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16. ABSTRACT
Between July 2014 and March 2015, a team of Caltrans engineers carried out a pilot project to develop and apply a Multi-Objective Decision Analysis (MODA) framework to prioritize projects within the State Highway Operation and Protection Program (SHOPP). Coupled with input from Caltrans subject matter experts, a preliminary decision analysis framework was developed that successfully demonstrated the calculation of project "value" using available project-specific data. A number of important conclusions were drawn from this pilot effort. a MODA-based approach brings transparency to the project prioritization process, provides a quantitative basis for decision-making, and provides a mechanism to communicate the alignment of project priorities with strategic objectives. As decision analysis is a highly specialized area of study, the team initially consulted wit two well regarded decision analysis experts to help identify best practices in project prioritization. This report documents that consultation work.

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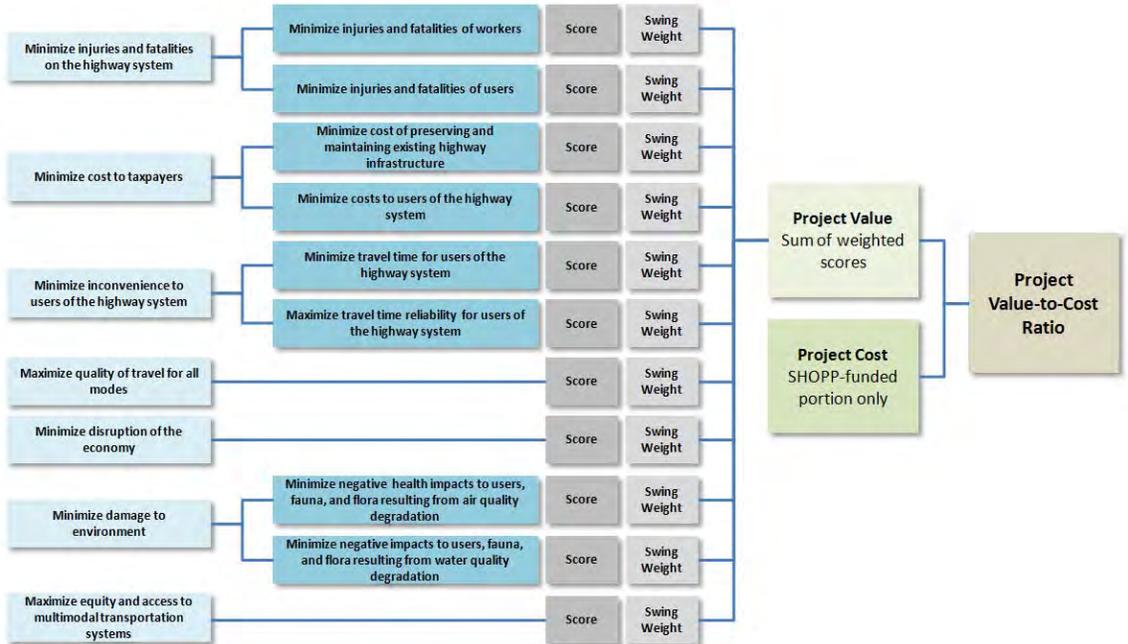
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Developing a Decision Making Framework for Caltrans Project Prioritization

Final Report

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DEVELOPING A DECISION MAKING FRAMEWORK FOR CALTRANS PROJECT PRIORITIZATION

Task 2785
Contract Nos. 65U5278500, 65U5652785

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1. INTRODUCTION

Between July 2014 and March 2015, a team of Caltrans engineers carried out a pilot project[1] to develop and apply a *Multi-Objective Decision Analysis (MODA)* framework to prioritize projects within the *State Highway Operation and Protection Program (SHOPP)*. Coupled with input from Caltrans subject matter experts (SMEs), a preliminary decision analysis framework was developed that successfully demonstrated the calculation of project "value" using available project-specific data. A number of important conclusions were drawn from that pilot effort. A MODA-based approach brings transparency to the project prioritization process, provides a quantitative basis for decision-making, and provides a mechanism to communicate the alignment of project priorities with strategic objectives. As decision analysis is a highly specialized area of study, the team initially consulted with two well regarded decision analysis experts to help identify best practices in project prioritization. This report documents that consultation work.

2. BACKGROUND

The goal of the SHOPP pilot project was to develop a more objective and transparent methodology for the prioritization of SHOPP projects based on best practices and decision-making sciences. An initial literature review indicated that there were various competing methodologies for decision-making and project prioritization. Recognizing the limited experience in decision analysis theory of the project team members, two well-regarded experts in the field of decision analysis were brought onboard in September 2014 to provide knowledge transfer and initial guidance. Dr. Ralph Keeney conducted interviews with Caltrans Executive Managers over the course of a day and delivered a report compiling observations, findings, and recommendations. In an independent effort, Dr. Lee Merkhofer organized a one-day workshop that included Caltrans Executives, SHOPP Division Chiefs, and SHOPP Program Managers. The workshop had both educational and framework development components. Guided by the findings and recommendations from the two consultants, the team pursued the development of a *Multi-Objective Decision Analysis (MODA)* approach for project prioritization.

3. DECISION ANALYSIS AND PROJECT PRIORITIZATION

Decision analysis encompasses the methods and tools to systematically consider key aspects of a decision-making problem, guides the selection of the best alternative, and establishes a logical and transparent framework that provides insight on how decisions are made. Decision analysis is a discipline that combines elements of operations research, management science, and systems analysis. The goal of

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[1] "SHOPP Pilot Project, Phase 1: A Framework for Project Prioritization, " June 17, 2015. http://www.dot.ca.gov/tam/documents/SHOPP_Pilot_Project_Final_Report_6-17-15.pdf

the decision-making process is to provide the decision maker(s) with a logical and defensible framework that can help articulate how choices were made and priorities established. Project prioritization is a specific implementation of decision analysis based on the same fundamental principles. Where in decision analysis the goal is to determine the single best alternative, project prioritization aims to identify an optimized portfolio of projects.

3.1. Literature Search

A cursory literature search was conducted to identify documents and tutorials that would help get the team up to speed and conversant in project prioritization and decision analysis methods. Online publications and articles served as a primary resource. An internet search on the topic of "project prioritization" led to a series of informative online articles by business consultant, Lee Merkhofer, which described overarching project prioritization principles and practical applications through examples. This, in turn, led to other online articles, tutorials, and presentations on the subject published by a wide variety of entities – university researchers discussing the merits of various methods and mathematical models, commercial software companies in the business of developing tools, businesses that have applied various decision-making methods and tools in practice, and governmental agencies and partners that have established processes based on decision analysis theory. A partial listing of online articles is presented in Table 3-1.

Table 3-1 - References

"Project Prioritization and Project Portfolio Management" (2014) Lee Merkhofer Consulting	This is a series of papers that explains project prioritization principles.	http://www.prioritysystem.com/papers.html
"Decision Analysis: An Overview" (1982) INFORMS, Operations Research, Vol. 30, No. 5., Ralph L. Keeney	This article presents an overview of decision analysis and provides additional sources for its foundations, procedures, history, and applications.	http://web.stanford.edu/class/cee115/wiki/uploads/Main/Schedule/OverviewDA.pdf
"Multiple-Objective Decision Analysis Involving Multiple Stakeholders" (2009) INFORMS, Tutorials in Operations Research, Robin Keller	This is a high-level tutorial that explains decision-making frameworks, development of objectives hierarchies, and case studies to illustrate application of the Multi-Objective Decision Analysis (MODA) methodology.	http://faculty.sites.uci.edu/lrkeller/files/2011/06/multiple-objective-decision-analysis-involving-ultiple-stakeholders.pdf
"Multi-Criteria Analysis: A Manual" (2009) Department for Communities and Local Government, UK	This manual provides guidance for government officials and other practitioners on how to undertake and make the best use of multi-criteria analysis for the appraisal of options for policy and other decisions.	https://www.gov.uk/government/publications/multi-criteria-analysis-manual-for-making-government-policy

Title	Description	Website
"Application of the Analytic Hierarchy Process in Road Asset Management: User Manual" (2007) Austroads, Association of Australian and New Zealand Road Transport and Traffic Authorities	This manual provides guidance for the application of the analytic hierarchy process (AHP) as a decision support tool in road asset management.	https://www.onlinepublications.austroads.com.au/items/AP-T84-07
"States' Approaches to Transportation Project Prioritization: Linking Policy, Planning and Programming" (2007) Metropolitan Planning Council	This document addresses the question of how Illinois should prioritize its transportation project investments. Included in the document is a synthesis of project prioritization practices of several state DOTs.	http://www.metroplanning.org/uploads/cms/documents/NationalPractices.pdf
"Project Prioritization Process Guidebook for Large Urban Areas" (2014) Mid-Region Council of Governments, New Mexico	This manual describes a project prioritization method used by a Metropolitan Planning Organization in New Mexico.	http://www.mrcog-nm.gov/transportation/metro-planning/project-prioritization-process
"Guide to Cross-Asset Resource Allocation and the Impact on Transportation System Performance" (2015) NCHRP Report 806 National Cooperative Highway Research Program	This guidance includes discussion of analytical tools to support decision-making and is supplemented by a prototypical spreadsheet-based implementation of the guide's analysis framework.	http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_806.pdf

Publications by state and local transportation agencies on project prioritization methods were of particular interest to the team.

3.2. The Need for Decision Analysis and Project Prioritization Methods

Project prioritization can be considered a *knapsack problem*[2], a term used in mathematics and computer sciences to describe an optimization problem. In the knapsack analogy, items are selected based on specific volumes and values and are to be packed in a knapsack with a limited volume capacity (Figure 3-1).

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[2] https://en.wikipedia.org/wiki/Knapsack_problem

Figure 3-1- Knapsack Problem

The knapsack problem closely parallels the project prioritization task in that a set of the highest priority projects must be determined from a pool of projects given a budget constraint. Each project is unique and produces some level of benefit (or value) based on a defined set of parameters and value judgments. Decision makers strive to select a portfolio of projects that provide the greatest overall benefit within the resource limits.

Unfortunately, the mathematical solution to the knapsack problem is not trivial, and approximate solutions are frequently used in practice. Decision analysis methods and tools are used to arrive at approximate solutions.

3.3. Methods for Decision Analysis

Various project prioritization and decision analysis methods were evaluated for applicability to SHOPP project prioritization. The methods considered all fall under a general class known collectively as *Multi-Criteria Decision Analysis (MCDA)* or *Multi-Criteria Decision Methods (MCDM).* Although methods differed in the details and implementation, for the most part each had elements that involved the identification of criteria or objectives, assignment of criteria or objective weights or importance, scoring, ranking, analysis, and portfolio optimization.

Within MCDA, two major types of analysis methods were identified in the literature – *Multi-Attribute Decision Analysis (MADA),* and *Multi-Objective Decision Analysis (MODA).* A paper published by the

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National Institute of Standards and Technology (NIST)[3] suggests that MODA methods are best suited to the task of resource allocation problems, as is the case for SHOPP project prioritization. Used in conjunction with these methods, a suite of additional decision-making methods are available. A partial listing is presented in Table 3-2.

<p align="center">***Table 3-2 - MCDA Methods***</p>

Partial Listing of Methods Used in Multi Criteria Decision Analysis (MCDA)	
Aggregated Indices Randomization Method (AIRM) Analytic Hierarchy Process (AHP) Analytic Network Process (ANP) Best Worst Method (BWM) Characteristic Objects METhod (COMET) Data Envelopment Analysis Decision EXpert (DEX) Disaggregation – Aggregation Approaches (UTA, UTAII, UTADIS) Dominance-based Rough Set Approach (DRSA) ELECTRE (Outranking) Evidential Reasoning Approach (ER) Goal Programming Grey Relational Analysis (GRA) Inner Product of Vectors (IPV) Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)	Multi-Attribute Global Inference of Quality (MAGIQ) Multi-Attribute Utility Theory (MAUT) Multi-Attribute Value Theory (MAVT) New Approach to Appraisal (NATA) Nonstructural Fuzzy Decision Support System (NSFDSS) Potentially all Pairwise Rankings of all Possible Alternatives (PAPRIKA) PROMETHEE (Outranking) Superiority and Inferiority Ranking Method (SIR method) Technique for the Order of Prioritisation by Similarity to Ideal Solution (TOPSIS) Value Analysis (VA) Value Engineering (VE) VIKOR Method Fuzzy VIKOR Method Weighted Product Model (WPM) Weighted Sum Model (WSM)

A comprehensive evaluation of all possible supporting methods was not possible within the scope of the SHOPP Pilot Project. The focus was primarily on what appeared to be the most commonly cited and implemented suite of methods within a Multi-Objective Decision Analysis (MODA) framework: *Multi-Attribute Utility Theory (MAUT), Multi-Attribute Value Theory (MAVT),* and the *Analytic Hierarchy Process (AHP).*

3.3.1. Multi-Attribute Value Theory (MAVT)

Multi-Attribute Utility Theory (MAUT) and *Multi-Attribute Value Theory (MAVT)* are closely related methods that are used in decision analysis. MAUT uses "utility functions," whereas MAVT uses "value functions." These are technical differences in the methods that are used to address aspects such as the treatment of decision uncertainty. In general, MAVT can be considered a more limited version of MAUT. MAVT implements value functions to transform criteria (e.g., GHG reduction, economic impacts, etc.) into a dimensionless, uniform scale referred to as "value." The aggregated value of the alternative can then be used to prioritize multiple alternatives.

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[3] Norris, G. A.; Marshall, H. E., 1995. "Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems," NISTIR 5663; 86 p. September 1995 (http://fire.nist.gov/bfrlpubs/build95/art066.html)

3.3.2. Analytic Hierarchy Process

The *Analytic Hierarchy Process (AHP)* is a prioritization technique that can be applied in its entirety to a decision-making or prioritization problem. Furthermore, it can be used as one component within the MAVT method. The AHP technique requires that the analyst elicit from the decision makers their preferences between pairs of criteria. The degree to which one criterion is preferred more than another is quantified, and through this pair-wise comparison approach, a set of criteria weights are established. Alternatives are assessed in a similar manner – pairs of alternatives are evaluated for their relative alignment with each criteria. The resulting pair-wise comparisons of alternatives combined with the weighting are then used to generate a final list of priorities.

3.3.3. Multi-Objective Decision Analysis for Project Prioritization

The Core Team pursued a MODA approach for the SHOPP Pilot Project. Specifically, a MAVT process was used and was carried out in a number of key steps, as shown in Figure 3-2.
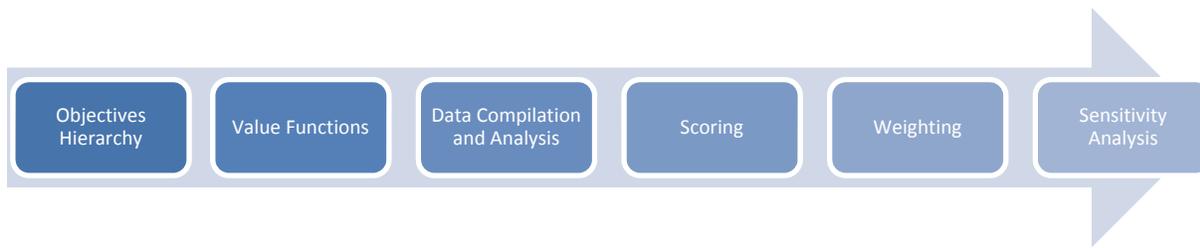

Figure 3-2- MODA/MAVT Process

In this process, an *Objectives Hierarchy* (Figure 3-3) is developed that ties the decision maker's high level goals to lower level criteria that can be measured. The objectives hierarchy provides a means to deconstruct organizational goals into fundamental objectives. Weights are determined for objectives, and a linear-additive, multi-attribute value function is then used to combine the products of the weighted values to determine the overall value that a project delivers. Portfolios of projects are analyzed for sensitivity to changes in the weighting assignment, which provides insight to the decision-making process.
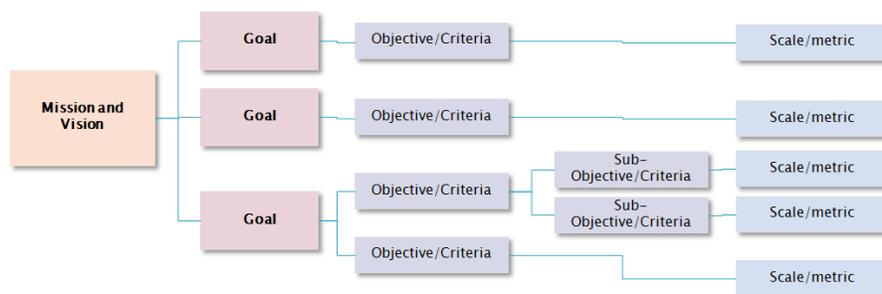

Figure 3-3 – Framework for an Objectives Hierarchy

In the MAVT process, scores are assigned to the lowest level elements in the hierarchy. These scores are then aggregated using the weighting on each score and summing the components. This aggregation provides a structured framework to bring together different considerations and perspectives of the decision makers. Furthermore, these differences can then be isolated, analyzed, and more effectively communicated through this framework.

4. ENGAGING DECISION ANALYSIS EXPERTISE

The team engaged the participation of two nationally recognized experts in the field of decision analysis. Dr. Ralph Keeney and Dr. Lee Merkhofer were independently contracted to facilitate development of preliminary criteria and provide recommendations on appropriate applications of decision-making methodology. The two experts conducted a cursory assessment of Caltrans' SHOPP processes and developed preliminary recommendations for moving forward with the pilot project.

4.1.Consultation with Dr. Ralph Keeney

Dr. Ralph Keeney, assisted by Dr. Johannes Siebert, conducted a series of meetings on September 22, 2014. There was an initial meeting with the project team and key stakeholders. Three additional meetings were conducted over the course of the day that included members from the Executive Board and the California Transportation Commission (CTC). Dr. Keeney's approach was to gather background information about the current SHOPP project prioritization process, interview key executives about overarching priorities and goals for the envisioned process, synthesize findings, and provide direction to Caltrans on moving forward with the development of a process. A final report was produced, documenting observations and recommendations and is included in the Appendix.

4.2.Workshop Facilitated by Dr. Lee Merkhofer

Dr. Lee Merkhofer conducted a day-long workshop on September 26, 2014, that included the project team and SHOPP Program Managers. Key executives participated during an hour-long session in the afternoon. Dr. Merkhofer's approach was to engage a broad group of stakeholders over the course of the day to raise awareness on the basic principles of decision analysis and project prioritization and begin to develop a generalized framework applicable to the SHOPP process. The workshop resulted in the development of a preliminary objectives hierarchy, a charter, and recommendations, summarized in a series of presentation slides included in the Appendix.

4.3. Key Findings and Outcomes

Significant observations and themes, common to both the Keeney and Merkhofer findings, are summarized as follows:

- The existing SHOPP project prioritization criteria (based on program priorities) and the current draft set of criteria under consideration (based on the new Caltrans' mission, vision, goals, objectives, and the draft California Transportation Plan (CTP) 2040)[4] are not consistent with key principles of a Multi-Objective Decision Analysis (MODA) framework.

- The recommended MODA approach differs significantly from the current SHOPP project prioritization processes in the way in which criteria are identified, and in the treatment of project value and cost. The concept of "value" is central to the proposed process, requiring that all aspects of the decision-making (e.g., establishing criteria, weighting, etc.) tie back to value.

- A MODA framework makes an important distinction between "means" criteria and "fundamental" criteria. Fundamental criteria represent core organizational values, whereas means criteria describe how to achieve them. (For example, "maximize seat belt use" is a means criteria, whereas "minimize injuries from automobile crashes" is a fundamental criteria.) The draft SHOPP criteria are predominantly means criteria. The use of means criteria in decision-making models leads to mathematical inconsistencies and bias in the results.

- Alternative project prioritization methods that require a comparison of one criterion to another (i.e., using pair-wise comparisons) without consideration of the impact on value can lead to ambiguity in establishing a logical theoretical basis for the prioritization task.

- A criterion's "weight" should not be interpreted as a criterion's "importance" in a MODA framework. Rather, a specific interval of change in one criterion compared with an interval of change in another criterion is used to establish the relative weight between criterion.

- Two alternative straw-man criteria hierarchies have been proposed. Dr. Keeney has proposed a subset of the existing Caltrans goals and objectives. In contrast, Dr. Merkhofer has proposed a different set of top-level criteria and using "cross-walks" to tie the hierarchy back to Caltrans' goals.

4.4. Recommendations on Draft Objectives Hierarchies

Dr. Keeney and Dr. Merkhofer offered recommendations for starting points for developing objectives hierarchies. Figure 4-1 and Figure 4-2 represent the project team's interpretations of the proposed objectives hierarchies. Again, these are interpretations of what the consultants provided that include some changes and extensions to normalize the two for comparative purposes.

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[4] http://www.dot.ca.gov/hq/tpp/californiatransportationplan2040/index.shtml

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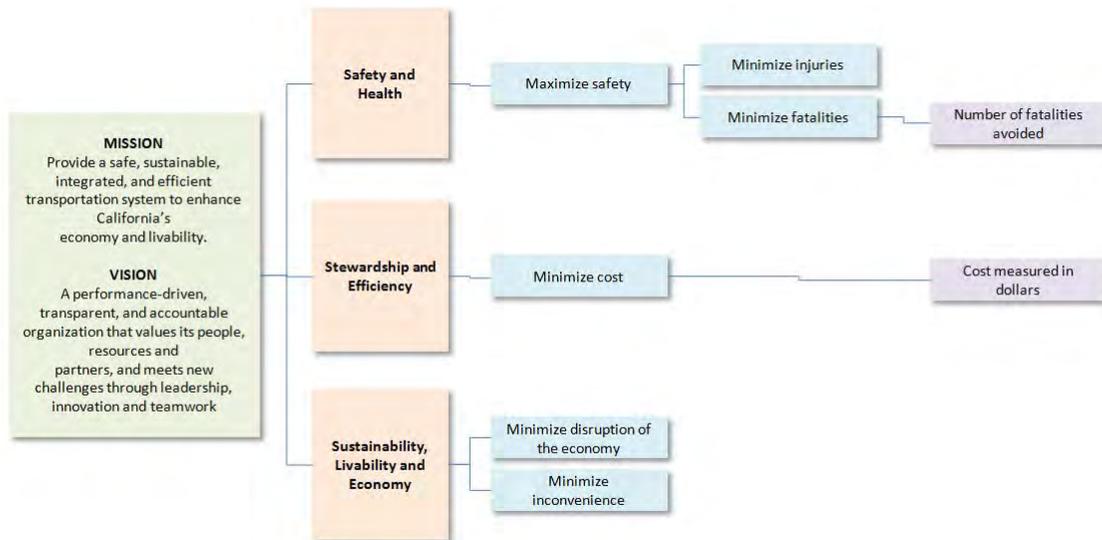
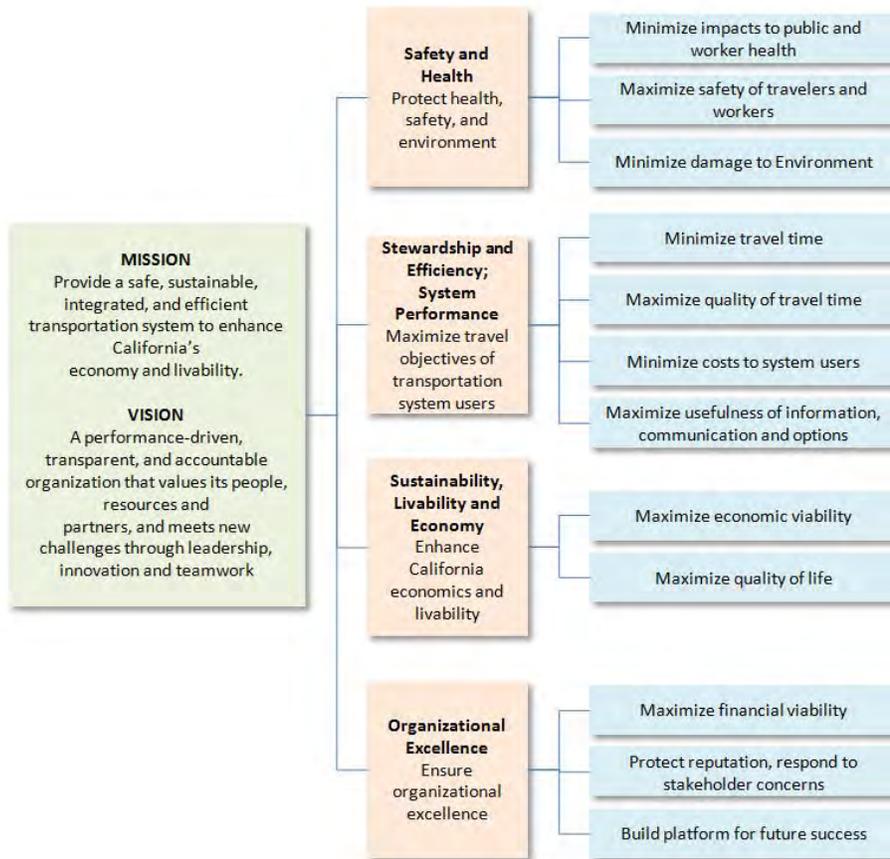*Figure 4-1 –Objectives Hierarchy Based on Dr. Keeney's Recommendations*

Figure 4-2 – Objectives Hierarchy Adapted from Dr. Merkhofer's Recommendations

5. DEVELOPMENT OF A DECISION ANALYSIS FRAMEWORK

The decision analysis framework is comprised of an objectives hierarchy, a value function and its sub-models, and scoring and weighting procedures. Collectively, these components are used to calculate a project's *value*. The project's *value-to-cost ratio* is then used to determine its priority relative to other projects. This framework is presented in this section.

5.1. Objectives Hierarchy

The project team developed an objectives hierarchy representing the Department's fundamental objectives, sub-objectives, and the relationships to Department values and data sources. The Department's current mission, vision, and goals statement[5] served as the starting point. From this, a set of fundamental objectives and sub-objectives were identified. These objectives were compiled by the project team and were based on early guidance provided by two decision analysis experts, Dr. Keeney and Dr. Merkhofer. The Appendix contains initial recommendations from Dr. Keeney in September 2014 and Dr. Merkhofer in October 2014.

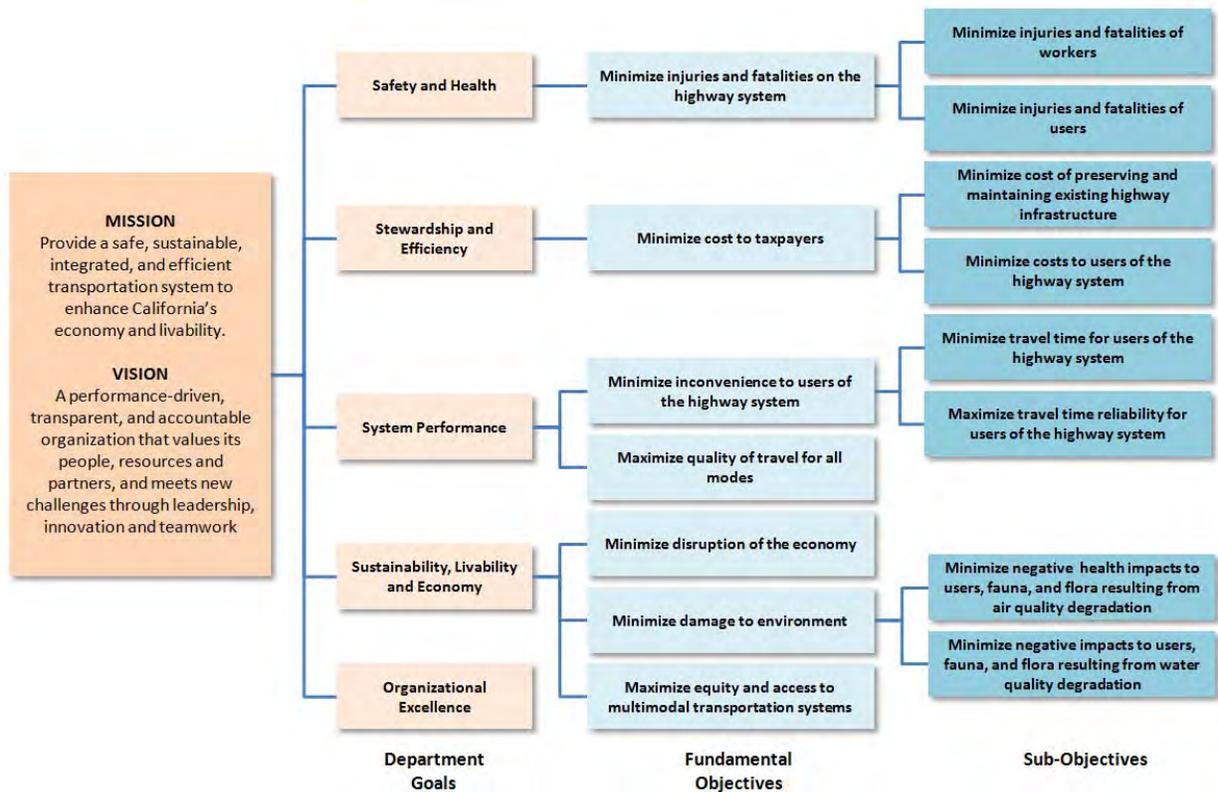[5] http://www.dot.ca.gov/hq/paffairs/about/mission.htm

Figure 5-1 - Objectives Hierarchy

The generalized objectives hierarchy, shown in Figure 5-1, shows the fundamental objectives and sub-objectives as well as their alignment to the Department's mission, vision, and goals. It is important to note that the "Organizational Excellence" goal does not have any fundamental objectives. This was based on recommendations by Dr. Ralph Keeney. His final report (included in the Appendix) states that the Organizational Excellence goal is "influenced more by the implications of the totality of Caltrans actions than by the selection of specific projects."

5.1.1. Safety and Health Objectives

The Department established the Safety and Health goal that states: "Provide a safe transportation system for workers and users and promote health through active transportation and reduced pollution in communities." Key strategic objectives are as follows:

- Zero Worker Fatalities.
- Reduce user fatalities and injuries by adopting a "Toward Zero Deaths" practice.
- Promote community health through active transportation and reduced pollution in communities.

One fundamental and two sub-objectives were identified, as shown in Figure 5-2.

Figure 5-2 - Safety and Health Objectives

5.1.2. Stewardship and Efficiency Objectives

The Department established the Stewardship and Efficiency goal that states: "Money counts. Responsibly manage California's transportation-related assets." Key strategic objectives are as follows:

- Effectively manage transportation assets by implementing the asset management plan, embracing a fix-it-first philosophy.
- Efficiently deliver projects and services on time and on budget.

One fundamental and two sub-objectives were identified, as shown in Figure 5-3:

Figure 5-3 - Stewardship and Efficiency Objectives
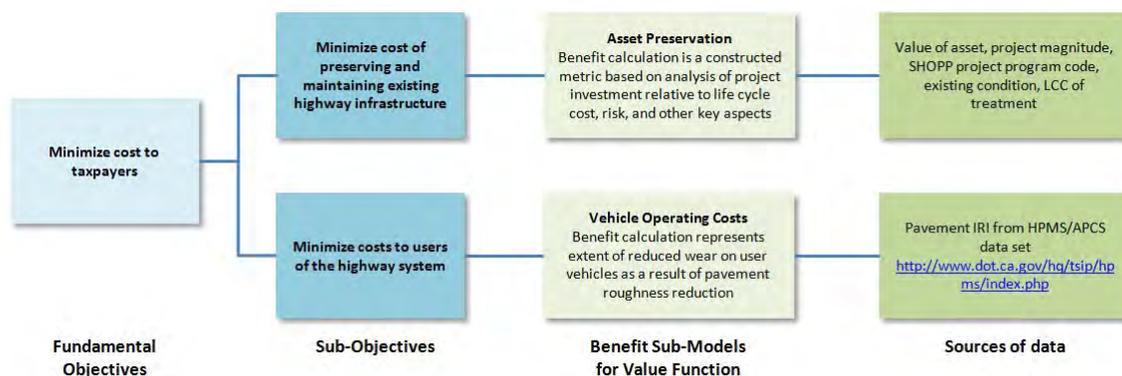
5.1.3. System Performance Objectives

The Department established the System Performance goal that states: "Utilize leadership, collaboration and strategic partnerships to develop an integrated transportation system that provides reliable and accessible mobility for travelers." Key strategic objectives are as follows:

- Improve travel time reliability for all modes.
- Reduce peak period travel times and delay for all modes through intelligent transportation systems, operational strategies, demand management, and land use/ transportation integration.
- Improve integration and operation of the transportation system.

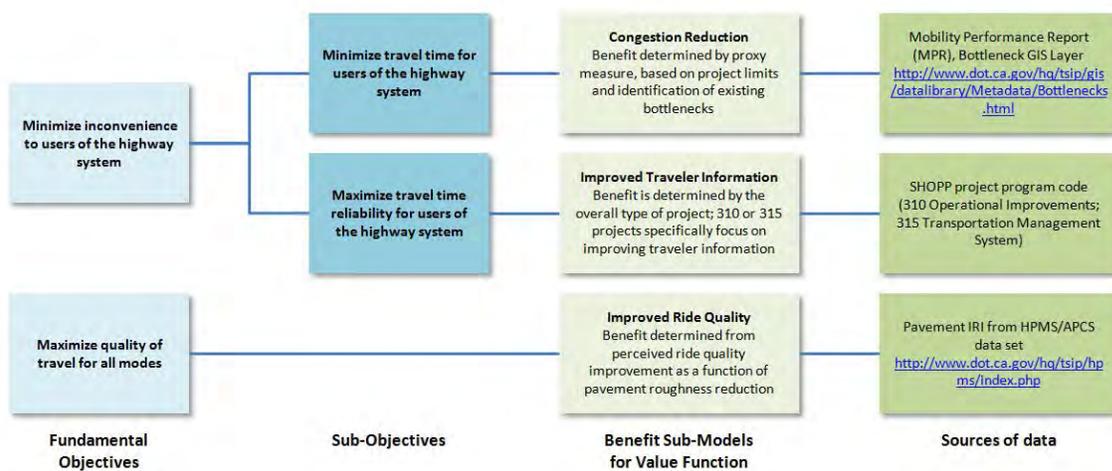Two fundamental and two sub-objectives were identified, as shown in Figure 5-4.

Figure 5-4 - System Performance Objectives

5.1.4. Sustainability, Livability and Economy Objectives

The Department established the Sustainability, Livability and Economy goal to "make long-lasting, smart mobility decisions that improve the environment, support a vibrant economy, and build communities, not sprawl." Key strategic objectives are as follows:

- PEOPLE: Improve the quality of life for all Californians by providing mobility choice, increasing accessibility to all modes of transportation and creating transportation corridors not only for conveyance of people, goods, and services, but also as livable public spaces.
- PLANET: Reduce environmental impacts from the transportation system with emphasis on supporting a statewide reduction of greenhouse gas emissions to achieve 80% below 1990 levels by 2050.

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- PROSPERITY: Improve economic prosperity of the State and local communities through a resilient and integrated transportation system.

Three fundamental and two sub-objectives were identified, as shown in Figure 5-5.

Figure 5-5 - Sustainability, Livability, and Economy Objectives

5.2. Calculation Framework

5.2.1. Value Function

A project's overall value, or benefit, is determined through the aggregation of benefits derived from benefit sub-models associated with each objective. In the calculation framework, shown in Figure 5-6, each objective or sub-objective has a sub-model that is used to determine a score. Those scores are multiplied by a weight, and the sum of the weighted scores is used to determine the *project value*. The project value is divided by the project cost to produce to *project value-to-cost ratio*, the key metric used to in project prioritization.

Figure 5-6 - Value Function Calculation Framework

The value function takes the generalized form:

$$Project\ Value = (Score_1)(Weight_1) + (Score_2)(Weight_2) + \dots + (Score_n)(Weight_n)$$

$$Project\ Value\ to\ Cost\ Ratio = \frac{Project\ Value}{Project\ Cost}$$

6. SUMMARY

This report documents the early stages of work carried out under a pilot project to develop and apply a Multi-Objective Decision Analysis (MODA) framework to prioritize projects within the State Highway Operation and Protection Program (SHOPP). Two leading experts in the field of decision analysis and project prioritization were engaged through a research project to provide initial guidance in this larger effort. The work led to the establishment of a prototype project prioritization framework.

7. APPENDIX

The following documents are included in the Appendix:

"Recommendations about Decision-Making for Caltrans SHOPP Project Prioritization Final Report for Service Agreement Number U5-652785-00"
(September 30, 2014)
By Ralph L. Keeney and Johannes Siebert, U.S. Marketing and Decisions Group, Inc.

Project Prioritization Framing Workshop
(October 1, 2014)
Select materials from final report to Caltrans by Lee Merkhofer, Ph.D., Lee Merkhofer Consulting

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Recommendations about Decision-Making for Caltrans SHOPP Project Prioritization

Final Report for Service Agreement Number U5-652785-00

by

Ralph L. Keeney and Johannes Siebert

U.S. Marketing and Decisions Group, Inc.

September 2014

The purpose of this report is to make suggestions that would help (a) bring SHOPP decision-making and action more consistent with the new Caltrans vision, mission, and goals, and (b) help the core project team frame their next steps to narrow the scope of what the team should do. Section 1 summarizes the process that we used to develop the product. Section 2 offers suggestions pertaining directly to the tasks in our contract concerning the decision methodology to evaluate prospective SHOPP projects. Section 3 comments on other issues raised by members of Caltrans regarding SHOPP.

1. Review Process

We first reviewed previously provided material that contained information about SHOPP planning and decision-making and a comprehensive list of criteria used in evaluating projects to be carried out with SHOPP funds. Then, on September 22 we had several meetings with groups of Caltrans employees in Sacramento to discuss SHOPP issues. These meetings involved the following individuals:

1. Initial meeting with the core project team: Steve Guenther, Ray Patron, Donna Berry, Loren Turner.
2. Steven Keck (Finance), Karla Sutliff (Project Delivery).
3. Steve Takigawa (Maintenance), Kome Ajise (Planning).
4. Amarjeet Benipal (District 3 Director), Andre Boutros (California Transportation Commission), Ryan Chamberlain (District 12 Director).
5. Follow-up meeting with the core project team.

The topics were to better understand how the SHOPP decision making process works and to gather aspirations about improvements that Caltrans would like in the process. The composition

of the discussion participants ensured that we heard a comprehensive overview about Caltrans from an organizational perspective.

2. Comments on the Decision Methodology to Evaluate Perspective SHOPP Projects

Four issues of the SHOPP decision methodology are discussed. They concern selection of the decision criteria for SHOPP projects, specifying metrics for these criteria, prioritizing the criteria, and evaluating prospective projects in terms of the multiple criteria.

<u>Identifying an Appropriate Set of Criteria to Evaluate SHOPP Projects</u>

To evaluate SHOPP projects reasonably and justifiably, it is necessary to identify an appropriate set of criteria to evaluate those projects.

In practice, the process of gathering evaluation criteria can often be characterized by separate phases. In a first phase, criteria that have been previously used in similar decision situations or that are easily available are identified. In a second phase, careful thinking and interviews with experts (individuals with responsibilities for specific processes, program managers, etc.) often lead to a more comprehensive set of criteria. The combined list is frequently large as was the case with the current SHOPP list of criteria. Based on the provided material and our discussions, we believe that the set of criteria identified by the Caltrans SHOPP project covers most of the important criteria. However, such a comprehensive list of criteria is only of limited use to evaluate projects.

In a third phase, the criteria have to be reduced to a reasonable number. In general, a first step is to eliminate redundant criteria. This occurs when the same or a similar criterion is listed in more than one category [*reduce fatalities and injuries* (from Safety, Health, and Equity) and *reduce fatalities, severe injuries, and collisions* (from Stewardship, Efficiency, and Multimodalism)] or the same concern is expressed with two criteria [*effectively manage taxpayers funds* and *maximize the use of available financial resources*, criteria 2 and 3 in Stewardship, Efficiency, and Multimodalism].

A second method to reduce the number of criteria is aggregation. For example, highly specific criteria could be *minimize forest clearing* or *minimize impact on native plants*. These and other criteria could be aggregated to *minimize impacts of flora*. By including animals, an even

broader criterion could be *minimize negative impacts on flora and fauna*. Broadening a bit further, we could have a criteria called *minimize environmental impact*.

The most important concept to reduce the number of criteria needed to evaluate projects uses the distinction between means and fundamental criteria. Means criteria are important because they help to achieve the fundamental criteria. For example, *improve pavement* is a means to *minimize accidents* which is a means to *minimize loss of life. Minimize loss of life* is a fundamental criterion because it is one of the things that we ultimately value. Evaluation of alternatives using only fundamental criteria includes all of our ultimate concerns. Including additional means criteria in an evaluation leads to double counting.

Most of the criteria Caltrans gathered for the SHOPP project are means criteria. One could go through a thorough analysis of all of the Caltrans SHOPP criteria to identify the fundamental criteria. However, the fundamental criteria for the Caltrans SHOPP project are essentially already specified in the new vision, mission, and goals of Caltrans. Directly from the goals, the fundamental criteria to evaluate potential SHOPP projects should be *maximize safety* from 'Safety and Health', *minimize costs* from 'Stewardship and Efficiency', and *minimize disruption of the economy* and *minimize inconvenience*, both from 'Sustainability, Livability, and Economy'. These four criteria capture most of what Caltrans can influence in terms of the first three goals. The other two goals, 'System Performance' and 'Organizational Excellence', are influenced more by the implications of the totality of Caltrans actions than by the selection of specific projects. It is useful to note that sometimes it is useful to divide a fundamental criterion into components. For example, the objective *maximize safety* could be replaced with *minimize injuries* and *minimize fatalities.*

Selecting Appropriate Metrics for Criteria

The decision frame for any analysis is defined by the set of fundamental criteria and the set of alternatives for achieving those criteria. To describe the consequences of alternatives and prioritize different criteria, it is necessary to identify a metric to measure each criterion. The terms *attribute* and *performance measure* are often used as synonyms for metric.

There are basically three different types of metrics: *natural metrics*, *constructed metrics*, and *proxy metrics* (Keeney 1992). In some cases, an metric may be a hybrid of two of these types, but this trichotomy is useful for discussing features of metrics.

Natural metrics are in general use and have a common interpretation. For a criterion such as *minimize cost,* a natural metric is *cost measured in dollars*. For a criterion such as *minimize fatalities*, a natural metric is *number of fatalities avoided*. Most natural metrics can be counted or physically measured. They also have the important property that they directly measure the degree to which a criterion is met.

Proxy metrics share certain qualities of natural metrics. A proxy metric usually involves a scale that is in general use that can be counted or physically measured. The difference is that it does not directly measure the criterion of concern. For a decision involving highway improvements, an example of a proxy metric for the criterion *minimize fatalities* is the *number of vehicle accidents avoided*. Certainly the number of vehicle accidents is related to the number of fatalities, but it does not directly measure those fatalities. A proxy metric is less informative than a natural metric because it indirectly indicates the achievement of the criterion. Proxy metrics typically are used when it is either difficult to gather information about how well various alternatives measure up in terms of a possible natural metric or when it is politically sensitive to use the natural metric, as may be the case with *number of fatalities avoided*. However, in such a case, the importance of an avoided vehicle accident depends on the avoided fatalities due to that avoided accident. Hence, the relationship between accidents and fatalities is still critical to understand and incorporate in any logically sound analysis.

A constructed metric is sometimes developed to measure directly the achievement of a criterion when no natural metric exists. For example, suppose that you thought that the proxy metric *number of vehicle accidents avoided* was inappropriate because it implicitly assumes that all vehicle accidents are equivalent. You could categorize vehicle accidents in two groups such as head-on collisions, other collisions, and single vehicle accidents. Then you need to relatively prioritize each of these. Suppose you analyze data and decided that a head-on collision is twice as bad as a collision that was not head-on and ten times as bad as a single vehicle accident. Now define x, y, and z respectively as the number of head-on collisions, other collisions, and single vehicle accidents avoided. With the data above, the metric c defined by $c = x + 0.5y + 0.1z$ is the equivalent number of head-on collisions avoided. This is a simple constructed metric that weights different types of accidents. Note that this constructed metric is similar to the common grade-point average used to indicate performance in school.

In evaluating alternatives, it is appropriate to address the issue usually referred to as life-cycle costs. To do this, one can use the full project cost and then also the full consequences of that financial investment. For example, if the project has an effective life of 10 years, estimates of the fatalities avoided and the other consequences should all be specified for the complete tenure. If desired, one can also convert both costs and other consequences to an annualized basis.

Prioritizing Criteria

When one refers to a decision problem as having multiple criteria, it usually means that there are multiple fundamental criteria. A decision with multiple means criteria that influence a single fundamental criterion, such as *maximize profit*, is not a multiple criteria decision. In multiple criteria decisions, the logical prioritization of the fundamental criteria is necessary to evaluate alternative courses of action.

Many people feel that prioritizing criteria is a straightforward intuitive task, namely to simply ask the decision-maker to prioritize the criteria for a problem. However, such a lack of attention in prioritizing criteria results in a number of important logical and practical errors summarized in Keeney (2005). Most of these errors result from an ambiguous meaning for the concept of 'importance of a criteria' and the lack of a logical theoretical basis for the prioritization task.

There is no clear meaning for the concept that 'one criterion is more important than another criterion'. There is a clear meaning for the concept that 'a specific change in the level of achievement on one criterion is more important than a specific change in the level of achievement on another criterion'.

To illustrate this critical point, suppose there are only two criteria for evaluating highway projects, *minimize accidents* and *minimize costs*, measured by metrics *number of accidents avoided* and *project cost in dollars*. You are asked which is more important, accidents or costs, and you answer accidents. Does that mean that one accident is more important than $1 billion? Probably not, as you likely think $1 billion is more important than one accident. Does it mean that one accident is more important than $1000? It does not mean this either, although in this case you may feel that one accident is more important than $1000.

The point is that you absolutely must consider the amounts of different metrics in order to logically prioritize criteria. You may feel that one collision is indifferent to about $2 million, in which case the priority of $2 million should be equivalent to the priority of one accident. You

may also than reason that the priority of one accident is twice the priority of $1 million and that the priority of 100 accidents is equal to the priority of $200 million.

If these were the only two criteria for evaluating projects, a project that cost $120 million and avoided 100 accidents would be desirable. The reason is that the positive equivalent value of avoiding 100 accidents is equivalent to the value of $200 million and the cost of the project is less than that, namely $120 million. Indeed, you could conclude that the net value of the project is equivalent to saving $80 million (*i.e.* $200 - $120 million).

Evaluating Prospective Projects in Terms of Multiple Criteria

The logical way to evaluate prospective projects using the prioritized criteria can be illustrated using three fundamental criteria, namely *minimize accidents*, *minimize cost*, and *reduce negative impacts on the California economy*. Suppose we select metrics *a = number of accidents avoided*, *c = cost in millions of dollars*, and *e = number of avoided days of delay delivery for large transportation vehicles (i.e. trucks)*. To prioritize these metrics, we will use units of each of the metrics as indicated in Table 1. The basic information is provided in the first four columns of the table. The task is to specify the relative importance of the changes of going from no impact to a unit impact on each of the metrics. Details on techniques to do this in a logically sound manner are discussed in numerous sources including Keeney and von Winterfeldt (2007). Regardless of how it is done, it relies on value judgments.

Table 1. Framework for Setting Priorities Necessary for an Evaluation Model.

Objectives	Metrics	No Impact	Unit Impact	Judged Priority
Minimize accidents	a = number of accidents avoided	0	1	2
Minimize cost	c = cost in millions of dollars	0	1	1
Reduce negative impacts on the California economy	e = days of delayed delivery avoided	0	1	0.005

Suppose it is decided that one accident is as important as $2 million and one day of delay of a delivery is valued at $5000. Then for consistency, one accident must be equivalent to 400 days of delayed delivery. If this implication seems out of line with the feelings and thoughts about

importance of those provided value judgments, adjustments need to be made until the priority seem reasonable. It is important to ensure that these priorities are in line with the intentions of the mission and vision of Caltrans, as the qualitative language there the basis for this quantification. If the stated equivalent values above remain, one can normalize the priorities by setting any one of the metrics priority to 1.0 or by making the three priorities sum to 1.0 or 100. It is often convenient to normalize this by setting one unit of the cost metric to 1.0, as costs are easily understood and fungible. In this case within the priority of $1 million is 1.0, so the priority of one accident 2.0 in the priority of one day of transportation delay is 0.005.

Projects can now be evaluated with an objective function that is either a utility function or a measurable value function (see Keeney and Raiffa, 1976; Dyer and Sarin, 1979). As the concepts are similar, we will use the utility function here to indicate those concepts.

Let u be a utility function for evaluating projects in terms of the three fundamental criteria discussed above, namely *minimize accidents*, *minimize costs*, and *reduce negative impacts on the California economy*. Now, the anticipated impact of a project can be described by the consequence (a,c,e). The utility $u(a,c,e)$ of this specific project is a number, which is an indicator of the desirability of consequence (a,c,e). If (a_1,c_1,e_1) is preferred to (a_2,c_2,e_2), then $u(a_1,c_1,e_1) > u(a_2,c_2,e_2)$ and vice versa. If one begins at a consequence (a_0,c_0,e_0), it is logical to say that an improvement to (a_1,c_1,e_1) is more important than an improvement to (a_2,c_2,e_2) if and only if $u(a_1,c_1,e_1) > u(a_2,c_2,e_2)$.

A utility function also allows one to characterize all the value tradeoffs among fundamental criteria that are necessary to consider in a particular decision. Value tradeoffs specify how much a specific achievement in terms of one criterion is worth in terms of achievement on another criterion. Suppose, $u(a_1,c_1,e_0) = u(a_2,c_2,e_0)$, so the consequences (a_1,c_1,e_0) and (a_2,c_2,e_0) are indifferent to each other. Then, with e_0 fixed, a change from a_1 to a_2 is compensated for by a change from c_1 to c_2, which is referred to as a value tradeoff or and even swap (Hammond et al., 1999).

The set of fundamental criteria is composed of mutually exclusive components of the overall value of potential consequences. This provides the logical basis for the utility function to be represented by additive form (Keeney, 1981), which for our illustrative problem is

$$u(a,c,e) = w_A\, u_A(a) + w_C\, u_C(c) + w_E\, u_E(e), \tag{1}$$

where u_A, u_C, and u_E are component utility functions and w_A, w_C, and w_E are weighting factors calculated from the priorities of the criteria.

Furthermore, for evaluating alternatives to be included in a portfolio of projects, it is reasonable that the component utility functions are linear. Hence,

$$u_A(a) = a, \quad u_C(c) = c, \quad u_E(e) = e. \tag{2}$$

It follows from (1) and (2) at an appropriate utility function is the additive function

$$u(a,c,e) = w_A\,a + w_C\,c + w_E\,e. \tag{3}$$

As the weights are only relative, we can use the normalization in Table 1 and conclude that

$$u(a,c,e) = 2a + 1c + 0.005e. \tag{4}$$

Equation (4) is appropriate for evaluating proposed projects.

3. Comments on Other Issues of Interest to Caltrans

The following includes some thoughts that relate the prioritization of SHOPP projects to other issues of importance to Caltrans.

How to Explain That an Evaluation Is Logical and Justifiable.

Selection of projects to pursue and communicating the process and its results to stakeholders are different decision problems with different objectives. The analysis for the selection has to be thorough and needs to take all relevant aspects into account in order to be logical or justifiable. If the selection of projects was not done in a logical manner, it would be extremely hard to justify. Such an analysis is often too complex for many stakeholders to readily understand. For this reason, one might also need to create a simplified version of the model to illustrate the information and logic used in the evaluation and decision process to all stakeholders and interested parties.

If the new Caltrans mission is the foundation to guide the selection of SHOPP projects, the task to justify the selection should be easier and better received.

Selection of Portfolios

The inclusion of projects in the SHOPP portfolio includes mandated and discretionary projects. The evaluation model may be thought to be useful only for evaluating discretionary projects. However, the same model could be used to evaluate mandated projects. If the mandates are consistent with the new Caltrans mission and vision, mandated projects should evaluate high enough that they should be funded in the portfolio even if they were not mandated. If some of these mandated projects are evaluated to be less beneficial to California than some discretionary

projects that are not funded, this suggests that guidelines for establishing mandated projects should be reviewed.

How to Combine Projects to Get Benefits "More Bang for the Buck"/Creating Better Alternatives

No incentives or disincentives to promote cooperative projects to capture potential positive synergies results in lost opportunities. If the evaluation model incorporating the fundamental criteria is used to evaluate projects, it would not be too difficult to evaluate a bridges project, a separate but related pavement project, and a collaborative project on this pavement and bridge. Comparing the sum of the two independent evaluations to the evaluation of the collaborative project would indicate the potential additional value of the collaborative project. Demonstrating such implications of the current system may lead to, and perhaps hasten, positive changes that would facilitate pursuing collaborative projects.

Funding Projects on Facilities

Projects involving facilities should be included in SHOPP. In such a case, the priority of these projects logically should be evaluated with the same criteria as other SHOPP projects. However evaluating a facilities development project using the fundamental criteria with the evaluation function (4) is not practical, as the consequences (a,c,e) for a facilities project are extremely difficult to specify.

It may be useful for Caltrans to recognize a different decision, namely how to routinely include an appropriate amount of facilities development in its annual plans. It may be possible to clearly identify a minimum percentage of the budget that is required to support a sustainable level of performance on all SHOPP projects. Suppose a sound logical analysis demonstrated that on average at least 3% of the annual budget should be used to develop facilities to avoid a degradation in overall SHOPP performance. Then it is reasonable to have a set-aside budget for facilities of at least 3%. To evaluate appropriate facilities projects to fund, it would be desirable to have a logical and justifiable approach analogous to the approach discussed for evaluating maintenance and improvement projects above.

Managing When Project Cost Comes in Lower or Higher Than Expected

It is not possible to always forecast the exact cost of future projects. Yet, it seems as if there are difficulties that occur when there is a mismatch of the estimates and actual costs of the

projects. Given that the circumstance seems to be common, it may be worthwhile to explicitly declare a Caltrans decision as 'what can we do to lessen any negative impacts of a mismatch of estimated and actual costs'. The first step is to thoroughly identify the negative consequences of mismatches. From these, the objectives of this new decision can be identified, as they are essentially to reduce the magnitude of the negative consequences. Then, each objective can be used to stimulate thoughts about alternatives that may be useful to achieve such objectives. Next, appraise the alternatives intuitively or with some analysis and then implement any new alternatives identified as desirable.

Increase Funding for SHOPP Projects

Using the metrics of the fundamental criteria and the model (4), one can identify the net benefits to Caltrans of any desirable projects that could not be funded with current funds. This information could be used to illustrate the relevance of the consequences for the state of California in negotiations about increasing its SHOPP budget.

In addition, Caltrans may figure out the fundamental consequences of other government spending programs, especially for safety measured with fatalities and severe injuries. Such comparisons could reveal the effectiveness of spending more money on the SHOPP program. For example, if increases in health care costs save one statistical life for each $20 million invested and some additional SHOPP projects could save statistical lives for only $1 million each, that information may be viewed as a sound argument to increase SHOPP funding.

Another possibility is the following. Suppose it can be shown that a currently unfunded SHOPP project could increase total commerce in California by $5 billion over a ten-year period and that the state of California would receive additional tax revenue of $300 million in current dollars because of this increase in commerce. This may support an argument to fund an additional project the costing $120 million if that were the cost to fund this new project.

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Executive Summary

- We conducted a one-day workshop to begin defining a framework for prioritizing SHOPP projects. The workshop included:
    - Training on the basic principles of project prioritization
    - An analysis of the pros and cons of alternative approaches to prioritizing transportation projects
    - Selecting a preferred approach to prioritizing SHOPP projects
    - Creating a charter to guide the development of improved prioritization capability
    - Specifying an objectives hierarchy, consisting of objectives structured in such a way as to support a defensible, accurate estimation of the value of candidate projects
    - Making preliminary choices regarding the "decision units" for the prioritization system
    - Training on influence diagrams, a tool used for identifying factors and metrics for evaluating the various types of project benefits, together with a sample application of the process to one type of benefit
    - A recommended path forward for continued development of improved prioritization capability

Key principles of project prioritization

- Projects should be ranked by the ratio of project value to project cost. Selecting projects from the top down until the budget is exhausted yields the value-maximizing portfolio of projects, assuming the projects are independent of one another
- The value of a project is the difference between the value that would result if the project is conducted and the value that would result if the project is not conducted
- Project value depends on the degree to which the project contributes to the achievement of different objectives. The objectives define different types of project benefits (e.g., safety benefit, environmental benefit, benefit to the users of the transportation system, etc.).
- The value of a project can be estimated by weighting and combining estimates of the different types of project benefits only if
    - the benefit types and objectives that define them are distinct and do not overlap or double count
    - the weights represent the value created per unit of benefit increase, not judgments about the relative importance of the objectives
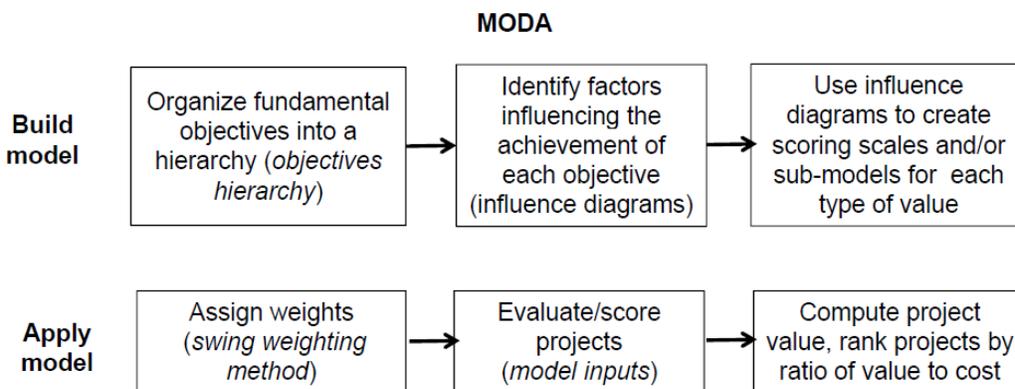
The methods SHOPP has been exploring to this point are not consistent with the key principles

- Too many criteria, many overlap and double count
- Equations for aggregating scores do not measure project value
- No accounting for loss of value that occurs if projects are not conducted
- Weights being assigned do not measure value per unit of score
- Ranking metric does not divide by cost to estimate "bang for the buck"

These methods cannot produce accurate or defensible project priorities

Our efforts to develop a prioritization process require a "fresh start"

- The approach consistent with key principles and viewed best-practice is known as multi-objective decision analysis (MODA)
- MODA is a formal process for building and then applying a project value model

MODA

Build model	Organize fundamental objectives into a hierarchy (*objectives hierarchy*)	→ Identify factors influencing the achievement of each objective (*influence diagrams*)	→ Use influence diagrams to create scoring scales and/or sub-models for each type of value
Apply model	Assign weights (*swing weighting method*)	→ Evaluate/score projects (*model inputs*)	→ Compute project value, rank projects by ratio of value to cost

MODA steps

Step	Output	Conducted or demonstrated in workshop?
1. Specify prioritization system design goals	Charter	Yes
2. Identify & structure objectives	Objectives hierarchy	Yes
3. Identify factors influencing each objective	Influence diagram	Yes
4. Identify those factors most impacted by project choices	Influence diagram drivers	
5. Develop scoring scales & equations for computing value	Initial quantification of of value model	
6. Create initial implementation of the model	Excel pilot model	
7. Specify weights & other model parameters	Weight assessment	
8. Test model to ensure inputs can be generated & validate outputs	Pilot test	
9. Make model refinements & provide "production version" software	Validated prioritization tool and process	

The Team created a charter to guide a MODA model development effort

Our goal is to develop and demonstrate a process for prioritizing SHOPP projects. The process should:
- Be based on best-practice and sound decision analysis science and is goal and objectives oriented
- Help us to communicate to stakeholders (e.g., visual)
- Be clear, understandable, transparent, and defendable
- Encourage more projects that meet multiple objectives (break down funding silos and the concept of individual programs) and develop a more well-rounded approach to selecting projects
- Align projects with the new Caltrans strategic goals, objectives, mission, and vision
- Clearly identify project values
- Gain support from internal and external stakeholders
- Recognize mandates and non-discretionary projects (though the value of doing mandated projects should be estimated as with other projects)

. The ultimate tool and process should:
- Recognize that initial software may not require expensive, third-party models; vendor software can be selected after gaining pilot experience
- Recognize and value partnership funding
- Quantify project value accounting for the consequences of not doing projects
- Enable us to address Caltrans Improvement Project Workgroup 2 recommendations
- Help us optimize Caltrans limited resources to maximum benefit relative to Caltrans goals and objectives
- Be adjustable to respond to changes in the political and economic climate, while allowing for political override
- Incorporate input from all managers to develop a sense ownership
- Help determine and indicate where additional resources for SHOPP are needed
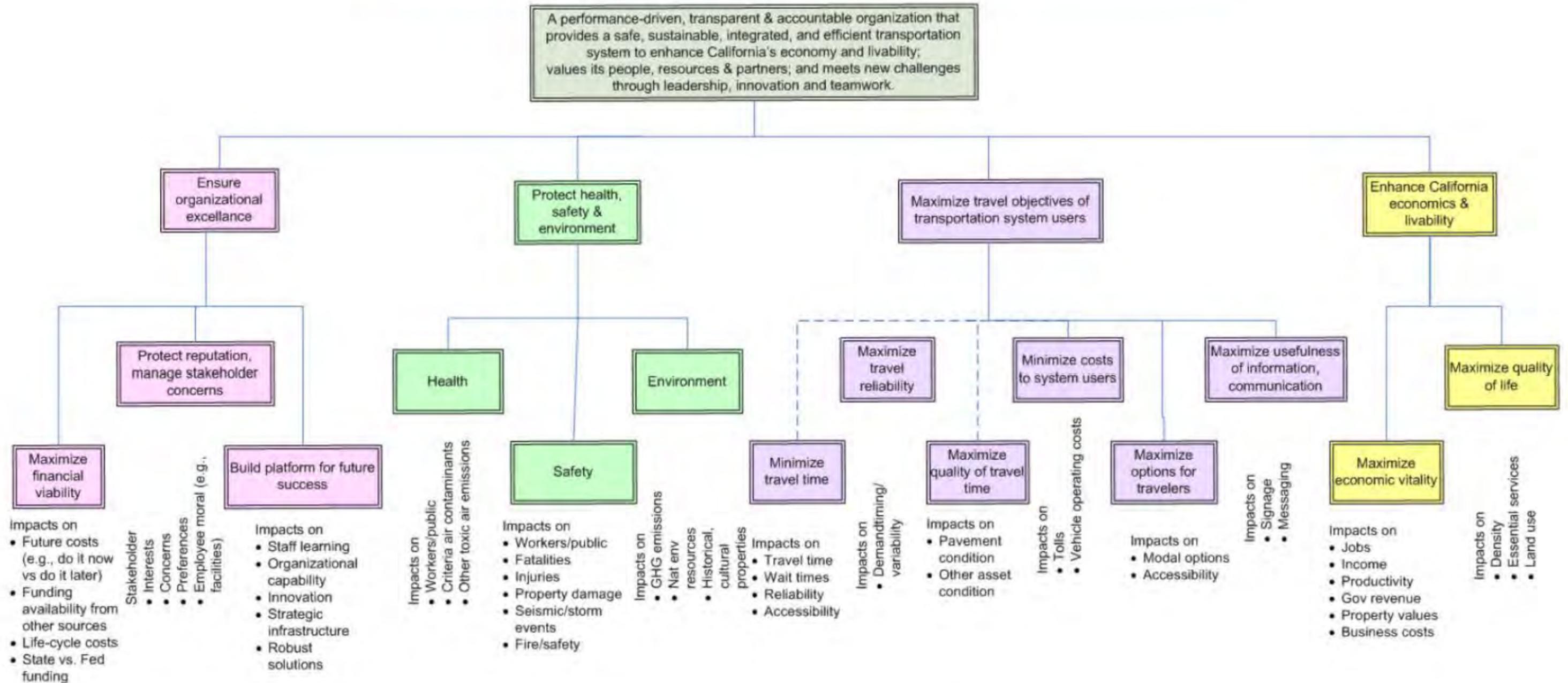
Schedule:
- We recognize the need to produce concrete process improvements within a couple months

In this one-day workshop we will
- Identify our project prioritization framework
- Identify prioritization approaches to avoid
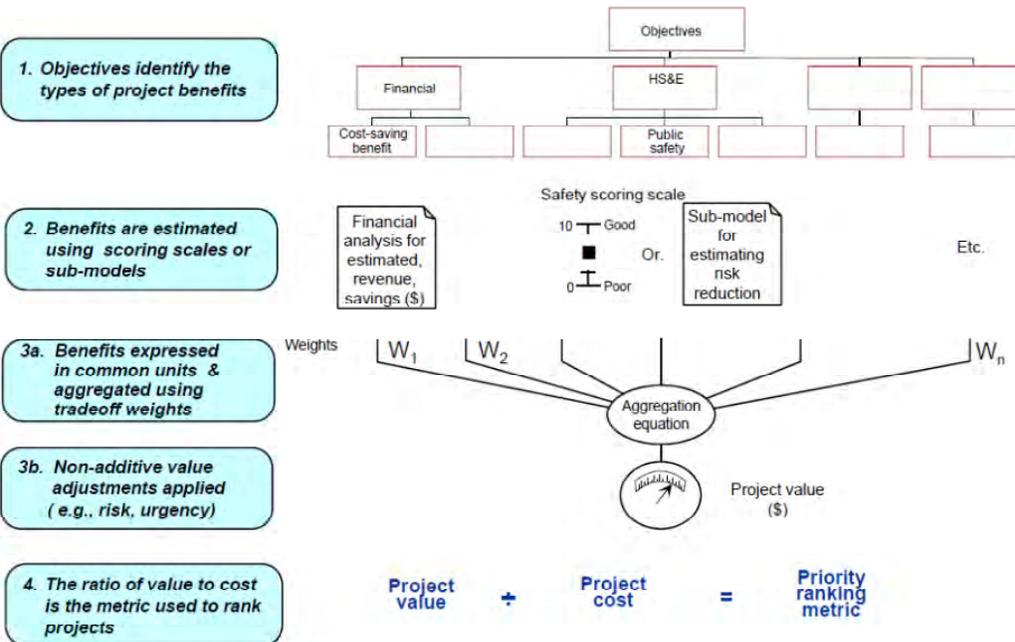- Identify next steps and a path forward

Following the MODA process, we produced a preliminary objectives hierarchy consisting of fundamental, non-overlapping objectives capable of being weighted and combined

Notes:
- Bulleting items indicate examples of influencing factors that projects might impact that could affect the achievement of the related objective. The lists are not meant to be exhaustive. Some influencing factors influence more than one objective (i.e., influencing the factor could simultaneously create multiple types of value).
- Sustainability is covered in part under "platform for future success, plus the understanding that project choices must continue over time to create value in all areas.

The objectives hierarchy provides the foundation for the quantitative prioritization model

Our recommendation is to complete the MODA framing process

- Review, validate, and complete the objectives hierarchy
- For each type of value in the hierarchy, create an influence diagram to identify the factors that must be considered when estimating that type of value
- Identify the drivers in each influence diagram; that is, those factors:
  - That may be impacted by projects and, if so, can significantly affect the achievement of the corresponding objective
  - That may be reasonably estimated based on available data or through informed judgments from knowledgeable staff without undo time or difficulty
- Provide simple, but well-defined scoring scales for documenting estimates
- Implement the resulting model for pilot testing using low-cost software for modeling and analysis (e.g., Excel)
- Test, refine, and apply the model to prioritize SHOPP projects