DCT 230

Advancing Asset Management at DelDOT

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November 2012

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A report submitted to the Delaware Center for Transportation (DCT) and Delaware Department of Transportation (DelDOT)

August 24, 2012

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1. Introduction

Problem Statement

Asset management is about the best way to use limited resources (1). The concepts are based on performance measures and goals and focus on both the long and short term goals of an organization. Asset management provides an opportunity to respond proactively to land use changes, growing demands, aging infrastructure, and safety and security challenges.

Despite these promises and opportunities, implementing asset management is challenging. A peer exchange focused on asset management in operations and planning identified six barriers to the implementation of asset management in agencies (2). These are:

- lack of integration using more sophisticated analytic tools to evaluate and prioritize maintenance and rehabilitation projects;
- database issues;
- lack of adequate communication tools and methods for different audiences;
- jurisdictional issues;
- institutional issues; and
- implementation and development costs.

Recognizing these barriers, the team from a 2005 international scan of asset management practices suggested that implementing asset management strategies for interstate highways might serve as a useful demonstration of the value of asset management and help to preserve one of the US's most important and visible assets (3). A National Cooperative Highway Research Program (NCHRP) project was launched. NCHRP Project 20-74

“Developing an Asset Management Framework for the Interstate Highway System” provided guidance for handling all interstate highway system (IHS) assets, particularly assets besides pavements and bridges (4).

During this same time frame, Delaware Department of Transportation (DelDOT) with assistance from the University of Delaware (UD) began exploring asset management. Many asset management activities are ongoing at DelDOT (for example, the MAXIMO system, pavement management, bridge management, highway safety improvement program, travel time monitoring surveys, and performance management). However, there is a need to link these various activities, begin to fill the gaps in data and procedures, and explore new tools to support the integration of existing tools and link the tools to decision making (5).

Objectives

To address some of these issues, DelDOT and UD launched a project to explore the application of the asset management framework for the interstates and interstate like highways in Delaware. The objective is to develop a practical framework for applying asset management principles and practices to the interstate highway system. The framework is intended to use existing data, tools and performance measures used by state departments of transportation including risk assessment. This research proposes to use this framework to address the issues identified above by focusing on I-95, I-295, I-495, and the tolled portion of Rte 1 in Delaware. Applying this framework to interstate and interstate-like highway systems in Delaware provides an opportunity for DelDOT to better understand asset management and how a limited set of performance measures can be used to better manage these assets. This project provides a small but manageable case study to illustrate concepts and strategies, and is applicable to many different highway divisions elsewhere.

Methodology and Scope

The framework documented in NCHRP Report 632 uses data, tools and performance measures that are commonly used by state departments of transportation and also includes strategies for risk assessment and risk management. NCHRP Report 632 recommends the following elements be included in an asset management plan for the interstates:

- Significance of the interstate highway system;
- Assets included in the plan;
- Measuring performance;
- Past and present funding;
- Risk assessment;
- Interstate investment strategy; and
- Updating the plan.

Using this framework, an application of asset management principles to I-95, I-295, I-495 and the tolled portion of State Route 1 (SR 1) in Delaware is developed. The work plan was as follows:

Task 1. Review asset management framework

The research team reviewed the asset management framework developed as part of the NCHRP 20-74 project and present concepts, data needs and detailed work plan.

Task 2. Apply the framework to I-95, I-295 and I-495, and tolled portion of Route 1 in Delaware

This involved exploration of the available data sets, the use of DelDOT's performance measures and tools such as HERS-ST, Pontis, and AssetManager NT to develop management strategies. This experience highlights both the strengths and weaknesses of existing practices.

Task 3. Evaluate the results

Summary data was developed to demonstrate the outcomes of the process and qualitatively assess the applicability of the framework to DelDOT.

Task 4. Develop lessons learned and identify concepts and ideas that are transferable to other areas

Based on our experiences and discussions lessons learned and transferable concepts to be shared are identified.

Report Outline

The report is organized as follows. The following section provides background on the NCHRP 20-74 asset management framework, asset management at DelDOT, the proposed approach for using asset management to better manage interstate highways and the tools available to support this process. Data sources and tools are then discussed and reviewed. The subsequent section presents the results from the asset management software and tools. These trade-off analysis results are analyzed and Data Envelopment Analysis (DEA) is adopted to benchmark various investment level and resource allocation scenarios within and cross assets. Finally conclusions are presented.

2. Background and Literature Review

Asset Management Overview

Transportation Asset Management is defined in the AASHTO Transportation Asset Management Guide (6) as “a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision-making based upon quality information and well defined objectives”. The core principles of asset management have increasingly gained acceptance in the transportation community in recent years. These principles hold that asset management has the following characteristics:

- **Policy-Driven**. Resource allocation decisions are based on a well-defined and explicitly stated set of policy goals and objectives.
- **Performance-Based**. Policy objectives are translated into system performance measures that are used for strategic management and tied to the resource allocation process.
- **Reliant on Analysis of Options and Tradeoffs**. Decisions on how to allocate resources within and across different types of investments are based on an analysis of how different allocations will impact the achievement of relevant policy objectives.
- **Focused on Yielding Decisions Based on Quality Information**. The merits of different options with respect to an agency’s policy goals are evaluated using credible and current data. Where appropriate, decision support tools are used to provide easy access to

needed information, to assist with performance tracking and predictions, and to perform specialized analysis.

- **Reliant on Monitoring to Provide Clear Accountability and Feedback**. Performance results are monitored and reported. Feedback on actual performance may influence agency goals and objectives, as well as resource allocation and utilization decisions in future budget cycles.

Figure 1 summarizes the basic asset management process highlighting issues at each step of the process.

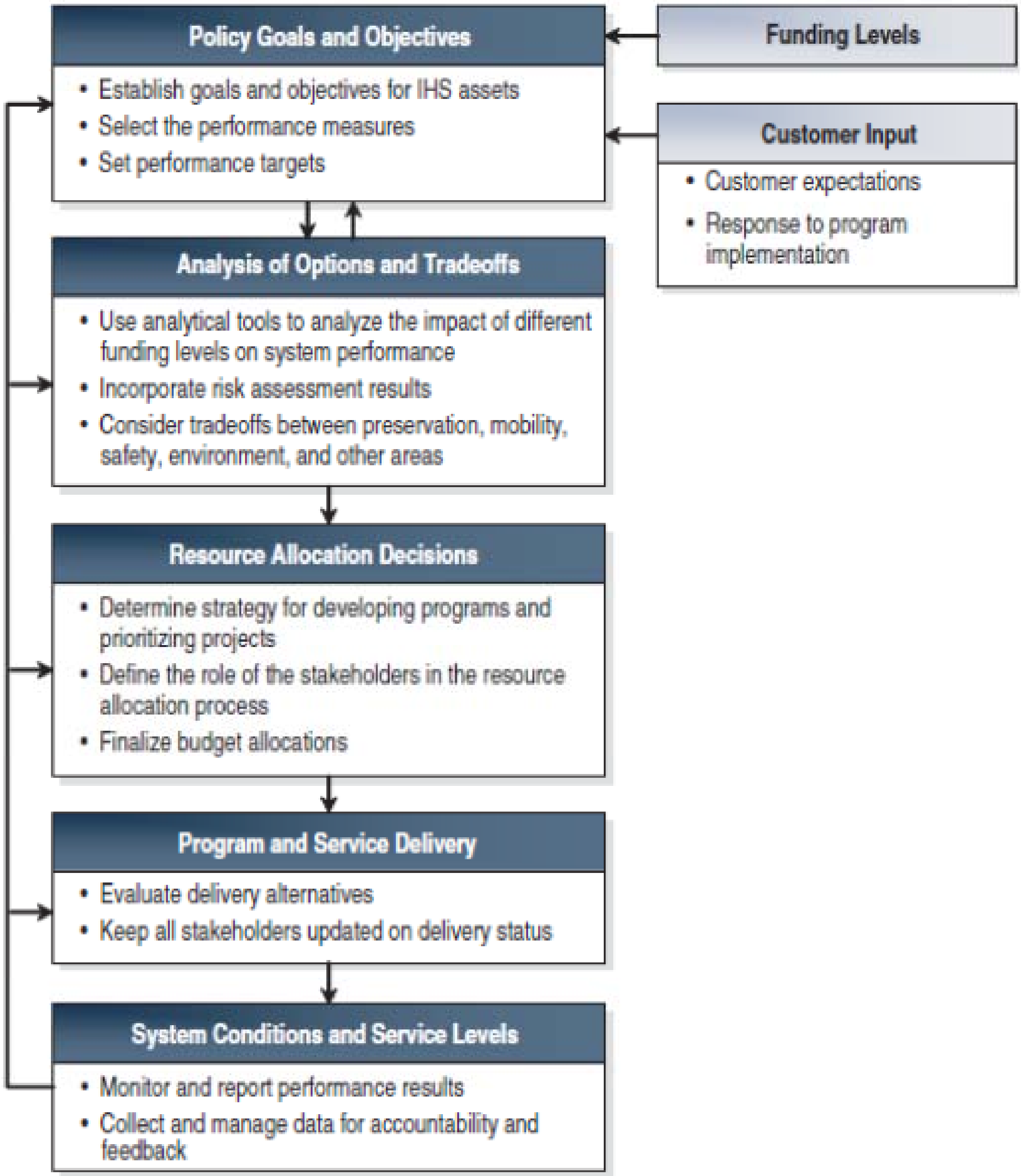


Figure 1 Generic Asset Management Process (4)

Asset Management for Interstate Highway System

Interstate Highway System (IHS) serves a very large share of the nation's highway transportation demand, disproportionate to the system's share of the nation's highway mileage. A major challenge in managing this asset lies in developing usable management principles and strategies that can be accepted and applied by the varied government agencies that share responsibility for the IHS. To assist agencies in applying sound asset-management principles and practices for the IHS, NCHRP Project 20-74 "*Developing an Asset Management Framework for the Interstate Highway System*" (4) developed guidance for developing a consistent framework for managing all interstate assets, including assets besides pavements and bridges. The project report (NCHRP Report 632) recommends a set of measures tailored for use in reporting and facilitating discussion of IHS performance and defines how better to incorporate assessment of the risks of system failure into an asset management framework.

Built on the previous work on transportation asset management, this project developed an asset management framework tailored to the HIS with focusing in on three selected areas (4):

- **Risk Management**: defining how to better incorporate assessment of the risks of system failure into an asset management framework;

  A scenario-based approach is presented for quantifying the risks to a set of IHS assets, including their likelihood, consequences if realized, and available mitigation approaches. The outcome of applying the scenario-based approach is a recommended allocation of resources to mitigating risk based on a determination of how an agency can best minimize the expected economic losses from the risks it perceives to its IHS assets. Several examples of the risks are listed in Table 1.

Table 1 Risk Types and Examples (4)

Risk Type	Examples
Unintentional Hazard	• Oil spill • Hazardous materials spill • Vehicular crashes
Intentional Threat	• Terrorist attack • Crime • War attack
Natural Hazards	• Heavy rain • Strong wind • Heavy snow and ice • Earthquake • Hurricanes • Flood • Mud/landside
Performance	• Substandard design • Construction defects • Materials defects • Unexpected heavy traffic

- **Comprehensive set of IHS Assets**: providing guidance for handling all IHS assets, particularly assets besides pavements and bridges;

Table 2 details the infrastructure assets associated with the IHS, organized by asset category. Agencies should make investment decisions across assets, modes, and investment categories, rather than concentrating decision making within narrowly defined “silos,” with each silo focusing on a specific asset and/or type of investment.

Table 2. IHS Infrastructure Assets (4)

Asset Category	Asset Type	
Roads	• Pavement	• Shoulders
Structures	• Bridges • Tunnels • Culverts/drainage • Noise barrier walls	• Retaining walls • Overhead sign structures • High mast light poles
Safety Features	• Pavement markings/delineators • Lighting • Guardrails • Median barriers	• Impact attenuators • Signs • Surveillance/monitor equip. • Signal/control equipment
Facilities	• Rest areas • Toll plazas • Weigh stations	• Maintenance depots • Pump houses • Communication facilities

- **Performance Measures**: Recommending a set of measures tailored for use in reporting and facilitating discussion of IHS performance both within an agency, to system users, industry partners, and nationally.

  Performance measures are used to monitor progress towards policy goals and objectives, reflect asset conditions, provide a long-term view of asset life cycles, and track program delivery. Performance targets are specific performance measure values an IHS owner plans to achieve. These are set based on consideration of past trends, predicted future performance, agency funding levels, and other factors. In developing the set of measures, the research team made a distinction between measures that every IHS owner should be in a position to report today, labeled “core” measures, and additional measures that would be desirable to report for IHS assets if an agency has sufficient data and resources, labeled “comprehensive” measures. Ideally, every IHS owner would report the core measures at a minimum, and plan to collect and report the full set of comprehensive measures in the future. Table 3 summarizes the recommended core measures. The comprehensive set includes measures of asset performance for each of the categories listed in Table 4.

Table 3. Recommended Core IHS Asset Management Performance Measures (4)

Category	Asset Type	Measure Type	Measure
Preservation	Pavement	Structural Adequacy	Present Serviceability Rating (PSR) or an agency’s pavement condition index
		Ride Quality	International Roughness Index (IRI)
	Bridges	Structural Deficiency	Percent classified as Structurally Deficient (SD), weighted by deck area
	Signs	Asset Performance	Percent functioning as intended
	Pavement Markings	Asset Performance	Percent functioning as intended
	Guardrails	Asset Performance	Percent functioning as intended
Mobility		Travel Time	Travel time index
		Delay	Delay per vehicle in hours
Safety		Crash Rate	Number of crashes expressed as number per year and per million vehicle miles traveled (VMT)
		Fatality Rate	Number of fatalities expressed as number per year and per VMT
Environment		Agency-specific report card	Pass/fail indication for each measure

Table 4 Recommended Comprehensive IHS Asset Management Performance Measures (4)

Category	Asset Type	Measure Type	Measure
Preservation	Shoulders	Asset Performance	Percent functioning as intended
	Tunnels	Asset Performance	Percent functioning as intended
	Culverts/drainage structures	Asset Performance	Percent functioning as intended
	Noise barrier walls	Asset Performance	Percent functioning as intended
	Retaining walls	Asset Performance	Percent functioning as intended
	Overhead sign structures	Asset Performance	Percent functioning as intended
	High mast light poles	Asset Performance	Percent functioning as intended
	Lighting	Asset Performance	Percent functioning as intended
	Median barriers	Asset Performance	Percent functioning as intended
	Impact attenuators	Asset Performance	Percent functioning as intended
	Surveillance and monitoring equipment	Asset Performance	Percent functioning as intended
	Signal and control equipment	Asset Performance	Percent functioning as intended
	Rest areas	Asset Performance	Percent functioning as intended
	Toll plazas	Asset Performance	Percent functioning as intended
	Weigh stations	Asset Performance	Percent functioning as intended
	Maintenance depots	Asset Performance	Percent functioning as intended
	Pump houses	Asset Performance	Percent functioning as intended
	Communication facilities	Asset Performance	Percent functioning as intended
Mobility		Winter Maintenance	Average time to restore pavement surface
Delivery		Schedule Adherence	Percentage of total projects finished on or before original scheduled contract completion date
		Cost Control	Annual ratio of actual construction cost to bid amount

Asset Management Data

Transportation asset management is a data-driven process that requires collecting, processing, storing, and retrieving data from a variety of sources and putting the data to use in investment decision making. Having sufficient, detailed data in a usable format is critical to successful asset management implementation. The ideal system for supporting transportation asset management would include the following functionality for all assets and investment types (4):

- Storing and retrieving condition data;
- Establishing goals and performance measures;
- Identifying needs;
- Predicting future conditions and service levels based on different investment scenarios and/or performance targets;
- Supporting development of capital and/or operating plans; and
- Monitoring results.

Federally mandated data sets and other types of databases commonly maintained by state DOTs (4) are reviewed and organized by asset type, with additional subsections on mobility, safety, and environmental data in the following sections.

Roadway Data

Highway Performance Management System (HPMS)

The HPMS is a national transportation data system providing detailed data on highway inventory, condition, performance, and operations. It describes functional characteristics, traffic levels, and pavement conditions for all IHS sections. The current version of the HPMS includes two measures of pavement condition: PSR and IRI. HPMS 2010 will contain additional measures of rutting/faulting and cracking, consistent with AASHTO standards for pavement data collection.

Pavement Management Systems (PMS) Databases

Most agencies collect pavement data required to run a pavement management system (PMS). PMS databases are needed for supporting the asset management framework, but there is no standard format for how this information is collected or stored. Variances exist in terms of the scopes and the types of the pavement inventory and condition data collected.

Structure Data

National Bridge Inventory (NBI)

The NBI is a federally mandated database of bridge inventory and conditions compiled by state DOTs for submission to FHWA. It contains data on all bridges and culverts on or over U.S. roads that are greater than 20 feet in length, and data on many tunnels. The NBI data set contains condition data by bridge component: deck, superstructure, substructure, channel/channel protection, and culvert. It also contains data on a bridge's functionality, such as under clearances and load posting information.

Pontis Bridge Management System (BMS)

Most states in the United States have licensed the AASHTO Pontis interface as the BMS database. The Pontis database contains all the NBI data items, as well as more detailed element-level inspection details. The Pontis database contains additional data on the distribution of conditions by condition state for each structural element of the superstructure, including elements such as girders, stringers, floor beams, etc. AASHTO has developed standard element descriptions and condition state language, referred to as "Commonly Recognized (CoRe) elements" for use with Pontis and other BMS (7). Most agencies that have implemented Pontis have added agency-specific data items to the Pontis database.

Other Structure Data

The NBI file described above contains inventory information for many tunnels and inventory and condition information for some culverts (where the length of the culvert measured along the centerline of the roadway is over 20 feet long). There are no other Federal databases containing data on non-bridge structures, including tunnels, culverts, retaining walls, sign support structures, and other structures. However, a number of agencies store data on other structures in their BMS. The collection of data on these assets varies significantly between state DOTs.

Safety Feature and Facility Data

Many state DOTs maintain inventory of their safety features and facilities. There are no Federal standards for collection of asset data for safety features and facilities, and no real consistency in the data available from one agency to another.

NCHRP Synthesis 371 (8) details data available for signals, lighting, signs, pavement markings, culverts, and sidewalks. The white paper titled “The Use of Highway Maintenance Management Systems in Statewide Highway Agencies” describes a survey of maintenance management data and systems performed in US (9). The report on the Transportation Asset Management Domestic Scanning Tour (10) details best practices examples for asset data collection in a number of agencies. The AASHTO Asset Management Data Collection Guide (11) provides examples of best practices for a number of assets, and recommends specific inventory and condition data items to collect for assets including signs, guardrails, and pavement markings.

Mobility Data

The HPMS is the major source of mobility data for the IHS, particularly at a national level. It contains average annual daily traffic (AADT) data for all segments and additional functional data needed for modeling mobility-related measures. The FHWA Highway Economic Requirements System—State Version (HERS-ST) (12) takes HPMS data as an input and can be used to model mobility measures.

Safety Data

Fatality Analysis Reporting System (FARS)

National Highway Traffic Safety Administration (NHTSA) maintains the FARS data. Established in 1975, FARS contains data describing all fatal accidents occurring on public roads in the United States.

Highway Safety Information System (HSIS)

The FHWA's HSIS is a multistate safety database that contains accident, roadway inventory, and traffic volume data. The participating states—California, Illinois, Maine, Michigan, Minnesota, North Carolina, Utah, and Washington—were selected based on the quality of their data, the range of data available, and their ability to merge data from the various sources.

State Crash Data Systems

Every state has a unique system for collecting crash data based on police accident reports (PAR), and an administrative structure for controlling the data. The TransXML schema is one example developed through NCHRP Project 20-64 (13).

State Highway Safety Improvement Plans (HSIP)

Each state is required to develop a HSIP on an annual basis detailing its use of federal transportation safety funding. The HSIP is a useful source of data for information on state-level safety improvement needs and trends.

Environmental Data

There exists little environmental data available, particularly on a consistent basis from agency to agency. NCHRP Web-Only Document 103 (14) details data sources and analytical tools used by transportation agencies for environmental management.

Risk-Related Data

Information on the risks to transportation infrastructure is particularly sparse. The NBI contains data on certain types of risks to structures, through detailing bridge design types and materials, through specifying whether or not a bridge has fracture critical details, and by storing information on bridges' vulnerability to scour. In many cases individual IHS owners have performed some form of assessment of the risks they perceive to be greatest (e.g., of seismic vulnerability in California, likelihood of flooding in the event of a hurricane in Gulf Coast states, etc.) (4). The National Asset Database provides a comprehensive listing of critical infrastructures and assets. However, consistency in classification of "critical assets" from state to state is an issue (15).

For predicting consequences of risks, many state DOTs and Metropolitan Planning Organizations (MPOs) do have statewide or regional travel demand models that can be used to model the disruption in the event of system failure. The Interstate 95 (I-95) Corridor Coalition

(16) is developing an integrated travel demand model for the states along I-95. For bridges, the NBI specifies the traffic on and under each IHS bridge, as well as the detour distance around the bridge. This information can be used to approximate consequences for bridge-related risks.

Asset Management Tools

Analytical tools are used to store and track data, and use the available data to support predictions of future conditions, analysis of investment need, and other applications. NCHRP 20-57 conducted a comprehensive review of the analytical tools to support the Interstate Asset Management Framework as illustrated in Table 5 (4).

The summary overview of these tools are mainly from the NCHRP 20-74 report (4) and more detailed descriptions can be found in this literature. FHWA's HERS-ST uses HPMS data to predict highway investment needs and measures. The system simulates both pavement preservation and highway capacity expansions needs. HERS-ST is notable in that it is one of few systems that generates needs for new capacity. This functionality is in contrast to that provided in other tools, which typically can evaluate a set of project or network improvements, but lack functionality for needs generation. HERS-ST also projects a wide range of performance measures, including selected preservation, mobility and accessibility, safety, and environmental measures.

The World Road Association (PIARC) offers HDM-4 for analysis of roadway management and investment alternatives. The system has been used internationally to evaluate road projects, budget scenarios, and roadway policy options. HDM-4 has functionality similar to HERS-ST, with a more detailed set of pavement models. However, the system does not use HPMS data as an input, and has not been implemented in the U.S.

Table 5. Analytical Tool Summary (4)

Tool	System Type	Available From	Notes
AssetManager NT	Investment analysis	AASHTO	Integrates investment analysis results from multiple sources
AssetManager PT	Needs and Project Evaluation	AASHTO	Prioritizes projects based on user-specified measures
BCA.Net	Needs and Project Evaluation	FHWA	Performs benefit/cost analysis for highway improvements
BLCCA	Needs and Project Evaluation	NCHRP	Bridge preservation life cycle cost analysis
DIETT	Risk Assessment	NCHRP	Prioritizes risks to transportation choke points
HDM-4	Investment Analysis	McTrans, Presses de l'ENPC (Paris)	Simulates highway investment needs, condition and performance
HERS-ST	Investment Analysis		Simulates highway investment needs, condition and performance
IDAS	Needs and Project Evaluation	McTrans and PCTrans	Evaluates network impact of ITS improvements
MOOS Bridge Level Model	Needs and Project Evaluation	NCHRP	Assist in developing bridge-level strategies using data from Pontis. Also can be used to prioritize investments to mitigate bridge risks
MOOS Network Level Model	Investment Analysis	NCHRP	Uses data from the bridge-level model to perform multi-objective analysis
NBIAS	Investment Analysis	FHWA	Simulates bridge investment needs, condition and performance
PONTIS	Management System	AASHTO	BMS licensed by most U.S. state DOTs
REALCOST	Needs and Project Evaluation	FHWA	Performs benefit/cost analysis for pavement projects
STEAM	Needs and Project Evaluation	FHWA	Evaluates network impact of multimodal improvements
TRNS*PORT	Results Monitoring	AASHTO	Supports preconstruction, contracting, and construction management

FHWA's National Bridge Investment Analysis System (NBIAS) is designed for modeling national-level bridge investment needs. The system uses a modeling approach originally adapted from the Pontis BMS to predict bridge preservation and functional improvement investment needs. The system takes NBI data as its input, but also can import element-level data.

Pontis is a comprehensive bridge management system based on bridge inventory and inspection data. The system formulates network-wide preservation and improvement policies for use in evaluating the needs of each bridge in a network, and makes recommendations on what projects to be included in an agency's capital plan for deriving the maximum benefit from limited funds. Pontis is an AASHTOWare product (17).

The Multi-Objective Optimization System (MOOS) network-level model is a spreadsheet tool for bridge investment analysis detailed in NCHRP Report 590 (18). The system uses data on work candidates generated separately to project future conditions and performance given performance and/or budget constraints and objectives. The tool supports use of a multi-objective approach, but requires extensive data to run, to be specified for each individual bridge using the MOOS bridge-level model.

AssetManager NT, developed through NCHRP Project 20-57 (4) and now released through AASHTO, is an investment analysis tool designed to integrate data from other investment analysis and management systems. It takes analysis results generated by systems such as HERS-ST, NBIAS, and agency management systems as inputs, and uses this information to show performance measure results over time for different funding scenarios. The system includes spreadsheet “robots” for automatically running HERS-ST and the Pontis BMS to generate system input.

Surface Transportation Efficiency Analysis Model (STEAM) and ITS Deployment Analysis System (IDAS) are tools for evaluating network performance for a specified set of transportation improvements. Both systems require information on the improvements to be evaluated, and output from a travel demand model. STEAM uses this information to calculate a wide range of measures of transportation and environmental performance for multimodal improvements. IDAS is designed to evaluate the benefits of more than 60 types of ITS investments.

A number of tools are available to evaluate project-level costs and benefits. BCA.Net is a web-based tool developed by FHWA for highway benefit-cost analysis. The system predicts costs and benefits for a range of different highway projects, and includes functionality for sensitivity analysis. StratBENCOST is another system that uses MicroBENCOST models, but applies them to multiple project alternatives. TransDec is a tool for multimodal, multi-objective project analysis. It helps prioritize projects or project alternatives considering multiple objectives and measures. AssetManager PT is a spreadsheet tool for project analysis. It helps prioritize projects given information on the costs, benefits, and performance impacts of a set of projects.

Several available tools are spreadsheet tools intended for detailed lifecycle cost analysis (LCCA) for pavement or bridge projects. RealCost is FHWA’s current tool for pavement LCCA. The system includes a number of advanced features, including models for predicting user costs due to construction, and probabilistic modeling of analysis inputs using Monte Carlo simulation. BLCCA is a lifecycle cost analysis tool designed for bridge LCCA. It is designed to use data from systems such as Pontis. It includes probabilistic modeling of input parameters.

There are relatively few tools available for assessing risks of system failure for IHS assets. The Disruption Impact Estimating Tool (DIET) developed by NCHRP can be used for prioritizing risks to transportation choke points such as bridges and tunnels (19). It includes an Access tool for filtering choke points and a spreadsheet for prioritizing choke points based on potential economic losses if the choke point were closed.

For monitoring project delivery all agencies have additional systems for construction and project management. A number of agencies use AASHTO's Trns*Port suite to support preconstruction and construction management. Trns*Port includes 14 separate modules, with functionality in areas such as construction cost estimation, letting and awards, construction administration, bidding, and construction management.

Asset Management at DelDOT

Working with an Asset Management Advisory Committee at DelDOT, the UD team explored the role of asset management as a strategic decision making tool. This project explored the current asset management practices at DelDOT, provided education and training, and conducted a self assessment exercise and an analysis of the exercise (5). A variety of databases and tools supports asset management activities at DelDOT. While not comprehensive, Table 6 provides a select list of these systems.

Table 6. DelDOT Asset Management Related Databases and Systems (5)

Name	Description
BCAT	Barcode Asset Traffic – inventory of signal locations
BCIS	Financial management system (to be replaced by statewide accounting system)
FACTS	Project financial system
Falcon	Plan Archive
HPMS	Highway Performance Monitoring System
HSIP	Highway Safety Improvement Program
INFORM	GIS data that links data between groups and supports video logging data
M4	Equipment
MAXIMO	Maintenance Management Systems
NBI	National Bridge Inventory
PMS	Pavement Management System
Pontis	Bridge Management Systems
Primavera	Scheduling software
PSS	Paving in Suburban Streets
RIMS	Roadway Inventory Management System
URS	Stormwater drainage data collection system and work order generation

Performance measures are one of the key components of asset management. DelDOT has also been reviewing and revising their performance measures. The Statewide Long Range Transportation Plan uses performance measures to guide what is needed to build, maintain and operate the state's transportation system and to support asset management. In 2007 DelDOT undertook an effort to streamline the performance measures used throughout the department. The objective is to develop performance measures that are comprehensible and comprehensive, as well as measurable. Examples of current performance measures include the following (5):

- Structurally Deficient Bridges
  - Deficiency is determined through inspection.

- Deficiency helps determine rehabilitation and replacement decisions.
- Any necessary closures will affect traffic patterns, signage, signal operations, expected pavement wear.

- Percent Pavement Ranked as Good/Excellent
  - Users can recognize pavement conditions through rideability.
  - Favorable pavement conditions reduce wear on vehicles and improve safety.
  - Scheduling preventative maintenance can prolong pavement life.
- Percent Drainage Work Plan Completed
  - Water is one of the worst enemies of roadways.
  - Proper drainage will reduce future maintenance and reconstruction.

Examples of proposed performance measures include the following:

- Vehicle Travel Time
  - Auto Vehicle Location system will be implemented to measure travel time consistency.
  - Incident Management Detection
  - Electronic detection system used to find incidents and initiate a response
- Vehicle Delay Traveler Information
  - Delay information conveyed to travelers on 1380 AM and via a website.
  - Time from the incident detection to broadcast will be measured

The DelDOT Advisory Group was also able to identify gaps and needs. The discussions and self assessment identified areas in which further research, education and documentation are required as follows:

- Documentation and dissemination of available tools, and current processes and practices;
- Promotion of existing tools;
- Communication of the roles and functions of current practices;
- Definition of terminology and linking asset management practices to performance measures;
- Identification and documentation of gaps in data and processes;
- Assessment of needs for new tools and processes;
- Linking of policies and decision making;
- Development of policies and strategies;
- Demonstration of organizational commitment;
- Conducting additional training;
- Continuation of existing asset management and related activities.

3. DelDOT Data

Interstate-like Highways in Delaware

This study aims to apply the asset management framework to the interstates and interstate-like highways in Delaware that are shown in Figure 2, including:

- Interstate 95 Delaware Turnpike: John F. Kennedy Memorial Highway
- Interstate 495 Delaware
- Interstate 295 Delaware
- U.S Route 1 tolled portion: Korean War Veterans Memorial Highway

I-95, I-295 and I-495 are all part of the Northeast corridor and are significant not just for Delaware but for the Atlantic states and the nation. They provide access to the Port of Wilmington, and connect Delaware to Maryland, New Jersey, and Pennsylvania. The tolled portions of SR 1 are constructed and maintained to standards similar to those for the interstate highways.SR 1 runs north-south from Exit 4 on I-95 to the state capital - Dover, and the beaches in Southern Delaware.

As this project is applicable to many different DelDOT divisions, the UD team met with the Asset Management Advisory Committee. This committee consists of DelDOT managers responsible for different assets including pavements, bridges, signs, linemarking, guardrail, and drainage. In consultation with the project advisory committee, the scope of the project was defined in terms of the asset considered and the time frame. Four types of assets were selected for the project: pavement, bridge, sign, and drainage. These assets were selected to illustrate the concepts and help to develop a plan for including other assets such as striping, and guardrail in the future when data are available and consistent.

Figure 2 Delaware's Interstates and Interstate-Like Highways under Study

Pavement

The HPMS database has been used to determine highway system condition, performance, and investment needs for the Biennial Report to Congress on the Status and Condition of the Nation's Roads and Bridges for several decades. The HPMS data also serve as an input to the HERS-ST software to explore the implications of various performance goals and budget constraints. HERS includes an elaborate modeling system for pavement ride, congestion, crashes, and emissions. To date, Delaware has not used HERS-ST. But the HPMS data have been carefully documented and saved thus could be used in HEST-ST to explore the implications of investment on highway performance. The HPMS data include two pavement performance components: International Roughness Index (IRI) and Pavement Serviceability Rating (PSR).

DelDOT has implemented its Pavement Management System (PMS) since 2002 to develop the agency's paving and rehabilitation program. The PMS data include Overall Pavement Condition, Surface/Alkali Silica Reactivity, Structural Number, IRI and condition data (various distress types) along with AADT.

Both HPMS and PMS data were obtained from DelDOT. It is generally believed that the PMS data have better data quality than those in the HPMS database. Therefore, efforts were initiated to replace the performance data in HPMS with those collected in the PMS database by following the HPMS data format. However, this task was turned out to be challenging due to the following reasons:

- No consistent relationships were found to link the HPMS sampled sections and PMS data collection pavement sections.

- The dates of the data collected in these two data sets are totally different.
- Prior to 2009, IRI data were collected in DelDOT's Planning office, and thus not in the PMS database.

As a result, HPMS data are used as the input to HERS-ST. To ensure consistency, the most current data in 2008 (when the project was conducted) and a planning horizon of 20 years made up four five-year funding periods were used in the research. Based on 2008 data, the characteristics of these routes are given in Table 7. In total there are 68.8 miles of road and 381.3 lane miles.

Table 7 Pavement Characteristics of Interstate and Interstate-Like Highways in Delaware

Route	Route Miles	Lane Miles	AADT Range	Vehicle Miles of Travel (million)
I-95	23.3	162.8	35,332 to 173,449	813
I-295	4.6	21.5	66,541 to 91,742	133
I -495	12.5	72.5	18,088 to 79,746	296
SR1	28.4	124.5	29,785 to 71,024	391

The HERS-ST logic flow begins with an evaluation of the current state of the highway system based on analyst-supplied input (12). From the initial state, HERS-ST projects future conditions and performance for each funding period through the end of the overall analysis period. At the end of any given period, HERS-ST examines each highway segment according to accepted engineering standards and checks for deficiencies (e.g., volume-to-capacity ratios), uses standard engineering practices to identify potential improvement options to correct each of the deficiencies. For each potential improvement, benefit cost analysis is conducted via the comparison of expected benefits (the reduction in user, agency, and societal costs) over the life of the improvement with the initial cost of implementing the project, and then the "best" improvement options are selected for each section. National default monetary values of benefits are provided in the HERS-ST model for the calculation of benefit-cost ratio. The HERS-ST data flow is illustrated in Figure 3 (20).

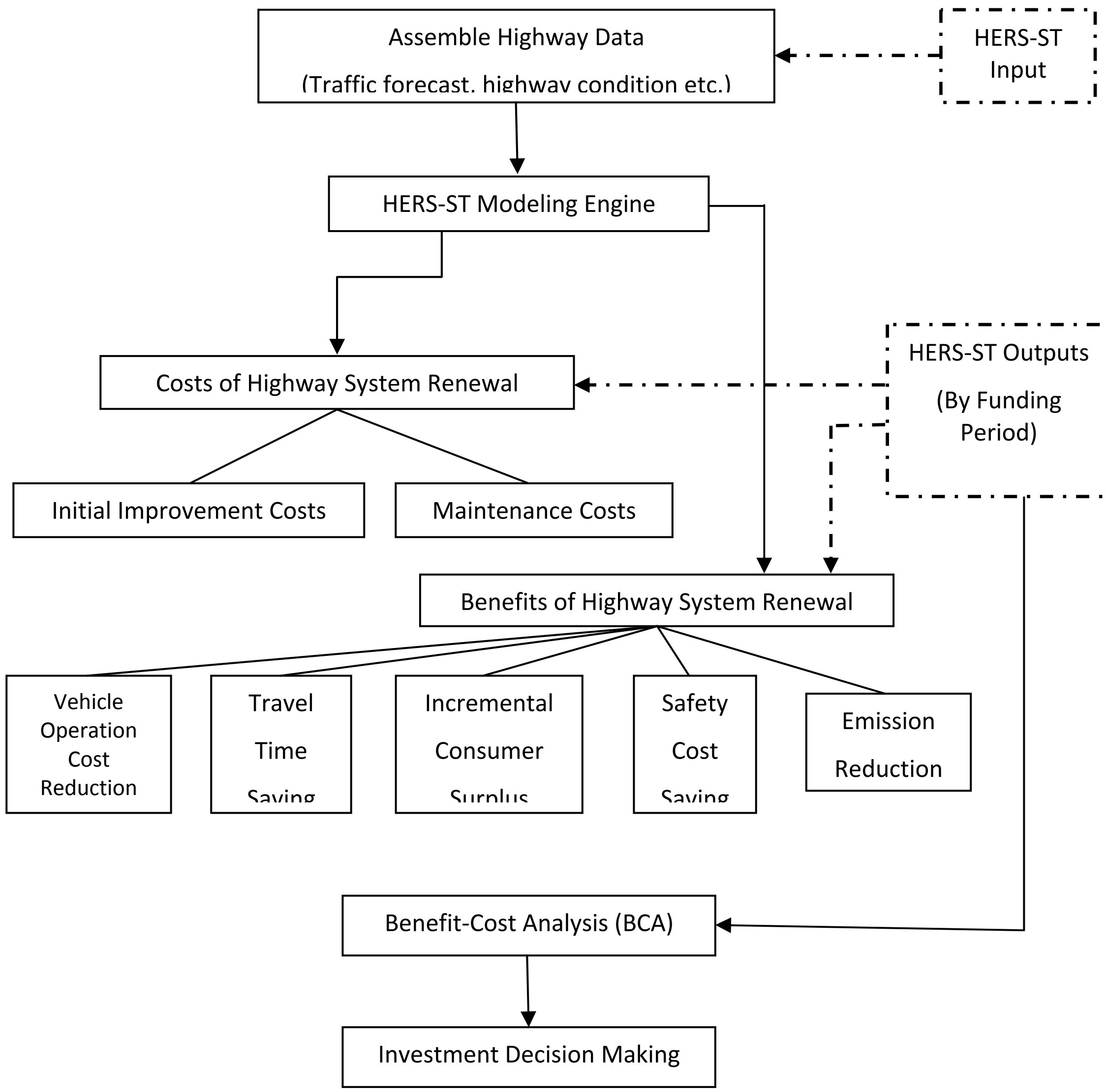


Figure 3 HERS-ST Modeling Logic (20)

For any section, HERS obtains the total initial improvement cost for combining pavement and widening improvements with alignment improvements by combining the cost of reconstructing part of the section on a modified alignment with the cost of the pavement and widening improvements made to the remainder of the section. As a result, the benefits of the investment are summarized in the System Conditions Output report by funding period, in which the following items are included (12):

- Miles in the system;
- Average PSR (paved sections only);
- Average IRI (inches per mile, paved sections only);
- Average speed;
- Congestion Delay (hours per 1000 vehicle-miles);
- Total Delay (hours per 1000 vehicle-miles);
- Total VMT;
- Travel-time costs (dollars per thousand vehicle-miles);
- Operating costs, listed for all vehicles combined and separately for four-tire vehicles and for trucks (dollars per thousand vehicle-miles);
- Crash costs (dollars per thousand vehicle-miles);
- Total user costs, which is a summation of travel-time costs, operating costs for all vehicles, and crash costs (dollars per thousand vehicle-miles);
- Number of crashes (per 100 million vehicle miles);
- Number of injuries (per 100 million vehicle miles);
- Number of fatalities (per 100 million vehicle miles);
- Annual maintenance costs (dollars per mile);

- Average cost of pollution damage (dollars per 1000 vehicle-miles); and
- Percent of total VMT on roads not meeting the user specified thresholds.

After exploring these data outputs, the following four aggregate performance measures for pavement are proposed for this research:

- User costs in dollars per 1000 vehicle miles of travel (VMT);
- Percentage of pavements in poor or fair condition based on mileage;
- Total delay in hours per 1000 VMT;
- Fatality rate in fatalities per million VMT.

Bridge

DelDOT collects bridge data using the Pontis BMS system. To collect this data, bridge inspections are conducted at least every two years. The Pontis data is used to help prioritize treatments, repair and replacement. Data based on the National Bridge Inventory (NBI) and bridge inspection and appraisal serves as input to Pontis. The Pontis process starts with the building of a relational database that includes importing NBI data and adding element-level inspection information. The process continues with development of a preservation policy for each element and environment combination in the database. A network analysis is performed to identify needs and benefits, and to support the allocation of resources for development of specific preservation and improvement program recommendations. From these recommendations, engineers and managers use the Project Planning module to identify an initial program of work. The Pontis process also includes tools for refining results, incorporating agency business practices, and allowing project tracking through the database.

Figure 4 illustrates the framework Pontis uses in recommending projects for an agency's capital or maintenance program. Inspection and cost data are used to help develop and update a preservation policy, the set of maintenance actions recommended for each state of each environment in which each bridge element may exist. The preservation policy is used as input to the program simulation, together with user-specified improvement costs and policies, the agency's budget, and other parameters. In the program simulation Pontis develops bridge-by-bridge project recommendations, and sums the needs, recommended work and other metrics across all bridges in a network to produce network-level results.

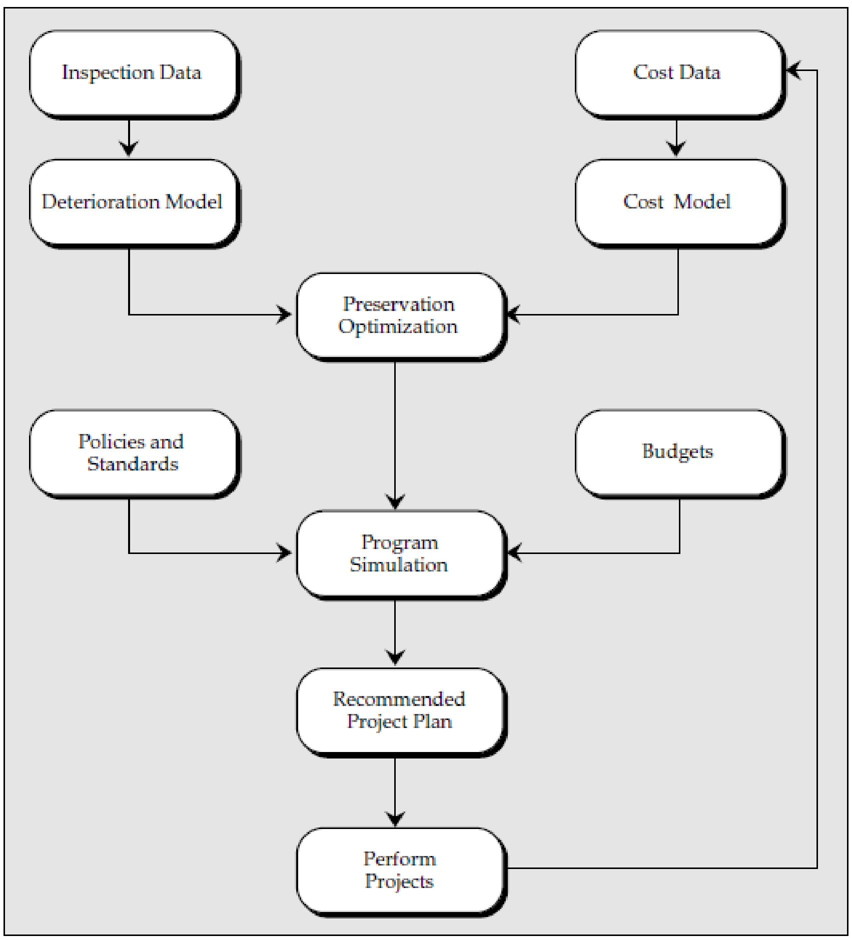


Figure 4 Pontis Modeling Framework (5)

Using 2008 NBI data sets, in total there are 208 bridges on these interstates and interstate-like highways with a total deck area of 4,437 thousand square feet.

Aggregate performance measures of bridge for the implementation of asset management framework include:

- Percentage of bridges classified as structurally deficient (SD) weighted by deck area;
- Percentage of bridges classified as SD weighted by number of bridges;
- Average bridge Health Index.

Traffic Signage

Introduction

Traffic sign asset management relies on information about the condition of signs in order to determine the maintenance method and budget necessary to ensure all traffic signs are visible to motorists. Sign performance during nighttime driving is dependent on retroreflectivity, measured by a coefficient of retroreflection. The coefficient of retroreflection is defined as:

$$\mathrm{Ra} = \frac{\text{Light that a sign reflects to a driver (candela,cd)}}{\text{Light that illuminates the sign (lux per unit area)}} \quad \text{..........................} \ (1)$$

Since the recommended retroreflectivity guidelines have been adopted in the FHWA’s 2003 edition of the *Manual on Uniform Traffic Control Devices* (*MUTCD*) (21), both compliance (for the safety and well being of the public) and proof of compliance (to protect against lawsuits) are necessary. Sign replacement procedures should be based in large part on the deterioration of a sign’s retroreflectivity over time. Table 8 shows the minimum retroreflectivity standard that a sign must meet to be compliant. The minimums vary based on sign type and color.

Table 9 shows the ASTM requirements (22) for brand new sheeting for sign colors and sheeting types typically used for permanent traffic signs. Note that the FHWA minimum retroreflectivity standards only cover white, yellow, orange, red, and green sheeting.

Condition assessment is a critical function of sign asset management systems. Sign condition and retroreflectivity assessments can be performed visually, using optical instruments, or by using management methods that attempt to predict when signs will be deficient. Visual inspection is the most commonly used condition assessment method for signs. Some agencies only observe signs during the daytime, while others observe during the daytime and nighttime. The advantage of nighttime inspections is that the retroreflective performance of the sign can be clearly viewed by those inspecting the sign. However, this assessment is subjective and various within different inspectors. Retroreflectometer measurement can be used as either an alternative or supplement to visual nighttime inspection. The main advantage of using portable retroreflectometers to assess sign condition is that retroreflectometers provide a quantitative determination of the sign's retroreflectivity that can be directly compared with the FHWA minimum retroreflectivity standards.

Table 8. FHWA Retroreflectivity Minimums (21)

Sign Color	Sheeting Type (ASTM D4956-04)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W*; G ≥ 7	W ≥ 120; G ≥ 15			Ground-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			(2)
	Y*; O*	Y ≥ 75; O ≥ 75			(3)
White on Red	W ≥ 35; R ≥ 7				(4)
Black on White	W ≥ 50				—

(1) The minimum maintained retroreflectivity levels shown in this table are in units of cd/lx/m2 measured at an observation angle of 0.2 ° and an entrance angle of -4.0 °.
(2) For text and fine symbol signs measuring at least 1200 mm (48 inches) and for all sizes of bold symbol signs
(3) For text and fine symbol signs measuring less than 1200 mm (48 inches)
(4) Minimum Sign Contrast Ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity) * This sheeting type should not be used for this color for this application.

Bold Symbol Signs

- W1-1, -2 – Turn and Curve
- W1-3, -4 – Reverse Turn and Curve
- W1-5 – Winding Road
- W1-6, -7 – Large Arrow
- W1-8 – Chevron
- W1-10 – Intersection in Curve
- W1-11 – Hairpin Curve
- W1-15 – 270 Degree Loop
- W2-1 – Cross Road
- W2-2, -3 – Side Road
- W2-4, -5 – T and Y Intersection
- W2-6 – Circular Intersection
- W3-1 – Stop Ahead
- W3-2 – Yield Ahead
- W3-3 – Signal Ahead
- W4-1 – Merge
- W4-2 – Lane Ends
- W4-3 – Added Lane
- W4-5 – Entering Roadway Merge
- W4-6 – Entering Roadway Added Lane
- W6-1, -2 – Divided Highway Begins and Ends
- W6-3 – Two-Way Traffic
- W10-1, -2, -3, -4, -11, -12 – Highway-Railroad Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3 – Deer Crossing
- W11-4 – Cattle Crossing
- W11-5 – Farm Equipment
- W11-6 – Snowmobile Crossing
- W11-7 – Equestrian Crossing
- W11-8 – Fire Station
- W11-10 – Truck Crossing
- W12-1 – Double Arrow
- W16-5p, -6p, -7p – Pointing Arrow Plaques
- W20-7a – Flagger
- W21-1a – Worker

Fine Symbol Signs – Symbol signs not listed as Bold Symbol Signs.

Special Cases

- W3-1 – Stop Ahead: Red retroreflectivity ≥ 7
- W3-2 – Yield Ahead: Red retroreflectivity ≥ 7; White retroreflectivity ≥ 35
- W3-3 – Signal Ahead: Red retroreflectivity ≥ 7; Green retroreflectivity ≥ 7
- W3-5 – Speed Reduction: White retroreflectivity ≥ 50
- For non-diamond shaped signs such W14-3 (No Passing Zone), W4-4p (Cross Traffic Does Not Stop), or W13-1, -2, -3, -5 (Speed Advisory Plaques), use largest sign dimension to determine proper minimum retroreflectivity level.

Table 9. ASTM Retroreflectivity Requirements for New Sheeting (22)

	Color	Sheeting Type						
		I	II	III	VII	VIII	IX	X
ASTM D4956-04	White	70	140	250	750	700	380	560
	Yellow	50	100	170	560	525	285	420
	Orange	25	60	100	280	265	145	210
	Green	9	30	45	75	70	38	56
	Red	14	30	45	150	105	76	84
	Blue	4	10	20	34	42	17	28
	Brown	1	5	12	N/A	21	N/A	17

All table values in $cd/lx/m^2$, observation angle of 0.2°, entrance angle of -4°

DelDOT Sign Data Collection and Analysis

In DelDOT, other than for parking restriction signs, no Type I material is used. Type IV sheeting is used for the balk of the signs, and Type IX for Stop & Yield signs. For the I-beam & overhead signs only use Type IX or higher sheeting are installed. All replacements are based on the signs general condition and/or the reflectivity value of the sign. The primary means of inspection is to perform nighttime visual reviews on all smaller ground mounted signs. For all large I-beam and overhead signs reflectivity readings are collected annually to confirm the value of each sign. Inspection dates are not documented for individual ground mount signs reviewed, but the roads and counties where inspections were completed are recorded. The installation date stickers are placed on the back of each sign at the time of placement in the field for smaller ground mounted signs. For large I-beam & overhead signs annual inspections are performed and the data sets are documented in a spreadsheet base inventory system. The following items are saved in the spreadsheet.

<u>For ground mounted I-beam signs</u>:

- Delaware State Plane Coordination System: Easting/Northing coordinates
- County
- Road Number
- Sign facing direction
- Sign Number
- Sign Type
- Sign panel dimensions: Sign Height, Sign Width, Total Sign, Exit Panel height, Exit Panel width, Total Exit, Total Area
- Physical sign condition: Beam Style, Sign Condition, Base Condition, Beam Condition
- Sheeting Material Type
- Retroreflectivity readings for : by color (Green, Silver , Yellow , Brown, Blue, and Red) for multiple years
- Install Date
- Others: attached pictures, layout, notes, MAXIMO issues (map or photos), etc.

For overhead signs:

- Codes: Structure type code, county code, structure number, location code, road number, etc.
- Sign facing direction
- ADC map and grid

- Sign panel dimensions: Sign Height, Sign Width, Total Sign, Exit Panel height, Exit Panel width, Total Exit, Total Area
- Date replaced
- Quantity of elements for numeric 5, 6, and 7
- Others: pictures, traffic span, layout, photo issues

The I-beam signs in the inventory are summarized in Table 10. In total there are 281 I-beam signs with a total panel area of 32427.5 square feet. Table 11 provides the sign inventory by sheeting type. The sign replacement data is summarized in Table 12. It can be seen that most majority of the signs have been replacement in the recent 5 to 6 years, ranging from 57.14% to 80.25%. However, it is noted that the replacement dates of many signs were missing, as shown in Table 13.

Table 10 I-beam Sign Inventory - Total

Route #	# Signs	Panel Area	Exit area	Total Area
US 1 (tolled portion)	162	14931.5	842.25	15773.75
I-95	82	10284.5	557.75	10842.25
I-295	7	1093	0	1093
I-495	30	4466	252.5	4718.5
Total	**281**	**30775**	**1652.5**	**32427.5**

Table 11 I-beam Sign Inventory – by Sign Types

Type	Route #	US 1 (tolled portion)	I-95	I-295	I-495
III	# Signs	102	54	1	11
	Panel Area	10294.25	6893	96	2029
	Exit area	578.5	510.75	0	96.25
	Total Area	10872.75	7403.75	96	2125.25
IV	# Signs	25	5	0	11
	Panel Area	2183.5	534	0	1251
	Exit area	146.25	0	0	76.25
	Total Area	2329.75	534	0	1327.25
Others	# Signs	25	19	3	6
	Panel Area	2046	2504.5	314	588.5
	Exit area	96.25	47	0	35
	Total Area	2142.25	2551.5	314	623.5
No Data	# Signs	10	4	3	2
	Panel Area	407.75	353	683	597.5
	Exit area	21.25	0	0	45
	Total Area	429	353	683	642.5

Table 12 % of I-beam Signs Replaced

Route #	2004	2005	2006	2007	2008	2009	2010	Total
US 1 (tolled portion)	1.23	4.32	11.11	35.19	22.84	5.56	0.00	80.25
I-95	3.66	0.00	9.76	40.24	8.54	4.88	1.22	68.3
I-295	0.00	28.57	0.00	0.00	0.00	28.57	0.00	57.14
I-495	0.00	0.00	16.67	10.00	36.67	3.33	0.00	66.67

Table 13 Number of Signs that the Replacement Dates Are Missing

Route #	# Signs	Panel Area	Exit area	Total Area
US 1 (tolled portion)	26	3186.25	244.5	3456.75
I-95	20	2230.5	60	2310.5
I-295	2	456	0	458
I-495	10	2086.5	100	2196.5
Total	**58**	**7959.25**	**404.5**	**8421.75**

This spreadsheet database also includes the inventory of over-head signs. However, no retroreflectivity reading is recorded. Table 14 provides the summaries of all sign including both I-beam and over-head signs on interstates and SR1 in Delaware.

Table 14 Sign Inventory – I-beam and Overhead Signs

Route #	# Signs	Panel Area	Exit area	Total Area
US 1 (tolled portion)	204	22937.3	1548	24485.3
I-95	276	47088.7	2220.1	49308.8
I-295	7	1093	0	1093
I-495	73	12561.8	727.5	13289.3
Total	**560**	**83680.8**	**4495.6**	**88176.4**

To be able to predict the useful lifetime of a sign, sign deterioration models are necessary. The deterioration rate are impacted by several factors, such as sign age, sign color, sheeting type, sign facing direction, time of the measurement, and sign background and color combination of the panel sheet. Appendix A summaries the detailed analysis of these impacting factors on the deterioration rate of retroreflectivity. The analysis of the data revealed inconsistencies in the data. In addition, instead of using absolute values for the signs, we also explored the relationship between the change of retroreflectivity reading at two continuous years and the age of the signs, the inconsistencies remain. Recognizing that historical data may not have good quality as the most recent ones, the same sets of analysis were performed using only the most recent two years' data (2010 and 2011). However, the data are still inconsistent and no reliable model has been achieved.

While performance measures such as percentage of signs with unacceptable retroreflectivity or percentage of signs beyond their useful life are possible, several assumptions (as documented in the next chapter) need to be made due to the absence of reliable retroreflectivity predictive models. Review of the data clearly indicated the need to pay attention to data quality. As this is a relatively new database, there are opportunities to improve the data and make it useful.

Drainage

DelDOT is required to maintain the structural condition of the state-owned drainage infrastructure as mandated by the National Pollutant Discharge Elimination System (NPDES). This includes the monitoring and improvement of the water quality discharged from outfall locations and Best Management Practices (BMPs). To facilitate the management of this program, a Geographic Information System (GIS) has been implemented to store data representing the infrastructure and the related inspections. The structure of the GIS database design includes tables, attributes, and valid value domains. There are three types of tables in the database: (1) Feature Classes representing graphic features in the GIS such as manholes, pipes, and BMPs; (2) Data Tables, which store relational information about feature classes, including inspection information; and, (3) Relationship Classes that create the relationships between the feature classes and the data tables.

Drainage data in the GIS database consists of an inventory that includes three GIS features (point, conveyance, and polygon) each with different performance measures. The point structures include inlet, manhole, outfall, swale end, junction box, dummy node, and riser. The location and generic attributes for structures and the components conditions data such as depth of debris and/or silt and description of the component defects found during inspection are stored in the database. The overall rating conditions of the components (good, fair and poor) are also provided. Conveyance features include pipes, ditches and hydraulic connection. The condition inspection data collected are type of ditch erosion (such as at base, bank, or flow line), amount of debris in ditch or pipe in percentage from 0 to 100%, and rating on the condition of the pipe seals and overall rating for pipe as good, fair, and poor. Polygon feature tables represent the location and generic attributes and inspection data related to BMPs. This BMP rating is a qualitative evaluation of the individual parameters to establish an overall rating value for the BMP facility. The objective of the rating classes is to evaluate the existing conditions, while also considering impending conditions. The rating is coded as A - No Remediation Required, B - Maintenance Required, C - Repair Required, D - Restoration/ Retrofit Required, or E - Immediate Response Required. The database also contains the rating for the individual parameters to establish an overall rating value for the BMP components.

The first draft version for review of the drainage database was complete in September 2007, and the database was redesigned in September 2009, and again revised in September

2010. Some data are updated annually, and some are updated biannually. As a result, most of the data are only available for one year. Also due to the fact that investments for these assets are missing in the database, understanding how different patterns of investment impact performance of these assets are vague based on the current data sets. In addition, it is challenging to combine these performance measures. These inconsistencies in the data base and several gaps in the data also made this data unsuitable for inclusion in the analysis. Again there are opportunities to improve this database in the future for the purpose of asset management.

4. Application to DelDOT

Introduction

The time frame for the analysis was selected to ensure consistency. Using data from 2008 a planning horizon of 20 years was used. HERS-ST is used for pavement assets, Pontis for bridge, and a spreadsheet developed for traffic signage. These tools are used to capture the changes in performance measures under various budget scenarios. The performance measures and budgets derived from these tools or systems are assembled in Asset Manager-NT to examine the implication of investment scenarios on their performance within and cross assets and alternative combinations explored. Again it should be noted that the scope of the study is interstates and interstate-like highways, including interstates 95, 295, 495, and the tolled portion of Route 1 in Delaware.

The following sections review the results for each asset and the system composing of these three asset type.

HERS-ST Results

Scenarios

Five scenarios were generated for modeling in HERS-ST:

- Minimum Investment ("Do-Nothing") Scenario: The highway section being considered remains unimproved for the duration of the analysis period and minimum investment is involved. It is coded as "MIN_INV" in the study.
- Constrained by Funds Scenarios: The base budget level is estimated from the Delaware Department of Transportation's current practice, to be approximately $80 million for a

4-year funding period. This budget is then increased by 20% ($96 million) and decreased by 30% ($56 million) to generate comparative scenarios. The available budgets for each funding period are kept the same for all periods. These scenarios are denoted as "BGT_96M", "BGT_80M", and "BGT_56M".

- Maintain Current Conditions: The level of system performance at the beginning of the run (derived from the HPMS data) is based on the current highway-user costs, and the least costly mix of improvements is selected to maintain that level of performance. This scenario is denoted as "MCC".
- Full Engineering Scenario: Without funding constraints, this scenario calculates the minimum funding required for each funding period in order to maintain the pavement condition rates "fair" and above. This scenario is denoted as "FULL ENGR".

Results

The most current 2008 Highway Performance Monitoring System (HPMS) data sets provided by the Delaware Department of Transportation (DelDOT) are used in HERS-ST. HERS-ST generates four broad classes of costs by funding period: (1) user costs (in dollars per 1000 Vehicle Mile Travelled (VMT)), (2) annual maintenance costs (in dollars per mile), (3) external costs (in dollars per 1000VMT) due to vehicular emissions of air pollutants; and (4) initial capital improvement costs (in thousands of dollars). Maintenance costs and initial capital costs are summed up to represent agency costs. We adopt the "Percent mileage of highway with International Roughness Index (IRI) less than 170 in./mi." indicator to represent highway performance and the analysis results are obtained using HERS-ST.

A 4% discount rate (d) is used in accessing the time value of money for all the cost related parameters, and all the calculations are presented in 2004 dollars. The costs at year n are converted to the present worth values from the individual cost in actual dollars (C):

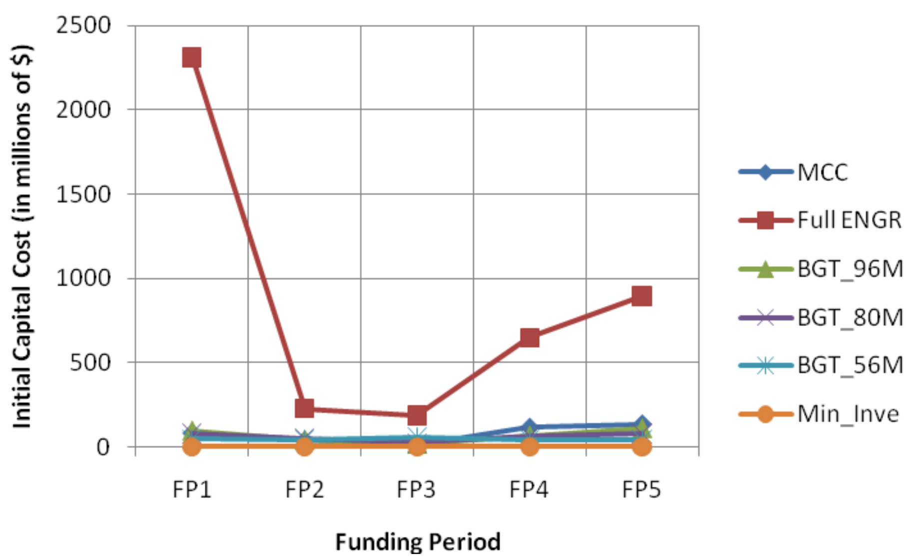
$$PW\$ = C \times (1 + d)^{-n} \quad \text{...} \; (2)$$

Due to the differences in the units used, the calculations of undiscounted dollars C varies. The initial capital requirements are provided in the HERS-ST model in dollars. The maintenance cost equals the maintenance costs per mile multiplied by the mileage of the network. While for user cost and emission cost, the corresponding costs from the HERS-ST model need to be multiplied by the Vehicle Miles Travelled during the funding period.

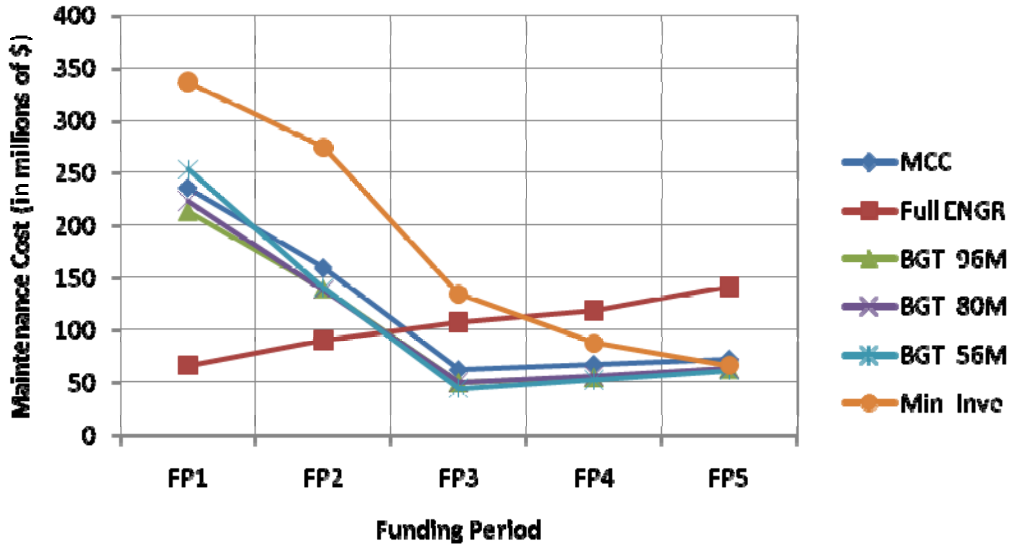
The analysis period consists of five four-year funding periods, with a total of 20 years. The analysis results, by funding period, of these scenarios from HERS-ST are illustrated in Figure 5. The Full Engineering scenario requires significantly more initial capital costs, especially for the first funding period. As a result, all pavement sections (100%) under this scenario have the roughness with IRI less than 170 inches per mile, and the user costs are slightly lower compared to the other five scenarios. The maintenance costs stay at a relatively constant level for Full Engineering scenario, much lower than the other scenarios for the first and second funding periods, and slightly higher than the others for the rest of the analysis periods. The Do-Nothing (or Minimum Investment) scenario, with very limited initial investment, always results in the highest maintenance costs, user costs, and the worst pavement roughness. It is found that the emission costs are not sensitive to the initial investments. The Full Engineering scenario produces slightly higher emission costs, probably because the good pavement condition under

Full Engineering scenario attracts more traffic (in terms of vehicle miles travelled - VMT) on the highway network. The VMTs for the scenarios are demonstrated in Figure 5.

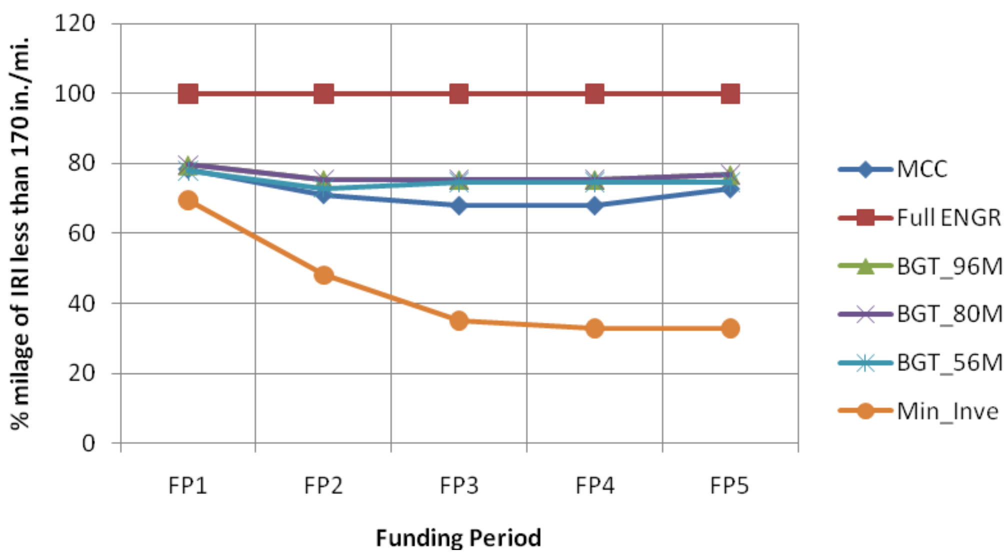
Figure 6 demonstrates the aggregate net present cost values for the whole 20-year analysis period. The initial capital investment costs versus the maintenance costs, agency costs versus user costs, social costs, and highway IRI are plotted. Similar results are observed as those for Figure 5. A much higher initial investments in the Full Engineering scenario results in lower maintenance costs, user costs, better highway performance and higher social costs, while in the Minimum Investment scenario the opposite trends are observed.



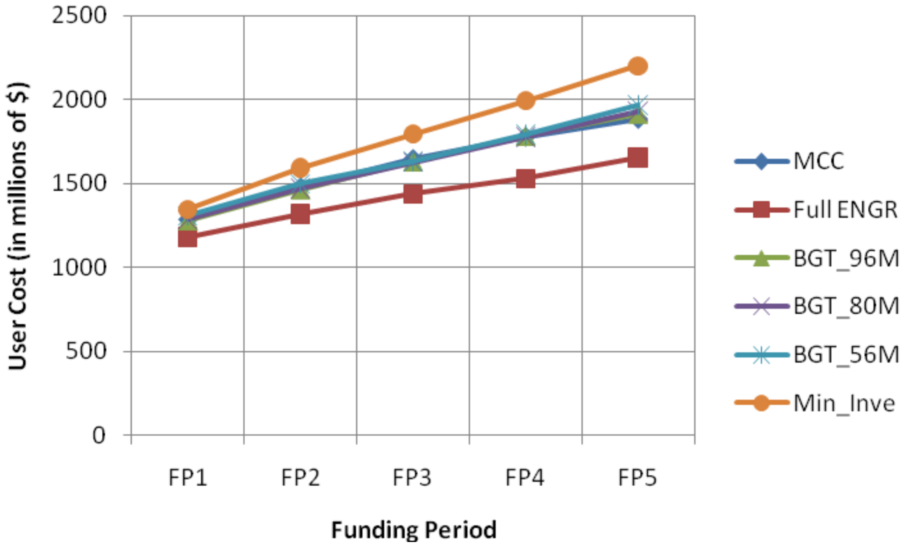
(a) Initial Capital Cost



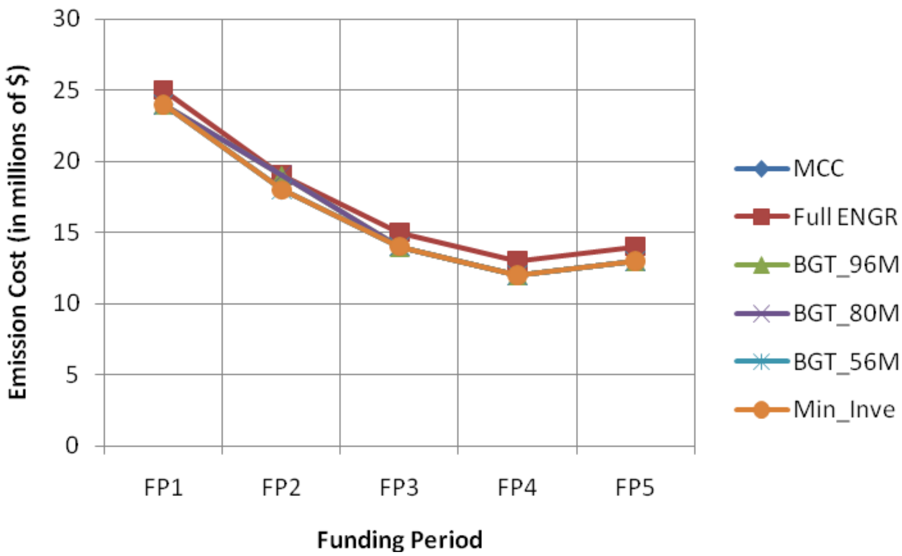
(b) Maintenance Cost



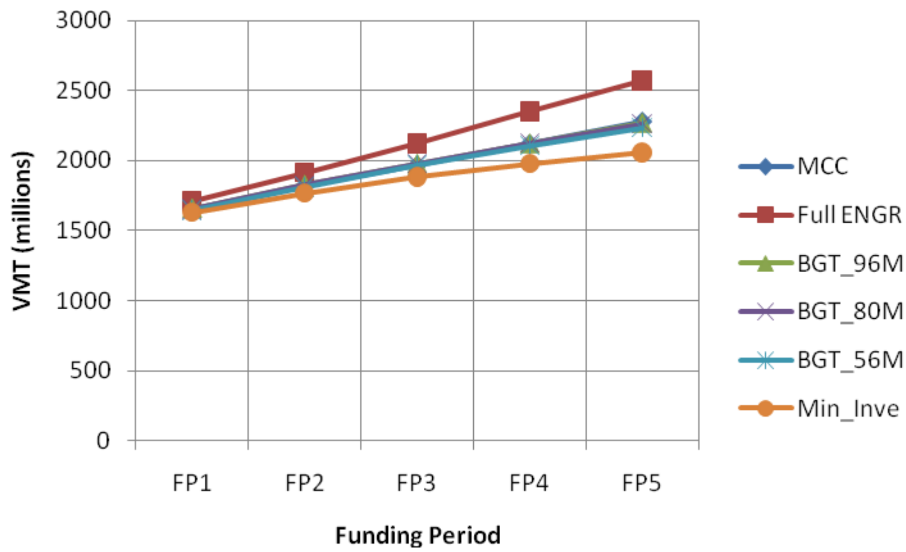
(c) % mileage of IRI less than 170in./mi.



(d) User Cost

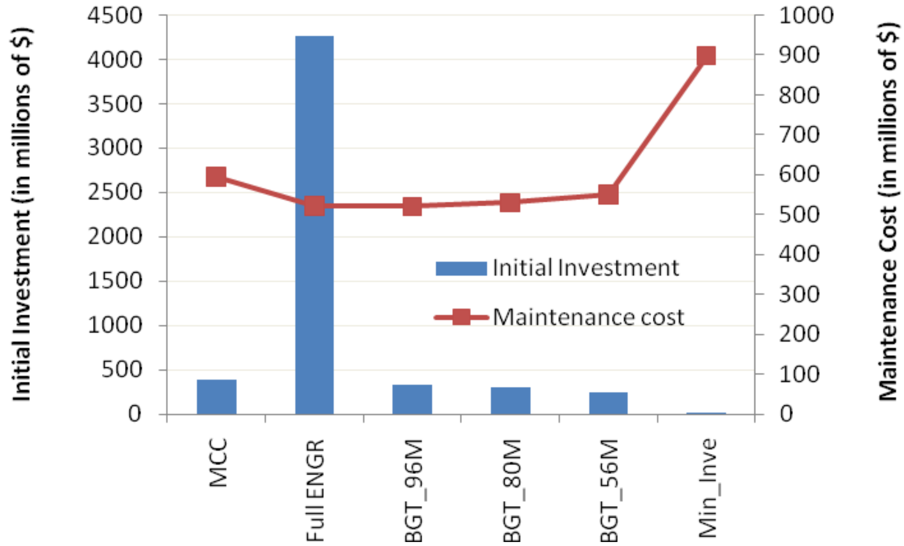


(e) Emission Cost



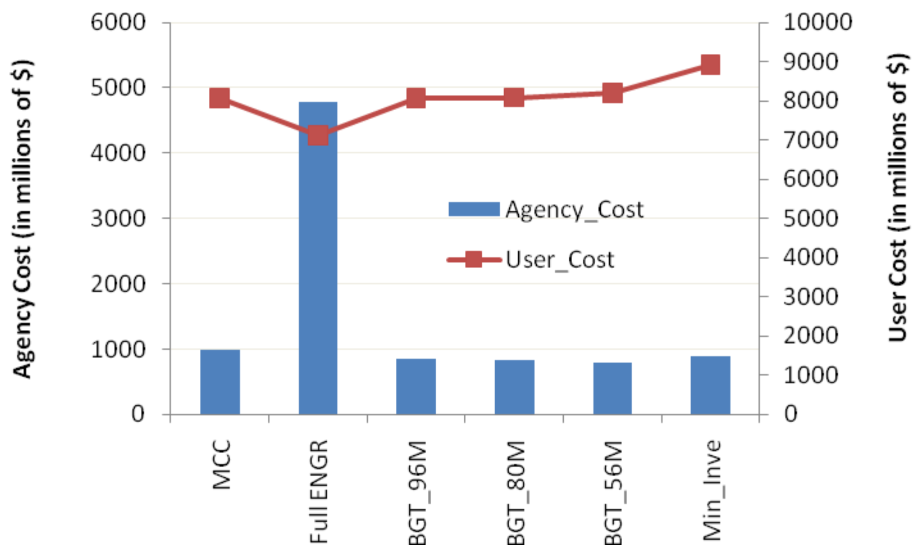
(f) VMT

Figure 5. Results from HERS-ST Analysis Scenarios (20)



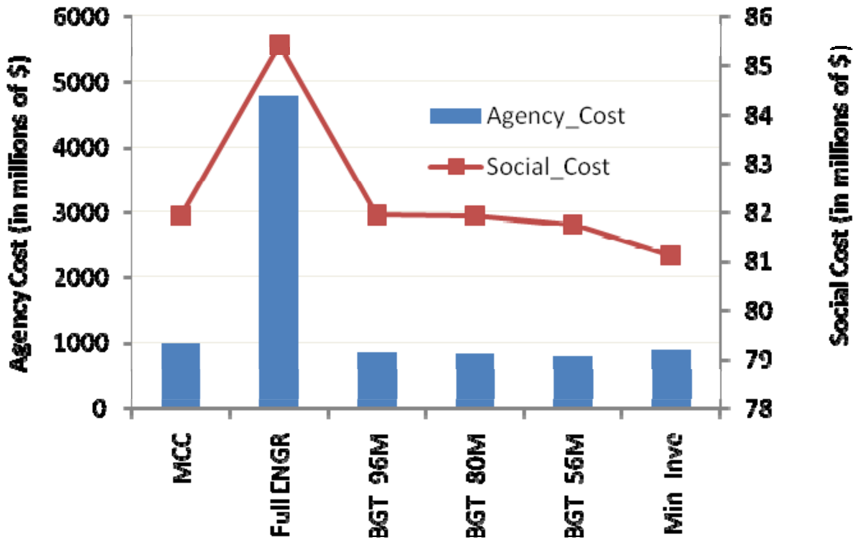
Initial Investment (in millions of $)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Maintenance Cost (in millions of $)
1000
900
800
700
600
500
400
300
200
100
0
Initial Investment
Maintenance cost
MCC
Full ENGR
BGT_96M
BGT_80M
BGT_56M
Min_Inve

(a)

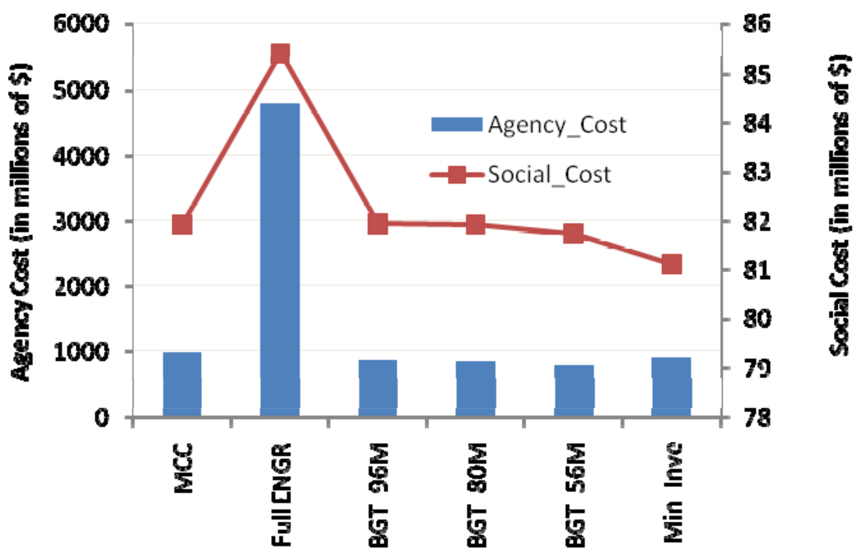


Agency Cost (in millions of $)
6000
5000
4000
3000
2000
1000
0
User Cost (in millions of $)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Agency_Cost
User_Cost
MCC
Full ENGR
BGT_96M
BGT_80M
BGT_56M
Min_Inve

(b)



(c)



(d)

Figure 6 Aggregate Results from HERS-ST Analysis Scenarios for the Whole Analysis Period

Pontis Results

The most current 2008 National Bridge Inventory (NBI) data sets were imported into PONTIS management system. Ten budget levels, from 0 to $10 million per year were simulated. The resources were consumed by PONTIS recommended bridge-by-bridge maintenance work. The network results in terms of structurally deficient (SD) bridges by the number of bridges and by deck area, and the bridge health index currently used in DelDOT are presented in Figures 7 to 9.

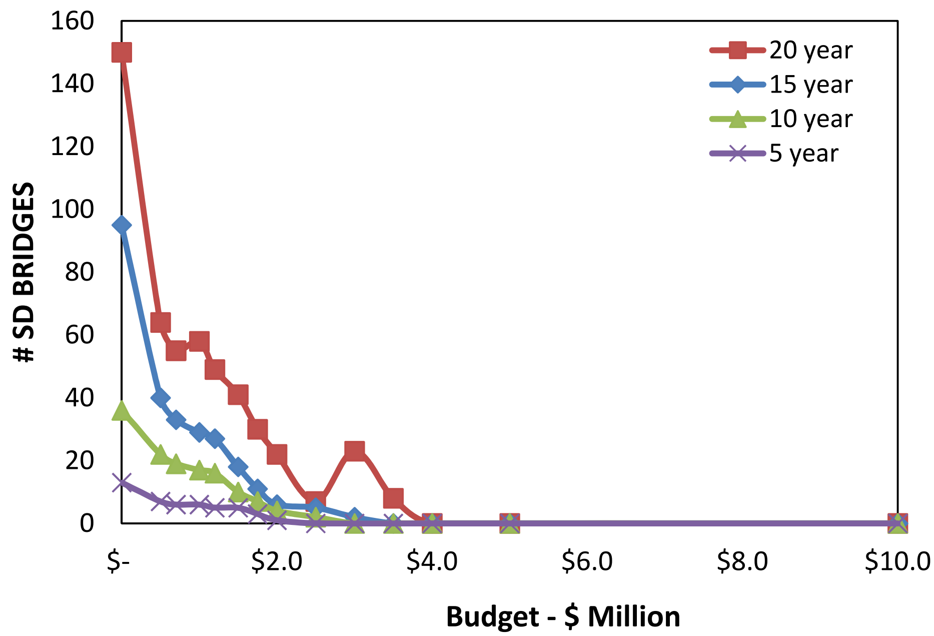


Figure 7 Projected # of Structurally Deficient Bridges at Various Budget Levels

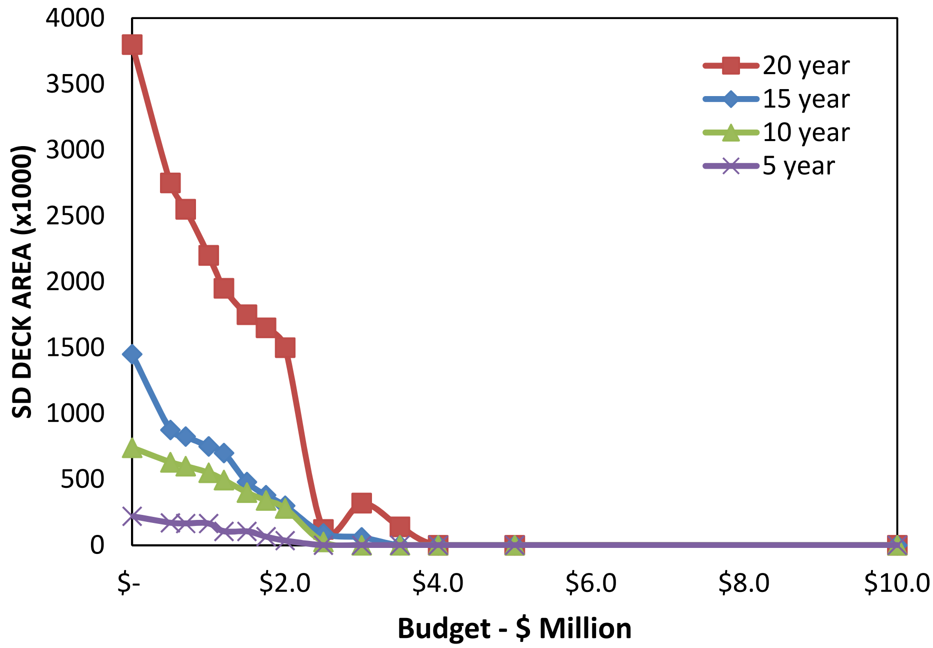


Figure 8 Projected Structurally Deficient Bridge Deck Areas at Various Budget Levels

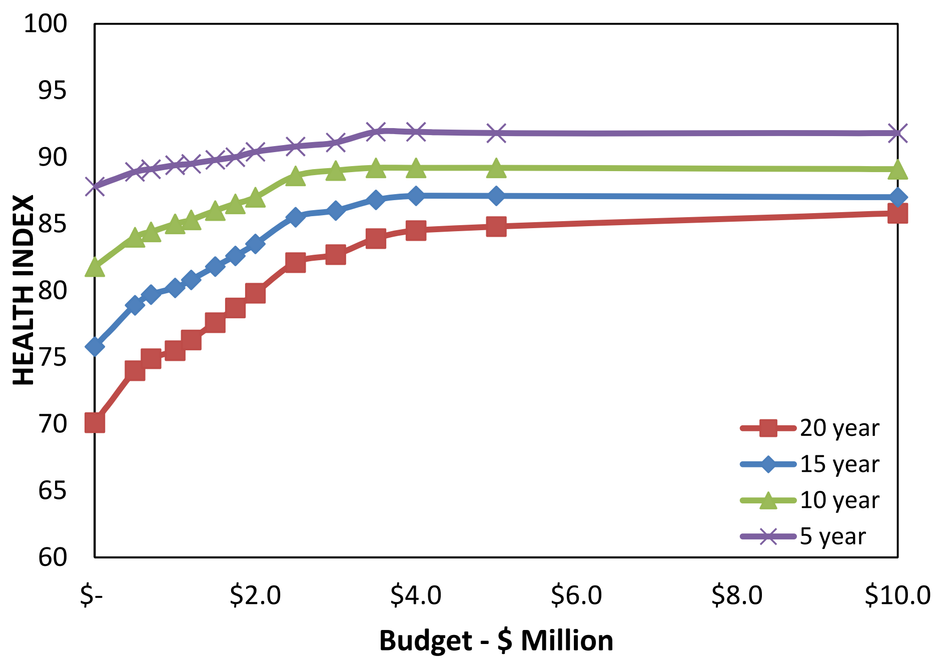


Figure 9 Projected Health Index at Various Budget Levels

It is noted that Pontis expenditures do not reflect the total cost to maintain the bridges. Pontis only uses the direct cost to perform maintenance actions and does not include indirect costs, such as traffic control, erosion control, design costs, etc. Based on an internal study at DelDOT, it was determined that the total cost is about 3.1 times the direct cost. For example, if DelDOT is spending roughly $4 million per year on this group of bridges based on the results from PONTIS, this $4 million budget reflects a total cost of $12.4 million. The average cost ratio was calculated from a group of rehabilitation projects conducted in the State of Delaware. Table 15 documents the direct and indirect costs from this study.

Table 15 Delaware Total Cost Bridge Study Results

Item	Definition	Amount
Direct Element Cost		$ 1.00
Indirect Cost	75% of Direct Element Cost	$ 0.75
Traffic Control Cost	15% of Direct Element Cost	$ 0.15
Subtotal		$ 1.90
Contractor's Construction Engineering	5% of Subtotal	$ 0.10
Initial Expense	5% of Subtotal	$ 0.10
Construction Costs		$ 2.09
Construction Engineering	15% of Construction Costs	$ 0.31
Contingency	15% of Construction Costs	$ 0.31
Total Construction Cost		$ 2.72
Preliminary Engineering	15% of Total Construction Cost	$ 0.41
Total Project Cost		$ 3.12

Signage Analysis

Sign condition assessment and replacement traditionally was performed through qualitative daytime and nighttime visual inspection. Ever since the FHWA began to study implementing minimum retroreflectivity standards, quantitative sign condition assessments using retroreflectometers was introduced. Regardless of which management method is used, it does not involve evaluating every sign in place on the roadways. Instead, management methods predict how long signs with similar characteristics (such as sign color and sheeting type) will maintain an above standard retroreflectivity, also known as the sign life. When the end of the sign's lifetime has been reached, it should be replaced. There are typically three accepted models:

- The **expected sign life method** calculates a sign life from known sign retroreflectivity deterioration rates for combinations of sign sheeting color and sheeting type. The expected sign life method requires tracking the age of signs either by using sign installation date labels on the back of each sign or maintaining a sign asset management system that can identify the age of every sign in the jurisdiction. When an individual sign's retroreflectivity is predicted to fall below the minimum it should be replaced.
- The **blanket replacement method** replaces all signs along a corridor, within an area, or of the same sign and sheeting type at intervals based on the expected sign life of the signs. For blanket replacement, the replacement interval can be selected by DOTs based on previous sign deterioration experience or the sign sheeting manufacturer's warranty period. Once the time interval has elapsed, all signs within the corridor/area/type are replaced, regardless of age.
- The **control sign method** uses signs either in a controlled study yard or a sample of signs from the field to determine sign life. The control sample of signs is used to represent all of the signs in an agency's jurisdiction. The sampling plan should ensure that the

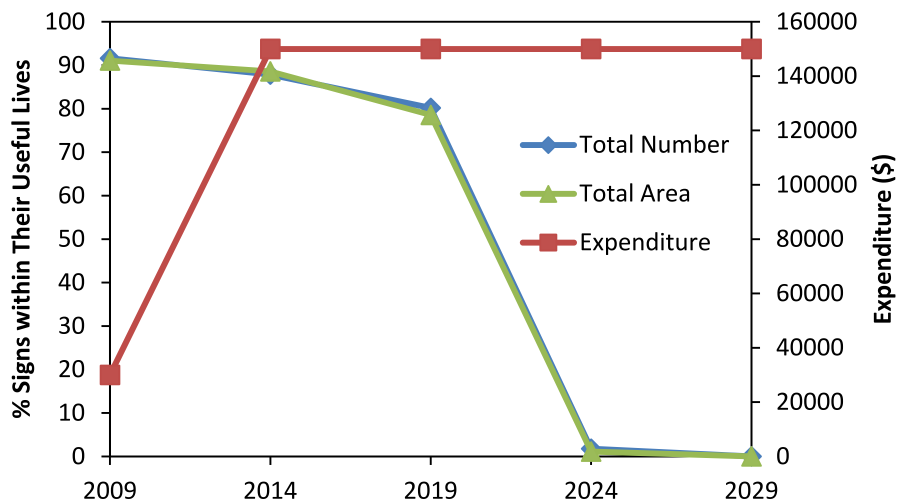
quantity and diversity of signs sampled represents the agency's sign population and that there is monitoring of sign retroreflectivity at regular intervals.

All three of these management methods require basic knowledge of the age and performance characteristics of the signs on the roadways. A database of signs by type, sheeting type, and age needs to be updated at regular intervals to ensure that the management condition assessment methods reflect actual conditions. As discussed in the previous chapter, DelDOT is maintaining a signage spreadsheet database which contains all those data sets for large ground mounted I-beam and overhead signs. However, due to the inconsistency of the data sets, no acceptable retroreflectivity deterioration model can be developed. As a result, all these three methods cannot be used for this study. In order to generate investment scenarios and their performance development, the following assumptions are made:

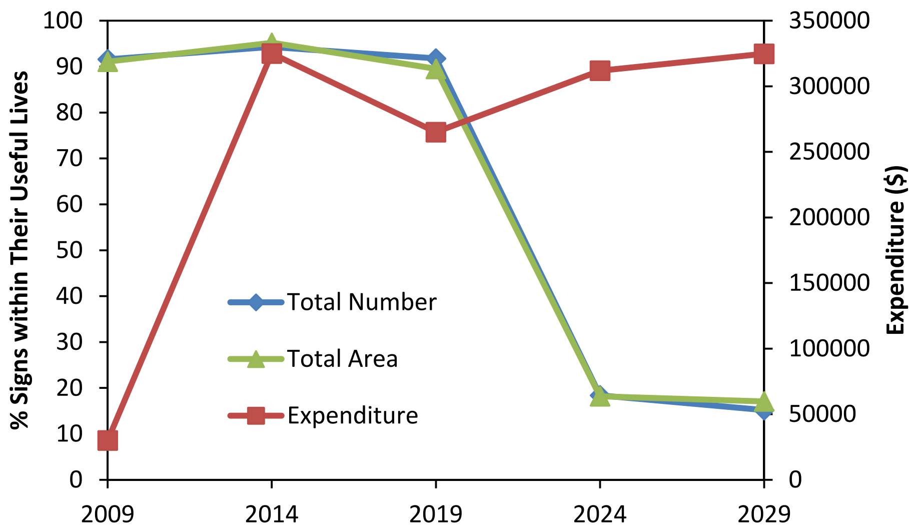
- Based on DelDOT's previous sign deterioration experience, it is assumed that the expected sign lives for large I-beam and overhead signs are 15 years.
- Over the last three years, DelDOT has averaged $30,000 per year for maintenance related issues on large I-beam & overhead signs.
- Per DelDOT's current contract, DelDOT pays $16 per square feet for replacement of sign panels for the I-beam and overhead signs. The estimate of the cost should be approximately $30/sq. ft if the costs of the new sign panel, MOT, and labor for removal of the old panel and installation of the new are included.

Based on these assumptions, six scenarios are generated. For each scenario, two measures are adopted to capture the performance for signage assets: % signs within their useful life by panel area and by the number of signs. Spreadsheet based analyses were conducted and the performance development for the six investment scenarios are presented in Figure 10. These scenarios are:

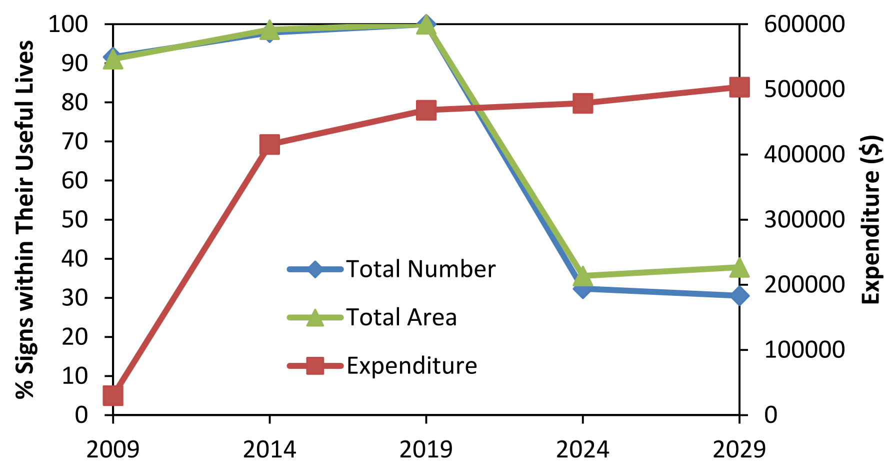
- No replacement
- 5% replacement per funding period
- 10% replacement per funding period
- 20% replacement per funding period
- 30% replacement per funding period
- 40% replacement per funding period



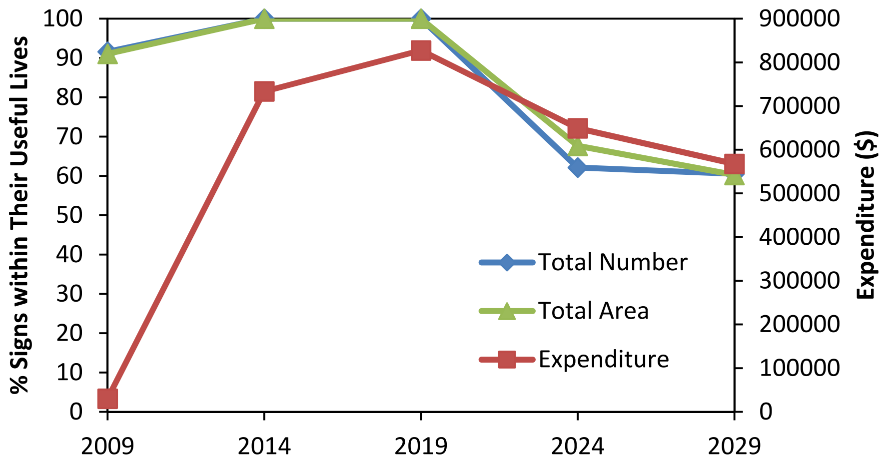
(a) Do-nothing scenario



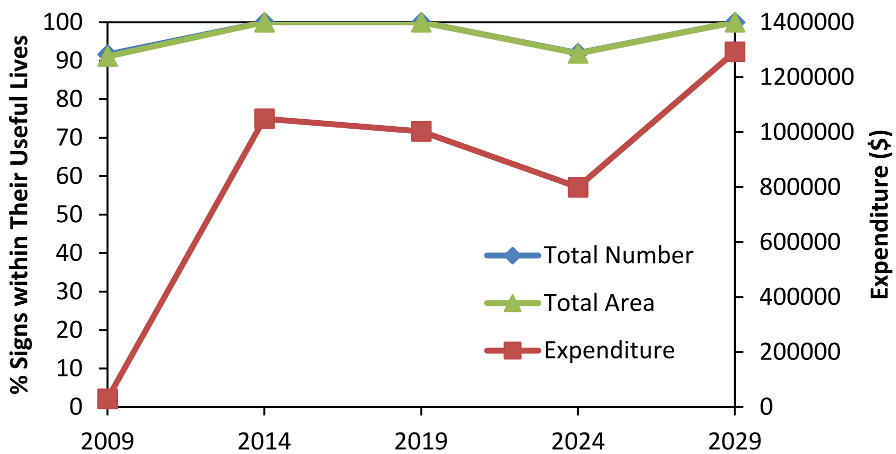
(b) 5% replacement per funding period



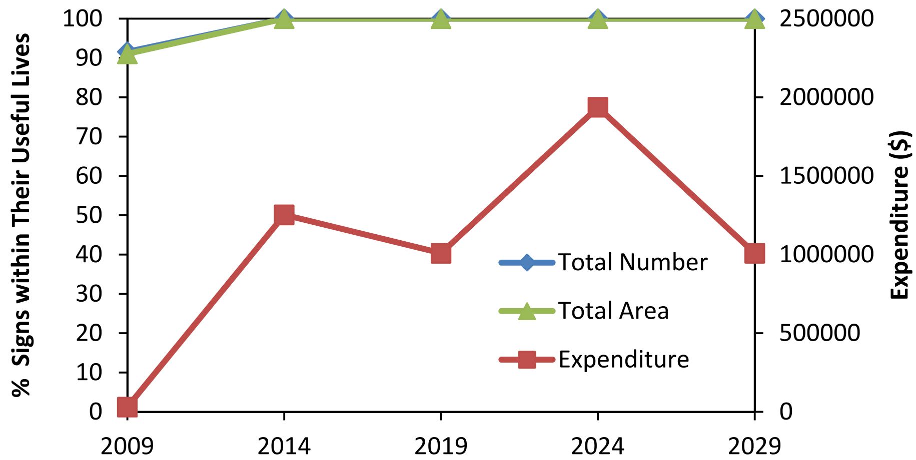
(c) 10% replacement per funding period



(d) 20% replacement per funding period



(e) 30% replacement per funding period



(f) 40% replacement per funding period

Figure 10 Performance of Signage Asset

It is observed that most of the signs are within their expected lives during the first and second funding periods due to the facts that most of the signs were newly replaced. However, during the third and the fourth funding periods, the performance in term of the measures used in the project depends on the budget level. The less we spend, the more signs are beyond their useful lives that need to be replaced. The results also reveal that when the replacement per funding period exceeds 30%, almost all the signs are within the expected lives.

AssetManagerNT Results

AssetManagerNT enables users to explore the implications of different budget levels for a set of investment categories, which can be defined based on asset types (e.g., pavement versus bridge), geographic areas (e.g., districts or regions), or system sub-networks (e.g., NHS, trunk line system, priority truck network, primary corridors, etc.). AssetManagerNT brings together analysis results from the existing management systems in an agency, and adds value by providing a quick-response “what-if” analysis tool for testing different investment options.

Recognizing that AssetManagerNT requires each asset type must have the same number of runs as the input to the software, five scenarios are selected for each asset. For pavement, those are no investment, full engineering, Maintain current condition, 30% increase and decrease of the current level. For bridge, those investment scenarios are no investment, $10 million budget per year, $1, $2, and $4 million per year. For signage, the scenarios are no replacement, 5%, 10%, 20%, and 30% replacement per funding period. More details why these scenarios are selected and the user’s guide for AssetManagerNT are provided in Appendix B.

AssetManagerNT provides four views that let you examine the impacts of budget levels and resource allocation decisions on the performance of the transportation system, as shown in Figure 11.

Figure 11 AssetManagerNT Views

- The **Budgeting view** lets you visualize the effect of up to six different budget levels on the resulting value of a single performance measure.
- The **Targeting view** lets you specify a target value for a performance measure, and then determines the budget that is required to meet the selected target.
- The **Dashboard view** lets you adjust an overall system's annual budget interactively as it dynamically indicates the effect of the budget on up to twelve different performance measures.

- The **Allocation view** lets you interactively set resource allocations for different assets and/or parts of your network and view the impacts over time on up to six performance measures at once.

Budgeting

The changes in performance measures over time for a given budget are shown in Figures 12 through 15. Each of the seven different performance measures is shown with the pavement or bridge budget that influences the performance. These budgets are the average annual expenditure over the entire 20 year period, which is required by the AssetManagerNT software. In this analysis, we examine four budget levels. AssetManagerNT provides an auto-fill capability that automatically sets up the graphs so that one is based on the minimum budget amount, another on the maximum budget amount, and the remainder on intermediate budget levels. Specifically:

- Figure 12 shows (1) total user costs over the planning horizon. The user costs in HERS-ST include travel time costs, operating costs, and safety costs; (2) the percentage of poor and fair pavements (by mileage) over the planning horizon; (3) total delay (in hours per 1000 vehicle miles of travel) over the planning horizon; and (4) fatality rates (in fatalities per million VMT) over the planning horizon.
- Figure 13 shows (1) the percentage of structurally deficient bridges by deck area over time; (2) the percentage of structurally deficient bridges by number over time; and (3) the bridge health index over the planning horizon.

- Figure 14 shows (1) the percentage of traffic signage by panel areas over time; and (2) the percentage of traffic signage by number of signs over time.
- Figure 15 shows the short term performance at the end of the first five-year funding period.

A cursory scan of Figures 12 through 15 reveals that from a performance point of view the lowest level of investment is clearly inferior. Other observations include:

- Total user costs are similar for all scenarios other than the lowest level of investment alternative;
- The less the investment, the longer it takes to reduce the mileage of pavements in poor or fair condition;
- For investments levels above the lowest level, there is little impact on total user costs, and the percentage of poor and fair pavements;
- Very minor impacts are observed for fatality rate under various budget levels;
- Other than the lowest level of investment alternative, there is little impact on bridge performance due to the fact that no structural deficient bridges present and the bridges are currently in good condition;
- The performance of the signs during the first and second funding periods stays stable because the signs are still brand new. However, during the third and the fourth funding periods, the performance drops significantly since most signs are approaching their useful lives. At the budget level of $207k, the performance remains consistent at the current level that is close to be 100%.

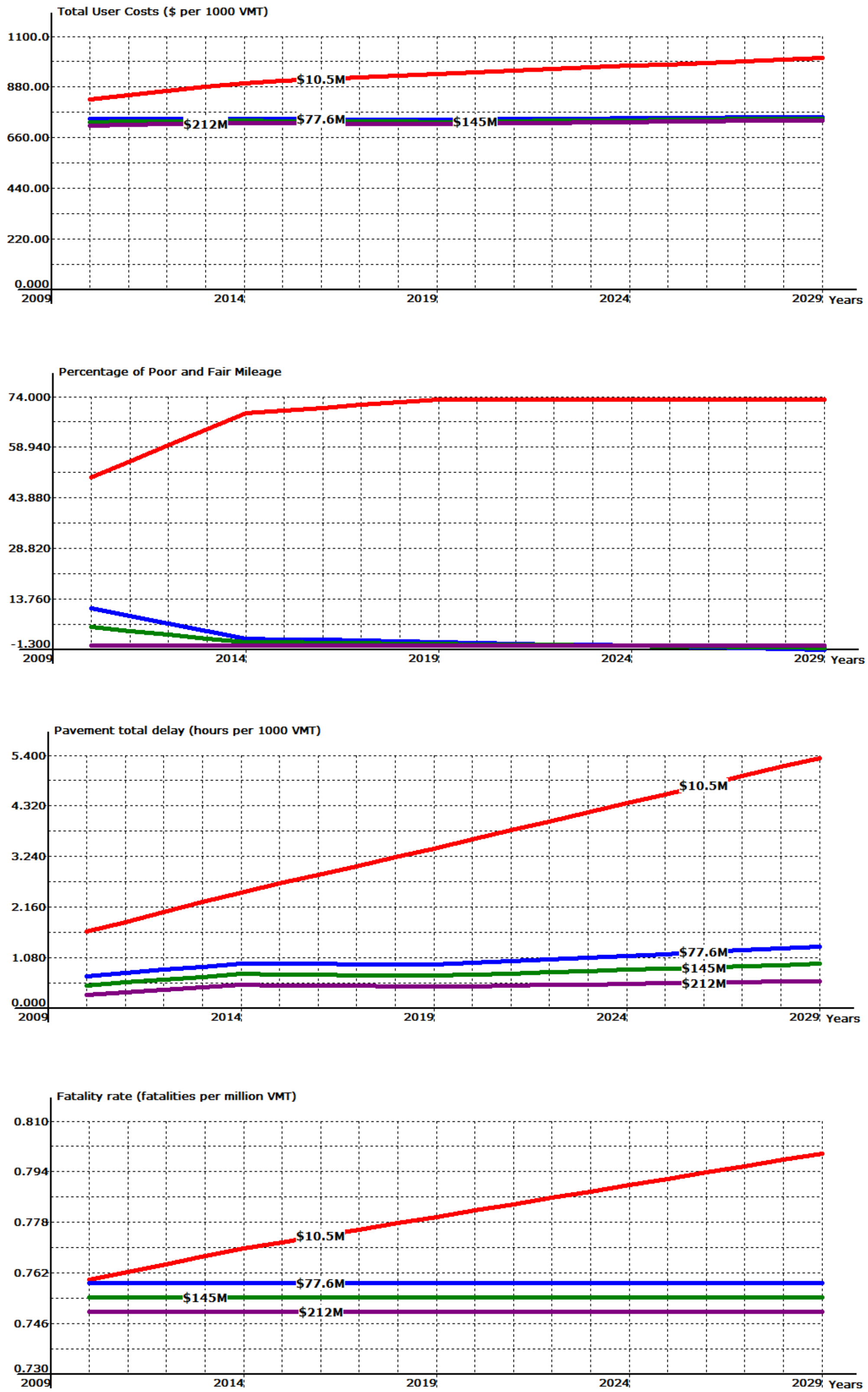


Figure 12 Pavement Budgeting View

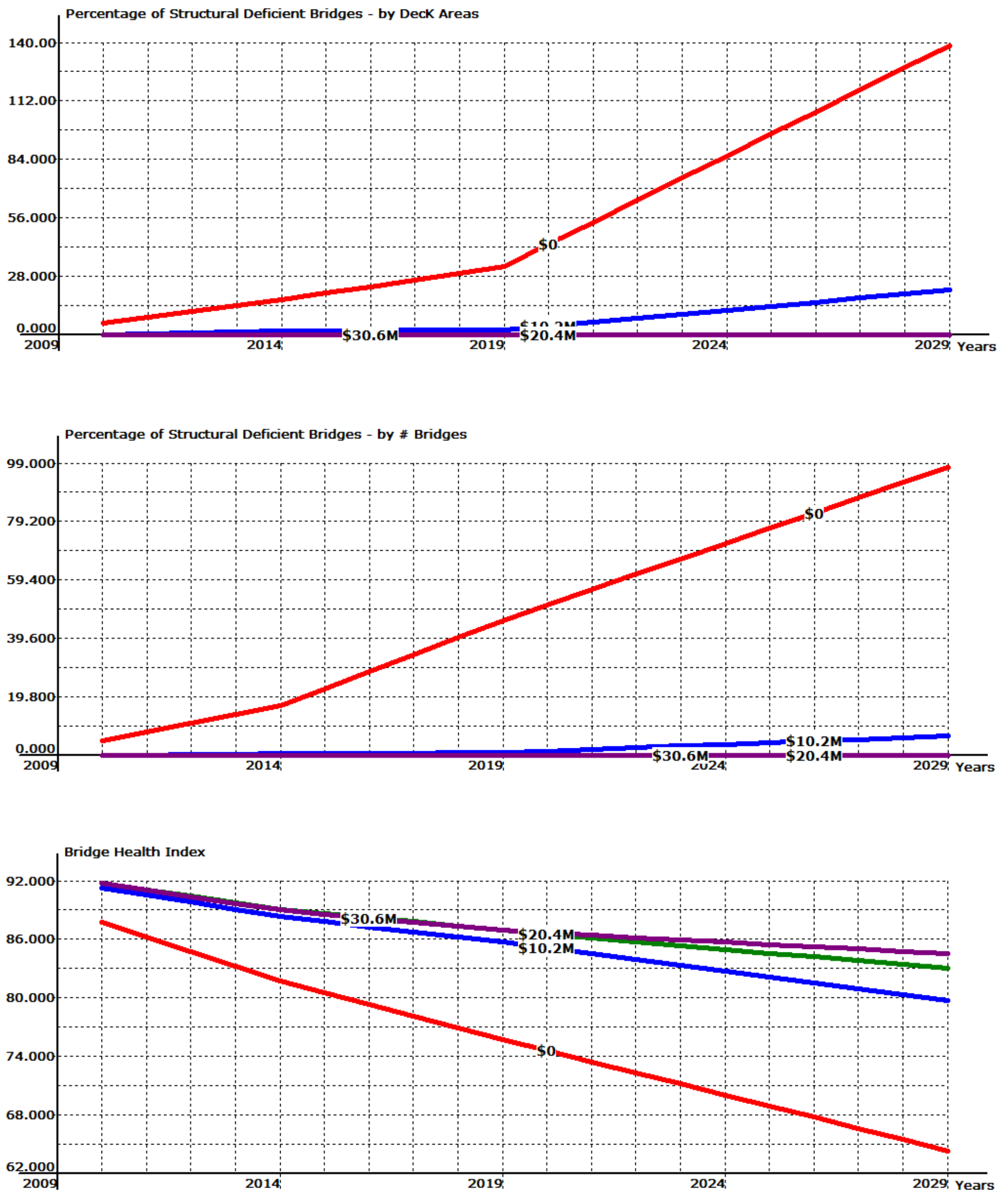


Figure 13 Bridge Budgeting View

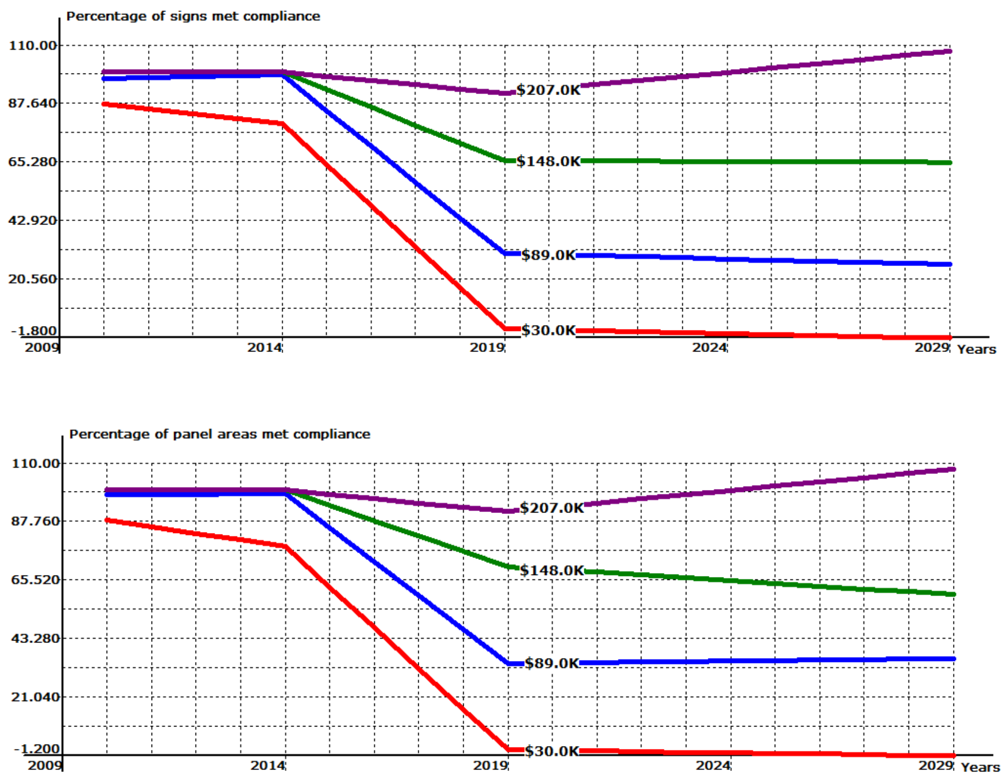


Figure 14 Traffic Signage Budgeting View

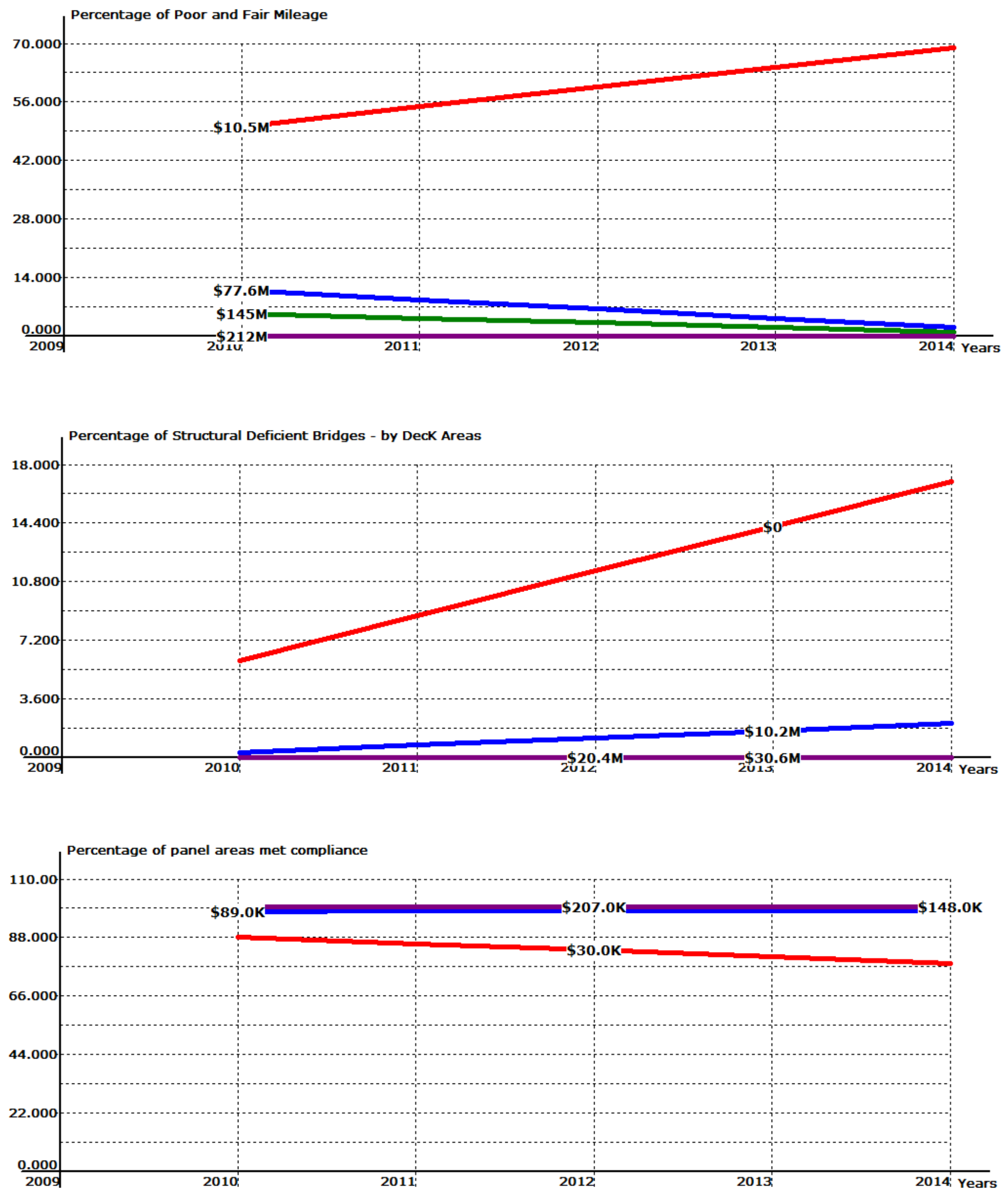


Figure 15 Budgeting View – Short Term (the End of First Five-year Funding Period)

Setting Targets

For assets as important as interstate highways, understanding what it takes to reach a particular target and how quickly that target is achieved can be important. Figures 16 through 19 show the change in performance over time for a given target. Specifically:

- Figure 16 shows the percentage of structurally deficient bridges over the planning horizon for targets of 0%, 10% and 20%. The annual budget required to reach these targets is $12.4m, $11.4m and $10.4m respectively in total costs. As there are currently no structurally deficient bridges on the interstates, hitting a target of 10% or 20% represents a disinvestment in bridges. To keep the current performance level without any SD bridges, $12.4 million total costs, which equals to approximately $4m indirect costs from Pontis, is needed. This investment needs are consistent with the current practices in DelDOT for bridges.
- Figure 17 shows the percentage of poor and fair pavements for targets of 0, 10, 20 and 30%. The annual budget levels are $204m, $32.6m, and $29.1m. Currently 2.86% of pavements are in poor or fair condition. For all targets, the pavement will initially get worse. In the case of a 0% target, the pavement will gradually improve. For all other targets the initial performance levels hold steady. It is notable that relatively small changes in budget, for example from $32.6m to $29.1m per year, cause significant changes in performance from 10% to 20% of pavements in poor or fair condition.
- Figure 18 shows the delay for targets of 1, 2 or 3 hours delay per 1000 VMT with annual budgets of $137m, $40.2m, and $28.8m. Current delay is just over 1 hour per 1000 VMT. Clearly significant savings can be realized if drivers are willing to tolerate delays.

- Figure 19 shows the percentage of signs within useful lives by panel areas for targets of 100%, 85% or 70% with annual budgets of $196.9k, $178.6k, and $159.9k. It is notable that very small changes in budget, for example from $159.9k to $196.9k annually, cause significant changes in performance from 70% to 100% of signs within useful lives.

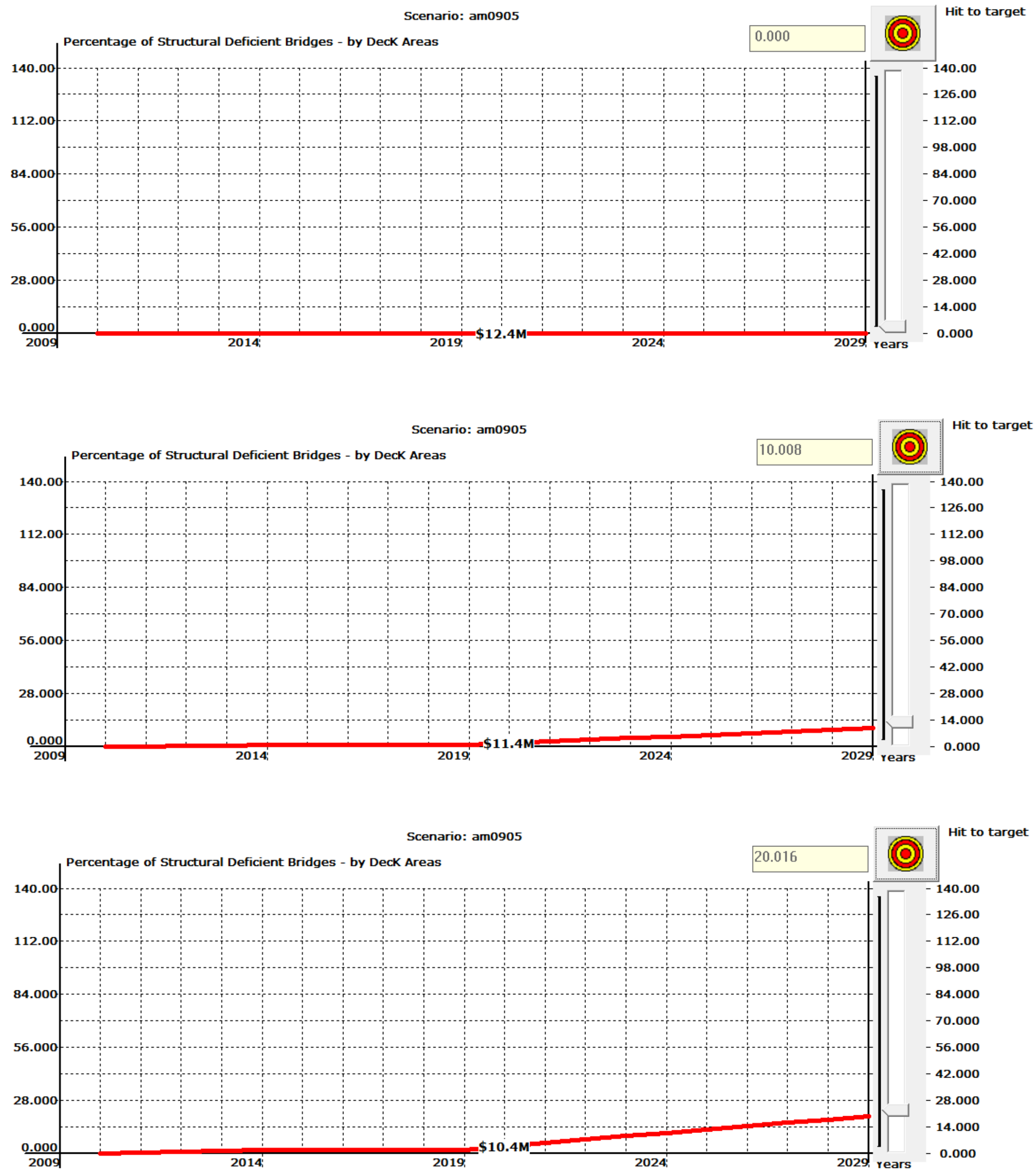
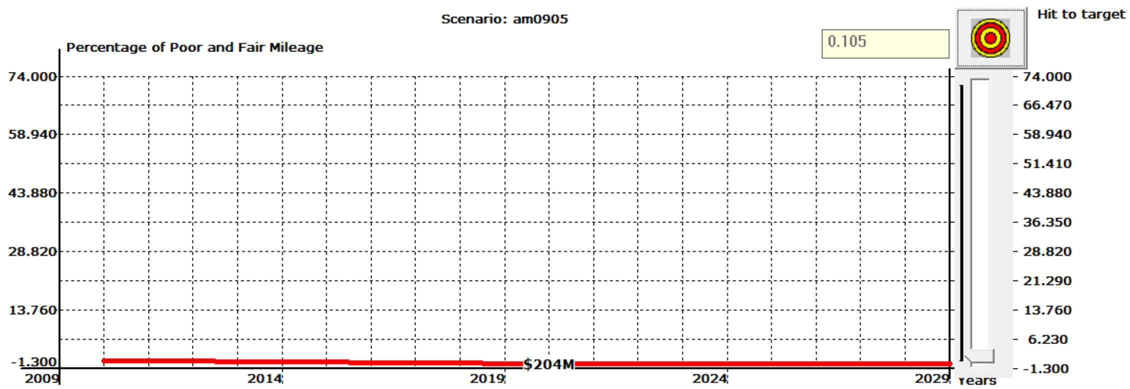
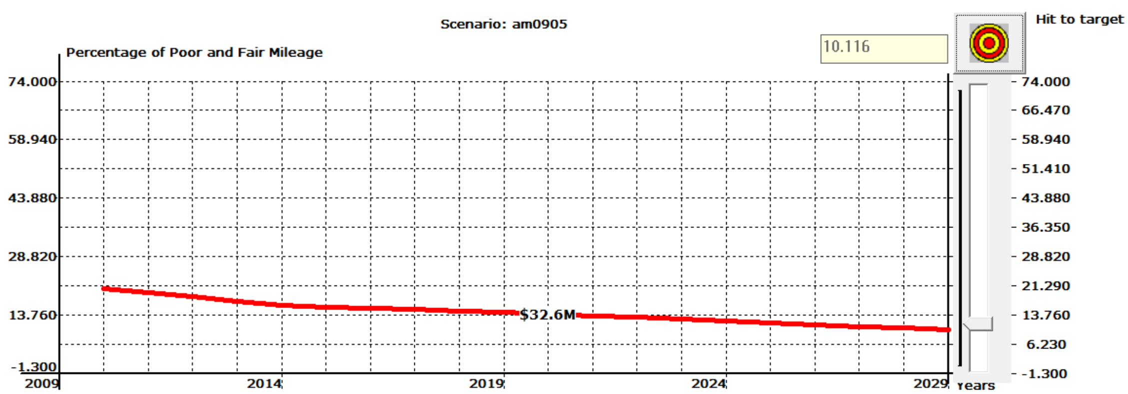


Figure 16 Targets for Structurally Deficient Bridges by Deck Area (0%, 10% and 20%)





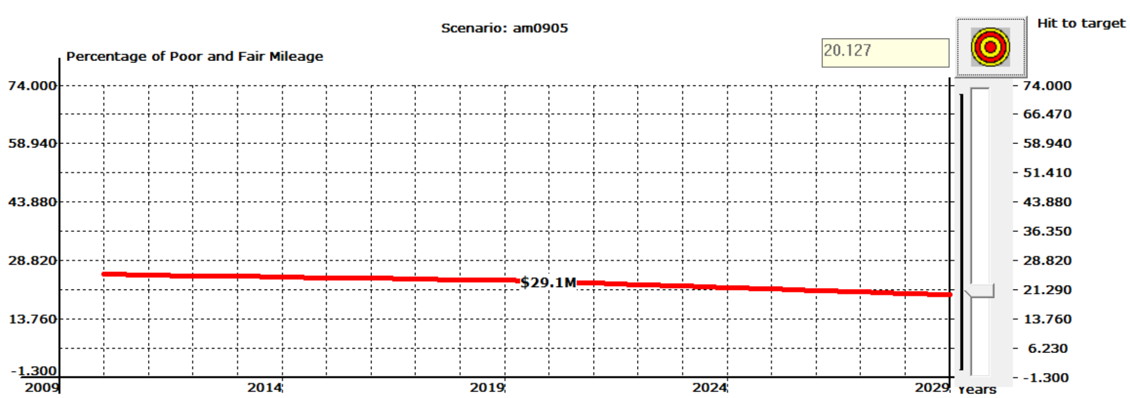
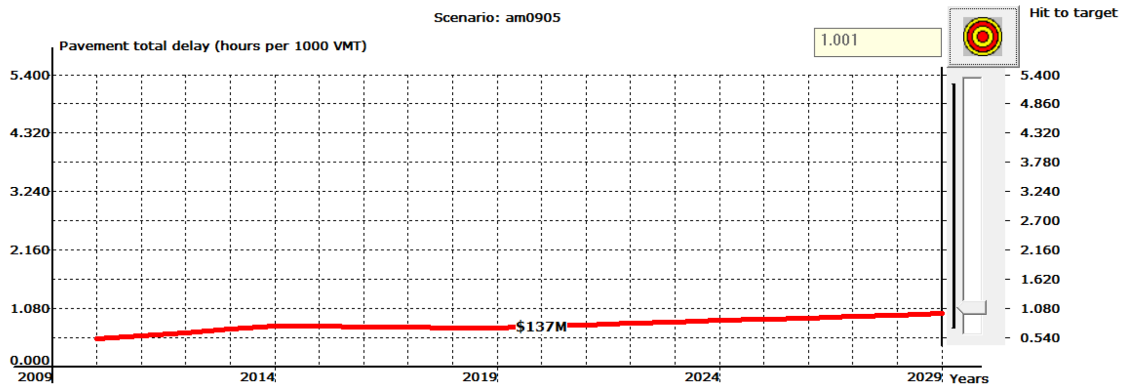
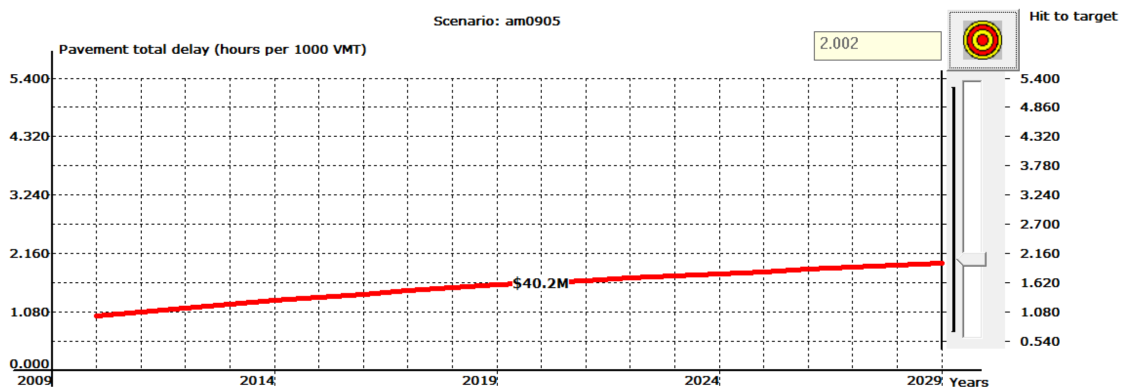


Figure 17 Targets for Percentage of Pavement in Poor and Fair Condition (0%, 10% and 20%)





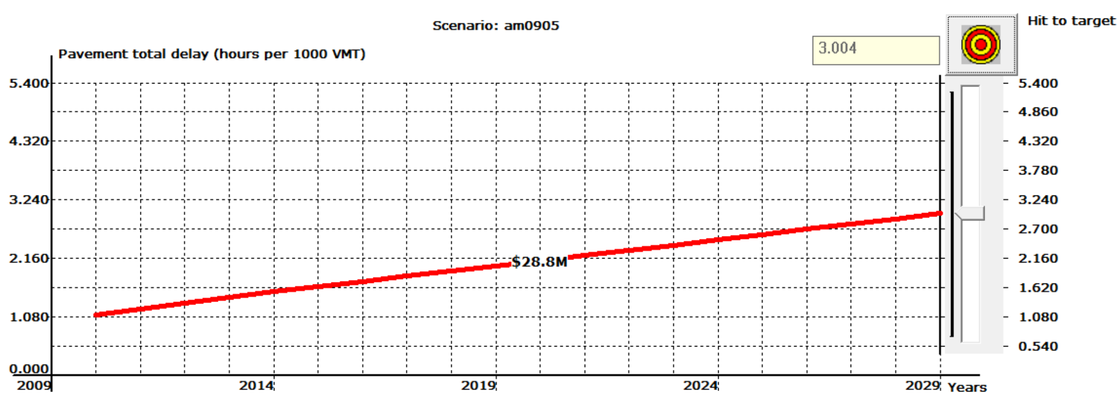
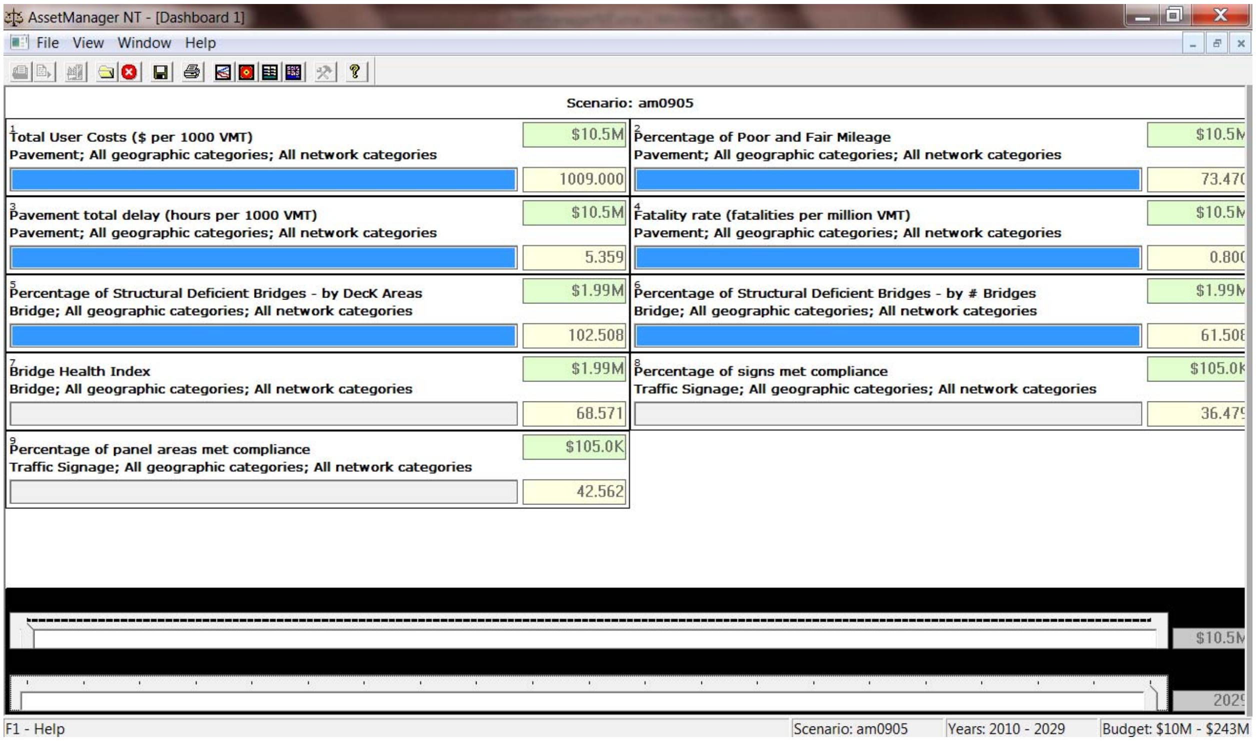


Figure 18 Targets for Pavement Total Delay (1, 2, 3 Hours per 1000 VMT)

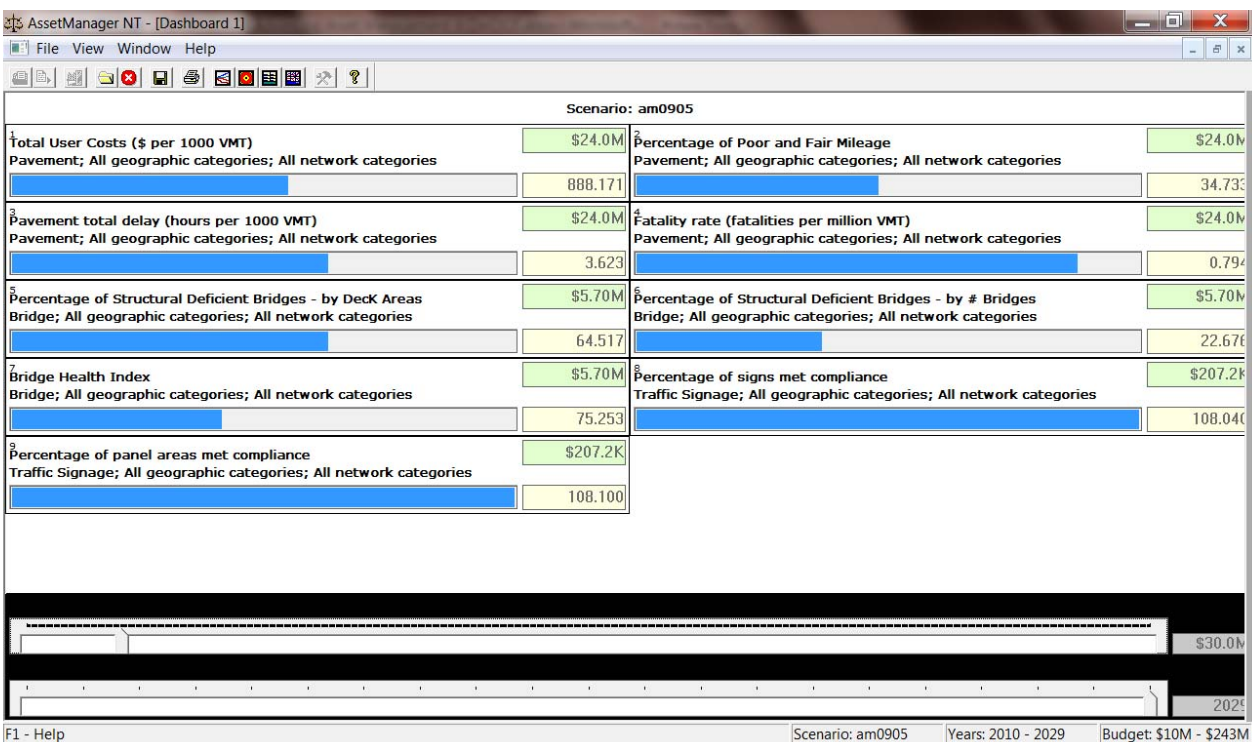
Figure 19 Targets for Percentage of Traffic Signs within Useful Lives by Panel Area (100%, 85% and 70%)

Dashboard

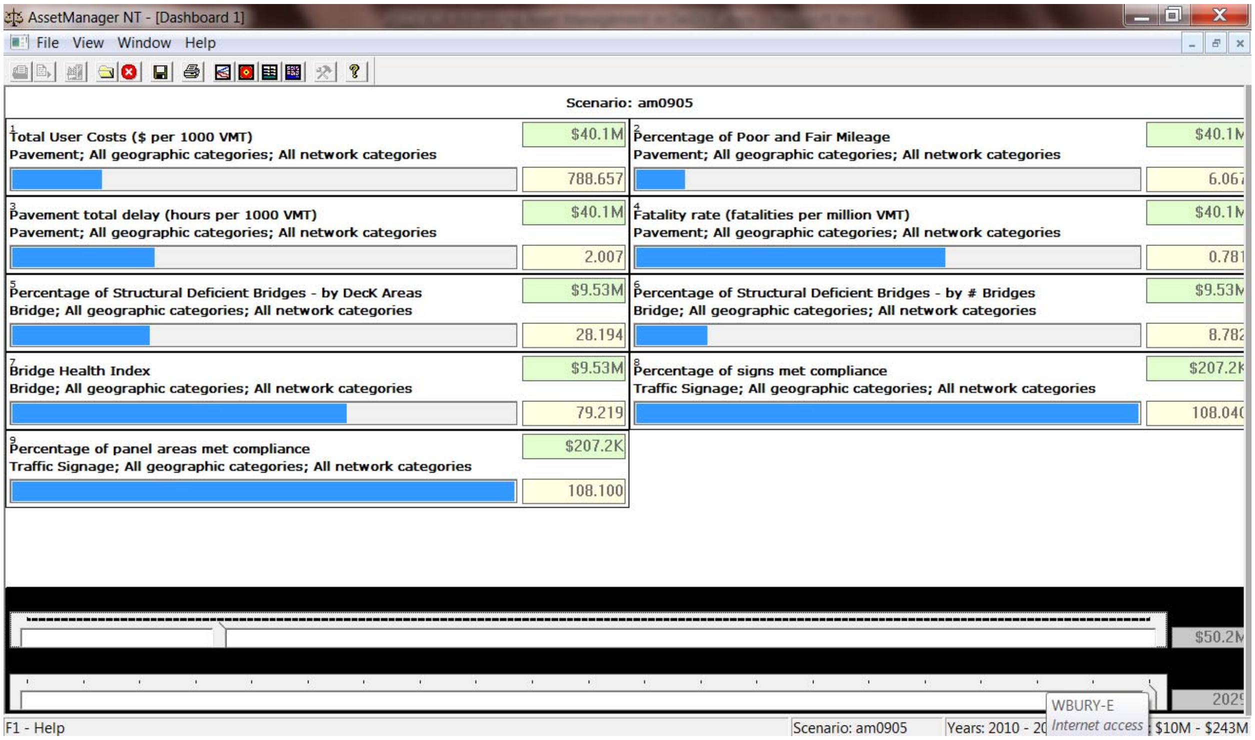
Dashboard displays are used to capture a set of performance measures for different budget scenarios. In this application three different budget allocations are shown in Figure 20 based on the resources allocation - 19% funding for bridges and 80% for pavements, 1% signage. Each dashboard corresponds to a budget level that defines a scenario and shows the value of each performance measure as a bar graph. The Dashboard view lets users adjust an overall system's annual budget interactively as it dynamically indicates the effect of the budget on performance measures. This view also allows users to customize the resources allocation among the asset types in terms of percentages.



a) Budget =$10.5m



b) Budget = $30.0m



c) Budget = $50.2m

Figure 20 Dashboard View

Allocation and Summary

Figure 21 is a summary of the performance measures for four different allocations of funds to bridge, pavement, and traffic signage assets. The performance measures shown in Figure 21 are total user costs, percentage of poor and fair mileage, total delay for pavement, % of structurally deficient bridges by deck areas and health index for bridge, and % of sign within useful lives by panel areas for signage asset. The budget levels are set to be $12.7m (the least budget level), $30m, $50m, and $100m, and the six panels in the Figure show the changes of the performance measures over time.

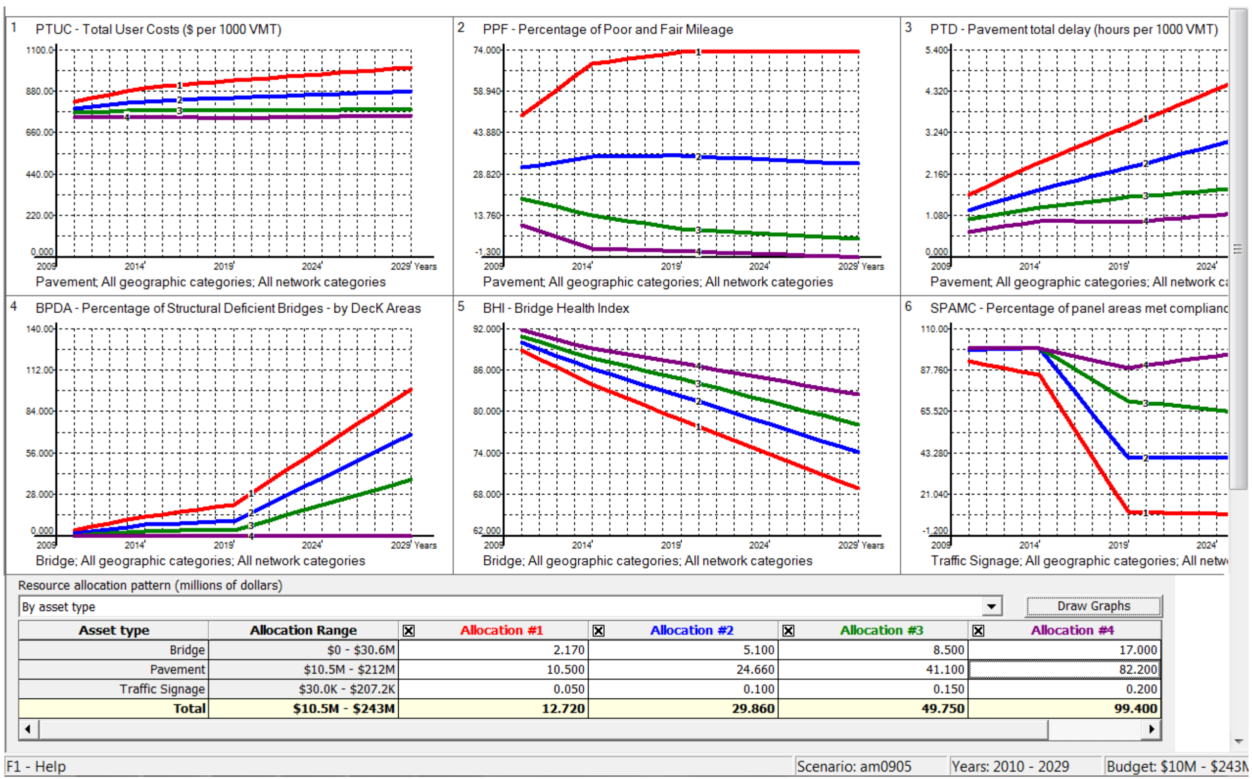


Figure 21 Resource Allocation View

5. Assessments of Investment Objectives based on Data Envelopment Analysis (DEA)

Introduction

For a given highway investment problem, there are typically several alternative decisions or actions, each with its unique set of costs and benefits. The monetary cost and benefit impact of each alternative are generally combined into a performance measure known as economic efficiency (often referred to as benefit-cost analysis), which can help guide transportation decision making at every stage of the project development process to select the best of several alternative actions.

For example, HERS-ST analysis provides the investment costs and the corresponding benefits by funding period for each alternative investment scenario, and assesses the economic efficiency based on incremental benefit cost analysis have converted all benefits to a monetary value, which is implicitly weighting each of these benefits. The predefined valuation of benefits in monetary terms for benefit cost analysis is well understood and accepted. However, with a variety of potential investment alternatives, multiple funding periods, plus multiple outputs from the HERS-ST analysis results, the benefit-cost analysis using monetarized benefits fails to capture the complex relationships. Several methods, often relying on weighting benefits or outputs, have been developed to combine different funding periods and multiple outputs (23, 24, and 25). These methods have limitations. First, weighting factors are generally decided by experts and prone to subjective preference (26 and 27). Further, the use of single measures ignores any interactions, substitutions or tradeoffs among various performance measures. As a result, it is challenging to benchmark the most efficient scenario, using limited resources (input) to produce the most performance output. Optimization techniques can be used to estimate the efficient frontier only if the functional forms for the relationships among various performance measures are known. In reality, the a priori information on the tradeoffs is generally unknown and the functional forms cannot be specified, consequently, we cannot fully characterize and evaluate the efficiency of performance to identify the best practice.

To deal with such difficulties, Data Envelopment Analysis (DEA) can be adopted to benchmark different investment scenarios. DEA is a linear programming methodology to measure the efficiency of multiple Decision-Making Units (DMUs) (28). Each DMU has a set of inputs and outputs, representing multiple performance measures of a business operation or process. In this project, the DMUs are investment scenarios. DEA process has several advantages, such as no need to explicitly specify a mathematical form for the production function, its capability of handling multiple inputs and outputs, etc. As a result, it has gained increasing application in numerous areas, such as business (29), supply chain (30 and 31), and transportation (32, 33, 34 and 35) subunits.

The results from the investment analysis scenarios generated from the HERS-ST application, Pontis system, and the traffic signage spreadsheet developed for this project can be used in the DEA process to benchmark the scenarios within each individual asset, while results from AssetManagerNT can be used to benchmark investment and resource allocation scenarios across asset classes.

The following sections illustrate how DEA can be used to benchmark investment scenarios: first by providing background on the DEA method, data sources, and input/output of DEA, data preprocessing, and then using the results for benchmarking.

Data ENVELOPMENT Analysis (DEA)

Data Envelopment Analysis (DEA) is a multi-factor productivity analysis model for measuring the relative efficiencies of a homogenous set of decision making units (DMUs). The efficiency score in the presence of multiple input and output factors is defined as (26, 27, and 28):

$$\text{Production Efficiency} = \frac{\text{Weighted sum of outputs}}{\text{Weighted sum of inputs}} \qquad \text{.......................... (3)}$$

The efficiency frontier defines the maximum combinations of outputs that can be produced for a given set of inputs. Assuming a set of n scenarios as DMUs, each DMU_j (j = 1, …, n) uses m inputs x_{ij} (i = 1, 2, …, m) to produce s outputs y_{rj} (r = 1, 2, …, s), the frontier can be determined by the model proposed by Charnes et al. (28):

$$\begin{aligned} &\sum_{j=1}^{n} \lambda_j x_{ij} \le x_i && i = 1,2,\ldots,m \\ &\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_i && r = 1,2,\ldots,s \\ &\sum_{j=1}^{n} \lambda_j = 1 \end{aligned} \qquad \text{.. (4)}$$

Various models have been developed to determine frontiers in Equation 4. One of the most widely used model, the input-oriented Envelopment Models with Variable Returns of Scale (VRS), aims to minimize the inputs while keep the outputs at their current levels, which is formulated in Equation 5 (26, 27, and 28):

$$\min \theta - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right)$$

Subject to

$$\begin{aligned}
&\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta x_{ip} && i = 1,2,\ldots,m \\
&\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{rp} && r = 1,2,\ldots,s \\
&\sum_{j=1}^{n} \lambda_j = 1 \\
&\lambda_j \geq 0 && j = 1,2,\ldots,n
\end{aligned} \tag{5}$$

The above problem is run n times in identifying the relative efficiency scores of all DMUs. Each DMU selects input and output weights that maximize its efficiency score. In Equation 5, DMU_p is the target DMU (one of the *n* DMUs under evaluation). θ represents the efficiency score of DMU_p. x_{ij} and y_{rj} are the i^th input and r^th output for DMU_i. λ_j is the unknown weight to be determined. s_i^- and s_r^+ are slacks of input and output. In general, if θ = 1, the current input levels cannot be reduced, indicating that DMU_p is on the frontier. Otherwise if θ < 1, DMU_p is dominated by the frontier and is inefficient, or the DMU under evaluation can reduce its inputs by the proportion of θ (26, 27, and 28).

It should be noted that in the conventional DEA models, such as the VRS Envelopment models, it is assumed that outputs should be increased (defined as desirable outputs) and the inputs should be decreased (defined as desirable inputs) to improve the performance or to reach the best-practice frontier in the DEA process (26, 27, and 28). There are several approaches to handling undesirable inputs and/or outputs. One simple method is to apply some transformations, such as multiply each undesirable output by "-1" and then find a proper constant to let all negative undesirable outputs be positive, which is used in this paper.

Benchmarking Analysis for Individual Asset

Traffic Signage

The six investment scenarios developed for this project are analyzed as six decision making units (DMUs) for the DEA benchmarking process:

- No replacement
- 5% replacement per funding period
- 10% replacement per funding period
- 20% replacement per funding period
- 30% replacement per funding period
- 40% replacement per funding period

The annual budget requirements for each scenario are used as the input for the DEA process, while the two performance measures (in terms of % signs within their useful life by panel area and by number of signs) as the outputs. Since the majority of the signs on the highways under study have been replaced within the last five years, the performance measures of these signs at the beginning of the analysis periods, especially the first and second funding periods, demonstrate very similar results and show very minor variations. As a result, only the performance measurement values at the end of the analysis period (which is funding period four) are used as the outputs for the DMUs. The data for the DMUs are presented in Table 16.

Table 16 Traffic Signage Data Input/Output for the DEA Process

DMU	Scenario	Annual Budget ($)	% sign within expected life by panel area (FP4)	% sign within expected life by # of signs (FP4)
1	No replacement	30000	0	0
2	5% replacement	61340	17.08	15.18
3	10% replacement	93289	37.81	30.54
4	20% replacement	138884	60.26	60.54
5	30% replacement	207206	100	100
6	40% replacement	271149	100	100

In order to improve the efficiency of the signage investment, we would like to achieve a higher percentage of signs within their expected life with less investment. In other words, the inputs and outputs of these DMUs are desirable and no data preprocessing or transformation is needed. The input-oriented envelopment CRS model is used to benchmark the most efficient investment alternatives. Solving the linear programming problem presented in Equation 5, we can observe that the results of the model not only identify benchmark scenario(s), but also identify improvement strategies for those scenario(s) that are currently inefficient.

The efficiency analysis results for the six investment scenarios are shown in Table 17. The results show that DMU #5 (30% replacement per funding period) receives an efficiency score of 1.0 and is considered to be efficient. The rest of the investment scenarios are benchmarked by DMU #5 with efficiency scores of less than 1.0 but greater than 0, and thus they are identified as inefficient. These DMUs can improve their efficiency, or reduce their inefficiencies proportionally, by reducing their inputs. For example, investment DMU #4 can improve its efficiency by reducing its input (investment dollars) up to 9.678% (which is 1.0 minus the efficiency score of 90.322%).

Table 17 Efficiency Results for Traffic Signage Investment Scenarios

DMU Name	Input-Oriented CRS Model Efficiency Score	Benchmarks	
		λ1	by
1	0.06907	0.010	DMU5
2	0.57696	0.171	DMU5
3	0.83981	0.378	DMU5
4	0.90322	0.605	DMU5
5	1.00000	1.000	DMU5
6	0.76418	1.000	DMU5

Obviously an efficient DMU may consider itself its own "benchmark". For example, the benchmark for DMU #5 is itself. However, for inefficient DMUs, their benchmarks are one or many of the efficient (benchmarked) DMUs. In this example, all the rest of DMUs are only benchmarked by DMU #5 since there is only one benchmark in this example.

If the scenario is inefficient, which inputs/outputs are needed to be reduced by calculated proportions? These reductions are called slacks. Table 18 shows the DEA run results for the output slacks when the input keeps at the current level since input-oriented model is applied. It is observed that the efficient DMU #5 doesn't have any slacks. Slacks exist only for those DMUs identified as inefficient. However, slacks represent only the leftover proportions of inefficiencies; after proportional reductions in inputs or outputs, if a DMU cannot reach the efficiency frontier (to its efficiency target), slacks are needed to push the DMU to the frontier (target). For example, DMU #2 cannot reduce any input, but must augment the output in terms of % sign within expected life (by number of signs) by 1.9%. It is noted that DMUs #1 and #6 have no slacks in the input and output, which indicate that these DMUs can reach efficiency frontiers after proportional reduction in inputs or increase in outputs.

Table 18 Input/Output Slacks for Traffic Signage Scenarios

DMU Name	Input Slacks	Output Slacks	
	Annual Budget ($)	% sign within expected life by panel area FP4	% sign within expected life by # of signsFP4
1	0.00	0.00	0.00
2	0.00	0.00	1.90
3	0.00	0.00	7.27
4	0.00	0.28	0.00
5	0.00	0.00	0.00
6	0.00	0.00	0.00

Table 19 prescribes the target input and output levels for these scenarios. The targets are the results of respective slack values added to outputs. To calculate the target values for inputs, the input value is multiplied with an optimal efficiency score, and then slack amount are subtract from this amount. As we can observe, the target values for efficient DMUs are equivalent to their original input and output values. For insufficient DMUs, in the CRS input-oriented DEA model, the targets for input variables will comprise proportional reduction in the input variables, by the efficiency score of the DMU minus the slack value. For example, the target input for DMU #3 can be calculated as:

$$\text{Target input for DMU\#3} = 93289 \text{ (original input)} \times 0.83981 \text{ (efficiency score)}$$
$$- 0.0000 \text{ (input slack)} = 78344.5886$$

Similarly, the output targets can be calculated by adding the original output value and the slack.

Table 19 Efficient Targets for Traffic Signage Scenarios

DMU Name	Efficient Input Target	Efficient Output Target	
	Annual Budget ($)	% sign within expected life by panel area FP4	% sign within expected life by # of signs FP4
1	2072.06000	1.00	1.00
2	35390.78480	17.08	17.08
3	78344.58860	37.81	37.81
4	125442.51240	60.54	60.54
5	207206.00000	100.00	100.00
6	207206.00000	100.00	100.00

Pavement

<u>HERS-ST Investment Scenarios</u>

HERS-ST is used as the analytical tool to generate the following six typical investment scenarios:

- Unlimited budget: full engineering, labeled as “FULL ENGR”;
- “Do nothing” or “do-minimal work” , labeled as “MIN_INV”;
- Maintain current conditions (to represent current budget level) , labeled as “BGT_80M” or “MCC”;
- 30% increase of the current level, labeled as “BGT_96M”;
- 30% decrease of the current level, labeled as “BGT_56M”;

The inputs to the DEA analysis are the net present value of agency costs of the highway system renewal, including the initial capital requirements for each funding period and the corresponding maintenance costs. The outputs are the benefits of the renewal, including system performance improvement in terms of “Percent mileage of highways with International Roughness Index (IRI) less than 170 in./mi.”, net present value of user costs, and net present value of social costs. The cost components are summed up into aggregated values in constant dollars over the entire analysis period based on the values at each funding period. The performance measures at the end of each funding periods in terms of “Percent mileage of highways with International Roughness Index (IRI) less than 170 in./mi.” are used as the outputs since an average or aggregate value doesn’t have any practical meaning for this case.

Because the input of this process is agency cost, the summation of initial capital investment (the cost component in HERS-ST) and the corresponding maintenance cost (the benefit or output of HERS-ST), it is not as straightforward as that for traffic signage asset to judge which input/output is desirable or in desirable. For example, by comparing the “MCC” and “BGT_56M” scenarios, the “BGT_56M” scenario has a relative lower capital investment but a higher maintenance cost than those in the “MCC” scenario. However, it is challenging to determine which scenario has a better smoothness in terms of IRI. To identify whether the input/output is desirable, the following scheme is proposed. For example, a better system performance requires decreased input that means less agency investment and increased output performance which is less user cost. In other words, to assure desirable inputs and outputs, there shall be a positive correlation between agency cost and user cost. However, engineering judgment tells us that generally more agency investments (increased inputs) result in reductions in user costs, thus undesirable input and output exists. For this purpose, a correlation matrix is generated to check the desirability of inputs and outputs using correlation analysis approach. The correlation coefficient is used to estimate the relationships and interactions among the input and output variables. If the correlation coefficient is negative, it is treated as undesirable.

The correlation analysis shows that the user cost has a negative correlation coefficient with the input and indicates it is an undesirable output, which is consistent with what we expected. All the other outputs, highway performance in terms of roughness and emission costs have positive correlations and are treated as desirable outputs.

Solving the linear programming DEA problem presented, the efficiency scores for the six analysis scenarios are shown in Table 20. The analysis demonstrated that the “BGT_96M” scenario, a 20% increase from the assumed current investment, has the highest efficiency score of 1.00 and is the benchmark of “BGT_80M”, “BGT_56M”, “MCC”, and “MIN_INV” scenarios. The efficiency score for the current budget level scenario (“BGT_80M”) is 98%, which indicates that if the outputs for that scenario are kept at current levels, the input (or the agency cost) can be reduced 2% (which is 160, 000 dollars) if it is as efficient as its benchmark. Even though “Minimum Investment” scenario requires almost no initial investment, it generates much higher maintenance and worse highway performance; as a result, its efficiency score is only 52% efficient. This supports the idea that under investment is not the most efficient way to manage our highway assets. On the other hand, the “Maintain Current Condition” scenario requires a slightly higher agency investment, however, its efficiency score is 92% of the benchmark investment alternative. From this perspective, it is shown that more investment does not guarantee a better overall outcome (in term of efficiency). There is an optimal investment alternative to achieve the best overall system efficiency.

It is noted that the "Full Engineering" scenario is also on the frontier with an efficiency score of 1.00. This scenario is significantly different from the other five scenarios, but still represents another point on the efficiency frontier. This assumption can be supported by the fact that it is benchmarked by itself and "FULL_ENGR" DMU is a minor benchmark for the other inefficient DMUs, as shown in Table 20.

Table 20 Efficiency Results for HERS-ST Pavement Investment Scenarios

DMU No.	DMU Name	Input-Oriented CRS model Efficiency Score	Benchmark			
			λ1	by	λ2	by
1	BGT_96M	1.00000	1.000	BGT_96M		
2	BGT_80M	0.98272	0.992	BGT_96M	0.008	FULL_ENGR
3	BGT_56M	0.89114	0.980	BGT_96M	0.020	FULL_ENGR
4	MCC	0.91892	0.914	BGT_96M	0.086	FULL_ENGR
5	MIN_INV	0.52045	0.814	BGT_96M	0.186	FULL_ENGR
6	FULL_ENGR	1.00000	1.000	FULL_ENGR		

In Table 20, efficient DMUs consider themselves as their own "benchmark" while inefficient DMUs are benchmarked by multiple efficient DMUs. For example, the benchmarks for DMU#2, are DMUs #1 and #6. This means, to become efficient, DMU #2 must use a combination from both DMU #1 and DMU #6 (a virtual DMU) to be efficient. How much of DMU #1 and DMU #6 (what combination) are calculated to achieve efficiency and reported next to each benchmark DMU. In this case, DMU #2 will attempt to become more like DMU #1 other than DMU #6 as observed from the respective λ weights ($\lambda1$=0.992 vs. $\lambda2$ =0.008).

The slack values and targets of the inputs and outputs are not terribly interesting for this case and eliminated from this report.

Bridge

Ten scenarios with budget levels from 0.5 to 10 million dollars generated from the PONTIS system by DelDOT bridge engineers are studied. The input of the DEA analysis is the annual average budget for each scenario, while the outputs are the performance measures in terms of the percentage of structurally sufficient bridges by deck areas, and Health Index. Even though these measures are simulated and recorded for each of the four funding periods, only the measures at the end of the 20-year analysis period are used as the DEA outputs. The reasons are: (1) currently there are no structurally deficient bridges, and the health index is over 92%, which indicates that the bridges are in excellent condition in terms of these measures; (2) an analysis period of 20 years is relatively short compared to the design lives of bridges. As a result, the deterioration in the coming 20 years turns out to be insignificant (see Table 21), and even more so if only one funding period (5 years) is studied.

The desirability of the inputs and outputs are checked. The higher the percentage of structurally deficient bridges, the worse the performance of the bridges is. It indicates that this measure is undesirable and need to be preprocessed. To make it desirable, the original output is adjusted by multiplying this undesirable output by “-1” and then adding a proper constant to let all negative undesirable outputs be positive.

The efficiency scores of the bridge investment DMUs are demonstrated in Table 22. It is interesting to note that the scenario that spends the least achieves the best efficiency. Again these results can be explained similarly to those when we choose the output performance measures, which are:

- the bridges on Delaware interstates are in excellent condition and none of them are structurally deficient;
- The deterioration in 20 years is not significant.

Table 21 Pontis Bridge DEA Data Input/Output

DMU #	Annual Budget (million)	% non-SD Bridges by Deck Area FP4	Health Index FP4
1	0.5	68.9	74
2	0.7	73.9	74.9
3	1	71.9	75.5
4	1.2	75.9	76.3
5	1.5	79.9	77.6
6	1.75	85.9	78.7
7	2	88.9	79.8
8	2.5	96.9	82.1
9	3	88.9	82.7
10	3.5	95.9	83.9
11	4	100	84.5
12	5	100	84.8
13	10	100	85.8

As a result, the costs needed for improvement outweighs the benefits of such improvement, and it comes to the conclusion that no investment is the most efficient approach in the short term. Another implication from this observation reveals the challenges of selecting appropriate performance measures that we currently adopted. It has showed that these two performance measures we used are not very sensitive to the amount of investment for these infrastructures. It also raise the awareness that using incremental benefit cost analysis (which is used in the PONTIS system) may be limited to capture the “true” benefits resulting from the costs or investment.

Table 22 Efficiency Results for Pontis Bridge Investment Scenarios

DMU #	Input-Oriented CRS Model Efficiency score	Benchmarks	
		λ1	By
1	1.00000	1.000	DMU1
2	0.76612	1.073	DMU1
3	0.52177	1.044	DMU1
4	0.45900	1.102	DMU1
5	0.38655	1.160	DMU1
6	0.35621	1.247	DMU1
7	0.32257	1.290	DMU1
8	0.28128	1.406	DMU1
9	0.21505	1.290	DMU1
10	0.19884	1.392	DMU1
11	0.18142	1.451	DMU1
12	0.14514	1.451	DMU1
13	0.07257	1.451	DMU1

Further exploration of the slacks and targets of inputs and outputs are shown in Table 23 and 24. They demonstrate that all the other DMUs are benchmarked by DMU #1, the least investment scenario. The output in terms of health index can be increased significantly for some scenarios if the same level of input is provided. The target inputs can be reduced significantly while the health index output targets increased.

Table 23 Input/Output Slacks for Pontis Bridge Scenarios

DMU #	Input Slacks Annual Budget (million)	Output Slacks % non-SD Bridges by deck area FP4	Health Index FP4
1	0.00	0.00	0.00
2	0.00	0.00	4.47
3	0.00	0.00	1.72
4	0.00	0.00	5.22
5	0.00	0.00	8.21
6	0.00	0.00	13.56
7	0.00	0.00	15.68
8	0.00	0.00	21.97
9	0.00	0.00	12.78
10	0.00	0.00	19.10
11	0.00	0.00	22.90
12	0.00	0.00	22.60
13	0.00	0.00	21.60

Table 24 Efficient targets for Pontis Bridge Scenarios

DMU #	Efficient Input Target Annual Budget (million)	Efficient Output Target % non-SD bridges by deck area FP4	Health Index FP4
1	0.50	68.90	74.00
2	0.54	73.90	79.37
3	0.52	71.90	77.22
4	0.55	75.90	81.52
5	0.58	79.90	85.81
6	0.62	85.90	92.26
7	0.65	88.90	95.48
8	0.70	96.90	104.07
9	0.65	88.90	95.48
10	0.70	95.90	103.00
11	0.73	100.00	107.40
12	0.73	100.00	107.40
13	0.73	100.00	107.40

Cross-Asset Benchmarking

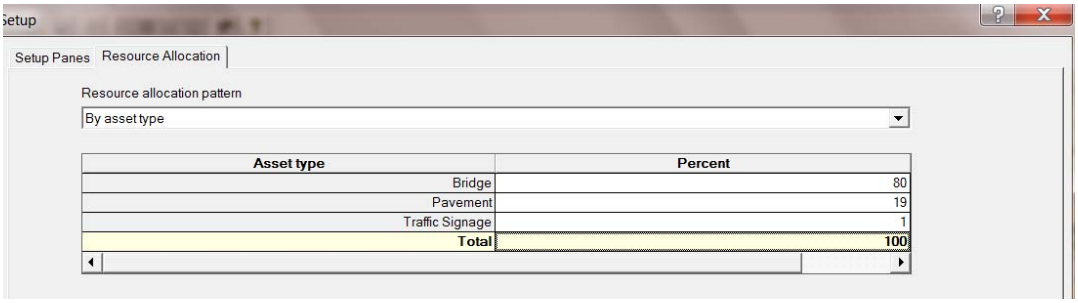
Introduction

At its core, Asset Management is about using limited transportation dollars in the most cost-effective way as possible. Meanwhile, a fundamental challenge in managing transportation infrastructure assets is to determine how to allocate scarce resources among disparate asset categories and types of needs. Transportation agencies must determine what funds to allocate by asset type, including roads, structures, safety features, facilities and other assets, as well as between competing needs for asset replacement, rehabilitation, routine maintenance and improvement.

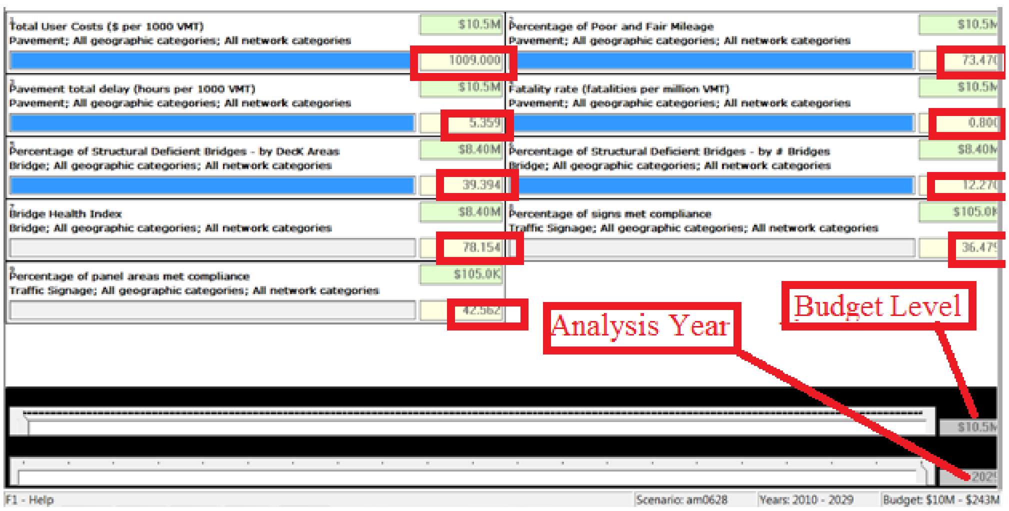
Allocating resources between these areas is a complex problem requiring consideration of multiple objectives and constraints. Specifically, effective decision making at the strategic level requires the ability to assess the very long-term effects of different alternative strategies over the entire network of assets. In the following session, DEA is adopted to benchmark the cross-assets resource allocation scenarios.

Data Sources

The inputs and outputs for the DEA analyses are obtained from the AssetManagerNT software, which is capable of providing a quick-response “what-if” analysis tool for testing different investment options. The Dashboard view lets you adjust an overall system’s annual budget interactively as it dynamically indicates the effect of the budget on different performance measures; it also provides the functionality of customizing the resources allocation among the asset type in percentage (as shown in Figure 22). By using the Dashboard view, the performance measure values at various resource allocation scenarios and various budget levels can be obtained and used as the inputs and outputs for further cross-asset DEA benchmarking.



(a) Resources allocation



(b) Performance measures at various budget level and analysis year

Figure 22 Dashboard View in AssetManagerNT for the Use of DEA Analysis

Selected Resources Allocations

Based on the real expenditure data in DelDOT and the engineering judgments of DelDOT engineers, it is estimated that (1) approximately $4.0 million (direct costs from Pontis) has been spent on the bridges on the highways under study; (2) the total cost is about 3.1 times of direct cost; (3) the current resource allocation between bridges and pavements is around 25% vs. 75%. (4) Compared to bridges and pavements, the spending on traffic signage is trivial.

Accordingly, we can assume that the current practice annual budget for pavement and bridges are roughly 50 million dollars in terms of total costs. The calculation comes as follows:

$$(\$ 4 \text{ million} \times 3.1) / 25\% = \$49.6 \text{ million}$$

It is should be noted that this budget estimate is different from that from HERS-ST to maintain current condition for pavement only. This estimate is in total costs, while the HERS-ST requirement is initial capital costs.

In the previous Chapter, it has shown that when an annual budget of $200,000 is spent for sign maintenance and replacement, the sign performance measures reach their maximum values at 100%. This $200,000 spending accounts for only 0.4% of the estimated annual overall system budget of $50 million. However, when customizing the cross-assets resources allocation (in percentage) in the Dashboard view of the AssetManagerNT software, no decimal is allowed in the input. As a result, the smallest resource allocation for signage is 1%, which is $500 thousand annually - 2.5 times of the spending that results in 100% of signs within their useful lives. Therefore, traffic signage assets are eliminated from the cross-assets analyses, and only bridges and pavements are considered.

The first analysis aims to examine the efficiency of various resources allocation scenarios at the current budget level of $50 million annually. Seven resource allocation scenarios are explored as shown in Table 25.

The projected values of the performance measures for pavement and bridges are obtained from the AssetManagerNT software for these scenarios and tabulated in Table 26.

Table 25 Resources Allocation Scenarios at the Current Budget Level

DMU #	Total Budget ($ million)	Resources Allocation (as a percentage)		Note
		Pavement	Bridge	
1	50	75	25	Current practice
2	50	100	0	Pavement only
3	50	90	10	In-between
4	50	80	20	
5	50	70	30	
6	50	60	40	
7	50	50	50	Even allocated

Table 26 Performance Measures for the Resources Allocation Scenarios

DMU #	Pavement		Bridge	
	% in poor and fair conditions	Total delay	% of SD bridges by panel area	Health Index
1	7.121	2.172	0	81.919
2	2.063	1.416	100	64.4
3	4.018	1.686	69.323	74.095
4	6.087	2.01	23.375	76.677
5	8.156	2.334	0	82.291
6	17.32	2.843	0	83.035
7	31.673	3.486	0	83.778

The system annual budget is served as the input of the DEA analysis, while the percentage in poor and fair conditions and total delay for pavement asset, the percentage of SD bridges by deck area and health index for bridge asset are utilized as outputs. The other two measures: total user cost and fatality rate are removed from the analysis because these measures demonstrate minor variations among the allocation scenarios. The “percentage of SD bridges by number of bridges” measure is removed as well due to its high correlations with the “percentages of SD bridges by deck area” measure.

Obviously, three outputs: the percentage in poor and fair conditions, total delay, and percentage of SD bridges by deck area are undesirable measures since the decreases of these measures result in better system performance. After they are adjusted by multiplying the original data by "-1" and then adding a proper constant to make them positive, the DEA analysis is performed and the efficiency scores of the allocation scenarios are presented in Table 27.

Table 27 DEA Efficiency Results of Allocation Scenarios

DMU #	Input-Oriented CRS Efficiency Score	Benchmarks	
		λ1	By
1	1.00	1.000	DMU1
2	0.98	1.032	DMU3
3	1.00	1.000	DMU3
4	1.00	1.000	DMU4
5	1.00	1.000	DMU5
6	0.99	1.009	DMU5
7	0.98	1.018	DMU5

Selected Budget Levels

The second analysis sets its objective to explore the efficiency at various budget levels. The current resources allocation practices between bridge and pavement (25% vs. 75%) is kept but five budget levels are explored (Table 28):

- Current budget level at $50 million annually;
- 30% decrease budget at $35 million annually;
- 10% decrease budget at $45 million annually;
- 10% increase budget at $55 million annually;
- 30% increase budget at $65 million annually;

Table 28 Various Budget Level Scenarios

DMU #	Total Budget ($ million)	Resources Allocation (as a percentage)		Note
		Pavement	Bridge	
1	35	75	25	30% decrease
2	45	75	25	10% decrease
3	50	75	25	Current practice
4	55	75	25	10% increase
5	65	75	25	30% increase

The data obtained from the AssetManagerNT for the budget level scenarios are shown in Table 29.

Table 29 Performance Measures for the Budget Level Scenarios

DMU #	Pavement		Bridge	
	% in poor and fair conditions	Total delay	% of SD bridges by panel area	Health Index
1	28.165	3.329	35.796	78.496
2	8.701	2.42	11.268	80.829
3	7.121	2.172	0	81.919
4	5.614	1.936	0	82.1
5	2.526	1.453	0	82.47

The efficiency scores for the various budget level scenarios with the adjusted undesirable outputs are illustrated in Table 30. Comparing to the scenario of estimated $50 million in total costs, it shows that more aggressive investment scenarios are not as efficient as the decreased investment scenarios. This is mainly due to the situation that the current pavements and bridges are performing well in terms of the performance measures used. Another reason maybe that the estimated current investment level ($50 million of total costs) is higher than the real practice investment. While DelDOT cannot directly determine how much is spent on management the interstate-like assets, estimates of an annual budget of $4.0 million direct costs for bridges from Pontis, and an empirical expansion factor of 3.1 to factor the direct costs up to total costs have been made. The other assumption of this estimate is the resources allocation ratio between pavement and bridge (75% vs. 25%), which is a reasonable estimate but may not truly reflect the real spending either. If we would like to maintain the health index or the percentage of SD bridge at the end of analysis year to the current condition (92.1 for health index and 0% of SD bridges), we cannot conclude that the estimated current budget is overinvesting. All these limitations need to be recognized when using the results. The results presented here are intended to facilitate discussion and provide tools to understand the tradeoffs, costs and consequences of various asset management decisions.

Table 30 DEA Efficiency Results of Budget Level Scenarios

DMU #	Input-Oriented CRS Efficiency Score	Benchmarks			
		λ1	by	λ2	by
1	1.00	1.000	DMU1		
2	1.00	1.000	DMU2		
3	1.00	1.000	DMU3		
4	0.91	0.372	DMU2	0.670	DMU3
5	0.78	0.004	DMU1	1.124	DMU2

6. Conclusions and Next Steps

Conclusions

This case study underscores the importance of good data. Our experience with the drainage and signage data provides some insights into strategies for quality control and quality assurance for data. The case study also emphasizes the limitations of the tools. HERS-ST does not have good pavement deterioration models and many of the recommended actions are not relevant to interstate highways. We also see the challenges involved in integrating risk into the decision making process. However, the case study has demonstrated that the pavement and bridge data is easily available and can be assembled in a format that can be used to understand the tradeoffs and the relative importance of different performance measures. The results presented here are intended to facilitate discussion and provide tools to understand the tradeoffs, costs and consequences of various asset management decisions.

This project has established the framework of utilizing DEA and current available tools such as HERS-ST, Pontis, and AssetManagerNT to help decision makers make more efficient investments within and cross-assets. The analysis demonstrates that multiple performance measures can be integrated into the decision making process without having to explicitly assigns weights. Planning for the management of the highway network can then be addressed in a systematic way that recognizes the tradeoffs among different funding periods and objectives such as preserving existing investments, safety, roughness and user costs.

This paper answerers this question by using currently available tools such as HERS-ST, and DEA to select the most efficient highway investment alternatives. Even though it is mathematical in nature, the theory behind is straightforward and can be easily implemented in highway agencies using a spreadsheet, and thus is currently ready for implementation at the practice level.

Future Work

Specifically, the following issues need to be addressed in the future when implementing comprehensive asset management in DelDOT:

- **Define Core Performance Measures**—Effective asset management requires organizations to identify what their core performance measures should be and then focus upon the achievement of those measures to accomplish the organization's mission. NCHRP 20-57 and this report can be used and served as a starting point.
- **Makes Use of Data and Identifies Data Limitations**— DelDOT has collect a great deal of condition and performance data that haven't been utilized to their full extend. Effective asset management will put these data to work and foster a greater understanding of the data's strengths and limitations.
- **Defensible Prioritization Approach**—Effective asset management facilitates the prioritization of investments based upon systematic data-driven analysis rather than anecdotes.
- **Comprehensive Evaluation, including Improved Economic Analysis**—Properly conducted, this systematic analysis extends beyond traditional measures of asset condition to include a broader range of considerations, including an economic evaluation of costs and benefits.

- **Strengthen Predictive Performance and Modeling Capability**—Bridge and pavement management systems typically include predictive modules that permit agencies to model the effects of different levels and types of investments on asset condition. Focusing on the data are often the most reliable and complete for other asset types will ultimately have broader benefits to the entire highway network of implementing asset management in DelDOT.
- **Rational Risk Approach**—A quantitative approach to characterizing risks of system failure and development of risk mitigation strategies are fundamental aspects of an asset management framework and particularly applicable to the assets where the consequences of disruption in service can be quite severe.

The approach to risk management outlined in NCHRP Report 632 is also a data driven process beginning by establishing risk tolerances and then identifying hazards and threats, assessing consequences, identifying mitigation strategies and developing a plan. The interstate highways in Delaware face several risks. There are risks of failure due to manmade and natural hazards, operational risks (for example, closure due to crashes or hazardous spills), and what are described as internal "programmatic" risks.

Bridges are generally considered the most vulnerable asset and tools such as "Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA)" can help transportation agencies allocate budgets to asset protection (36). The application of CAPTA with some enhancements to bridges in Delaware identified critical bridges and proposed mitigation actions (37). No consideration was given to how these actions would be distributed over the planning horizon.

Further discussion with the Asset Management Advisory Committee is needed to better understand internal “programmatic” risks at DelDOT.

- **Continuous Improvement of a Replicable Process**—Asset management establishes a process that can be repeated annually through each program cycle and provides the basis for continued fine-tuning of that process to improve efficiency and effectiveness.
- **Meet Stakeholder Expectations**—Asset management improves an agency’s ability to meet stakeholder expectations in terms of both results on the ground and conveying an image of an effectively managed results-oriented organization.
- **Building Consensus in Political Environment**—A consistent record of achieving expectations builds consensus in the political environment that an agency is effectively managed and can deliver on its promises.

When asset management is properly implemented in DelDOT, the outcomes are expected to be but not limited to the following:

- **More Effective and Efficient Allocation of Financial and Other Resources** — The foundation of asset management is resource allocation. If it is not influencing the allocation of resources, its utility has to be questioned.
- **Improved Performance with Constrained Funding** — Application of asset management principles (e.g., early intervention strategies before significant deterioration occurs) can lead to improved asset condition even with limited funding.

- **Defensible and Timely Decisions**.
- **Preventive Maintenance Funding** — Effective asset management lends support to early intervention strategies.
- **Fewer Unmitigated Disasters** (i.e., more averted system failures) — Asset management, particularly when enhanced with risk management processes, provides the early warning signals to support proactive intervention before a situation becomes untenable.

Acknowledgements

This work was partially supported by the Delaware Center for Transportation, and Delaware Department of Transportation. The assistance of Project Manager Curt Cole, the Asset Management Advisory Committee, and DelDOT staff in helping us to assemble the data and information is gratefully acknowledged.

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Appendix A Analysis of Traffic Sign Retroreflectivity Data

By Sign Color

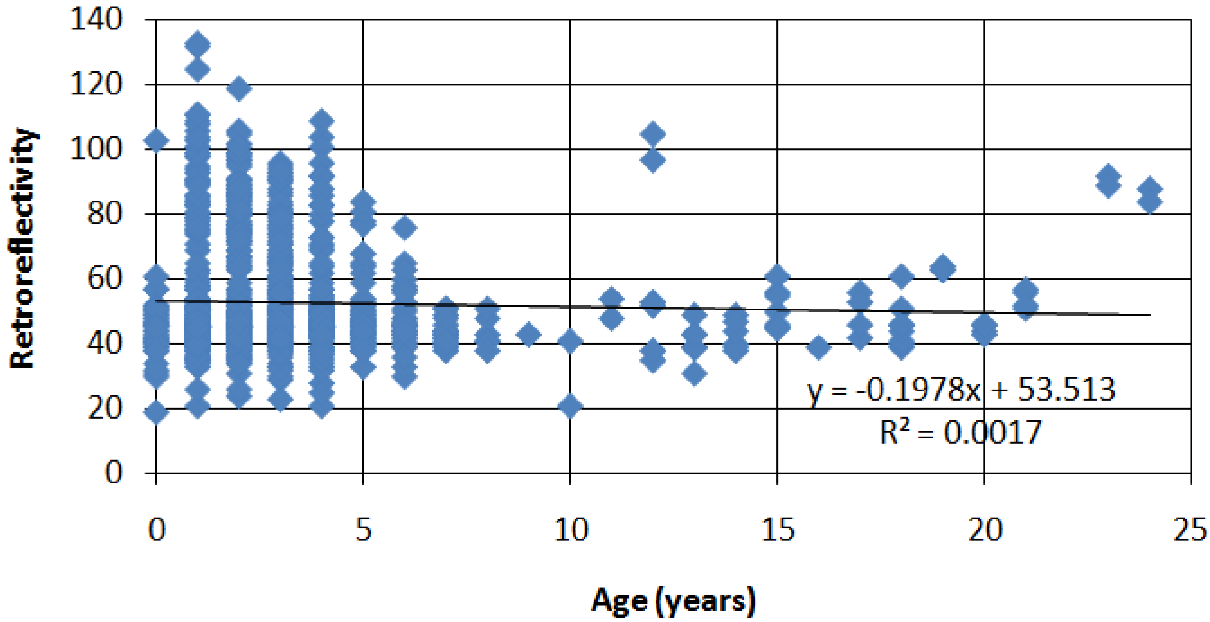


Figure A.1 Green Retroreflectivity

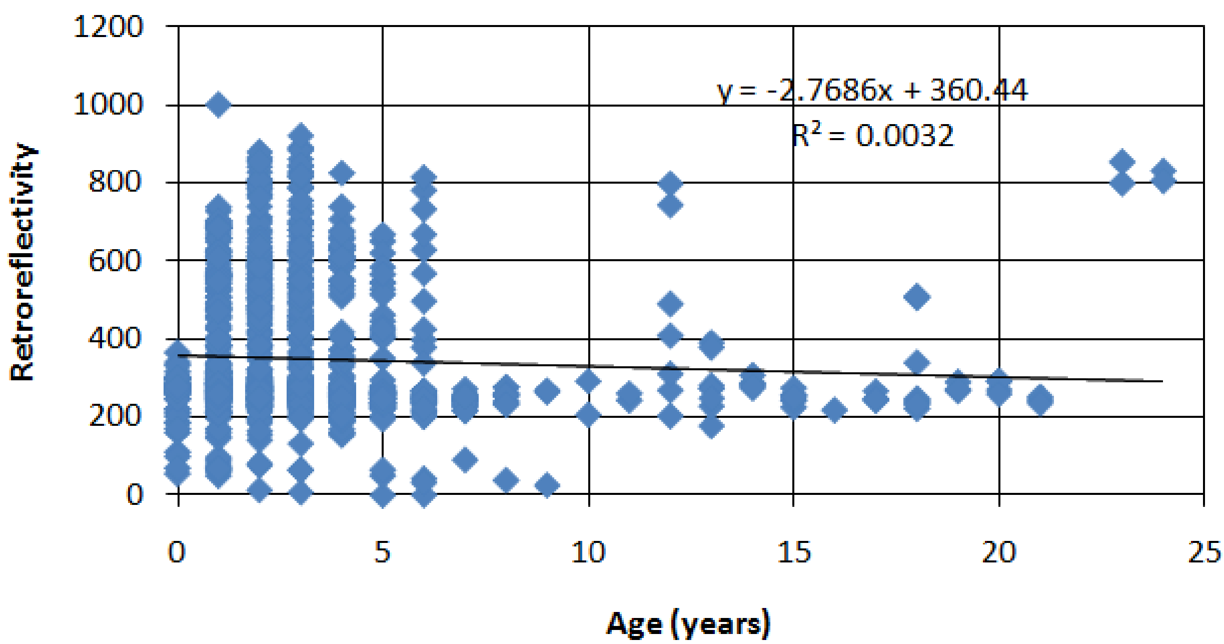


Figure A.2 White Retroreflectivity

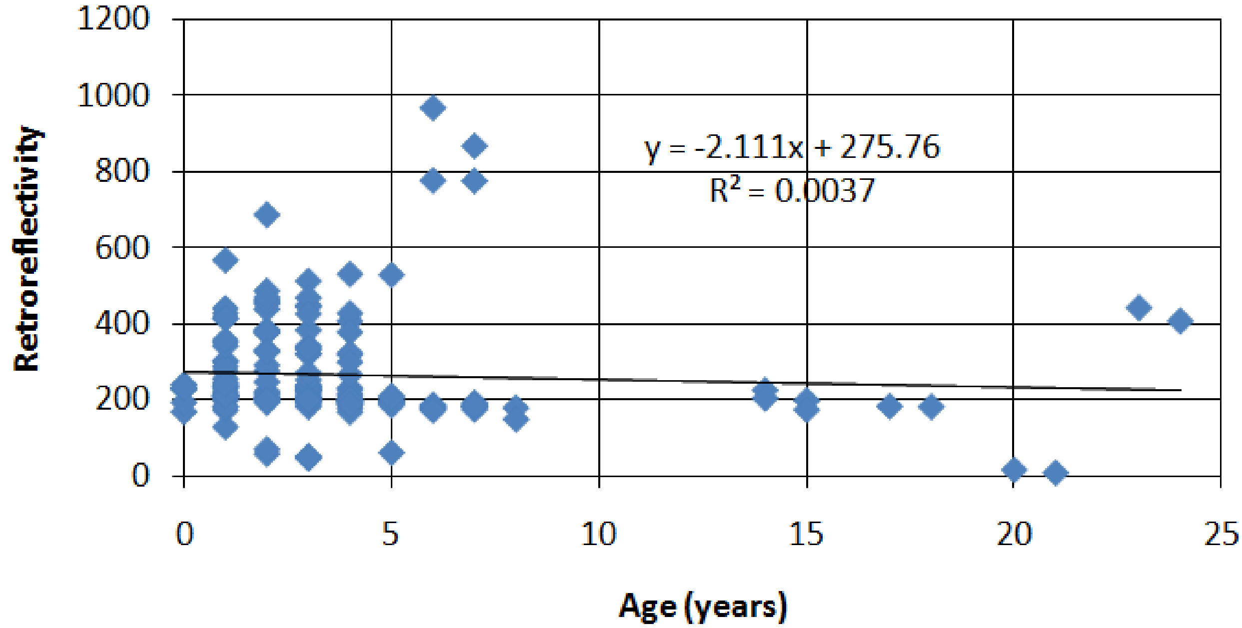


Figure A.3 Yellow Retroreflectivity

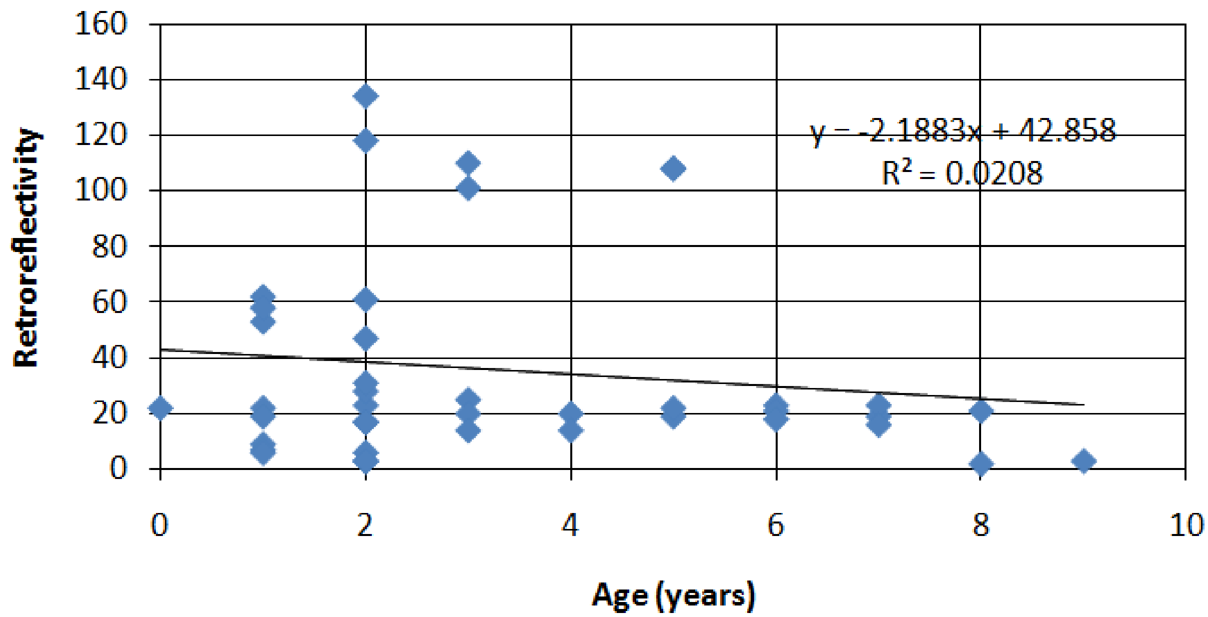


Figure A.4 Brown Retroreflectivity

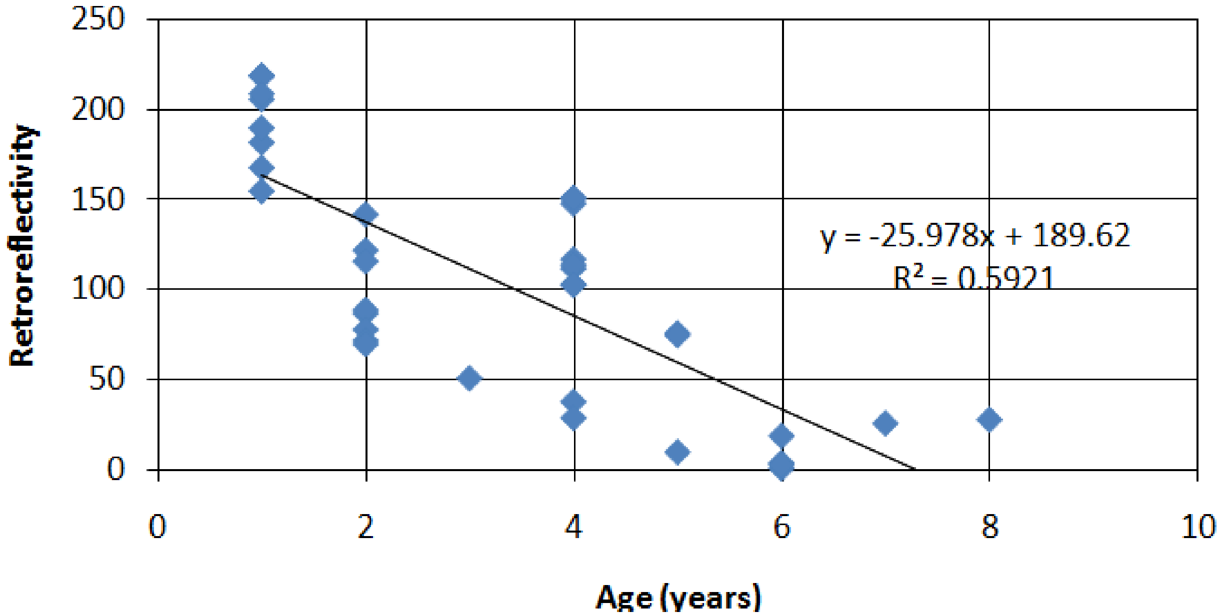


Figure A.5 Red Retroreflectivity

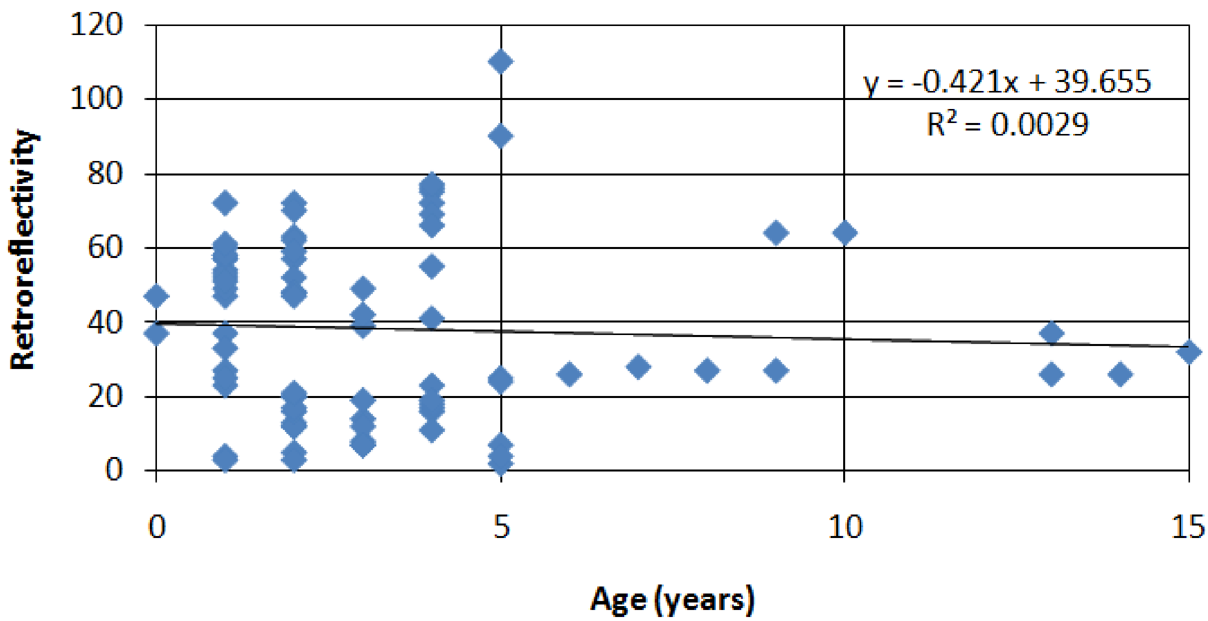


Figure A.6 Blue Retroreflectivity

By Sheeting Type

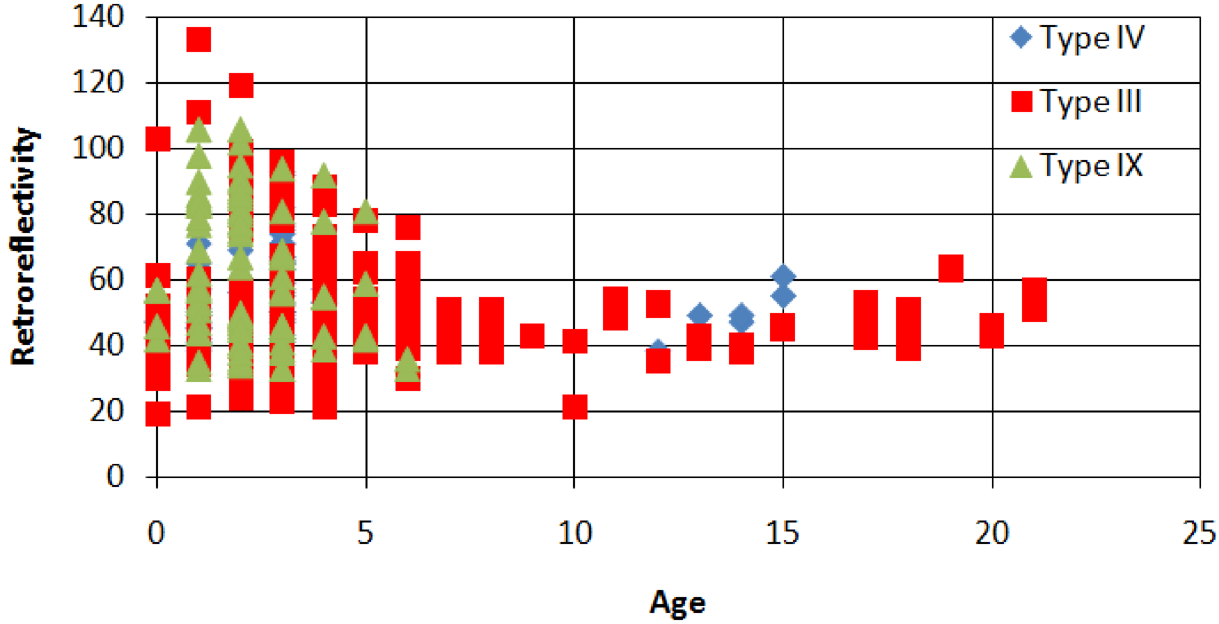


Figure A.7 Green Retroreflectivity

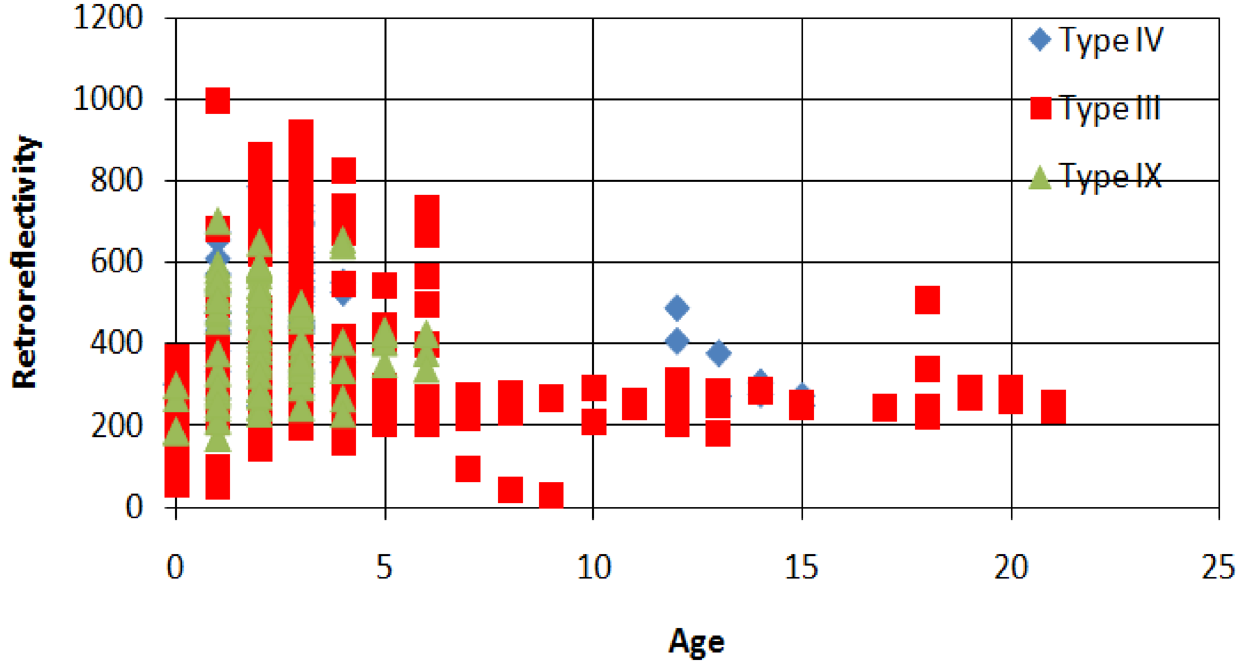


Figure A.8 White Retroreflectivity

By Sign Direction

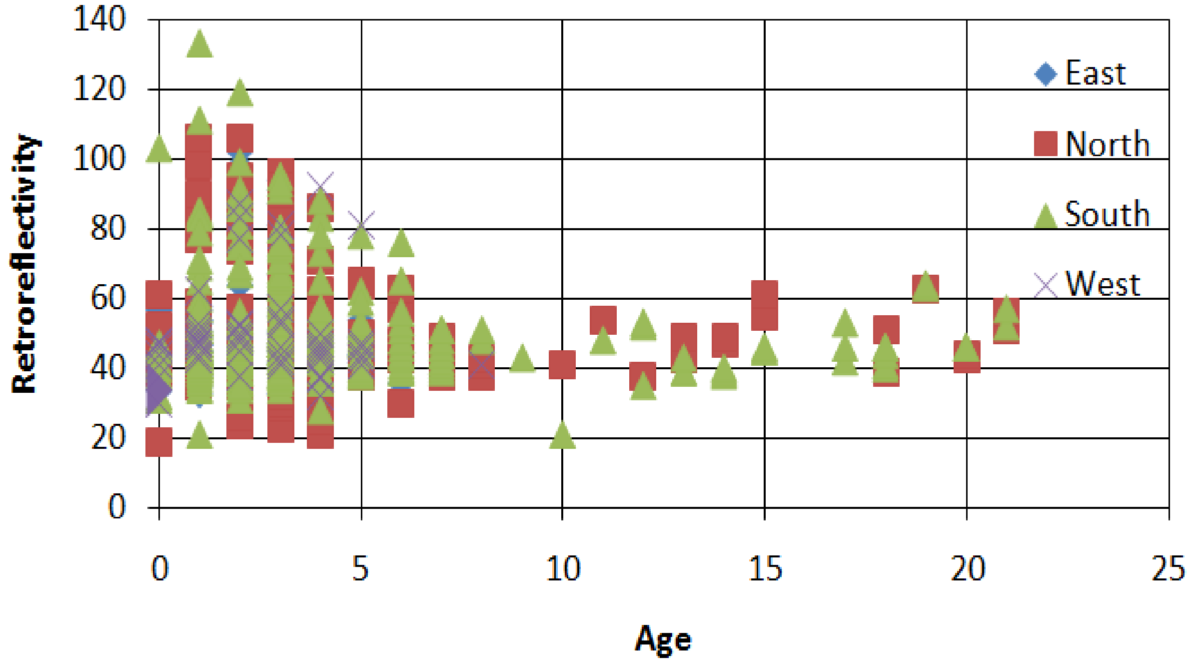


Figure A.9 Green Retroreflectivity

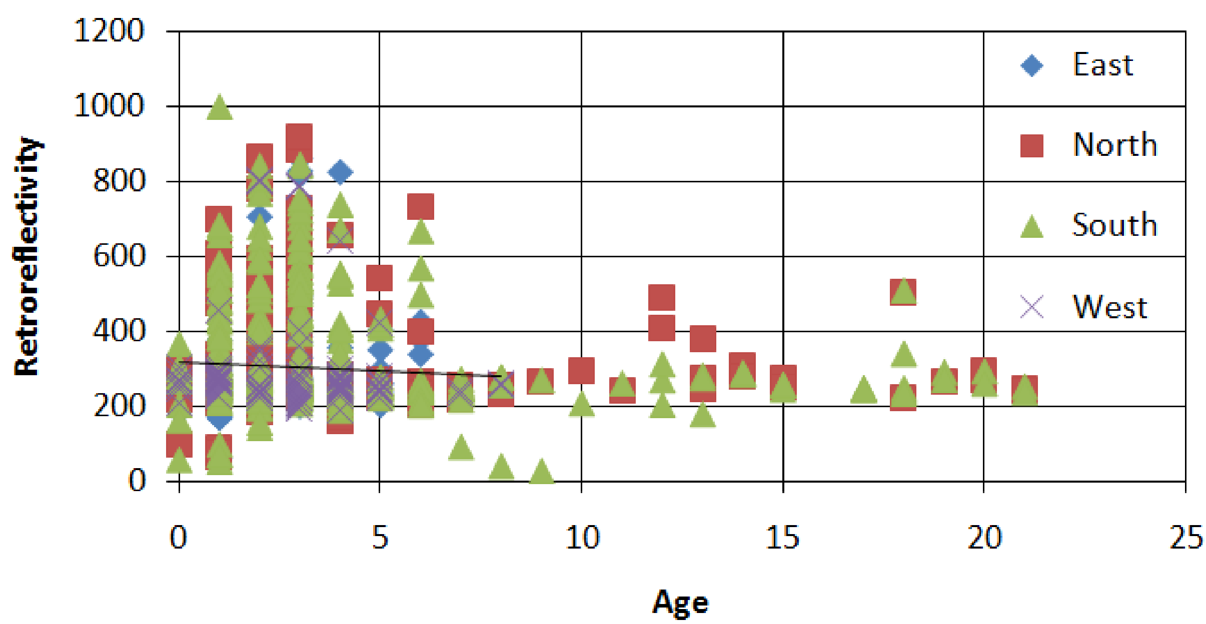


Figure A.10 Silver Retroreflectivity

By Color Type/ Combinations

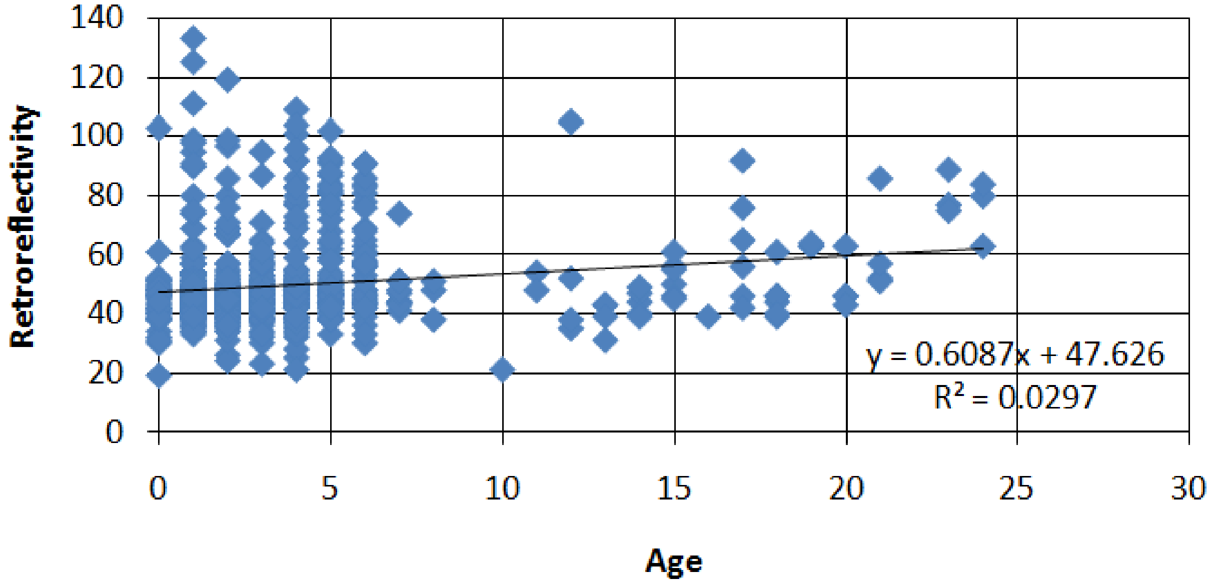


Figure A.11 White on Green Signs – Green Color

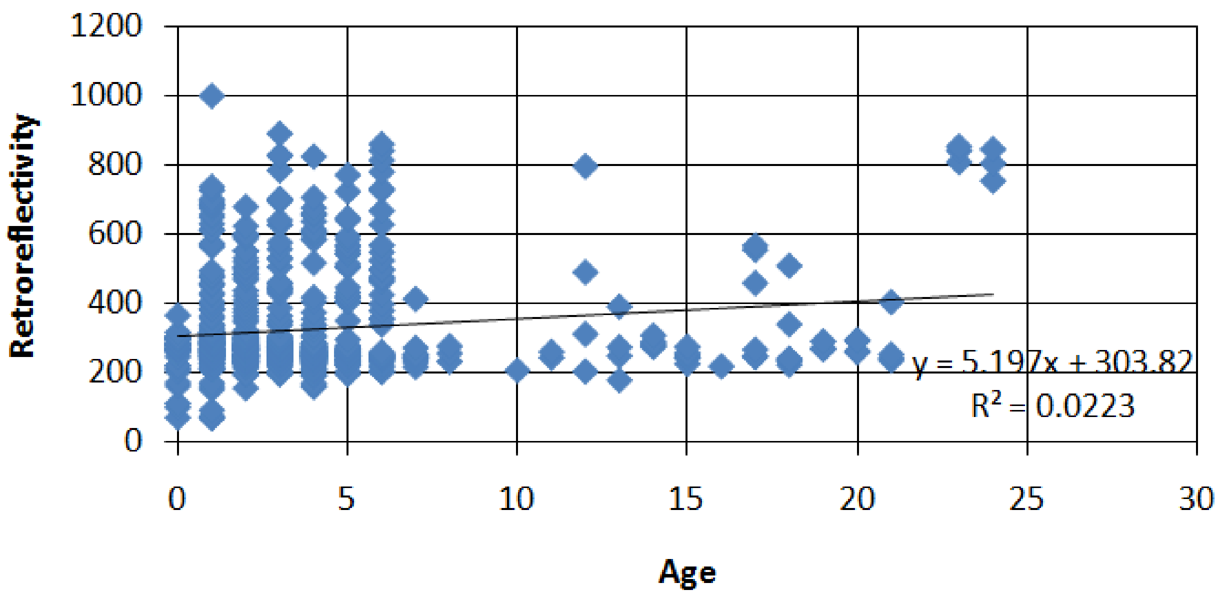


Figure A.12 White on Green Signs – White Color

By Inspection Year & Color Type/ Combinations

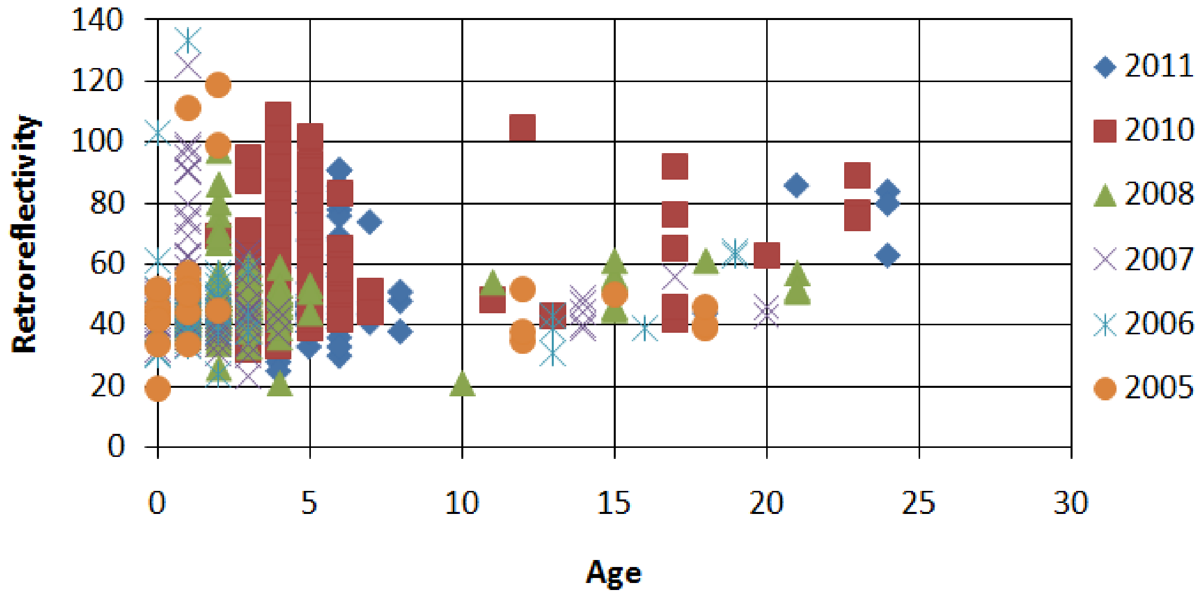


Figure A.13 White on Green Signs – Green Color

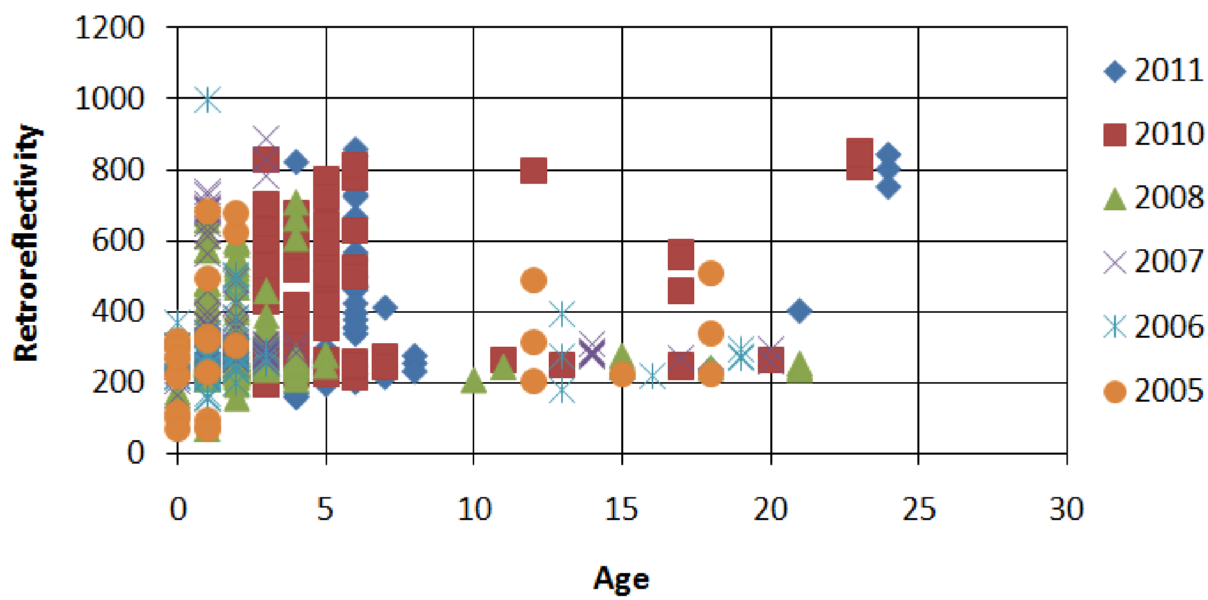


Figure A.14 White on Green Signs – White Color

2010 and 2011 Year Data Only

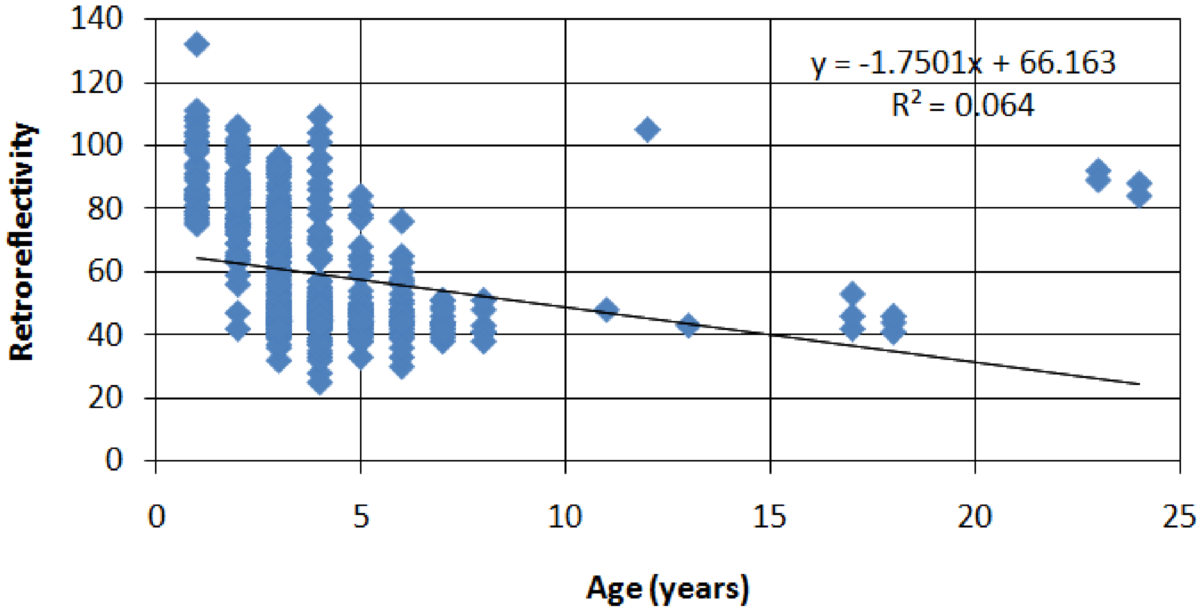


Figure A.15 Green Retroreflectivity

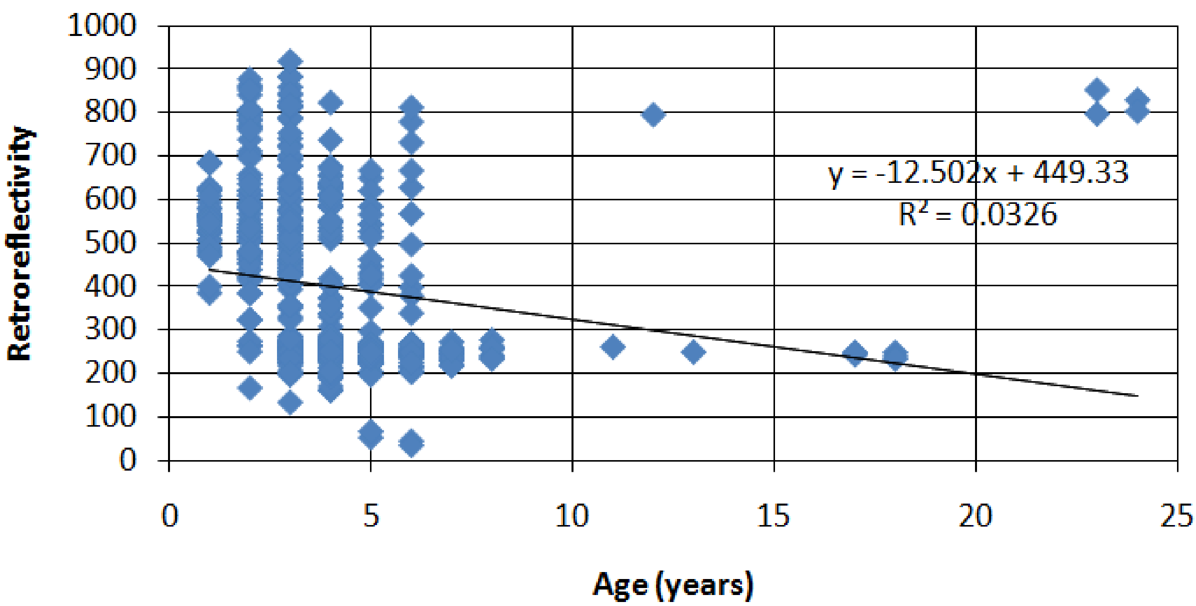


Figure A.16 Silver Retroreflectivity

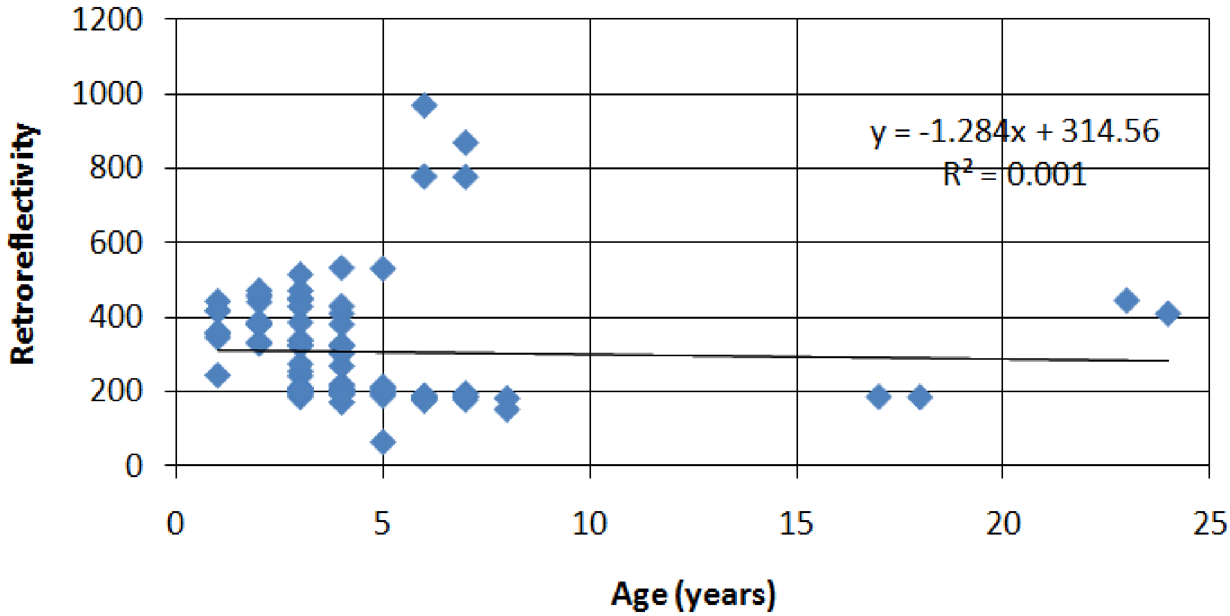


Figure A.17 Yellow Retroreflectivity

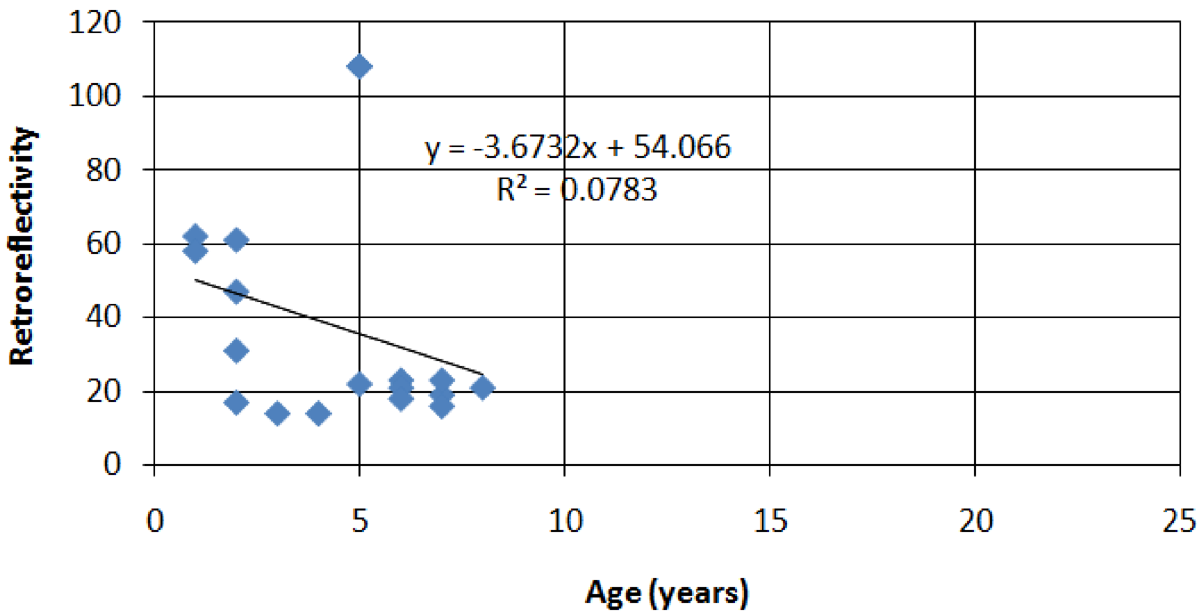


Figure A.18 Brown Retroreflectivity

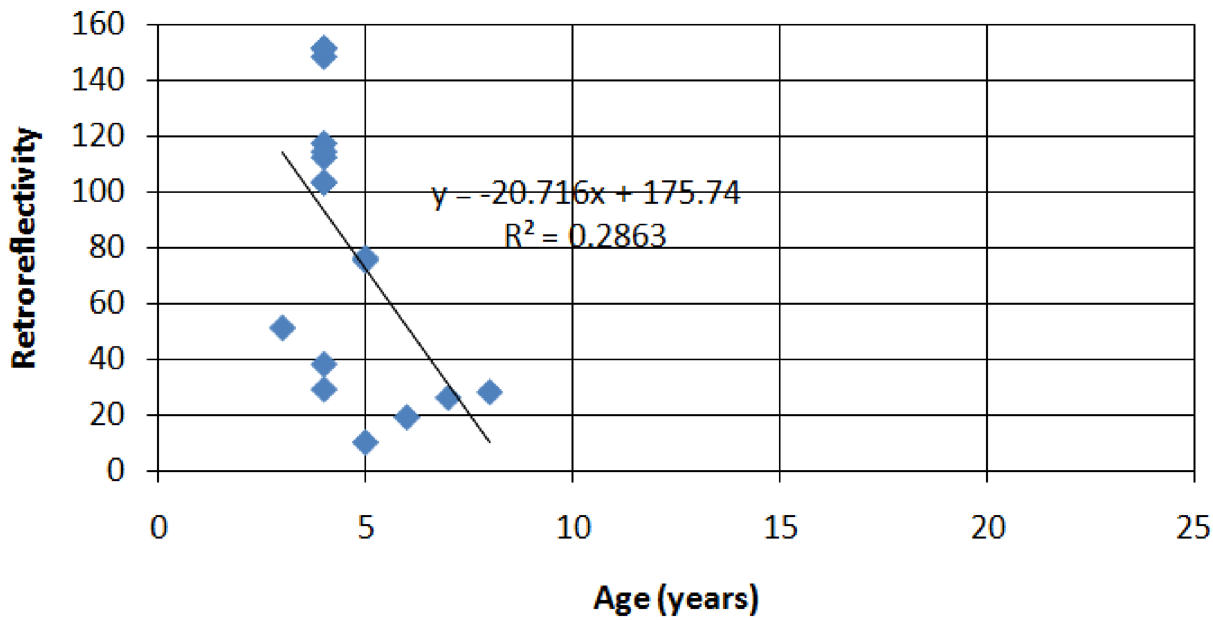


Figure A.19 Red Retroreflectivity

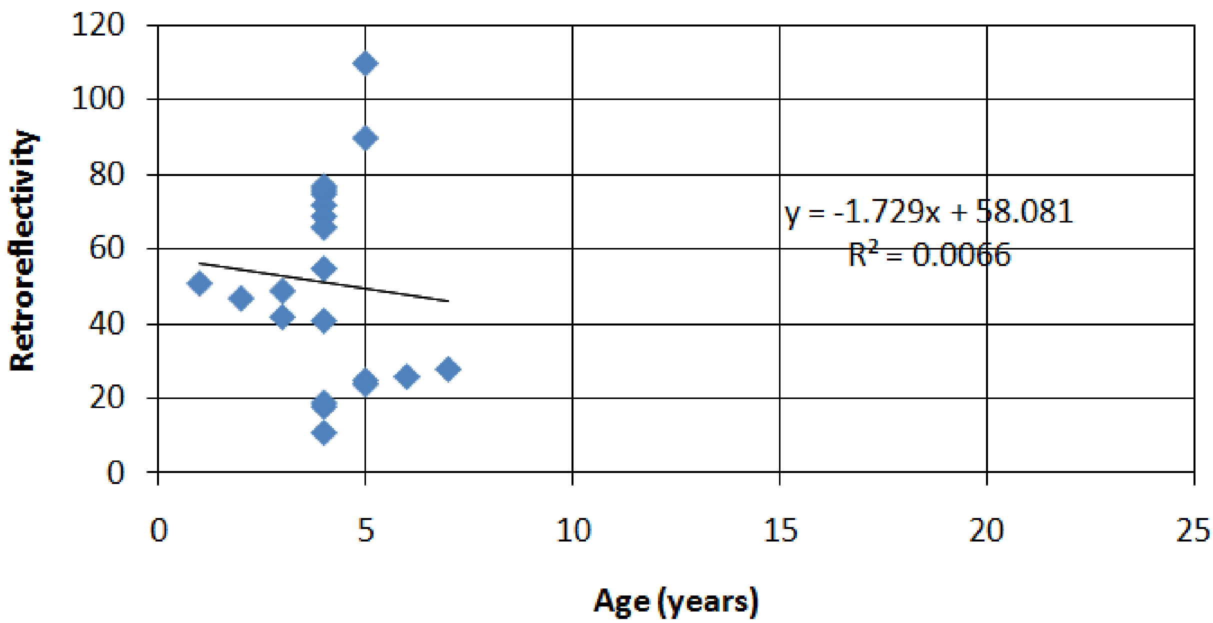


Figure A.20 Blue Retroreflectivity

By Change of Retroreflectivity (2010 and 2011 data only)

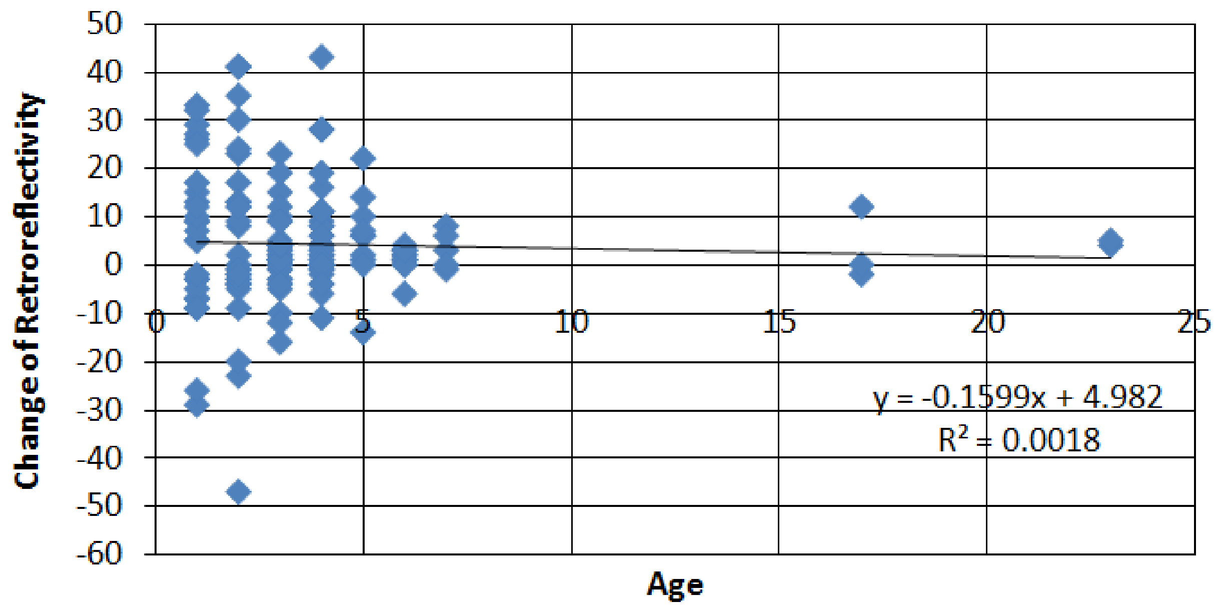


Figure A.21 Change of Green Retroreflectivity

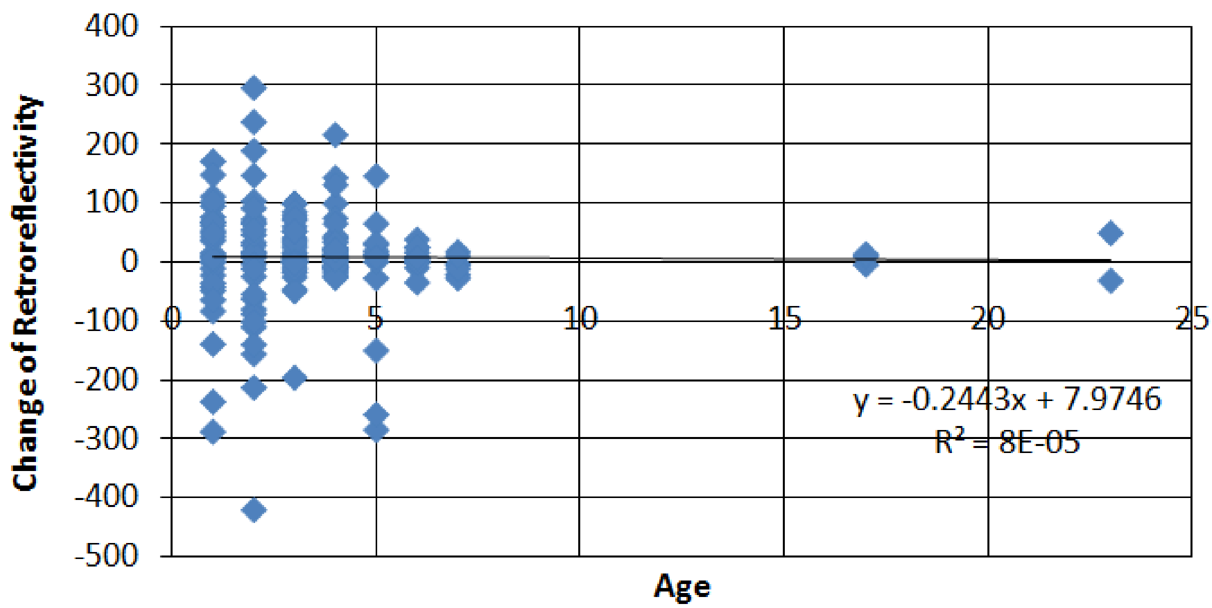


Figure A.22 Change of White Retroreflectivity

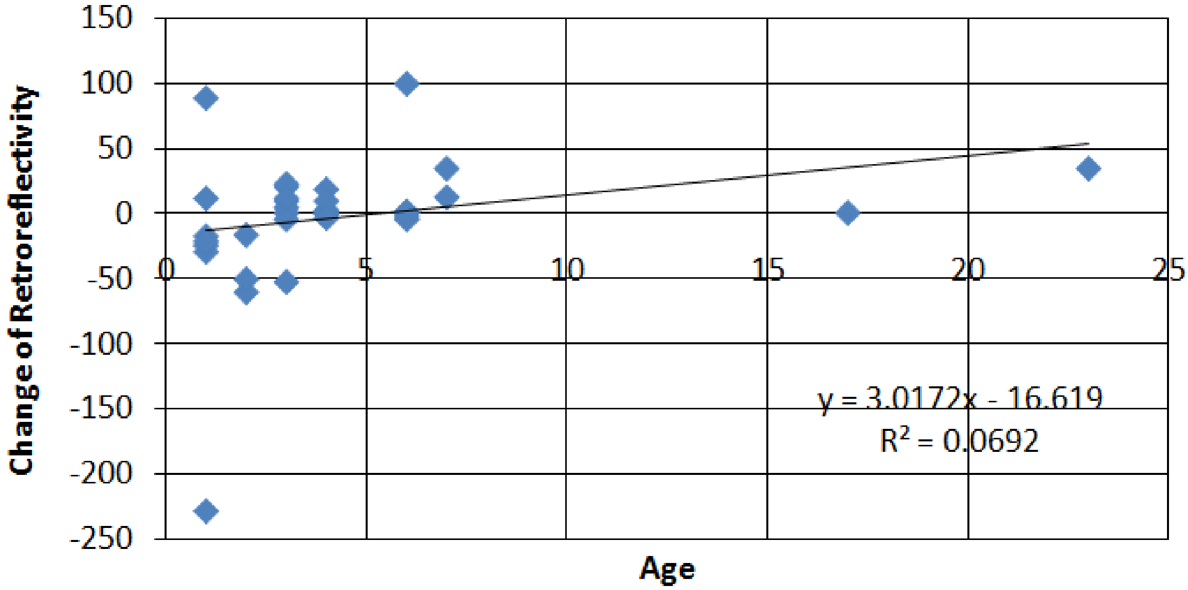


Figure A.23 Change of Yellow Retroreflectivity

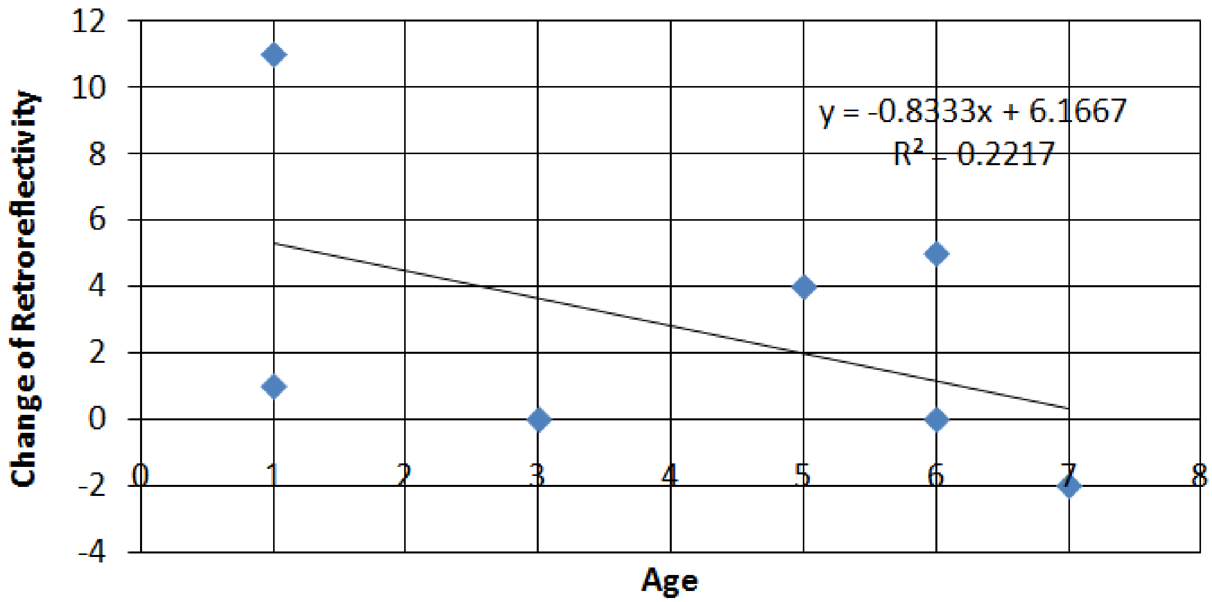


Figure A.24 Change of Brown Retroreflectivity

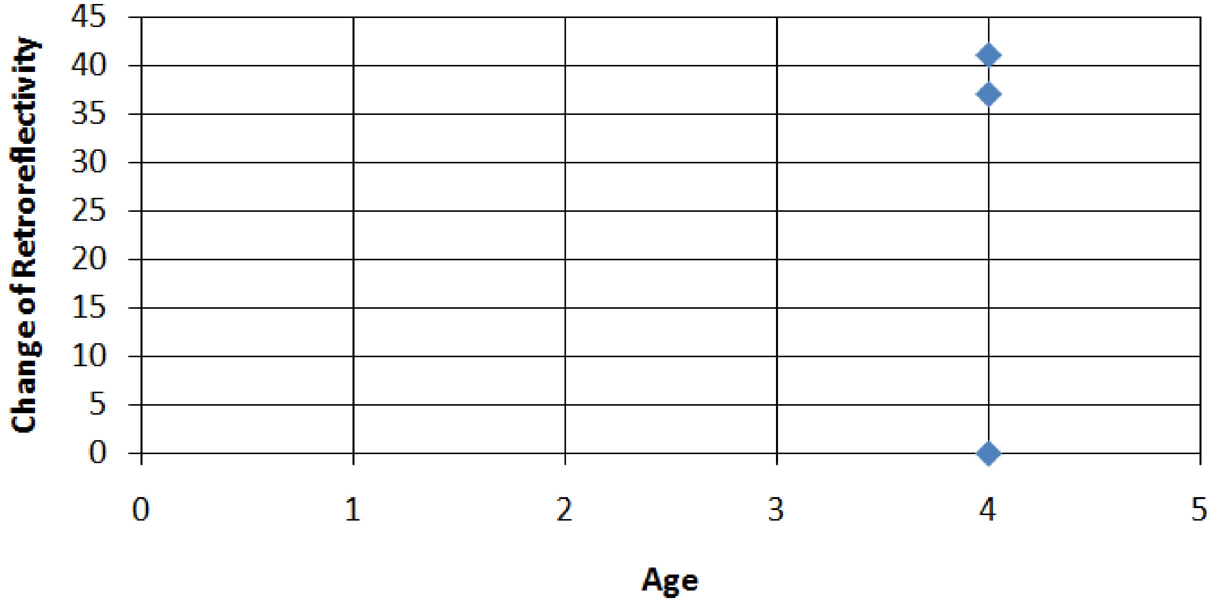


Figure A.25 Change of Red Retroreflectivity

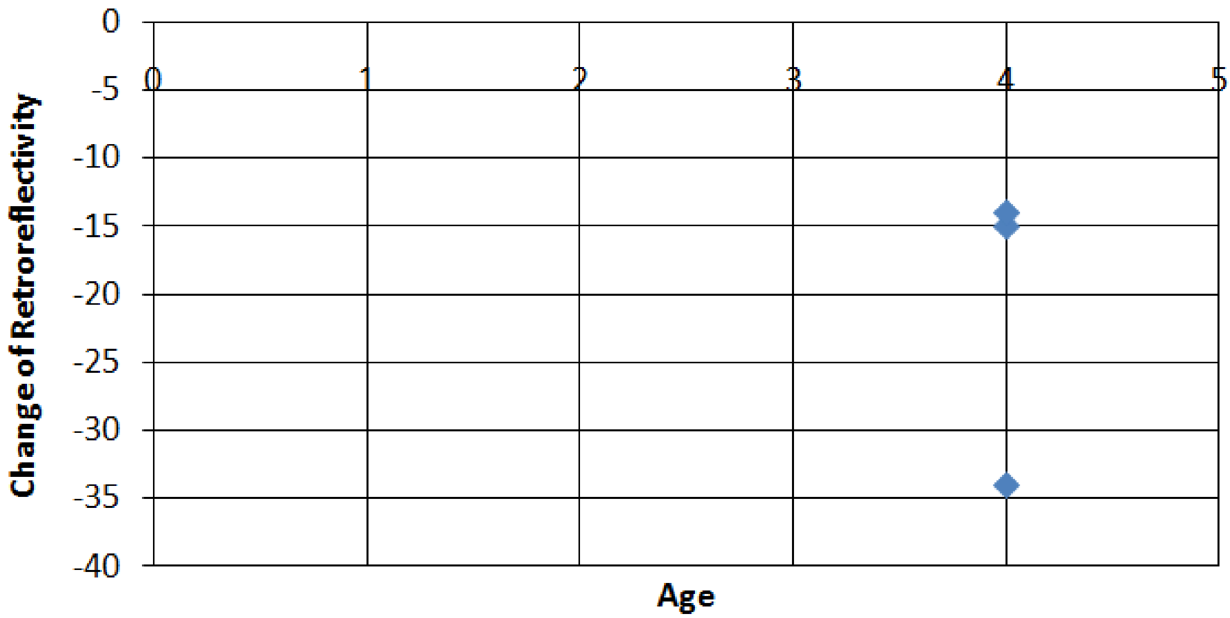


Figure A.26 Change of Blue Retroreflectivity

Appendix B AssetManagerNT User's Guide

AssetManagerNT Basics

AssetManagerNT brings together analysis results from the existing management systems in an agency, and adds value by providing a quick-response "what-if" analysis tool for testing different investment options.

External Management Systems

AssetManagerNT relies on output produced by other asset management systems, must have the capability to (a) simulate an annual program of work based on different budget levels, and (b) produce output that indicates the cost and impacts of the work. In other words, each external system is used to produce a collection of forecasts at a variety of different budget levels.

Asset Type

AssetManagerNT can work with between one and four different types of Assets (e.g., pavement, structures, guardrails, etc.). For each asset type you choose to use, your agency must have an external system to predict the system-level performance associated with different expenditure levels for a multi-year period.

Performance Measure

You use AssetManagerNT to define up to 40 performance measures. Most performance measures are derived from a set of indicators that are generated by the external systems. These indicators are measures of the impact over time of expenditures on a single type of asset. You may define performance measures that are identical to the available indicators. You can also define performance measures that are derived by combining these indicators using a variety of methods.

Partitioning the System

AssetManagerNT allows you to partition the system into up to 20 mutually exclusive geographic categories and up to 10 mutually exclusive network categories. The same set of geographic and network categories must be available for each type of asset to be analyzed in the system. Thus, the external systems must be capable of summarizing expenditures and performance results for each possible system subset. Only one level of hierarchy may be defined.

Time Horizon

AssetManagerNT accepts up to 20 planning periods (typically years) of input data from external systems, who must provide data for a minimum of two planning periods. The length of the planning period must be the same for each of the external systems you use. Multiple-year planning periods are acceptable as long as all simulations use the same length.

Weighting Metrics

When you break the transportation system down into geographic or network categories, you need weighting metrics to indicate the relative size of each category for calculating weighted averages of performance indicators. For example, you might define a weighting metric call “Lane-Miles of Pavement” which indicates the total amount of pavement in each DOT district.

Scenarios

A scenario is defined by a set of asset types, network categories, geographic categories, performance indicators and measures, weighting metrics, and a collection of input files that contain the results produced by the external systems. When you use AssetManagerNT to run a scenario, you produce a file containing scenario results. This file is used by AssetManagerNT to produce graphical output and support a number of interactive budget analysis capabilities.

For each asset type, you must prepare a series of simulations that reflect different budget levels, as described here:

- The first simulation should represent either an unlimited budget, or at least two to three times the highest feasible budget level that your agency would expect to spend. The objective is to set a total system budget level that is sufficiently high so that the resulting level of expenditure recommended within each subset of the network will provide a reasonable upper bound for purposes of tradeoff analysis.
- The second simulation should represent the “do nothing” or “do minimal work” option.
- For each management system, set up and run up to eight additional simulations with budget limits in between the previous two. There must be between two and ten simulation runs per asset type, representing different budget levels. Each asset type must have the same number of runs.

Every simulation run (across all asset types) must have an identical set of network and geographic categories, the same length planning period, and a common time horizon. Runs for a given asset type must report information for the same set of indicators.

Budget Analysis

AssetManagerNT provides four views that let you examine the impacts of budget levels and resource allocation decisions on the performance of the transportation system.

- The Budgeting view lets you visualize the effect of up to six different budget levels on the resulting value of a single performance measure.
- The Targeting View lets you specify a target value for a performance measure, and then determines the budget that is required to meet the selected target.
- The Dashboard view lets you adjust an overall system's annual budget interactively as it dynamically indicates the effect of the budget on up to twelve different performance measures.
- The Allocation view lets you interactively set resource allocations for different assets and/or parts of your network and view the impacts over time on up to six performance measures at once.

Preparing scenario files

To run a scenario analysis, AssetManagerNT requires the following files:

- Scenario input file
- Weighting metrics file
- Configuration file

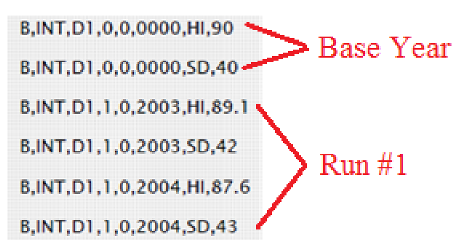
Scenario input file

AssetManagerNT requires a separate Scenario Input File (SIF) for each asset. Each file must contain the results of a series of simulation runs, plus some additional information to link these results with the configuration settings in AssetManagerNT.

The Scenario Input File (SIF) is a comma-delimited text file, containing a series of identically-structured lines of data. Each line (or record) in the file represents a particular stratification cell – that is, a particular combination of asset type, network category, geographic category, simulation run number, and year. Each record consists of the following items:

- Asset type label (string), e.g., “B” for bridges or “P” for pavements.
- Network category label (string), e.g., “INT” for Interstates.
- Geographic category label (string), e.g., “South,” “Central.”
- Run ID (string) identifying the simulation from which the results were obtained, e.g., “1” or “00.”
- Investment level in $1,000,000s (float); e.g., 0, 3.75.
- Planning period as a calendar year (string), e.g., “2008.”
- Indicator label (string), e.g., “PCI,” or “SD.”
- Indicator value (float); e.g., 95.0.

Following shows a sample input file:



As an option, several indicators and values can be included on a single line of the input file, as shown in Example 2:

```
B,INT,D1,0,0,0000,HI,90,SD,40
B,INT,D1,1,0,2003,HI,89.1,SD,42
B,INT,D1,1,0,2004,HI,87.6,SD,43
```

When preparing the input file, special attention should be paid on the following:

- Text labels are restricted to 8 characters in length.
- The Investment Level represents the dollar amount actually "spent" in this stratification cell during a particular planning period, not the budget constraint value that may have governed the scenario run.
- If the planning period is multiple years in length, you should use a consistent convention for identifying each period, e.g., the first or the last calendar year of the period.
- If the file includes a base year value of an indicator, the planning period should be labeled as "0000."
- AssetManagerNT requires using annual average budget for the entire planning horizon in the input files. If you analyze each asset by funding period, remember to use annual average budget instead of average budget among funding periods.
- It is interesting to find that at the end of input files, an empty row should be presented. Otherwise the software crashes and a warning massage pops out "you have inconsistent number of input parameters".

Weighting Metrics File

If you segment your transportation system into geographic or network categories, AssetManagerNT requires certain information on the makeup of these categories in order to compute aggregate results for the system as a whole.

The weighting metrics file is a comma-delimited text file containing one line (or record) for each combination of a geographic category and a network category. Each record consists of the following items:

- Network category label (string), e.g., “ON” for On-NHS, “OFF” for Off-NHS.
- Geographic category label (string), e.g., “1,” “South,” or “District 2.”
- One or more pairs of weighting metric IDs and values, in the form “MetricID=nn,” where the values can be expressed as a number or a percentage.

The following sample file includes three weighting metrics: Length, Area, and Bridge_Count:

```
Example:
ON, D1, LENGTH=1000, AREA=4000, BRIDGE_COUNT=50
ON, D2, LENGTH=900, AREA=600, BRIDGE_COUNT=52
OFF, D1, LENGTH=100, AREA=400, BRIDGE_COUNT=5
```

If you are not segmenting your system into geographic or network categories, you still need to provide a weighting metrics file, with a single line:

```
Example:
ALL, ALL, LENGTH=100, AREA=100, BRIDGE_COUNT=100
```

Configuration File

Once you have executed your simulation runs and prepared your input files (see Chapter 4), you need to set up AssetManagerNT to import and utilize these results. To accomplish this, you need to tell AssetManagerNT how to read and interpret the asset types, geographic and network categories, indicators, and weighting metrics it finds in these files. In addition, you need to create one or more Performance Measures, which are the primary metrics used by AssetManagerNT to evaluate transportation system performance.

Following is an example file for the DelDOT asset management project, as shown in Figure B.1.

- You can use up to four different **types of assets** with AssetManagerNT. For each one, you need to identify the text label you used to identify that asset type in preparing your input files, and assign it a longer name that will be used for all AssetManagerNT reports.
- If you utilize system subsets as defined by **geographic or network categories**, then you have prepared a weighting metric file containing information for each combination of geographic and network category. In this section, you tell AssetManagerNT how to interpret the weighting metric labels in this file.
- **Indicators** are derived from external management systems and will be used to create and define performance measures. Some management systems produce a series of related indicators for a particular variable (e.g., there might be four indicators that identify the percent of pavement in excellent, good, fair, and poor condition.) You must create four separate performance measures in order to capture these results in AssetManagerNT.
- Based on the indicators, you can derive a **performance measure** in different ways:

- Based on a single indicator from an individual management system (e.g. average pavement condition) – weighted averages can be calculated using available system metrics (e.g. lane miles, centerline miles)
- Based on a combination of indicators from different management systems (e.g. backlog of bridge work + backlog of pavement work)
- By combining other performance measures (e.g. Lane Miles of Pavement Work = Lane Miles of Rehabilitation + Lane Miles of Resurfacing)

When configure the set up file, you need to pay attention to the following:

- When you combine indicators to produce a single performance measure, you must verify that the calculation of these measures is consistent across the different management systems.
- Each performance measure is tied to one or more indicators. If you delete indicators to which these performance measures are assigned, they will become invalid, as indicated by a red warning message on the Configuration window.
- The DelDOT's asset management project only include one geography and network category, and the performance measures are based on (actually the same as) the indicators. However, the software requires users to use "weighting average" (under the drop down of the "Function" tab) instead of "average". If "average" function is used, the software crashes.

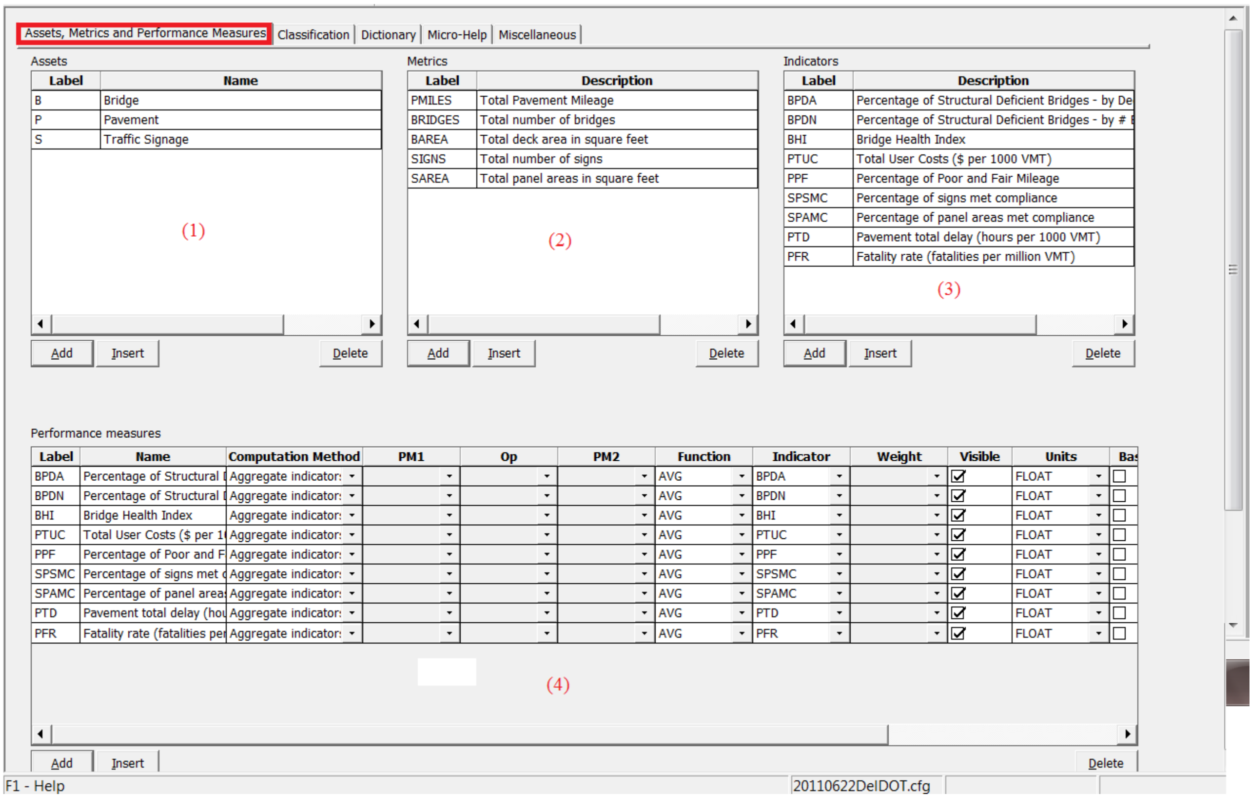


Figure B.1 Configuration Set Up

In the configuration file, you also need to define geography and network categories. up to twenty geographic categories and ten network categories can be defined in AssetManagerNT. For each one, you need to identify the text label you used to identify that category in your input files, and assign it a longer name that will be used for all AssetManagerNT reports.

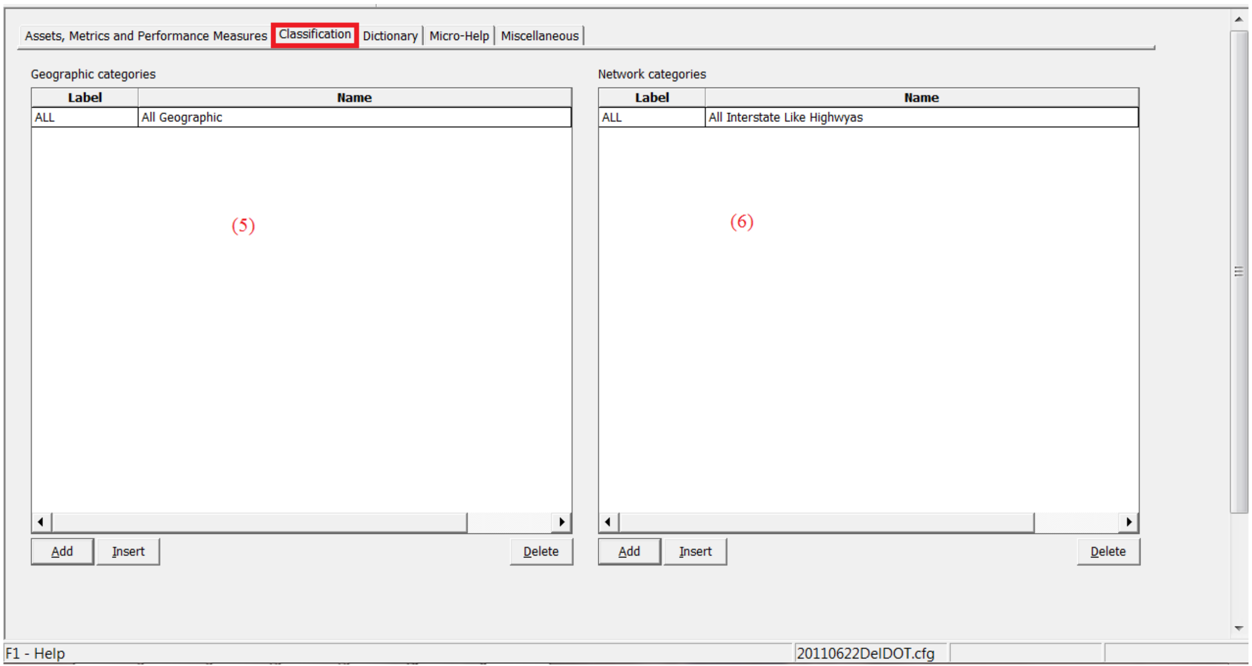


Figure B.2 Configuration Set Up (Continue)

AssetManagerNT Analysis

Create Scenarios

You create a scenario by selecting one or more categories of assets, identifying the input file that contains results for each asset from the appropriate external management system, and identifying the years of interest to be extracted from these external files.

Click the "Create and run a new scenario" tab (Figure B.3) and the software requires the analysis name, inputs of configuration file, weighting metrics file, and the scenario input files for the assets (Figure B.4).

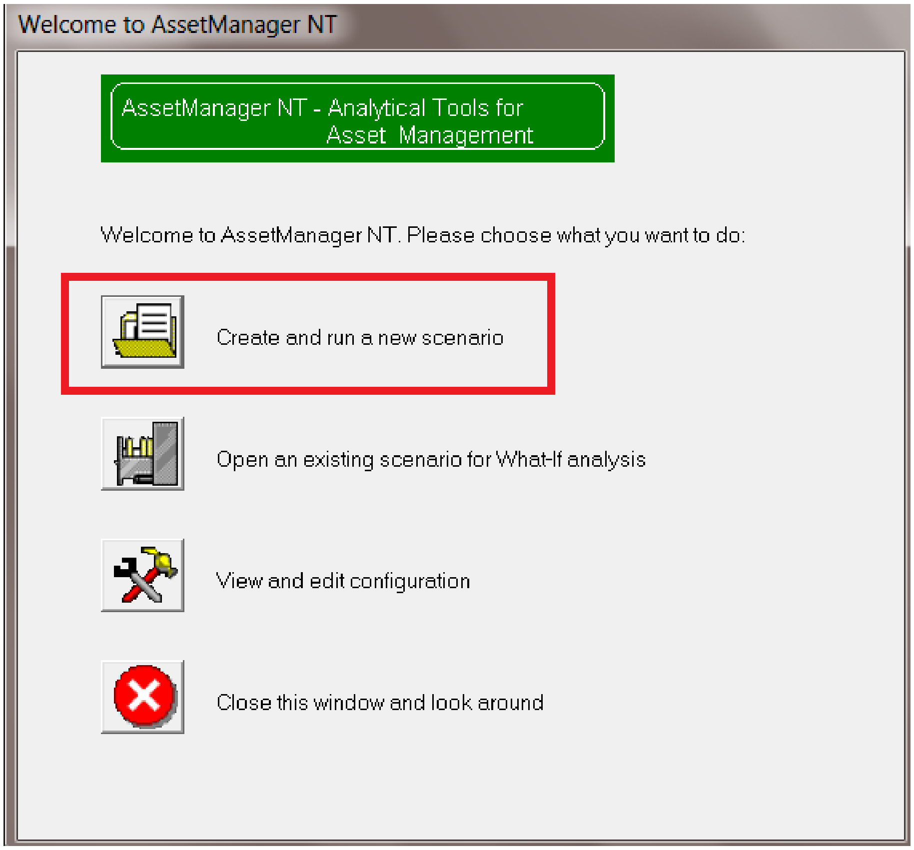


Figure B.3 Create New Scenario

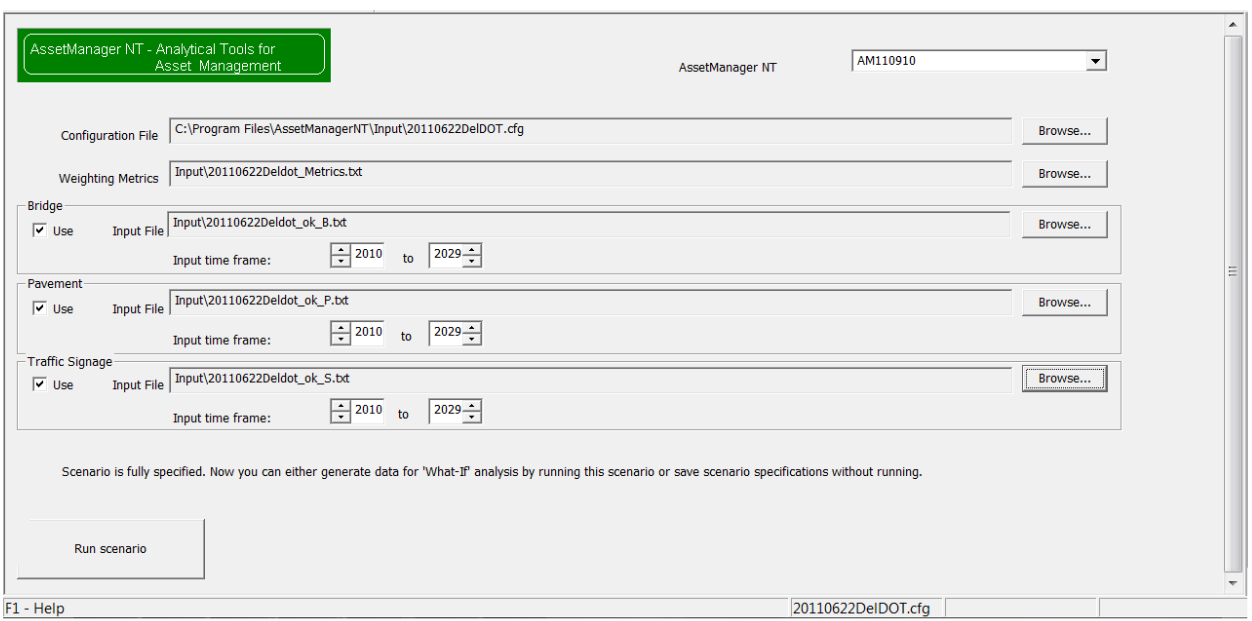
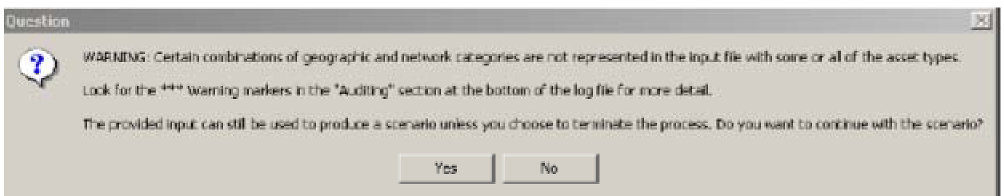


Figure B.4 Create New Scenario (Continue)

You may see a warning screen indicating that there are no input values for some combination(s) of a geographic category and network category for an asset. This can occur for example, if the asset doesn't exist for that combination (e.g. no bridges in district A on the NHS). The combinations which are missing data will be listed in the scenario's log file (open the log file and search for "***Warning"). You may want to check the log file to verify that these data holes occur where you expect. However, the warning will not prevent the system from performing what-if analysis. Click Yes to continue.



What-if analysis

AssetManagerNT provides four different kinds of what-if analyses:

- Budgeting
- Targeting
- Dashboard
- Resources Allocation

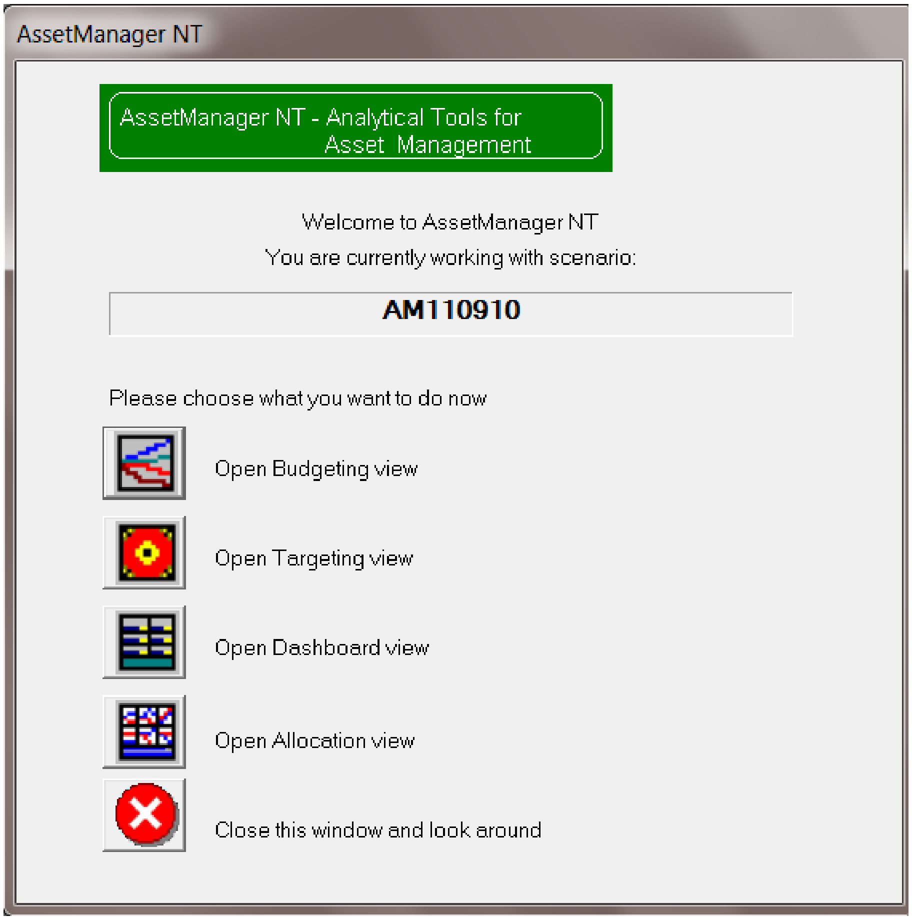


Figure B.5 Budget Analysis

On the Budget Analysis window (Figure B.5), click on the “Open Budgeting View” tab, a window as shown in Figure B.6 pops up and you need to set up the asset type, analysis year, performance measures, etc. You can also set up the components to shown in the Budget view by identifying the budget level, figure line color and style (Figure B.7). There is a auto fill tab that the software can automatically fill out the budget level based on your input. Click “OK” and the beget view is shown in Figure B.8.

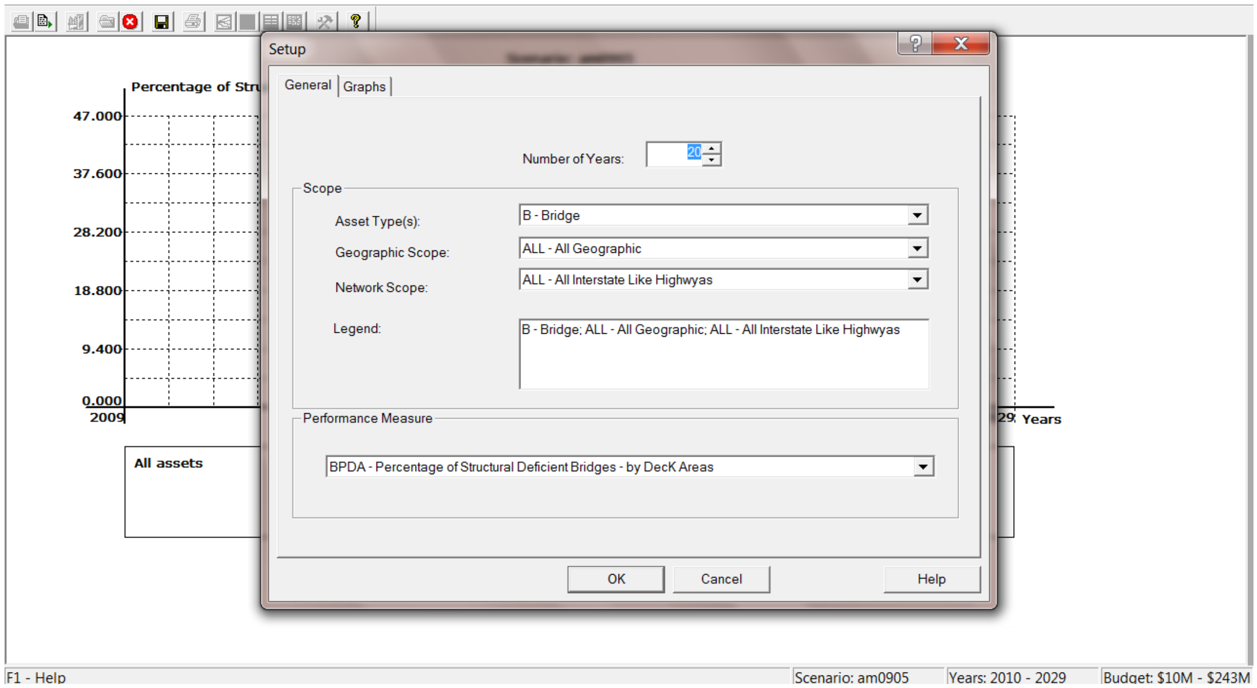


Figure B.6 Budget View

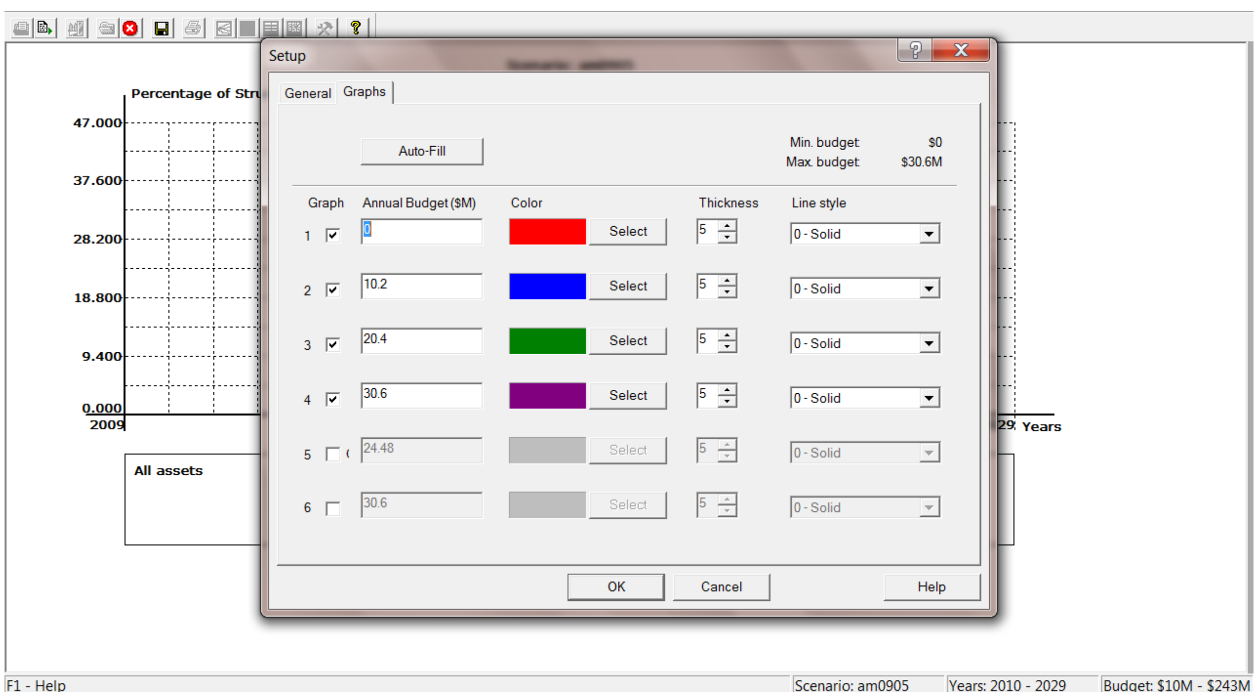


Figure B.7 Budget View (Continues)

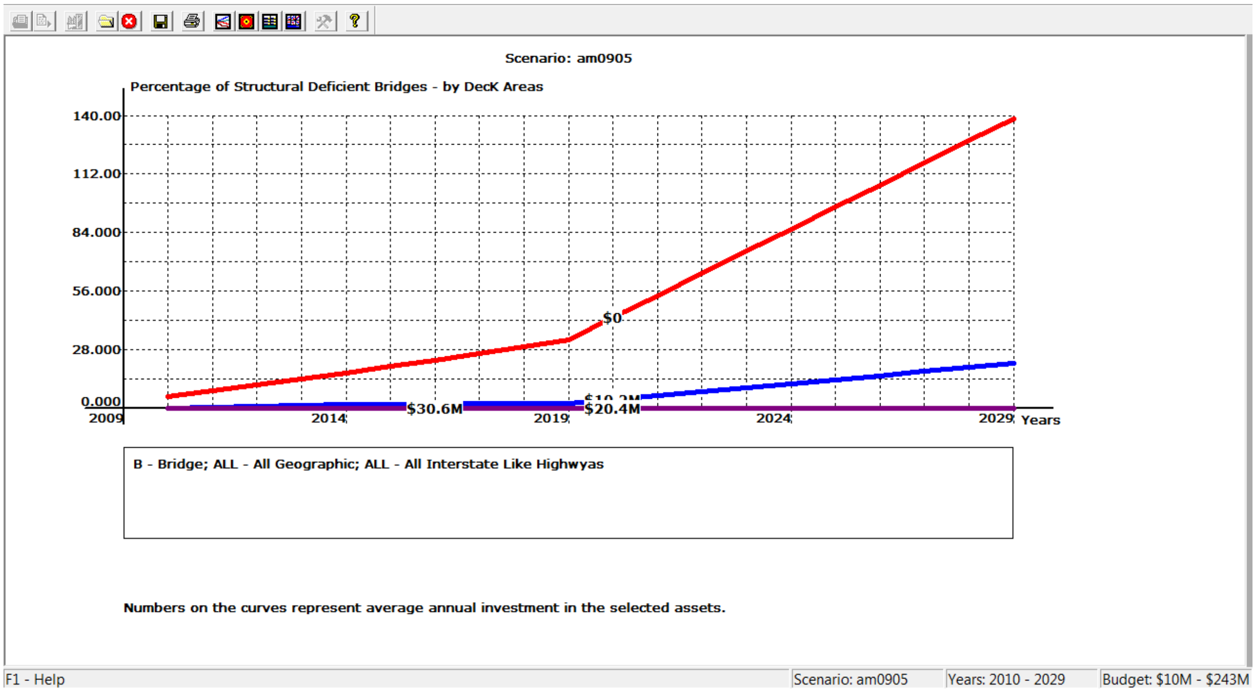


Figure B.8 Budget View (Continues)

The Targeting View lets you specify a target value for a performance measure, and then determines the budget that is required to meet the selected target. Using of this functionality is very straightforward and not discussed here.

The Dashboard view lets you adjust an overall system's annual budget interactively as it dynamically indicates the effect of the budget on up to twelve different performance measures. In this view, users need to set up the performance measures that would show in the Dashboard view (Figure B.9), and the resources allocation among the asset type in percentage (Figure B.10).

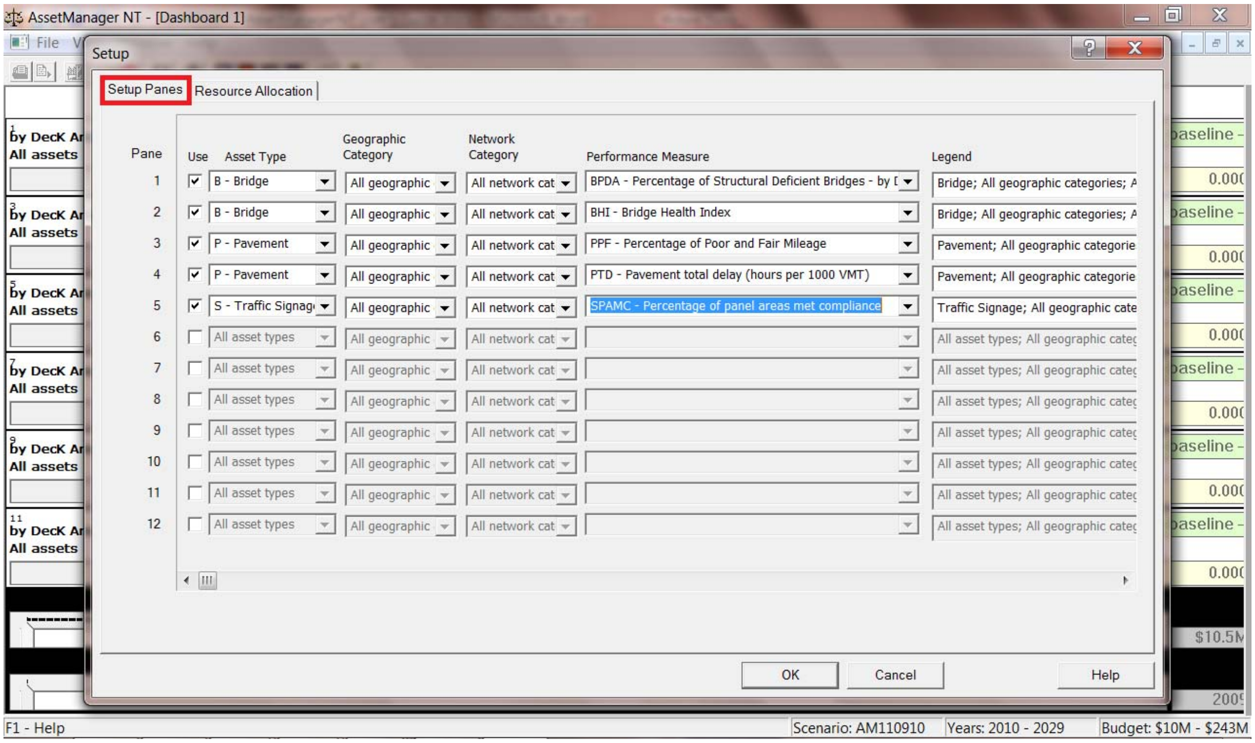


Figure B.9 Dashboard View

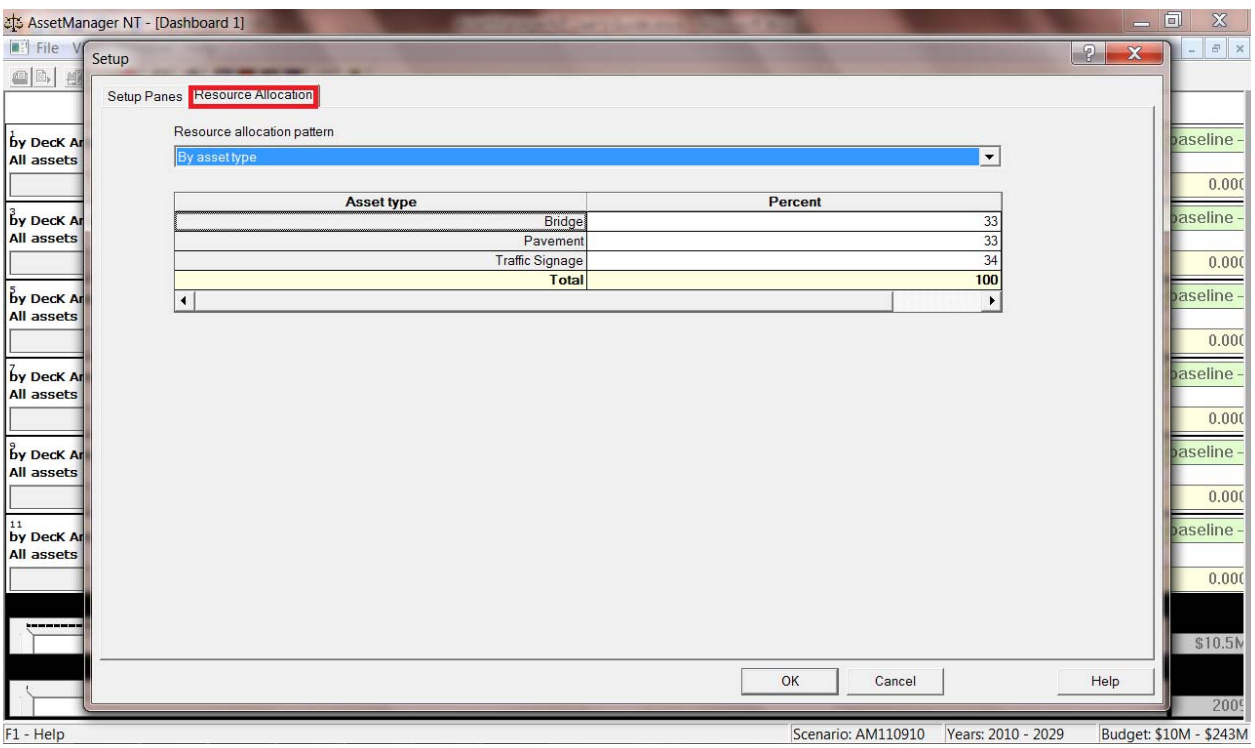


Figure B.10 Dashboard View (Continues)

In the Dashboard View, users can change the budget level and analysis year by dragging the bars at the bottom of the screen, and the values for performance measures change dynamically (Figure B.11).

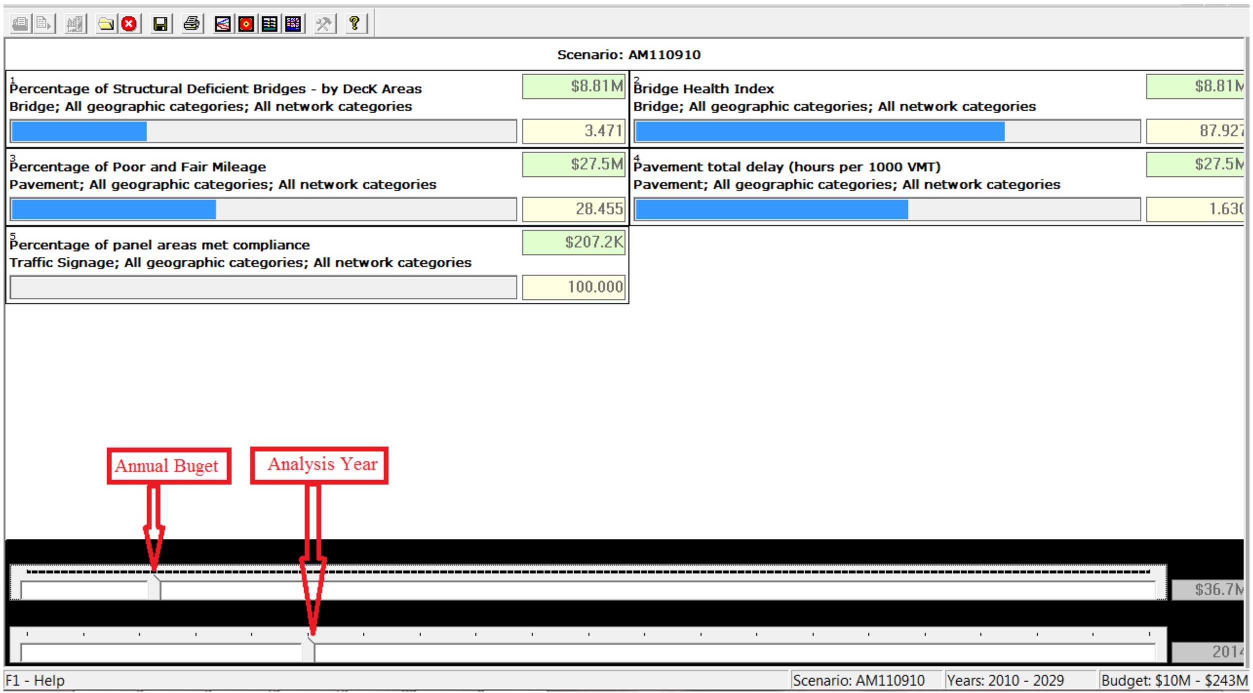


Figure B.11 Dashboard View (Continues)

The Allocation view lets you interactively set resource allocations for different assets and/or parts of your network and view the impacts over time on up to six performance measures at once. Same as the Dashboard view, users need to specify the performance measures to shown on the view.

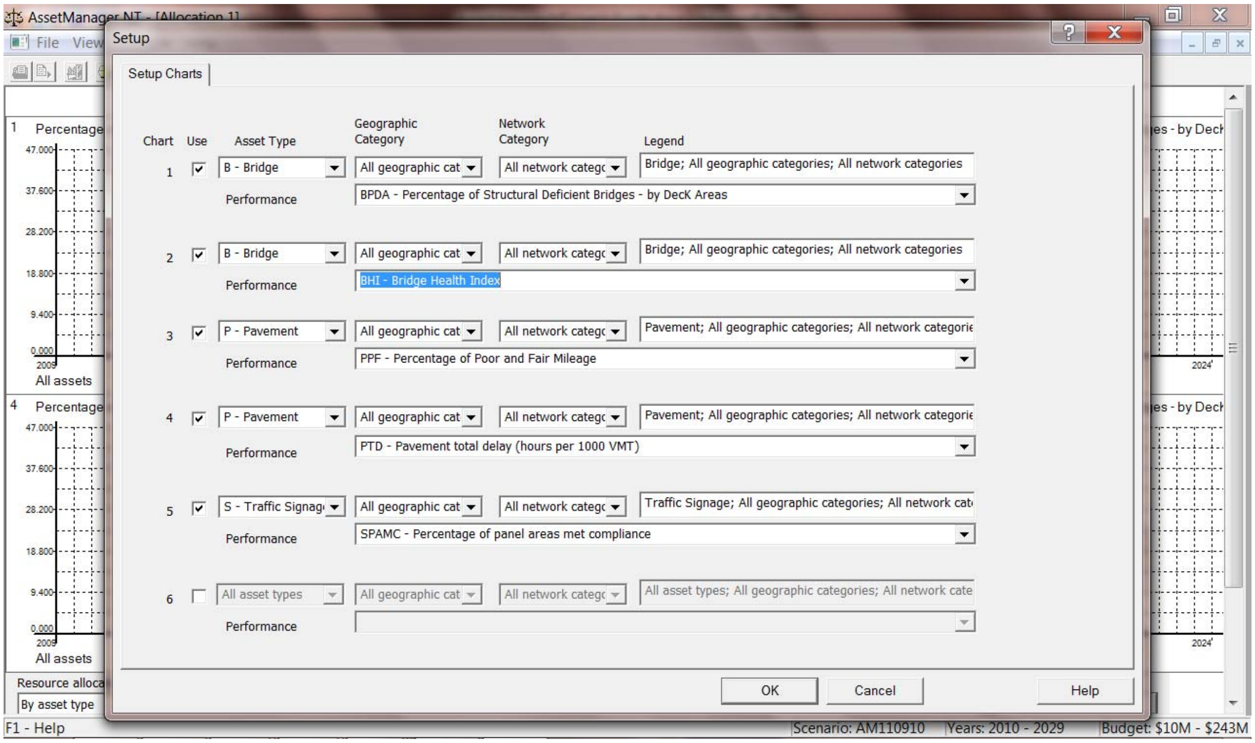


Figure B.12 Resources Allocation View

The AssetManagerNT software automatically generates four resources allocation patterns equally distributed among the budget range for each assets and plots on the performance measure curves. Users can change the resources allocation patterns to reflect the real word practices and explore the output for decision making in their agencies.

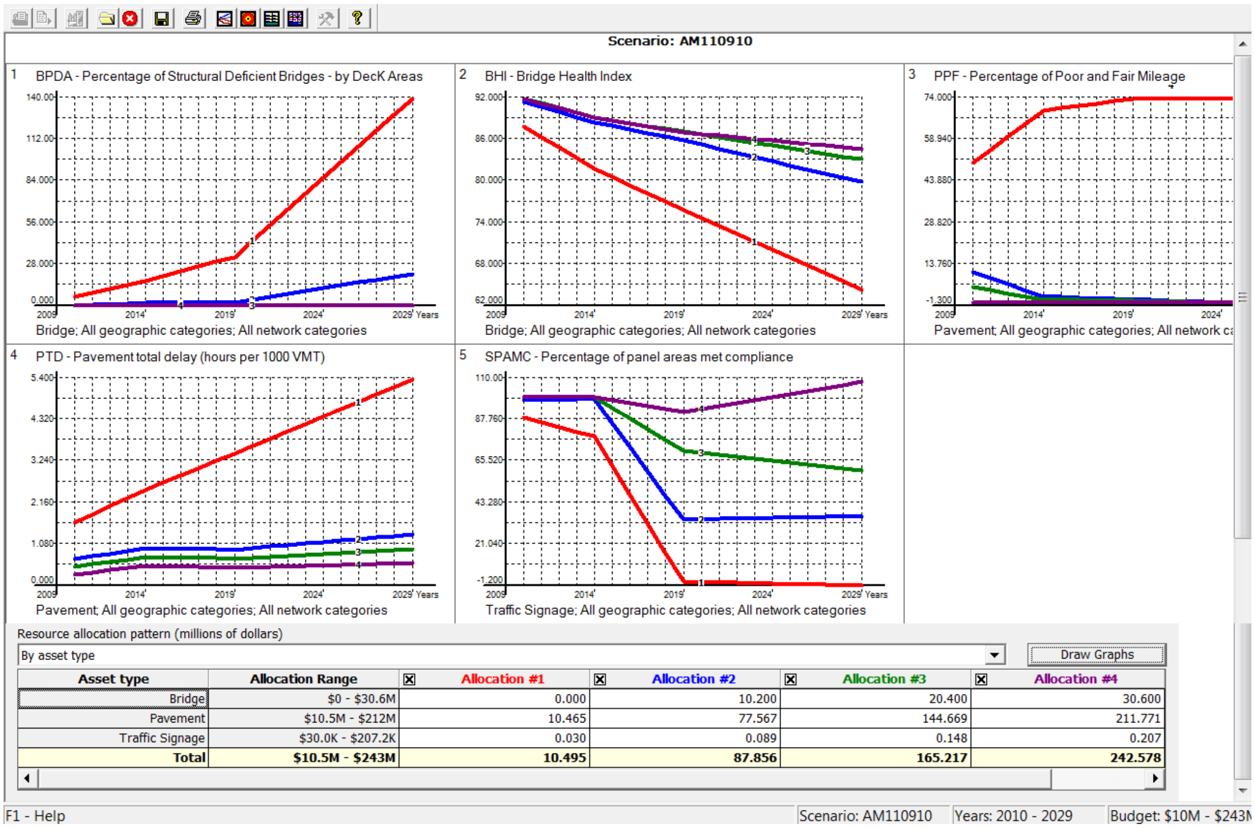


Figure B.13 Resources Allocation View (Continues)

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The Delaware Center for Transportation is a university-wide multi-disciplinary research unit reporting to the Chair of the Department of Civil and Environmental Engineering, and is co-sponsored by the University of Delaware and the Delaware Department of Transportation.

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