PART B — ROADWAY SAFETY MANAGEMENT PROCESS

CHAPTER 8—PRIORITIZE PROJECTS

EXHIBITS

APPENDIX A

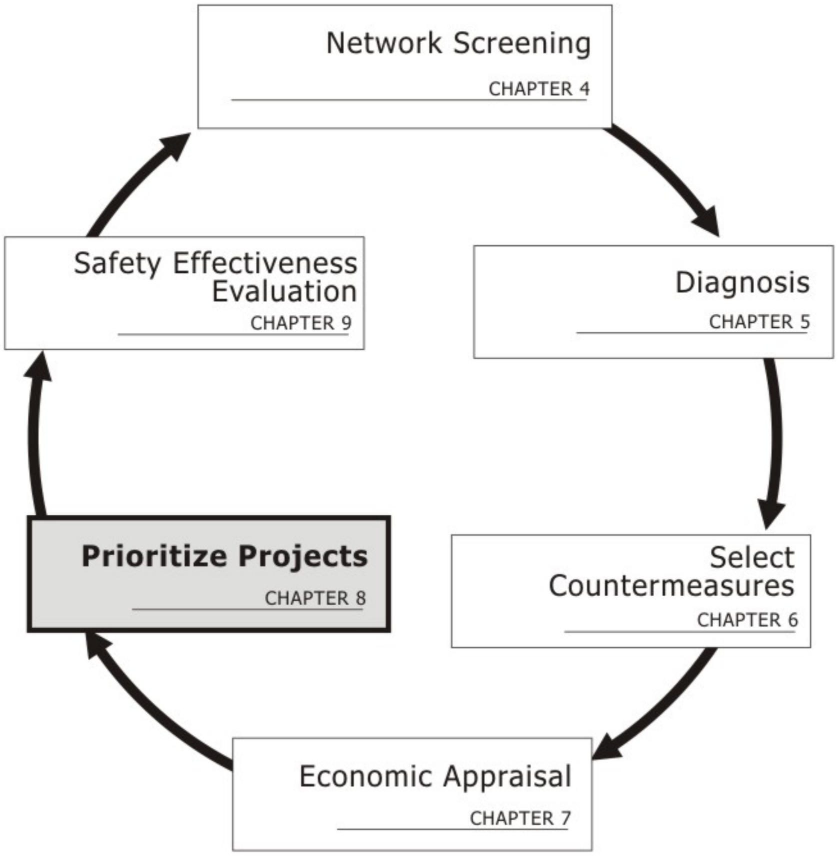
CHAPTER 8 PRIORITIZE PROJECTS

8.1. INTRODUCTION

Chapter 8 presents prioritization methods to select financially optimal sets of projects.

Chapter 8 presents methods for prioritizing countermeasure implementation projects. Prior to conducting prioritization, one or more candidate countermeasures have been identified for possible implementation at each of several sites, and an economic appraisal has been conducted for each countermeasure. Each countermeasure that is determined to be economically justified by procedures presented in *Chapter 7* is included in the project prioritization process described in this chapter. Exhibit 8-1 provides an overview of the complete Roadway Safety Management process presented in *Part B* of the manual.

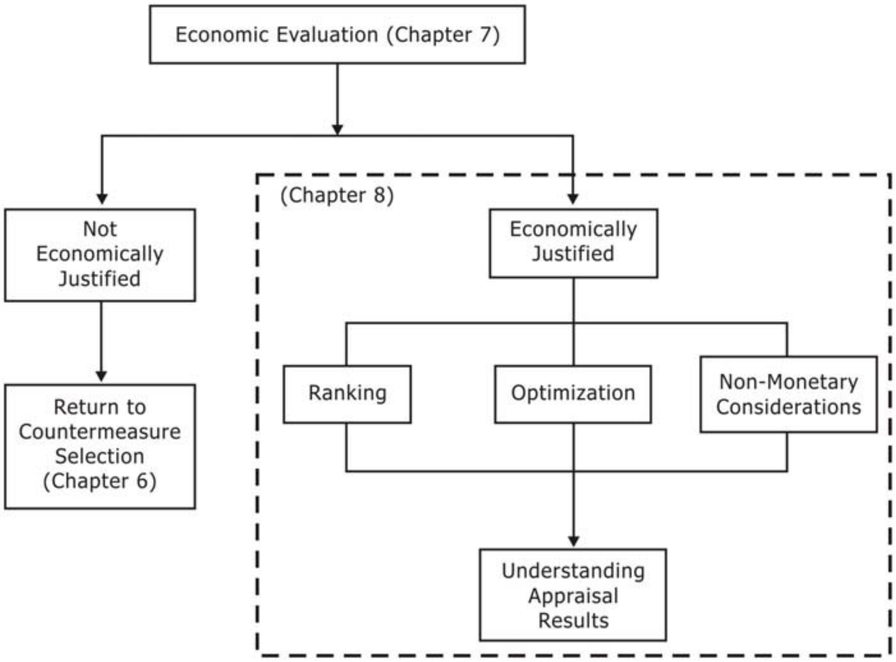
Exhibit 8-1: Roadway Safety Management Process Overview



In the HSM, the term "prioritization" refers to a review of possible projects or project alternatives for construction and developing an ordered list of recommended projects based on the results of ranking and optimization processes. "Ranking" refers to an ordered list of projects or project alternatives based on specific factors or project benefits and costs. "Optimization" is used to describe the process by which a set of projects or project alternatives are selected by maximizing benefits according to budget and other constraints.

This chapter includes overviews of simple ranking and optimization techniques for prioritizing projects. The project prioritization methods presented in this chapter are primarily applicable to developing optimal improvement programs across multiple sites or for an entire roadway system, but they can also be applied to compare improvement alternatives for a single site. This application has been discussed in *Chapter 7*. Exhibit 8-2 provides an overview of the project prioritization process.

Exhibit 8-2: Project Prioritization Process



8.2. PROJECT PRIORITIZATION METHODS

Chapter 8 provides an overview of six methods for prioritizing a list of potential improvements.

The three prioritization methods presented in this chapter are:

- Ranking by economic effectiveness measures
- Incremental benefit-cost analysis ranking
- Optimization methods

Ranking by economic effectiveness measures or by the incremental benefit-cost analysis method provides a prioritized list of projects based on a chosen criterion. Optimization methods, such as linear programming, integer programming, and dynamic programming, provide project prioritization consistent with incremental benefit-cost analysis, but consider the impact of budget constraints in creating an optimized project set. Multiobjective resource allocation can consider the effect of non-monetary elements, including decision factors other than those centered on crash reduction, and can optimize based on several factors.

Incremental benefit-cost analysis is closely related to the benefit-cost ratio (BCR) method presented in *Chapter 7*. Linear programming, integer programming, and dynamic programming are closely related to the net present value (NPV) method presented in *Chapter 7*. There is no generalized multiple-site method equivalent to the cost-effectiveness method presented in *Chapter 7*.

A conceptual overview of each prioritization method is presented in the following sections. Computer software programs are needed to efficiently and effectively use many of these methods, due to their complexity. For this reason, this chapter does not include a step-by-step procedure for these methods. References to additional documentation regarding these methods are provided.

8.2.1. Ranking Procedures

Ranking by Economic Effectiveness Measures

The simplest method for establishing project priorities involves ranking projects or project alternatives by the following measures (identified in *Chapter 7*), including:

- Project costs,
- Monetary value of project benefits,
- Number of total crashes reduced,
- Number of fatal and incapacitating injury crashes reduced,
- Number of fatal and injury crashes reduced,
- Cost-effectiveness index, and,
- Net present value (NPV).

The ranking process develops a list of sites based on particular factors. Examples of these factors are shown in 8.2.1.

As an outcome of a ranking procedure, the project list is ranked high to low on any one of the above measures. Many simple improvement decisions, especially those involving only a few sites and a limited number of project alternatives for each site, can be made by reviewing rankings based on two or more of these criteria.

However, because these methods do not account for competing priorities, budget constraints, or other project impacts, they are too simple for situations with multiple, competing, priorities. Optimization methods are more complicated but will provide information accounting for competing priorities, and will yield a project set that provides the most crash reduction benefits within financial constraints. If ranking sites by benefit-cost ratio, an incremental benefit-cost analysis is performed, as described below.

Incremental Benefit-Cost Analysis

Incremental benefit-cost analysis is an extension of the benefit-cost ratio (BCR) method presented in *Chapter 7*. The following steps describe the method in its simplest form:

1. Perform a BCR evaluation for each individual improvement project as described in *Chapter 7*.
2. Arrange projects with a BCR greater than 1.0 in increasing order based on their estimated cost. The project with the smallest cost is listed first.
3. Beginning at the top of the list, calculate the difference between the first and second project's benefits. Similarly calculate the difference between the costs of the first and second projects. The differences between the benefits of the two projects and the costs of the two are used to compute the BCR for the incremental investment.

4. If the BCR for the incremental investment is greater than 1.0, the project with the higher cost is compared to the next project in the list. If the BCR for the incremental investment is less than 1.0, the project with the lower cost is compared to the next project in the list.
5. Repeat this process. The project selected in the last pairing is considered the best economic investment.

To produce a ranking of projects, the entire evaluation is repeated without the projects previously determined to be the best economic investment until the ranking of every project is determined.

There may be instances where two projects have the same cost estimates resulting in an incremental difference of zero for the costs. An incremental difference of zero for the costs leads to a zero in the denominator for the BCR. If such an instance arises, the project with the greater benefit is selected. Additional complexity is added, where appropriate, to choose one and only one project alternative for a given site. Incremental benefit-cost analysis does not explicitly impose a budget constraint.

It is possible to perform this process manually for a simple application; however, the use of a spreadsheet or special purpose software to automate the calculations is the most efficient and effective application of this method. An example of incremental benefit-cost analysis software used for highway safety analysis is the Roadside Safety Analysis Program (RSAP), which is widely used to establish the economic justification for roadside barriers and other roadside improvements.(3)

8.2.2. Optimization Methods

At a highway network level, a jurisdiction may have a list of improvement projects that are already determined to be economically justified, but there remains a need to determine the most cost-effective set of improvement projects that fit a given budget. Optimization methods are used to identify a project set that will maximize benefits within a fixed budget and other constraints. Thus, optimization methods can be used to establish project priorities for the entire highway system or any subset of the highway system.

It is assumed that all projects or project alternatives to be prioritized using these optimization methods have first been evaluated and found to be economically justified (i.e., project benefits are greater than project costs). The method chosen for application will depend on:

- The need to consider budget and/or other constraints within the prioritization, and
- The type of software accessible, which could be as simple as a spreadsheet or as complex as specialized software designed for the method.

Basic Optimization Methods

There are three specific optimization methods that can potentially be used for prioritization of safety projects. These are:

- Linear programming (LP) optimization
- Integer programming (IP) optimization

- Dynamic programming (DP) optimization

Each of these optimization methods uses a mathematical technique for identifying an optimal combination of projects or project alternatives within user-specified constraints (such as an available budget for safety improvement). *Appendix A* provides a more detailed description of these three optimization methods.

In recent years, integer programming is the most widely used of these three optimization methods for highway safety applications. Optimization problems formulated as integer programs can be solved with Microsoft Excel or with other commercially available software packages. A general purpose optimization tool based on integer programming is available in the FHWA *Safety Analyst* software tools for identifying an optimal set of safety improvement projects to maximize benefits within a budget constraint (www.safetyanalyst.org). A special-purpose optimization tool known as the Resurfacing Safety Resource Allocation Program (RSRAP) is available for identifying an optimal set of safety improvements for implementation in conjunction with pavement resurfacing projects.(2)

Multiobjective Resource Allocation

The optimization and ranking methods discussed above are all directly applicable to project prioritization where reducing crashes is the only objective being considered. However, in many decisions concerning highway improvement projects, reducing crashes is just one of many factors that influence project selection and prioritization. Many highway investment decisions that are influenced by multiple factors are based on judgments by decision makers once all of the factors have been listed and, to the extent feasible, quantified.

A class of decision-making algorithms known as multiobjective resource allocation can be used to address such decisions quantitatively. Multiobjective resource allocation can optimize multiple objective functions, including objectives that may be expressed in different units. For example, these algorithms can consider safety objectives in terms of crashes reduced; traffic operational objectives in terms of vehicle-hours of delay reduced; air quality benefits in terms of pollutant concentrations reduced; and noise benefits in terms of noise levels reduced. Thus, multiobjective resource allocation provides a method to consider non-monetary factors, like those discussed in *Chapter 7*, in decision making.

All multiobjective resource allocation methods require the user to assign weights to each objective under consideration. These weights are considered during the optimization to balance the multiple objectives under consideration. As with the basic optimization methods, in the multiobjective resource allocation method an optimal project set is reached by using an algorithm to minimize or maximize the weighted objectives subject to constraints, such as a budget limit.

Examples of multiobjective resource allocation methods for highway engineering applications include Interactive Multiobjective Resource Allocation (IMRA) and Multicriteria Cost-Benefit Analysis (MCCBA).(1,4)

8.2.3. Summary of Prioritization Methods

Exhibit 8-3 provides a summary of the prioritization methods described in Section 8.2.

Exhibit 8-3: Summary of Project Prioritization Methods

Method	Input Needs	Outcomes	Considerations
Ranking by Safety-Related Measures	Various; inputs are readily available and/or derived using the methods presented in Chapter 7.	A ranked list or lists of projects based on various cost and/or benefit factors.	• The prioritization can be improved by using a number of ranking criteria. • Not effective for prioritizing many project alternatives or projects across many sites. • The list is not necessarily optimized for a given budget.
Incremental Benefit-Cost Analysis	Present value of monetary benefits and costs for economically justified projects. Spreadsheet and/or a software program.	A ranked list of projects based on the benefits they provide and their cost.	• Multiple benefit cost ratio calculations. • Spreadsheet or software is useful to automate and track the calculations. • The list is not necessarily optimized for a given budget.
Linear Programming (LP)	Present value of monetary benefits and costs for economically justified projects. Spreadsheet and/or a software program.	An optimized list of projects that provide: 1) Maximum benefits for a given budget, or 2) Minimum cost for a predetermined benefit.	• Generally most applicable to roadway projects without defined limits. • Microsoft Excel can be used to solve LP problems for a limited set of values. • Other computer software packages are available to solve LP problems that have many variables. • There are no generally available LP packages specifically customized for highway safety applications.
Integer Programming (IP)	Present value of monetary benefits and costs for economically justified projects. Spreadsheet and/or software program.	An optimized list of projects that provide: 1) Maximum benefits for a given budget, or 2) Minimum cost for a predetermined benefit.	• Generally most applicable to projects with fixed bounds. • Microsoft Excel can be used to solve IP problems for a limited set of values. • Other computer software packages are available to efficiently solve IP problems. • SafetyAnalyst and RSRAP provide IP packages developed specifically for highway safety applications.
Dynamic Programming (DP)	Present value of monetary benefits and costs for economically justified projects. Software program to solve the DP problem.	An optimized list of projects that provide: 1) Maximum benefits for a given budget, or 2) Minimum cost for a predetermined benefit.	• Computer software is needed to efficiently solve DP problems.
Multiobjective Resource Allocation	Present value of monetary benefits and costs for economically justified projects. Software program to solve the multiobjective problem.	A set of projects that optimizes multiple project objectives, including safety and other decision criteria, simultaneously in accordance with user-specified weights for each project objectives.	• Computer software is needed to efficiently solve multiobjective problems. • User must specify weights for each project objective, including crash reduction measures and other decision criteria.

The methods presented in this chapter vary in complexity. Depending on the purpose of the study and access to specialized software for analysis, one method may be more appropriate than another. Each method is expected to provide valuable input into the roadway safety management process.

8.3. UNDERSTANDING PRIORITIZATION RESULTS

The results produced by these prioritization methods can be incorporated into the decision-making process as one key, but not necessarily definitive, piece of information. The results of these prioritization methods are influenced by a variety of factors including:

Prioritization methods are used to select among a variety of projects. This chapter provides an overview of ranking and optimization methods.

- How benefits and costs are assigned and calculated;
- The extent to which the evaluation of costs and benefits are quantified;
- The service lives of the projects being considered;
- The discount rate (i.e., the minimum rate of return); and,
- The confidence intervals associated with the predicted change in crashes.

There are also non-monetary factors to be considered, as discussed in *Chapter 7*. These factors may influence the final allocation of funds through influence on the judgments of key decision makers or through a formal multi-objective resource allocation. As with many engineering analyses, if the prioritization process does not reveal a clear decision, it may be useful to conduct sensitivity analyses to determine incremental benefits of different choices.

8.4. SAMPLE PROBLEMS

The sample problems presented here illustrate the ranking of project alternatives across multiple sites. The linear programming, integer programming, dynamic programming, and multi-objective resource allocation optimization methods described in *Chapter 8* require the use of software and, therefore, no examples are presented here. These methods are useful to generate a prioritized list of countermeasure improvement projects at multiple sites that will optimize the number of crashes reduced within a given budget.

8.4.1. The Situation

The highway agency has identified safety countermeasures, benefits, and costs for the intersections and segments shown in Exhibit 8-4.

Exhibit 8-4: Intersections and Roadway Segments Selected for Further Review

						Crash Data		
Intersections	**Traffic Control**	**Number of Approaches**	**Major AADT**	**Minor AADT**	**Urban/ Rural**	**Total Year 1**	**Total Year 2**	**Total Year 3**
2	TWSC	4	22,100	1,650	U	9	11	15
7	TWSC	4	40,500	1,200	U	11	9	14
11	Signal	4	42,000	1,950	U	12	15	11
12	Signal	4	46,000	18,500	U	10	14	8
						Crash Data (Total)		
Segments	**Cross-Section (Number of Lanes)**	**Segment Length (miles)**	**AADT**		**Undivided/ Divided**	**Year 1**	**Year 2**	**Year 3**
1	2	0.60	9,000		U	16	15	14
2	2	0.40	15,000		U	12	14	10
5	4	0.35	22,000		U	18	16	15
6	4	0.30	25,000		U	14	12	10
7	4	0.45	26,000		U	12	11	13

Exhibit 8-5 summarizes the countermeasure, benefits, and costs for each of the sites selected for further review. The present value of crash reduction was calculated for Intersection 2 in *Chapter 7*. Other crash costs represent theoretical values developed to illustrate the sample application of the ranking process.

Exhibit 8-5: Summary of Countermeasure, Crash Reduction, and Cost Estimates for Selected Intersections and Roadway Segments

Intersection	**Countermeasure**	**Present Value of Crash Reduction**	**Cost Estimate**
2	Single-Lane Roundabout	$33,437,850	$695,000
7	Add Right Turn Lane	$1,200,000	$200,000
11	Add Protected Left Turn	$1,400,000	$230,000
12	Install Red Light Cameras	$1,800,000	$100,000
Segment	**Countermeasure**	**Present Value of Safety Benefits**	**Cost Estimate**
1	Shoulder Rumble Strips	$3,517,400	$250,000
2	Shoulder Rumble Strips	$2,936,700	$225,000
5	Convert to Divided	$7,829,600	$3,500,000
6	Convert to Divided	$6,500,000	$2,750,000
7	Convert to Divided	$7,000,000	$3,100,000

8.4.2. The Question

Which safety improvement projects would be selected based on ranking the projects by Cost-Effectiveness, Net Present Value (NPV), and Benefit-Cost Ratio (BCR) measures?

8.4.3. The Facts

Exhibit 8-6 summarizes the crash reduction, monetary benefits and costs for the safety improvement projects being considered.

Exhibit 8-6: Project Facts

Location	Estimated Average Reduction in Crash Frequency	Present Value of Crash Reduction	Cost Estimate
Intersection 2	47	$33,437,850	$695,000
Intersection 7	6	$1,200,000	$200,000
Intersection 11	7	$1,400,000	$230,000
Intersection 12	9	$1,800,000	$100,000
Segment 1	18	$3,517,400	$250,000
Segment 2	16	$2,936,700	$225,000
Segment 5	458	$7,829,600	$3,500,000
Segment 6	110	$6,500,000	$2,750,000
Segment 7	120	$7,000,000	$3,100,000

8.4.4. Solution

The evaluation and prioritization of the intersection and roadway-segment projects are both presented in this set of examples. An additional application of the methods could be to rank multiple countermeasures at a single intersection or segment; however, this application is not demonstrated in the sample problems as it is an equivalent process.

Simple Ranking - Cost-Effectiveness

STEP 1 – Estimate Crash Reduction

Divide the cost of the project by the total estimated crash reduction as shown in Equation 8-1.

$$\text{Cost-Effectiveness} = \text{Cost of the project}/\text{Total crashes reduced} \qquad (8\text{-}1)$$

Exhibit 8-7 summarizes the results of this method.

Exhibit 8-7: Cost-Effectiveness Evaluation

Project	Total	Cost	Cost Effectiveness (Cost/Crash Reduced)
Intersection 2	47	$695,000	$14,800
Intersection 7	6	$200,000	$33,300
Intersection 11	7	$230,000	$32,900
Intersection 12	9	$100,000	$11,100
Segment 1	18	$250,000	$14,000
Segment 2	16	$225,000	$14,100
Segment 5	458	$3,500,000	$7,600
Segment 6	110	$2,750,000	$25,000
Segment 7	120	$3,100,000	$25,800

STEP 2 – Rank Projects by Cost-Effectiveness

The improvement project with the lowest cost-effective value is the most cost-effective at reducing crashes. Exhibit 8-8 shows the countermeasure implementation projects listed based on simple cost-effectiveness ranking.

Exhibit 8-8: Cost-Effectiveness Ranking

Project	Cost-Effectiveness
Segment 5	$7,600
Intersection 12	$11,100
Segment 1	$14,000
Segment 2	$14,100
Intersection 2	$14,800
Segment 6	$25,000
Segment 7	$25,800
Intersection 11	$32,900
Intersection 7	$33,300

Simple Ranking - Net Present Value (NPV)

The net present value (NPV) method is also referred to as the net present worth (NPW) method. This method is used to express the difference between discounted costs and discounted benefits of an individual improvement project in a single amount.

STEP 1 - Calculate the NPV

Subtract the cost of the project from the benefits as shown in Equation 8-2.

$$NPV = \text{Present Monetary Value of the Benefits} - \text{Cost of the project} \qquad (8\text{-}2)$$

STEP 2 - Rank Sites Based on NPV

Rank sites based on the NPV as shown in Exhibit 8-9.

Exhibit 8-9: Net Present Value Results

Project	Present Value of Benefits ($)	Cost of Improvement Project ($)	Net Present Value
Intersection 2	$33,437,850	$695,000	$32,742,850
Segment 5	$7,829,600	$3,500,000	$4,329,600
Segment 7	$7,000,000	$3,100,000	$3,900,000
Segment 6	$6,500,000	$2,750,000	$3,750,000
Segment 1	$3,517,400	$250,000	$3,267,400
Segment 2	$2,936,700	$225,000	$2,711,700
Intersection 12	$1,800,000	$100,000	$1,700,000
Intersection 11	$1,400,000	$230,000	$1,170,000
Intersection 7	$1,200,000	$200,000	$1,000,000

As shown in Exhibit 8-9, Intersection 2 has the highest net present value out of the intersection and roadway segment projects being considered.

All of the improvement projects have net present values greater than zero, indicating they are economically feasible projects because the monetary benefit is greater than the cost. It is possible to have projects with net present values less than zero, indicating that the calculated monetary benefits do not outweigh the cost of the project. The highway agency may consider additional benefits (both monetary and non-monetary) that may be brought about by the projects before implementing them.

Incremental Benefit-Cost Analysis

Incremental benefit-cost analysis is an extension of the benefit-cost ratio (BCR) method presented in *Chapter 7*.

STEP 1 – Calculate the BCR

Chapter 7, Section 7.6.1.2 illustrates the process for calculating the BCR for each project.

STEP 2 – Organize Projects by Project Cost

The incremental analysis is applied to pairs of projects ordered by project cost, as shown in Exhibit 8-10.

Exhibit 8-10: Cost of Improvement Ranking

Project	Cost of Improvement
Intersection 12	$100,000
Intersection 7	$200,000
Segment 2	$225,000
Intersection 11	$230,000
Segment 1	$250,000
Intersection 2	$695,000
Segment 6	$2,750,000
Segment 7	$3,100,000
Segment 5	$3,500,000

STEP 3 – Calculate Incremental BCR

Equation 8-3 is applied to a series of project pairs ordered by cost. If the incremental BCR is greater than 1.0, the higher-cost project is preferred to the lower-cost project. If the incremental BCR is a positive value less than 1.0, or is zero or negative, the lower-cost project is preferred to the higher-cost project. The computations then proceed comparing the preferred project from the first comparison to the project with the next highest cost. The preferred alternative from the final comparison is assigned the highest priority. The project with the second-highest priority is then determined by applying the same computational procedure but omitting the highest priority project.

$$\text{Incremental BCR} = (PV_{benefits\ 2} - PV_{benefits\ 1}) / (PV_{costs\ 2} - PV_{costs\ 1}) \tag{8-3}$$

Where,

$PV_{benefits\ 1}$ = Present value of benefits for lower-cost project

$PV_{benefits\ 2}$ = Present value of benefits for higher-cost project

$PV_{costs\ 1}$ = Present value of cost for lower-cost project

$PV_{costs\ 2}$ = Present value of cost for higher-cost project

Exhibit 8-11 illustrates the sequence of incremental benefit-cost comparisons needed to assign priority to the projects.

Exhibit 8-11: Incremental BCR Analysis

Comparison	Project	PV$_{benefits}$	PV$_{costs}$	Incremental BCR	Preferred Project
1	Intersection 12	$1,800,000	$100,000	-6	Intersection 12
	Intersection 7	$1,200,000	$200,000		
2	Intersection 12	$1,800,000	$100,000	9	Segment 2
	Segment 2	$2,936,700	$225,000		
3	Segment 2	$2,936,700	$225,000	-307	Segment 2
	Intersection 11	$1,400,000	$230,000		
4	Segment 2	$2,936,700	$225,000	23	Segment 1
	Segment 1	$3,517,400	$250,000		
5	Segment 1	$3,517,400	$250,000	67	Intersection 2
	Intersection 2	$33,437,850	$695,000		
6	Intersection 2	$33,437,850	$695,000	-13	Intersection 2
	Segment 6	$6,500,000	$2,750,000		
7	Intersection 2	$33,437,850	$695,000	-11	Intersection 2
	Segment 7	$7,000,000	$3,100,000		
8	Intersection 2	$33,437,850	$695,000	-9	Intersection 2
	Segment 5	$7,829,600	$3,500,000		

As shown by the comparisons in Exhibit 8-11, the improvement project for Intersection 2 receives the highest priority. In order to assign priorities to the remaining projects, another series of incremental calculations is performed, each time omitting the projects previously prioritized. Based on multiple iterations of this method, the projects were ranked as shown in Exhibit 8-12.

Exhibit 8-12: Ranking Results of Incremental BCR Analysis

Rank	Project
1	Intersection 2
2	Intersection 5
3	Intersection 7
4	Segment 6
5	Segment 1
6	Intersection 2
7	Segment 12
8	Segment 1

Comments

The ranking of the projects by incremental benefit-cost analysis differs from the project rankings obtained with cost-effectiveness and net present value computations. Incremental benefit-cost analysis provides greater insight into whether the expenditure represented by each increment of additional cost is economically justified. Incremental benefit-cost analysis provides insight into the priority ranking of alternative projects, but does not lend itself to incorporating a formal budget constraint.

8.5. REFERENCES

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2. Harwood, D. W., E. R. Kohlman Rabbani, K.R. Richard, H.W. McGee, and G.L. Gittings. *National Cooperative Highway Research Program Report 486: Systemwide Impact of Safety and Traffic Operations Design Decisions for 3R Projects*. NCHRP, Transportation Research Board, Washington, DC, 2003.

3. Mak, K. K., and D. L. Sicking. *National Cooperative Highway Research Program Report 492: Roadside Safety Analysis Program.* NCHRP, Transportation Research Board, Washington, DC, 2003.

4. Roop, S. S., and S. K. Mathur. *Development of a Multimodal Framework for Freight Transportation Investment: Consideration of Rail and Highway Tradeoffs*. Final Report of NCHRP Project 20-29. Texas A&M University, 1995.

APPENDIX A – BASIC OPTIMIZATION METHODS DISCUSSED IN CHAPTER 8

A.1 Linear Programming (LP)

Linear programming is a method commonly used to allocate limited resources to competing activities in an optimal manner. With respect to evaluating improvement projects, the limited resource is funds, the competing activities are different improvement projects, and an optimal solution is one in which benefits are maximized.

A linear program typically consists of a linear function to be optimized (known as the objective function), a set of decision variables that specify possible alternatives, and constraints that define the range of acceptable solutions. The user specifies the objective function and the constraints and an efficient mathematical algorithm is applied to determine the values of the decision variables that optimize the objective function without violating any of the constraints. In an application for highway safety, the objective function represents the relationship between benefits and crash reductions resulting from implementation.

Typical optimization methods are: linear programming, integer programming, dynamic programming, and multi-objective resource allocation.

The constraints put limits on the solutions to be considered. For example, constraints might be specified so that incompatible project alternatives would not be considered at the same site. Another constraint for most highway safety applications is that it is often infeasible to have negative values for the decision variables (e.g., the number of miles of a particular safety improvement type that will be implemented can be zero or positive, but cannot be negative). The key constraint in most highway safety applications is that the total cost of the alternatives selected must not exceed the available budget. Thus, an optimal solution for a typical highway safety application would be decision-variable values that represent the improvements which provide the maximum benefits within the available budget.

An optimized linear programming objective function contains continuous (i.e., non-discrete) values of the decision variables, so is most applicable to resource allocation problems for roadway segments without predefined project limits. A linear program could be used to determine an optimum solution that indicates, for example, how many miles of lane widening or shoulder widening and paving would provide maximum benefits within a budget constraint.

While there are methods to manually find an optimized solution, computer software programs are typically employed. Microsoft Excel can solve LP problems for a limited set of variables, which is sufficient for simple applications. Other commercial packages with a wide range of capabilities for solving linear programs are also available.

Linear programming has been applied to highway safety resource allocation. Kar and Datta used linear programming to determine the optimal allocation of funding to cities and townships in Michigan based on their crash experience and anticipated crash reductions from safety programs.(4) However, there are no widely available software tools that apply linear programming specifically to decisions related to highway safety. Also, there are no known applications of linear programming in use for prioritizing individual safety improvement projects because integer programming, as described below, is more suited for this purpose.

A.2 Integer Programming (IP)

Integer programming is a variation of linear programming. The primary difference is that decision variables are restricted to integer values. Decision variables often represent quantities that are only meaningful as integer values, such as people, vehicles, or machinery. Integer programming is the term used to represent an instance of linear programming when at least one decision variable is restricted to an integer value.

The two primary applications of integer programming are:

- Problems where it is only practical to have decision variables that are integers; and,
- Problems that involve a number of interrelated "yes or no" decisions such as whether to undertake a specific project or make a particular investment. In these situations there are only two possible answers, "yes" or "no," which are represented numerically as 1 and 0, respectively, and known as binary variables.

Integer programming with binary decision variables is particularly applicable to highway safety resource allocation because a series of "yes" or "no" decisions are typically required (i.e., each project alternative considered either will or will not be implemented). While linear programming may be most appropriate for roadway projects with undetermined length, integer programming may be most appropriate for intersection alternatives or roadway projects with fixed bounds. An integer program could be used to determine the optimum solution that indicates, for example, if and where discrete projects, such as left-turn lanes, intersection lighting, and a fixed length of median barrier, would provide maximum benefits within a budget constraint. Because of the binary nature of project decision making, integer programming has been implemented more widely than linear programming for highway safety applications.

As in the case of linear programming, an integer program would also include a budget limit and a constraint to assure that incompatible project alternatives are not selected for any given site. The objective for an integer program for highway safety resource allocation would be to maximize the benefits of projects within the applicable constraints, including the budget limitation. Integer programming could also be applied to determine the minimum cost of projects that achieve a specified level of benefits, but there are no known applications of this approach.

Integer programs can be solved with Microsoft Excel or with other commercially available software packages. A general purpose optimization tool based on integer programming is available in the FHWA *Safety Analyst* software tools for identifying an optimal set of safety improvement projects to maximize benefits within a budget constraint (www.safetyanalyst.org). A special-purpose optimization tool known as the Resurfacing Safety Resource Allocation Program (RSRAP) is available for identifying an optimal set of safety improvements for implementation in conjunction with pavement resurfacing projects.(3)

A.3 Dynamic Programming (DP)

Dynamic programming is another mathematical technique used to make a sequence of interrelated decisions to produce an optimal condition. Dynamic programming problems have a defined beginning and end. While there are multiple paths and options between the beginning and end, only one optimal set of decisions will move the problem toward the desired solution.

The basic theory of dynamic programming is to solve the problem by solving a small portion of the original problem and finding the optimal solution for that small portion. Once an optimal solution for the first small portion is found, the problem is enlarged and the optimal solution for the current problem is found from the preceding solution. Piece by piece, the problem is enlarged and solved until the entire original problem is solved. Thus, the mathematical principle used to determine the optimal solution for a dynamic program is that subsets of the optimal path through the maze must themselves be optimal.

Most dynamic programming problems are sufficiently complex that computer software is typically used. Dynamic programming was used for resource allocation in Alabama in the past and remains in use for highway safety resource allocation in Kentucky.(1,2)

A.4 Appendix References

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