

# Asset Management Decision Support System Model

## Technical Report

Submitted by  
Cambridge Systematics, Inc.



NJDOT Research Project Manager  
Camille Crichton-Summers

In cooperation with

New Jersey  
Department of Transportation  
Bureau of Research

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## EXECUTIVE SUMMARY

Allocating limited resources across investment categories (e.g., preservation versus congestion management) is a challenge faced by state transportation departments across the nation. The objective of this research effort was to assist the New Jersey Department of Transportation (NJDOT) Office of Capital Investment Strategies (CIS) in developing an asset management decision support model for use in its resource allocation decisions. This effort both integrates with and builds off of NJDOT's existing asset management program.

Best practices in asset management were first reviewed followed by an assessment of asset management systems currently in place at NJDOT. These findings helped the research team formulate an appropriate decision support model that would inform NJDOT's project prioritization strategy and assist the NJDOT in its cross-asset resource allocation decisions.

The result of this research effort is an asset management decision support model that calculates the utility for a user-specified project. The model specifies how NJDOT should use asset management data and systems to support integrated high-level resource allocation decisions and also focuses on how to use available data to prioritize identified problems (also termed "candidate projects" or "project alternatives" in this report), as well as planned projects.

As a next step, the research team recommends that NJDOT test the model using actual project data. This would entail using the model to calculate utilities for candidate projects, test the ranking of projects, and solve the project-level optimization model formulated in the document on trial basis. Implementing the asset management decision support model detail here in theory should help NJDOT better prioritize projects in a manner that is consistent with agency goals and objectives, improve cost effectiveness, and ultimately lead to an improved transportation system.

## **BACKGROUND**

The New Jersey Department of Transportation (NJDOT) faces a significant set of challenges with respect to determining what investments to make in its transportation system. New Jersey's transportation network is extensive and well-developed. The State's transportation assets, including its roads, bridges, and other elements of its transportation infrastructure, are in widely varying condition, and have a vast range of needs. The available funds for transportation are not sufficient for supporting all of the needs that have been identified for preserving and improving the transportation network. Thus, NJDOT is challenged to balance investments in different asset and investment categories to best preserve the State's transportation network, while making targeted improvements in mobility, safety and other areas.

Transportation asset management – defined as a “strategic approach to managing transportation infrastructure” – provides a framework that enables NJDOT to manage its transportation network more effectively. NJDOT is interested in implementing asset management concepts to make the best possible use of available transportation funding, in support of the Department's objectives. To this end NJDOT's Office of Capital Investment Strategies (CIS) has embarked on an asset management program, assessed its existing asset management systems, and begun the process of integrating its asset management data. As part of this effort NJDOT tasked Cambridge Systematics (CS) and its subcontractor Howard Stein Hudson (HSH), with the development of an asset management decision support model for use in supporting resource allocation decisions. This report details the results of that effort.

## **OBJECTIVES**

The basic objectives of the research described in this report are as follows:

- Research best practices in asset management, present options for NJDOT to consider for an Asset Management Decision Support Model.
- Examine NJDOT management systems and the decision making/prioritization algorithms, as well as how the outputs of these are used.

Based on the review of best practices and NJDOT systems, develop logical models/algorithms for allocating NJDOT resources, prioritizing problems and projects, and optimizing project timing.

## INTRODUCTION

This report details the results of the research effort for NJDOT. The project was performed through the set of tasks detailed below.

**Existing practice review:** for this task the research team reviewed current asset management practices, systems, and tools in use at other U.S. transportation agencies and identify elements applicable to New Jersey.

**Asset management systems review:** this task focused on review of existing and planned systems for supporting asset management at NJDOT and identification of system needs to be addressed in the development of a decision support model.

**Model development:** After reviewing existing practices and NJDOT staff, the research team developed an asset management decision support model that specifies how NJDOT should use asset management data and systems to support integrated high-level resource allocation decisions. The model development effort specifically focused on how to use available data to prioritize identified problems (also termed “candidate projects” or “project alternatives” in this report), as well as planned projects.

**Asset management workshop:** initially a workshop was planned at the end of the project to communicate the asset management decision support model to NJDOT managers and staff. Over the course of the research, the emphasis of the workshop shifted from reviewing the conclusions of the research to walking through an exercise of prioritizing NJDOT investments at a high-level, which provided key input to the decision support model.

**Implementation support:** for this task the research team provided additional support in implementing the decision support model, and performing other activities not otherwise included in the scope of the other tasks.

## SUMMARY OF WORK PERFORMED

### Existing Practice Review

This section provides background information on existing asset management practices, systems, and tools in use at targeted transportation agencies in the U.S., and discusses key management systems used by NJDOT.

The review considered approaches for prioritizing resource allocation investments, including practices, systems, and tools that support integrated pavement, bridge, and safety investment decisions. The review focused on examples of other U.S. state transportation departments that have developed tools and approaches for integrating resource allocation decisions for multiple asset types.

### Literature Review

Information on existing practices was compiled through a targeted literature review, and based on research team experience. The literature consulted was not intended to be exhaustive, but rather instructive of the practices, information, systems, and decision support tools that currently are being used by transportation agencies to support asset management, specifically in the areas of pavement, bridge, mobility and safety. Current literature in the field applicable to the NJDOT effort included:

- *National Cooperative Highway Research Program (NCHRP) Report 632: An Asset-Management Framework for the Interstate Highway System* (2009) describes an asset management approach for managing interstates. It includes a comprehensive review of highway asset management data, tools, and performance measures.
- *Transportation Research Board (TRB) Circular E-C131: Transportation Asset Management Strategic Workshop for Department of Transportation Executives* (2008) describes the results of an international scan of asset management practices, documents a workshop on asset management attended by a set of state department of transportation (DOT) executives, and presents numerous examples of existing practices.
- *U. S. Domestic Scan Program: Best Practices in Transportation Asset Management* (2007) details the results of a domestic scan of asset management practice performed as part of NCHRP Project 20-68.
- *NCHRP Report 551: Performance Measures and Targets for Transportation Asset Management* (2006) details performance measures used for asset management, describes how performance measures can be used to support decision-making, and presents a framework for performance measure development.

- *NCHRP Report 545: Analytical Tools for Asset Management (2005)* reviews asset management tools and systems, and details the development of a set of two tools, AssetManager NT and PT, for supporting resource allocation.
- *American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management Guide (2002)* details basic principles of asset management, presents an approach to assessing an organization's asset management approach, and presents a series of best practice examples.

These documents provided not only the basis for selecting representative best practice examples, but a foundation for how an asset management decision support model could be applied to NJDOT.

A common perspective underscores all of the literature, best summarized in the *AASHTO Transportation Asset Management Guide*. As described in the guide, asset management is a **strategic approach** to managing transportation infrastructure. More specifically, asset management helps agencies to get the best results/performance for the preservation, improvement, and operation of infrastructure assets given available resources.

Basic asset management **principles** are:

- **Policy Driven** – decisions reflect policy goals and objectives
- **Performance Based** – Performance measures are defined and target values are established
- **Options Evaluated** – comprehensive choices and tradeoffs are examined at each level of decision-making
- **Decisions Based On Quality Information** – management systems and tools support decision makers
- **Clear Accountability** – performance results are monitored and reported

The overall **benefits** of asset management can be grouped into two discrete categories:

- Performance and cost effectiveness – deliver policy goals and objectives; lower long-term costs for infrastructure preservation; improved performance and service to customers; and improved use of available resources.
- Communication, accountability, and credibility – improved communication within agency and with customers; and improved credibility and accountability for decisions.

In addition to promoting a common perspective on what asset management is, the documents reviewed share a common perspective on why it is important. Namely, the reality of transportation management today is that state DOTs are required to do more

with less, as available funds are not sufficient to support all of the preservation and improvement needs a DOT may wish to fund. One aspect of effectively managing the transportation network is balancing investments across different asset categories to both preserve the system and implement targeted improvements. Resource allocation informed by asset management concepts provides an opportunity to prioritize needs and better inform decision-making with respect to allocating funds across asset categories.

### **Existing Practice Examples**

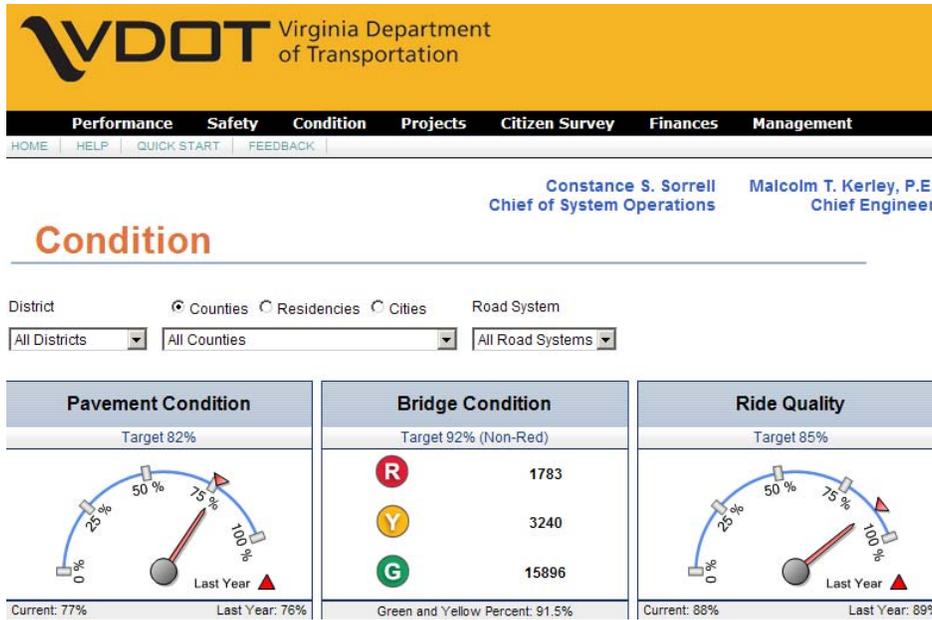
Existing practices have been summarized with particular attention to four areas within asset management of greatest relevance to development of an asset management decision support model for NJDOT. These include: Performance measure reporting;

- Cross-asset resource allocation;
- Maintenance budgeting; and
- Project ranking.

For each of these areas, the following discussion summarize best practices, and present one or more examples of how other state DOTs currently are addressing the identified area.

**Performance Measure Reporting.** Performance measures have received a great deal of attention in recent years, and the recent emphasis on performance measures is only likely to increase with the next transportation reauthorization bill. Establishing a set of performance measures for characterizing asset conditions is an important first step in implementing an asset management approach. Once an agency has established a set of measures, the next step is to track performance over time, and begin to set performance targets, using this information for high-level budgeting. Further, an agency may provide information on performance trends for internal or external use.

A number of state DOTs have developed reports, report cards, and other approaches for communicating target and actual performance. Of particular note, the Commonwealth of Virginia developed the Virginia Performs initiative, which promotes transparency by tracking performance measures for each state agency. The initiative is designed to align specific state agency outcomes with larger statewide goals. As part of this effort Virginia DOT developed an interactive performance dashboard. Widely recognized as an effective performance reporting tool, the dashboard rolls up real-time or near-time performance information into easy to understand graphics. Summary information is provided for key measures covering pavement and bridge condition, roadway safety, highway congestion, and agency performance (e.g., project delivery). An example of the performance dashboard is shown below in Figure 2.2.



Source: Virginia DOT.

Figure 1. VDOT Dashboard

**Cross-Asset Resource Allocation.** Determining how to allocate funds between asset or investment types is a fundamental challenge in asset management. Typically agencies have pavement and bridge management systems that recommend funding levels and projects specifically for those assets, and they have a variety of other types of investment needs that may or may not be supported by a management system.

One can envision an ideal asset management system that performs both the asset-level analysis that existing management systems perform, and that considers how best to optimize between asset/investment categories. In practice, systems that combine asset/investment categories tend to either use pretabulated results from other management systems, or simplify the problem, performing a less detailed analysis than that performed by other asset-specific management systems. Thus, documents that provide guidance, such as NCHRP Report 551, tend to focus on approaches to using best-of-breed management systems, with additional processes or analyses, to support cross-asset decision-making.

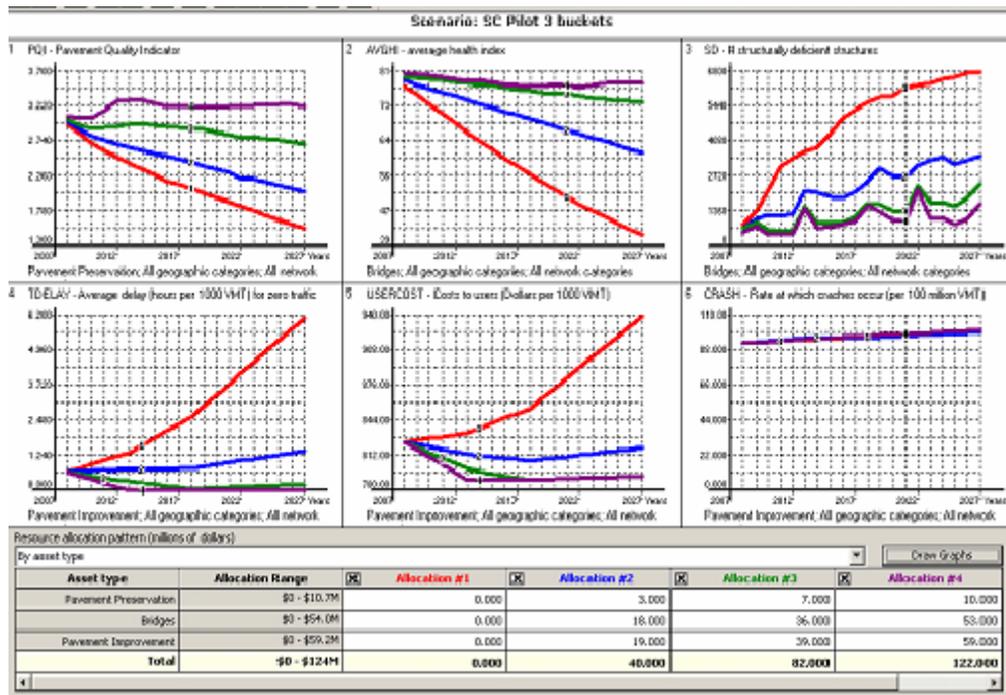
Given the state of existing systems, a common approach to making cross-asset allocation decisions is to use asset/investment-specific systems to predict the performance that will result from a given budget level, and then comparing the performance of different funding allocations in terms of their impact on selected performance measures. In fact, this is the basic approach CIS follows in developing its budgeting.

Several state DOTs have implemented the AssetManager NT tool for supporting such a process. AssetManager NT is designed to integrate results from multiple management systems to facilitate what-if analysis. The end user can configure what data are to be

imported, what measures to display, and how funds are distributed (e.g., by district, region, or other groupings). The system can then display, for a given overall budget and allocation between assets, the predicted performance of the system over time.

This tool is detailed in NCHRP Report 545. Following its initial development through NCHRP, AASHTO incorporated the tool in its AASHTOWare program, and, through this program, the tool was implemented in approximately 10 agencies.

Figure 2.3 shows an example screen from AssetManager, in this case configured with data from South Carolina DOT for NCHRP Project 20-74. Here the system is using results from South Carolina DOT’s pavement and bridge management systems, as well results from runs of the Federal Highway Administration (FHWA) Highway Economics Requirements System (HERS) to simulate mobility improvements. The screen shows predicted performance for six measures, including pavement and bridge conditions, delay, crash costs and overall user costs. These are projected for three different budget allocations (each plotted as a separate series). The budget allocations are specified at the bottom of the screen.



Source: NCHRP Report 632.

Figure 2. AssetManager NT

There are a number of examples of agencies, including NJDOT, that either use AssetManager, or perform similar analyses through manual or spreadsheet approaches. As noted above, all of these rely on data from external systems, such as a pavement and bridge management system. Less common are approaches that perform integrated analysis within a single system. The review yielded two such examples operating in a

production environment (versus as a research effort): Utah DOT and New Brunswick DOT.

Utah DOT utilizes the Deighton dTIMS system to model pavement and bridge investment needs. dTIMS was originally designed as a pavement management system, but Deighton has extended the system such that it can support analysis of other asset types. In Utah DOT’s case, the system already was being used as the agency’s pavement management system. Utah DOT added bridges to dTIMS. Though the bridge modeling in dTIMS is more rudimentary than that supported by the agency’s bridge management system (Pontis), Utah DOT concluded it was nonetheless sufficient for high-level resource allocation decisions. In using dTIMS, Utah DOT allocates funds between pavement and bridges on the basis of remaining service life, with adjustments based on a variety of factors. Figure 2.4 shows the factors Utah DOT has established.

New Brunswick DOT has established a cross-asset resource allocation process using a different approach. The agency uses the Remsoft Woodstock model for performing a long-term optimization of pavement and bridge needs. This model was originally intended to optimize investments in the forestry industry, but has been adapted to incorporate pavement and bridge deterioration models to optimize project selections between asset categories over a 100-year period. This approach also provides a least life cycle cost solution for pavement and bridge preservation.

<b>Social</b>		<b>Pavements</b>	<b>Structures</b>
	Human Health	1.17	2.25
	Community/connectivity	3.00	1.83
	Cultural/Historical	1.83	2.92
	Multi/Modal	2.83	1.17
	Homeland Security	1.00	2.33
<b>Economic</b>			
	Productivity	2.33	2.67
	Congestion	2.17	2.67
	Employment	3.00	2.08
	Tax Burden	2.83	2.33
	Trade	3.00	2.17
	Recreation/Tourism	3.00	2.00
<b>Environmental</b>			
	Pollution	2.67	2.00
	Energy Consumption	2.50	2.17
	Habitat Preservation	2.67	1.67
	Aesthetics	1.83	3.00

**Note: scored on a 1,2,3 basis with 1 being low, 2 medium and 3 high priority.**

Source: Utah DOT.

Figure 3. Utah DOT dTIMS Objective Weights

Maintenance Budgeting. Though asset management ostensibly addresses the full range of assets and investment types of interest to a DOT, in practice, much of the

focus in this area has been on pavement and bridges. There are examples of systems and sketch planning tools for analyzing other assets/investment types, particularly with regard to mobility and safety investments, but relatively few examples of working systems that perform functions such as recommending funding levels or predicting future performance. The review focused on the area of maintenance budgeting (also termed “maintenance levels of service” or “maintenance quality assurance”) as this is the most common analytical approach used for analyzing investment needs for other physical assets besides pavement and bridges, and may be of relevance to NJDOT.

Maintenance budgeting is used to establish a target level of performance for a DOT’s maintainable assets, such as paved surfaces, shoulders, roadside assets, and rest areas. Generally, the conditions of these assets are characterized using a level of service (LOS) description (often expressed using letter grades), and the approach results in a prediction of the level of funding required to maintain a specified LOS. To support the approach, the agency typically collects sample data on existing LOS, such as through conditions at some number of randomly selected sites on an annual basis. Maintenance budgeting has been used by a number of states to help establish an appropriate level of funding for maintenance, but is not intended to support analysis of capital projects.

Arizona’s implementation of maintenance budgeting is representative of the state-of-the-practice. Arizona DOT uses a maintenance budgeting system for implementing the approach described above, relating maintenance expenditures to asset conditions, with LOS defined by letter grades (A through F). A web-based application, depicted in Figure 2.5, has been developed to store data on LOS, and explore trade-offs in maintenance budgeting. With the system, the agency can determine the funding required to achieve a certain level of performance, or alternatively, view the impact of a given level of funding.



# Maintenance Budgeting System

Budgets | Reports | Data | Admin

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## Budget Worksheet

Budget Name:

Budget Total: **111,377,000**

Budget Year:  Base Year:

Ceiling Budget:

Description:

Remaining Budget:

Official FY2006 budget?

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	Baseline			Target		
	LOS	Cost \$	Adj. Cost \$	LOS	Cost \$	Adj. Cost \$
<input type="checkbox"/> Paved Surfaces	A-	9,052,000	16,704,000	A-	9,052,000	16,704,000
<input type="checkbox"/> Roadside	B-	17,506,000	32,307,000	B-	17,506,000	32,307,000
<input type="checkbox"/> Traffic	C+	12,365,000	22,819,000	C+	12,365,000	22,819,000
<input type="checkbox"/> Landscape	C	3,868,000	7,138,000	C	3,868,000	7,138,000
<input type="checkbox"/> Vegetation	C	2,383,000	4,397,000	C	2,383,000	4,397,000
<input type="checkbox"/> Rest Areas	A-	2,118,000	3,909,000	A-	2,118,000	3,909,000
<input type="checkbox"/> Winter		2,491,000	2,491,000		2,491,000	2,491,000
<input type="checkbox"/> Leave		5,829,000	5,829,000		5,829,000	5,829,000
<input type="checkbox"/> Training		2,005,000	2,005,000		2,005,000	2,005,000
<input type="checkbox"/> QOE		10,920,000	10,920,000		10,920,000	10,920,000
<input type="checkbox"/> Central		2,858,000	2,858,000		2,858,000	2,858,000
	<b>Baseline Total:</b>		<b>111,377,000</b>	<b>Total:</b>		<b>111,377,000</b>

Source: Arizona DOT.

Figure 4. Arizona DOT Maintenance Budgeting System

**Project Prioritization.** Given the focus of the research effort, this area is of particular relevance to NJDOT. The review identified a number of examples of project prioritization approaches. Generally speaking, most examples in this area are cases where an agency has developed an approach to calculating a score for some set of previously identified set of projects – often mobility projects considered for a state’s Transportation Improvement Plan (TIP). Typically scoring is used where there is no management system available and/or where there are subjective elements to the process that would not be well-supported by the available systems, even if they were implemented. Less common are examples of scoring pavement or bridge preservation work, or calculating scores across all of an organization’s investment types.

Georgia DOT’s experience is typical of the state-of-the-practice. Recently Georgia DOT initiated an effort to improve its approach to project prioritization. Working with Cambridge Systematics Inc., the agency developed an approach that adapts models from HERS to predict direct transportation benefits for capacity expansion projects. A score is then computed for each project, combining benefit measures with other noneconomic measures and a set of agency-specified weights. The approach was implemented using a web-based system, as shown in Figure 2.6. The approach is notable in its adaptation of the HERS models for predicting a set of quantitative measures that can be used for prioritization, and for its ability to accommodate different

weighting approaches, such as a Georgia DOT weighting approach, and alternative approaches specified by Metropolitan Planning Organizations (MPOs).

Tier	ID	County	Score	B/C	Cost	Percent Deficient Bridge	Pvmt	Crash Reduction	Delay Reduction	Travel Time Red. on Key Corridor	Activity Centers	Land Use Plan	Access Mgmt	Change in GSP \$M	Policy Area	Dev.
1	0001757	Forsyth	83	44.69	\$277,960,000	7 %	0 %	2,670	211,522	N/A	P	Y	N	\$1,131	N	
1	0003164	Gwinnett	82	12.98	\$492,385,464	52 %	0 %	1,474	105,621	35 %	P	N	N	\$565	N	
1	0001759	Cobb	82	4.68	\$1,356,192,500	53 %	0 %	4,307	109,278	25 %	P	N	N	\$584	N	
1	0003436	Henry	81	64.76	\$81,512,000	0 %	0 %	1,202	89,731	38 %	P	Y	N	\$474	N	
1	0003168	Gwinnett	77	12.60	\$338,964,200	0 %	0 %	949	71,659	N/A	P	Y	Y	\$383	N	
1	0006419	Cobb	75	41.88	\$80,100,000	0 %	0 %	615	56,902	36 %	P	Y	Y	\$305	N	
1	0003167	Clayton	75	27.10	\$117,536,742	0 %	0 %	1,360	54,593	38 %	P	Y	Y	\$292	N	
1	0002868	DeKalb	74	277.10	\$18,450,000	0 %	0 %	49	87,698	N/A	P	Y	N	\$469	N	
1	0006417	Cobb	74	15.66	\$182,604,000	20 %	0 %	444	49,729	38 %	P	Y	Y	\$260	N	
1	0000715	DeKalb	74	7.36	\$501,502,000	0 %	0 %	1,595	63,299	38 %	P	Y	N	\$338	N	
1	0006418	Cobb	71	25.07	\$98,400,000	0 %	0 %	806	42,145	38 %	P	Y	Y	\$225	N	
1	0001760	Douglas	70	11.97	\$283,013,750	100 %	0 %	1,444	56,730	25 %	P	N	N	\$303	N	
1	0003433	Fulton	68	5.29	\$358,000,000	0 %	0 %	1,888	35,578	20 %	P	Y	Y	\$190	N	
1	0004069	Gwinnett	68	18.49	\$127,260,000	0 %	0 %	377	40,182	N/A	P	Y	Y	\$215	N	
1	0006243	Cherokee	67	128.19	\$22,170,000	0 %	0 %	9	49,166	45 %	N	Y	Y	\$258	N	
1	0003432	DeKalb	67	4.92	\$458,000,000	32 %	0 %	2,966	41,824	22 %	P	Y	N	\$224	N	
1	0000178	DeKalb	65	25.40	\$80,300,000	0 %	0 %	244	39,152	23 %	P	Y	N	\$209	N	
1	0003165	Douglas	65	15.51	\$185,823,000	0 %	0 %	964	49,652	24 %	P	N	N	\$260	N	
1	0003434	Cherokee	64	12.50	\$147,908,396	16 %	100 %	0	31,830	35 %	N	Y	Y	\$170	N	
1	0003431	Fulton	61	14.87	\$90,000,000	100 %	0 %	737	22,174	9 %	P	Y	N	\$119	N	
3	0000762	Lowndes	60	0.01	\$43,343,921	100 %	0 %	287	513	0 %	3	Y	Y	\$4	N	

Figure 5. Georgia DOT Project Prioritization

A general issue with the approaches that have been implemented for project prioritization is that there is often a desire to simplify the myriad of data on a project to single score. However, even if one can reach consensus within an agency with regard to how to compute that score, it is often unclear what one is to do with it. In a world without budget or other constraints, an agency would presumably focus on its highest-scoring projects, but it is the problem constraints (e.g., funding by district or region, agreements on local distribution of funds, issues such as project readiness) that often drive decisions. Given this issue, project scores or priorities, when computed, are often used as information that assists decision-making, but are by no means authoritative. In cases such as Georgia DOT, the score is often displayed along with a matrix of other quantitative and qualitative measures, to be used by the human decision-maker developing the actual capital plan.

### Agency Profiles

To supplement the review of existing practice in selected focus areas, the research team performed an in-depth review of asset management approaches in selected agencies. An overview of these practices focused on addressing the following key topic areas: asset inventory and condition data; performance measurement; allocation of funds across programs; candidate work (project) generation; and project prioritization.

Table 1 describes state practices in these areas at the following state DOTs: Florida, Georgia, Michigan, Ohio, and Utah.

The in-depth profiles are useful for understanding the contrasting approaches agencies have taken to meeting their asset management challenges. Nonetheless, certain common themes emerge from the analysis, including:

- The agencies reviewed all have established a basic set of asset management systems, including a pavement management system, bridge management system, and some form of road inventory system.
- Defining performance measures is a fundamental step in implementing an asset management approach. All of the agencies profiled have established some set of performance measures for tracking and reporting, though they vary in the scope and application of their performance measures.
- The most common approach implemented for cross-asset allocation is performance targeting, where targets are set for key performance measures and then asset management systems are used to predict performance given a budget scenario.
- Varying approaches are used for making project-level resource allocation decisions. Often projects are prioritized within categories using management systems or scoring approaches. In this area there is generally less reliance on information systems, and greater reliance on manual processes.
- Common issues with implementing asset management resource allocation approaches include: combining system results with candidate project lists; handling other assets beside pavements and bridges and resolving the tension between obtaining good results; implementing a straightforward approach; and maintaining the status quo.

Table 1. Asset Management Practices in Selected States  
Michigan Department of Transportation (MDOT)

	Statewide Capital Investment Strategy (SCIS) Categories				
	Roads Assets – Maintenance	Roads Assets – Pavement	Bridge Assets	Safety Management	Congestion Relief
<i>Asset Inventory and Condition Data</i>	MDOT conducts an annual maintenance inspection that covers pavement, traffic features, shoulders, and roadside.	MDOT uses a Pavement Management System (PMS) for maintaining its pavement data. Most data on pavements is collected on a two-year cycle. Pavement friction data collection is collected annually for approximately one-third of the network.	The Bridge Management System (BMS) encompasses both a Michigan-specific tool and Pontis™. Most data collected on bridges is collected on a two-year cycle.	The Safety Management System (SMS) houses crash data collected throughout the State.	MDOT collects HPMS data and analyzes congestion trends using its Congestion Management System (CMS).
	MDOT uses six management systems (pavement, bridge, congestion, intermodal, public transit facilities and equipment, and safety management systems). These systems are integrated in the sense that they use the same set of data conventions, mapping and referencing systems, technical platforms, etc. Physical feature inventory details (including some bridge data) are stored in spreadsheet format and are not linked to any other data system. MDOT uses a statewide linear referencing system for storing data, with all of the major databases integrated through the use of a physical reference number (unique number assigned to each segment of road). The linear reference system is tied to latitude/longitude and is designed to accommodate GIS so that as long as an asset can be related to a geographic point, it can be linked with all other assets.				
<i>Performance Measurement</i>	N/A	MDOT has developed a Road Quality Forecasting System (RQFS) and Bridge Condition Forecasting System (BCFS), to predict future pavement and bridge conditions based on various investment strategies. Each strategies consists of an overall funding levels and a mixture of preventive maintenance, rehabilitation, and reconstruction work. MDOT uses these tools to identify the most appropriate mix of fixes, predict the resulting performance, and set performance targets.		MDOT uses fatality rate to track safety performance.	MDOT reports change in VMT per lane-mile and duration of congestion.
<i>Allocation of Funds across Programs</i>	MDOT uses an investment template to identify the investment level for each program category over a multiyear and annual timeframe. This statewide template represents the MDOT’s overall investment plan. It links funding levels to program categories in a manner that is consistent with policy direction and program emphasis. Dollars are assigned to program categories, such as road and bridge preservation, safety, and capacity improvements. The allocation is based on the results of the analysis described above for comparing pavement and bridge condition to funding levels; and a qualitative assessment of the funding required to achieve other goals in the long-range plan. Development of this investment strategy is a cooperative process between the finance, planning, and program coordinators in the Department. The investment template is approved annually by the Director and State Transportation Commission.				
<i>Candidate Work (Project) Generation</i>	Maintenance work is identified and prioritized based on a comparison of current condition to maintenance standards and work guidance documented in a series of “Maintenance Memos.”				
<i>Project Prioritization</i>	The Statewide Planning Division, in cooperation with the Chief Operations Office, issues an annual Integrated Call for Projects letter. In the letter, key emphasis areas and strategic objectives are outlined and specific technical instructions are detailed for regional system managers. An example of the type of technical instructions provided includes a table that identifies appropriate work by bridge condition. Regional managers identify candidate work based on the guidance set forth in this document.		Projects are prioritized based on the goals and funding targets in the investment template, technical instructions in the Call for Projects, and engineering judgment.	MDOT uses “time of return” to prioritize safety projects. In this approach, costs are estimated using recent actual bidding information. User costs are determined by running project-level data such as traffic volumes and construction traffic plans through a software program called Construction Congestion Cost (CO3).	MDOT has developed a Prioritization Model to assess the benefits and costs of capacity improvement projects. There are two components of the model, one that assesses corridor projects and another that evaluates interchanges.

Table 1. Asset Management Practices in Selected States  
Ohio Department of Transportation (ODOT)

<i>Asset Inventory and Condition Data</i>	ODOT conducts maintenance inspections annually. The inspections cover drainage obstruction, guardrails, litter, pavement markings, pavement deficiencies, pavement drop-off, sign deficiencies, and vegetation obstruction.	Pavement on the priority road network is evaluated annually using a 100-point Pavement Condition Rating (PCR) that takes into account surface distresses and roughness.	ODOT's BMS is based on collecting NBI data. The agency tracks this data, along with overall bridge conditions.	The Ohio Department of Public Safety maintains the State's data on highway crashes.	ODOT collects HPMS and additional travel reliability data.
	Separate asset inventory systems exist for pavements, bridges, road inventory, safety, congestion, traffic counts, traffic signals, and maintenance condition data. ODOT uses a Base Transportation Referencing System and highway log-mile system to locate and associate highway asset data.				
<i>Performance Measurement</i>	ODOT tracks 65 key performance measures. They include a mixture of preservation measures, safety, capacity, and organizational efficiency measures. Maintenance, pavement, and bridge condition is reported on a "percent deficient" basis. The measures are reviewed quarterly by executive management. ODOT sets target values for maintenance, pavement, and bridge condition and tracks progress towards the targets.				
<i>Allocation of Funds across Programs</i>	Fund managers evaluate current system conditions and system degradation trends and determine funding levels for the various programs. Funds are then allocated to districts based on relative need.				
<i>Candidate Work (Project) Generation</i>	Maintenance deficiency data are collected during the inspection process.	Defined through expert judgment using the various management systems to compare existing conditions to target conditions.			Capacity program projects are annually nominated by ODOT, MPOs, county engineers or commissions, transit authorities, municipalities, or port authorities.
<i>Project Prioritization</i>	ODOT's districts prioritize maintenance and preservation activities based on an assessment of current conditions, target conditions, and engineering judgment. ODOT's central office compiles the maintenance and preservation programs and analyzes them to determine their expected impact on future condition. The results are incorporated into next resource allocation cycle, when fund managers allocate funds to the various programs and districts.			A nine-member Transportation Review Advisory Council (TRAC) sets policies and criteria for choosing safety and capacity projects. Numerical ratings are assigned to each proposed project. Seventy percent of the score is based on transportation efficiency and effectiveness factors. Thirty percent is based on economic development factors. The process does not result in specific project rankings. Rather, projects are grouped into three tiers – Tier I (recommended for construction), Tier II (funded for additional activities), and Tier III (not recommended).	

Table 1. Asset Management Practices in Selected States  
Utah Department of Transportation (UDOT)

<i>Asset Inventory and Condition Data</i>	UDOT uses three management systems – a Maintenance Management System (MMS), a Maintenance Features Inventory (MFI) system, and a Maintenance Management Quality Assurance (MMQA). The MMQA is used to store condition data.	Pavements are inspected every two years. Pavement distress data is stored in the Deighton Pavement Management System (dTIMS).	UDOT uses Pontis to store, enter, and maintain NBI and element-level bridge data. High-level data are export to dTIMS for analysis.	UDOT uses the Centralized Accident Records System (CARS) to store crash data provided by police.	In addition to collecting HPMS data, UDOT collects VMT data and travel times between key intersections in the Salt Lake City area.
	Integration of data takes place within UDOT’s asset management system (AMS). The AMS has been implemented within dTIMS CT. Data integration is achieved by importing and exporting data from each separate management system. In the future, the completed development of a corporate data warehouse by UDOT and the development of the location referencing system engine will facilitate easier data integration within UDOT. The AMS will pull the most recent data out of the data warehouse for analysis as opposed to each individual management system.				
<i>Performance Measurement</i>	UDOT reports the condition of maintenance features using letter grades, and has modeled the relationship between funding level and expected performance. UDOT has established target values for select maintenance features.	UDOT reports “percent of pavement in good or fair condition.” It uses the AMS to conduct scenario analysis and determine the effects of different funding levels on system performance. UDOT has defined pavement targets that vary by functional class.	UDOT reports “bridges in good condition” and “bridges in fair condition.” It uses the AMS to conduct scenario analysis and determine the effects of different funding levels on system performance. UDOT has set target values for both measures.	UDOT tracks annual fatalities and annual pedestrian fatalities and has established targets for each. The targets are based on the percent reduction in current levels.	Once baseline values for travel times have been established, UDOT will develop targets for improvement.
<i>Allocation of Funds across Programs</i>	UDOT has a preservation first policy. Funds are first allocated to system preservation, second to improving system performance, and third enhancing system capacity. Dedicated funding is provided to the safety program. The allocation of funds between the pavement and bridge preservation programs is based on analysis conducted with the AMS. The AMS enables cross-asset analysis based on Remaining Service Life (RSL), and a qualitative assessment of the impacts of bridge and pavement investments on social, economical, and environmental factors. UDOT also uses the AMS to help in determining the split of funds across regions/districts.				
<i>Candidate Work (Project) Generation</i>	UDOT uses a “Plan for Every Section” database to track planned and completed pavement preventive maintenance activities.	Once the cross-asset analysis is complete, preservation work candidates are identified within the asset silos. UDOT uses its management systems (Pontis for structures and dTIMS for pavements) to support this process. Project. The results are incorporated into a 10-year preservation plan published every two years.	UDOT uses the AMS to calculates a safety index for each one-mile section of pavement based on crash data in CARS. The AMS recommends safety spot improvements based on this analysis. These recommendations are used by the Traffic and Safety Division when it prioritizes safety projects throughout the State.	Identified based on an assessment of future traffic demand versus capacity and stakeholder input.	
<i>Project Prioritization</i>	Maintenance work is prioritized based on local knowledge and engineering judgment.			Projects are assigned a score based on functional classification of the facility, current and projected traffic volumes, truck traffic volumes, and projected safety benefits.	
	This final step in program process is a manual process of examining all of the projects that have been selected for investment over the programming timeframe to determine if there are some projects that can be combined. In some cases, projects are deferred and in others they are moved up. This harmonization effort is intended to apply engineering judgment in order to selecting the best/optimal package of investments.				

Table 1. Asset Management Practices in Selected States  
*GDOT Department of Transportation (GDOT)*

<i>Asset Inventory and Condition Data</i>	GDOT conducts daytime and nighttime maintenance inspections annually. The daytime inspection covers pavements, shoulders, drainage, guardrail, bridges, signs, and vegetation. The nighttime inspection covers signs and striping. Results are stored in a maintenance management system.	GDOT collects Pavement Condition Evaluation System (PACES) ratings, which reflect the amount of pavement distress in of terms rutting, transverse cracking, longitudinal cracking, load-related cracking, and rutting. Pavement data is stored in a pavement management system.	GDOT collects NBI and element-level bridge data. Information is stored in Pontis.	GDOT uses the Crash Analysis and Reporting System (CARS) to gather, store, and analyze crash data in the State of Georgia.	GDOT's Road Characteristic (RC) database represents a complete inventory of all roads in Georgia. It includes information on administrative characteristics of roads (e.g., ownership), physical characteristics (e.g., lane width), operational characteristics (e.g., speed limits), pavement condition (from the PMS), and usage data (e.g., AADT).
<i>Performance Measurement</i>	N/A	Pavement condition is reported as percent with PACES rating greater than 70. The target for this measure for state routes is 90.	Bridge condition is reported as percent of bridges with SR less than 50. The target for this measure is based on decreasing the current number of bridges in this category.	GDOT's safety performance measure is fatalities per 100 million VMT. The target for this measure is 1.	GDOT reports a travel time index and average speed. The target travel time index is 1.35.
<i>Allocation of Funds across Programs</i>	GDOT allocates funds across the program areas based largely on historic precedence.				
<i>Candidate Work (Project) Generation</i>	Maintenance deficiencies are identified during the inspection process. Local knowledge and engineering judgment are used to identify additional work and to prioritize work.	GDOT uses its PMS to identify pavement candidates.	GDOT identifies candidate bridge projects based on SD thresholds (e.g., a bridge with and SD less than 50 is a candidate for replacement) and engineering judgment.	Projects are identified based on traffic and safety analysis.	Projects are identified by regional offices and local project sponsors based on local knowledge and engineering judgment.
<i>Project Prioritization</i>		GDOT uses its PMS to support the prioritization of pavement projects. The approach considers the expected rate of deterioration and traffic volumes.	GDOT is developing a new approach that considers structural condition, load capacity bridge, traffic volumes, and project costs.	Projects are prioritized based on benefit/cost analysis. The benefits are estimated with crash reduction factors.	GDOT recently developed a prioritization methodology combines a series of performance measures that relate to agency goals and benefit/cost analysis. Project impact is measured in terms of pavement preservation, bridge preservation, delay, travel time, crash reduction, land use, access, and economic development. GDOT developed a prioritization system to apply this methodology to a backlog of over 1,000 projects.

**Table 1. Asset Management Practices in Selected States**  
*Florida Department of Transportation (FDOT)*

<i>Asset Inventory and Condition Data</i>	FDOT's Maintenance Rating Program (MRP) includes an evaluation of roadway condition, traffic features; roadside, drainage, and litter. FDOT conducts this inspection on 100% of the network.	FDOT's Pavement Management System (PMS) holds information from an annual condition survey that covers ride quality, crack severity, and rutting.	FDOT collects NBI and element-level bridge data. FDOT uses Pontis to manage bridge data.	The Florida Department of Highway Safety and Motor Vehicles maintains the State's Crash Records Database (CRD), which is accessed by FDOT.	FDOT collects HPMS data and has established a Mobility Management Process (MMP) that relies on MPOs to identify congested locations and recommend strategies for alleviating congestion.
	FDOT's Roadway characteristics inventory (RCI) is database of physical data related to the roadway networks, with mileposts used as the major referencing system (some districts are moving to a GIS reference). The RCI contains data from FDOT's Maintenance, Operations, and Planning offices.				
<i>Performance Measurement</i>	Maintenance performance is reported as percent of network with an MRP score over 80. The MRP score is a combination of the items described above. The target for this measure is 100%.	Pavement performance is reported as percent of network meeting agency standards. The target for this measure is 80%.	Bridge performance is reported as percent of network meeting agency standards. The target for this measure is 90%.	Safety performance is reported in terms of fatalities per 100 million VMT, and crash rates for pedestrians, bicyclists, and motorcyclists.	Congestion is reported in terms of person-hours of delay.
<i>Allocation of Funds across Programs</i>	The allocation of funds is driven by a series of preservation first policies. The funding required to meet the maintenance and pavement targets is taken off the top. Funding for bridges is set aside to meet the following operating policy – structurally deficient or posted bridges will be replaced or repaired within six years after the bridge is so listed. The remaining funds are split between the other program areas. FDOT also has a Strategic Intermodal System (SIS). The portion of funding allocated to this system is legislatively mandated.				
<i>Candidate Work (Project) Generation</i>	Identified based on the results MRP inspections.	Identified using the PMS and local knowledge.	Identified through the bridge inspection process and by Pontis.	As part of the strategic highway safety planning process, safety projects are identified and prioritized. The goal of the process is to maximize safety improvement, as measured by reduction in fatalities and serious injuries.	Capacity improvement projects are either identified and prioritized as part of the SIS planning process or by Regions based on local knowledge, engineering judgment, and stakeholder input.
<i>Project Prioritization</i>	Prioritized by district offices based on local knowledge and engineering judgment.	Prioritized based on local knowledge and engineering judgment.	Prioritized based on the operating policy described above, local knowledge, and engineering judgment.		

## **NJDOT Asset Management Systems**

Interviews were conducted with NJDOT staff to determine how the outputs of existing agency systems currently are being used and how they are integrated into the resource allocation process. Interviews were performed in March 2009 with individuals from the following program areas and related management systems:

- Congestion – Congestion Management System (CMS);
- Safety – NJ Crash Records Database;
- Pavement and Drainage – Pavement Management System (PMS);
- Bridge – Bridge Management System (BMS);
- Maintenance – Maintenance Management System (MMS);
- Capital Investment Strategy – STIP Database;
- Facilities;
- Straight Line Diagram; and
- Information Technology.

These interviews provided an opportunity to gain a better understanding of the information systems used to support asset management at NJDOT as well as plans for future improvements to systems. Interview results helped to clarify and were factored into formulating an appropriate approach to project prioritization. Critical issues/key findings that emerged from the interview include:

- NJDOT has a well-defined approach to developing its overall capital investment strategy. The approach defines key performance measures, a possible set of budget scenarios, and relies on use of existing management systems to generate predictions of future performance for each budget scenario – all consistent with best practices in this area.
- NJDOT's pavement and bridge measures are well-defined, but further work is needed to define effective congestion and safety measures. Absent an alternative, investment strategy development uses the backlog of investment needs as the key indicator in these areas. However, work in defining the performance measures was ongoing during the interviews.
- Concerning NJDOT systems, the pavement and bridge management systems (dTIMS and Pontis) are state-of-the-art asset management systems. NJDOT is using these systems for managing asset data, and for performing needs analyses. However, these systems are not being used to recommend capital projects. Of the

other existing systems, the CMS is used to identify potential mobility improvements. Other systems help characterize asset conditions, but do not predict future needs or help recommend specific capital improvements.

- NJDOT has a business process for defining problems (candidate projects), and then developing these into projects. However, there is no formal relationship between project prioritization and development of the high-level investment strategy – hence the need for an asset management decision support model.
- The lack of integration between existing systems hinders efforts to improve asset management processes. The effort to build a data warehouse integrating asset data, which is being performed as a separate effort, is expected to create new opportunities for system and process improvements.

### **Asset Management Decision Support Model Development**

This section recommends an asset management decision support model and details how it can be implemented by NJDOT. The challenge NJDOT faces in determining how best to allocate its finite resources to preserve and improve its transportation system, while a well-understood problem, is nonetheless an inherently complex one. This complexity is introduced by factors, including:

- **Difficulty in comparing outcomes.** Fundamentally, in order to make a resource allocation decision one must evaluate the outcomes of two or more investment alternatives to determine which has a more favorable outcome. Arguably, in the case of a private company, whichever outcome maximizes profit (or more generally, maximizes net present value) is the preferred. In the case of a public agency, it is less obvious how to evaluate alternative outcomes. A public agency does not exist to maximize profit, but instead to fulfill a public mission. Wise stewardship of scarce resources helps an agency operate more efficiently, but ultimately measuring success of a set of public investments involves evaluating what value those investments provide to the public. Thus, comparing the value of alternative investments requires some form of user benefits model that allows for combining agency and user costs and benefits, typically by monetizing them. Even with such models, objectives, such as equity or risk aversion, cannot easily be monetized.
- **Problems in predicting outcomes.** To even grapple with the problems described above in comparing two outcomes, one must start by predicting a set of outcomes. A number of factors complicate the process of predicting the outcomes of a resource allocation decision (e.g., the resulting condition, traffic, additional asset life, etc.). NJDOT's transportation system has a number of different assets, and there are a number of different types of investments that can be made. Predicting outcomes for all assets and investments requires significant model development and data collection. In practice, the necessary models and data are not readily available for certain asset/investment types. Further, there is great uncertainty in future conditions, and thus great uncertainty in investment outcomes. This uncertainty

compounds itself as one projects further into the future. As transportation investments tend to be long-term investments that result in outcomes that can be difficult to predict even over the short-term, there is often great uncertainty in the outcome of a given investment.

- **Challenges in optimizing.** A third class of issues lies in determining how best to allocate resources once the above issues have been resolved. That is, given an approach to judging one outcome compared to another, and given a set of potential projects to perform, how should one determine which to fund? In an unconstrained scenario this is not difficult question to answer – one should fund whatever set of projects yields the best outcomes, and this can be accomplished by simply reviewing a list of projects rank-ordered by outcomes. However, agencies must contend with many constraints, and addressing these significantly complicates the problem. Factors, such as the available budget, project timing, minimum/maximum budget constraints by type of work, geographic area or other variables, all conspire to obfuscate the process of obtaining an optimal allocation of resources to a set of potential investments.

The remainder of this section recommends an approach to asset management resource allocation decisions considering the materials presented in previous sections, as well as the challenges described above. First presented is the concept of utility, and details the derivation of an initial utility function for use in prioritizing NJDOT investments. Next is an approach to optimizing project selection using the utility function. Finally, there is a discussion of alternative strategies for implementing the proposed utility and optimization approaches.

## **Utility Function**

### ***Concept of Utility***

In the context of economic analysis, “utility” is defined as “the level of satisfaction that a person gets from consuming a good or undertaking an activity.”<sup>1</sup> The concept of utility is frequently used to quantify otherwise subjective preferences individuals have in selecting between different alternatives (e.g., between alternative “market baskets” of goods). Though it may seem novel, the concept is well established. Its first formal description is generally attributed to Daniel Bernoulli in *Commentaries of the Imperial Academy of Science of Saint Petersburg* (1738). More recently, in 1944 John von Neumann and Oskar Morgenstern provided the first modern treatment of utility theory, mathematically deriving expected utility from a set of axioms of rational behavior they proposed in their landmark work on game theory.<sup>2</sup>

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<sup>1</sup> Pindyck, Robert S. and Daniel L. Rubinfeld. *Microeconomics*, Third Edition, Prentice Hall, Englewood Cliffs, 1995, p.85.

<sup>2</sup> von Neumann, John and Oskar Morgenstern, *Theory of Games and Economic Behavior*, Princeton University Press, Princeton, 1944.

The concept of utility is extremely useful for addressing resource allocation problems. Essentially, NJDOT's objective in making resource allocation decisions is to *maximize utility*. If we can define a utility function that reflects NJDOT's collective preferences, then that utility can in theory be used as the fundamental basis for prioritizing investments. If one outcome has a higher utility than another, it is strictly preferred, though problem constraints may nonetheless dictate that an outcome with lower utility must be selected if the higher-utility action is infeasible.

The basic concept of making decisions that maximize one's utility function is well-established as a model for human decision-making. However, it is important to note that the applicability of this model rests on certain assumptions: namely, that people behave rationally, and that it is possible to define a utility function that accurately reflects a society's preferences. State-of-the-art research in decision analysis (i.e., determining how to allocate resources in the face of climate change or other issues with deep uncertainty) is calling these assumptions into question.<sup>3</sup> While one might argue for using an alternative approach to decision analysis rather than constructing and optimizing a utility function, we nonetheless recommend this approach, given that:

- The recommended approach best represents the current state-of-the-practice in decision analysis, and nonetheless represents a step beyond the current state-of-the-practice in the transportation community.
- Alternative approaches to decision analysis, such as minimizing regret or finding the most robust solution, often start with definition of a utility function, and seek a solution that improves that using utility maximization in some fashion. These approaches tend to benefit from, if not explicitly require, some form of utility function.
- Decision analysis approaches tend to be data-hungry. The utility maximization approach described here is recommended in part based on the available data. A more complex approach would be more data intensive, and would be an even greater challenge to implement.

Given the approach to developing a decision support model for NJDOT based on a utility function, it is important to consider what properties are desirable in the utility function. We recommend the following, based on a combination of theoretical and practical concerns:

- Utility should be expressed as a unitless value between zero percent (no utility) and 100 percent (maximum utility). The practical interpretation of the function is that if one candidate project has a higher utility than another, then it is preferable, ignoring budgets or other constraints.
- For analytic convenience, it is desirable to combine the decision variables for the utility function into a score, and then calculate utility as a function of the score.

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<sup>3</sup> Lempert, Robert L. and Myles T. Collins, "Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum and Precautionary Approaches," *Risk Analysis*, Vol. 27, No. 4, 2007.

When plotting utility as a function of score, the utility function should be bounded (constrained to lie between 0 and 100 percent), monotonic (increasing as a function of score), and smooth (continuously differentiable).

- The variables needed to calculate the utility of a candidate project should be readily available at NJDOT and not require additional data collection.
- Lacking more detailed data on NJDOT preferences, we have assumed that utility should be correlated with agency and direct transportation benefits (travel-time savings, operating cost savings, and reductions in accidents costs). That is, generally we would expect that if one project candidate has greater agency and direct transportation benefits than another, it also would have greater utility.
- The utility function should support calculations for different types of investments, using NJDOT conventions for investment types. As a practical matter, NJDOT should be able to make overall adjustments to the utility function by investment type to reflect agency preference (e.g., through adjusting a set of weights).

The following sections describe development of a utility function for NJDOT resource allocation decisions with the properties outlined above.

### **Model Development Approach**

An initial NJDOT utility function has been formulated based on analysis of NJDOT asset data, use of FHWA models for predicting agency and direct transportation benefits for representative, candidate projects, and elicitation of NJDOT preferences elicited through a project workshop. This section describes the steps in model development.

**Defining investment types.** The initial step in the model development process was to determine what investment types should be modeled. The review described previously suggested that though NJDOT invests in a number of different types of projects, for the purpose of high-level analysis with NJDOT the major categories of capital investments include: pavement preservation, bridge preservation, major and minor mobility improvements, and safety improvements. Overall budgets are set for each of these categories, amongst others, though any one project may include funding for work related to multiple categories.

**Generating candidate projects.** For the next step of the analysis, the research team reviewed the available candidate project data, and found that though detailed information is specified for funded projects, the existing NJDOT database contains only summary data for identified problems (candidate projects) that have not yet been funded. For generating the utility function it was necessary to obtain data on representative candidate projects. Because the data set for candidate projects was found to be sparsely populated, and limiting the analysis to funded projects would have significantly reduced the data set (and could have biased the results), the research team generated a set of candidate improvements using the FHWA HERS and National Bridge Investment Analysis System (NBIAS).

HERS and NBIAS are FHWA's systems for national level highway needs analyses. These systems use readily available Highway Performance Monitoring System (HPMS) and National Bridge Inventory (NBI) data to predict future asset conditions, identify investment needs, and estimate agency and direct transportation benefits from transportation improvements. Both models have been subjected to extensive peer review and used for development for the biannual Report to Congress on the Condition of the Nation's Highway, Bridges and Transit. These tools were used to generate candidate projects for the purpose of this exercise, as they are well-established tools supported by FHWA, and because they use readily available data for their analysis.

HERS analyzes needs for highway improvements, including mobility and pavement preservation needs, and predicts agency cost savings, travel-time saving, vehicle operating costs savings and crash cost savings resulting from these investments. HERS was run with NJDOT HPMS data and an unconstrained budget. The system generated a set of 213 potential mobility improvements and pavement preservation projects in its initial analysis period. Relevant data, including HPMS data for the improved sections and resulting benefits calculated, were tabulated for each of the NJDOT HPMS sections with a candidate project.

NBIAS, which is similar to the Pontis system licensed by NJDOT (though less data-intensive), analyzes bridge needs, including preservation and functional improvement. It predicts agency costs, as well as travel-time savings, operating cost reductions and reductions in crash costs resulting from bridge replacements and functional improvements. HERS was run with NJDOT NBI data and an unconstrained budget. The system generated a set of 2,517 potential bridge projects in its initial analysis period. Relevant data, including NBI data for the improved bridge and resulting benefits calculated, were tabulated for each of the bridges with a candidate project.

**Deriving score functions.** Provided with a set of candidate improvements, and predicted agency and direct transportation benefits of those improvements, the research team then developed a set of score functions for approximating the benefits by investment type. The score functions were intended to be easily computed functions correlated with the HERS/NBIAS benefits. For instance, for two similar highway improvements, one would generally expect the improvement on the section with higher average daily traffic (ADT) to have the higher score. Standard statistical techniques, informed by knowledge of the underlying models in HERS and NBIAS, were used to determine statistically significant variables, and an appropriate functional form for the score functions.

For major mobility improvements, key explanatory variables were found to be ADT, section length, and number of lanes before and after improvement. The HERS models incorporate consideration of a number of other factors (e.g., truck percentages, road grade and curvature, lane and shoulder widths, etc.) but these were not found to be statistically significant, at least for the purpose of ordering candidate improvements by their benefits. For pavement preservation work, ADT and section length also were important, as well as pavement condition before and after improvement.

For bridges, the analysis indicated that different score functions were needed for predicting bridge safety benefits from widening or replacing a bridge and for predicting benefits of other bridge improvements. Key explanatory variables for the bridge score functions included bridge length, deck area, roadway width, condition and appraisal ratings, truck percentage, detour distance around the bridge and type of work performed.

Neither HERS nor NBIAS include adequate models for predicting impacts of minor mobility improvements or safety improvements (with the exception of bridges). Based on review of NJDOT data and discussions with NJDOT staff, the research team determined that at present, all that can be consistently determined for such improvements when problems are identified is ADT. Based on the limited amount of data available, one would expect the utility of a minor mobility or safety improvement to be proportional to ADT. Thus a simple score function was developed to predict score as a function of ADT, using NJDOT HPMS data to obtain a distribution of NJDOT traffic data.

**Specifying utility as a function of score.** The next step of the analysis was to specify the utility of a potential improvement as a function of the score determined previously. Work on this step was performed using an approach recently used in developing a bridge utility function for the California Department of Transportation (Caltrans). This approach entails investigating the statistical distribution of the scores for a representative sample. Then the utility function is selected such that the functional form of the utility function approximates the cumulative distribution function (CDF) of the distribution of scores. The Excel Solver is used to find a best fit for the utility function parameters such that the difference between the utility function and score function CDF is minimized. The rationale for this approach is that it results in a utility function that has the properties outlined previously (range between 0 and 100 percent, monotonic and smooth) for which the sample data are well distributed between the minimum and maximum values.

Using this approach, for each score function the research team first inspected the distribution of scores for the sample data, and found that the scores tended to have a log-normal distribution (that is, the logarithm of the score was normally distributed). Based on prior experience, the research team used the following function to approximate the CDF of the log-normal distribution:

$$U(x) = \frac{1}{1 + \kappa * e^{(-\lambda \ln x)}}$$

where  $U$  is the utility,  $x$  is the score and  $\kappa$  and  $\lambda$  are parameters. Note this function is defined only where the score is positive.

The end result of this analysis step is that utility terms were estimated for each of the five improvement types using functional forms of the desired properties outlined above.

**Determining utility function weights.** The steps described previously result in a utility function with five terms, with each term ranging from 0 to 100 percent. The total utility of a given improvement is defined to be the weighted sum of the five terms. To complete the utility function it is necessary to establish an set of weights on each of the terms.

The decision of how to weight utilities for each improvement type is necessarily a subjective one. Though in theory one might specify monetized benefits for each improvement type and simply combine the benefits, in practice the available data and models are such that there exists no widely accepted model for monetizing the benefits of potential transportation investments given the available NJDOT data. Thus, at least in this instance, considering the limitations in existing models and data, the approach of monetizing all benefits has the same subjective elements embedded in it as a weighted average utility function, without the virtue of making its subjective elements explicit.

To determine how to weight the different utility function terms, the research team facilitated a workshop with NJDOT staff. Prior to the workshop, NJDOT provided network-level data on predicted future conditions given alternative funding assumptions. This data was used to create a range of candidate scenarios reflecting different weights on each of the improvement types. These scenarios were shown to human decision makers, who then expressed their preferences concerning the different scenarios, ultimately resulting in a consensus concerning which scenario was preferred, which dictated the appropriate set of weights on the utility function.

The Cambridge Systematics tool Multiobjective Evolutionary Tool for Interactive Solution (METIS) was used to automate the process of generating and reviewing alternative scenarios. METIS is a combination of a visualization multiobjective optimization tool. The system uses information on which alternative from a set is the least preferred alternative to perform a multiobjective optimization using the Nelder-Mead algorithm. This optimization results in three new candidate solutions. The decision maker selects one of the candidates to add to the original set, and then continues to select between candidate solutions until the set of candidates converges. At this point, one can then observe what weights led to the selected candidate solution.

Appendix A presents further detail on METIS, describes the METIS workshop, and presents the results candidate solution on utility function weights resulting from use of METIS. Note that of the options presented in the memorandum, NJDOT ultimately selected Option 1 as that most representative of agency preferences. One general concern with this approach is that it relied on network-level data, and did not utilize project-level details. If the utility generated from a set of projects, based on project level data, is significantly different from that suggested through the network-level analysis, it may be necessary to recalibrate the METIS-derived weights. However, this evaluation cannot be made until NJDOT has developed sufficient project-level data to support such a calculation. In the interim, we recommend use of the weights derived through the METIS workshop as a starting point.

## Recommended Utility Function

This section details the utility function developed for prioritizing NJDOT project-level data. The following paragraphs detail the model formulation. Appendix B details parameter values for the equations shown here. A supplemental spreadsheet has been developed for illustrating the calculations.

As described above, the utility function developed for NJDOT is a weighted average of the utilities for five types of improvements. The function is expressed as follows:

$$U = \sum_{i=1}^5 \beta_i \delta_i u_i \quad (1)$$

where:

$U$  = utility

$\beta_i$  = weight for utility of type  $i$

$\delta_i$  = 1 if the candidate includes investments of type  $i$ , 0 otherwise

$u_i$  = utility of investment of type  $i$

$i$  = index on improvement type: 1 for pavement, 2 for bridge, 3 for major mobility improvements, 4 for minor mobility improvements, and 5 for safety improvements

Unless otherwise specified, the  $u_i$  terms are computed by first calculating a score intended to be correlated with monetized benefits of the investment, then transforming the score into a utility function ranging from 0 to 100 percent, using the following functional form:

$$u_i = \frac{1}{1 + \kappa_i * e^{(-\lambda_i \ln S_i)}} \quad (2)$$

where  $S_i$  is the score for type  $i$ , and  $\kappa_i$  and  $\lambda_i$  are parameters for investment type  $i$ .

For pavement surface improvement, key parameters include traffic, section length, number of lanes, and pavement surface condition. Based on these characteristics, the score for pavement improvement is calculated using the formula:

$$S_1 = k_{1,1} * LENGTH * \left[ \begin{array}{l} LANES * \left( k_{1,2} + k_{1,3} * (P_a - P_b) + k_{1,4} * (P_a^2 - P_b^2) + k_{1,5} * \frac{P_a}{P_b} \right) \\ + ADT * \left( k_{1,6} + k_{1,7} * (P_a - P_b) + k_{1,8} * \frac{1}{LANES} + k_{1,9} * e^{\left( \frac{(P_a - P_b)}{k_{1,10} * LANES} \right)} \right) \end{array} \right] \quad (3)$$

where:

$S_1$  = pavement score

$LENGTH$  = length of the road segment in miles

*LANES* = number of lanes

*ADT* = average daily traffic

*P<sub>a</sub>* = pavement condition after the project, respectively, expressed as a score from 0 (lowest) to 100 (highest)

*P<sub>b</sub>* = pavement condition before the project

*k<sub>1,1...1,10</sub>* = parameters

In the above formula, the first term is correlated with agency savings in future maintenance costs from improving pavement condition, and the second term is correlated with user benefits (e.g., reduced operating costs and travel time).

The score function for bridges reflects agency savings from improving bridge conditions, as well as user benefits (reduced travel time and operating costs) from raising, strengthening or replacing bridges. Bridge projects that increase lane or shoulder widths are expected to have additional safety benefits. These are captured through the safety investment type described subsequently. A number of parameters determine the bridge score. All of these are readily available NBI data items, or can easily be determined based on the scope of the proposed project. The score function is as follows:

$$\begin{aligned} S_2 = & DR * DM \left( k_{2,1} + k_{2,2} * A * \left( k_{2,3} + k_{2,4} * DRD * (7 - RD) + k_{2,5} * DRS * (7 - RS) + k_{2,6} * DRU * (7 - RU) \right) \right) \\ & + (1 - DR) * DM * \left( k_{2,7} + k_{2,8} * A * \left( k_{2,9} + k_{2,10} * DRD * (7 - RD) + k_{2,11} * DRS * (7 - RS) + k_{2,12} * DRU * (7 - RU) \right) \right) \\ & + DRD * DM * \left[ DR * \left( k_{2,13} + k_{2,14} * (7 - RD) * ADT * L \right) + (1 - DR) * \left( k_{2,15} + k_{2,16} * (7 - RD) * ADT * L \right) \right] \\ & + DRC * DC * \left[ k_{2,17} + k_{2,18} * (6 - RC) * \sum_j (ADTTU_j * DU_j) \right] \\ & + DRL * DL * \left[ k_{2,19} + k_{2,20} * (6 - RL) * ADTT * D \right] \end{aligned} \quad (4)$$

where:

*DR* = 1 if the bridge is being replaced or undergoing complete rehabilitation, otherwise 0

*DM* = 1 if maintenance, repair and rehabilitation needs are being addressed, otherwise 0

*DC* = 1 if the project addresses an under clearance deficiency, otherwise 0

*DL* = 1 if the project addresses a load capacity deficiency, otherwise 0

*RD* = deck condition rating (NBI Item 58)

*RS* = superstructure condition rating (NBI Item 59)

*RU* = substructure condition rating (NBI Item 60)

*RC* = under clearance rating (NBI Item 69)

*RL* = structural rating (NBI Item 67)

*DRD* = 1 if *RD* ≤ 6, 0 otherwise

*DRS* = 1 if *RS* ≤ 6, 0 otherwise

*DRU* = 1 if *RU* ≤ 6, 0 otherwise

*DRC* = 1 if *RC* ≤ 5, 0 otherwise

*DRL* = 1 if *RL* ≤ 5, 0 otherwise

*A* = deck area in square meters

*L* = bridge length in meters (NBI Item 49)

*ADT* = average daily traffic

$ADTT$  = average daily truck traffic on the bridge

$ADTTU_j$  = average daily truck traffic over the  $j$ -th roadway under the bridge

$D$  = detour length for the on-roadway in kilometers (NBI Item 19)

$DU_j$  = detour length for the  $j$ -th roadway under the bridge in kilometers (NBI Item 19)

$k_{2,1...2,20}$  = parameters

For major mobility projects the score is determined by ADT, section length and the increase in capacity of the project. The increased capacity is approximated by the ratio of added lanes to existing lanes. In projects that add capacity without adding lanes, this ratio should be replaced with the percentage increase in capacity. The score function is expressed as follows:

$$S_3 = k_{3,1} * ADT * LENGTH * \frac{ADDLANES}{LANES} \quad (5)$$

where:

$ADT$  = average daily traffic

$LENGTH$  = length of the road section in miles

$LANES$  = existing number of lanes

$ADDLANES$  = number of added lanes

$k_{3,1}$  = parameter

For minor mobility projects, such as intersection improvements, it may not be feasible to calculate a section length or increase in capacity. For these projects (as well as for safety improvements), the benefit of the project, and thus the score, is expected to be proportional to ADT multiplied by number of improved locations. Thus, the score function is as follows:

$$S_4 = \sum_{j=1}^N ADT_j \quad (6)$$

where  $N$  is the number of sites addressed by the project and  $ADT_j$  is the ADT for the  $j$ -th site.

For safety improvements, two score functions were developed. The function described above for minor mobility is applicable for safety projects, though safety improvements have a different overall weight than minor mobility projects. Bridge projects that increase lane or shoulder width have a safety benefit, as well. This benefit depends on ADT, lanes, design roadway and shoulder width, and existing width. The function is specified as follows:

$$S_5 = (KAL * k_{5,1} + (1 - KAL) * k_{5,2}) * C_{FC} * LANES * ADT * \frac{\left( \frac{1}{RW} - \frac{1}{LANES * DW_L + 2 * DW_S} \right)}{1000} \quad (7)$$

where:

$KAL = 1$  if approach alignment (NBI Item 72)  $\leq 6$ , 0 otherwise

$C_{FC}$  = average cost per accident in dollars

$LANES$  = number of lanes on the bridge (NBI Item 28)

$ADT$  = average daily traffic

$RW$  = roadway width in meters (NBI Item 51)

$DW_L$  = design lane width in meters (typically 3.7)

$DW_S$  = design shoulder width in meters (typically 4.9 for interstates and 2.4 otherwise)

$k_{5,1...5,2}$  = parameters

Though it is likely atypical, where a project involves both bridge safety improvements and nonbridge safety improvements, we recommend calculating the utilities separately for bridge and nonbridge components and summing these, with a limit of 100 percent on the total.

Appendix B documents the values fit for each parameter in the above formulation. A supplemental spreadsheet has been prepared illustrating the utility calculation.

## **Optimization Model**

### ***The Capital Budgeting Problem***

The mathematical problem NJDOT faces in determining how to allocate a fixed budget to a set of capital projects in order to maximize utility is a variant of the Capital Budgeting Problem, first formally expressed as an operations research problem in 1963.<sup>4</sup> In this problem, an organization seeks to maximize its net present value (NPV) through performing a set of capital projects, with a limit on the available budget. The basic problem has one budget constraint and one decision period, and assumes that projects are independent of each other. An exact solution to this problem requires formulating and solving an integer programming problem. However, integer programs are time-consuming to solve, with solution times increasing exponentially as the size of the problem increases.

Fortunately, there exist quick, reasonable heuristic approaches to approximate the exact solution to the Capital Budgeting Problem. The most common approach is to simply rank projects in decreasing order of their benefit/cost ratio and allocate funds in this order until the budget is expended. An alternative approach is to formulate the problem as a linear programming problem. Linear programs can be solved more efficiently than integer programs, but the resulting solution may result in recommending fractional parts of a project. To obtain a feasible solution, the fractional portions of the project are rounded off.

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<sup>4</sup> H. Weingartner, H. *Mathematical Programming and the Analysis of Capital Budgeting Problems*, Prentice Hall, Englewood Cliffs, New Jersey, 1963.

The implication of the above discussion is that if NJDOT's resource allocation could be reduced to a single period decision with a single budget constraint, a reasonable approach to allocating resources would be to rank projects based on benefit/cost ratios (or in this case, utility/cost ratios) and fund those for which funds are available. Unfortunately, reality is not so tidy. NJDOT has a multiperiod problem with a whole series of budget constraints, as well as other types of constraints, and this rather complicates matters. It is still quite possible to formulate the problem mathematically, but then solving the problem once formulated becomes nontrivial. Further, heuristic approaches of ranking projects – be it by utility, utility/cost ratio, benefit/cost ratio, or any other single measure – are by no means guaranteed to generate an optimal solution.

The following section formulates an optimization model intended to address NJDOT's asset management decision support problem, and discusses alternative solution approaches for solving the model.

### **Model Formulation**

The objective of NJDOT's asset management resource allocation problem is to select the set of projects to perform in each period over a range of years in order to maximize utility, subject to a series of constraints. The problem may be formulated as follows:

$$\max \sum_t \alpha^t \sum_i \delta_{i,t} U_i \quad (8)$$

such that:

$$\forall_i \forall_t \delta_{i,t} = \begin{cases} 0 \\ 1 \end{cases} \quad (9)$$

$$\forall_i \sum_t \delta_{i,t} \leq 1 \quad (10)$$

$$\forall_m \sum_i \sum_t \delta_{i,t} \sum_j \sum_k \sum_l C_{i,j,k,l,m,t} \leq B_m \quad (11)$$

$$\forall_j \forall_m \sum_i \sum_t \delta_{i,t} \sum_k \sum_l C_{i,j,k,l,m,t} \leq J_{j,m} \quad (12)$$

$$\forall_k \forall_m \sum_i \sum_t \delta_{i,t} \sum_j \sum_l C_{i,j,k,l,m,t} \leq K_{k,m} \quad (13)$$

$$\forall_l \forall_m \sum_i \sum_t \delta_{i,t} \sum_j \sum_k C_{i,j,k,l,m,t} \geq L_{l,m} \quad (14)$$

where:

$\alpha$  = discount factor

$\delta_{i,t} = 1$  if alternative  $i$  is programmed beginning in period  $t$ , 0 otherwise

$U_i$  = utility of alternative  $i$

$C_{i,j,k,l,m,t}$  = cost of performing alternative  $i$  beginning in period  $t$  for investment type  $j$ , work phase  $k$ , region  $l$ , period  $m$

$B_m$  = maximum budget in period  $m$

$J_{j,m}$  = maximum budget for investment type  $j$  in period  $m$

$K_{k,m}$  = maximum budget for work phase  $k$  in period  $m$

$L_{l,m}$  = minimum budget for region  $l$  in period  $m$

Solving this problem yields a set of recommendations on what project alternatives to fund. In this formulation, Equation (8) is the objective function, illustrating that the objective is to select the set of project alternatives that maximize utility. Note it is assumed that an alternative can be programmed beginning in any period  $t$ . Also, note that a discount factor is applied, so that all things being equal, greater utility is obtained by performing a project sooner rather than later. For the discount factor to be calculated correctly, the first period should be  $t = 0$ .

Equations (9) to (14) are constraints. Equation (9) is an integer constraint, that specified any given alternative  $i$  may be programmed beginning in period  $t$  ( $\delta_{i,t}$  has a value of 1) or not (in which case  $\delta_{i,t}$  has a value of 0). Equation (10) specifies that an alternative may be programmed only once. Equations (11) to (14) are budget constraints. For calculating the costs one must know the cost in each period of performing a given alternative  $i$  beginning in period  $t$ , with the cost specified by investment type (pavement, bridge, major mobility, minor mobility, safety), work phase (design, preconstruction, construction), geographic region, and period.

This formulation allows for specifying a time series of different costs, which vary on the timing of the project. Equation (11) enforces the constraint on maximum budget by period. Equation (12) enforces the constraint on maximum budget by investment type and period. Likewise, Equation (13) enforces the constraint on maximum budget by work phase and period. Equation (14) specifies the minimum budget by region and period.

Note that the model formulation is designed to accommodate additional constraints. These can be added to indicate that selected projects are either required to occur (“pipelined”), that a project alternative can occur only in selected time periods, that certain projects are mutually exclusive (e.g., two different alternatives for the same asset), and/or that certain projects are mutually inclusive (bundled).

The recommended model formulation carries with it a number of important implications. These include the following:

- A project may have benefits outside of a single investment type. For instance, a major mobility project that involves safety upgrades and improvements to existing pavement would have pavement, mobility and safety utility. It is for this reason that the pavement and safety categories, where NJDOT makes a budget allocation but does not necessarily detail all of its planned projects in its capital plan, are included in the formulation.
- If the objective of the model is to maximize utility, then only projects with positive utility will be recommended. While the utility function detailed previously predicts utility for any pavement, bridge, major mobility, minor mobility or safety improvements, there may be other worthwhile projects that NJDOT wishes to incorporate in this framework outside of these categories. Basic approaches to addressing this issue include creating new utility terms, adjusting the score function for one of the existing terms (e.g., minor mobility enhancements) to include adjustments for certain types of improvements (e.g., including “smart growth” elements might increase the score for a mobility project by a specified value), or making adjustments to the overall utility (not recommended). Further, additional constraints can be created to trigger a minimum level of spending on certain types of investments.
- The model will yield optimal results, but only for the set of project alternatives provided as inputs. That is to say, the outputs of the model are only as good as the inputs. In using the model, it will be important to define all potentially worthwhile investments, and capture changes to costs and project feasibility projected over time. For instance, if a bridge rehabilitation is proposed, but NJDOT engineers feel that the rehabilitation would need to be upscaled to a more costly replacement if the project is deferred, it would be necessary to quantify the increased cost if the project is deferred. Also in this case, it may be the case that a constraint must be added to force selection of a project for a given asset over a given period of time to maintain the asset in service.
- The model is likely to yield results that are generally consistent with, but nonetheless different from, NJDOT’s management systems. To the extent that the utility function recommended here is consistent with the benefits considered by NJDOT’s management systems, the recommendations of this model should be consistent with those systems. However, because the model described here optimizes over time considering a number of additional constraints, one would not expect the results to be identical. Further, the model detailed here does not answer certain questions the management systems are intended to address, such as what is the backlog of investment needs, or how much investment is required to maintain a certain LOS.

### ***Solution Approaches***

As noted previously, the recommended model is an integer programming problem, and in practice these problems can be complicated to solve. We recommend evaluating three basic strategies for solving the model, described below.

**Exact Solution.** There are a number of existing commercial-off-the-shelf (COTS) and open source packages for solving integer programming problems that could be used to obtain an exact solution to the problem. Examples include IBM's CPLEX, Lindo Systems' LINGO, and Frontline System's Solver Platform (which extends the Excel Solver). For further research and testing of the approach, a COTS solver could be used without additional software development. CPLEX and LINGO include environments for formulating problems, though these tools also can be accessed automatically by external systems. The Frontline solver works within Microsoft Excel, supporting testing through a spreadsheet environment. Note that the solver included with Microsoft Excel is not up to the task, as it is limited in both the number of variables and constraints it will accept. For a production environment, NJDOT would likely need to develop software to integrate the COTS solver with NJDOT data, and display the results of the optimization.

This approach has a number of advantages, and several potential disadvantages. Of the three approaches described here, it is the only one that will provide exact solutions to the proposed model, though without testing it is unclear how great an advantage this is. Also, this approach would be an effective way to test the modeling approach. Given data, NJDOT could begin testing the approach immediately. However, as an approach to developing a production system, this strategy may require longer than the other approaches, as it requires more extensive integration, and may involve additional, recurring software licensing costs, unless the solver used is one of the open source alternatives. Also, without further investigation, it is unclear how much computation time would be required with this strategy. It would likely take several minutes to solve a typical optimization problem, but it may require longer.

**Heuristic Approach.** Heuristics based on use of benefit/cost ratios (or incremental benefit/cost ratios where there are mutually exclusive projects) typically perform well for solving capital budgeting problems. For example, recently Cambridge Systematics, working with Virginia DOT, developed an approach to optimizing bridge project recommendations over a 10-year period with budget constraints specified by work type and year using an incremental benefit/cost approach.<sup>5</sup> With this strategy, NJDOT would find an approximate solution to the model through implementing a heuristic approach adapted from existing techniques used in pavement and bridge management systems.

The major advantage of this strategy is that is known to be readily feasible, and could be implemented with a modest development effort without requiring supplemental license fees. However, implementing the approach would require at least some development effort, and because it implements a heuristic approach, will not yield an exact solution.

**COTS Management System.** As an alternative to performing development work, NJDOT could implement a COTS asset management system for solving its resource allocation problem. However, realistically, using one of the existing systems would

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<sup>5</sup> Robert, William; Gurenich, Dmitry and Richard Thompson. "Multi-Period Bridge Investment Optimization Utilizing Pontis Results and Budget Constraints by Work Type," paper presented at the 88<sup>th</sup> Annual Meeting of the Transportation Research Board, 2009.

entail simplifying the problem rather significantly, such as by taking away budget constraints or eliminating the optimization over multiple years. We recommend against such an approach. The one COTS system that may support model recommended here is the Remsoft Woodstock system implemented for optimizing pavement and bridge investments for New Brunswick DOT. Further investigation would be required to assess the capabilities of this system. Even with this approach, additional work would be required to integrate the selected system.

## **Use of the Model for Decision Support**

### ***Support for Ranking***

Even once NJDOT has developed a utility function and optimization model for NJDOT asset management decision support, there remains the question of how these products can actually be applied to support the decision-making process. Realistically, if the model is useful, it will support decision-making in a variety of ways, and will not function simply as a “black box” that mysteriously emits recommendations.

A basic use the resulting model is for supporting project ranking. Though we have noted already that a simple ranking approach is unlikely to yield an optimal solution to NJDOT’s resource allocation problem given the constraints the agency faces, ranking is nonetheless an extremely valuable tool. Ranking candidate projects provides a very general indication of what projects should be performed, absent constraints, and a general indication of priorities even with constraints. Most importantly, ranking provides human decision-makers an intuitive tool for sorting lists of candidate projects and reaching consensus on what projects to pursue. While noting the inherent limitations of any ranking approach, we contend that the utility function described previously provides an excellent basis for project ranking, and recommend it be used as follows:

- When a problem is first defined in NJDOT’s process, an initial estimate of the utility should be generated using the model described here or some variant thereof.
- Ideally, the list of problems should be supplemented with outputs from NJDOT’s management systems, to the extent these systems recommend specific candidate projects subject to NJDOT’s project approval process.
- NJDOT may wish to develop additional procedures for refining the initial utility estimates once a problem seems likely to become an actual project. For instance, further information, if available, could be used to evaluate safety and minor mobility projects based on more data than simply the number of sites included in the project and ADT per site.
- Given either the initial utility, or a revised calculation, and the capital cost of the project, NJDOT should calculate the utility/cost ratio of the project. This metric can then be used for general project ranking purposes. Given the limitation of ranking, where feasible ranking should be used for comparing subsets projects that are

subject to similar constraints (e.g., for ranking potential mobility improvements in Central New Jersey for 2015). As the subsets used may vary from one application to the next, one would not have absolute ranks, but instead, different rankings of groups of projects calculated on an as-needed basis.

- Ranking should be supported on an ad-hoc basis to support periodic reviews and resource allocation decisions. Once a problem (candidate project) is scheduled, the project should be marked as scheduled or “pipelined” and it should be omitted from further rankings.

With the approach described above, all NJDOT candidate projects would have utility/cost values that could be served to rank projects, but ranking would be performed on an as-needed basis to support decision-making, preferably for prioritizing within sets of similar projects. The next section describes how this process could be supplemented by using optimization results.

### ***Applying Optimization Results***

Determining how to use the results of an optimization can be a real challenge, as an optimization procedure provides little or no insight on how it arrived at its solution – only that the solution is “optimal” based on the manner in which the term is defined in the context of the problem.<sup>6</sup> Thus, there is a tendency for an optimization result, when used as input to a decision-making process, to land on the scene with a bit of a thud. If one is willing to accept the results of an optimization, then there is nothing left to discuss. If, however, the optimization result appears somewhat short of ideal, one is left to ask “now what?” There is little that can be done to address this conundrum, other than to try to formulate a model that so effectively solves the problem at hand that one is willing to live with the inherent issues, while simultaneously managing one’s expectations about what even the ideal optimization routine can reasonably accomplish. Having already attempted the former strategy in formulating the model, in this section we recommend additional guidance with an eye to accomplishing the latter.

In considering how to apply the results of an optimization, it is important to recognize that the final set of decisions concerning what projects are funded is necessarily an interactive process, and that extra information will be introduced into the process that will not be captured in the model, but nonetheless has an impact on the result. Thus, the value of a set of optimization results is ephemeral. If an optimization routine helps NJDOT reach project-level decisions at a particular point in time, then the routine will have served its purpose. However, the next day there may be new information that impacts the results, necessitating revisiting of prior conclusions. With this perspective, we recommend the following in applying optimization results:

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<sup>6</sup> In all fairness, we should note that for linear programs an optimization routine provides some insights through “shadow costs” that show which constraints drove the solution, and the marginal value of relaxing a given constraint.

- Final decisions on what projects to fund are in all cases made by human-decision makers, and the process NJDOT follows should explicitly recognize this fact. At no point should there be a process step in which machine-generated results are treated as final without human review.
- When optimization is used, it is important that the optimization routine recognize selections made previously by human decision-makers. This can be accomplished by creating constraints requiring the optimization to recognize any “pipelined” projects.
- The primary use of an optimization routine should be to help “fill in the gaps” in NJDOT’s project-level plans. For instance, NJDOT may wish to make all decisions on near-term projects based on review of project ranks (as discussed above), and then run the optimization routine to generate a set of initial recommendations to follow the specified set of near-term projects.
- A secondary use of the optimization would be to quickly test different strategies. For instance, if NJDOT wanted to determine how changing regional splits would impact the results of the resource allocation process, the optimization routine could be used to quickly test this scenario, whereas a human-driven process may be overly time consuming.
- A tertiary use of the optimization would be to compare machine-generated recommendations to actual decisions. One would not expect the two to match, as the human decision-maker will tend to have additional data and objectives beyond that considered in the optimization routine (and in any case, is not a machine), but if the models and data are being improved then one would expect to observe some degree of convergence over time.

### ***Required System Functionality***

A prototype system has been developed to help illustrate how the NJDOT asset management decision support model can be implemented, tentatively titled the “NJDOT Project Planner.” This section discusses the functional requirements of a system that would support the model, and presents screens from the prototype illustrating the proposed approach at a conceptual level.

Fundamentally, the NJDOT Project Planner is envisioned as a system that would track information and perform a series of calculations on candidate projects being considered for inclusion in the NJDOT capital plan, including problems and proposed projects. Figure 6 depicts the primary view of the system, the project list. This screenshot suggests functionality to:

- Define candidate projects.

- Store and display a project identifier, geographic region of the project, project description, investment (work) type, and cost of the project. Also, the system includes the ability to store and show the year the system recommends performing the project (labeled “S-Year”), year the user intends to perform the project (labeled “U-Year”), and an indication of whether the project year is locked, the utility calculated for the project, the utility/cost ratio (UCR), and a project rank.
- Select/unselect a group of projects, with selections indicated using the checkboxes on the left side of the list.
- Show a selected set of projects on a map.
- Rank a selected set of projects based on utility/cost ratio.
- Run an optimization for a selected set of projects.
- Find a specific project by identifier, description or other fields.

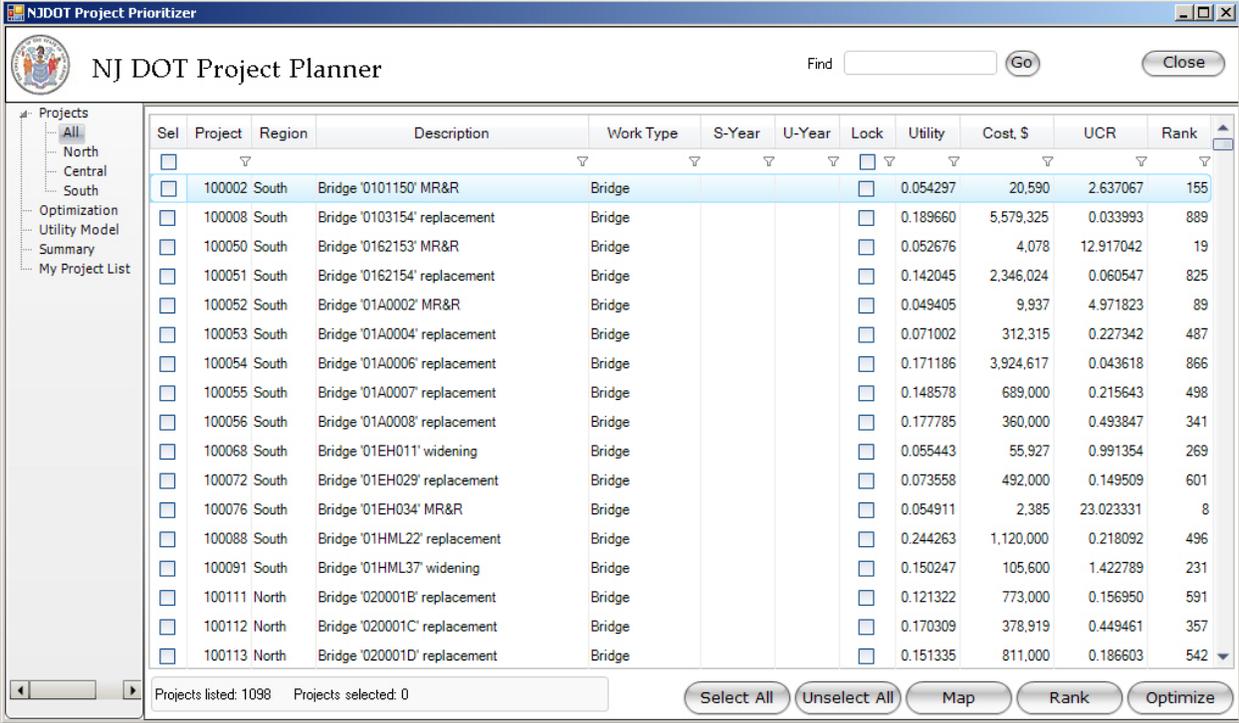


Figure 6. Project List

When working with the project list, the user should have the ability to sort and filter the list as needed, as well as to select between a small set of predefined project lists, as well as the ability to create one’s own lists. In the screenshot, the left pane has labels for each region of the State. Clicking one of these filters the list by region. Alternatively, one can drag and drop projects into the user defined list.

Once a list has been selected, one should be able to sort and filter it using standard grid controls. Typically these allow for sorting a list in ascending or descending order by clicking on the header, and for filter the list based on some set of criteria. Figure 7 demonstrates a sort of the list by UCR.

Double clicking on a specific project should display project details. The fields listed above, as well as any data items required for the utility function or optimization model, should be shown on the project detail screen. Also, this screen should support calculation of the utility for the project and entry of a user-defined utility. Figure 8 shows an example of project detail for a bridge project. Figure 9 shows project detail that might be required for a mobility or pavement improvement project. Note that in reality, NJDOT would have many more pieces of data on a project. Only those fields required for implementing the decision support model are shown here.

Sel	Project	Region	Description	Work Type	S-Year	U-Year	Lock	Utility	Cost, \$	UCR	Rank
<input type="checkbox"/>	300879	North	Section '0078 015500' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.136581	31,114,100	0.004390	1082
<input checked="" type="checkbox"/>	301513	North	Section 'P0444 137390' congestion relief (... Congestion Reli...				<input type="checkbox"/>	0.189832	43,228,500	0.004391	1081
<input checked="" type="checkbox"/>	301171	North	Section 'P0444 130630' congestion relief (... Congestion Reli...				<input type="checkbox"/>	0.188923	42,423,000	0.004453	1080
<input type="checkbox"/>	301507	North	Section '0078 053010' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.066409	14,868,000	0.004467	1079
<input type="checkbox"/>	300847	North	Section 'NULL' congestion relief (widening) Congestion Reli...				<input type="checkbox"/>	0.194089	43,292,500	0.004483	1078
<input type="checkbox"/>	300354	Central	Section '0042 008780' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.163513	35,920,300	0.004552	1077
<input type="checkbox"/>	300359	Central	Section '0070 002640' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.020442	4,426,100	0.004618	1076
<input type="checkbox"/>	300348	Central	Section '0030 047910' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.017447	3,768,800	0.004629	1075
<input type="checkbox"/>	300744	North	Section '0078 056630' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.077526	16,084,400	0.004820	1074
<input type="checkbox"/>	300880	North	Section '0078 017540' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.040353	8,347,700	0.004834	1073
<input type="checkbox"/>	301502	North	Section '0024 052880' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.033957	6,829,900	0.004972	1072
<input type="checkbox"/>	301138	North	Section 'NULL' congestion relief (widening) Congestion Reli...				<input type="checkbox"/>	0.037136	7,425,600	0.005001	1071
<input type="checkbox"/>	300023	South	Section '0040 063430' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.019041	3,796,000	0.005016	1070
<input type="checkbox"/>	301533	North	Section '0022 004050' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.055534	10,932,500	0.005080	1069
<input type="checkbox"/>	300878	North	Section '0078 014410' congestion relief (w... Congestion Reli...				<input type="checkbox"/>	0.065288	12,648,000	0.005162	1068
<input type="checkbox"/>	301139	North	Section 'NULL' congestion relief (widening) Congestion Reli...				<input type="checkbox"/>	0.067051	12,566,400	0.005336	1067
<input type="checkbox"/>	301515	North	Section 'P0444 141080' congestion relief (... Congestion Reli...				<input type="checkbox"/>	0.191825	35,812,000	0.005356	1066

Figure 7. Project List – Sorted

Project Detail window showing project information for a Mobility/Pavement project. The window title is "Project Detail".

Project: 300382 Region: Central Work Type: Congestion Relief (major) Total Cost, \$K: 25,981

Section Record No: 382 Section ID: 00000295QQ63 Beg. MP: 30.39 End MP: 32.20

Section Detail:

- Length (miles): 1.81
- Number of Lanes: 8
- AADT: 123,946
- PCI (0-100): 56

Project Detail:

- Project Cost, \$K: 25,981 Start in Year: 0 Lock
- Improvement Type: 4 - Resurfacing with normal-cost lane adding (RSNC)
- Added Lanes: 2 Alignment Improvement

Project Cost Structure:

Ye...	%%	Phase
1	15	Design
2	15	Pre-construction
3	15	Construction
4	30	Construction
5	25	Construction

Utility: 0.169281054536274 Save Close

Figure 8. Project Detail – Mobility/Pavement

Project Detail window showing project information for a Bridge project. The window title is "Project Detail".

Project: 100002 Region: South Work Type: Bridge Total Cost, \$K: 21

Bridge Rec. No: 2 Bridge ID: 0101150 Functional Class: 14 - Urban Other Principal Arterial

Bridge Detail:

- Length (meters): 16.5
- Road Width (meters): 13.4
- Deck Area (sq. meters): 293.7
- Number of Lanes: 2
- AADT (total) - On: 13,280
- AADTT (trucks) - On: 354
- AADTT (trucks) - Under:
- Detour Length - On (km): 3.0
- Detour Length - Under (km):

Project Detail:

- Project Cost, \$K: 21 Start in Year: 0 Lock
- Replacement  Maintenance
- Widening  Raising  Strengthening

Ratings:

- Underclearances: N
- Structure: 5
- Deck: 5
- Superstructure: 6
- Substructure: 5

Project Cost Structure:

Ye...	%%	Phase
1	15	Design
2	15	Pre-construction
3	15	Construction
4	35	Construction
5	20	Construction

Utility: 0.054297218678233 Save Close

Figure 9. Project Detail – Bridge

With the functionality suggested by Figures 6 to 9, one could calculate project-level utilities, filter the list of projects, and perform ranking. Once one established when a project was to be performed, the year could be entered in the system, and the user could lock the year to prevent the user recommendation from being overridden.

We anticipate that final project decisions would be made through an iterative process of reviewing project details, sorting and ranking projects, and discussing finalizing decisions in a group setting. As discussed previously, the optimization routine could be used as a tool for speeding the process of resource allocation, such as through helping “fill in the gaps” in the out year of the program. Figure 7 depicts the parameters one would need to specify when performing an optimization, including the time horizon for analysis, weights on investment types, and budget constraints by year, region and

investment type (labeled “program”) on this screen. Not depicted, but anticipated in the model, are additional constraints on work phase (e.g., design or construction). To perform an optimization, one would click the button depicted in Figure 6. The system would then use user-specified information for projects that have already been programmed (“pipelined” projects with a locked year), or recommend what projects should be performed given the specified constraints through populating the system year.

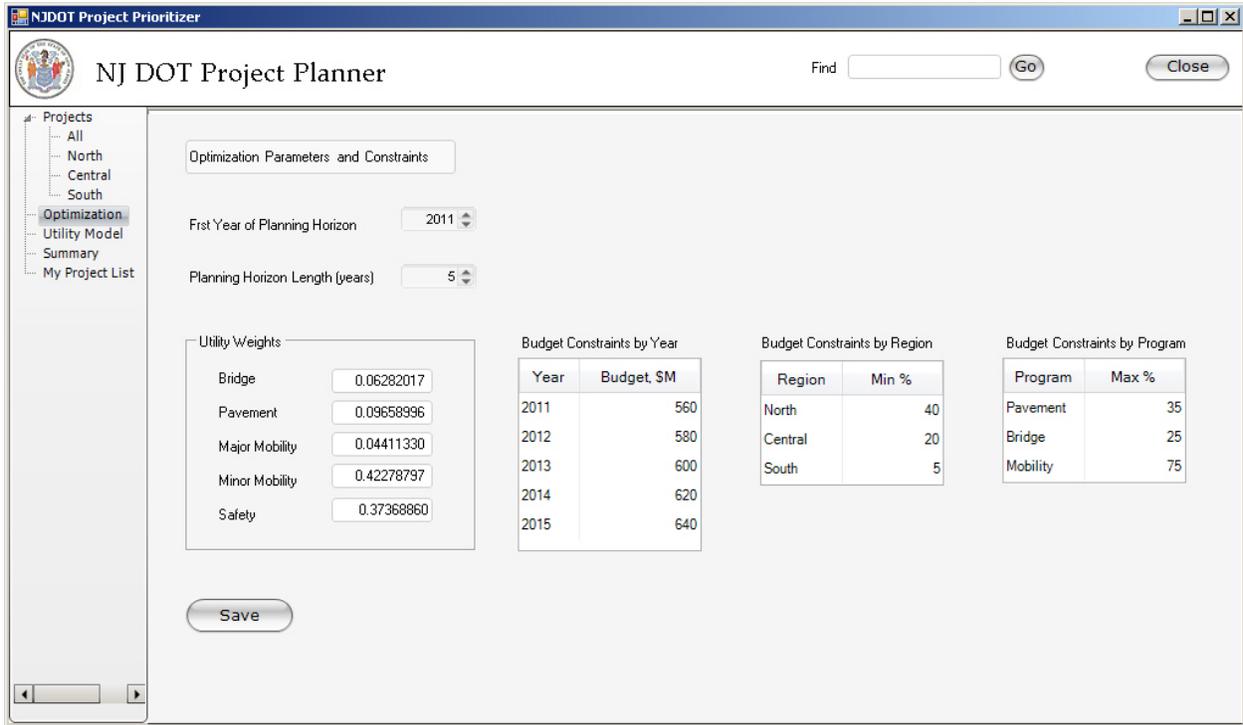


Figure 10. Optimization Configuration

Figures 11 and 12 depict the results of an analysis. Figure 11 shows summary data on the capital program, with work funded by year. Figure 12 depicts this information graphically.

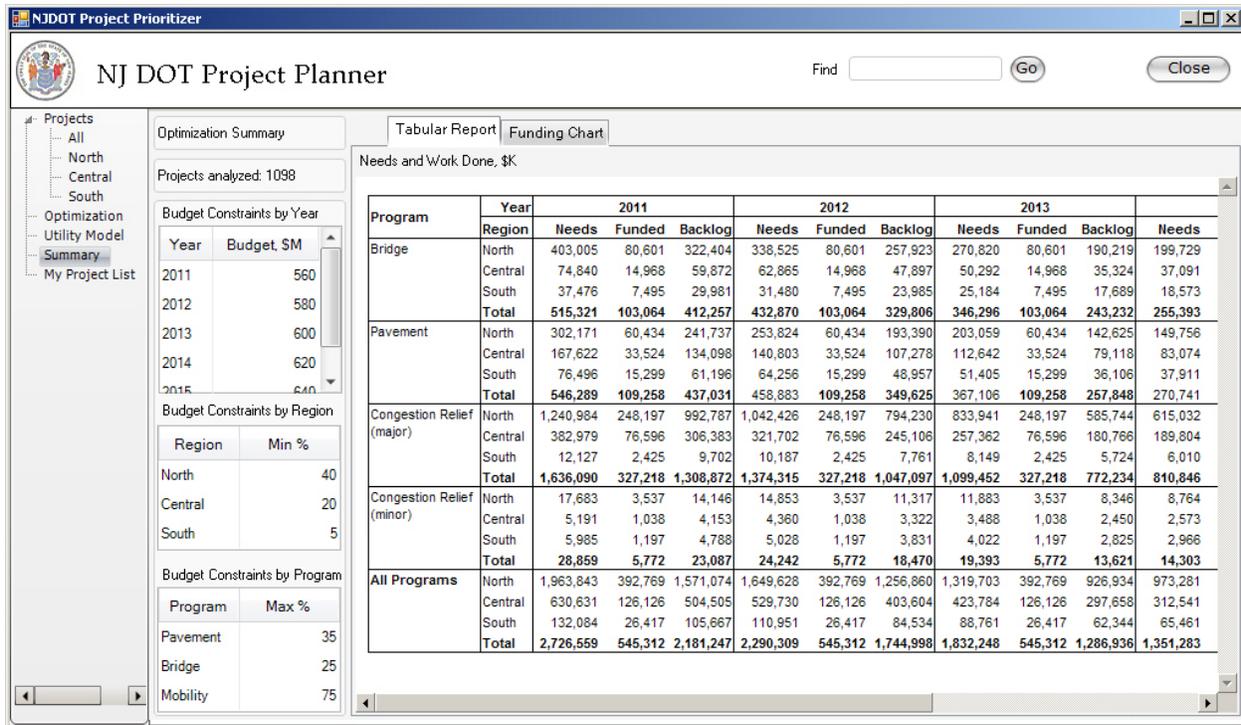


Figure 11. Analysis Summary Results

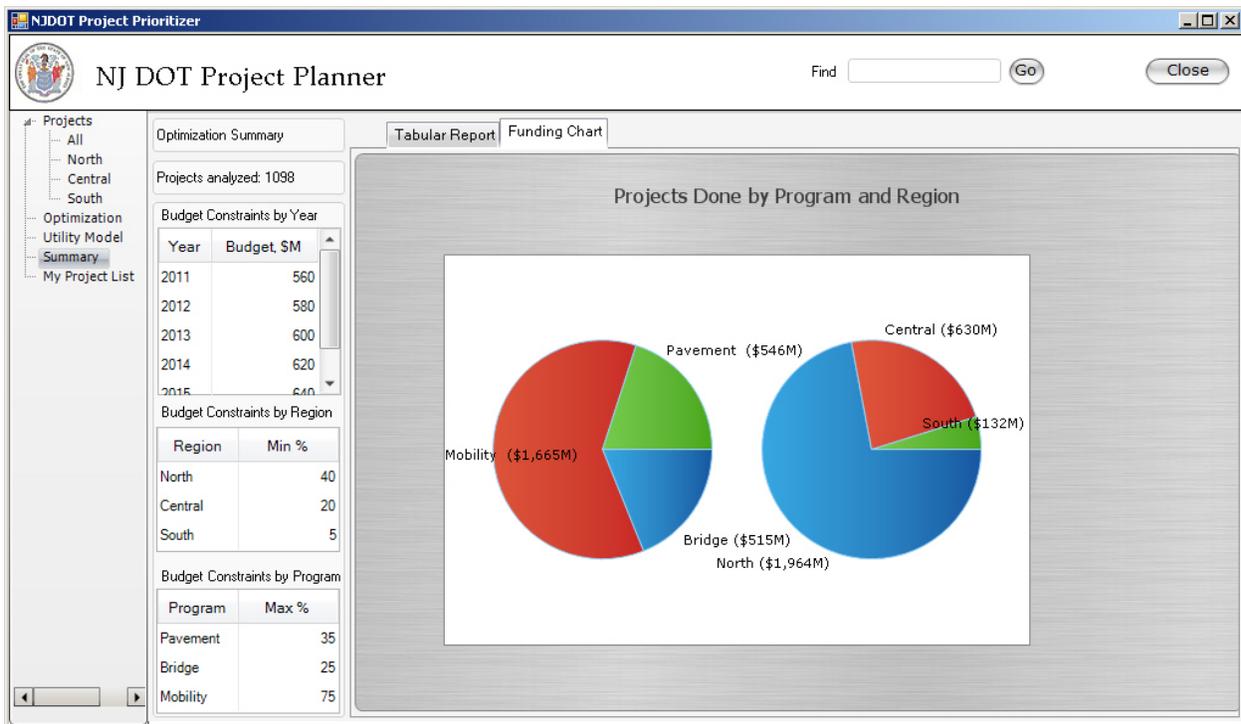


Figure 12. Analysis Summary Graph

Additional functionality would likely be required for a production system beyond that depicted here. This would likely include, but not be limited to functionality to:

- Specify additional project-level data to be determined;
- Define users and user roles;
- Import and export data to/from the future NJDOT data warehouse;
- Print and/or e-mail results;
- Generate reports; and
- Save historic data.

## CONCLUSIONS

The research effort described here reviews existing practices in asset management, both in the literature and at NDJOT, and details an asset management decision support model recommended for use in prioritizing problems and projects, setting budgets, and optimizing project timing. NJDOT is well positioned to move forward with implementing an improved asset management approach. The organization's business process already is consistent with the current state-of-the-practice in asset management, demonstrated through implementing pavement, bridge and other management systems, developing performance measures for reporting and high-level budgeting, and using the available systems, data and performance measures to support development of a capital investment strategy. Linking this strategy to project prioritization is a logical next step. Implementing an asset management decision support model in theory should help NJDOT better prioritize projects in a manner that is consistent with agency goals and objectives, improve cost effectiveness, and ultimately lead to an improved transportation system.

The basic approach that is recommended for the asset management decision support model is to calculate a new measure, *utility*, for each problem and project, and then prioritize projects with an objective of maximizing utility. NJDOT managers already try to maximize the utility of the capital program when they make decisions about problems and projects, but these decisions are made largely in a qualitative manner. The proposed model, if implemented, will provide a quantitative basis for the prioritization process, though in the final analysis decisions will and should still be made with a human "in the loop."

Implementing the proposed model should not require extensive additional data but will require extensive *integration* of existing data. The data warehouse effort now underway as a separate effort should serve as the foundation meeting NJDOT's data integration needs. To support future project prioritization efforts, the data warehouse should include information on both actual projects, and potential future projects ("problems"), with the data described in the model development section included for each project.

Though the data warehouse will help enable implementation of the asset management decision support model, additional work is needed to complete the task. We recommend starting the process by performing a walk through with the recommended model, which would entail calculating utilities for candidate projects, testing project rankings performed using the utility function, and performing one or more optimizations of the capital program with the recommended optimization model to help evaluate how realistic the model is, what additional factors it may need to address, and explore the implementation challenges. If the walk through demonstrates that it is feasible to implement the model, and that the model does indeed have the potential to improve NJDOT's business process, then further software development effort will be needed to implement the model in a production setting.

# APPENDIX A – METIS WORKSHOP SUMMARY



## Memorandum

**TO:** John Dourgarian, New Jersey Department of Transportation  
**FROM:** Jocelyn Hoffman and Bill Robert, Cambridge Systematics, Inc.  
**DATE:** August 19, 2009  
**RE:** METIS Workshop Results

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### Background

Cambridge Systematics, Inc. (CS) has been contracted by the New Jersey Department of Transportation (NJDOT) to develop an asset management decision support model to inform NJDOT's project prioritization strategy. As part of this process, CS is developing a utility function that characterizes the benefits of transportation investments. Ultimately this utility function will be used to help prioritize NJDOT projects that involve improving pavement conditions, bridge conditions, capacity, and/or safety.

An important step in developing the utility function is to set weights on different potential objectives of transportation investments. Fundamentally, choosing between these objectives requires human judgment – there is no right or wrong answer that can be derived mathematically. To assist in calibrating the NJDOT utility function, on July 30, 2009 NJDOT conducted a workshop with a set of representatives from the pavement, bridge, safety, and mobility areas. The workshop participants used a tool called the Multi-objective Evolutionary Tool for Interactive Solutions (METIS) to interactively calibrate the NJDOT utility function.

METIS serves as a basic engine for running multi-objective resource allocation problems and has been populated with data used for the recently updated capital investment strategy (CIS). Candidate solutions involving the following performance measures are displayed for users to evaluate:

- Pavement - Percent Acceptable
- Bridge - Percent Acceptable
- Safety - Mitigation Locations (Number)
- Mobility - Bottlenecks/Interchange And Other Projects (Number Addressed And Number Remaining)

METIS displays different candidate solutions, each of which represents a different version of the utility function. The candidate solutions vary in the weights placed on different investment objectives. As participants select different candidate solutions, the systems narrows down the weights in the utility function, ultimately recommending a set of weights based on participants' preferences. During the workshop, participants reviewed a number of candidate solutions, and

4800 Hampden Lane, Suite 800  
Bethesda, MD 20814  
www.camsys.com

tel 301 347 0100

fax 301 347 0101

discussed their approach to evaluating each candidate solution. However, during the workshop, participants found issues with the behavior of METIS that later were determined to stem from issues with the configuration of the system. In part as a result of these issues, and in part due to time constraints, it was not possible within the time allotted to the workshop to converge on a single utility function. Instead, the workshop participants arrived at a consensus that CS and Howard/Stein Hudson staff should investigate the data issues reported by workshop participants, and using the guidance provided by workshop participants, develop several basic solutions from which NJDOT staff could choose.

Following the workshop CS investigated the data issues reported in METIS, and found that, there were issues with how the input data were configured that led the system to appear to “get stuck” on certain results. After addressing these configuration issues, CS then proceeded as agreed upon at the workshop. This memorandum presents a set of three candidate sets of solutions for NJDOT review. These are essentially alternative utility functions that reflect varying preferences identified by NJDOT staff. The following sections describe the solution approach, present the alternative solutions, and discuss next steps.

## Solution Approach

### *Preferences*

Workshop participants determined that the METIS exercise would be guided by a number of instructions:

- Funding should be allocated across all system management categories;
- Bridge and Pavement are major focus areas for NJDOT;
- Resolving bottlenecks and interchanges is expensive, but shouldn't come at the expense of overall mobility; and
- The assumed annual budget is \$1 billion.

### *Performance Ranges*

Workshop participants outlined potential achievement levels to consider when evaluating the value of each candidate solution. The intent of this exercise was to determine acceptable performance ranges, beginning with current performance and ending with desired performance levels at the end of the 10 year period.

Management System	Current	Goal
Pavement	47%	80%
Bridge	84%	92%
Safety	680 Mitigation Locations	1,400 Mitigation Locations
Mobility - Bottlenecks / Interchange	30 Locations Addressed	60 Locations Addressed
Mobility - Other Projects	60 Locations Addressed	120 Locations Addressed

### *Determining Alternative Solutions*

Based on the preferences and performance ranges identified in the workshop, CS identified three sets of solutions for review. Each solution set represents a slightly different balance between the competing philosophies that drive tradeoffs in resource allocation at NJDOT. As a result, performance goes up or down across the asset categories between the different alternatives. It is important to note that there are declining returns in some areas, such as bridge, where performance levels are less affected even with increases in the budget allocation.

When reviewing the options, it may be helpful to consider the following questions:

- Are the tradeoffs reasonable?
- What are we getting for our money?
- Are we spending too much or too little?

### **Alternative Solutions**

This section presents the alternative solutions derived using METIS. For each solution, the text describes the underlying philosophy used to derive the solution. A screen shot shows the resulting METIS screen. Note that METIS shows a panel of five candidate solution. For any one alternative the system has been exercised such that the weights on different objectives are within a tolerance that is generally within 5 percent between the candidates shown. However, even the slightest variation in weight results in a slightly different allocation of resources. Thus, any two candidates may vary slightly.

These sets have been saved in METIS to facilitate further review. The saved name is shown for each set. These can be viewed under the "Saved Evolutions Session" tab at the following URL: <http://webservices2.camsys.com/METIS>.

Alternative 1 (NJDOT\_Workshop Results V1)

For this alternative, highest priority was placed on improving pavement and bridge condition. However, improvements in these areas were only allowed to the extent this could be accomplished without reducing safety performance. Thus, with this alternative, there is less investment in improving mobility, specifically with regard to the ability to fund large congestion projects (i.e., bottleneck/interchange).

Plan "A" <span style="color: red;">✗</span> <span style="color: green;">✓</span>				Plan "B" <span style="color: red;">✗</span> <span style="color: green;">✓</span>				Plan "C" <span style="color: red;">✗</span> <span style="color: green;">✓</span>				Plan "D" <span style="color: red;">✗</span> <span style="color: green;">✓</span>				Plan "E" <span style="color: red;">✗</span> <span style="color: green;">✓</span>			
Characteristic	Value	R(%)	r(%)																
Funds spent over 10 years, \$M				Funds spent over 10 years, \$M				Funds spent over 10 years, \$M				Funds spent over 10 years, \$M				Funds spent over 10 years, \$M			
Total	9998.9			Total	9998.9			Total	9998.9			Total	9998.9			Total	9998.9		
Pavement	2840.0			Pavement	2840.0			Pavement	2840.0			Pavement	2840.0			Pavement	2840.0		
Bridges	4680.0			Bridges	4680.0			Bridges	4680.0			Bridges	4680.0			Bridges	4680.0		
Safety	1100.0			Safety	1100.0			Safety	1100.0			Safety	1100.0			Safety	1100.0		
B-necks/interchg	873.8			B-necks/interchg	873.8			B-necks/interchg	873.8			B-necks/interchg	873.8			B-necks/interchg	873.8		
Mobility other	505.1			Mobility other	505.1			Mobility other	505.1			Mobility other	505.1			Mobility other	505.1		
Achieved acceptability level, percent				Achieved acceptability level, percent				Achieved acceptability level, percent				Achieved acceptability level, percent				Achieved acceptability level, percent			
Pavement	80.8	80.83	80.83																
Bridges	81.0	84.30	84.30																
Safety	17.4			Safety	17.4			Safety	17.4			Safety	17.4			Safety	17.4		
Number of addressed locations				Number of addressed locations				Number of addressed locations				Number of addressed locations				Number of addressed locations			
Safety	680	33.83	33.83																
B-necks/interchg	5	4.00	4.95																
Other mobility	40	24.24	24.24	Other mobility	40	24.24	24.24	Other mobility	40	24.24	24.24	Other mobility	40	24.24	24.24	Other mobility	40	24.24	24.24
Number of remaining congested locations				Number of remaining congested locations				Number of remaining congested locations				Number of remaining congested locations				Number of remaining congested locations			
B-necks/interchg	120			B-necks/interchg	120			B-necks/interchg	120			B-necks/interchg	120			B-necks/interchg	120		
Other	125			Other	125			Other	125			Other	125			Other	125		
r - Statistics				r - Statistics				r - Statistics				r - Statistics				r - Statistics			
Minimum		4.95		Minimum		4.95		Minimum		4.95		Minimum		4.95		Minimum		4.95	
Maximum		84.30		Maximum		84.30		Maximum		84.30		Maximum		84.30		Maximum		84.30	

Alternative 2 (NJDOT\_Workshop Results V2)

For this alternative, the general philosophy and data used were the same as for Alternative 1. However, here greatest emphasis was placed on improving pavement conditions, safety, and mobility. Less emphasis was placed on improving bridge conditions.

Plan "A" <span style="color:red">✖</span> <span style="color:green">✔</span>				Plan "B" <span style="color:red">✖</span> <span style="color:green">✔</span>				Plan "C" <span style="color:red">✖</span> <span style="color:green">✔</span>				Plan "D" <span style="color:red">✖</span> <span style="color:green">✔</span>				Plan "E" <span style="color:red">✖</span> <span style="color:green">✔</span>			
Text																			
Characteristic	Value	R(%)	r(%)																
Funds spent over 10 years, \$M																			
Total	9994.6			Total	9998.1														
Pavement	2840.0			Pavement	2840.0			Pavement	2840.0			Pavement	2840.0			Pavement	2840.0		
Bridges	660.0			Bridges	660.0			Bridges	660.0			Bridges	660.0			Bridges	660.0		
Safety	1417.0			Safety	1417.0			Safety	1417.0			Safety	1417.0			Safety	1417.0		
B-necks/Interchg	4041.7			B-necks/Interchg	4067.3														
Mobility	1036.0			Mobility	1013.8														
other																			
Achieved acceptability level, percent																			
Pavement	80.8	80.83	80.83																
Bridges	55.1	57.35	57.35																
Safety	22.4			Safety	22.4			Safety	22.4			Safety	22.4			Safety	22.4		
Number of addressed locations																			
Safety	761	37.84	37.84																
B-necks/Interchg	33	26.40	32.67	B-necks/Interchg	34	27.20	33.66												
Other mobility	82	49.70	49.70	Other mobility	80	48.48	48.48	Other mobility	80	48.48	48.48	Other mobility	80	48.48	48.48	Other mobility	80	48.48	48.48
Number of remaining congested locations																			
B-necks/Interchg	92			B-necks/Interchg	91														
Other	63			Other	65														
r - Statistics																			
Minimum		32.67		Minimum		33.66													
Maximum		80.83		Maximum		80.83		Maximum		80.83		Maximum		80.83		Maximum		80.83	

**Alternative 3 (NJDOT\_Workshop Results V3)**

As for Alternatives 1 and 2, the same general philosophy and data were used for Alternative 3. Here funding was spread more evenly across the management systems, resulting in an increased ability to address safety and mobility, specifically with regard to funding other congestion relief projects, at the cost of pavement and bridge investments.

Plan "A" <span style="color: red;">✖</span> <span style="color: green;">✔</span>				Plan "B" <span style="color: red;">✖</span> <span style="color: green;">✔</span>				Plan "C" <span style="color: red;">✖</span> <span style="color: green;">✔</span>				Plan "D" <span style="color: red;">✖</span> <span style="color: green;">✔</span>				Plan "E" <span style="color: red;">✖</span> <span style="color: green;">✔</span>			
Text																			
Characteristic	Value	R(%)	r(%)																
Funds spent over 10 years, \$M				Funds spent over 10 years, \$M				Funds spent over 10 years, \$M				Funds spent over 10 years, \$M				Funds spent over 10 years, \$M			
Total	9998.9			Total	9998.9			Total	9998.9			Total	9998.9			Total	9998.9		
Pavement	2120.0			Pavement	2120.0			Pavement	2120.0			Pavement	2120.0			Pavement	2120.0		
Bridges	2420.0			Bridges	2420.0			Bridges	2420.0			Bridges	2420.0			Bridges	2420.0		
Safety	2367.9			Safety	2367.9			Safety	2367.9			Safety	2367.9			Safety	2367.9		
B-necks/Interchg	1192.4			B-necks/Interchg	1192.4			B-necks/Interchg	1192.4			B-necks/Interchg	1192.4			B-necks/Interchg	1192.4		
Mobility	1096.6			Mobility	1096.6			Mobility	1096.6			Mobility	1096.6			Mobility	1096.6		
other				other				other				other				other			
Achieved acceptability level, percent				Achieved acceptability level, percent				Achieved acceptability level, percent				Achieved acceptability level, percent				Achieved acceptability level, percent			
Pavement	66.6	66.61	66.61																
Bridges	68.8	71.60	71.60																
Safety	37.4			Safety	37.4			Safety	37.4			Safety	37.4			Safety	37.4		
Number of addressed locations				Number of addressed locations				Number of addressed locations				Number of addressed locations				Number of addressed locations			
Safety	1002	49.07	49.07																
B-necks/Interchg	10	8.00	9.90																
Other mobility	151	91.52	91.52	Other mobility	151	91.52	91.52	Other mobility	151	91.52	91.52	Other mobility	151	91.52	91.52	Other mobility	151	91.52	91.52
Number of remaining congested locations				Number of remaining congested locations				Number of remaining congested locations				Number of remaining congested locations				Number of remaining congested locations			
B-necks/Interchg	115			B-necks/Interchg	115			B-necks/Interchg	115			B-necks/Interchg	115			B-necks/Interchg	115		
Other	14			Other	14			Other	14			Other	14			Other	14		
r - Statistics				r - Statistics				r - Statistics				r - Statistics				r - Statistics			
Minimum		9.90		Minimum		9.90		Minimum		9.90		Minimum		9.90		Minimum		9.90	
Maximum		91.52		Maximum		91.52		Maximum		91.52		Maximum		91.52		Maximum		91.52	

## Summary

The following table summarizes the performance results of the three alternatives and their associated investment levels spent over a 10 year period.

Performance Measure	Performance Values		
	Alternative 1	Alternative 2	Alternative 3
Pavement Percent Acceptable	80.8% (\$2.84B)	80.8% (\$2.84B)	66.6% (\$2.12B)
Bridge Percent Acceptable	81.0% (\$4.68B)	55.1% (\$660.0M)	68.8% (\$2.42B)
Safety Mitigation Locations	680 (\$1.10B)	761 (\$1.42B)	1002 (\$2.37B)
Mobility - Bottlenecks / Interchange Number Addressed	5 (\$873.8M)	34 (\$4.07B)	10 (\$1.19B)
Mobility - Other Projects Number Addressed	40 (\$505.1M)	80 (\$1.01B)	151 (\$1.90B)

Note: Totals may not add up due to rounding.

The table below compares the results of the three alternatives, and shows the resulting objective weights used in the utility function. To the extent that a range of slightly different candidates are illustrated for any one alternative, the results have been averaged to characterize that alternative.

Performance Measure	Weights		
	Alternative 1	Alternative 2	Alternative 3
Pavement	0.36737082	0.369639695	0.098503358
Bridge	0.292652626	0.094302455	0.064643099
Safety	0.115598067	0.216462149	0.37170214
Mobility - Bottlenecks / Interchange	0.103427543	0.136338355	0.045323949
Mobility - Other Projects	0.120950945	0.183257346	0.419827454

## Next Steps

After reviewing these solutions, NJDOT should select one of the alternatives described above. Alternatively, if none of the alternatives seem representative of NJDOT preferences, an additional group session may be warranted to reach consensus. Once an alternative has been selected, the objective weights from the alternative will be used in the project utility function being developed as part of the project. CS will provide NJDOT with a recommended model formulation using these weights, and illustrate how the model functions in prototype form, for further review by NJDOT.

## APPENDIX B – UTILITY FUNCTION PARAMETERS

Table 2. Utility Function Weights

Type	Description	Value
1	Pavement	0.3674
2	Bridge	0.2927
3	Mobility – Major	0.1034
4	Mobility – Minor	0.1210
5	Safety	0.1156

Table 3. Utility Function Parameters

Type	Description	$\mu$	$\lambda$
1	Pavement	1.6054E+14	1.777300000
2	Bridge	4,593,861.967	1.208531097
3	Mobility – Major	32,921.410	1.667347000
4	Mobility – Minor (use for nonbridge safety)	41,068.880	1.131807000
5	Safety (bridge only)	41,156,545.124	1.643075256

Table 4. Default Accident Costs

Functional Classification	Value (2006 \$)
01 – Rural Interstate	153,058
02 – Rural Principal Arterial	199,474
06 – Rural Minor Arterial	159,117
07 – Rural Major Collector	179,129
11 – Urban Interstate	72,394
12 – Urban Freeways and Expressways	63,526
14 – Urban Other Principal Arterial	57,139
16 – Urban Minor Arterial	46,567
Other	43,309

Table 5. Other Model Parameters

Parameter	Value
$k_{1,1}$	1.0000
$k_{1,2}$	120,118.2728
$k_{1,3}$	25,872.1727
$k_{1,4}$	-236.9062
$k_{1,5}$	49,769.6761
$k_{1,6}$	-12,130.2935
$k_{1,7}$	-22.4128
$k_{1,8}$	-23,458.4113
$k_{1,9}$	15,275.2667
$k_{1,10}$	20.0000
$k_{2,1}$	47,793.26308
$k_{2,2}$	0.603114187
$k_{2,3}$	-145.1927583
$k_{2,4}$	93.98495038
$k_{2,5}$	172.8173283
$k_{2,6}$	93.30721024
$k_{2,7}$	74,844.25595
$k_{2,8}$	0.318086046
$k_{2,9}$	-199.1767068
$k_{2,10}$	84.55355338
$k_{2,11}$	133.6423972
$k_{2,12}$	56.90323884
$k_{2,13}$	5,761.127418
$k_{2,14}$	0.005544295
$k_{2,15}$	4,352.030123
$k_{2,16}$	0.005366316
$k_{2,17}$	993,717.3751
$k_{2,18}$	72.15246599
$k_{2,19}$	-3464.68317
$k_{2,20}$	35.50042581
$k_{3,1}$	0.0197153
$k_{5,1}$	0.7899000
$k_{5,2}$	0.4531000