MRUTC Project 08-03: Optimal Investment Decision-Making for Highway Transportation Asset Management under Risk and Uncertainty

Review of Literature on
Highway Project Benefit-Cost and Tradeoff Analyses

Prepared by

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LIST OF ABBREVIATIONS

AAA	American Automobile Association
AASHTO	American Association of State Highway and Transportation Officials
CAL-B/C	California Life Cycle Benefit/Cost Analysis Model
CALTRANS	California Department of Transportation
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOT	Department of Transportation
FHWA	Federal Highway Administration
HDM	Highway Development and Management
HERS	Highway Economic Requirements System
HOV	High-Occupancy Vehicle
IDAS	ITS Deployment Analysis System
NCHRP	National Cooperative Highway Research Program
NO_X	Oxides of Nitrogen
NSC	National Safety Council
PM	Particulate Matter
PDO	Property Damage Only
SO_X	Oxides of Sulfur
STEAM	Surface Transportation Efficiency Analysis Model
SUV	Sport Utility Vehicle
TTI	Texas Transportation Institute
USDOT	U.S. Department of Transportation
VOC	Vehicle Operating Costs / Volatile Organic Compounds

INTRODUCTION

Transportation facilities constitute one of the most valuable public assets and accounts for a major share of public sector investment worldwide. These investments serve to build, operate and preserve infrastructure that supports movement of people and goods by various modes. Efficient, economical and safe transportation is critical to a society in meeting its goals toward economic progress, social welfare and emergency preparedness. As being one of the critical facilities it demands better investment decisions for system preservation, expansion and operation based on comprehensive information in a holistic and proactive way. Defined as a systematic process of maintaining, upgrading and operating physical assets cost-effectively, highway asset management combines engineering principles with sound business practices and economic theory, and provides a tool to facilitate an organized, logical and integrated approach to highway investment decision-making [FHWA, 1999].

Over the past two decades, state transportation agencies have developed management systems as analytical tools to support highway investment decision-making. These mainly include pavement, bridge, and maintenance management systems dealing with physical highway assets; and congestion and safety management systems handling highway system operations. The existing methodologies for project benefit-cost analysis in these management systems maintain limited capacity of risk-based analysis of project benefits affected by factors such as travel demand and asset performance, but they do not handle cases under uncertainty. In project selection process, existing models do not consider uncertainty of budget and other constraints. Furthermore, the management systems typically work independent of each other or only partially integrated. Therefore, they will at best provide locally optimal investment decisions for individual physical assets or single aspect of system operations. The proposed research will develop new procedures that address uncertainty and system integration in project benefit-cost analysis and project selection using different tradeoff scenarios to produce truly global optimal investment decisions. As the first step of the research, literature review was conducted on existing methodologies for project benefit-cost analysis and project selection as summarized in the following sections.

METHODS FOR BENEFIT-COST ANALYSES

Project-Level versus Network-Level Analyses

Benefit-cost analysis frequently provides a quantitative basis for comparing and prioritizing alternative projects. When choosing a method for benefit-cost analysis, tradeoffs must be considered between the accuracy and it simplicity of a method. In general, the methods fall into one of the following two categories: 1) project-level benefit-cost analysis that uses standard assumptions to compute direct project benefits in immediate project area and indirect benefits or disbenefits of project affected areas; and 2) network-level benefit-cost analysis that estimates project benefits based upon the output of a regional planning model so as to capture significant project benefits.

The ease or difficulty in implementation is crucial in adopting project-level versus network-level analysis. As compared to project-level analyses, network-level analyses generally require more time, data, and assumptions, necessitate the use of travel demand forecasting models such as the traditional four-step model, and are more costly than route-specific analyses. Project, facility, and land area type characteristics that well suited to project-level and network-level analyses are listed in Table 1.

Table 1. Decision Criteria for Project-Level versus Network-Level Benefit-Cost Analyses

<table>
<tr><th rowspan="2">Benefit-Cost Analysis</th><th colspan="2">Decision Criterion</th></tr>
<tr><th>Project Type</th><th>Facility or Area Type</th></tr>
<tr><td>Project Level</td><td>1. Resurfacing, restoration, and rehabilitation
2. Safety improvements, including roadway geometry, lane, access, and roadside improvements
3. Minor capacity improvement, such as addition of passing, auxiliary, and truck climbing lanes</td><td>1. Facilities with no alternative routes, such as bridges and tunnels
2. Low-volume systems well under capacity
3. Rural areas with relatively sparse roadway networks</td></tr>
<tr><td>Network Level</td><td>1. ITS projects, such as ramp metering, traffic surveillance, and region-wide traveler information systems
2. Addition of high-occupancy-vehicle (HOV) lanes
3. New or improved park-and-ride lots
4. Interchange additions or improvements
5. New construction and significant capacity expansion
6. Traffic signal systems
7. Traffic control</td><td>1. High-volume systems at or over capacity
2. Urban areas with relatively dense roadway networks with alternative path choices</td></tr>
</table>

The Concept of Life-Cycle Cost Analysis

The costing procedure that includes all agency and user costs in project service life-cycle is called life-cycle costing. Agency costs mainly consist of capital costs associated with project construction and the discounted future costs of maintenance and rehabilitation (including resurfacing, restoration, and reconstruction). Whereas user costs are those concerned with vehicle operation, travel time, vehicle crashes, and vehicle air emissions. The life-cycle cost analysis allows the decision-maker to determine how much cost savings will occur with higher initial capital costs, if these higher costs result in lower overall life-cycle agency and user costs. Many state Departments of Transportation (DOTs) have started to use life-cycle cost analysis for asset management in recent years [FHWA, 1991]. The following sections summarize the general procedure for life-cycle cost analysis.

Project Direct Costs

The project direct costs generally include direct agency costs and additional user costs associated with construction. Direct agency cost elements largely cover capital costs of project land acquisition, design and engineering support, and construction. User costs associated with construction include increased costs of vehicle operation, delays, crashes, and air emissions within work zones.

Life-Cycle Agency and User Costs

In life-cycle cost analysis, the overall agency costs generally include direct agency costs regarding project construction and subsequent costs of maintenance and rehabilitation (including resurfacing, restoration, and reconstruction) incurred during project service life-cycle. On the user costs side, the primary cost categories include vehicle operating costs, travel time, crashes, and air emissions. Life-cycle user costs are estimated on the basis of the four user cost elements for all years in project service life-cycle.

Project Life-Cycle Benefits

The overall benefits of a highway project in its service life-cycle may be extracted from both the agency and user perspectives. With the investment in project construction, it may decrease project life-cycle agency costs and also cause reductions or savings of life-cycle user costs in terms of vehicle operation, travel time, crashes, and air emissions. In order to estimate the change of life-cycle agency costs, the activity profiles containing information on frequency, timing, and magnitude of construction, maintenance, and rehabilitation work for key highway facilities such as pavements and bridges need to be established. For instance, different activity profiles are needed for flexible, right, and composite pavements; and for concrete and steel bridges, respectively. The potential reduction in life-cycle agency and user costs after project implementation (i.e., with certain investment) is considered as the overall project life-cycle benefits. Table 2 lists the analytical steps involved with project benefit-cost analysis.

Table 2. Analytical Steps of Highway Project Benefit-Cost Analyses

Analytical Step	Information Needed
1. Define base case and project alternatives	a. The network elements affected b. Engineering characteristics c. Project build-out schedule d. Project agency cost schedule e. Project user cost schedule
2. Determine level of details required	a. Types of benefits and costs b. Link versus corridor perspective c. Vehicle classes to be studied d. Hourly, daily, and seasonal details e. Time periods within a day to be explicitly modeled
3. Develop basic agency cost factors	a. Facility performance models b. Activity frequency, timing, and magnitude
4. Develop basic user cost factors	a. Vehicle operating unit costs b. Vehicle occupancy rates c. Values of travel time d. Vehicle crash rates and unit costs e. Vehicle air emission rates and units costs
5. Select economic factors	a. Discount and inflation rates b. Analysis period c. Facility service life-cycle assumptions d. Facility salvage values at the end of useful service life-cycle
6. Obtain traffic data for base case and project alternatives for explicitly-modeled periods	a. Travel demand and traffic assignment models b. Hourly, daily, and seasonal traffic volumes, speeds, and occupancy before and after improvement c. Traffic growth rate factors d. Volume-delay function factors e. Peak-spreading assumptions
7. Measure agency costs for base case and project alternatives	a. Project direct agency costs of construction b. Discounted life-cycle costs of maintenance and rehabilitation
8. Measure user costs for base case and project alternatives for affected links or networks	a. Operating, delay, crash, and emission costs during construction b. Life-cycle vehicle operating costs c. Life-cycle travel time costs (including delay costs) d. Life-cycle accident costs e. Life-cycle air emission costs
9. Calculate overall agency and user benefits as the summation of respective differences in agency and user costs between a project alternative and the base case	a. Data from Steps 7 and 8 b. Life-cycle agency benefit formulae c. Life-cycle user benefit formulae

Calculation of Agency Benefits Using the Life-Cycle Cost Analysis

Life-cycle cost analysis for highway assets such as pavements and bridges is a process that evaluates the total economic worth of the initial cost and the discounted future cost of maintenance and rehabilitation associated with the assets. The agency benefits are regarded as reductions in life-cycle agency costs resulted from certain amount of investment. As highway asset management involves various physical assets that have different service lives, life-cycle costing needs to be carried out to allow comparison of investments on of an equal basis. The following section briefly describes life-cycle agency cost analyses conducted on highway pavements and bridges in the last ten years.

Pavement Life-Cycle Agency Cost Analysis

The Federal Highway Administration (FHWA) has made a concerted effort for the use of life-cycle cost analysis in highway pavement design [FHWA, 1998]. In a research on Life-cycle cost analysis of rigid pavements, Wilde et al. [1999] came up with the life-cycle cost component framework for rigid pavements. Three components of cost were indicated as agency cost, user cost, and external cost components. In the agency cost component, it included initial cost, maintenance, rehabilitation and overlays. Rehabilitation and maintenance cost were calculated as per the prediction of distress that will occur by the end of each year and initial costs as per the design.

Hicks and Epps [1999] presented the establishment of alternative design strategies with a logical comparison between conventional mixtures and the mixture containing asphalt rubber pavement materials. Estimate of agency cost includes the construction cost, all administrative cost including supervision, preliminary engineering cost and the cost of routine and preventive maintenance and rehabilitation cost that will be invested within the analysis period. Salvage value has been taken into account to compare the investments by the end of analysis period and is a function of expected life of rehabilitation alternate, portion of expected life consumed, and cost of rehabilitation strategy.

Hall et al. [2003] presented guidelines for life-cycle cost analysis of pavement rehabilitation strategies. These researchers discussed the key issues that need serious considerations while adopting rehabilitation strategies. The key issues include selection of appropriate analysis period difference in vehicle operating costs in relation to predicted serviceability trends and differences in user delay cost in relation to lane drop time and length.

Falls and Tighe [2003] presented improving life-cycle cost analysis through the development of cost models using the Alberta roadway maintenance and rehabilitation analysis application. These researchers particularly examined maintenance cost models to compute maintenance cost which forms a part of life-cycle cost analysis and could be utilized to analyze the rehabilitation alternatives using location based data relevant to surface condition data and maintenance work. Such type of application would help improve system for monitoring and tracking costs.

Labi and Sinha [2003] developed life-cycle preventive maintenance cost-effectiveness models for different pavement families. The families were categorized according to pavement type, traffic, and service class. The functional forms of the preventive maintenance cost-effectiveness models suggested that the cost effectiveness of preventive maintenance is a function of preventive maintenance effort, expressed in dollar values per lane-mile of road. The models could help conduct tradeoff analysis of different investment strategies over pavement service life-cycle.

Peshkin et al. [2004] studied systematic preventive maintenance and the optimum timing strategies to achieve minimum life-cycle costs. The methodology was based on analyzing pavement performance over a period of time to identify the optimal timing of treatment. The optimal timing was said to be the point of greatest benefit-to-cost ratio. Benefits were measured as the quantitative influence on pavement performance measured in relation to one or more condition indicators as rutting, cracking, and friction.

Costs included the agency cost for the treatment, work-zone user delay cost, cost of rehabilitation at the point where the preventive maintenance was considered failed, and cost of routine maintenance.

Harrigan [2002] investigated the performance of pavement subsurface drainage and conducted the life-cycle cost analysis to illustrate the various subsurface drainage features. Effects of subsurface drainage on rigid and flexible pavements were studied. The methodology adopted for the study was on impact of subsurface drainage, direct comparisons of the performance of drained and non drained experimental sections, and distress predictions for mechanistic-empirical models based on all available performance data.

Bridge Life-Cycle Agency Cost Analysis

Purvis et al. [1994] conducted life-cycle cost analysis of protection and rehabilitation of concrete bridges relative to reinforcement corrosion. The rehabilitation work was applied only when the concrete deterioration was associated with chloride induced corrosion of reinforcing steel. Agency cost included deck treatment and structural treatment cost, while user cost included prior treatment cost for its effect on traffic flow and during treatment cost. Computer method of life-cycle cost analysis was proposed to determine the timing of the activity aimed to minimize life-cycle overall discounted agency and user cost.

Meiarashi et al. [2002] compared two highway suspension bridges made both of conventional steel and advanced all-composite of carbon fiber using life-cycle cost analysis. The initial construction cost and maintenance cost were taken into account for the life-cycle cost analysis.

Hawk [2003] carried out bridge life-cycle cost analysis that categorized the overall costs into three different categorizes: agency cost, user cost, and vulnerability cost which included both agency and user costs. In the life-cycle agency cost analysis, cost items cost included routine maintenance cost, bridge element rehabilitation cost, bridge element replacement costs, and bridge replacement costs. User cost included detour costs and crash costs. Vulnerability cost consisted of condition-related reduction in load capacity, life or both, seismic vulnerability, bridge scour, and overloads. As part of the study, a Bridge Life-Cycle Cost Analysis software tool was developed to evaluate two fronts associated with bridges. First, it could be used to assess the tradeoffs between initial cost and long term maintenance. Second, it could provide information on whether rebuild of a bridge to the future capacity was feasible or expansion in the future would be better. The major strength of the program was its flexibility of varying cost and timing in the analysis.

Chandler [2004] developed life-cycle cost models to evaluate the sustainability of bridge decks. Both agency cost and social cost were considered in the analysis. The agency cost included construction cost and salvage value at the end of useful service life-cycle. The social cost was comprised of emission damage costs from agency activities, congestion, delays, crashes, and vehicle operating costs across all stages of bridge service life-cycle. To model the life-cycle cost, two types of bridge decks were compared. The decks with conventional concrete joints were compared with engineered cement composite link-slabs. It was found that fluctuations on annual average daily traffic had major effect while detours had little effect on bridge life-cycle costs.

Calculation of User Benefits

Calculation of User Benefits on a Directly Affected Road Segment with Shift in Demand

The user benefits as a resulted of a transportation improvement is captured by the concept called consumer surplus. Provided with a demand curve, the consumer surplus is the difference between what road users in the aggregate would have been willing to pay, and what they are actually asked to pay. The change in consumer surplus between a project alternative and the base case is considered as the user benefits associated with the project alternative. For a generalized case where the demand curve shifts upward as a result of a project improvement, the user benefits can be calculated as illustrated in Figure 1.

The user benefits could be the daily, weekly, monthly, or annual benefits of either element of vehicle operating costs, travel time, vehicle crashes, and air emissions.

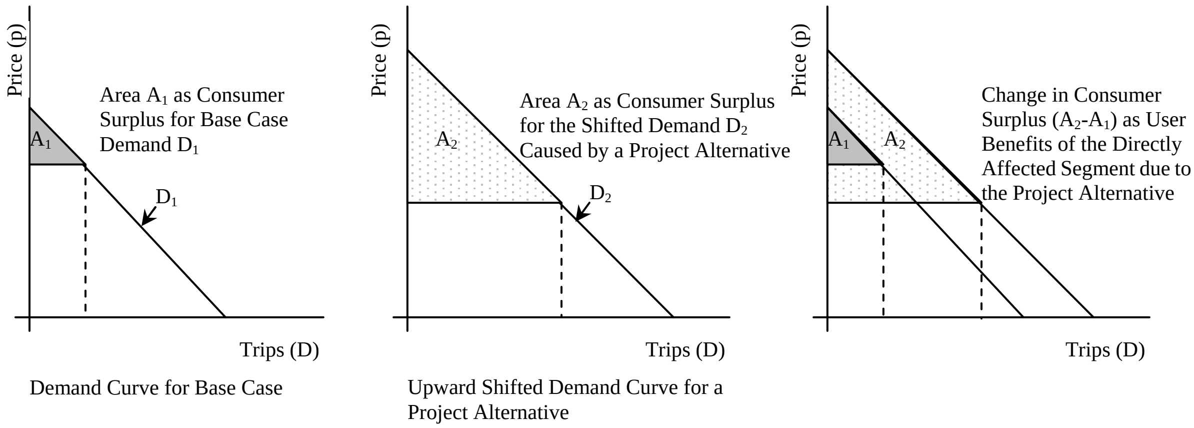

Figure 1. Illustration of Calculating User Benefits on a Directly Affected Road Segment with Shift in Demand

Calculation of User Benefits on an Indirectly Affected Road Segment with Shift in Demand

If improvements cause traffic to shift to the improved segment, other indirectly affected segments may see a backward shift in demand on the indirectly-affected segments. That is, the travel demand on the indirectly-affected segments is less at every user cost. As illustrated in Figure 2, the change in consumer surplus is just analogues of the change of consumer surplus that is measured on the directly affected segment. The approach can be applied to every affected link to accounts for all changes in consumer surplus.

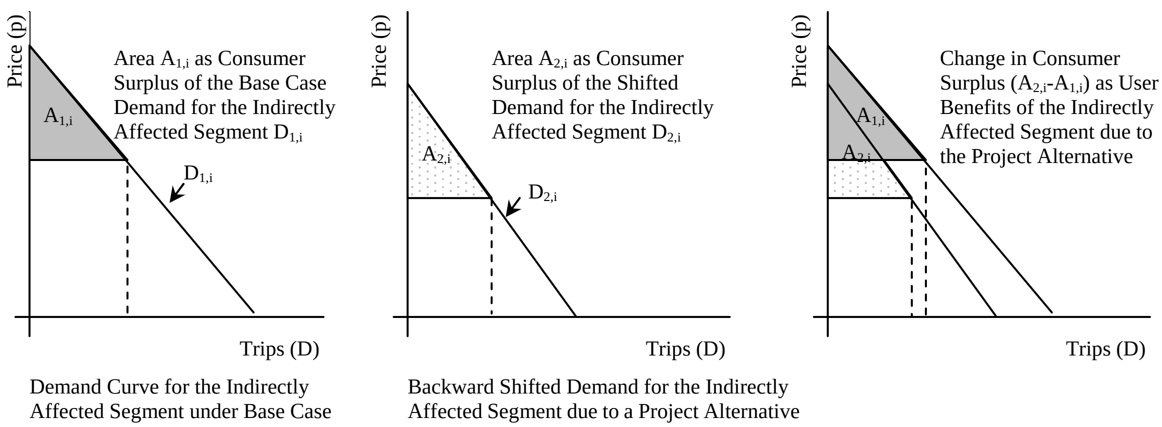

Figure 2. Illustration of Calculating User Benefits on an Indirectly Affected Road Segment with Shift in Demand

Overall User Benefits of a Project Alternative

The overall user benefits of a project alternative as compared to the base case is the summation of changes in all consumer surpluses associated with directly and all indirectly affected road segment. Once obtaining an estimation of annual overall user benefits, the life-cycle user benefits can be extrapolated accordingly.

Unit Values of User Cost Elements

Vehicle Operating Unit Costs

Vehicle operating costs refer to costs of fuel, tires, maintenance and repair, and mileage-dependent vehicle depreciation that vary with usage and are measured in terms of dollars per vehicle-mile. Costs that do not vary with usage, such as insurance, storage, financing, and time-dependent vehicle depreciation, are not included in this definition of operating costs.

Transportation projects can affect vehicle operating costs directly by improving operating conditions such as fewer changes in speed, reduced grades, smoother pavements, and wider curves or indirectly by influencing traveler behavior including more frequent usage and more direct routing. The highway vehicle operating costs are affected by vehicle type, vehicle speed, speed changes, gradient, curvature, and road surface condition, as briefly described in Table 3. In addition, Table 4 provides a range of estimates used in several benefit-cost models.

Table 3. Factors Affecting Vehicle Operating Costs

Factor	Brief Description
1. Vehicle type	Generally, cars have lower operating costs than trucks, due to lower fuel and oil consumption, and lower price of vehicle and parts, maintenance and repairs. Since vehicle technology, fuel efficiency and price/costs change over time, vehicle operating costs for various classes of vehicles will also change and must be periodically updated.
2. Vehicle speed	Empirical research indicates that vehicle speed is the dominant factor in determining vehicle operating costs. They decreases as vehicle speed increases, reaching an optimum efficiency point at mid-range speeds, after which point costs will increase as vehicle speed increases further.
3. Speed changes	Empirical research indicates that vehicle operating costs increase with speed cycles and the added cost of speed cycling is higher at higher speeds.
4. Gradient	Driving a vehicle up a steep, positive grade requires more fuel than driving it along a level road at the same speed, and the additional load on the engine imposes added costs of maintenance. Roadway sections with negative gradient would have an opposite effect. However, as the steepness of the down grade increases, it may be necessary to apply the brakes and this also imposes an added operating cost burden.
5. Curvature	Curves impose costs through the centrifugal force that tends to keep the vehicle following a tangent rather than a radial path. The force is countered by super-elevation of the roadway and the side friction between the tire tread and the roadway surface. As a result, there is a greater usage of energy and more fuel is required to negotiate curved sections. In addition, the side friction increases tire wear and raises this component of operating costs.
6. Road surface condition	The motion of a vehicle on a rough surface meets with greater rolling resistance, which requires more fuel consumption compared to traveling at a similar speed on a smooth surface. The roughness of road surface contributes to reduction of speed, additional tire wear and influences the vehicle maintenance and repair expenses incurred in the operation of a vehicle.

Table 4. Summary of Vehicle Operating Cost Estimation Methods

Model	Attribute				
	VOC Items	Factors Considered	VOC Range $/veh-mile (Year)	Vehicle Types Included	Source
AASHTO Red Book	Fuel, oil, tire, maintenance	speed, speed cycling, grade, curvature, pavement condition	Auto: - 0.039-0.117 gal fuel/veh-mile Truck: - 0.158-0.503 gal fuel/veh-mile (1992) Car, SUV, and van: - $0.095 - 0.124/ veh-mile (2000)	Car, SUV, van, truck	AAA [1999] Cohn et al. [1992]
CAL-B/C	Fuel, non-fuel	Speed (for fuel only)	Auto: - 0.033-0.182 gal fuel/veh-mile - $0.165/veh-mile for non-fuel cost (2000) Truck: - 0.008-0.511 gal fuel/veh-mile - $0.285/veh-mile for non-fuel cost (2000)	Auto, truck	USDOT [1992]
HERS	Fuel, oil, tire, maintenance and repair, depreciation	Speed, speed cycling, grade, curvature, and pavement condition	$0.18 (1995)	2 car types, 5 truck types	Zaniewski et al. [1982]
STEAM	Fuel, tire, maintenance and repair	Speed (for fuel only)	$0.05 - 0.09 (1994)	Car, truck	USDOT [1992]
StratBENCOST	Fuel, oil, tire, maintenance and repair, depreciation	Speed, speed cycling, grade, curvature, and pavement condition	$0.17 - 0.32 (1996)	Car, truck, bus	Zaniewski et al. [1982]

Value of Travel Time

Highway projects often lead to higher speeds and lower travel times for drivers, passengers, and freight. Since travel time reductions can make-up a major portion of user benefits, it is important to use an appropriate value of time when converting these benefits into dollar terms. The time cost of travel generally includes two components: the resource cost reflecting the value to the traveler of an alternative use of time such as work; and the disutility cost as the level of discomfort, boredom, or other negative aspect associated with time lost due to travel. Table 5 lists factors affecting the value of travel time.

Table 5. Factors Affecting the Value of Travel Time

Travel Time Cost Component	Factor	
1. Resource Cost	a. Wage rate	It is generally thought that higher income groups value travel time at a higher price than lower income groups. The USDOT recommends that different wage rates be used as the basis for calculating time values for truck drivers, air travelers, and travelers on surface passenger modes.
	b. Trip purpose	There is consensus that on-the-clock work travel should be valued at the wage rate including fringe benefits, while other trip purposes should be valued at some fraction of the wage rate.
	c. Amount of timing saving	There has been substantial disagreement in the literature on the value of small units of time. Some studies suggest that small increments of time have lower unit values than do larger increments of time. Other valued time savings at the same rate, regardless of the amount of time savings.
2. Disutility cost	a. Congestion	Travel under congested conditions puts extra stress on the driver. As a result, reductions in travel time during peak periods, which are most likely to be congested, are likely to be valued more highly than reductions in travel time during off-peak periods.
	b. Passenger versus driver time	It is logical that the stresses of driving may make travel time savings more important to drivers than to passengers and to suggest a higher value of time for drivers.
	c. Level of service, walking, and waiting time	There is disagreement about whether distinctions should be made between transportation modes due to differences in comfort and other service attributes. It is generally accepted that time spent walking and waiting for a vehicle exposure to adverse weather) has a higher value to the rider than time spent riding in the vehicle.

The methods derived for measuring value of travel typically fall into types of analyses: mode choice, route choice, speed choice, dwelling choice, and wage rate-based analyses. These methods are briefly summarized in Table 6.

Table 6. Methods for Estimating the Value of Travel Time

Method	Brief Description
1. Mode choice	Mode choice analysis attempts to compare a fast, but expensive mode with inexpensive, but slow one. The difference in cost is presumably equal to the value of the difference in time. Most of these analyses compare automobiles with some sort of transit.
2. Route choice	In route choice analysis, a slow and inexpensive route option is compared with a faster and more expensive route option for a single travel mode. The difference in cost is presumably equal to the value of the difference in time.
3. Speed choice	Speed choice analysis is one attempt to supplement the results of route choice analysis. The analyses are based on the economic assumption that rational, utility maximizing individuals adopt driving speeds that minimize their total trip costs. While travel time is one component of the trip cost, there are other trip costs, such as vehicle operating costs and accident costs. Assuming that all costs are perceived by drivers and that the least cost speed is selected, the perceived time costs can then be determined.
4. Dwelling choice	In this form of analysis, the value of time is calculated by comparing housing value against the time it takes to reach the work. The analysis results can be used to corroborate other estimating methods.
5. Wage rate	For "off-the-clock" travel, the hourly wage rate is treated as a standard against which the value of time is measured. The concept underlying this approach is that travelers' hourly wages give the opportunity cost of their time. The percentage of wage rate appears to be a convenient metric to measure value of time associated with "off-the-clock" travel.
	For the value of "on-the-clock" travel time, there is a general consensus that a driver's wage rate is the right measure of the value of his or her time when highway travel is part of the person's work. Thus, the average labor cost for truck drivers is an appropriate value of time for truck traffic.

The values of travel time established in various existing models are summarized in Table 7.

Table 7. Summary of Values of Travel Time in Existing Models

Model	Auto	Bus	Truck	Source
AASHTO Red Book STEAM CAL-B/C	- 50% of the wage rate for driving alone commute - 60% of the wage rate for carpool driver commute - 40% of the wage rate for carpool passenger commute - 50% of the wage rate for personal local trip - 70% of the wage rate for personal intercity trip - 100% of total compensation for business	- 50% of the wage rate for in-vehicle commute - 50% of the wage rate for in-vehicle personal - 100% of the wage rate for non-business waiting, walking or transfer time - 100% of total compensation for business	- 100% of total compensation for in-vehicle business - 100% of total compensation for business waiting time	USDOT [1997]
HERS	Work-related travel: $9.59/veh-hour (1988 dollar)	-	Work-related travel: - $10.87/veh-hour for 4-tire truck - $20.42/veh-hour for 6-tire truck - $23.34/veh-hour for 3-4 axle truck - $25.94/veh-hour for 4-axle comb. truck - $26.09/veh-hour for 5-axle comb. truck	USDOT [1997]
	Non-work travel: 60% of the wage rate	-	Non-work travel: 60% of the wage rate	Jack Faucett Assoc. [1991]
StratBENCOST	- Low: $10.97/veh-hour - Med: $11.78/veh-hour - High: $23.36/veh-hour (1996 dollar)	- Low: $77.25/veh-hour - Med: $82.94/veh-hour - High: $164.46/veh-hour (1996 dollar)	- Low: $30.07/veh-hour - Med: $32.28/veh-hour - High:$64.01/veh-hour (1996 dollar)	TTI [1990] Jack Faucett Assoc. [1991]

Vehicle Crash Unit Costs

Vehicle crashes can vary in severity and the number of individuals involved. By severity, vehicle crash types can be divided into fatal, injury, and property damage only (PDO) categories. Fatalities result in lost years of life, while injuries result in lost years of productive life. Injuries may also cause pain and suffering. In addition, all accidents result in property damages of varying severity. Table 8 presents methods valuating vehicle crash losses.

Table 8. Methods for Valuating Vehicle Crash Losses

Method	Brief Description
1. Direct cost	This method measures only the easily-measurable out-of-pocket costs of accidents, which include crash clean-up, injury treatment, property repair and replacement, accounting for workplace disruption, and insurance claims processing and related costs. The personal costs, emotional and physical, are ignored in the direct costs method.
2. Human capital	This method calculates values as a function of salary. As a result, lower values are computed for women and children than for men. This method ignores pain, suffering, and lost quality of life. Human capital costs are useful to determine the dollars lost to injury and death, and form the basis for legal compensation awards.
3. Years of loss plus direct cost	This method estimates two sets of costs: the years of life lost to fatalities and the years of productive life lost to nonfatal injuries, and the dollar value of the medical costs. Since the medical costs for a serious injury are much higher than for a sudden death, the combined value could be misleading.
4. Willingness-to-pay	This method involves evaluating the reduction of accident risk by estimating the amount people pay for small decreases in safety and health risks, often obtained through the analysis of safety equipment purchases made by individuals. The method places a value on people's behavior of exchanging money, time, comfort, and convenience for safety. Frequently these values are added to the results of the direct cost approach to obtain an overall crash value.

The unit costs of vehicle crashes established in various existing models are summarized in Table 9.

Table 9. Summary of Vehicle Crash Unit Costs in Existing Models

Model	Fatality	Injury	PDO	Source
AASHTO Red Book (2000 dollar)	$3,366,388	Critical: $2,402,997 Severe: $731,580 Serious: $314,204 Moderate: $157,958 Minor: $15,017	$3,900	USDOT [2000]
CAL-B/C (2000 dollar)	$3,104,738	$81,572	$6,850	NSC [1995]
HERS (1988 dollar)	$2,000,000	Urban: $10,000- 18,000 Rural: $17,000- 20,000	Urban: $5,000- 6,000 Rural: $4,000- 5,000	Jack Faucett [1991]
STEAM (1997 dollar)	$2,726,350	$59,718	$3,323	FHWA [1994]
StratBENCOST (1996 dollar)	Low: $809,054 Med: $3,521,359 High: $8,097,408	Low: $14,946 Med: $83,848 High: $216,698	Low: $1,442 Med: $5,806 High: $11,720	FHWA [1994]

Vehicle Air Emission Unit Costs

Transportation investments affect the environment because of the construction process, impacts of the facility itself, and resulting changes in travel behavior. Vehicle emissions generally fall into two categories: vehicle emit pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_X), volatile organic compounds (VOC), particulate matter (PM), and oxides of sulfur (SO_X); and greenhouse gas emissions, mainly caused by carbon dioxide (CO_2). Air pollutants can cause damage to human health, building materials, and agriculture and vegetation, as well as limit visibility. Increasing concentrations of greenhouse gases in the atmosphere may be causing changes in the Earth's climate that could potentially impose substantial costs on society in terms of flooding, crop loss, and increased incidence of disease. Factors that affect vehicle air emission quantities are summarized in Table 10.

Table 10. Factors Affecting Vehicle Air Emission Quantities

Factor	Description
1. Vehicle age	The engine fuel efficiency decreases with the increase of vehicle age. This accordingly will increase air emission rates.
2. Vehicle speed	Speeds are of particular importance in determining vehicle emission rates. In general, VOC emission rates tend to drop as speed increases, whereas NO_X and CO emission rates increase at higher speeds (above 55 miles per hour).
3. Vehicle composition	Mix of vehicles types in the traffic stream and changes in the mix affect air emission rates.
4. Traffic condition	Emission rates are also higher during stop-and-go, congested traffic conditions than during free flow conditions at the same average speed.
5. Ambient air temperature and cold-start trips	Starting a cold vehicle results in additional emissions because a vehicle's emissions control equipment has not reached its optimal operating temperature.

The air emission unit costs are typically estimated based either on damage costs or control costs. Damage cost valuation involves estimating the actual value of the harm caused by air emissions, whereas control cost valuation examines simply the cost of the measures necessary to reduce air pollutant emissions. Damage cost valuation is preferable because studies that use control costs to value air pollution rely on the assumption that the controls placed on pollution are efficient. The steps involved with a damage cost valuation are listed in Table 11.

Table 11. Damage Cost Method for Estimating the Unit Cost of Vehicle Air Emissions

Step	Description
1. Impact of pollutant emissions on air quality	Ambient air pollution concentrations are the result of air pollutant dispersion, reaction, and residence, complicated by meteorology and topography. These processes result in non-linear relationships between pollutant emissions and air concentrations that can be determined through computer modeling.
2. Increase of health problems caused by air quality deterioration	The dose-response functions can be used to estimate the increased risk of developing a certain adverse health effect, such as headaches, chronic respiratory problems, or mortality, in response to increased air pollutant concentrations.
3. Dollar costs per health effect	Health impacts in monetary terms can be quantified using revealed preferences method that estimates costs based on people’s behavior; and expressed preferences that asks people about the cost of an impact.
4. Estimation of unit costs	The unit costs per ton of pollutants emitted can be estimated based on information in Steps 1-3.

The unit costs of vehicle air emissions established in various existing models are summarized in Table 12.

Table 12. Summary of Vehicle Air Emission Costs per Ton in Existing Models

Model	CO	NO_X	PM	SO_X	VOC	Source
CAL-B/C (2000 dollar)	Rural: $54 Urban: $60	Rural: $10,144 Urban: $13,646	Rural: $78,618 Urban: $110,258	Rural: $39,732 Urban: $55,069	Rural: $749 Urban: $954	McCubbin and Delucchi [1996]
STEAM StratBENCOST (1991 dollar)	Urban Low: $9 High: $90	Urban Low: $1,440 High: $21,200	Urban Low: $12,500 High: $170,100	Urban Low: $8,700 High: $82,500	Urban Low: $140 High: $1,440	McCubbin and Delucchi [1996]

Classical Benefit-Cost Analysis Methods

Net Present Worth Method

The net present worth method uses the chosen discount rate to convert the project benefits and costs to its equivalent present value and then compares these values. The present value of the benefits and costs is equal to the summation of the values of these effects multiplied by3 the present worth factor appropriate to the period over which the benefits and costs occur. The net present worth then equals the difference between the present value benefits and costs.

Equivalent Uniform Annual Cost Method

The equivalent uniform annual cost method converts non-uniform series of project benefits and costs into uniform annualized amounts of benefits and costs, respectively. The annualized benefits and costs are then used to compare project alternatives on equal basis.

Benefit-to-Cost Ratio Method

The benefit-to-cost method compares the discounted benefits and costs for each project and then compares each alternative to another.

Cost-Effectiveness Method

The “effectiveness” of a project alternative is usually represented as a scaled quantity relating to a specific goal. For instance, number of car pools formed and reduction in vehicle air emission quantities. Cost-effectiveness ratios can thus be calculated to show the degree of goal attainment per dollar of net expenditure. This method is particularly useful when it is difficult to reach a consensus in unit values of user cost elements, such as values of travel time, vehicle crashes, and air emissions.

Consideration of Risk and Uncertainty

Highway project benefit-cost analysis is fraught with risk and uncertainty because of the nature of the information that is available, developed, and used. Forecasting future conditions of pavements and bridges, travel patterns, costs, and effect levels is based on many assumptions, extrapolation of past behavior, and less-than-perfect understanding of causal relationships. In the case of risk, the decision-maker is ignorant of possible outcomes but the range and distribution of possible outcomes are known. For uncertainty, on the other hand, either the range or distribution of possible outcomes, or both, are not known. Some notable probabilistic project benefit-cost analyses conducted are briefly discussed in the following:

Walls and Smith [1998] recommended Life-cycle analysis on pavements and provides the detail computation process of user cost which they distributed evenly among the useful life period and introduces probabilistic approach to deal with risk and uncertainty associated with the project. In the user cost analysis the study does not take account of the vehicle emissions but it put forth the idea of computing work zone user cost which is the delays, crashes, and increased vehicle operating costs during the maintenance and rehabilitation process. It combines variability of inputs to generate the probability distribution of the results. It essentially quantifies the uncertainties using probability distribution resulted either form subjective or objective analysis. Normal distribution is used to define the variability of agency cost but for the cases which does not have measurable data triangular distribution has been suggested.

Tighe [2001] conducted a probabilistic life-cycle cost analysis by incorporating mean, variance, and probability distribution for the typical construction variables, such as thickness and cost. The researcher concluded that the cost distribution follows a lognormal distribution rather than a normal distribution. Ignoring the lognormal nature of these variables would introduce significant biases in the overall life-cycle cost estimation.

Setunge et al. [2002] developed a methodology for whole of life-cycle cost analysis of alternative rehabilitation treatments for bridge structures. The input parameters for the analysis were identified as initial cost, maintenance, monitoring and repair cost, user cost, and failure cost. The methodology utilized Monte Carlo simulation to combine a number of probability distributions to establish the distribution of bridge whole life-cost costs.

Comparison of Available Benefit-Cost Analysis Software Tools

Table 13 lists software packages most often used by analysts to estimate the benefits of highway projects. The features of individual models in terms of level of analysis, special features, and software limitations are summarized.

Table 13. Comparison of Available Benefit-Cost Analysis Models

Name	Source	Project Type	Level of Analysis	Special Feature	Limitation
AASHTO Red Book	AASHTO	Highway operational improvements and safety projects	Project level	Travel time, VOC, and crash benefits of additional lanes, new highways, traffic control, signal systems, ITS improvements, pricing and regulatory policies; geometry, lane, access, and roadside safety improvements	Limited accounting for network effects; no accounting for modal interaction
Cal- B/C	CALTRANS	Highway, transit	Network level	Travel time, VOC, crash, and emission benefits of highway improvements, ITS, and transit improvements	No accounting for interaction between modes
HDM4	World Bank	Highway improvements	Network level	Includes 16 motorized and 8 non-motorized vehicle types; includes roadway deterioration model for asphalt, concrete, gravel, and dirt roads; estimates emissions and energy consumption	No accounting for interaction between modes
IDAS	Cambridge Systematics	ITS improvements	Project level	Estimates benefits and costs for signals, ramp metering, incident management, electronic payment, traveler information, weigh-in-motion, and traffic surveillance	Evaluates ITS options only
MicroBENCOST	TTI	Highway improvements and safety projects	Project level	Includes intersection and interchange delay, bridges, RR crossings, HOVs, and safety improvements; analyze emissions, construction delays; estimates discomfort costs based on road condition	Limited accounting for network effects; no accounting for interaction between modes
Roadside	AASHTO	Roadside improvements	Project level	Integrated with design tool	Only accounts for safety-related benefits
STEAM	FHWA	Highway, transit, TDM, tolls, multimodal	Network level	Accepts input from four-step models; separate analysis of peak and off-peak periods by trip purpose and mode; emissions; fuel consumption; revenue transfers	Some costs must be estimated outside model; requires trip tables and network from external travel demand model
StratBENCOST	HLB	Highway improvements	Network level	Risk analysis, environmental effects, separate modules for network-wide or single-roadway analysis; includes construction delays	No accounting for interaction between modes

METHODS FOR HIGHWAY PROJECT SELECTION AND TRADEOFF ANALYSES

Classical Project Selection and Tradeoff Analysis Methods

Highway asset management entails a comprehensive view across a range of physical highway assets and their usage. The management process encourages developing the most cost-effective mix of projects under various program categories and examining the implications of shifting funds between different program categories. Through tradeoff analysis, the economic benefit and cost of shifting funds from one program category to another can be assessed. In addition, the service level possible at different program funding levels can also be defined. Ranking, prioritization, and optimization offer an approach that allows for selection of different types of projects in the priority setting process [FHWA, 1991].

Ranking is the simplest form of priority setting for the selection of highway projects for a single year period, which is also called single year prioritization. The ranking procedure mainly includes two steps. The first step is to determine project items of a highway asset type that should be considered for preservation or improvement. For each set of candidate projects, the best alternative for each candidate project is identified and the corresponding cost is determined. The next step involves prioritization of candidate projects according to a given set of criteria. The ranking procedure may be implemented by using single criterion, such as distress, condition, initial cost, least present cost and timing, life-cycle cost, benefit-cost ratio, cost-effectiveness, or composite criteria such as a ranking function combining condition, geometry, traffic, maintenance, and safety factors [Zimmerman, 1995]. The ranking procedure produces a ranked list of projects to be carried out, the cost associated with each project, and a cut-off line established based upon the level of funding available. As the timings of alternative projects are not considered in the ranking process, the long-term impacts of delaying or accelerating projects from one year to another cannot easily be evaluated.

Multi-year prioritization is a more sophisticated approach to project selection that is closer to an optimal solution for addressing highway network scheduling and budgeting needs. This method requires the use of performance prediction models, or remaining service life estimates. It also requires the definition of trigger points to identify needs and provisions that allow the acceleration or deferral of treatments during the analysis period. Common approaches used to perform prioritization include marginal cost-effectiveness, incremental benefit-cost, and remaining service life analysis. Multi-year prioritization differs from the ranking procedure in a number of ways. First, different strategies that include alternatives and timings are considered in multi-year prioritization. Another difference lies in the complexity of the analysis. In the ranking procedure, the most common criteria considered are current condition and existing traffic levels. In a multi-year prioritization, an agency is able to simulate future conditions through the use of performance models and consider other factors in the analysis. Furthermore, with multi-year prioritization, the option of timing of maintenance, rehabilitation, or reconstruction can be included in the analysis. The impact of various funding levels can also be assessed [FHWA, 1991].

Through the use of mathematical programming techniques, such as linear programming, integer programming, and dynamic programming, an optimal solution can be developed in accordance with goals established, such as maximizing total agency benefits or minimizing agency cost to achieve certain condition levels [Zimmerman, 1995]. Unlike prioritization, optimization analysis can yield outputs that are provided in terms of percentage of miles of roads or bridges that should be improved from one condition to another, rather than identifying candidate projects. Optimization addresses several important considerations that are not covered in prioritization analysis. These include the incorporation of tradeoff analysis among candidate projects during strategy selection. Optimization also guarantees that the selection of strategies adheres to budgetary limits. Furthermore, optimization allows multi-year network level planning and programming aimed at moving the overall system towards a defined performance level. Table 14 summarizes programs and project tradeoff tools used by state transportation agencies [Cambridge Systematics, 2000].

Table 14. Highway Project Selection Tools Used by State Departments of Transportation

State	Program Category	Project Tradeoff Criterion
Arizona	- Interstate construction and reconstruction - Non-Interstate major construction - Bridge, railroad crossing, hazard elimination - Transportation system management	Prioritization by - Benefit-cost analysis - Sufficiency ratings - Engineer's recommendations
California	- Highway Operation and Protection Program - Transportation Improvement Program - Traffic Systems Management Plan	Technical and policy screen, scoring based on technical merits, policy priority, and air quality control measures
Indiana	- Bridge preservation - Pavement preservation - Safety and roadside improvements - System expansion - ITS improvements - Maintenance	- Ranking by utility values - Prioritization by incremental benefit-cost analysis - Optimization by mix-integer programming
Minnesota	- Preservation - Management and operations - Replacement - Expansion	Ranking by - Sufficiency/ deficiency ratings - Benefit-cost analysis - Cost-effectiveness analysis
Montana	- Maintenance - Rehabilitation - Expansion	- Ranking - Prioritization by incremental benefit-cost analysis - Optimization
New York	- State pavement - Statewide congestion/ mobility	Ranking by - Sufficiency/ deficiency ratings - Life-cycle cost - Cost-effectiveness - Benefit-cost analysis
Oregon	- Preservation - Modernization - Operations Safety	- Technical ranking and scoring
Pennsylvania	- Bridge rehabilitation and replacement - Interstate/ expressway restorations - Congestion reduction - Safety, mobility, and congestion - New facilities and services	Ranking by - Sufficiency ratings
Texas	- Added capacity and new location - Highway rehabilitation and construction - Bridge replacement and rehabilitation - Maintenance	Ranking by - Cost-effectiveness, - Sufficiency/deficiency ratings
Washington	- Maintenance - Preservation and improvement - Operations	Ranking by - Benefit-cost analysis
Wisconsin	- Maintenance - Rehabilitation, restoration, and reconstruction - Interstate - Bridge	- Ranking by deficiency ratings, benefit-cost analysis - Multi-objective optimization

Solution Algorithms for Project Selection and Tradeoff Analysis

Similar to project selection and programming process used in pavement and bridge management systems, the optimization process for overall highway asset management can also be treated as a capital budgeting problem [Lorie and Savage, 1955] because a subset of mixed projects is selected from a systemwide candidate project list to yield maximum system benefits subject to budget constraints. However, the optimization process is more complicated for highway asset management because multiple asset types are involved and additional budget constraints by asset category may be required. Furthermore, as projects are implemented by contracts in which multiple projects may come from different asset types, a project inter-dependence relationship must be considered. In this case, project selection and programming for overall highway asset management evolves to a multi-choice multidimensional Knapsack problem, where the budget is achievable from different sources and the analysis is conducted for multiple years.

The multi-choice multidimensional Knapsack problem is considered as NP-hard in the sense that no non-deterministic polynomial algorithm exists, i.e., the time requirement for the optimal solution grows exponentially with the size of the problem instances. Algorithms for these problems can be classified into two group, exact algorithms and heuristic algorithms. The exact algorithms are mainly based on branch-and-bound, dynamic programming, and are a hybrid of the two techniques. Heuristic algorithms may solve the problem close to optimal in polynomial time but do not guarantee optimality. Notable algorithms are largely based on dual simplex and Lagrangian relaxation techniques [Martello and Toth, 1990]. Algorithms developed during the past two decades for solving the multi-choice multidimensional Knapsack problem, including the multi-choice Knapsack problem, where multiple budget sources and a single analysis period are involved and the multidimensional Knapsack problem, where a single budget source and multiple periods for the analysis are considered, are briefly discussed as follows.

Exact Solution Algorithms

Sinha and Zoltners [1979] presented a branch-and-bound algorithm for the multi-choice Knapsack problem that resided with quick solution of linear programming relaxation and its efficient, subsequent re-optimization as a result of branching. This algorithm performed well on the basis of a large set of test problems. Armstrong et al. [1983] conducted a computational study based on the branch-and-bound algorithm developed by Sinha and Zoltners, wherein, data list structures, sorting techniques, and fathoming criteria were investigated. These researchers further improved the algorithm by inserting a heap sort in the algorithm, which resulted in a substantial reduction in computational time. Aggarwal et al. [1992] proposed a two-stage algorithm based on Lagrangian relaxation and branch-and-bound. In this algorithm, the first stage was aimed at determining in polynomial time an optimal Lagrangian multiplier, which was then used in the second stage within a branch-and-bound scheme to rank order solutions and finally lead to an optimal solution in a relatively low depth of search. A hybrid algorithm that combined dynamic programming and the branch-and-bound algorithm was developed by Dyer et al. [1995] to solve the multi-choice Knapsack problem. In this algorithm, Lagrangian duality was used in a computationally efficient manner to compute tight bounds on every active node in the search tree. Computational experience indicated that the resulting algorithm ran fast and was simple to code. Klamroth and Wiecek [2001] also proposed a dynamic programming approach to find all nondominated solution to the multi-choice multidimensional Knapsack problem. Osorio and Glover [2001] presented a method of logic cuts from dual surrogate constraint analysis before solving the multidimensional Knapsack problem with branch-and-bound, and computational testing showed that the approach solved different problems in a reasonable amount of time.

Heuristic Solution Algorithms

Frieze and Clarke [1984] described a polynomial time approximation scheme for the multidimensional Knapsack problem based on the used of a dual simplex algorithm for linear programming. Toyoda [1975] suggested a simplified heuristic algorithm based on Lagrangian relaxation for an approximate solution to the multi-choice multidimensional Knapsack problem. Magazine and Oguz [1984] presented a polynomial time-generalized Lagrangian Multiplier approach based on Toyoda's algorithm. Volgenant and Zoon [1990] further extended the algorithm, which also enabled the determination of an upper bound to the optimal solution by allowing more multipliers to be computed simultaneously and sharpened the upper bound by changing some multiplier values. Lee and Guignard [1988] presented an approximation algorithm for the multidimensional Knapsack problem that was controlled by three user-controllable parameters affecting the tradeoff between solution quality and computational time. Zemel [1984] presented a linear time algorithm for the linear multi-choice Knapsack problem and its D-dimensional generalization based on Megiddo's algorithm. In the same period, Dyer [1984] also suggested a linear time algorithm for the multi-choice Knapsack problem with solution quality within a constant factor of optimality. Freville and Plateau [1994] introduced a subgradient heuristic algorithm for the multidimensional Knapsack problem that provided sharp lower and upper bounds on the optimal value and also a tighter equivalent representation by reducing the continuous feasible set and by eliminating constraints and variables. Moser et al. [1997] introducted a heuristic algorithm based on the Lagrangian multiplier method for a solution to the multi-choice multidimensional Knapsack problem with polynomial time complexity. Teng and Tzeng [1996] suggested an effective distance heuristic optimization algorithm for the multidimensional Knapsack problem involving a project inter-dependence relationship. The algorithm was able to provide a near optimal solution. Chu and Beasley [1998] presented an algorithm that incorporated problem-specific knowledge into the standard genetic algorithm for the multidimensional Knapsack problem. Computational results showed that the genetic algorithm gave superior solutions to a number of other heuristics with only a modest amount of computational efforts. Akbar et al. [2001] developed two heuristic algorithms for solving the multi-choice multidimensional Knapsack problem based on sorting the items of each group in non-decreasing order according to the value associated with each item. The study's experimental results suggested that the heuristic algorithms find near optimal solutions with much less computational complexity.

REVIEW SUMMARY

This literature review focused on two technical aspects: methods for highway project benefit-cost analysis and for tradeoff analysis. In the review of benefit-cost analysis methods, emphases were first given to the clarification of project-level versus network-level analyses, computation of life-cycle agency and user benefits regarded as the reductions of the respective costs resulted from certain amount of project costs. Life-cycle agency costs include direct agency cost regarding project construction and subsequent costs of maintenance and rehabilitation in the course of project service life-cycle. The user cost elements consist of vehicle operating costs, travel time, vehicle crashes, and air emissions. Then, factors affecting the unit values of individual user cost elements, methods for estimating the unit values, and estimated unit values were then identified and summarized. Subsequently, the issue of risk and uncertainty and some recent studied accomplished on highway pavement and bridges facilities were investigated. Comparison of available benefit-cost analysis tools was provided in the last part of the section.

The review of project selection and tradeoff analysis concentrated on the methods that facilitate highway project selection and tradeoff analysis and solution algorithms to accomplish the analysis efficiently. The methods could generally be classified into ranking, prioritization, and optimization. The solution algorithms include exact and heuristic algorithms. The findings from this review form the basis of executing next step tasks that are involved with developing methodologies for improved risk and uncertainty-based project benefit-cost analyses and project tradeoff analyses incorporating risk and uncertainty.

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