 5	0 :Injured B	CRF for INJ C: 15%	Cost of INJ C: $71,800
INJ B: 0	0 :Injured A	CRF for INJ B: 15%	Cost of INJ B: $127,600
INJ A: 0	0 :Killed	CRF for INJ A: 15%	Cost of INJ A: $349,600
FAT: 0		CRF for FAT: 15%	Cost of FAT: $1,906,200
			Interest Rate: 5%
			AADT Growth Factor: 2%
			Service Life: 10
			Capital Recovery Factor: 0.130
			Annual Maintenance/Delay Cost: $0

Improvement Cost: $1000
Days: 1095
Type: Review & Correction of Yellow+All-Red Timing Intervals
Notes: Broadside & Approach Turn Crashes Only
Benefit/Cost Ratio: 221.54

☐ BC Calc by # of Crashes ☑ BC Calc by # of Injuries

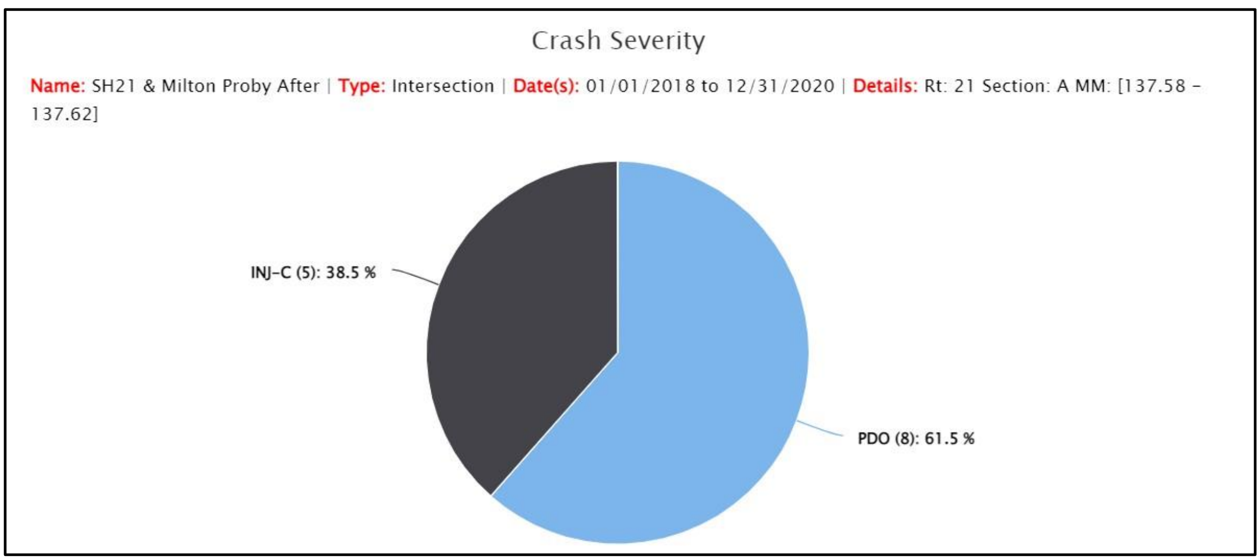

Figure 2.77: Broadside and Approach Turn Crash Distribution, Powers & Milton Proby 1/1/18-12/31/20

Table 2.57 following provides a summary of results for the preceding ten locations where benefit cost analysis was performed using composite and stratified injury costs.

Table 2.57: Summary of BCA at Example Locations with Composite & Stratified Injury Costs

Location	Countermeasure	Cost ($)	Composite BCR		Stratified BCR		Stratified Difference (+/-%)		Crash Severity (%) Before (Bef.) and After (Aft.)									
-	-	-	**Before**	**After**	**Before**	**After**	**Before**	**After**	**PDO Bef.**	**PDO Aft.**	**C Bef.**	**C Aft.**	**B Bef.**	**B Aft.**	**A Bef.**	**A Aft.**	**K Bef.**	**K Aft.**
16th St. & Havana	All-Way Stop Control	10K	712.52	1104.08	572.77	881.85	-19.6	-20.1	46	73	43	23	11	0	0	4	0	0
US6 & SH139	Signals & LT Lanes	2.6M	1.28	1.07	1.15	0.97	-10.2	-9.3	37	33.3	37	66.6	26	0	0	0	0	0
SH34 & 83rd Ave	Signals	300K	52.41	56.48	57.27	61.71	+9.3	+9.3	25.5	56.4	48.9	23.1	17	7.7	8.5	12.8	-	-
Dahlia St & I-76 Frontage	Roundabout	3.0M	2.9	-	2.43	-	-16.2	-	53.1	-	42.9	-	2	-	2	-	0	-
Lookout Mountain Rd.	"Motorcycles Use Extreme Caution"	3K	62.04	-	121.67	-	+19.6	-	22.2	-	0	-	44.4	-	33.3	-	0	-
US550	EB Right Side Guardrail	105K	38.28	-	47.05	-	+23	-	20	-	0	-	20	-	40	-	20	-
SH66 & 75th St	FP LTs Time of Day	16K	241.44	-	282.92	-	+17.2	-	25.8	-	41.9	-	22.6	-	9.7	-	0	-
US40	Rumble Strips & Increase De-Icing	22.5K	55.65	-	51.15	-	+8	-	62.1	-	27.6	-	6.9	-	0	-	3.4	-
Nevada Ave & Platte Ave	Roundabout	10.5M Comp. breakeven 9.22M Strat. breakeven	1	-	1	-	-7.8 ($)	-	46.7	-	44	-	6.7	-	1.3	-	1.3	-
SH21 & Milton Proby Pkwy	FP LTs East-West	20K	467.29	-	545.67	-	+16.8	-	30	-	35	-	15	-	15	-	5	-
SH21 & Milton Proby Pkwy	Review & Correct Timing – all 4	1K	308.74	-	221.54	-	-28.2	-	61.5	-	38.5	-	0	-	0	-	0	-

As outlined previously and as witnessed in the summarized results in **Table 2.57**, there is a difference in benefit-cost-analysis when the stratified approach to injury costing is implemented. The results indicate that the difference is not always as significant as was initially expected, but it serves to show that there is indeed a difference that can be captured with the stratified approach. The results of the analysis indicate that on more rural facilities, on facilities with higher speeds, in instances where there are more vulnerable road users and in instances where there are more people injured and a higher degree of injury, stratifying injury cost in the benefit-cost-analysis provides a more sensitive analysis and a more accurate reflection of the benefits to be obtained.

Chapter 3 – Examination of the Cost of a Fatality

The literature review which was performed as part of this research along with the examination of practices across ten states, showed that there is wide disparity in the approach to assigning a dollar value to a statistical life. While the loss of life is always tragic, it cannot always be prevented, and the literature review showed that there is consensus that placing a value on a life lost is necessary in order to make trade-offs and policy decisions. Moreover, it showed that a lack of a uniform value for a statistical life (VSL) is problematic.

Challenges

The VSL employed by states is generally obtained from sources such as the U.S. DOT, FHWA, the AASHTO HSM, the National Safety Council and/or the National Highway Traffic Safety Administration (NHTSA). The VSL assigned at the Fatality level was found to dramatically vary from as low as $239,292 ($2015) in Alabama, to as high as $9,600,000 ($2016) in Oklahoma. The randomness which this introduces into analysis needs to be dampened.

One such person who has looked to offer solutions for a broadly accepted and adopted methodology in the valuation of a life is Hauer. In the literature by Hauer which was reviewed as part of this study, he addresses the matter of disparity in the VSL employed nationally, and it is worth summarizing some of the pitfalls he highlights in the current approach. Those include:

- The premises behind the cost-benefit analysis (CBA) as a tool are difficult to apply to area of road safety,
- Time savings tend to be valued too highly against the value of life and
- Discounting diminishes the value of future lives.

While Hauer does offer some solutions to the standardization of the VSL, the solutions he offers are not simple. One such solution is to toss aside the cost-benefit analysis tool and replace it with a cost-effectiveness-analysis. However, even this would require such strict criterion which cannot be met consistently and are rarely achievable. Furthermore, the CBA is one of the most widely used and accepted forms of policy and decision making, particularly within the field of road safety that would not be an immediate or easy option to consider disposing with it.

Hauer also asserts that having a standardized VSL is only useful if it is applied in a standardized manner across all domains, not just road safety, and outlines that this is achievable only under the following conditions:

1. If budgeted money can get to the agency that can save a life at the lowest cost, then there is a value in declaring the lowest cost at which a life can be saved. This is independent of the value of a life.
2. All agencies' budgets are adjusted so that the cost of saving a life is the same in each agency and does not exceed a common value, in which case a common value of life based on revealed preferences is acceptable.

As is clear, particularly in the case of the second point, these conditions are not easily achieved nor ready to be met at present and would require a tremendous shift in policy by multiple involved parties at a widespread scale.

Recommendations

As such, under the scope of the present research, decisions still need to be made while at the same time in an effort to reduce randomness. It is our recommendation that the VSL which should be adopted in BCA is that which is currently set forth by the National Safety Council adjusted for inflation to a present dollar value. Moreover, we recommend that adoption of the average economic cost for a fatality, which was set as $1,750,00 in $2020, rather that the comprehensive cost ($11.449,000 in $2020).

This value is recommended over the comprehensive cost and over other cost sources, such as for example the U.S. D.O.T which places the VSL in $2021 at $11.8 million, in order to smooth the large disparity between these fatal values which are in the millions, and the typical values assigned to injury level and property damage only crashes, which tend to be in the tens or hundreds of thousands. If a larger VSL is used it would potentially skew any random event to such an extent as to make resource allocation impossible.

Furthermore, when the current KABCO societal and human capital costs employed by CDOT are considered (see **Table 3.1**), the proportions in which one crash severity category is amplified compared to the next, lie within the threshold of 1.77 to 6.24.

Table 3.1: CDOT Current Crash Costs by Severity

Crash Severity	Value ($)	Description
Fatal (K)	$1,906,200	2021 CPI – Adjusted Human Capital Cost
Disabling Injury (A)	$349,600	2021 ECI Adjusted Comprehensive Society Cost
Evident Injury (B)	$127,600	2021 ECI Adjusted Comprehensive Society Cost
Possible Injury (C)	$71,800	2021 ECI Adjusted Comprehensive Society Cost
PDO (O)	$11,500	2021 ECI Adjusted Comprehensive Society Cost

To illustrate, if we consider the cost of each successively more severe category of crash in proportion to its predecessor, we see that the proportions (or amplification factors) are as follows:

- C to O: $71,800 to $11,500 = 6.24
- B to C: $127,600 to $71,800 = 1.77
- A to B: $349,600 to $127,600 = 2.4
- K to A: $1,906,200 to $349,600 = 5.45

In no instance does the proportional exceed a factor of seven. Indeed, if we consider PDO, injury and fatal as three separate categories we can see that moving from the PDO category into the injury category the proportion is a factor of 6.24 and in the same way moving from the injury category into the fatal category the proportion is a factor of 5.45. The procedure can be repeated for the economic values set out by the National Safety Council (see **Table 1.5**) and the largest proportion seen there is between fatal and disabling injury, at about 17.

This serves to reinforce the earlier point: a disproportionately larger value on a fatal crash would skew any calculations. Conversely, if the proportionate differences in costs between crash levels stay the same, the conclusions or outcomes of the BCA will stay the same no matter how big the numbers get, but if the cost of fatal crash is disproportionately bigger, say 20 times, than even the highest-level injury crash, then the outcome becomes unbalanced.

In conclusion we believe that the adoption of the National Safety Council's value of a fatal injury crash at the economic cost level is the most sensible compromise and the most practical solution to what is a complex and philosophical dilemma.

Chapter 4 – Conclusions

Cost-benefit analysis is a data-driven tool which assists decision making when it comes to safety projects. Limited resources and competing needs dictate that funding must be optimized and allocated to safety projects in a way that is most cost-effective. The definition and cost of serious injuries is one critical data component in the cost-benefit analysis. The CBA is commonly criticized for the ethically controversial need to assign a monetary value to life and limb, as well as the historical lack of convergence on a singular value across studies and in application for the value of a statistical life (VSL). There is however consensus that placing a value on a life lost is necessary in order to make trade-offs and that a lack of a uniform value is problematic.

Review of extant literature as well as a review of practices in ten states across the nation showed that the most commonly used scale in transportation safety is the KABCO injury level scale as outlined in the AASHTO Highway Safety Manual. However, definitions for A/B/C level injury coding differs across the states, with stratification of injury levels across the states varying widely. The importance of resolving the impact of injury level scale on the estimation of crash costs has been recognized as nationally beneficial in terms of safety BCA.

The VSL employed by states is generally obtained from sources such as the U.S. DOT, FHWA, the AASHTO HSM, the National Safety Council and/or the National Highway Traffic Safety Administration (NHTSA). The VSL assigned at the Fatality level also dramatically varies from as low as $239,292 ($2015) in Alabama, to as high as $9,600,000 ($2016) in Oklahoma.

The relationship between injury and cost was examined by determining the cost for every injury level crash over a 10-year period on a carefully selected set of facilities and crash types. The facilities and crash types selected for analysis were those which are well represented in terms of crash history, and therefore sample size. The categories selected, in addition to being well represented in terms of crash volume and history, demonstrate variability in facility type, environment and crash type. The calculation process implemented the KABCO injury level scale with societal and human capital costs. To determine if the differences observed in the average cost of an injury crash across these varying facility types, environments and crash types were statistically significant, two types of t-test were performed: a paired two-sample means t-test and a two-sample assuming unequal variances t-test.

Results of the statistical analysis completely dismissed the null hypothesis with alpha values supporting a 99% confidence interval in the observed results of the t-tests. The results of our analysis indicate that the alternative hypothesis is true i.e., there is a statistically significant difference between the mean cost of an injury crash across samples and therefore across facility type and crash type.

An examination was made of ten sample locations in Colorado to compare the results of performing a benefit cost analysis on safety countermeasures (some historically implemented, some suggested) using the composite approach to injury crash valuation and the stratified approach to injury crash valuation. The results of this analysis showed that while the differences between the composite and the stratified approach were not consistently as significant as was initially expected, there is indeed a difference between the two. Moreover, the results indicate that the stratified approach is more sensitive to instances when there a more people injured, or more vulnerable road users involved. As such, it appears that the stratified approach ought to be considered as the preferred approach, offering a more sensitive analysis of a particular crash history and severity and therefore a more informed basis on which to allocate resources for the highest return on investment.

Finally, in the midst of ongoing debate regarding the appropriate VSL which might be adopted congruously across the board on a national level in all domains, we recommend that the average economic cost value set out by the National Safety Council ($1,750,000 in $2020), be adopted by CDOT in benefit cost analysis. While this is not a perfect solution to a complex and sensitive argument, it is a sensible and rational one which ensures that the cost of a fatal injury crash is in the same order of magnitude as other crash levels, preventing the skewing of outcomes making resource allocation impossible. Ultimately, a more sensitive data-driven approach will improve the quality of project selection and road safety in Colorado.

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