An Interactive Multiobjective Decision Support Framework for Transportation Investment

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16. Abstract

This report presents a multiobjective decision framework to support the decision making process in transportation investment analysis. One important capability of the multiobjective decision framework is that it allows many intangible objectives that are difficult to express on an absolute numerical scale to be considered without the need to convert the units into monetary scale.

The proposed multiobjective decision framework allows a decision maker to select a reduced number of alternatives from a larger number of all available alternatives while ensuring that the selected alternatives are the best possible options. This framework could also be used to generate decision options for optimal allocation of resources between competing projects.

The proposed decision framework is based on three multiobjective analysis concepts: the Surrogate Worth Tradeoff method for continuous decision problems and the Multiattribute Utility and Minimum Tolerance methods for discrete decision problems. These concepts help decision makers choose among, prioritize, and generate the most feasible and optimal alternatives. The four case studies presented as appendices demonstrate the application of the proposed decision framework to real-world projects.

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EXECUTIVE SUMMARY

Transportation infrastructure decisions that optimize available resources and provide maximum benefits hold tremendous value to the transportation profession. Decision maker attempts to reach their goals with well-timed and cost effective decisions that invest limited available resources according to future needs. Thus, it becomes increasingly important for decision maker to use objective tools to make proper investment choices.

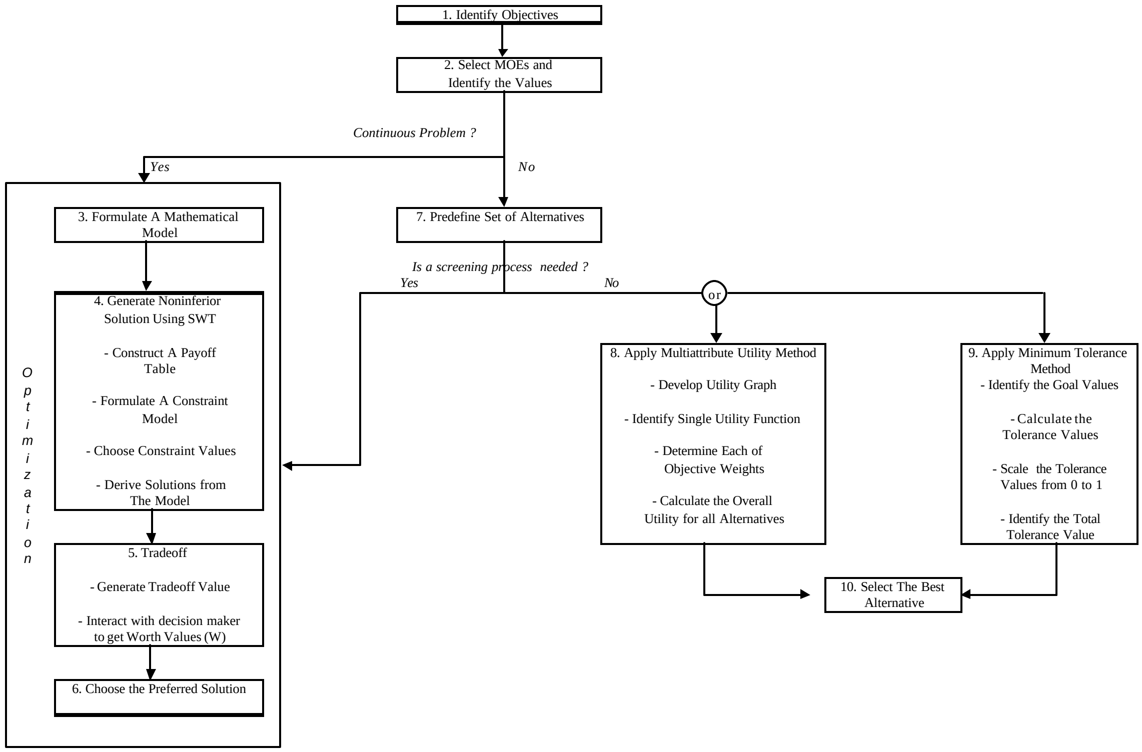
Most decision making scenarios in the transportation field are complex and include multiple, and often conflicting objectives. Often, these objectives cannot be measured in monetary units alone. Trading off labor costs versus environmental impacts is a challenge for all transportation projects. This and several other tradeoff scenarios comprise the multitude of criteria that a project must serve. To effectively reach the optimal decision, a practitioner must utilize a decision making framework.

The framework shown graphically on the following page developed in this report uses various mathematical and the analytical concepts of multiobjective analysis to provide such aid to decision maker. Multiobjective analysis allows a decision maker to select a reduced number of alternatives from the larger number of all available alternatives, while ensuring that the selected alternatives are the best possible options. This tool also allows optimal allocation of resources between competing projects.

This report outlines a variety of approaches based on multiobjective analysis concepts to choose among, prioritize and generate the most feasible alternatives. These “non-dominated alternatives” essentially provide the decision maker with a menu of acceptable investment levels and choices. The usefulness of each approach depends on the specific type of decision problem.

Based on the type of decision problem, continuous or discrete, the appropriate approaches can be identified. In a discrete problem, a predefined set of alternatives is available before the multiobjective part of the analysis begins. Most transportation investment projects have this characteristic as the selection of project alternatives is from a number of possible alternatives (or the selection of a project site from several possible sites). Continuous problems are not characterized by a predefined set of alternatives. Instead, for a continuous problem (such as miles of a particular road that need to be reconstructed), a mathematical model including decision variables, constraints, and multiple objective functions must be formulated to generate alternatives. The decision alternatives are not predefined in continuous problem while a finite number exist in discrete problems. The authors here present an optimization approach based on the Surrogate Worth Tradeoff (SWT) method for continuous problems, and Multiattribute Utility and Minimum Tolerance Methods for discrete problems.

Decision Making Framework



The decision making framework developed includes three multiobjective methods: optimization through Surrogate Worth Tradeoff, Multiattribute Utility and Minimum Tolerance Methods. If the multiobjective problem is continuous in nature, then only the optimization approach could be applied, whereas non-continuous problems can follow either Multiattribute Utility or Minimum Tolerance Method. The adoption of either Multiattribute Utility or Minimum Tolerance Method is a matter of individual choice.

When the number of discrete alternatives is greater than eight, the optimization method should be followed first to eliminate non-optimal alternatives. The main differences and advantages of the different methods are shown in following the table.

Applicability by Criteria of the Proposed Methods

Criteria	Method		
	Surrgate Worth Tradeoff	Multiattribute Utility	Minimum Tolerance
Methods used to find a best solution	optimization	preference assessment	goal tolerance value
Type of decision variable	continuous, discrete	discrete	discrete
Number of predefined alternatives in discrete problem	high	low	low
Capability to generate alternatives	yes	no	no
Interaction with decision maker	yes	yes	yes
How to find the best alternative	Closest to zero of worth value	Maximum of overall utility value	Minimum of total tolerance value
Advantages	Can be used to do tradeoff between objectives Ability to generate alternatives	Easy to use in evaluating alternatives Ability to express the weight of each objective Decision maker can express preference directly for each alternative	Easy to use in evaluating alternatives Ability to express the weight of each objective Interaction time is minimized with decision maker

The optimization approach also allows an optional method where the analyst demonstrates the relative tradeoff between competing alternatives. This optional approach allows the decision maker to receive additional input before selecting a final project. The strength of this approach is that after generating optimal solutions, the analyst can leave the decision maker to choose a project. If further selection is required, the analyst can guide the decision maker to a project through an interactive question-and-answer process that is factored into the equations.

Although no approach dominates the others, the optimization approach is more objective than the Multiattribute Utility approach. The Multiattribute Utility and Minimum Tolerance Methods are highly reliant upon decision maker input and criteria weighting. Final output and project selection may be influenced by personnel changes among the decision maker. The Multiattribute Utility approach includes decision maker’s input as a part of developing the output. Input is sought through a set of questionnaires on the relative importance of selected measures of effectiveness (MOEs).

The Minimum Tolerance Method ranks alternatives based on the tolerance values (below which cannot be tolerated) of selected criteria. The lower tolerance value shows the urgency or priority of a project with respect to a project with higher tolerance value.

This report presents four case studies that demonstrate the application of the decision making framework to real-world projects: the Capital Beltway Corridor, Ohio River Bridge Project, Pickaway County (Ohio) Resurfacing Problem, and Richland County (Ohio) I-71 Project. The study area for Capital

Beltway Corridor is in Washington D.C, on Maryland's 42-mile portion of I-95/I-495. The Ohio River Bridge project is located between Jefferson County, Kentucky and Clark County, Indiana. The Pickaway County (Ohio) Resurfacing Problem is located on Routes 674 (PIC-674), PIC-207, and PIC-138. The last case study area is the Richland County I-71 Project, which is located on the I-71 Cleveland to Columbus corridor. These four case studies were presented to demonstrate the applicability of the different paths the decision making framework can take under different decision scenarios.

These case studies were developed based on actual project data. The multiobjective optimization approach was applied in the Capital Beltway Corridor and Ohio River Bridge projects. The Capital Beltway Corridor case study simultaneously evaluated two decision problems, continuous (high occupancy vehicle (HOV) projects) and discrete (rail transit projects). The HOV lane evaluation included how many miles of HOV lane were needed in each of the five competing segments. The rail transit evaluation involved a choice between light and heavy rail transit projects. The decision making framework combined both decision problems and demonstrated two alternatives that were optimal to maximize economic development, transit ridership, and other criteria. Each returned varying investment levels in HOV and rail transit. Compromises must be made when choosing one of optimal alternatives, when they were the best alternatives generated.

The Ohio River Bridge project provided access between Jefferson County, Kentucky and Clark County, Indiana and represented a discrete decision problem with twenty-seven project alignment and structural alternatives. The case study evaluated a list of alternatives that would improve regional mobility, reduce traffic congestion, and increase safety in eastern Jefferson and southeastern Clark counties. The process resulted in two optimal projects that demonstrated acceptable solutions, one involving a single bridge crossing and a second choosing two smaller bridges with separated alignments.

The Multiattribute Utility Method was applied to study Richland County, Ohio pavement reconstruction along Interstate 71. The case study evaluated transportation solutions from six predefined alternatives to maintain acceptable traffic operations during a pavement reconstruction project. Based on the "Richland County, Ohio Interstate 71 Corridor Major Investment Study (MIS)," this project addresses a proposed lane addition to I-71 from the Morrow/Richland County (Ohio) line north to the Richland/Ashland County line. This MIS was a result of the Ohio Department of Transportation's (ODOT) "Cleveland to Columbus Pavement Reconstruction Study". The recommendation to construct a third lane was developed to address operational deficiencies caused by existing and future traffic volumes and truck traffic passing through the frequent steep grades along the corridor. ODOT conducted the MIS to determine the impacts of various alternatives. Application of the decision making framework suggested that widening the roadway shoulders and bridges optimally maintained two travel lanes in each direction during the reconstruction.

The Minimum Tolerance Method was applied to the Pickaway County (Ohio) Resurfacing Problem, which is managed by ODOT District 6. ODOT District 6 faced the task of prioritizing among three Resurfacing Problems. Traditionally, ODOT prioritized resurfacing projects based on the Pavement Condition Rating (PCR), where the lower the PCR, and the more inferior the pavement conditions, the higher the priority for resurfacing. ODOT faced another problem prioritizing these projects because one route generated more complaints than the other two projects, but had lower PCRs and was less traveled. PCR criteria alone would not have made the Pickaway County highly traveled corridor receive priority for resurfacing. The case study applied a decision scenario where other factors, such as crash rate and traffic volume, were considered as factors in addition to PCR, to prioritize these competing projects based on a goal tolerance value. The framework resulted in a project selection that chose the most heavily traveled road, even though PCR alone would not have qualified the project.

The approaches presented in this study provide public agencies with an alternative to traditional economic analysis. The methods should be integrated with an agency’s funding processes and management systems to adequately program projects. The decision making framework also provides flexibility to the user by being severable. Applying selected parts of the decision making framework based on the specific types of decision scenarios allows the practitioner to make informed decisions. The decision making framework, since it is not reliant upon a particular mode’s characteristics, could also be applied to other transportation areas, such as aviation, rail, and water. Use of the decision making framework would lead to optimal allocation of agency resources.

The authors propose that a software program be developed based on the decision making framework presented. The mathematical formulas involved in the decision making framework involve complex and repetitive manual calculations. Software would automate the process and lead to a considerable timesavings.

One limitation of the existing framework is the inability to factor in the preferences of multiple decision makers. Further research should be conducted to include multiple decision maker in the modeling framework. This addition would allow the proposed model to receive different input from a number of decision makers with different agendas. The organization would then be able to produce a decision output based on these varied inputs and preferences.

1. INTRODUCTION

1.1 Problem Statement

Most decision making scenarios involve multiple objectives that often conflict and cannot be measured in monetary units. This makes the process difficult. Since the resources to fund transportation projects are limited, using the available limited resources in an optimal manner by selecting the best alternative becomes very important.

A transportation agency should always want to make the best use of the resources allocated for projects. The main problems an agency faces are limited resources and the need to select an alternative from competing projects. Two projects are said to be mutually exclusive if it is not possible for both of them to be selected simultaneously. Therefore, decision maker have to choose which project is to be funded and at what level. This decision becomes difficult because there are numerous criteria that should be considered during the selection process. A project can have multiple, and often conflicting, objectives.

In the past, cost benefit analysis has been used as a tool for project evaluation. This approach requires that the effects of all project options be transformed into a single monetary dimension. This restriction leads to many difficulties in the practical application of this tool, since many objectives (such as customer satisfaction and environmental quality) cannot be readily transformed into monetary units.

Recognition of the need to extend available methods so that multiple and conflicting objectives could be incorporated into the decision making process led to the development of multiobjective decision making concepts in the late 1970s and early 1980s. In multiobjective decision making analysis, all objectives are approached on an equal basis, regardless of whether they can be estimated in monetary or non-monetary terms. In a transportation investment project, the objectives of the proposed project might be to improve access control, reduce congestion and delay, improve air quality, and/or improve traffic safety.

Multiobjective decision analysis gives planners technical tools that enable them to solve a decision problem where several objectives conflict. The effects of each objective might then be evaluated according to each of the selected measures of effectiveness (MOEs). The MOEs derived from these objectives might include a resulting reduction in environmental impacts, level of improved access to cultural facilities, and level of comfort with the given alternatives. In the case of complex transportation planning problems, no single option may exist that is considered the best by all measures. Economic, safety and operational measures may produce varied results.

Multiobjective decision making analysis can support the decision making process for transportation organizations. Two major players are involved in transportation investments: decision maker(s) and analyst(s). The decision maker makes important judgments regarding the relative significance of the objectives. The analyst generates alternatives and tradeoffs among objectives using mathematical tools. The other important capability of multiobjective decision making analysis is that it allows many intangible objectives that are difficult to express on an absolute numerical scale to be considered without the need to convert units into a monetary scale. For instance, safety and satisfaction are very important intangible factors in the transportation area.

The multiobjective decision making framework improves the state-of-the-art tools available to the transportation engineer to select project alternatives. Traditional approaches such as a benefit cost method or incremental cost benefit analysis evaluate a single investment at a time. The result obtained is usually for individual alternatives and cannot be comparatively ranked because the alternatives are evaluated over a different set of objectives. On the other hand, a multiobjective method evaluates sets of alternatives simultaneously over common sets of objectives and ranks the results. As seen in the literature, multiobjective analysis can be a good analytical technique to select the best alternative for transportation investments.

1.2 Objectives

The general objective of the research documented in this report was to develop a multiobjective decision support system that will aid the decision making process in a more systematic way. Specific objectives are listed below:

1. Develop a decision making framework for selecting between multiple competing alternatives while maximizing the desired and minimizing the undesired attributes.
2. Include an interaction between the analyst and the decision maker that will help the decision maker selects the best alternative.
3. Demonstrate the practical application of the methodology to actual transportation projects.

1.3 Scope

This research addressed how multiobjective decision analysis helps a decision maker think systematically about complex decision problems and improve the quality of the resulting decision. Analysts use multiobjective decision making approaches as tools to develop useful information for the decision maker to select and evaluate competing alternatives.

This research focused on decision making for investments in surface transportation projects. The report presents methods that are useful for continuous problems in which solutions are not predefined and discrete problems, which are useful for problems with a finite number of predefined alternatives. Those methods are discussed in Section 2.

The detailed modeling framework, which helps generate feasible alternatives and select the best-preferred project from a list of project alternatives, is presented in Section 3. Section 4 includes conclusions and recommendations. Appendices A, B, C, and D present four case studies that follow the modeling framework discussed in Section 3.

2. OVERVIEW OF MULTIOBJECTIVE DECISION ANALYSIS

This section describes the basic concepts of multiobjective decision analysis and how different methods based on these concepts could be applied to support the decision making process. Additionally, discussions of several studies that applied different multiobjective methods to develop tools for making decisions in transportation investments are included.

2.1 Characteristics of a Transportation Project and Multiobjective Analysis

It is important to establish the characteristics of a typical transportation investment project. An investment project may be dependent on other projects or be mutually exclusive. An investment project is said to be dependent when two projects complement each other. For example, in the Ohio River Bridge Project case study (see Appendix B), the proposed new bridge and the proposed interchange reconstruction complemented each other. Without the reconstruction, the network of access roads could still serve the community near the bridge site, but the bridge would be inaccessible without reconstruction of the road network. Under these circumstances, the proposed project to reconstruct the access road network is said to be a requirement of the proposed bridge build.

On the other hand, a proposed bridge and a proposed underwater tunnel near the same site of the river crossing may have a substitutional effect for each other due to the lack of sufficient traffic volume to justify the construction of both. In fact, if the construction of one makes it technically and economically infeasible to construct the other, one of the proposed projects would be eliminated by the acceptance of the other.

Transportation projects usually have multiobjective goals and needs. Most projects deal with efforts to achieve a set of focused objectives covering such areas as operation, safety, environment, and cost. The project objectives are initiated by a need. A need may be identified or evolve from any number of sources, including a request submitted by a local, county, or city organization. If the need is considered important and feasible solutions exist, a study to evaluate alternative projects may be initiated.

Every process to determine the project solution deals with two or more sets of projects or alternatives. Each alternative is evaluated based on a determined set of performance measures and the most promising alternatives are put on a candidate list. Cost estimates for development and the impact associated with each objective or criteria are used to develop a decision making framework used to select the optimal alternative. In addition to developing the decision making framework, budget considerations, resource availability, environmental factors related to government regulations, and technical requirements need to be considered.

Multiobjective decision analysis is an investment decision strategy used to select the best project among a set of alternatives based on the needs and objectives of the organization. The project must implement a solution that gives the highest benefit impact. Comprehension of the problem, project goals, and related performance measures are the bases used to evaluate and select alternatives. For example, a 1997 Texas study developed guidelines for selecting appropriate performance measures for use in a transportation investment study. The research team surveyed MPOs and other transportation agencies in Texas (Turner, et al., 1996) to identify various performance measures. The performance measures were then used to quantify the benefits or impacts of transportation improvements in five basics categories: transportation performance, financial/economic performance, social impacts, land use/economic development impacts, and environmental impacts. The specific performance measures are shown in Table 1.

2.2 Multiobjective Decision Analysis Strategy

There are two approaches to implementing multiobjective decision analysis. The first emphasizes preference assessment and the second is based on generating solutions or alternatives.

The preference assessment approach requires an explicit statement of preferences by decision maker prior to the solution process. Many state DOTs use this approach to rank or compare projects. The preferences are expressed in many different forms, including weighting or use of a multiattribute utility function. The decision maker can then determine how to allocate resources among a set of projects.

The solution generating approach emphasizes generation of a range of solutions and tradeoffs to be presented to the decision maker for consideration. The main purpose of this approach is to produce the entire set of non-dominated or effective solutions. The analyst then helps decision maker choose among possible solutions. The solution chosen is called the most preferred solution or the best-compromise solution. This solution is attained by examining and exploring the various tradeoffs between objectives for the entire set of possible solutions. This approach allows decision maker to be involved and in control of the decision making process.

Three techniques are used with these approaches: Multiattribute Utility Method, Surrogate Worth Tradeoff Method, and Minimum Tolerance Method. Each technique is described in the following paragraphs.

Table 1. Performance Measures

Transportation Performance	**Financial Economic Performance**	**Social Impacts**	**Land Use/ Economic Development Impacts**	**Environmental Impacts**
• Average travel time • Total delay • Person miles of travel • Congestion ranges • Person hours of travel • Person movement speed • Average speed streets • Average vehicle • Hours of congestion • Average daily traffic • Level of service • Volume-to-capacity ratio • Queue length	• Cost effectiveness • Financial feasibility • Cost per new person-trip • Total cost • User benefits • Stage improvement feasibility	• Number of displaced persons • Number or value of displaced homes • Accessibility to community services • Construction traffic and disruption • Public lands or facility • Recreation benefits	• Number or value of displaced businesses • Accessibility to employment • Accessibility to retail shopping • Tourism benefits	• Noise levels (db) • Mobile source • Emissions/ air quality • Visual quality/ aesthetics • Water resources • Wildlife/ vegetative habitat • Parklands/ open green space • Wetlands/ flood plain • Agriculture/ forest • Resources • Cultural/ historic • Archaeological resources • Hazardous waste

2.2.1 Multiattribute Utility Method

The Multiattribute Utility Method is based on utility or relative importance functions. A utility function represents the relationship between the utility and attribute values. If the function considers the single utility function of several attributes, then it is called a Multiattribute Utility function (MUF). The solution with the highest score or utility is referred to as the most preferred solution.

Multiattribute Utility Method has many advantages over other multiobjective techniques ("Multi Criteria Analysis: A Manual," Department for Transport, Local Government and the Regions). These include:

- The method is easy to use in evaluating the alternatives.
- The choice of objectives and criteria that any decision making group may make are open to analysis and change as they feel appropriate.
- Scores and weights are explicit and are developed based on established techniques. They can be cross-referred to other sources and changed if necessary.
- Performance measurements of the attributes are done by experts, so they are not left in the hands of the decision maker.

The disadvantages of Multiattribute Utility Method include the following:

- The process is very subjective with regard to weights.
- Output can vary from decision maker to decision maker. It becomes less biased if more decision makers are involved.
- If the attribute values are not accurate, then the output of the decision making process will be inappropriate.
- More time and patience is required of the decision maker because the model is developed and evaluated based upon the decision maker's preference.

2.2.2 Interactive Approach - Surrogate Worth Tradeoff Method

Haimes introduced the SWT method in 1974 and it has been applied in water resources systems (Haimes, et al., 1975). The SWT method is used to generate surrogate worth functions. The method is composed of several consecutive phases in two major steps. The first step generates the non-dominated solutions using the constraint (ε) method. The constraint method suggested by Haimes (1971) is applied by optimizing one objective while all of the other objectives are constrained to some value (ε). The solution to the problem largely depends on the chosen ε vector. It must be chosen so that it lies within the minimum or maximum values of the individual objective function.

The second step in the SWT method, known as the interactive process, includes direct interaction between the analyst and the decision maker. It can guide the decision maker to develop tradeoff among objectives from the set of feasible solutions generated earlier to find the preferred solution. In many situations, transportation projects consider both economic factors and financial return on the investment and other factors such as quality of life and preservation of the environment. However, even though the generation of non-dominated solutions meets those criteria, decision maker need to make tradeoff among such criteria.

The set of non-dominated solutions obtained earlier can serve as a screening process. The results of the screening may indicate that the solution possesses merit and deserves further consideration by the decision maker. To do the interactive approach, the decision maker may be asked to state preferences. The information concerning preferences can be assumed or elicited directly from the decision maker. The tradeoff information between two objectives is useful as an interactive connection between the decision maker and the model so that the final choice can be effectively chosen among the set of non-dominated solutions. The tradeoff value is a ratio that depends on the type of problem, whether it is continuous or discrete (see Section 3).

2.2.3 Minimum Tolerance Method

In the Minimum Tolerance Method, the lower the tolerance value of a project, the sooner that project needs to be prioritized (cannot be tolerated). This method is a straightforward way to express priorities among projects when all criteria have equal or different weights. The analyst interacts with the decision maker to determine the weight for each attribute, which is then used to determine its relative importance. The goal of this method is to rank projects according to their respective tolerance values.

Usually, no project satisfies all objectives or criteria simultaneously. For example, in the Pickaway County (Ohio) Resurfacing Problem case study (see Appendix C), the criteria for prioritizing resurfacing projects were PCR, ADT (Average Daily Traffic), truck ADT, and number of accidents at project location. Priority was given to projects with a low PCR level, high ADT, high truck ADT, and high number of accidents at that location compared to standard value. The PCR level was considered low when below the standard or aspiration level. The ADT, truck ADT, and number of accidents were considered high when they were higher than standard level. In this case, the PCR for one project could be below standard level (low), despite of fact that the ADT is still below the standard level. On the other hand, the second proposed project had higher PCR, but the ADT was also high. As a result, the PCR and the ADT criteria had equal weight. In such as these cases, it would be difficult to decide which project needs to be resurfaced sooner.

2.3 Application of Multiobjective Decision Analysis to Specific Transportation Projects

2.3.1 Virginia DOT

Haimes and Lambert (1998) developed a decision making framework for comparing and choosing prospective projects. The district traffic engineers in the Virginia DOT use this framework to allocate various total budgets among district, state or federal budget six-year plans. In addition, the framework can be used as a tool to aid in the comparison of design alternatives. The comparison of the diverse projects is based on the effects of the projects on performance, crash risk, and project cost.

Tradeoffs are involved among these three important factors. The number of crashes avoided per year for each project site after the particular project is implemented quantifies crash risk. Performance gain is measured by reduced travel time in the peak hour. Cost is considered as the sum of preliminary engineering, right-of-way acquisition, and construction costs. The comparison of a project's effects is performed using a multiobjective chart called a Project Comparison Chart. Figure 1 is a graphical depiction of the comparison of five different projects. The horizontal axis shows saved travel time in minutes. The farther out the project's effect is on the horizontal axis, the more preferable it is. The vertical axis represents the value of crashes avoided per year. The farther out the value on the vertical axis, the more preferable it is. The circle mark represents the project cost. The larger the circle area, the higher the cost. Project E shows the largest crash avoided and the lowest cost. Project D has the largest travel time saved. The advantage of using a Project Comparison Chart is the ability to present the tradeoffs between crashes avoided, travel time saved, and project cost for each project. One disadvantage of this chart is that it is limited to three objectives or criteria.

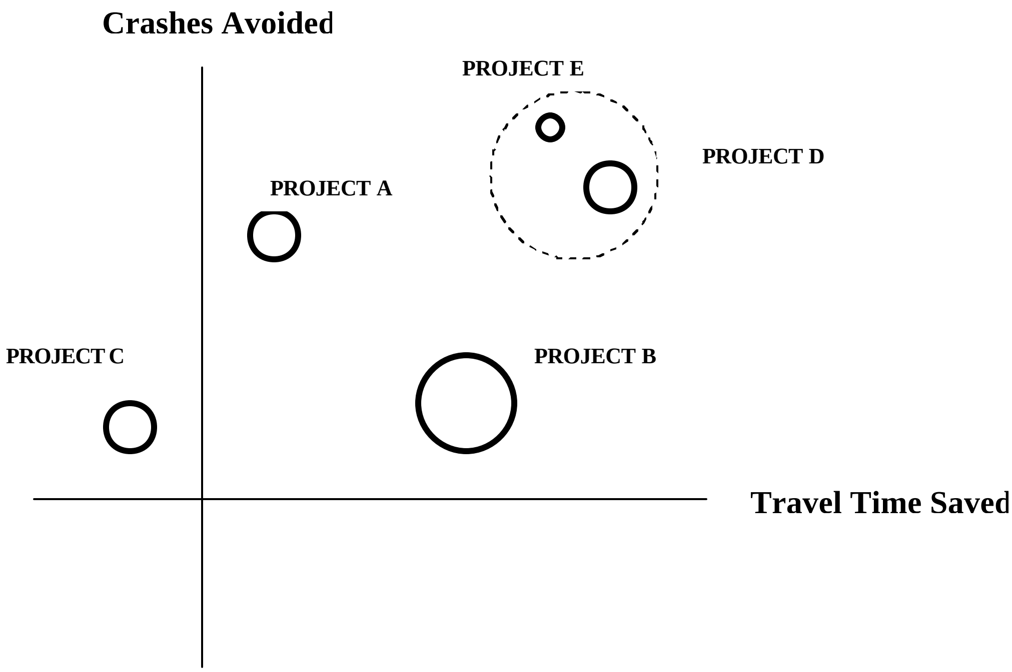


Figure 1. Project Comparison Chart (*Source: Haimes Y.Y, (1998) A Tool to Aid the Comparison of Improvement Projects For Virginia Department of Transportation)*

2.3.2 Twin Cities Metropolitan Area

The Twin Cities Metropolitan Area used prioritizing criteria to select projects for funding in the 2001 Solicitation for Federal Transportation Projects. The proposed projects had to be responsive to the adopted goals and objectives of the region. A series of qualifying criteria were scored and ranked against other qualifying projects. The Transportation Advisory Board was responsible for allocating the Surface Transportation Program funds. Selection of projects covered the seven-county area and funds were available for roadway construction and reconstruction, capacity, safety, transit, congestion management, and intelligent transportation systems projects. The Surface Transportation program consists of seven different categories, each with separate qualifying and prioritizing criteria. Each proposed project should meet all the criteria to qualify for priority evaluation. A Technical Advisory Committee reviewed the qualifying criteria for each proposed project to determine its eligibility. The eligible projects were scored based on the criteria and the total score ranked projects in each category. The ranked lists were forwarded to the Technical Advisory Funding and Programming Committees for review based on funding options.

2.3.3 Kansas City, MO

The city of Kansas City, Missouri also uses a process of rating criteria. The Community Infrastructure Committee introduced a process to assign a numerical score to each project being considered for funding in the five-year plan. Their five-year capital improvements plan attempts to balance resources among reconstruction, maintenance need, and demand for new construction.

Generally, projects come from citizen requests, analysis of the city's present and future needs, and field inspections. Each department submits a project proposal, accompanied by cost estimates, land acquisition plans, and project descriptions. All the information is compiled and reviewed using a relational database. After the initial review, the prescreening process conducted by the Committee can be supplemented to develop the preliminary project program. A rating committee and rating process are created to give points for each project and compare them with other similar projects. The higher the rating score, the greater the need for the project. Points are given based on the impact a project will have on the operating budget. A project can impact the operating budget by the need for additional administrative and maintenance staff and increased need for maintenance. The decision maker should know a project's impact on the operating budget before recommending it. A project that creates a new asset, heavily impacts the operating budget, or substantially adds to the city's current inventory would receive fewer points.

2.3.4 State of Washington DOT

In 1999, the State of Washington DOT selected the Highway Construction Program, in which the planned work for each of the eight types of structure needs is ranked on a statewide list. The ranking considers the structure condition, length of alternative route needed, and the amount of traffic that uses the structure. Projects are selected from the ranked lists, but also with consideration of the cost. The decisions relate to the best use of funding for various projects such as safety, rehabilitation, preventive maintenance, etc., and take several criteria or decision variables into consideration. For example, the decision variables considered for a highway reconstruction project are cost, traffic volume, roadway capacity, and other factors. The interactive decision model that helps the agency optimally allocate available funding for an investment in transportation projects allows several objectives to be considered. Among these are economic efficiency, environmental impact, high priority project, and safety.

A multi-criteria decision making approach was used to identify the critical highway safety needs of special populations groups (Transportation Research Record, No. 1693). Six special population groups were considered for this study: older drivers, younger drivers, school-age children, international tourists, new immigrants, and people with disabilities. A survey conducted to determine the most critical special population group found older drivers as the most critical group. The second critical special population group was school-age children. An index was developed to determine corresponding critical highway safety issues and concerns. This index corresponded to a score representing a multidimensional situation and estimated the weighted sum of all six criteria.

The six criteria considered were:

- Impact of crash rates,
- Effectiveness of applying roadway design changes to address the issue,
- Effectiveness of applying policy changes to address the issue,
- Cost of implementing the change,
- Ease of implementing the change, and
- Priority to address the issue.

The reliability of the outcome was found by changing the weights for the six criteria and comparing the ranking orders. The ranking orders were consistent irrespective of the weights changed; therefore, decision maker can use this approach to decide which transportation safety issues should be addressed first. This phase of the project only identified and ranked the special population groups and highway safety issues and concerns.

2.3.5 National Cooperative Highway Research Program

In a project conducted under the National Cooperative Highway Research Program (NCHRP), researchers developed a software package called the Transportation Decision Analysis Software, or TransDec. This software was intended to assist state and local planners make alternative investment decisions in various modes such as railway, highway, or construction projects (NCHRP No 258, 2001). The main objectives of this project were to (1) expand and adapt the framework developed in NCHRP Project 20-29 for multi-modal, multi-criteria transportation investment, (2) develop a generic software package to facilitate such analysis, and (3) prepare user-oriented materials to facilitate the use of the methodology developed. This project was an extension of the previous NCHRP Project 20-29, "Development of a Multimodal Framework for Freight Transportation Investment: Consideration of Rail and Highway Trade-Offs." This software was written in Microsoft Visual Basic and operated under Windows 3.1 or higher with at least 8MB of random access memory.

TransDec allows transportation practitioners to evaluate and provide structure to transportation investment decisions on the basis of multiple goals, objectives, and measures. The decision making process was, therefore, guided through project goals with each objective assigned a value measure. This process added reliability and structure in prioritizing the best projects based on selected value measures. This model may be applied to evaluate large or small projects in terms of addressing national, regional, or local goals and objectives. It helped to measure the progress toward performance targets, so it may support state and MPO planning. This tool is considered to be good, but needs to be revised to make it user-friendly.

2.3.6 Multiobjective Resource Allocation Tool

"Multiobjective Methodology for Highway Safety Resource Allocation" presented an Interactive Multiobjective Resource Allocation (IMRA) tool to help decision maker minimize the frequency and severity of vehicular crashes by selecting countermeasures and allocating resources optimally among various competing highways (Chowdhury, et al., 2000). This methodology also illustrated the tradeoff between various decision options and how to set priorities for a variety of potential crash countermeasures. The main objective of this research was to develop a tool that would aid in optimal resource allocation to improve highway safety. This tool supported interaction between the analyst and the decision maker that would help the decision maker select the best among various options.

The input data to IMRA methodology included crash, specific countermeasures to crashes, and cost of countermeasures. Although the IMRA methodology introduced a systematic approach to allocating resources among competing highway projects, it only considered crashes, severity of crashes and cost of crash countermeasures as objectives. It did not consider other operational objectives, such as speed and level of service, which would be impacted by implementing countermeasures that would change the number and severity of crashes. By introducing other operational objectives, the IMRA methodology could become a useful tool for highway operational analysis.

2.3.7 ConnDOT Decision Support System

Davis, et al. (1995) developed a decision support system to select pavement markings as part of a study sponsored by the Connecticut Department of Transportation (ConnDOT). The ConnDOT task force was the principal investigating agency that identified and structured a goal hierarchy. Many meetings were held between the principal investigating agency and individuals and the subgroups from the task force to identify goals that were relevant to the selection of pavement markings; therefore, a goal hierarchy was developed based on the inputs from the meetings. The major categories of the classified goals included safety, cost, and convenience. The goal hierarchy shown in Figure 2 includes 12 measures. A scale is defined for each of the following measures: initial dry retroreflectivity, initial wet retroreflectivity, final dry retroreflectivity, final wet retroreflectivity, reliability, application safety, total cost, installation insensitivity, in-house capability, life cycle predict, supplier availability, and applicator availability. The scales used discrete values ranging from 1 to 5 for some goals while for the others the scales were continuous based on units such as dollars per meter per year.

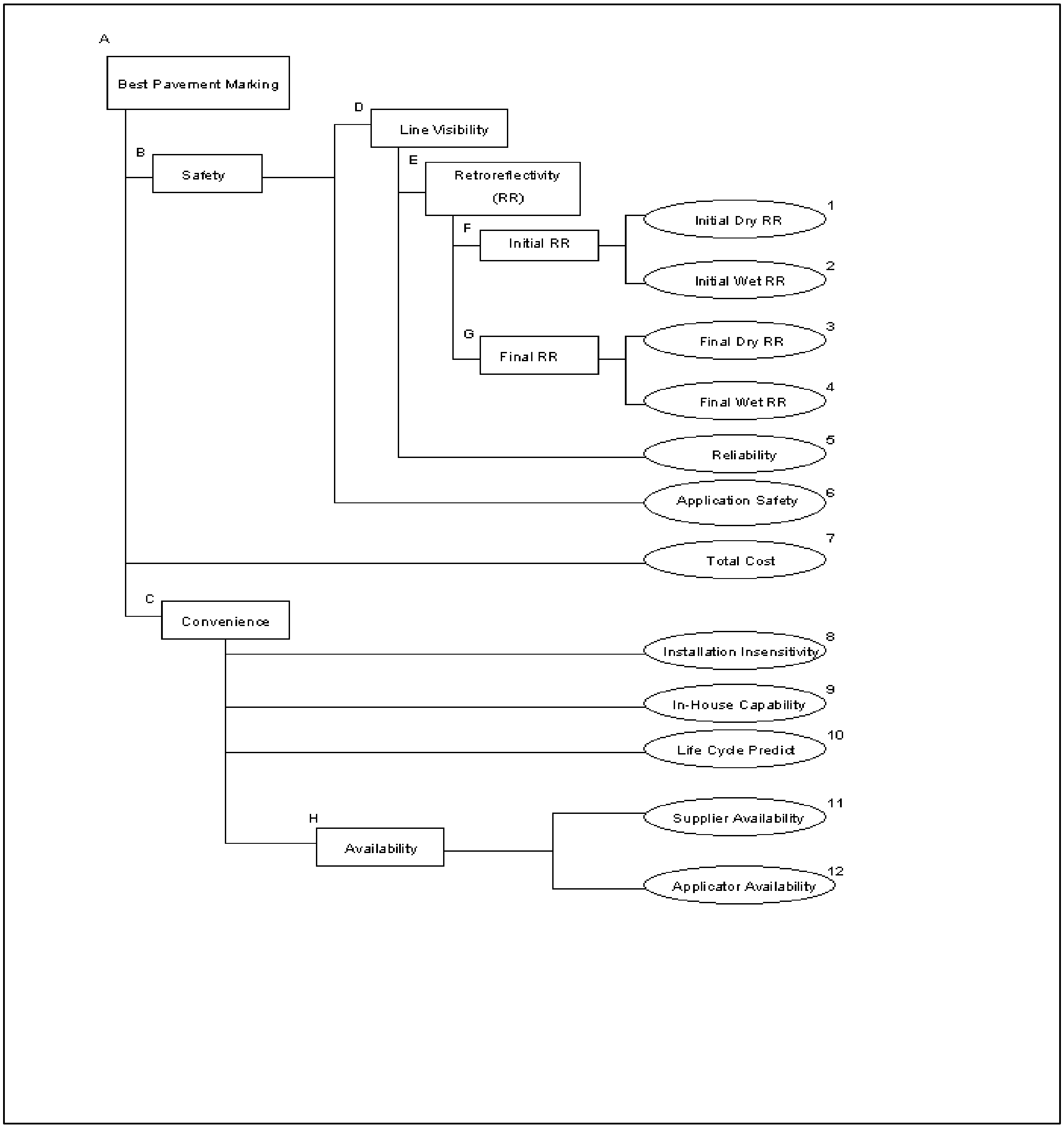


Figure 2. Goals Hierarchy *(Source: Christian F. Davis and Gerald M. Campbell, "Selection of Pavement Markings using Multi-Criteria Decision Making," Annual Meeting of Transportation Research Board, 1995)*

The task force then established the weights and single measure utility functions to compute the model's objective function once the model was developed. The model with all these inputs was entered into a software package called Logical Decisions for Windows (Logical Decisions, Golden Colorado). The model thus described can be changed; therefore, as new information and measurement techniques become available. Permanent changes can be made to the base model itself.

2.3.8 ODOT Draft Major New Construction Program

ODOT presented a comprehensive approach for the selection process for roadway improvement projects in a publication titled "Draft Major/New Construction Program 1998-2005." In this draft, a methodology for selecting roadway improvement projects based on a multi-attribute approach was developed. The approach applied to capacity projects of more than $2 million. A scoring method was used where the project received up to a maximum number of points based on its performance with regard to its respective objective. An overall score was calculated by adding all the points received by the project. The ranking criteria for the implementation priority of the project were based on the overall score. The project with highest overall score was the "first priority" for implementation. These rankings were subsequently subject to review and possibly change. The objectives used for the ODOT approach were the following:

- Transportation efficiency,
- Safety,
- Economic development,
- Funding, and
- Unique multi-modal or regional impacts.

These objectives were further broken down into criteria and a maximum obtainable score was assigned to each. This methodology may appear to be objective, but the way the points were attributed to the projects is quite subjective. The main benefit of this approach is the ability to communicate to the public because any person can replicate the departmental process of prioritization. Since the main focus is the overall score of the project, this methodology is not very helpful in finding the tradeoff between different objectives.

3. DECISION MAKING FRAMEWORK

3.1 Framework Steps

This section focuses on the specific framework for the decision making process. A framework allows the decision maker or analyst to justify the selection of the most appropriate multiobjective method in a given circumstance. It is very important to know the type of problem at the outset of the process. Decision problems can be either discrete or continuous; they differ only by the characteristics of the alternatives under consideration. In a discrete problem, a predefined set of alternatives is available before the multiobjective part of the analysis begins. Most transportation investment projects have this characteristic, as in the selection of project alternatives from a number of possible alternatives or the selection of a project site from several possible sites.

The decision of how many miles of road need to be constructed is an example of a continuous decision problem. The total miles can be all values between zero and a certain maximum available for the particular road segment. In other words, continuous multiobjective problems are not characterized by a predefined set of alternatives. Instead, a mathematical model that includes decision variables, constraints, and multiple objective functions must be formulated to generate the alternatives.

Each activity in the framework is presented in Figure 3 and explained in the following paragraphs. Figure 3 presents a general framework, which could be used to choose a particular multiobjective method based on the types of decision scenarios; i.e., whether it is a discrete or continuous problem. Each task is designated as a step. Step 1: Identify Objectives and Step 2: Select Measures of Effectiveness (MOEs) are common to all methods; they must be performed irrespective of the decision scenario and corresponding selected multiobjective method. If a decision scenario represents a continuous problem, then Steps 3 through 6 are performed. If the decision scenario is a discrete problem, then Step 7 is performed. Step 7 identifies the alternatives that are being considered. After identifying the alternatives, an evaluation is made regarding the need to narrow the number of alternatives. This is called the “Screening Process.” If it is decided that the number of alternatives that should be finally evaluated need to be narrowed (which means that a screening process is required), then Steps 3 through 6 are performed. If screening process is not required, then either Step 8 (based on the Multiattribute Utility Method) or Step 9 (based on the Minimum Tolerance Method) is adopted to select the best alternative. This framework is applied in four case studies presented in Appendices A through D. The steps that were applied in each case study were shaded. The following paragraphs explain in detail each in the decision making framework detail.

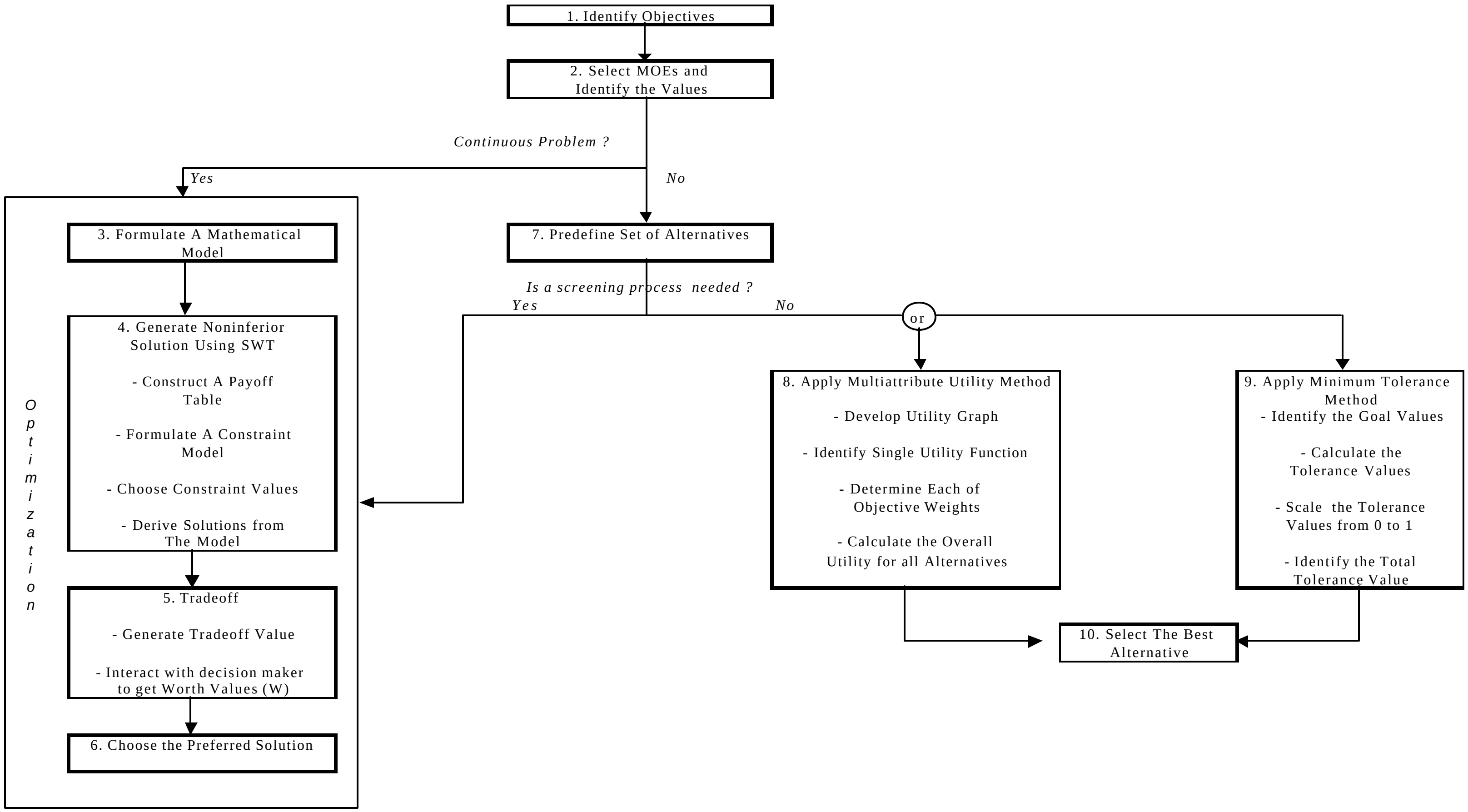


Figure 3. Decision Making Framework

Step 1. Identify Objectives

The first activity is to identify the objectives to be measured. An objective is a statement about the desired state of the system under consideration. The objectives should be specific and cover the main goal or need, such as minimizing delay time, minimizing cost, and maximizing safety. It is very important to have a thorough understanding of the problem. Although some projects have a single objective, most transportation projects have multiple objectives. The analyst should consider all of the objectives in this process.

Step 2. Select Measures of Effectiveness

In this step, the objectives to be measured are defined. The effectiveness of each project alternative is measured according to the performance of these alternatives on all of the objectives specified in Step 1.

Step 1 and 2 are critical processes to decide the method to be used to develop the multiobjective model. The method chosen is based on the answer to the question, "could the decision scenario be categorized as a continuous problem?"

If the scenario is a continuous problem, such as deciding the road mileage to be constructed, the Surrogate Worth Tradeoff Method (Step 3) would be chosen. One of the capabilities of this method is the ability to generate optimal alternatives to specified problems.

In the case of a discrete problem, where there are a finite number of alternatives to be considered, the user would go to Step 7, where the set of alternatives are predefined. In this framework, discrete problem can be solved either by using the SWT Method (Step 3), Multiattribute Utility Method (Step 8), or Minimum Tolerance Method (Step 9). The SWT method should be used when the number of predefined alternatives is eight or more (which will require a screening process to narrow the number of alternatives). In this scenario, the SWT method is used to screen those predefined alternatives to find the optimum alternatives, which means the list of predefined alternatives can be reduced. The Multiattribute Utility or Minimum Tolerance Methods would be used in discrete problems when the number of alternatives is less than eight (considered a manageable number). Additionally, if a decision scenario includes a combination of discrete and continuous cases, then the optimization process (continuous case scenario) should be followed.

Step 3. Formulate a Mathematical Model

The mathematical model is expressed as a mathematical function that represents the problem. The model is used to generate the value of decision variables and maximize or minimize the objective function subject to the specified constraints. If there are n-related decisions to be made, they are represented as decision variables ($x_1, x_2, \ldots, x_n$) whose respective values are to be determined.

The appropriate measures of effectiveness, such as cost and travel time, are then expressed as a mathematical function of these decision variables. This function is called the objective function. For example, in the scenario given above, the objective is to minimize cost and the decision variables (x_i) are number of miles of road to build in area i = 1, 2, and 3. The identification of the decision variables leads to essential answers to the questions the decision maker is seeking. The constant values (C_i) here are the cost per mile of road built in area i = 1, 2, and 3. So, the objective function would be $C = C_1x_1 + C_2x_2 + C_3x_3$. Any restrictions on the values that can be assigned to these decision variables are also expressed mathematically, typically by means of inequality or equality. This mathematical restriction is called a constraint function.

A constraint function can restrict or reduce the number of alternatives. In a transportation project common constraints are funding, right of way, and sometimes technology. For example, a district may have established a monetary limit per fiscal year for pavement programs, a budget constraint. A highway project in a metropolitan city has a right-of-way constraint to build new access, and an ITS project usually has a technological constraint to meet the specifications.

The decision variables (x_i), objective function (Z_j), and constraint function are used to represent the decision making problems by transforming them into a mathematical model. The decision variable is used to differentiate the mathematical model between a continuous and discrete problem. In a continuous problem, the decision variables will be continuous, such as the case where decision variable, x_{ij} represents miles of pavement type i in area j that will be built.

x_{11} = number of miles of asphalt pavement to be built in area A
x_{21} = number of miles of concrete pavement to be built in area A
x_{12} = number of miles of asphalt pavement to be built in area B
x_{22} = number of miles of concrete pavement to be built in area B

$x_{11} \geq 0,\ x_{21} \geq 0,\ x_{12} \geq 0,\ x_{22} \geq 0$

x_{11}, x_{21}, x_{12}, and x_{22} are the decision variables for the model. The mathematical model can be expressed as follows:

Minimize $Z = \sum_{i=1}^{2} \sum_{j=1}^{2} x_{ij} * C_{ij}$, C_{ij}= cost per mile of pavement type i for area j

Subject to,

$$\sum_{i=1}^{2} \sum_{j=1}^{2} x_{ij} * D_{ij} \leq \varepsilon_D$$, D_{ij}= durability per mile of pavement type i for area j

$$\sum_{i=1}^{2} \sum_{j=1}^{2} x_{ij} * L_{ij} \leq \varepsilon_L$$, L_{ij}= life cycle per mile of pavement type i for area j

Specific case studies that show the detailed formulations of this mathematical model are given in Appendices A and B.

In a discrete problem, the decision maker simply decides which projects are to be chosen. The mathematical model for this type of problem uses the following decision variables:

$$x_i = \begin{cases} 1 & \text{if a project i is selected, i = 1,2,…,m} \\ 0 & \text{if not,} \end{cases}$$

Each x_i is a binary variable, which has value of 0 or 1. Binary variables are important in mathematical models because they represent yes/no decisions. In this case, a yes/no decision means “should project i be selected?” After solving the mathematical model, the result will show that $x_A = 1$ when project A is selected. However if the result show $x_A = 0$, this means Project A is not selected. For example, minimizing cost may be the objective subject to set of constraints such as travel time and emission that are less than some amount or number, ε_K. The mathematical model can be expressed as follows:

Minimize Cost, $Z = \sum_{i=1}^{m} x_i * C_i$, C_i= cost of project i

Subject to,

$$\sum_{i=1}^{m} x_i * T_i \leq \varepsilon_T$$, T_i= travel time of project i

$$\sum_{i=1}^{m} x_i * E_i \leq \varepsilon_E$$, E_i= emission of project i

$x_i = 0$ or 1

Step 4. Generate Non-dominated Solutions Using Surrogate Worth Tradeoff Method (SWT)

The SWT Method is a multiobjective method used to generate a set of solutions and provide technique that incorporates the decision maker's preferences in choosing the optimal solution. This method is also referred to as the Tradeoff Method. The following tasks are performed in this step:

- *Construct a Payoff Table*

A payoff table (Table 2) consists of all objective values, when each objective is optimized subject to constraint using optimization software such as What's*Best!* 5.0. The first row in the table shows that the result $Z_1(X^1)$ represents the objective values for the first optimization run, X^1, optimizing objective Z_1. This process (optimization run) is repeated for a number of times equal to the number of objectives, Z1, Z2,.., Zp. For example, when total number of objectives are three (Z1, Z2, and Z3), the optimization should be ran three times to construct a payoff table.

Table 2. Payoff Table

	$Z_1(X^k)$	$Z_2(X^k)$	…	$Z_P(X^k)$
X^1	$Z_1(X^1)$	$Z_2(X^1)$	…	$Z_p(X^1)$
X^2	$Z_1(X^2)$	$Z_2(X^2)$	…	$Z_p(X^2)$
.	.	.	…	.
.	.	.	…	.
.	.	.	…	.
X^p	$Z_1(X^p)$	$Z_2(X^p)$	…	$Z_p(X^p)$
Max	Max $Z_1(X^k)$	Max $Z_2(X^k)$		Max $Z_P(X^k)$
Min	Min $Z_1(X^k)$	Min $Z_2(X^k)$		Min $Z_P(X^k)$

The purpose of developing a payoff table is to help formulate the constraint model in the next task by determining the lower and upper bounds for the constraint ε value, such as cost or travel time constraints.

- *Transform a Multiobjective Problem into a Single Objective Problem (Constraint Model)*

This task involves considering one objective as primary and transforming other objectives as constraints. The general form of a multiobjective problem with p objectives and m constraints is shown below transformed into a constraint model.

Maximize $Z_1(X_1, X_2,\ldots,X_n)$, $Z_2 (X_1, X_2,\ldots,X_n),\ldots,Z_p(X_1, X_2,\ldots,X_n)$

subject to: $g_1(X_1, X_2,\ldots,X_n) \leq 0$,
$g_2(X_1, X_2,\ldots,X_n) \leq 0$,
$\ldots, g_m(X_1, X_2,\ldots,X_n) \leq 0$
$X_j \geq 0$, $j = 1,2,\ldots,n$

The constraint model has only a single-objective problem. The objective is called the primary objective where the h^{th} objective was arbitrarily chosen to be optimized.

Maximize $Z_h(X_1, X_2,\ldots,X_n)$
subject to: $g_1(X_1, X_2,\ldots,X_n) \leq 0$,
$g_2(X_1, X_2,\ldots,X_n) \leq 0$,
$\ldots, gm(X_1, X_2,\ldots,X_n) \leq 0$
$Z_k(X_1, X_2,\ldots,X_n) \leq \varepsilon_k$ $k = 1,2,\ldots,h-1, h+1,\ldots,p$

$X_j \geq 0$, $j = 1,2,\ldots,n$

- *Choose the different values of e_k from the range of minimum and maximum values for each objective (identified in Step 1).*

The minimum and maximum values (for each column representing $Z_1(X^k)$, $Z_2(X^k),\ldots, Z_p(X^k)$ in the payoff table) are derived from the payoff table. By selecting a different number of constraint values, ε_k, the non-dominated solutions generated will represent a different satisfaction level of objectives.

- *Solve the Constraint Model using Optimization Software for Every Combination of Values for the* ε_k.

The mathematical models (constraint model) with every combination of constraint values, ε_k are solved in this task to generate a set of non-dominated solutions. The model may be solved by using commercially-available optimization software packages, such as What's*Best!* 5.0.

Step 5. Tradeoff Evaluation

The analyst can leave the selection of final decision from the set of non-dominated solutions to the decision maker. So, from Step 4 one can go directly to Step 6. Alternatively, the analyst can pursue Step 5 to guide the decision maker to a solution from the set of non-dominated solutions.

The following tasks are included in this step:

- *Generate Tradeoff Value (l)*

The decision maker's preference from a set of generated solutions is constructed through tradeoff evaluation between objectives. The tradeoff value, λ_{ij}, is computed as the change in value between a pair of alternatives in objective i given changes in value between a pair of alternatives in objective j.

Z_i^1 means value of objective i for alternative 1 and Z_i^2 means value of objective i for alternative 2. The following equation illustrates the calculation:

$$\lambda_{ij} = (Z_i^1 - Z_i^2)/ (Z_i^1 - Z_i^2) = \Delta Z_i/\Delta Z_i$$

- *Interact with Decision Maker to Get Worth Value (W)*

By interacting with the decision maker, the analyst can identify the regression function between the worth, W_{ij} and tradeoff value, λ_{ij}. W_{ij} ranges from –10 to +10, where +10 indicates that the decision maker prefers changing the λ_{ij} unit for objective i, Zi, over one unit change of objective j, Zj. However, -10 indicates the opposite extreme - that the decision maker does not prefer the change of λ_{ij} unit of Zi to one-unit change of Zj. A zero indicates indifference or signifies equal preference between objective Zi and Zj.

The optimum solution would result in average worth values closest to zero, signifying the point at which the decision maker cannot trade between objectives. The worth function can be determined by asking the decision maker a set of questions to determine how much of λ_{ij} he or she has the greatest desire (W_{ij} = +10) to change Zi by per one unit change of Zj. The questions would continue for Wij values of +5, -5, and –10 to get the worth regression function. This exercise is shown in more detail in Appendices A and B.

Step 6. Choose the Preferred Solution

The preferred solution is defined as the solution with an average worth value close to zero (computed in Step 5). This indicates that the decision maker is indifferent to the various objectives.

Step 7. Identify Predefined Set of Alternatives and Determine the MOEs Value for Each Alternative

Step 7 should be taken when the decision scenario is based on a discrete problem. The goal is to choose the best project from the set of predefined project alternatives. The predefined alternatives are generated directly based on the purpose and needs of the project, history of technical documentation, or public meetings that are held to solicit comments or aid in the development of alternatives.

The selection of predefined alternatives considers the value for each MOE decided at Step 2 including cost, accident, level of service and other criteria values. The decision process involving a choice between constructing a concrete or an asphalt pavement generally needs to assess other criteria besides cost when both meet the required standards. A concrete road is significantly more expensive than an asphalt road, but requires less maintenance and less frequent replacement. For a complex transportation problem, political or other values may be more important than cost in determining the set of alternatives. In planning a bridge, for instance, there are usually several alternative sites. The Ohio River Bridge Project (Appendix B) details a case in which different bridge locations were considered. The location options depended on societal decisions regarding the relative importance of accessibility, congestion, and other environmental and political impacts, in addition to cost.

Step 8 involves determining the need for a screening process to narrow the number of alternatives. A large number of predefined alternatives (eight or more) necessitates a screening process based on a mathematical model (go to Step 3 and continue until Step 6). The process is designed to eliminate proposals that are clearly infeasible or without merit. When a screening process is deemed necessary, the SWT method should be applied. On the other hand, a small number of alternatives eliminates the need for a screening process (go to Step 8 or Step 9 and continue Step 10). In this case, proposed project alternatives are analyzed to determine the most prominent criteria or prevailing conditions that may be acceptable.

The results of the screening process are placed on a candidate list for comparative analysis, which may indicate that the proposed project possesses some merit and deserves further investigation. For example, the Ohio River Bridge project included 27 predetermined alternatives at Step 7. After the screening process, the alternatives were reduced to five at Step 4 by using the SWT method to screen alternatives.

When the screening process is not necessary, the next step is preference assessment, which is conducted in Step 8 or 9. The main goal of the preference assessment is to carefully prioritize the relative strengths and weaknesses of each candidate and obtain a weight ranking. Ideally, the ranking indicates the most preferred project over the other candidates.

Step 8. Apply Multiattribute Utility Method

This method is related to a mathematical function called the utility function that associates a utility with each alternative so that all alternatives may be ordered or ranked based on utility value (Cohon, 1978). Utility functions are used to capture the preferences of a decision maker for various attributes of alternatives. Given any two alternatives A and B, the utility function will allow the decision maker to state that A is preferable to B, B is preferable to A, or A and B are indifferent. For instance, attributes in a resurfacing problem are traffic, total cost, and pavement strength. These attributes are associated with alternatives, every alternative implies values for each attribute, and a multiattribute utility function associates a single number (utility value) with the combination of values for the objectives.

The general form of a multiattribute utility function is based on utility (relative importance) functions. A utility function represents the relationship between the utility and the attribute values. The alternative with the highest score or utility is referred to as the most preferred solution.

The development of the utility function depends on the decision maker's values, so they must fit the preferences. The utility function consists of two major values, weight and utility. Weight values are used to measure the relative worth among the attributes assigned by the decision maker. For example, there are three alternatives being compared in the Ohio River Bridge project, say alternatives A, B, and C. The attributes used to measure and compare those alternatives are cost, capacity, and delay. The decision maker will be asked to assign weight values for those attributes based on the relative importance of each weight. The total weight value for all attributes should be equal to 1 ($\sum w_i = 1$). The decision maker may say that the capacity attribute is the most important criteria in choosing the alternative, so the individual may say capacity weight value is 0.5; cost is 0.25; and delay is 0.25.

The other value that represents decision maker preference is single attribute utility. This value indicates the degree of preference assigned to each attribute value of each alternative on a scale of 0 to 10, 0 being the lowest degree of preference and 10 being the highest. For example, alternative A, B, and C cost $3, $5, and $7 million, respectively. The analyst would then ask the decision maker to rank the degree of preference by assigning single attribute and cost utility values. The decision maker assigns cost utility values of 9, 7, and 5 to alternatives A, B, and C. A questionnaire could also be conducted to obtain these values as shown for the Richland County I-71 Case Study (Appendix G).

The following tasks are included in this step (and detailed in Appendix D):

- *Develop Utility Graph*

A utility graph is a graphical representation of the relationship between the utility and the attribute values (MOEs value). A utility graph is developed based on the decision maker's preference of an attribute's value. Interacting with the decision maker and asking them a set of questions about their preferences is one way to determine the preferences for the attributes. The main purpose of this graph is that for a known value of an attribute, the corresponding utility can be determined from the graph. For example, a utility graph for minimum average speed for I-71 is shown in Figure 4.

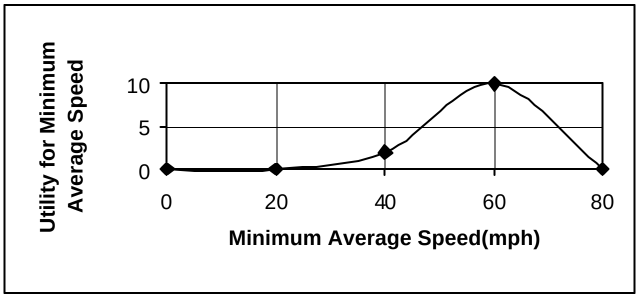


Figure 4. Utility Graph for Minimum Average Speed

From the figure, 0 is the least desired utility and 10 is the most desired utility of minimum average speed. This implies that the minimum average speed of 60 mph is most desired as it has a utility value of 10.

- *Identify Single Utility Function*

A single measure utility value (SU_i, when i = 1,2,3,…) is found by creating a mathematical relationship between each attribute and the corresponding utility found in the utility graph. A curve is fitted through the decision maker's preference and the equation of the curve is determined. Therefore, for a known value of an attribute, the unknown utility is determined from this equation. Regression equations and simulation modeling can also be used to develop these mathematical relationships.

- *Determine the Weight of Each Attribute*

The weight for each attribute is determined by interacting with the decision maker. This weight (W_i) is used to determine the relative importance of each attribute. The sum of the weights for all the attributes should be 1 (for example, $w_1+w_2+w_3+\ldots+ w_m = 1$).

- *Calculate the Overall Utility of all Alternatives*

The next task is to calculate the final or overall utility for each alternative. For example, if there are three attributes for a problem then the overall utility for alternative 'A' is determined as follows:

$MU_A = W_1\ SU_1 + W_2\ SU_2 + W_3\ SU_3$
$W_1 + W_2 + W_3 = 1$

where,
SU_1 = Single Measure Utility of Attribute '1' for Alternative 'A'
SU_2 = Single Measure Utility of Attribute '2' for Alternative 'A'
SU_3 = Single Measure Utility of Attribute '3' for Alternative 'A'
MU_A = Total Multiple Measure Utility or overall utility of Alternative 'A'
W_i = Weight of the i^{th} utility

Similarly, the total multi-measure or overall utility is computed for other competing alternatives.

Step 9. Minimum Tolerance Method

The difference between Multiattribute Utility Method and Minimum Tolerance Method is the way of choosing or ranking the best alternative. The Multiattribute Utility Method ranks alternatives based on the maximum utility value, which captures the decision maker's preferences for various attributes of alternatives. The Minimum Tolerance Method ranks alternatives based on the Minimum Tolerance values (below which cannot be tolerated) of selected criteria. The Minimum Tolerance value shows the urgency of a project with respect to the tolerance values.

The tolerance value (T_{ij}) is the difference between actual condition and acceptable or standard value. The tolerance value is measured per criterion (j) for each project alternative (i). Negative tolerance values of a project criterion indicate a heightened sense of urgency related to the program. Conversely, positive tolerance values indicated a lower sense of urgency.

Calculation of the different values depends on the objective of the problem. As explained earlier, the objective might involve maximizing one criterion while minimizing another. The conditions for each project can be contradictory. The analyst tries to help decision maker select the most urgent projects (low tolerance value). Calculations of the tolerance value can be seen from the equations below (considering four project alternatives, X^i and three criteria, Cj). Table 3 shows the value of existing conditions for each project at each criterion, X_{ij}. The information in Table 4 is the value of acceptable conditions obtained from policy goals, A_{ij}.

Usually, no project satisfies all objectives simultaneously. For example, in the Pickaway County (Ohio) Resurfacing Problem case study (see Appendix C), the criteria for prioritizing resurfacing projects were PCR, ADT, truck ADT, and number of accidents at project location. Priority will be given to roads that have low PCR level, high ADT, high truck ADT, and a high number of accidents compared to standard value. The PCR level is considered low when below the standard or aspiration level. The ADT, truck ADT, and number of accidents are considered high when higher than standard level. In this case, the PCR for one project road can be below standard level (low), despite the fact that the ADT is still below the standard level. On the other hand, the second proposed project has higher PCR, but the ADT number is also high. The problem is the PCR and ADT criteria have equal weight. In these cases, it is difficult to decide which project needs to be resurfaced sooner.

Maximum value of criterion, $T_{ij} = (A_{ij} - X_{ij})$

Minimum value of criterion, $T_{ij} = -(A_{ij} - X_{ij}) = (X_{ij} - A_{ij})$

Table 3. Existing Condition Value

Project	Criterion 1 (min/max)	Criterion 2 (min/max)	Criterion 3 (min/max)	Criterion 4 (min/max)
X^1	X_{11}	X_{12}	X_{13}	X_{14}
X^2	X_{21}	X_{22}	X_{23}	X_{24}
X^3	X_{31}	X_{32}	X_{33}	X_{34}

Table 4. Acceptable Condition Value

Project	Criterion 1 (min/max)	Criterion 2 (min/max)	Criterion 3 (min/max)	Criterion 4 (min/max)
X^1	A_{11}	A_{12}	A_{13}	A_{14}
X^2	A_{21}	A_{22}	A_{23}	A_{24}
X^3	A_{31}	A_{32}	A_{33}	A_{34}

Figure 5 shows the example of minimizing the tolerance value for criteria 1. T_{11} has a positive value and T_{31} has the most negative value (the most urgent in term of criterion 1).

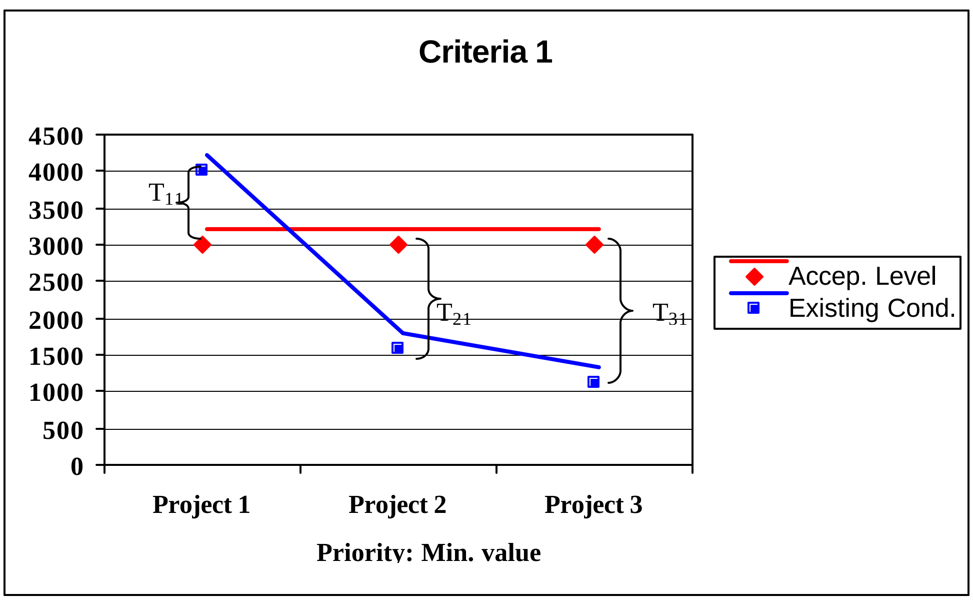


Figure 5. Tolerance Value

Since the units among criteria vary to make the analysis easier, the different unit values obtained are transformed into a scale from zero to one (T_{ij}*). The zero number of tolerance shows greater urgency in the project.

$$T_{ij}^* = \{T_{ij} - T_{ij}(min)\} / \{T_{ij}(max) – T_{ij}(min)\}$$

A decision will be based on the minimum total tolerance value (T_{ij}*). This indicates that the most important project is the one that has minimum total tolerance value.

Tolerance value (T_{ij}) is the difference between the actual condition value and acceptable or standard value. The tolerance value is measured for each criterion (j) for each project alternative (i). Negative tolerance values of a project criterion indicate a heightened sense of urgency related to the program. Conversely, positive tolerance values indicate a lower sense of urgency.

There are four tasks in this step (see example in Appendix C):

- *Identify the Goal Value Based on Policy Objectives*
  The goal values (A_{ij}) of alternative i and criteria j vary based on policy objectives. For example, the Ohio Department of Transportation provides acceptable pavement condition goals. The roadway system is divided into two categories: (1) priority system (high-volume) routes with a PCR of 65 or above would provide an acceptable ride; (2) general and urban system (lower volume, and lower speed) routes with a PCR of 55 or above are considered acceptable. PCR values range from 0 to 100 with 100 is being a new pavement.

  The existing condition value (X_{ij}) is determined in Step 7. The MOEs value of every predefined alternative is measured. For example, when the PCR is one of the MOEs criteria, personnel from the office of Pavement Engineering will inspect and report on the PCR.

- *Calculate the Individual Tolerance Value for all Criteria*
  The tolerance value (T_{ij}) is computed for each proposed project i and criterion j based on the project priority. When the project priority is to minimize criterion, the tolerance value is computed by subtracting the existing condition (X_{ij}) value from the acceptable value (A_{ij}) and vice versa.

  Maximum value of criterion, $T_{ij} = (A_{ij} – X_{ij})$

  Minimum value of criterion, $T_{ij} = -(A_{ij} – X_{ij}) = (X_{ij} – A_{ij})$

- *Scale the Tolerance Value to Zero*
  The tolerance scale value (T_{ij} *) is the relative value among alternatives. This value is computed by the following equation:

$$T_{ij}^* = \{T_{ij} - T_{ij}(min)\} / \{T_{ij}(max) – T_{ij}(min)\}$$

- *Sum the Tolerance Scale Values for all Criteria for Each Alternative*
  The tolerance values for all criteria in each alternative are summed. The weight of each criterion can be equal to each other or different. As in Step 8, the weight for each attribute is determined by interacting with the decision maker. The weight (w_j) is used to determine the relative importance of each attribute. The sum of the weights for all the attributes should be 1 (for example, $w_1+w_2+w_3+…+ w_j = 1$).

$$\underset{i = 1,\dots,I}{\text{Minimize}}\ T_i^* = \sum_{j=1}^{J} w_j (A_{ij} – X_{ij})$$

Step 10. Select the Best Alternative

The final step in the Multiattribute Utility and Minimum Tolerance Methods is to select an alternative. This depends on the overall tolerance or utility value of an alternative. In the Multiatrribute Utility Method, the alternative with the highest overall utility value is recommended as the best alternative. In the Minimum Tolerance Method, the alternative with the lowest total tolerance value is the recommended (most urgent) project, which means that it needs to be completed sooner compared to the other alternatives. By following the previous steps, a framework is provided to define the problem, select appropriate MOEs, and evaluate the alternatives using the specific method based on the type of problem (i.e., continuous or discrete).

3.2 Sensitivity Analysis

Sensitivity analysis is the study of how the variation in the output of a model (can be a numerical value) depends upon the input to the model. Sensitivity analysis is used to deal with uncertainties in the input parameters and will provide an understanding of how the model responds when inputs are changed. To better evaluate the impact of any parameter, the amount of the input parameter variation must be determined to effect a change in outcome. This analysis emphasizes the importance and significance of particular aspects or criteria of a problem.

In this report, the evaluation of the sensitivity of the project performance criteria is measured by the correlation coefficient, $r_{xj,y}$ (Salteli, Chan, Scott, 2000). This coefficient is based on the concepts of the correlation between the input variable (X_{ij}) and the output Y_i. In this case, X_{ij} is the constraint of sample i for criteria j. Y_i is the optimum solution for sample i.

$$r_{xj,y} = \frac{\sum_{i=1}^{N}(x_{ij} - x_j)(y_i - \bar{y})}{\left[\sum_{i=1}^{N}(x_{ij} - x_j)^2\right]^{1/2}\left[\sum_{i=1}^{N}(y_i - \bar{y})^2\right]^{1/2}}$$

$$\bar{y} = \sum_i \frac{y_i}{N} \quad , \quad \bar{x} = \sum_i \frac{x_{ij}}{N}$$

Coefficient $r_{xj,y}$ provides a measure of the importance of a particular criterion to the output. It can either be a positive or negative value. The closer the value is to zero, the lesser the importance of the criteria to impacting the output. A value of 1 shows the highest importance of the particular criteria to impacting the output. An example of this application is shown in Appendix A (Capital Beltway Corridor case study).

4. Conclusions and Recommendations

4.1 Conclusions

Most decision making in transportation agencies involves multiple objectives that often conflict and cannot be measured in monetary units. This makes the use of traditional investment analysis tools, such as benefit-cost analysis, difficult. This study presented different multiobjective models that could be applied under different decision scenarios in transportation investment processes. Instead of transforming all different project alternatives or objectives into monetary values, these alternatives or objectives can be approached on an equal basis in their own measures of effectiveness, either in monetary or non-monetary terms.

This report shows that a considerable variety of approaches exist to choose among alternatives, rank the priority of feasible alternatives, and also generate non-dominated alternatives. The usefulness of each proposed approach depends on the type of decision problem. No method has been found to dominate the others. The proposed approaches should be selected based on the type of decision problem: continuous or discrete. In continuous problems, the decision alternatives are not predefined and in discrete problems, a finite number of predefined alternatives exist. This report presents an optimization process based on the Surrogate Worth Tradeoff Method for continuous problems, and Multiattribute Utility Method and Minimum Tolerance Method for discrete problems.

This report presents four case studies that demonstrate the application of the proposed approaches to real-world projects: Capital Beltway Corridor (Appendix A), Ohio River Bridge Project (Appendix B), Pickaway County (Ohio) Resurfacing Problem (Appendix C), and Richland County I-71 Project (Appendix D). These case studies could be followed to apply the approaches for other projects. The approaches could potentially be used by public agencies to allocate resources between competing projects and/or select a project between competing alternatives.

The approaches could lead to new practices for decision analysis and decision making in the transportation industry. They allow interaction between the analyst and the decision maker in the selection of final projects, enhancing objective project selection.

4.2 Recommendations

The researchers recommend the following:

- When optimization is adopted from the proposed decision making framework for a particular decision scenario, the analyst should only perform the tradeoff analysis (Step 5 in the proposed framework) where such an exhaustive process is justified or required. Otherwise, the analyst should only generate the optimal lists of projects (Step 4) and leave the task of selecting a final decision to the decision maker (Step 6).

- The approaches presented in this study should be considered by public agencies as an alternative to traditional economic analysis. They should be integrated with agency funding processes and management systems.

- These approaches could also be applied to other transportation areas, such as aviation, rail and water.

- A software program should be developed based on the decision making framework presented in this report. Involved in the software would automate the complex and repetitive manual calculations process and lead to a time saving over manual calculations.

- Further research could be conducted to include multiple decision makers in the decision making framework. This would allow the proposed model to receive different input from a number of decision makers with different agendas and produce a decision based on these varied inputs.

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APPENDIX A

CAPITAL BELTWAY CORRIDOR

A. Capital Beltway Corridor (by SWT Method)

A.1 Project Description

The Capital Beltway corridor is located in the metropolitan Washington D.C area. The Capital Beltway provides an essential highway link on the East Coast serving local, regional and interstate travel. It is the only circumferential route in the D.C. area connecting many radial routes. Current traffic exceeds 200,000 vehicles per day in some sections and is expected to increase to 300,000 vehicles per day by 2020. Traffic conditions on the Capital Beltway include regular occurrences of very congested (or gridlock) conditions, particularly during rush hour periods. This condition will continue to worsen as traffic volumes increase due to the growing number of households and jobs in the region. The study corridor is approximately 42 miles of the I-95/I-495 Capital Beltway from the American Legion Bridge to Woodrow Wilson Bridge.

A study conducted by the Maryland State Highway Administration shows that the projected travel demand within the Beltway corridor in the year 2025 will be so great that both HOV lanes and rail transit will be needed. Therefore, the study recommended that both HOV lane and rail transit alternatives be considered. HOV lanes and rail transit each perform a different function and serve different markets within the region and corridor. HOV lanes are added to concurrent lanes by adding one lane in each direction. HOV lanes provide commuters who are willing to carpool or take a bus with one lane on the Beltway that operates at an acceptable level of service. Because a large percentage of total trips in the corridor would be made by automobile, even if rail transit would also be available, the HOV lanes would help to improve travel conditions for those willing to use them. They would not, however, decrease traffic demand on the Beltway itself.

These transit improvements would provide commuters with additional travel options within the Beltway region and consequently a congestion-free alternative to moving from one activity center to another and allow consistent travel times to those activity centers.

The impact study was conducted separately from the HOV lane and the rail transit studies. The HOV lane corridor was divided into five segments: The American Legion Bridge to I-270 West Spur, I-270 West Spur to T-270 East Spur, I-270 East Spur to I-95, I-95 to US 50, and US 50 to the Woodrow Wilson Bridge. Rail transit was divided into six different alignments (P1, P2, P3, P4, P5, P6), in which P1, P2, P3 are aligned for heavy rail, and P4, P5, and P6 for light rail transit. Each alignment serves four segments within Beltway area: Tyson's Corner to Rock Spring Technology Park/Bethesda, Rock Spring Technology Park/Bethesda to New Carrollton, New Carrollton to Branch Avenue/Suitland, and Branch Avenue/Suitland to Alexandria. In this study case, the decision making problem was solved using the Surrogate Worth Tradeoff Method. The best solution was achieved by combining both HOV lane and rail transit options and deciding how many miles of HOV lane were needed for each segment. An alignment was selected and the corresponding light or heavy rail transit.

Figure 6 shows the general decision making framework, with the shaded portion representing the steps that were applied in this case study. This case study involved two different scenarios: a continuous (miles of HOV lane) and a discrete scenario (selection of alignment with associated rail service). Both scenarios were satisfied simultaneously. The steps for the continuous scenario were followed when any one of the scenarios is continuous, irrespective of other scenarios that may be discrete. Consequently, Steps 1 through 6 were followed in this case study.

A.2 Problem Solving

Step 1

The identification of objectives is the first step in the decision making process. The objectives for the Capital Beltway Corridor project are as follows:

- Support regional mobility and address travel demand,
- Minimize incremental costs while maximizing transportation capacity, and
- Improve accessibility to existing and planned economic development areas and regional activity centers.

Step 2

Measure of Effectiveness uses five different criteria to evaluate each alternative.

- Total costs
- Annual ridership
- Daily new ridership
- Public support, and
- Economic development.

Each HOV segment and transit alternative was evaluated and measured for their effectiveness. The measured effects are shown in Tables 5 and 6.

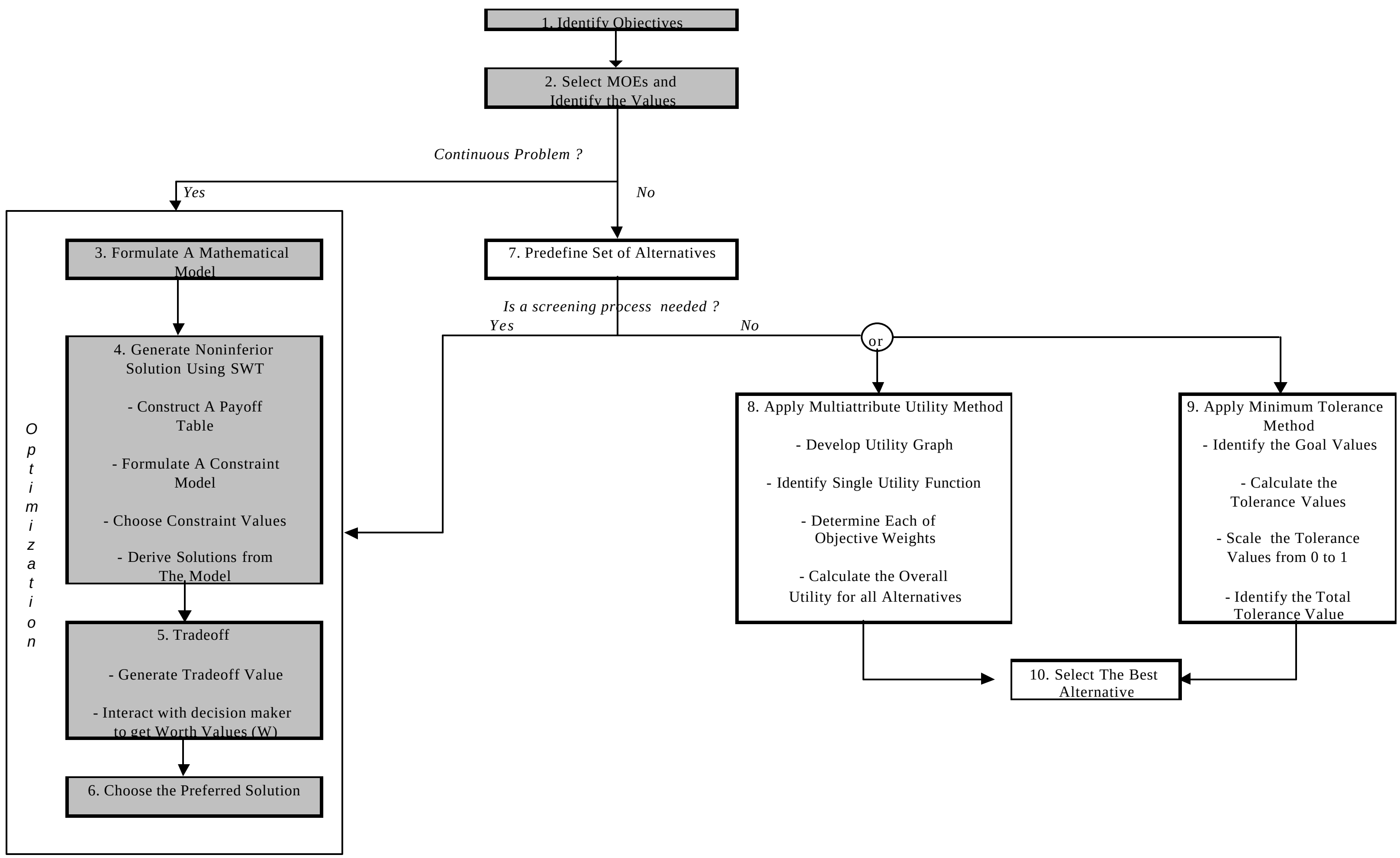


Figure 6. Decision Making Framework for Capital Beltway Corridor
(Shaded areas show the steps that were applied in this case study)

Table 5. Measured Effectiveness Value for HOV Lanes

SEGMENT	Cost per mile (M)	Annual Ridership per mile (K)	Daily New Ridership per mile	Public Support*	Economic Development*
1	$17	399	1,347	2	3
2	$17	25	83	2	3
3	$41	297	1,002	2	3
4	$43	96	324	2	3
5	$24	86	292	2	3

** scores from 0 to 5 (low to high)*

Each of the criteria is measured in terms of cost, annual ridership, and daily new ridership. Public support and economic development are scored between 0 and 5 (negative to positive impact). This case study is basically a combination of a continuous (HOV) and a discrete (rail transit) problem. The goal is to generate how many HOV miles need to be built and decide which rail transit alignment should be chosen. The Surrogate Worth Tradeoff Method was chosen to evaluate the decision making process.

The rail transit alternatives are based on alignment and rail transit type (light and heavy rail):

P1 = heavy rail transit alternative with alignment 1
P2 = heavy rail transit alternative with alignment 2
P3 = heavy rail transit alternative with alignment 3
P4 = light rail transit alternative with alignment 4
P5 = light rail transit alternative with alignment 5
P6 = light rail transit alternative with alignment 6

The MOE values are shown in Table 6.

Step 3

Develop a Mathematical Formulation

There are two types of decision variables in this model. One is for the HOV alternative, representing how many miles of road need to be built for each segment. The HOV alternative is divided into five different segments,

Xi = miles of road in segment i, i = 1,2 …,5

The second is for rail transit representing a "yes" or "no" decision (1 = yes and 0 = no) based on six different alignments (Pj with j = 1,2,…,6) and type of rail transit/heavy rail (P1, P2, P3) or light rail (P4, P5, P6).

$$P_j = \begin{cases} 1 & \text{if a project j is selected} \quad , j = 1,2,\ldots,6 \\ 0 & \text{if not,} \end{cases}$$

Table 6. Measured Effectiveness Value for Rail Transit

Total Cost						
	ALIGNMENT					
SEGMENT	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	$2,136,000,000	$1,659,000,000	$2,136,000,000	$786,000,000	$857,000,000	$786,000,000
2	$3,766,000,000	$3,019,000,000	$3,066,000,000	$1,254,000,000	$1,257,000,000	$1,430,000,000
3	$2,599,000,000	$2,599,000,000	$2,599,000,000	$766,000,000	$630,000,000	$630,000,000
4	$1,418,000,000	$1,418,000,000	$1,418,000,000	$470,000,000	$423,000,000	$423,000,000
Annual Ridership						
	ALIGNMENT					
SEGMENT	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	5,935,403	4,382,770	5,228,753	3,507,785	5,376,469	3,492,959
2	33,810,886	40,724,948	28,604,913	53,625,924	30,363,296	39,989,544
3	11,133,474	10,531,544	10,789,939	10,251,554	15,392,336	12,122,800
4	4,522,762	4,338,398	4,317,583	6,005,887	9,396,844	8,627,636
Daily New Ridership						
	ALIGNMENT					
SEGMENT	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	10,028	7,401	8,830	5,925	9,085	5,900
2	30,847	32,054	26,090	42,332	27,696	31,822
3	10,156	9,606	9,840	9,360	14,036	11,063
4	7,636	7,325	7,291	10,148	15,870	14,578
Public Support						
	ALIGNMENT					
SEGMENT	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	4.00	5.00	4.00	4.00	4.00	4.00
2	4.00	4.33	4.00	4.00	4.00	4.33
3	4.00	4.00	4.00	4.00	4.00	4.00
4	5.00	5.00	5.00	4.00	5.00	5.00
Economic Development						
	ALIGNMENT					
SEGMENT	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	5.00	5.00	5.00	5.00	4.00	5.00
2	4.00	4.67	4.00	4.33	4.50	4.33
3	4.00	4.00	4.00	4.50	4.00	4.00
4	4.00	4.00	4.00	4.00	4.00	4.00

Five objectives are considered based on the MOEs selected earlier,

1. Minimize Total Cost, $Z1 = \sum_{i=1}^{5} Xi * Ci + \sum_{j=1}^{6} Pj * Cj$

2. Maximize Annual Ridership, $Z2 = \sum_{i=1}^{5} Xi * Ai + \sum_{j=1}^{6} Pj * Aj$

3. Maximize Daily New Ridership, $Z3 = \sum_{i=1}^{5} Xi * Di + \sum_{j=1}^{6} Pj * Dj$

4. Maximize Public Support, $Z4 = \sum_{i=1}^{5} Xi * Si + \sum_{j=1}^{6} Pj * Sj$

5. Maximize Economic Development, $Z5 = \sum_{i=1}^{5} Xi * Ei + \sum_{j=1}^{6} Pj * Ej$

Ci = total cost per mile for HOV in segment i
Cj = total cost for rail transit alternative j
Ai = annual ridership per mile for HOV in segment i
Aj = annual ridership for rail transit alternative j
Di = daily new ridership per mile for HOV in segment i
Dj = daily new ridership for rail transit alternative j
Si = score of public support per mile for HOV in segment i
Sj = score of public support for rail transit alternative j
Ei = score of economic development per mile for HOV in segment i
Ej = score of economic development for rail transit alternative j

Constraints:
$X1 \leq 4.0$ miles
$X2 \leq 2.6$ miles
$X3 \leq 8.6$ miles
$X4 \leq 8.3$ miles
$X5 \leq 16.6$ miles
$P1 + P2 + P3 + P4 + P5 + P6 = 1$
$Xi \geq 0$

There is a restriction for Pj (j = 1,2,…,6) where the sum of Pj should equal 1, representing mutually exclusive alternatives (i.e., only one rail transit alternative needs to be chosen). In addition, the total HOV mileage should be less than or equal to the total segment length.

Step 4

Generate a Non-dominated Solution using the SWT, using the following tasks:

Construct a Payoff Table

The first task is to construct a payoff table (Table 7) by optimizing each of the five objectives separately (i.e., cost, annual ridership, daily new ridership, public support, and economic development) to get maximum and minimum values.

Table 7. Payoff of Capital Beltway Corridor

		Z_1	Z_2	Z_3	Z_4	Z_5
Min Cost	X^1	$3,167,000,000	60,528,944.40	66,686.90	17.00	16.50
Max Annual Ridership	X^2	$4,497,745,000	79,832,327.60	89,523.10	26.00	32.83
Max Daily New Ridership	X^3	$4,497,745,000	79,832,327.60	89,523.10	26.00	32.83
Max Public Support	X^4	$9,916,745,000	66,418,837.10	78,142.70	28.33	32.67
Max Economic Dev.	X^5	$4,497,745,000	79,832,327.60	89,523.10	26.00	32.83
	Min	$3,167,000,000	60,528,944.40	66,686.90	17.00	16.50
	Max	$9,916,745,000	79,832,327.60	89,523.10	28.33	32.83

Formulate a Constraint Model

The second task is to transform a multiobjective problem into a single objective problem using the constraint method. In this case, the maximized public support objective (Z4) is chosen as a primary objective and all other objectives (Z1, Z2, Z3, and Z5) are transformed as constraints, as shown below:

$$\text{Maximize Public Support, } Z4 = \sum_{i=1}^{5} Xi * Si + \sum_{j=1}^{6} Pj * Sj$$

Constraints:

$$Z1 = \sum_{i=1}^{5} Xi * Ci + \sum_{j=1}^{6} Pj * Cj \leq L1$$

$$Z2 = \sum_{i=1}^{5} Xi * Ai + \sum_{i=1}^{6} Pj * Aj \leq L2$$

$$Z3 = \sum_{i=1}^{5} Xi * Di + \sum_{j=1}^{6} Pj * Dj \leq L3$$

$$Z5 = \sum_{i=1}^{5} Xi * Ei + \sum_{j=1}^{6} Pj * Ej \leq L5$$

$X1 \leq 4.0$ miles
$X2 \leq 2.6$ miles
$X3 \leq 8.6$ miles
$X4 \leq 8.3$ miles
$X5 \leq 16.6$ miles
$P1 + P2 + P3 + P4 + P5 + P6 = 1$
$Xi \geq 0$

Choose Constraint Values

The L value (Table 8) is chosen from different values of the range of minimum and maximum for objectives 1, 2, 3, and 5 from the payoff table (Table 7). By selecting a different combination of L values from Table 8, the non-dominated solutions generated will represent different satisfaction levels.

Table 8. Constraint Value of Capital Beltway Corridor

Constraint	**Selected Constraint Values**		
L_1	$5,416,915,000.00	$7,666,830,000.00	$9,916,745,000.00
L_2	66,963,405.47	73,397,866.53	79,832,327.60
L_3	74,298.97	81,911.03	89,523.10
L_5	21.94	27.39	32.83

Derive Solutions from the Model

The final task is to solve the constraint problem by maximizing the public support score subject to all constraints for every combination of values for L_1, L_2, L_3, and L_5. The model was solved by running the optimization software, What's*Best!* 5.0, for 80 runs with each run including a different combination of objective constraint values. The optimization process shows that $P_j = 1$ when project J is selected. If the result shows $P_j = 0$, Project J is not selected. Seven project alternatives (Y1, Y2, Y3, Y4, Y5, Y6, and Y7) exist as combinations of HOV and rail transit projects generated by software. The combinations are shown in Table 9.

Table 9. Generated Solutions of the Capital Beltway Corridor

Project Selection	HOV					Rail Transit
	X1	X2	X3	X4	X5	
Y1	4.00	2.60	8.60	8.30	16.60	P2
Y2	2.01	2.60	0.00	0.00	0.00	P2
Y3	4.00	2.60	8.60	2.94	0.00	P2
Y4	4.00	2.60	2.06	0.00	16.60	P2
Y5	4.00	2.60	8.60	4.28	0.00	P5
Y6	2.65	2.60	0.00	0.00	0.00	P5
Y7	4.00	2.60	8.60	8.30	16.60	P6

Y1 represents the result of the optimization process that HOV decision variable values of X1, X2, X3, X4, and X5 equal to 4, 2.6, 8.6, 8.3, and 16.6; also the result of rail transit decision variable values of P1, P2, P3, P4, P5, and P6 equal to 0, 1, 0, 0, 0, and 0.

Based on the decision variable values generated in Table 9, the objective values (Z1, Z2, Z3, Z4, and Z5) for each alternative are shown in Table 10. To show the relative importance of its objective values, the objective values are transformed (as shown in Table 11) into a 0-to-1 (Z_p*) scale using the equation below. This shows their relative importance or utility in graphical format.

$$Z_p^* = \{Z_p - Z_p(min)\}/ \{Z_p(max) - Z_p(min)\}$$

The relative importance value of objective 1 (Z1*) for alternative Y1 is:

$$Z_1^* = \{7666830000 - 5416915000\}/ \{9294426400 - 5416915000\} = 0.58$$

Table 10. Objective Value of Generated Solution of Capital Beltway Corridor

Project Alternative	Objective				
	Z_1 (min cost)	Z_2(max annual ridership)	Z_3(max daily new ridership)	Z_4(max public support)	Z_5(max economic development)
Y1	7666830000.0	68183307.3	81035.6	27.9	32.5
Y2	7666830000.0	60954471.3	61376.5	21.1	21.9
Y3	7666830000.0	64630147.7	74572.9	24.7	27.4
Y4	9294426400.0	63682935.7	68904.4	24.8	27.4
Y5	5416915000.0	64989685.3	79309.7	24.4	27.4
Y6	5416915000.0	61433500.7	66446.4	20.8	21.9
Y7	7666830000.0	68183307.3	81035.6	27.9	32.5

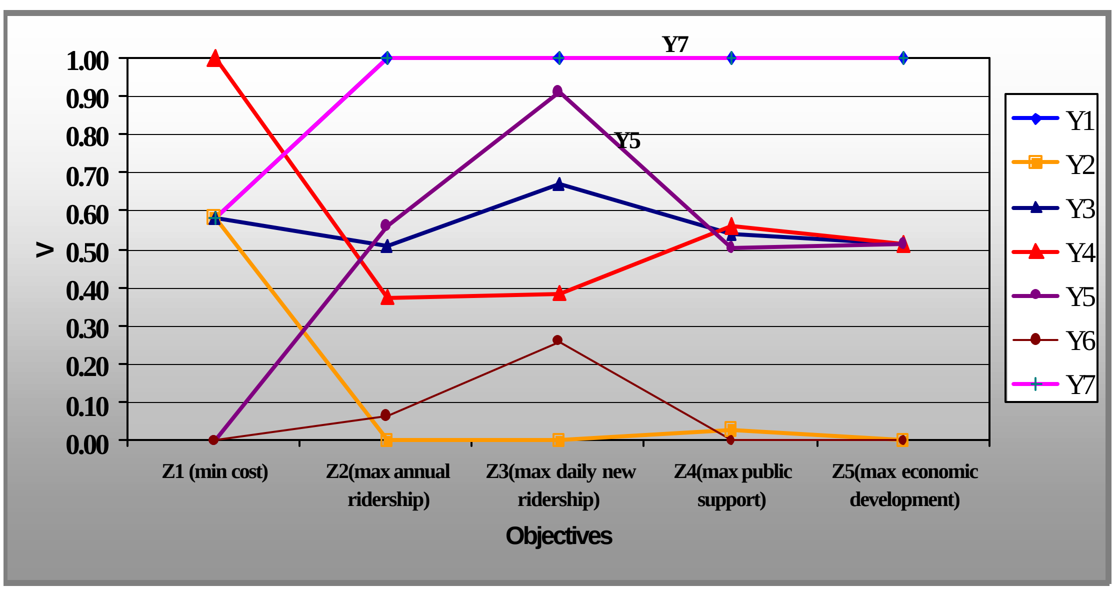
Table 11. Objective Value Scale of Capital Beltway Corridor

Project Alternative	Objective				
	$Z_{1\ (min)}$	$Z_{2(max)}$	$Z_{3(max)}$	$Z_{4(max)}$	$Z_{5(max)}$
Y1	0.58	1.00	1.00	1.00	1.00
Y2	0.58	0.00	0.00	0.03	0.00
Y3	0.58	0.51	0.67	0.54	0.51
Y4	1.00	0.38	0.38	0.56	0.51
Y5	0.00	0.56	0.91	0.51	0.51
Y6	0.00	0.07	0.26	0.00	0.00
Y7	0.58	1.00	1.00	1.00	1.00

The values were used to plot a value path graph (shown in Figure 7). From this value path graph, the highest value of the i^{th} objective is the one that has the value of 1 and the lowest value is shown as 0. For example, alternative Y4 has the highest cost compared to other alternatives but its public support score is third highest among other alternatives, and third lowest annual and new daily ridership. Alternative Y6 has the lowest cost but has the second lowest annual and daily new ridership.

The analyst can leave the final choice to the decision maker who can choose a solution from the set of optimal solutions presented in this step. Alternatively, the analyst can guide the decision maker to a solution by presenting tradeoffs between different objective functions and assessing the desired weights. This interactive process presents the tradeoff to the decision maker and allows assessment of weights assigned to tradeoffs.

Figure 7. Utility Objective Value of Capital Beltway Corridor in Value Path Graph



Step 5

Tradeoff analysis as part of Surrogate Worth Tradeoff Method involves the following tasks:

Generate Tradeoff Value

As part of the SWT method, a tradeoff evaluation between objectives is needed to choose the preferred solution among the seven generated alternatives (Y1, Y2, …,Y7). These values were based on the objective values from generated alternatives shown in Table 10. The analyst presents the tradeoff values between different alternatives to help the decision maker select an alternative. The tradeoff value is obtained from the public support value divided by the difference of the other objective value (Table 12). The value can be negative or positive. A positive value means that by increasing the primary objective, in this case public support, the other objective will increase. A negative value means that by increasing the primary objective, the other objective will decrease.

In the example of the tradeoff value for project Y2/Y1, if the score of public opinion (Z_4) increases by 0.95, the annual ridership (Z_2) will also increase to 1,000,000 riders. For project Y3/Y4, if the score of public support (Z_4) increases by 0.17, the annual ridership (Z_2) will decrease to 1,000,000 riders. The ~symbol means that a tradeoff between two objectives is not influenced by another particular objective.

Table 12. Tradeoff Value of Capital Beltway Corridor

Project	?$_{4,1}$/10^8	?$_{4,2}$/10^6	?$_{4,3}$/10^3	?$_{4,5}$
Y2/Y1	~	0.95	0.35	1.55
Y3/Y1	~	0.92	0.51	0.64
Y4/Y1	-0.19	0.69	0.26	0.60
Y5/Y1	0.16	1.10	2.03	0.68
Y6/Y1	0.31	1.05	0.48	0.67
Y2/Y3	~	0.97	0.27	0.66
Y2/Y4	0.23	1.37	0.50	0.69
Y2/Y5	-0.15	0.83	0.19	0.61
Y2/Y6	0.10	-0.47	-0.04	~
Y2/Y7	0.45	0.95	0.35	0.65
Y3/Y4	0.01	-0.17	-0.03	~
Y5/Y3	0.01	-0.65	-0.05	~
Y6/Y3	0.17	1.19	0.47	0.70
Y3/Y7	0.23	0.92	0.51	0.64
Y5/Y4	0.01	-0.30	-0.04	~
Y6/Y4	0.10	1.76	1.61	0.73
Y4/Y7	-0.19	0.69	0.26	0.60
Y6/Y5	~	1.00	0.28	0.66
Y5/Y7	~	1.10	2.03	0.68
Y6/Y7	~	1.05	0.48	0.67

For example, in project Y2/Y3, public support of (Z_4) alternative Y2 can increase from 21.1 to 24.7, but the cost (Z_5) will be the same at $766,683,000.

Interact with Decision Maker to Get Worth Values (W_{ij})
A regression analysis was done to develop the relationship between objective tradeoff value and worth values based on decision maker opinion (which is Facilitated by question-and-answer process between the analysis and decision maker) as presented in Appendix E.

Step 6
The final stage of this decision scenario is to select the preferred solution based on alternatives with an average value of decision maker weight, W, closest to zero. Table 18 shows that alternatives Y5 and Y7 have a tradeoff value closest to zero, 0.26. As a result, the decision maker can select either Y5 or Y7 based on preference. Compromises must be made when choosing one of those alternatives, but both are the best alternatives given.

Table 13. Worth Value for Capital Beltway Corridor

Project	$W_{4,1}$	$W_{4,2}$	$W_{4,3}$	$W_{4,5}$	Average W
Y2/Y1	~	-5.194	-3.184	3.793	-1.528
Y3/Y1	~	-5.445	-2.659	-0.293	-2.799
Y4/Y1	-2.240	-7.208	-3.473	-0.440	-3.340
Y5/Y1	-5.437	-3.676	4.542	-0.083	-1.164
Y6/Y1	-6.367	-4.192	-2.730	-0.141	-3.358
Y2/Y3	~	-4.942	-3.426	-0.192	-2.853
Y2/Y4	-5.914	-0.184	-2.688	-0.053	-2.210
Y2/Y5	-2.714	-6.212	-3.680	-0.390	-3.249
Y2/Y6	-5.041	-6.670	-4.316	~	-5.342
Y2/Y7	-6.893	-5.194	-3.184	-0.241	-3.878
Y3/Y4	-4.289	-8.333	-4.275	~	-5.632
Y5/Y3	-4.292	-5.261	-4.327	~	-4.627
Y6/Y3	-5.530	-2.574	-2.787	0.002	-2.722
Y3/Y7	-5.916	-5.445	-2.659	-0.293	-3.578
Y5/Y4	-4.291	-7.748	-4.299	~	-5.446
Y6/Y4	-5.051	6.333	2.207	0.140	0.907
Y4/Y7	-2.240	-7.208	-3.473	-0.440	-3.340
Y6/Y5	~	-4.633	-3.405	-0.196	-2.745
Y5/Y7	~	-3.676	4.542	-0.083	0.261
Y6/Y7	~	-4.192	-2.730	-0.141	-2.355

A.3 Sensitivity Analysis

The research team conducted a sensitivity analysis for the Capital Beltway Corridor project. The sensitivity analyses change different values for constraint (ε_k) based on the objectives (k). The criteria of the correlation coefficients are shown in Tables 14 through 17. Some variation in the input parameter values was determined based on the maximum and minimum range value (see Table 18) to measure the effect of a change on the outcome. The result of this analysis shows that economic development has the strongest correlation output (r=1). This model is sensitive to economic development criteria.

Table 14. Correlation Coefficients Between Total Cost Criteria and Public Support

Sample No.	Total Cost (xi1)	Total Support	(xi1 - x1)	(yi - y)	(xi1 – x1)(yi -y)	$(xi1 - x1)^2$	$(yi - y)^2$
1	$5,416,915,000.00	20.85	-2249915000	-3.68	8280811715	5.06212E+18	13.55
2	$7,666,830,000.00	21.07	0	-3.45	0	0	11.93
3	$9,916,745,000.00	21.18	2249915000	-3.34	-7519318871	5.06212E+18	11.17
4	$5,416,915,000.00	24.42	-2249915000	-0.11	242239704.2	5.06212E+18	0.01
5	$7,666,830,000.00	24.65	0	0.12	0	0	0.02
6	$9,916,745,000.00	24.81	2249915000	0.29	645372673.8	5.06212E+18	0.08
7	$5,416,915,000.00	27.50	-2249915000	2.97	-6692979396	5.06212E+18	8.85
8	$7,666,830,000.00	27.92	0	3.39	0	0	11.50
9	$9,916,745,000.00	28.33	2249915000	3.81	8565073474	5.06212E+18	14.49
Total					3521199300	5511143715	8.46

Total Cost Average (x1)

= $7,666,830,000.00

Total Support Average (y)

= 24.53

$r_{x1,y}$ = 0.08

Table 15. Correlation Coefficients Between Annual Ridership and Public Support

Sample No.	Annual Ridership (xi2)	Total Support	(xi1 – x1)	(yi - y)	(xi1 - x1)(yi - y)	$(xi1 - x1)^2$	$(yi - y)^2$
1	66,963,405.47	20.85	-6434461.067	-3.68	23682032.69	4.14023E+13	13.55
2	73,397,866.53	20.85	-7593432133	-3.68	27947625474	5.76602E+19	13.55
3	79,832,327.60	20.85	-7586997672	-3.68	27923943442	5.75625E+19	13.55
4	66,963,405.47	21.07	-7599866595	-3.45	26244579649	5.7758E+19	11.93
5	73,397,866.53	21.07	-7593432133	-3.45	26222359558	5.76602E+19	11.93
6	79,832,327.60	21.07	-7586997672	-3.45	26200139467	5.75625E+19	11.93
7	66,963,405.47	21.18	-7599866595	-3.34	25399101876	5.7758E+19	11.17
8	73,397,866.53	21.18	-7593432133	-3.34	25377597613	5.76602E+19	11.17
9	79,832,327.60	21.18	-7586997672	-3.34	25356093350	5.75625E+19	11.17
10	66,963,405.47	24.42	-7599866595	-0.11	818248438.5	5.7758E+19	0.01
11	73,397,866.53	24.42	-7593432133	-0.11	817555664.8	5.76602E+19	0.01
12	79,832,327.60	24.42	-7586997672	-0.11	816862891.1	5.75625E+19	0.01
13	66,963,405.47	24.65	-7599866595	0.12	-944236471.3	5.7758E+19	0.02
14	73,397,866.53	24.65	-7593432133	0.12	-943437029.3	5.76602E+19	0.02
15	79,832,327.60	24.65	-7586997672	0.12	-942637587.3	5.75625E+19	0.02
16	66,963,405.47	24.81	-7599866595	0.29	-2179969565	5.7758E+19	0.08
17	73,397,866.53	24.81	-7593432133	0.29	-2178123884	5.76602E+19	0.08
18	79,832,327.60	24.81	-7586997672	0.29	-2176278204	5.75625E+19	0.08
19	66,963,405.47	27.50	-7599866595	2.97	-22607854311	5.7758E+19	8.85
20	73,397,866.53	27.50	-7593432133	2.97	-22588713270	5.76602E+19	8.85
21	79,832,327.60	27.50	-7586997672	2.97	-22569572229	5.75625E+19	8.85
22	66,963,405.47	27.92	-7599866595	3.39	-25769677145	5.7758E+19	11.50
23	73,397,866.53	27.92	-7593432133	3.39	-25747859132	5.76602E+19	11.50
24	79,832,327.60	27.92	-7586997672	3.39	-25726041120	5.75625E+19	11.50
25	66,963,405.47	28.33	-7599866595	3.81	-28931499978	5.7758E+19	14.49
26	73,397,866.53	28.33	-7593432133	3.81	-28907004994	5.76602E+19	14.49
27	79,832,327.60	28.33	-7586997672	3.81	-28882510010	5.75625E+19	14.49
Total					-27947625474	38717806326	14.65

Total Annual Cost (x2)

= $73,397,866.53

Total Support Average (y)

= 24.53

$r_{x2,y}$ = -0.05

Table 16. Correlation Coefficients Between Daily New Ridership Criteria and Public Support

Sample No.	Daily New Ridership(xi3)	Total Support	(xi1 - x1)	(yi – y)	(xi1 - x1)(yi - y)	$(xi1 - x1)^2$	$(yi - y)^2$
1	74,298.97	20.85	-7612.066667	-3.68	28016.20987	57943558.94	13.55
2	74,298.97	21.07	-7612.066667	-3.45	26286.71009	57943558.94	11.93
3	74,298.97	21.18	-7612.066667	-3.34	25439.87508	57943558.94	11.17
4	81,911.03	20.85	0	-3.68	0	0	13.55
5	81,911.03	21.07	0	-3.45	0	0	11.93
6	81,911.03	21.18	0	-3.34	0	0	11.17
7	89,523.10	20.85	7612.066667	-3.68	-28016.20987	57943558.94	13.55
8	89,523.10	21.07	7612.066667	-3.45	-26286.71009	57943558.94	11.93
9	89,523.10	21.18	7612.066667	-3.34	-25439.87508	57943558.94	11.17
10	74,298.97	24.42	-7612.066667	-0.11	819.5619734	57943558.94	0.01
11	74,298.97	24.65	-7612.066667	0.12	-945.7522549	57943558.94	0.02
12	74,298.97	24.81	-7612.066667	0.29	-2183.469072	57943558.94	0.08
13	81,911.03	24.42	0	-0.11	0	0	0.01
14	81,911.03	24.65	0	0.12	0	0	0.02
15	81,911.03	24.81	0	0.29	0	0	0.08
16	89,523.10	24.42	7612.066667	-0.11	-819.5619734	57943558.94	0.01
17	89,523.10	24.65	7612.066667	0.12	945.7522549	57943558.94	0.02
18	89,523.10	24.81	7612.066667	0.29	2183.469072	57943558.94	0.08
19	74,298.97	27.50	-7612.066667	2.97	-22644.14672	57943558.94	8.85
20	74,298.97	27.92	-7612.066667	3.39	-25811.04523	57943558.94	11.50
21	74,298.97	28.33	-7612.066667	3.81	-28977.94374	57943558.94	14.49
22	81,911.03	27.50	0	2.97	0	0	8.85
23	81,911.03	27.92	0	3.39	0	0	11.50
24	81,911.03	28.33	0	3.81	0	0	14.49
25	89,523.10	27.50	7612.066667	2.97	22644.14672	57943558.94	8.85
26	89,523.10	27.92	7612.066667	3.39	25811.04523	57943558.94	11.50
27	89,523.10	28.33	7612.066667	3.81	28977.94374	57943558.94	14.49
Total					0	32295.26375	14.65

Total Daily New Ridership (x3)

= $81,911.03

Total Support Average (y)

= 24.53

$r_{x3,y}$ = 0.00

Table 17. Correlation Coefficients Between Economic Development Criteria and Public Support

Sample No.	Daily New Ridership(xi5)	Total Support	(xi1 - x1)	(yi – y)	(xi1 - x1)(yi - y)	$(xi1 - x1)^2$	$(yi - y)^2$
1	21.94	20.85	-5.44	-3.68	20.03	29.62	13.55
2	21.94	21.07	-5.44	-3.45	18.79	29.62	11.93
3	21.94	21.18	-5.44	-3.34	18.19	29.62	11.17
4	27.39	24.42	0.00	-0.11	0.00	0.00	0.01
5	27.39	24.65	0.00	0.12	0.00	0.00	0.02
6	27.39	24.81	0.00	0.29	0.00	0.00	0.08
7	32.83	27.50	5.44	2.97	16.19	29.62	8.85
8	32.83	27.92	5.44	3.39	18.45	29.62	11.50
9	32.83	28.33	5.44	3.81	20.72	29.62	14.49
Total					112.39	13.33	8.46

Total Economic Development (x5)

= 27.39

Total Support Average (y)

= 24.53

$r_{x5,y}$ = 1.00

(strongest correlation)

The sensitivity analysis showed that economic development was the most sensitive parameter. Any changes in economic development may change the optimal set of alternatives.

Table 18. Range Value of All Criteria

Constraint	Selected Constraint Values		
L_1	$5,416,915,000.00	$7,666,830,000.00	$9,916,745,000.00
L_2	66,963,405.47	73,397,866.53	79,832,327.60
L_3	74,298.97	81,911.03	89,523.10
L_5	21.94	27.39	32.83

APPENDIX B

OHIO RIVER BRIDGE PROJECT

B. OHIO RIVER BRIDGE PROJECT (BY SWT METHOD)

B.1 Project Description

The study location is between Jefferson County, Kentucky and Clark County, Indiana. Several specific factors were used to demonstrate the need for action, including: existing conditions; planned population growth and employment in the downtown area, eastern Jefferson, and southeastern Clark counties; traffic congestion on the Kennedy Bridge on Ohio River in the I-65 corridor (connecting Indiana and Kentucky over Ohio River) and in the Kennedy interchange; and traffic safety problems in the interchange and on the bridge. Bridge/highway alternatives considered included reconstruction of the Kennedy interchange, constructing one or two new bridges with several alignment options across the Ohio River; and a combination of these improvements. If no bridge is built, traffic on the three existing bridges will increase 40 percent by 2025. As a result, all existing bridges would be over capacity. Employment in the area is projected to increase 54 percent from 555,000 to 860,000. Population is projected to increase 29 percent from 880,000 to 1.14 million. This study used the SWT method to recommend alternatives that would improve regional mobility, reduce traffic congestion, and increase traffic safety in eastern Jefferson and southeastern Clark counties.

Figure 8 shows the general decision making framework with the shaded portion representing the steps that were applied in the case study. This case study involved a discrete scenario where 27 alternatives were evaluated. These alternatives were identified in Step 7. As the number of alternatives was large (more than 8), a screening process was adopted to reduce the number of alternatives. Steps 3 through 6 were followed to reduce the number of alternatives and select an optimal alternative.

B.2 Problem Solving

Step 1

The objectives of Ohio River Bridge project are to:

A. Improve regional mobility and address existing and planned growth in population and employment in the downtown area, in eastern Jefferson, and southeastern Clark counties.

B. Reduce traffic congestion on the Kennedy Bridge and in the Kennedy Interchange.

C. Solve traffic safety problems in the Kennedy Interchange and on the Kennedy Bridge and its approach roadways.

Step 2

The following impact categories (MOEs) were identified to be analyzed:

1. Vehicle miles of travel (VMT)

2. Vehicle hours of travel (VHT)
3. Vehicle hours of delay (VHD)
4. Volume to capacity ratios (v/c)
5. Level of service at Kennedy
6. Level of service at Sherman
7. Level of service at Clark
8. Traffic safety
9. Local plan compatibility
10. Noise - Number of sites exceeding noise area classification (NAC)
11. Acres of terrestrial wildlife/habitat impacted
12. Number of residential displacements
13. Capital cost

The problems addressed in this case study involve selecting of the best alternatives from the finite set of alternatives.

Step 7

The project alternatives were developed from different combinations of alignments. The following combinations were considered:

1. Build one bridge/highway alternative (see Figures 9 and 10). This includes reconstructing of the Kennedy interchange and adding of a new river crossing in either the far east (A-2, A-9, A-13, A-15, A-16), near east (B-1), or downtown (C-1, C-2, C-3) corridors. In addition, this alternative includes Transportation Demand Management (TDM), Transportation System Management (TSM), and Mass Transit components of the Transportation Management (TM) Alternative.

2. Build two bridges/highway alternative. This includes reconstructing of the Kennedy Interchange and adding of two new river crossings, with one in the downtown corridor and one in either the far east or near east corridor. In addition, this alternative includes the TDM, TSM, and Mass Transit components of the TM Alternative.

A total of 27 predetermined alternatives (Xi, i = 1,2,…,27) were investigated. The impact of each alternative was quantified for all 13 MOE criteria (see Table 19). The number of alternatives is quite high (the usual manageable number of alternatives is less than eight), so the screening process using optimization method (Step 3 through Step 6) was done in this case. As explained before, the screening process is used to compare the alternatives on the basis of which alternative would best solve the problem.

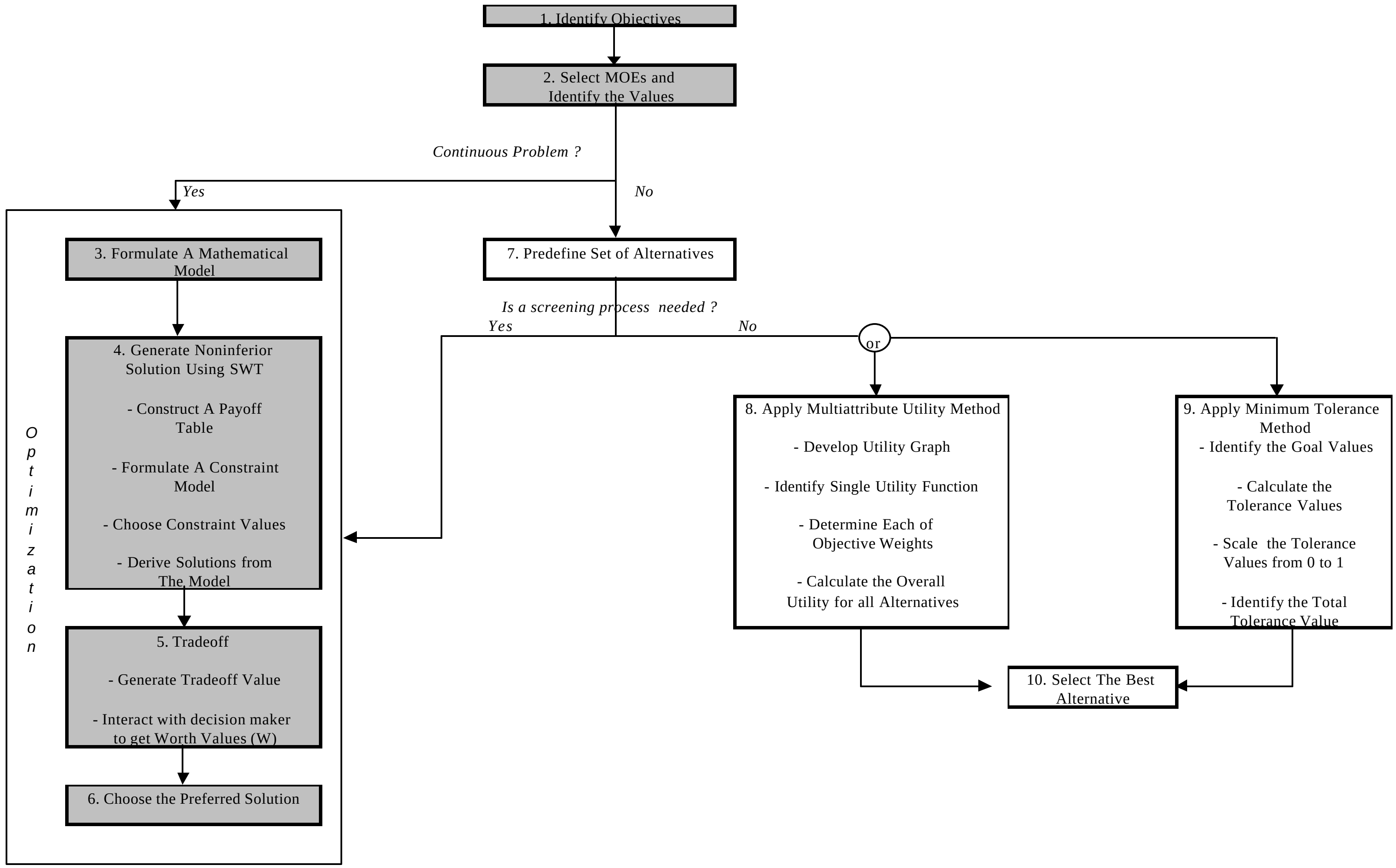


Figure 8 Decision Making Framework for Ohio River Bridge Project
(Shaded areas show the steps that were applied in this case study)

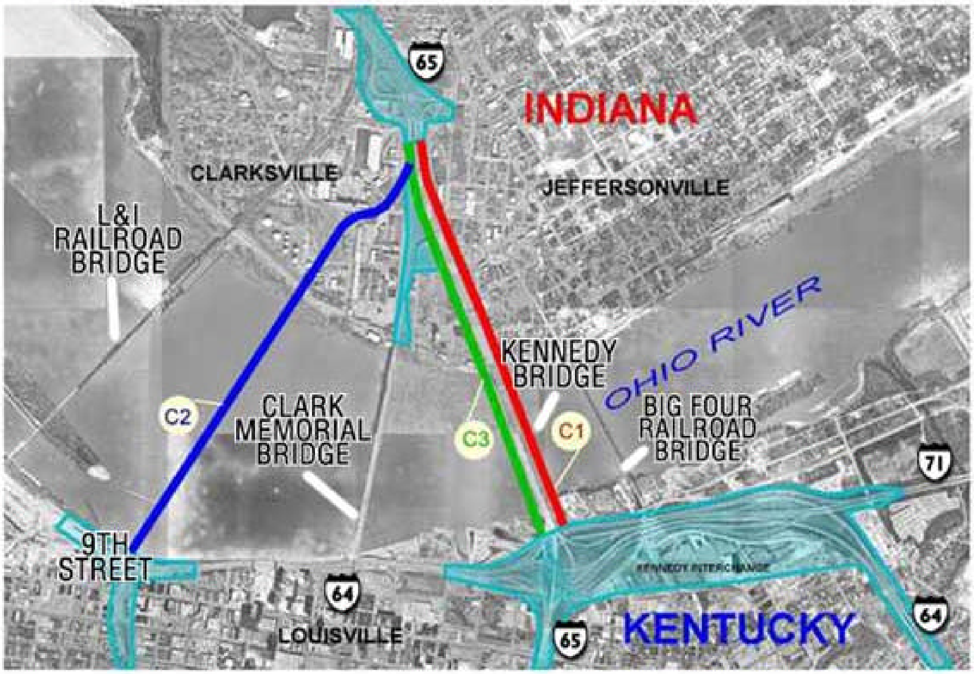


Figure 9. Three Downtown Bridge Locations

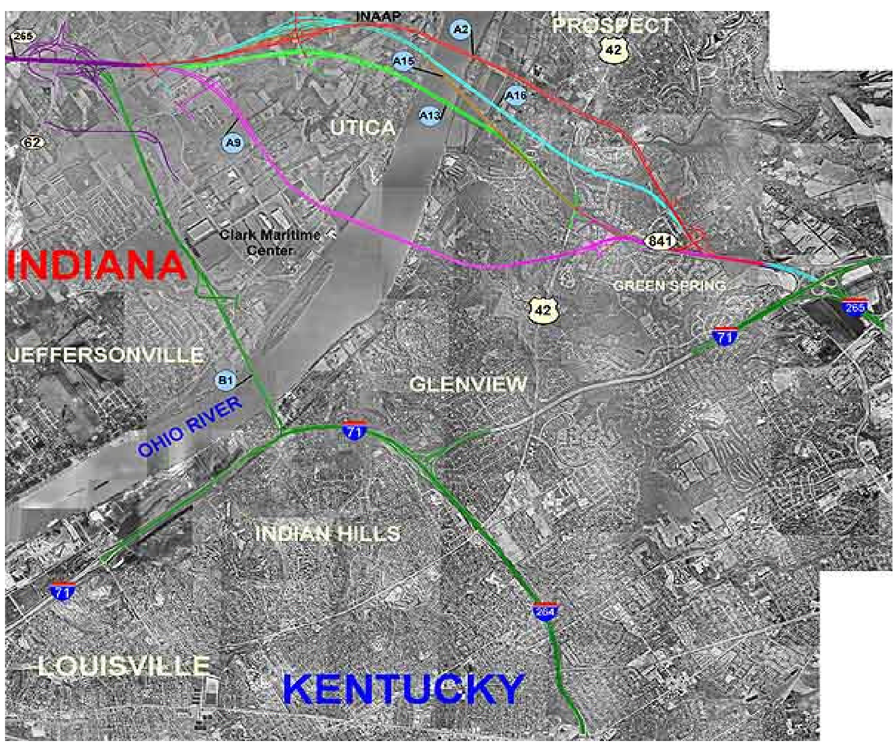


Figure 10. Six Bridge and Highway Alignments in Eastern Jefferson and Clark Counties

The screening process was done by the SWT method to help the decision maker narrow the list of alternatives to identify the optimal solution. The screening process used the categories of measures determined before including vehicle miles of travel, vehicle hours of travel, and vehicle hours of delay.

Step 3

Formulate Mathematical Model

The decision variable in this model represents a “yes” or “no” decision on a set of predefined alternatives. The decision variables are in binary form (1 or 0) in which 1 represents a “yes” decision and 0 represents a “no” decision. The decision making is related to the question: “should a certain project alternative (Xi, i = 1,2,…,27) be chosen?”

$$X_i = \begin{cases} 1 & \text{if a project i is selected, i = 1,2,…,27} \\ 0 & \text{if not} \end{cases}$$

The objectives would be to:

1. Minimize vehicle miles of travel (VMT), Z_1
2. Minimize vehicle hours of travel (VHT), Z_2
3. Minimize vehicle hours of delay (VHD), Z_3
4. Minimize the volume to capacity ratios (v/c), Z_4
5. Maximize the level of service at Kennedy, Z_5
6. Maximize the level of service at Sherman, Z_6
7. Maximize the level of service at Clark, Z_7
8. Maximize traffic safety, Z_8
9. Maximize local time compatibility, Z_9
10. Minimize noise - number of sites exceeding NAC, Z_{10}
11. Minimize acres of terrestrial wildlife/ habitat impacted, Z_{11}
12. Minimize number of residential displacements, Z_{12}
13. Minimize capital cost, Z_{13}

Table 19. Measured Effectiveness Value of Ohio River Bridge

Alternatives				Population and Employment Growth % Change			Total River	Traffic Congestion Bridge Level of Service*			Traffic Safety**	Local Plan Compatibility	Capital Cost $M
				VMT	VHT	VHD	V/C	Kennedy	Sherman	Clark			
One Bridge	A-2	X_1	0	0	-3	-14	0.98	1	1	3	1	1	1016.1
	A-9	X_2	0	0	-3	-14	0.98	1	1	3	1	1	1173.2
	A-13	X_3	0	0	-3	-14	0.98	1	1	3	1	1	1080.5
	A-15	X_4	0	0	-3	-14	0.98	1	1	3	1	1	1104
	A-16	X_5	0	0	-3	-14	0.98	1	1	3	1	1	1077.9
	B-1	X_6	0	0	-3	-13	0.98	2	1	3	1	1	1286.7
	C-1	X_7	1	0	-2	-9	1	2	1	3	2	1	934.9
	C-2	X_8	0	0	-2	-8	1.06	1	1	3	1	1	1197.3
	C-3	X_9	0	0	-2	-9	1	2	1	3	2	1	943
Two Bridges	A-2 and C-1	X_{10}	0	-1	-6	-22	0.78	3	1	4	2	1	1311.8
	A-2 and C-2	X_{11}	0	-1	-6	-22	0.81	2	1	4	1	1	1574.2
	A-2 and C-3	X_{12}	0	-1	-6	-22	0.78	3	1	4	2	1	1319.9
	A-9 and C-1	X_{13}	0	-1	-6	-22	0.78	3	1	4	2	1	1468.9
	A-9 and C-2	X_{14}	0	-1	-6	-22	0.81	2	1	4	1	1	1731.3
	A-9 and C-3	X_{15}	0	-1	-6	-22	0.78	3	1	4	2	1	1477
	A-13 and C-1	X_{16}	0	-1	-6	-22	0.78	3	1	4	2	1	1376.2
	A-13 and C-2	X_{17}	0	-1	-6	-22	0.81	2	1	4	1	1	1638.6
	A-13 and C-3	X_{18}	0	-1	-6	-22	0.78	3	1	4	2	1	1384.3
	A-15 and C-1	X_{19}	0	-1	-6	-22	0.78	3	1	4	2	1	1399.7
	A-15 and C-2	X_{20}	0	-1	-6	-22	0.81	2	1	4	1	1	1662.1
	A-15 and C-3	X_{21}	0	-1	-6	-22	0.78	3	1	4	2	1	1407.8
	A-16 and C-1	X_{22}	0	-1	-6	-22	0.78	3	1	4	2	1	1373.6
	A-16 and C-2	X_{23}	0	-1	-6	-22	0.81	2	1	4	1	1	1636
	A-16 and C-3	X_{24}	0	-1	-6	-22	0.78	3	1	4	2	1	1381.7
	B-1 and C-1	X_{25}	0	0	-5	-18	0.79	3	1	4	2	1	1582.4
	B-1 and C-2	X_{26}	0	-1	-5	-19	0.81	2	1	4	1	1	1844.8
	B-1 and C-3	X_{27}	0	0	-5	-18	0.79	3	1	4	2	1	1590.5

Note:
*) LOS was scored from 1 to 5 to represent E to A
**) Safety was scored by 1 and 2 to represent medium and high impact

Table 19. Measured Effectiveness Value of Ohio River Bridge (*Continued)*

Alternatives			**Noise**	**Wildlife/Habitat Impacted Acres**	**Number of Residential Displacements**
One Bridge	A-2	X_1	14	280	39
	A-9	X_2	23	200	33
	A-13	X_3	30	196	42
	A-15	X_4	30	208	34
	A-16	X_5	18	296	35
	B-1	X_6	16	259	252
	C-1	X_7	6	39	115
	C-2	X_8	9	37	21
	C-3	X_9	4	39	160
Two Bridges	A-2 and C-1	X_{10}	20	319	154
	A-2 and C-2	X_{11}	23	317	60
	A-2 and C-3	X_{12}	18	319	199
	A-9 and C-1	X_{13}	29	239	148
	A-9 and C-2	X_{14}	32	237	54
	A-9 and C-3	X_{15}	27	239	193
	A-13 and C-1	X_{16}	36	235	157
	A-13 and C-2	X_{17}	39	233	63
	A-13 and C-3	X_{18}	34	235	202
	A-15 and C-1	X_{19}	36	247	149
	A-15 and C-2	X_{20}	39	245	55
	A-15 and C-3	X_{21}	34	247	194
	A-16 and C-1	X_{22}	24	335	150
	A-16 and C-2	X_{23}	27	333	56
	A-16 and C-3	X_{24}	22	335	195
	B-1 and C-1	X_{25}	22	298	367
	B-1 and C-2	X_{26}	25	296	273
	B-1 and C-3	X_{27}	20	298	412

$$Z_1 = \sum_{i=1}^{27} X_i * C_{i1} \quad , C_{ij}\text{= Effect of alternative i associated with criteria j}$$

$$Z_2 = \sum_{i=1}^{27} X_i * C_{i2}$$

.
.
.

$$Z_{13} = \sum_{i=1}^{27} X_i * C_{i13}$$

Constraint:

$$\sum_{i=1}^{27} X_i = 1$$

Since only one project will be selected, the summation of decision variable is set to 1 (i.e., $\sum_{i=1}^{27} X_i = 1$)

Step 4

Generate a non-dominated solution using the SWT method, using the following tasks:

Construct a Payoff Table

Each objective is optimized individually, as shown in Table 20. The What's*Best!* 5.0 solver was used to solve these optimizations. The table shows the range of minimum and maximum values for each objective.

Formulate a Constraint Model

The second step is transforming a multiobjective problem into a single objective problem using the Constraint Method. In this case, the minimized volume by capacity ratio objective (Z4) is chosen as a primary objective and all other objectives (Z1, Z2, Z3, Z5, …, Z13) are transformed as constraints, as shown below:

$$\text{Minimize V/C, } Z_4 = \sum_{i=1}^{27} X_i * C_{i4}$$

Subject to

$$Z_2 = \sum_{i=1}^{27} X_i * C_{i2} \leq L_2$$

.

.

$$Z_{13} = \sum_{i=1}^{27} X_i * C_{i13} \leq L_{13}$$

Choose Constraint Values

In Step 3, the range of the right-hand side or constraint value (L) is established as shown in Table 21. The L values are chosen from different values of the range of minimum and maximum for objectives 1, 2, 3,…,13 from the payoff table (Table 20). By selecting a different combination of L values from Table 21 the non-dominated solutions generated will represent different satisfaction levels.

Derive Solutions from the Models

The final step is solving the constraint problem by minimizing V/C ratio, Z4, subject to all objective constraints for every combination (L_1, L_2, L_3, L_5,…L_{13}). The model was solved by running optimization software, What's*Best!* 5.0, for 32 runs with each run having different combinations of objective constraint values. The result of the optimization process will show that $X_j = 1$, when project i is selected and $X_j = 0$, when Project i is not selected.

Table 20. Payoff Table Ohio River Bridge

	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	Z_{11}	Z_{12}	Z_{13}
X_1	-1	-5	-19	0.81	2	1	4	1	1	25	296	273	1844.8
X_2	-1	-6	-22	0.78	3	1	4	2	1	22	335	195	1381.7
X_3	-1	-6	-22	0.78	3	1	4	2	1	22	335	195	1381.7
X_4	-1	-6	-22	0.78	3	1	4	2	1	22	335	195	1381.7
X_5	0	-5	-18	0.79	3	1	4	2	1	20	298	412	1590.5
X_6	0	-3	-14	0.98	1	1	3	1	1	23	200	33	1173.2
X_7	0	-5	-18	0.79	3	1	4	2	1	20	298	412	1590.5
X_8	0	-5	-18	0.79	3	1	4	2	1	20	298	412	1590.5
X_9	0	-3	-14	0.98	1	1	3	1	1	23	200	33	1173.2
X_{10}	0	-2	-9	1	2	1	3	2	1	6	39	115	934.9
X_{11}	0	-2	-9	1	2	1	3	2	1	4	39	160	943
X_{12}	0	-2	-8	1.06	1	1	3	1	1	9	37	21	1197.3
X_{13}	0	-2	-8	1.06	1	1	3	1	1	9	37	21	1197.3
Min	-1	-6	-22	0.78	1	1	3	1	1	6	37	21	943
Max	0	-2	-9	1.06	3	1	4	2	1	25	335	412	1844.8

Table 21. Constraint Value of Ohio River Bridge

Constraint	Selected Constraint Values		
L_1	0		≤
L_2	-2		≤
L_3	-15.5	-9	≤
L_5	3		≤
L_6	1		≤
L_7	4		≤
L_8	2		≤
L_9	1		≤
L_{10}	15.5	25	≤
L_{11}	186	335	≤
L_{12}	216.5	412	≤
L_{13}	1394	1845	≤

The project selection generated by the software is shown in Table 22. The 27 predefined alternatives were reduced to 5 alternatives (X1, X7, X9, X12, X24).

To show the relative important of objective values for each alternative, the objective values were transformed into a 0-to-1 scale using the equation below. The result is shown in Table 23. The highest and the lowest objective values for each project alternative are presented in value path graph form (see Figure 11). Project X24 has the highest cost compared to other alternatives, but has the greatest impact in travel time reduction. Project X7 has the lowest impact in travel time and delay reduction but has the lowest cost.

$$Z_p^* = \{Z_p - Z_p(\min)\} / \{Z_p(\max) - Z_p(\min)\}$$

Table 22. Objective Value of Ohio River Bridge

Alternative	OBJECTIVE												
	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13 ($M)
Project X1	0	-3	-14	0.98	1	1	3	1	1	14	280	39	1016.1
Project X7	0	-2	-9	1	2	1	3	2	1	6	39	115	934.9
Project X9	-1	-2	-9	1	2	1	3	2	1	4	39	160	943
Project X12	-1	-6	-22	0.78	3	1	4	2	1	18	319	199	1319.9
Project X24	-1	-6	-22	0.78	3	1	4	2	1	22	335	195	1381.7

Table 23. The Objective Scale Value of Ohio River Bridge

Alternative	OBJECTIVE										
	Z1* (Min)	Z2* (Min)	Z3* (Min)	Z4* (Min)	Z5* (Max)	Z7* (Max)	Z8* (Max)	Z10* (Min)	Z11* (Min)	Z12* (Min)	Z13* (Min)
Project X1	1	0.75	0.61	0.9	0	0	0	0.55	0.81	0	0.18
Project X7	1	1	1	1	0.5	0	1	0.11	0	0.475	0
Project X9	0	1	1	1	0.5	0	1	0	0	0.75625	0.018
Project X12	0	0	0	0	1	1	1	0.77	0.94	1	0.86
Project X24	0	0	0	0	1	1	1	1	1	0.975	1

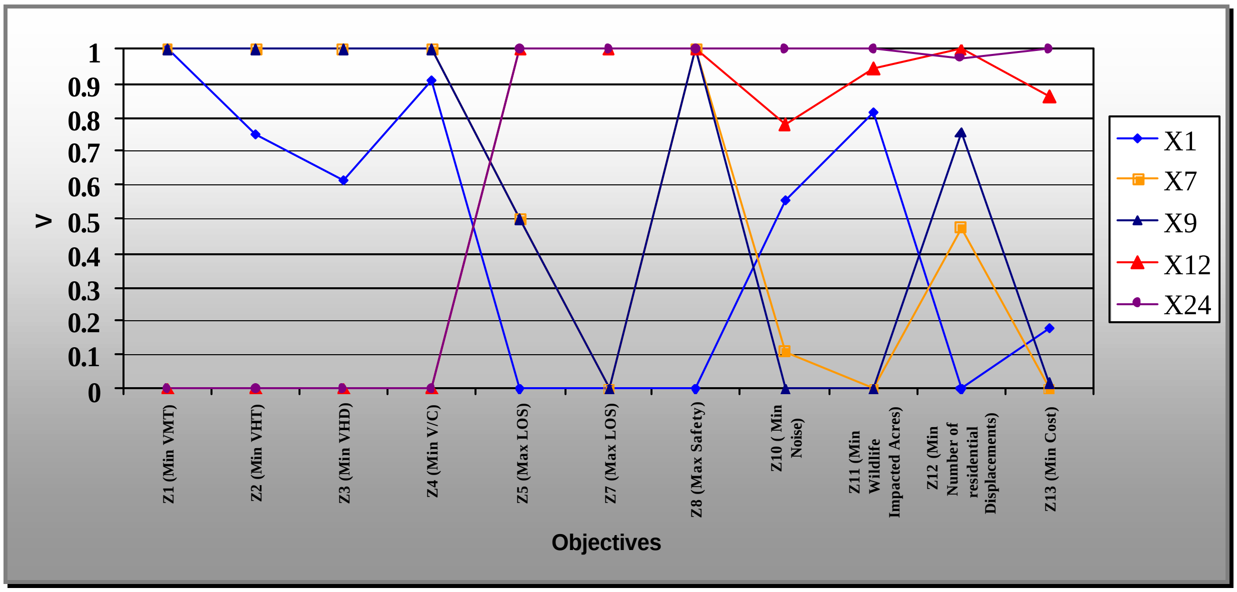


Figure 11. Utility Objective Values of Ohio River Bridge Shown in Value Path Graph

Step 5

The next stage is a tradeoff evaluation as part of Surrogate Worth Tradeoff Method to find the compromise (or preferred) solution as explained in the following tasks:

Generate Tradeoff Values

The tradeoff values are presented in Table 24. As mentioned before, the tradeoff values can be both negative and positive. In this case, the primary objective (Z_4) is to minimize the volume by capacity (v/c) ratio, so that a positive value means that a decrease in the primary objective will result in a decrease in the other objectives. A negative value means that by decreasing the primary objective, the other objective (constraint objective) will increase. For example, in project X7/X1, if the v/c (Z_4) decreases by 0.02, the vehicle hour travel (Z_2) will decrease by 1 unit. When the tradeoff between v/c (Z_4) and cost (Z_{13}) is considered, it shows that by decreasing the v/c by 0.02, the cost increases by 100 million units. A tradeoff value of zero means that v/c (Z4) can never increase and will have the same value of zero regardless of whether the other objective changes.

Interact with Decision Maker to get Worth Value (W_{ij})

This task is done by interacting directly with the decision maker. In this study, the author acted as decision maker to get worth values for each tradeoff activity through regression analysis. Based on the tradeoff between two objectives, the decision maker's preference (in terms of weight between –10 to +10, where –10 represents non preference towards the change of λij unit objective i, Zi and 1 unit of Zj, +10 represents the most preference at the change of λij unit objective i, Zi, and 1 unit of Zj, and "0" represents an indifference between the objectives) is recorded. The regression graphs related to weight or worth and corresponding tradeoff values are presented in Appendix F.

Table 24. Tradeoff Value of Ohio River Bridge

Project	$?_{4,1}$	$?_{4,2}$	$?_{4,3}$	$?_{4,5}$	$?_{4,7}$	$?_{4,8}$	$?_{4,10}$	$?_{4,11}$	$?_{4,12}$	$?_{4,13}/100$
X7/X1	~	0.020	0.0040	0.020	~	0.020	-0.003	-0.00830	0.02632	-0.02463
X9/X1	~	0.020	0.0040	0.020	~	0.020	-0.002	-0.00830	0.01653	-0.02736
X1/X12	0.20	0.067	0.03	-0.100	-0.200	-0.200	-0.050	-0.51282	-0.12500	-0.06583
X1/X24	0.20	0.067	0.03	-0.100	-0.200	-0.200	-0.025	-0.36364	-0.12821	-0.05470
X7/X9	0.00	0.000	0.00	0.000	0.000	0.000	0.000	0.00	0.00	0.00
X7/X12	0.22	0.055	0.02	-0.220	-0.220	~	-0.018	-0.07857	-0.26190	-0.05714
X7/X24	0.22	0.055	0.02	-0.220	-0.220	~	-0.014	-0.07432	-0.27500	-0.04924
X9/X12	0.22	0.055	0.02	-0.220	-0.220	~	-0.016	-0.07857	-0.56410	-0.05837
X9/X24	0.22	0.055	0.02	-0.220	-0.220	~	-0.012	-0.07432	-0.62857	-0.05015
X12/X24	0.00	0.000	0.00	0.000	0.000	0.000	0.000	0.00	0.00	0.00

Table 25. Worth Value of Ohio River Bridge

Project	$W_{4,1}$	$W_{4,2}$	$W_{4,3}$	$W_{4,5}$	$W_{4,7}$	$W_{4,8}$	$W_{4,10}$	$W_{4,11}$	$W_{4,12}$	$W_{4,13}$	Average W
X7/X1	-	-2.84	-5.02	-5.87	-	-5.87	-7.00	-8.55	-8.77	-7.69	-6.45
X9/X1	-	-2.84	-5.02	-5.87	-	-5.87	-7.13	-8.55	-8.48	-7.61	-6.42
X1/X12	6.03	1.38	-4.05	-7.32	-5.35	-5.35	5.17	8.86	-4.45	-6.37	-1.15
X1/X24	6.03	1.38	-4.05	-7.32	-5.35	-5.35	-1.08	5.78	-4.36	-6.73	-2.11
X7/X9	-6.28	-4.40	-5.18	-6.40	-6.40	-6.40	-7.67	-9.00	-8.00	-8.50	-6.82
X7/X12	8.11	0.25	-4.44	-4.61	-4.61	-	-2.80	-4.94	-0.75	-6.65	-2.27
X7/X24	8.11	0.25	-4.44	-4.61	-4.61	-	-4.00	-5.14	-0.40	-6.90	-2.42
X9/X12	8.11	0.25	-4.44	-4.61	-4.61	-	-3.49	-4.94	6.77	-6.61	-1.51
X9/X24	8.11	0.25	-4.44	-4.61	-4.61	-	-4.40	-5.14	8.25	-6.87	-1.50
X12/X24	-6.28	-4.40	-5.18	-6.40	-6.40	-6.40	-7.67	-9.00	-8.00	-8.50	-6.82

Step 6

Finally, the decision maker chooses based on the pair of alternatives, which have an indifferent band of tradeoff values determined by searching for a worth value closest to zero. Alternatives X1 and X12 shown in Table 25 show worth values closest to zero. The choice between those two alternatives is left to the decision maker’s preference. X1 is the alternative of builds one bridge with alignment A-2; and X12 is the alternative for builds two bridges in alignments A-2 and C-3. The alignment locations can be seen in Figures 9 and 10.

APPENDIX C

PICKAWAY COUNTY (OHIO) RESURFACING PROBLEM

C. Pickaway County (Ohio) Resurfacing Problem (by Minimum Tolerance Method)

C.1 Project Description

ODOT District 6 faced resurfacing of Pickaway County (PIC) Routes 674, PIC-207, and PIC-138. Pickaway County residents suggested resurfacing PIC-674 sooner than what the PCR justified. PIC-674 is a commuter route used by residents working in Columbus. This route generates more complaints than other smaller volume roads in the county with lower PCRs. District 6 representatives could follow their stated priorities and resurface based on the lower PCR or choose the project with the highest public input. Relying on PCR, the first roads due for resurfacing would be PIC-207 and PIC-138.

This case study considered other criteria besides PCR, such as ADT (Average Daily Traffic), truck ADT, and total number of accidents for those routes, to prioritize projects. Figure 12 shows the general decision making framework with the shaded portion representing the steps that were applied in this case study. This case study involved a discrete scenario where three alternatives were evaluated, and identified in Step 7. The analyst had a choice between the Multiattribute Utility and Minimum Tolerance Methods to help decision maker select an alternative. In this case, the Minimum Tolerance Method (Step 9) was adopted.

C.2 Problem Solving

Step 1

The process is shown in the shaded area of Figure 12. The process starts by identifying the objective: to select the resurfacing projects needed to meet the District's goals.

Step 2

The next stage is identifying the MOEs. Four criteria are to be quantified:

- PCR (Pavement Condition Rating)
- ADT (Average Daily Traffic)
- Truck ADT
- Total number of accident in those routes

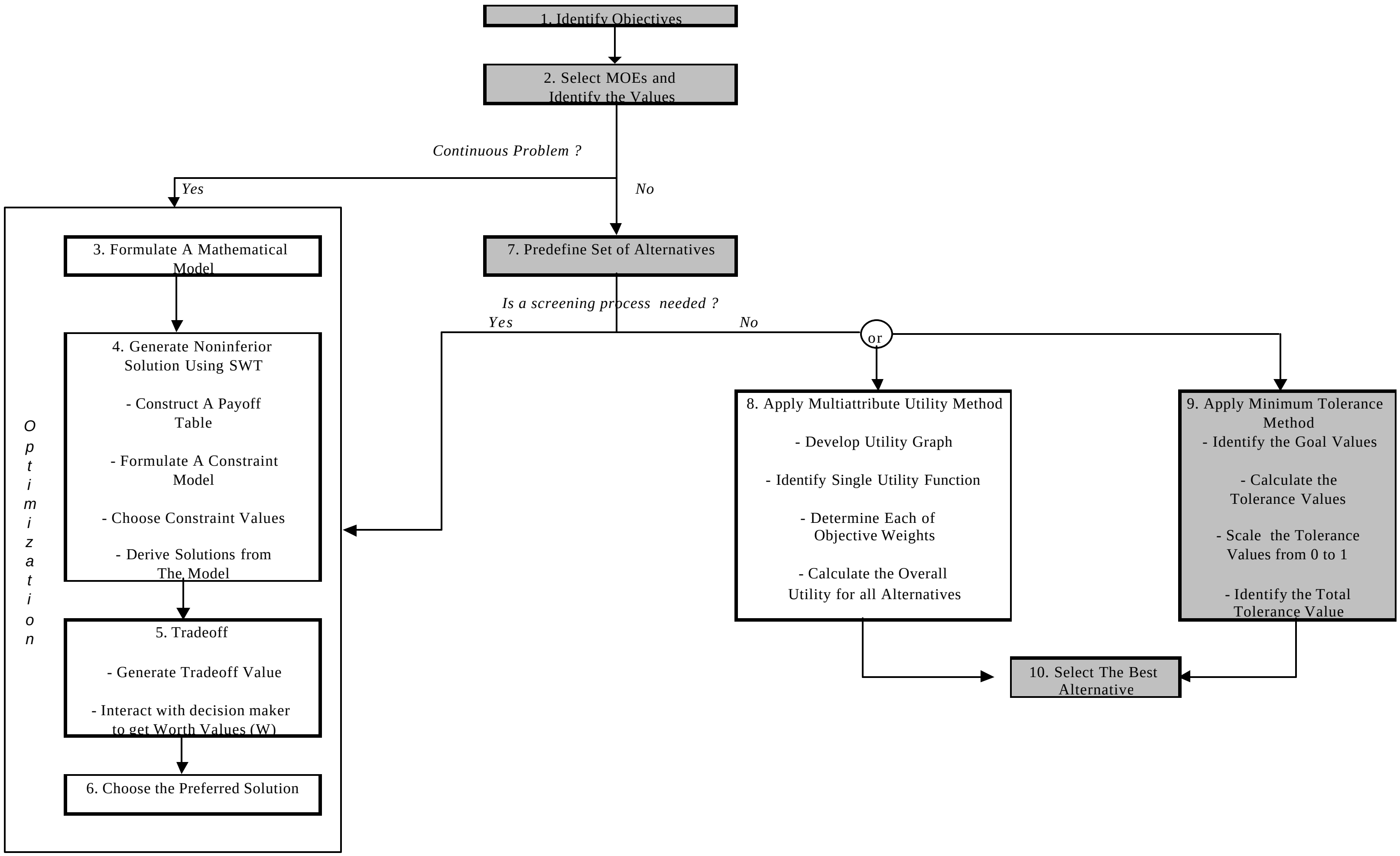


Figure 12. Decision Making Framework for Pickaway County (Ohio) Resurfacing Problem
(Shaded areas show the steps that were applied in this case study)

In this case study, the researchers solved a discrete decision problem by choosing the project with the highest priority. The list of project alternatives is developed in Step 7.

Step 7

The project alternatives considered for funding are listed below:

1. Pickaway Route (PIC) 674
2. PIC-207
3. PIC-138.

The following list of MOE values (Table 26) were collected by ODOT District 6 for each project.

Table 26. Existing Condition Criteria Value (X_{ij})

Project	Length (mile)	PCR	ADT	Truck ADT	Number of Accidents
PIC-674	10.91	66	4018	155	58
PIC-207	9.57	58	1592	136	34
PIC-138	9.13	55	1113	67	27

The three project alternatives represent a manageable number. The optimization screening process is not needed in this case study. The next step is to solve the problem by developing a priority ranking among the projects. Either the Multiattribute Utility Method or Minimum Tolerance Method can be used here. In this case, the research team used the Minimum Tolerance Method.

Step 9

Identify Goal Values Based on Policy Objective

The first task is to identify the goal value for each criterion. This is obtained from predetermined policy goals or a decision maker's opinion. The research team assumed the goal or acceptable objective values shown in Table 27, except for PCR acceptable values. ODOT District 6 presented these acceptable values.

Table 27. Acceptable Condition Criteria Value (A_{ij})

Project	Length (mile)	PCR	ADT	Truck ADT	Number of Accidents
PIC-674	10.91	55	3000	100	30
PIC-207	9.57	55	3000	100	15
PIC-138	9.13	55	3000	100	15

Calculate the Tolerance Values

The tolerance value (T_{ij}) is computed for each proposed project i and criterion j based on the project priority. When the project priority is to minimize criterion, the tolerance value is computed by subtracting the existing condition (X_{ij}) value from acceptable value (A_{ij}) and vice versa.

$$\text{Maximum value of criterion, } T_{ij} = (A_{ij} – X_{ij})$$

$$\text{Minimum value of criterion, } T_{ij} = -(A_{ij} – X_{ij}) = (X_{ij} – A_{ij})$$

The tolerance value, T_{ij} is measured for each criterion j, (j = 1,2,3,4) for each project alternative i (i = 1,2,3), as shown in Table 28 and Figures 13 through 16.

The project priority is given by considering all criteria: minimum PCR, maximum ADT, maximum Truck ADT, and maximum number of accidents.

Table 28. Tolerance Value

Project	Length (mile)	PCR (min)	ADT (max)	Truck ADT (max)	Number of Accidents (max)
PIC-674	10.91	11	-1018	-55	-28
PIC-207	9.57	3	1408	-36	-19
PIC-138	9.13	0	1887	33	-12

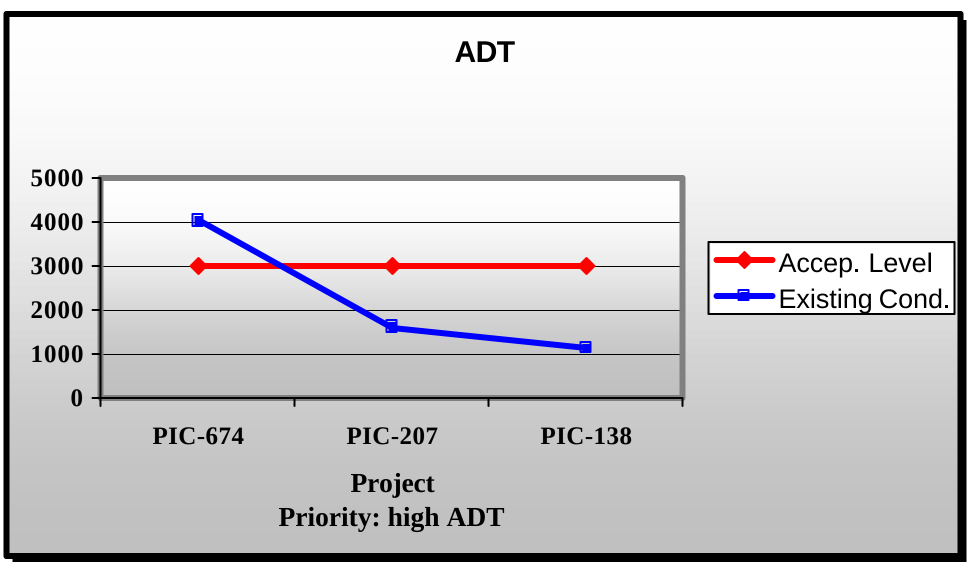


Figure 13. ADT Criteria

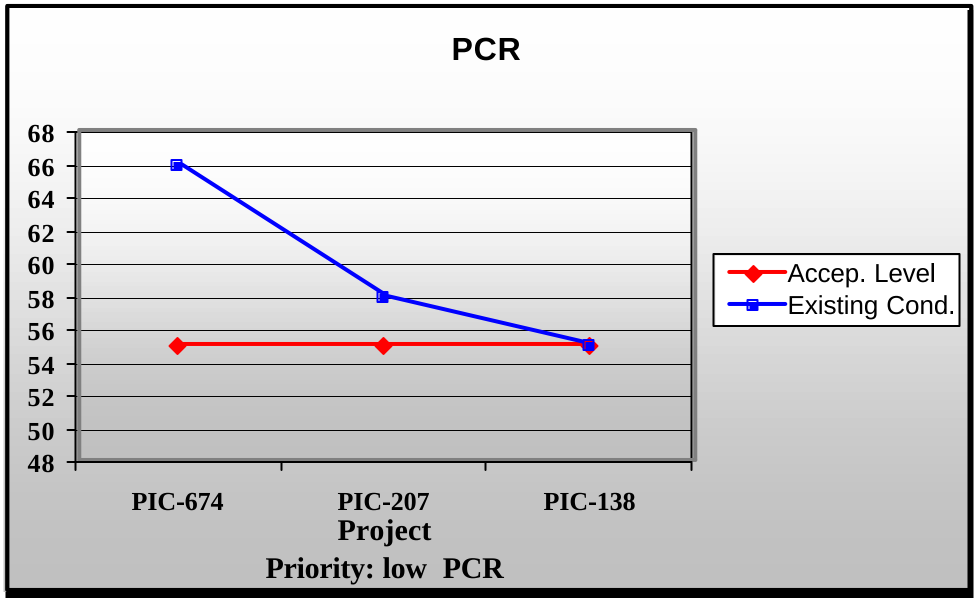


Figure 14. PCR Criteria

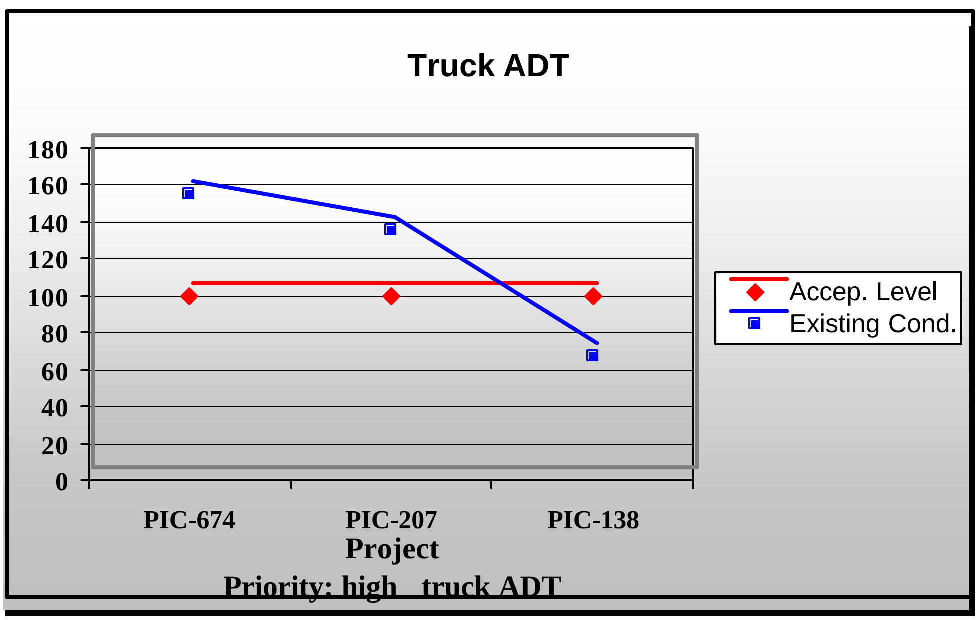


Figure 15. Truck ADT Criteria

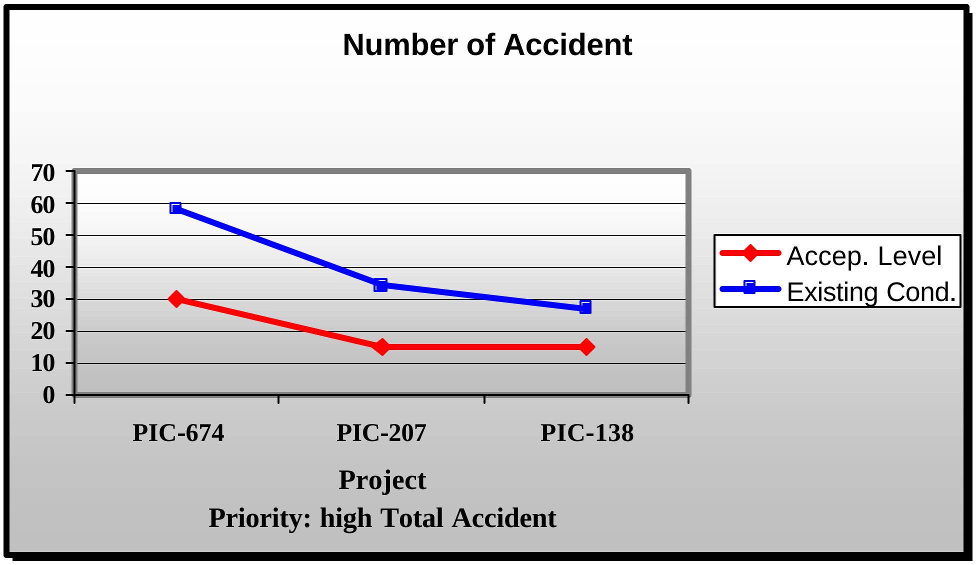


Figure 16. Total Accident Criteria

The more negative tolerance values mean that the criterion is urgent and should be considered. Higher tolerance values indicate a lack of urgency.

Scale the Tolerance Value to Zero

The values in Table 28 are in different units. To calculate the combined tolerance level and relative value, a scale from 0 to 1 is used (Table 29). The tolerance scale value (T_{ij} *) is the relative value among alternatives. This value is computed by the following equation:

$$T_{ij}^* = \{T_{ij} - T_{ij}(min)\} / \{T_{ij}(max) - T_{ij}(min)\}$$

Sum the Tolerance Scale Value for all Criteria for Each Alternative

In this task, the tolerance value for all criteria in each alternative is summed. Based on interviews conducted with ODOT personnel, the weight for each criterion is different. The weight on PCR criteria is the most emphasized (w_{PCR} = 0.4). Each of the other criteria is weighted 0.2. The total tolerance value is computed using the following equation and shown in Table 29.

$$\underset{i = 1,\ldots,I}{\text{Minimize}}\ T_i^* = \sum_{j=1}^{J} w_j (A_{ij} - X_{ij})$$

Table 29. Scale Number of Tolerance Value

Project	Length (mile)	PCR (w =0.4)	ADT (w =0.2)	Truck ADT (w = 0.2)	Number of Accident (w= 0.2)	Total Tolerance
PIC-674	10.91	1.000	0.000	0.000	0.000	0.400
PIC-207	9.57	0.273	0.835	0.216	0.563	0.432
PIC-138	9.13	0.000	1.000	1.000	1.000	0.600

Step 10

Table 29 shows that the PCR tolerance value of PIC-674 has the highest score. This means the PCR of PIC-674 is the best compared to the other projects. But the other tolerance values of PIC-674 have the lowest score compared to two other alternatives. This means PIC-674 has the worst ADT, Truck ADT, and accident number compare to PIC-207 and PIC-138. After combining all the factors, PIC-674 was ranked first in terms of project importance, where the priority is based on the minimum of total tolerance value. Conveniently, PIC-674 also obtained public support.

APPENDIX D

RICHLAND COUNTY, I-71 CORRIDOR
MAJOR INVESTMENT STUDY

D. Richland County, I-71 Corridor (by Multiattribute Utility Method)

D.1 Project Description

This case study is based on the "Richland County, Ohio Interstate 71 Corridor Major Investment Study (MIS)." This project addresses a proposed I-71 lane addition from the Morrow/Richland County line north to the Richland/Ashland County line. This MIS was a result of the Ohio Department of Transportation's (ODOT) Cleveland to Columbus Pavement Reconstruction Study. The recommendation to construct a third lane was developed to address operational deficiencies caused by existing and future traffic volumes and truck traffic passing through the frequent steep grades along the corridor. ODOT conducted the MIS to determine the impacts of various alternatives and to verify whether the I-71 pavement reconstruction program recommendations were compatible with the Richland County Planning Commission principles and Transportation Plan.

The main problem identified along the corridor between Columbus and Cleveland was that pavement conditions had deteriorated and large segments of the corridor needed reconstruction. Reconstruction of this pavement over the next nine construction seasons was proposed. The traditional approach to reconstruct the pavement has been to work on one lane or direction at a time and limit vehicular traffic to one lane in each direction. This traditional approach would result in heavy traffic volumes and unacceptable delays; therefore, ODOT conducted a planning study to investigate a series of alternatives to maintain acceptable traffic operations during the I-71 pavement reconstruction projects.

This case study shows how using the Multiattribute Utility Function and data from the MIS study allowed the decision maker to select the best alternative. Figure 17 shows the general decision making framework with the shaded portion representing the steps that were applied in the case study. This case study involved a discrete scenario where six alternatives were evaluated. These alternatives were identified in Step 7. The analyst had a choice between the Multiattribute Utility and Minimum Tolerance Method. In this case, the Multiattribute Utility Method (Step 8) was adopted.

D.2 Problem Solving

Step 1

As shown in Figure 17, the first step in this process was to identify the objectives – to address the short-term issues related to maintaining acceptable traffic operations throughout the pavement reconstruction projects and to address the long-term mobility needs on the I-71 Cleveland to Columbus corridor.

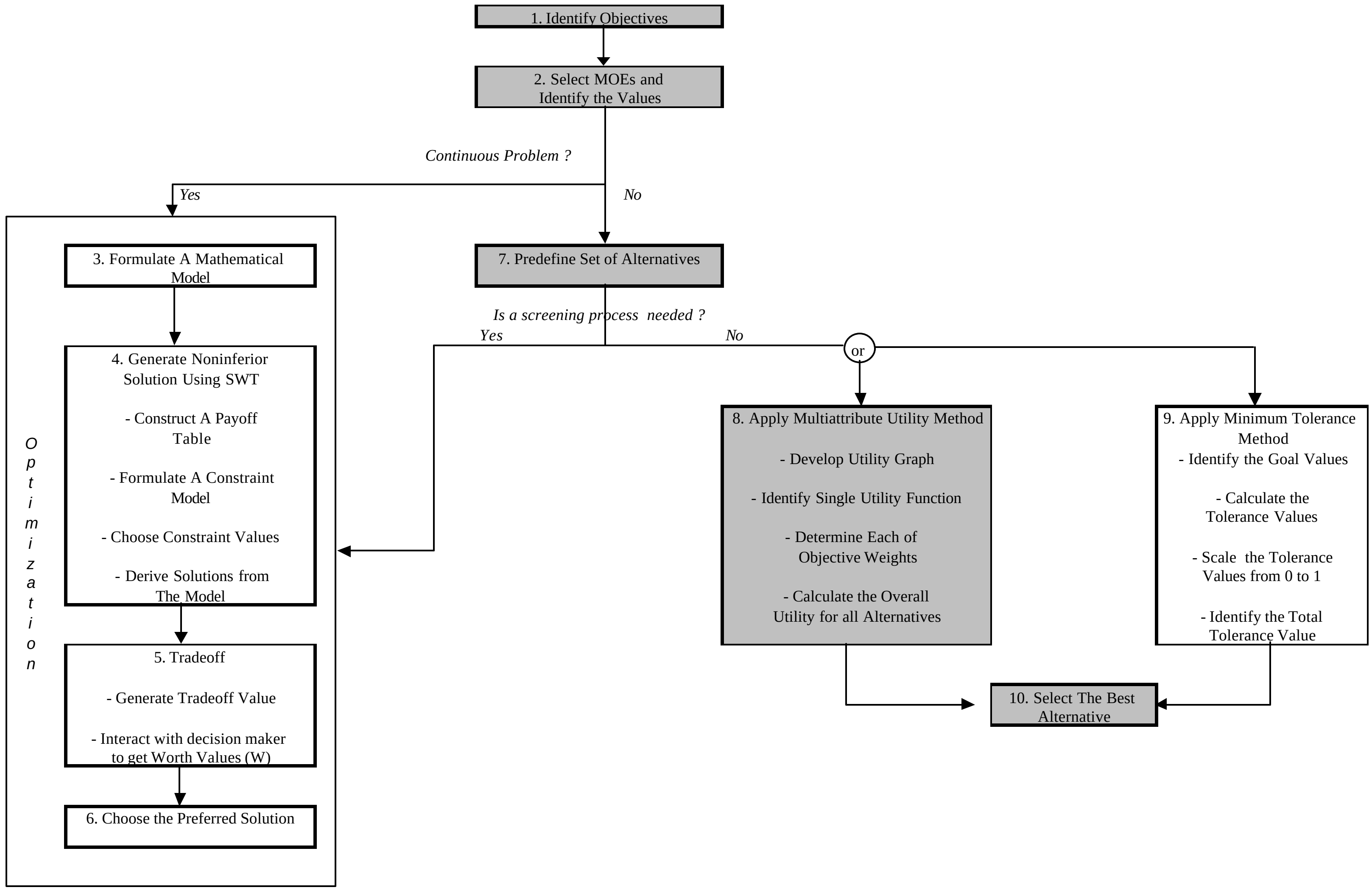


Figure 17. Decision Making Framework for Richland County, I-71 Corridor
(Shaded areas show the steps that were applied in this case study)

Step 2

The decision maker and the manager for this project were identified as the decision maker for this case study. Seven MOEs attributes were considered appropriate for this project:

1. Travel time saved (hrs/mins).
2. Minimum average speed (mph).
3. Maximum daily cost of delay ($ thousands).
4. Total cost of delay ($ millions).
5. Maximum queue length (miles).
6. Cost/mile ($ millions).
7. Future annual operational and maintenance cost ($ millions).

This problem is a discrete problem, so the next step was to determine the alternatives and the MOE values of those alternatives.

Step 7

The alternatives were as follows:

1. No build.
2. Widen the roadway shoulders and bridges to maintain two travel lanes in each direction during reconstruction projects.
3. Construct truck hill climbing lanes, in combination with wide shoulders, to address long-term operational problems associated with heavy truck volumes in the corridor.
4. Construct a third lane through the entire corridor to maintain two travel lanes during reconstruction projects and address existing and future congestion in the corridor.
5. Introduce inter-city passenger rail service as an alternative to automobile travel during the reconstruction program.
6. Provide detours on adjacent US and state routes as an alternative to I-71 travel during the reconstruction program.

The values of the attributes for each alternative were given by ODOT, and are shown in Table 30. ODOT used the computer program QUEWZ to estimate the values of the attributes.

Table 30. Attribute Value

Alternatives	Travel Time Saved (hrs.min)	Min. Avg. Speed (mph)	Max Daily Cost of Delay ($ thousands)	Total Cost of Delay ($ millions)	Max. Queue Length (miles)	Cost/mile ($ millions)	Future Annual O & M ($ millions)
1	0	25	3,150	1,522	29.2	2.57	8.66
2	2.41	60	147	77	0.2	4.57	8.66
3	2.41	60	147	77	0.2	4.71	9.17
4	2.44	62	102	58	0.0	5.01	12.99
5	0.24	28	2,714	1,205	26.8	2.84	9.77
6	1.03	33	1,968	903	20.2	3.30	10.46

The next step was to decide whether to do the screening process. Since the number of alternatives was manageable, the screening process was not needed. As a result, all of the alternatives were considered in the evaluation process.

Step 8

The Multiattribute Utility Function was used to help the decision maker select the best alternative using the following tasks:

Develop Utility Graph

A questionnaire was sent to the decision maker (in this case ODOT) to obtain the preferences for a range of attributes. An example of a questionnaire is shown in Appendix G.

Following this, a series of utility graphs were developed based on decision maker preference. For each MOE, such as travel time saved, the decision maker's preferences (from 0 to 10, 0 being least preferred and 10 being most preferred) were recoded for various travel time as shown in Table 31. This data is then drawn in graphical form as shown in Figure 18. Similar exercises were performed for other MOEs as presented in Tables 32 through 37 and corresponding Figures 19 through 24.

Table 31. Utility Table for Travel Time Saved

T.T.S. (hrs)	Utility
0.0	0
0.5	0
1.0	4
1.5	10
2.0	10
2.5	10

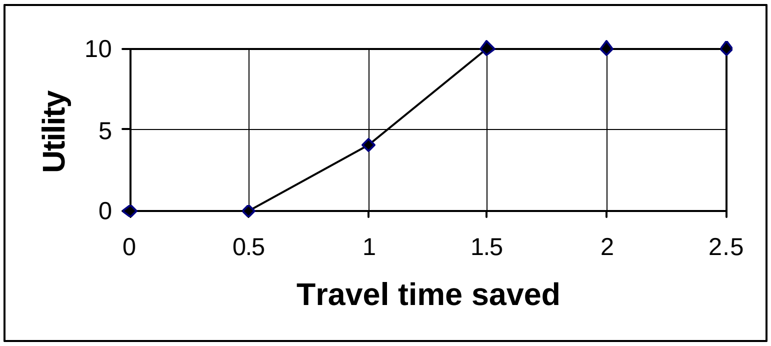


Figure 18. Utility Graph for Travel Time Saved

Table 32. Utility Table for Minimum Average Speed (mph)

Minimum Avg. Speed (mph)	Utility
0	0
20	0
40	2
60	10
80	0

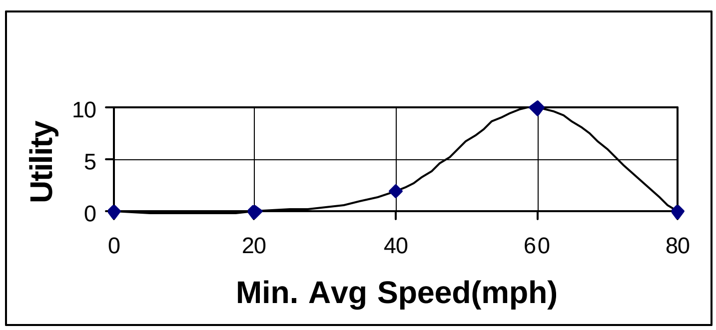


Figure 19. Utility Graph for Minimum Average Speed

Table 33. Utility Table for Maximum Daily Cost of Delay

Max Daily Cost of Delay ($ thousands)	Utility
3500	0
3000	0
2500	0
2000	0
1500	1
1000	2
500	6
0	10

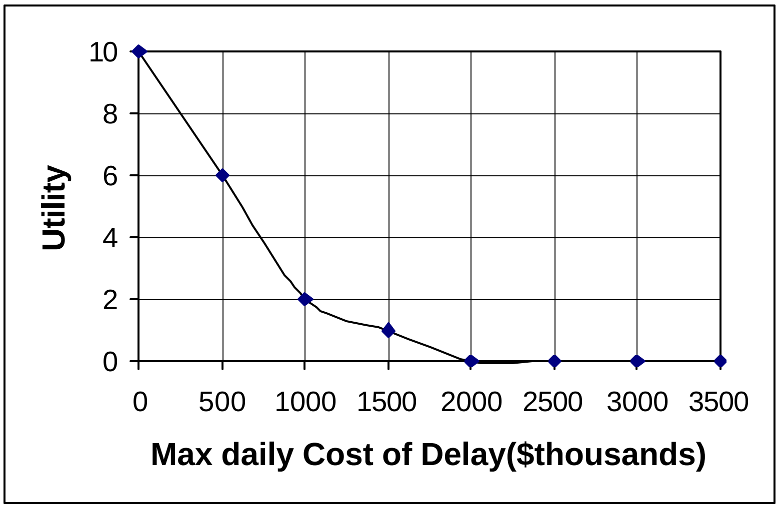


Figure 20. Utility Graph for Maximum Daily Cost of Delay

Table 34. Utility Table for Total Cost of Delay

Total Cost of Delay ($/thousands)	Utility
2000	0
1500	0
1000	0
500	5
0	10

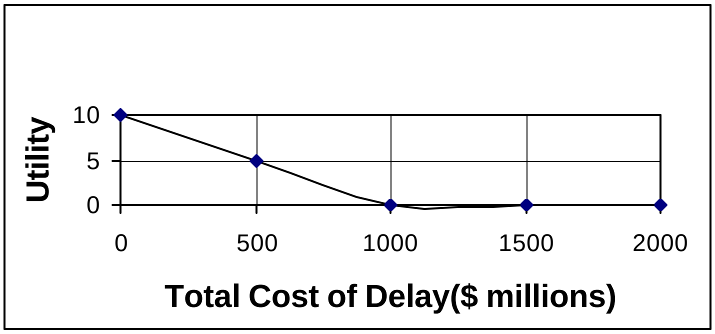


Figure 21. Utility Graph for Total Cost of Delay

Table 35. Utility Table for Maximum Queue Length (miles)

Max. Queue Length (miles)	Utility
30	0
28	0
26	0
24	0
22	0
20	0
18	0
16	0
14	0
12	0
10	1
8	1
6	2
4	3
2	5
0	10

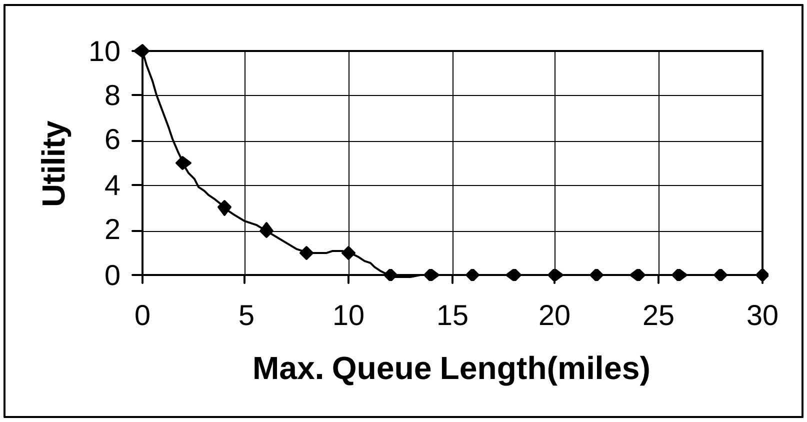


Figure 22. Utility Graph for Maximum Queue Length (miles)

Table 36. Utility Table for Cost/Mile ($millions)

Cost/Mile ($millions)	Utility
5.5	5
5.0	7
4.5	8
4.0	8
3.5	9
3.0	9
2.5	10

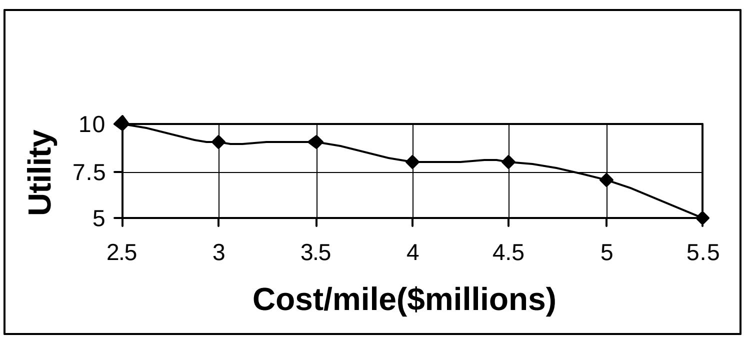


Figure 23. Utility Graph for Cost/Mile ($millions)

Table 37. Utility Table of Future Annual Operational and Maintenance Cost ($ millions)

Future Annual O & M Cost ($ millions)	Utility
13.0	7
12.5	7
12.0	8
11.5	8
11.0	8
10.5	9
10.0	9
9.5	9
9.0	10
8.5	10
8.0	10

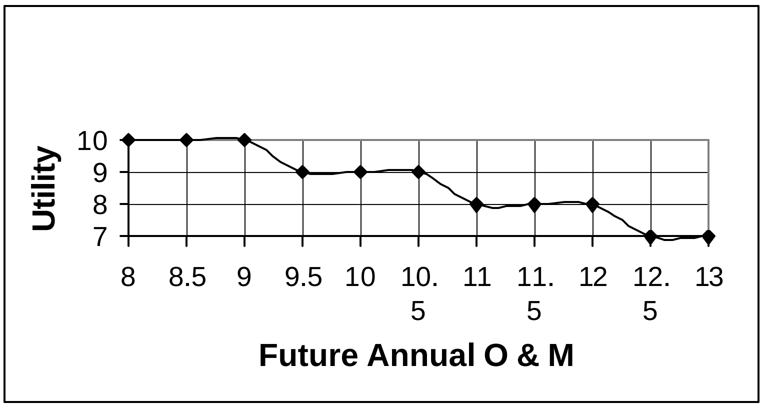


Figure 24. Utility Graph for Future Annual Operational and Maintenance Cost ($millions)

Identify Single Utility Function

The next step was to determine a single-attribute measure utility value from the utility graph. The expected utilities ranged on a scale from 0 to 10, with 0 being the least desirable preference and 10 being the most desirable. Table 38 shows the utility values obtained from the graphs for the respective attribute values.

Table 38. Utility Value Obtained from the Utility Graphs

Alternatives	Utility Values						
	Travel Time Saved	Minimum Avg. Speed	Max daily Cost of Delay	Total Cost of Delay	Max. Queue Length	Cost/mile	Future Annual O & M
1	0	0.5	0	0	0	9.86	10
2	10	10	8.824	9.23	9.5	7.86	10
3	10	10	8.824	9.23	9.5	7.58	9.66
4	10	9	9.184	9.42	10	6.96	7
5	0	0.8	0	0	0	9.32	9
6	4.36	1.3	0.064	0.97	0	9	9

Determined Each of Objective Weights

The relative weights for the attributes were determined based upon the decision maker's preference (Table 39). The sum of the seven weights should be 1 (for example, $W_1+W_2+W_3+W_4+W_5+W_6+W_7 = 1$, where W_1 = weight associated with travel time saved, W_2 = weight associated with minimum average speed, W_7 = weight associated with future annual operation & maintenance).

Table 39. Weights for Each Attribute

Weights of ith attribute	Weight
W_1	0.100
W_2	0.025
W_3	0.025
W_4	0.025
W_5	0.025
W_6	0.200
W_7	0.600

Calculate the Overall Utility for al Alternatives

The next step was to calculate the overall utility of an alternative. For example, the overall utility for alternative 'A' is determined as follows:

$MU_A = W_1 SU_1 + W_2 SU_2 + W_3 SU_3 + W_4 SU_4 + W_5 SU_5 + W_6 SU_6 + W_7 SU_7$

$W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 = 1$

where,

SU_1 = Single Measure Utility of Travel Time Saved

SU_2 = Single Measure Utility of Minimum Average Speed

SU_3 = Single Measure Utility of Maximum Daily Cost of Delay

SU_4 = Single Measure Utility of Total Cost of Delay

SU_5 = Single Measure Utility of Maximum Queue Length

SU_6 = Single Measure Utility of Cost/mile
SU_7 = Single Measure Utility of Future Annual Operational & Maintenance
MU_A = Total Multiple Measure Utility of Alternative 'A'
W_i = Weight of the *i*th utility

Step 10
The final step was to select the best alternative. The alternative with the highest multi-measure utility value (Alternative 2) was recommended as the best alternative. Table 40 details how the overall utility was calculated.

Table 40. Utility Evaluation for All Alternatives

Alternatives	Travel Time Saved (hrs.min) weight	Utility	Minimum Average speed (mph) weight	Utility	Max daily cost of Delay ($thousands) weight	Utility	Total cost of Delay ($millions) weight	Utility	Max. Queue Length (miles) weight	Utility	Cost/Mile ($millions) weight	Utility	Future Annual O&M (millions) weight	Utility	MUFi
1	0.1	0	0.025	0.5	0.025	0	0.025	0	0.025	0	0.2	9.86	0.6	10	7.98
2	0.1	10	0.025	10	0.025	8.824	0.025	9.23	0.025	9.5	0.2	7.86	0.6	10	9.51
3	0.1	10	0.025	10	0.025	8.824	0.025	9.23	0.025	9.5	0.2	7.58	0.6	9.66	9.25
4	0.1	10	0.025	9	0.025	9.184	0.025	9.42	0.025	10	0.2	6.96	0.6	7	7.53
5	0.1	0	0.025	0.8	0.025	0	0.025	0	0.025	0	0.2	9.32	0.6	9	7.28
6	0.1	4.36	0.025	1.3	0.025	0.064	0.025	0.97	0.025	0	0.2	9	0.6	9	7.69

APPENDIX E

REGRESSION GRAPHS FOR CAPITAL BELTWAY CORRIDOR

$W_{4,1}$	$?_{4,1}$
10	-1
5	-0.5
-5	1
-10	0.5

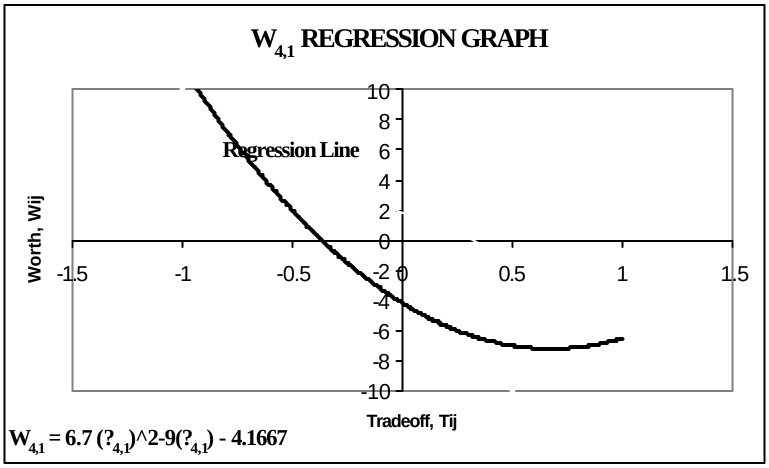


Figure E-1 Worth and Tradeoff Regression Graph, W4,1

$W_{4,2}$	$?_{4,2}$
10	2
5	1.6
-5	-0.6
-10	-0.01

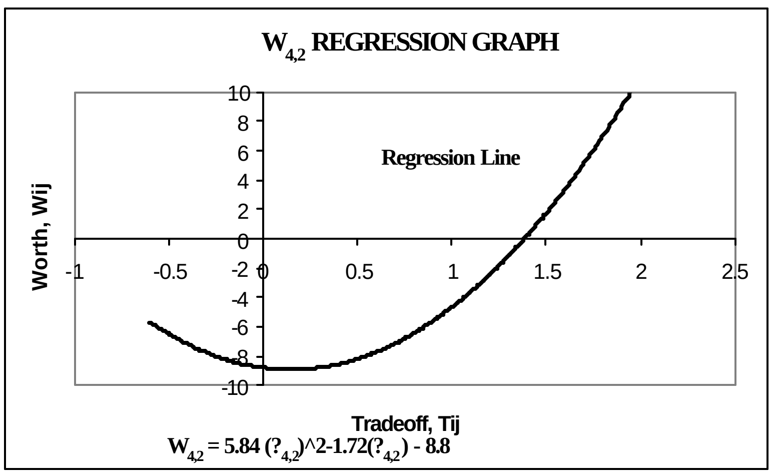


Figure E-2. Worth and Tradeoff Regression Graph, W4,2

$W_{4,3}$	$?_{4,3}$
10	3
5	1
-5	-2
-10	-0.01

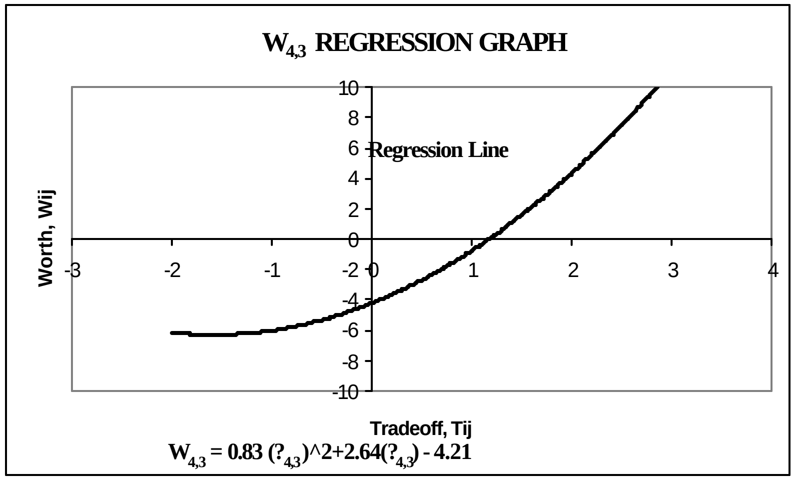


Figure E-3. Worth and Tradeoff Regression Graph, W4,3

$W_{4,5}$	$?_{4,5}$
10	3
5	2
-5	-0.7
-10	-1

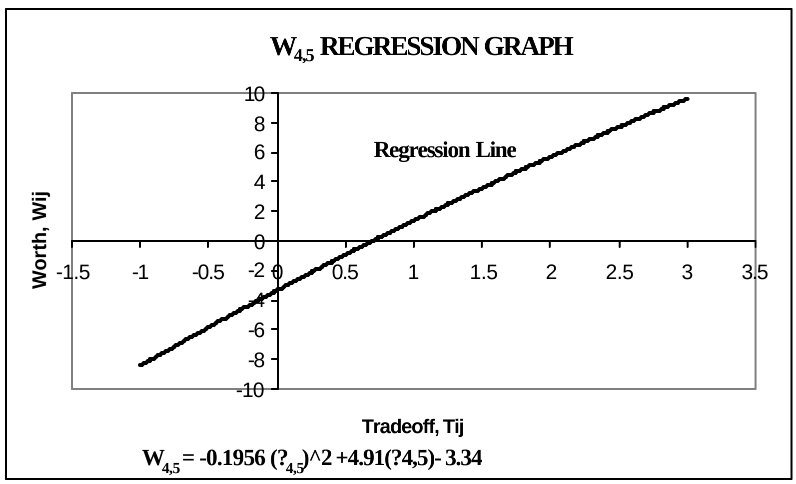


Figure E-4. Worth and Tradeoff Regression Graph, W4,5

APPENDIX F

REGRESSION GRAPHS FOR OHIO RIVER BRIDGE PROJECT

$W_{4,1}$	$?_{4,1}$
10	0.25
5	0.15
-5	-0.1
-10	-0.005

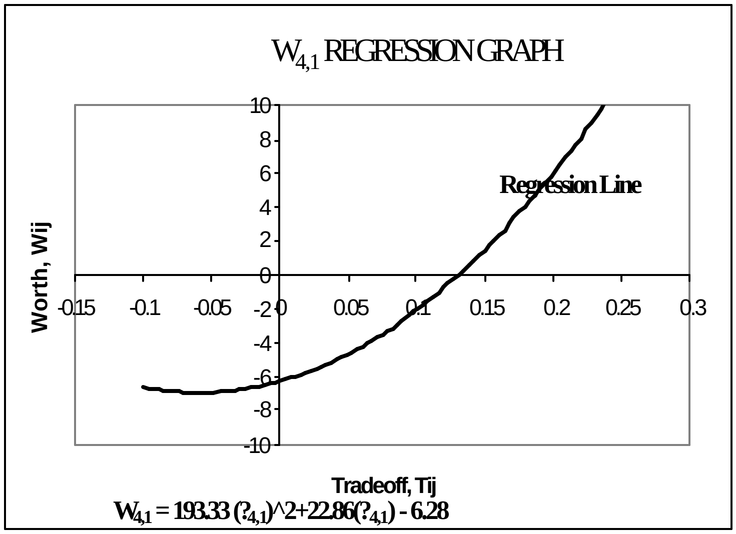


Figure F-1. Worth and Tradeoff Regression Graph, W4,1

$W_{4,2}$	$?_{4,2}$
10	0.15
5	0.07
-5	-0.05
-10	-0.01

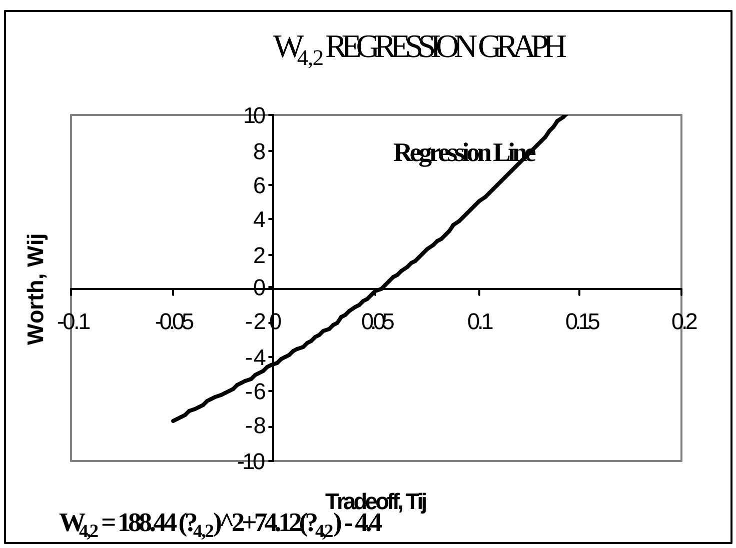


Figure F-2. Worth and Tradeoff Regression Graph, W4,2

$W_{4,3}$	$?_{4,3}$
10	0.2
5	0.12
-5	-0.1
-10	-0.05

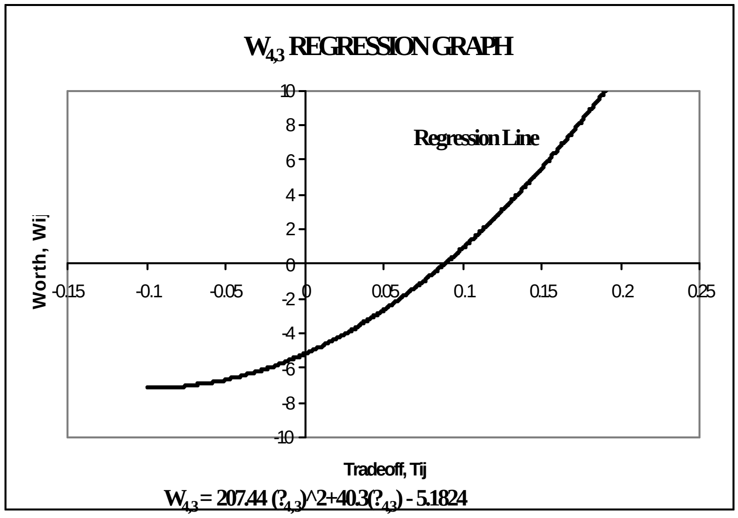


Figure F-3. Worth and Tradeoff Regression Graph, W4,3

$W_{4,5}$, $W_{4,7}$ $W_{4,8}$	$?_{4,5}$, $?_{4,7}$ $?_{4,8}$
10	0.28
5	0.17
-5	-0.17
-10	-0.04

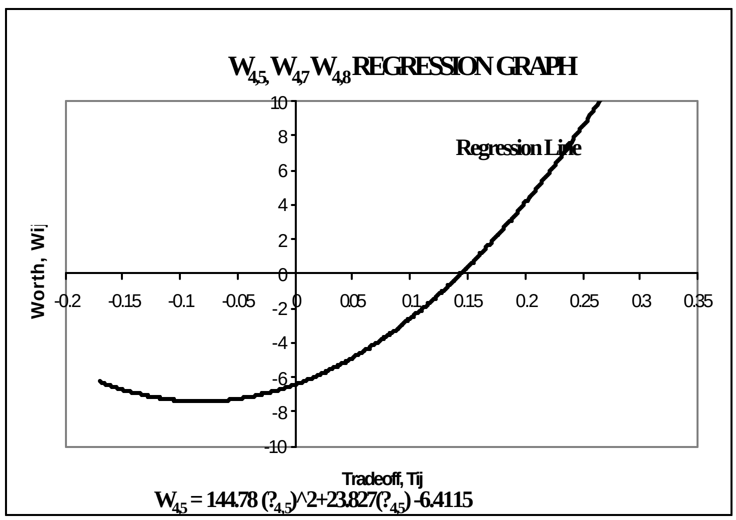


Figure F-4. Worth and Tradeoff Regression Graph, W4,5;W4,7;W4,8

$W_{4,10}$	$?_{4,10}$
10	-0.07
5	-0.05
-5	-0.001
-10	0

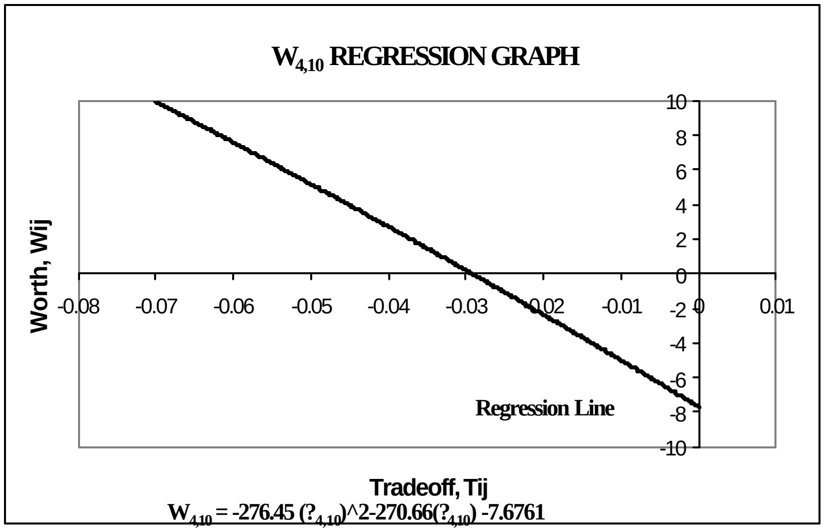


Figure F-5. Worth and Tradeoff Regression Graph, W4,10

$W_{4,11}$	$?_{4,11}$
10	-0.6
5	-0.35
-5	-0.05
-10	-0.001

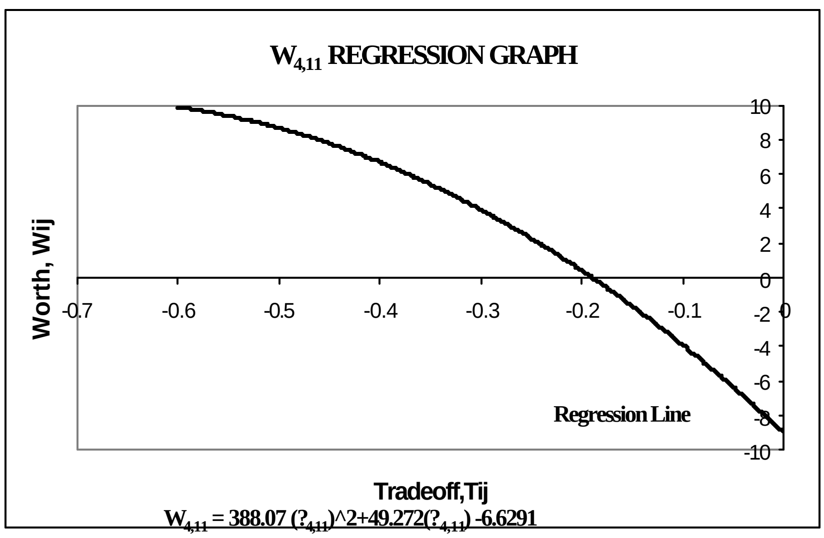


Figure F-6. Worth and Tradeoff Regression Graph, W4,11

$W_{4,12}$	$?_{4,12}$
10	-0.7
5	-0.5
-5	-0.02
-10	-0.001

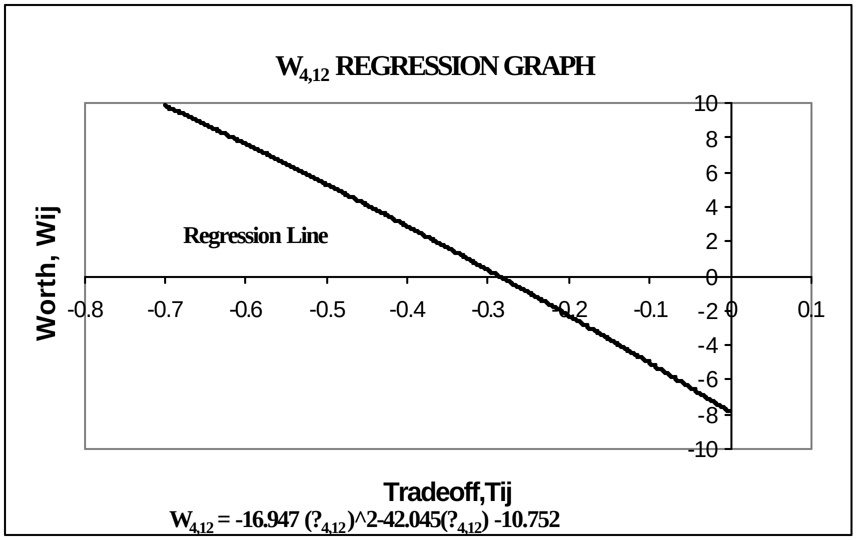


Figure F-7. Worth and Tradeoff Regression Graph, W4,12

$W_{4,13}$	$?_{4,13}$
10	-0.7
5	-0.5
-5	-0.05
-10	-0.001

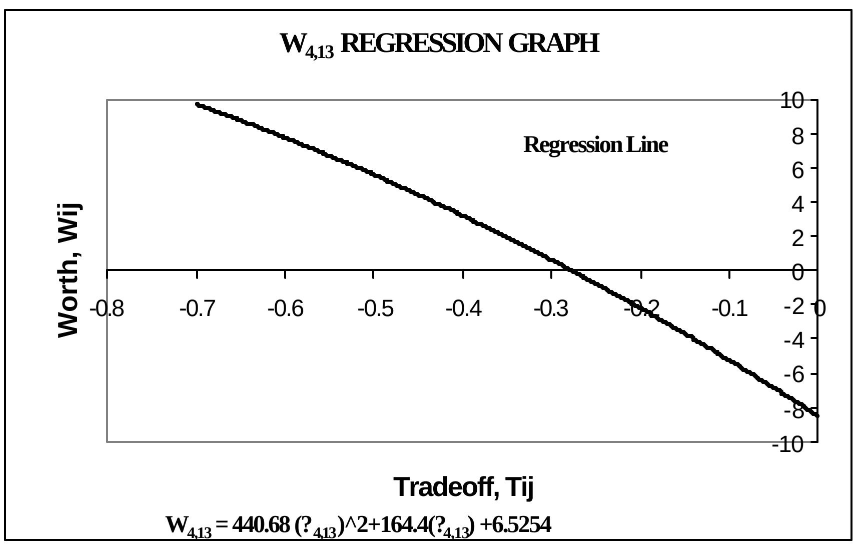


Figure F-8. Worth and Tradeoff Regression Graph, W4,13

APPENDIX G

QUESTIONNAIRE FOR RICHLAND COUNTY, I-71 CORRIDOR MAJOR INVESTMENT STUDY

Information about Richland County, Ohio Interstate 71 Corridor Major Investment Study:

(1) Please weigh the seven objectives in terms of relative importance for this project (such that W1+ W2+ W3+ W4+ W5+ W6+ W7 = 1)

Table G-1: Relative weights of the objectives

Objectives	**Weights**
Travel Time Saved (hrs.min)	
Minimum Avg. Speed (mph)	
Max Daily Cost of Delay ($thousands)	
Total Cost of Delay($ millions)	
Max. Queue Length (miles)	
Cost/mile ($millions)	
Future Annual O & M ($millions)	

(2) Please give your preference (by assigning weights) for the travel time saved. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-2: Preference of the decision maker for the travel time saved

Travel Time Saved (hrs.min)	**Weight (range:0-10)**
0.0	
0.5	
1.0	
1.5	
2.0	
2.5	

(3) Please give your preference (by assigning weights) for minimum average speed. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-3: Preference of the decision maker for minimum average speed

Minimum Avg. Speed (mph)	Weight (range: 0-10)
0	
20	
40	
60	
80	

(4) Please give your preference (by assigning weights) for maximum daily cost of delay. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-4: Preference of the decision maker for maximum daily cost of delay

Max Daily Cost of Delay ($thousands)	Weight (range: 0-10)
3500	
3000	
2500	
2000	
1500	
1000	
500	
0	

(5) Please give your preference (by assigning weights) for total cost of delay. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-5: Preference of the decision maker for total cost of delay

Total Cost of Delay ($ millions)	**Weight (range: 0-10)**
2000	
1500	
1000	
500	
0	

(6) Please give your preference (by assigning weights) for maximum queue length. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-6: Preference of the decision maker for maximum queue length

Max. Queue Length (miles)	Weight (range: 0-10)
30	
28	
26	
24	
22	
20	
18	
16	
14	
12	
10	
8	
6	
4	
2	
0	

(7) Please give your preference (by assigning weights) for cost per mile. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-7: Preference of the decision maker for cost per mile

Cost/mile ($millions)	Weight (range: 0-10)
5.5	
5.0	
4.5	
4.0	
3.5	
3.0	
2.5	

(8) Please give your preference (by assigning weights) for future annual operational and maintenance cost. Weights range from 0 to 10, 0 being least desirable and 10 being most desirable.

Table G-8: Preference of the decision maker for future annual operational and maintenance cost

Future Annual O & M ($millions)	**Weight (range: 0-10)**
13.0	
12.5	
12.0	
11.5	
11.0	
10.5	
10.0	
9.5	
9.0	
8.5	
8.0	