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Integrated Planning and Budget Allocation for Highway Maintenance, Rehabilitation, and Capital Construction Projects

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Integrated Planning and Budget Allocation for Highway Maintenance, Rehabilitation, and Capital Construction Projects

by

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Dedication

To my parents, Mr. John Frederick Mensah and Mrs. Angelina Mensah, and my sisters, Nana Ama and Nana Appiawah. Thank you for your love, patience, support, and understanding.

Acknowledgements

"If I have seen further than others, it is by standing upon the shoulders of giants"

- **Isaac Newton**

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Abstract

Integrated Planning and Budget Allocation for Highway Maintenance, Rehabilitation, and Capital Construction Projects

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Highway infrastructure is one of the critical components of the infrastructure network needed for the socio-economic development of a country. However, increased urbanization, limited funds, the need to consider sustainability continue to challenge the planning process for developing and maintaining highway infrastructure. Accordingly, decision-makers are tasked with making optimal decisions while achieving the strategic goals set by federal, state, district, and/or local highway agencies. Pivotal to making such resource allocation decisions, is the availability and accuracy of asset-related data and planning constraints which can guide data-driven decisions to be made by State Highway agencies (SHAs). Currently, several decision-makers still depend significantly on subjective engineering judgment to make decisions on funds allocation. Hence, there is a need for more formal and logical approaches to resource allocation as well as evaluation metrics for conducting alternatives analysis.

This notwithstanding, the development of multiple incompatible legacy systems and the presence of several funding categories with stringent project eligibility requirements underpins a "siloed" approach to planning for highway infrastructure. There

are often multiple functional groups working on the same asset network but with heterogeneous information systems and distinct decision-making practices. This "siloed" approach can create inefficiencies in projects selection and lead to inter-project conflicts in the highway projects proposed by these different functional groups. When left unaddressed, these spatial-temporal conflicts among projects can result in the misuse of limited taxpayer dollars and ultimately, a lower performance of the network.

To address these issues with budget allocation and integrated highway planning, this study contributes to the body of knowledge in three primary ways. First, the study provides a synthesized analysis of budget allocation methods and provides a comprehensive approach to evaluating the performance of different methods employed for M&R decision-making. Secondly, this study formulates and accounts for the impact of multiple funding categories and project eligibility restrictions in budget allocation models. The inclusion of this pragmatic characteristic of M&R decision-making demonstrates the inefficiencies that can result from having increasing restrictions on multiple funding categories. Thirdly, a shared ontology is developed to enable a dynamic link between planning information and projects information. The resulting formalized representation (ontology) was validated by using multiple approaches including automated consistency checking, task-based evaluation, and data-driven evaluation. An implementation tool was also developed and applied to an actual case study problem. The tool was validated by using a Charrette test and feedback from subject-matter experts.

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Chapter 1 Introduction

A key indicator of economic growth is a well-functioning transportation infrastructure system (Saha and Ksaibati 2015a). Transportation infrastructure plays a pivotal role in the economics and mobility of goods and human resources in modern society (Boyles et al. 2010). Over the last five decades, highway agencies have made huge investments in building new highway infrastructure throughout the United States. For some highway agencies, the focus has shifted from constructing new facilities to preserving the existing systems and assets (Chou 2009; Gao and Zhang 2008). Although the construction of new infrastructure tends to attract increased public scrutiny and is usually more disruptive to transportation services, the maintenance and operation of extant infrastructure often consumes more resources and occurs more frequently. Accordingly, maintenance activities can constitute as much as 60% to 70% of infrastructure budgets in countries with well-developed transportation infrastructure systems (Mild and Salo 2009a).

Highway infrastructure planners have the task of addressing mobility, safety, accessibility, and economic development issues for multi-modal corridors stretching thousands of miles with different functional classifications (Chen et al. 2015). This task is increasingly challenging due to limited funds availability coupled with the rapid deterioration of pavement infrastructure over time (Augeri et al. 2010; Ismail et al. 2009; Lamptey et al. 2008b). Urbanization also plays a pertinent role in the fast deterioration of infrastructure because it leads to increased pressure on highway facilities. Consequently, a major concern of highway agencies is the development of effective maintenance and rehabilitation (M&R) plans which account for the constraints of available funding as well as the differing objectives of relevant stakeholders (Gao and Zhang 2008). Due to the constrained availability of resources, highway agencies managing large-scale road networks can only execute pavement treatments on small sections of their network each year. Accordingly, it is important for pavement engineers to make the most cost-effective choices while achieving the best time efficiencies across the network and among project alternatives (Gao and Zhang 2013b).

There are several levels of decision-making in highway asset management. These include the strategic, network, and project levels of decision-making (Figure 1-1). Developing an effective policy for the maintenance of highway infrastructure requires the establishment of strategic goals and policies concerning the functional and structural performance of the network. These goals should take into account the available resources, sustainability considerations, and performance targets for the infrastructure network. Key to this process is the development of Pavement Management Systems (PMSs) to aid in pavement maintenance and rehabilitation decision-making tasks. PMSs typically contain information on roadway condition history, treatment history, traffic volume data like the Annual Average Daily Traffic (AADT), and many other pavement data (Woldesenbet et al. 2015). This information is useful for performance modeling, scenario analysis, and needs analysis at the network-level. PMSs help agency staff in making decisions concerning pavement sections which need interventions, the appropriate maintenance treatment option to apply, and the optimal scheduling periods (Shah et al. 2014).

At the network-level of decision-making (Figure 1-1), the problem can be divided into two main categories namely budget allocation and budget planning (Gao et al. 2012). A budget planning problem is a network-level analysis that attempts to minimize the total M&R cost over a specified planning horizon, such that a selected condition requirement is satisfied. This is usually done at a higher level in the decision-making process and leads to the proposal of a minimal budget required to meet specific state-wide agency goals. The budget allocation problem, on the other hand, attempts to maximize the effectiveness of M&R treatments and/or minimize the user cost, while accounting for specified budget constraints in the model (Gao et al. 2012). Accordingly, network-level decisions include the selection of projects prioritization criteria, an appropriate funds allocation approach, and the consideration of local factors which affect decision-making.

At the project level, decisions to be made include the choice to use in-house versus out-sourced contracts for projects, scheduling maintenance activities, coordination with other highway agencies, and other operational tasks. It is also important to develop measurable and consistent metrics for evaluating the proposed M&R treatments to benefit from lessons learned from previous implementation periods. With a growing gap between available funds and M&R needs, it is becoming increasingly important to develop defensible approaches for the optimal allocation of limited budgets for effective pavement M&R programming. In view of this, several approaches to projects prioritization and budget allocation for highway infrastructure management have been proposed in the extant literature. The literature provides numerous quantitative budget allocation models, and yet few SHAs have fully transitioned to using such models (Wu et al. 2012). Many highway agencies today continue to use a hybrid of engineering judgment, needs-based, and/or performance-based condition assessments to guide the allocation of highway funds to M&R projects (Wiegmann and Yelchuru 2012).

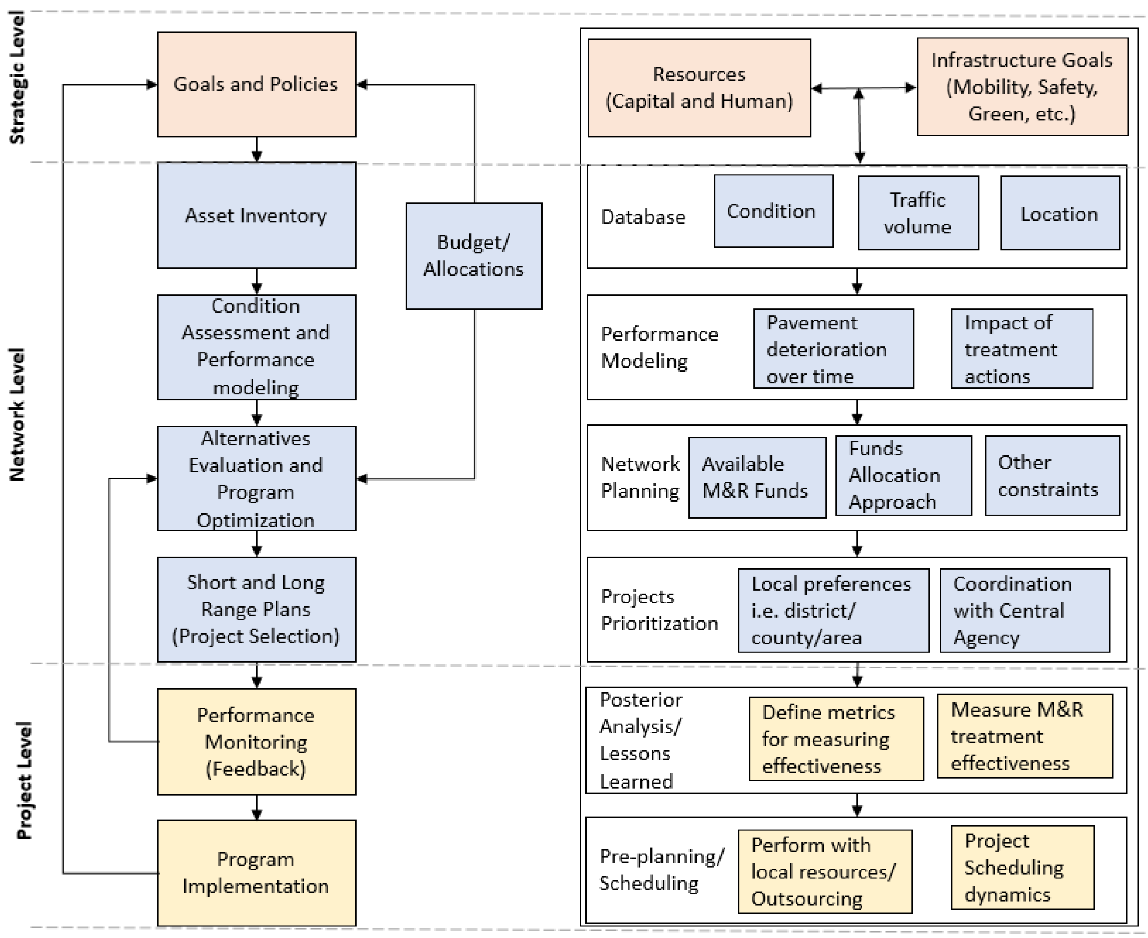


Figure 1-1. Conceptual representation of the asset management process (modified from Federal Highway Administration 1999).

For some highway agencies, there is still is no formal and consistent analytical approach towards the selection and funding of M&R projects at the network-level. Some of the reasons for the slow implementation of mathematical optimization techniques in pavement M&R decision-making is the lack of understanding of some complex methods, resistance to change, lack of quantitative evidence supporting the benefits of using novel techniques, and inadequate data to run proposed models. Addressing these some of these issues involves conducting evaluations of different budget allocation models and improving the pragmatic representation of the decision-making context for the proposed models in the literature.

Furthermore, it is also important to integrate the M&R programming process with the execution of other highway construction projects which are usually undertaken by different functional groups within the same highway agency. The cross-functional nature of highway planning means that different functional groups within the same agency will be proposing several highway projects scheduled to take place on the same highway network. However, there is heterogeneity in the information systems employed by these functional groups evidenced by fragmented databases and multiple incompatible legacy systems which lack interoperability and integration capabilities. Moreover, the information on highway projects often changes in response to variations in the funding anticipated, asset conditions, urbanization trends, and a host of other factors which may affect the scheduled projects by SHAs. The problem with this aspect of the challenge is two-fold. First, multiple functional groups working on the same asset can lead to spatial-temporal conflicts in projects scheduled for the same pavement sections. Secondly, unanticipated changes in the aforementioned factors require a re-assessment of the priority list of projects in consonance with the strategic goals of the agency. Thus, there is an interplay between the planning knowledge required for projects selection and the projects coordination process itself. These can be addressed by exploring formalized representations that standardize planning knowledge and projects coordination knowledge in an integrated manner.

1.1 READER'S GUIDE

This dissertation addresses issues with the selection and coordination of highway projects proposed by different functional groups working on the same asset network. Accordingly, this research study collectively aims to conduct a comparative analysis of budget allocation models, assess the impact of M&R budgetary restrictions, and develop an approach towards the integrated planning of highway projects. The rest of this report is organized as follows. Chapter 2 provides an extensive review of pavement management practices and the extant challenges with M&R planning. This is followed by a motivating case study involving the decision making process of a metropolitan district of the Texas Department of Transportation (TxDOT). Findings from this case study underpin the three main objectives that were explored in this dissertation. Most of the contents of this chapter were extracted from the publication: **France-Mensah, J., O'Brien, W. J., Khwaja, N., and Bussell, L. C. (2017a). "GIS-based visualization of integrated highway maintenance and construction planning: a case study of Fort Worth, Texas." Visualization in Engineering, 5(1), 7.** The research objectives presented in Chapter 4 were then presented based on key issues identified from the case study on maintenance and capital construction projects planning. For each objective, an in-depth presentation of the methodology, major findings and their intellectual contributions to the body of knowledge and practice are then presented. Thus, Chapter 5 presents a detailed comparative analysis of different budget allocation models and how to evaluate candidate M&R programs based on effectiveness, equity, and the strategic goal of the decision-making agency. Contents from this chapter were reprinted from the publication: **France-Mensah, J., and O'Brien, W. J. (2018). "Budget Allocation Models for Pavement Maintenance and Rehabilitation: Comparative Case Study." Journal of Management in Engineering, 34(2), 05018002.** Based on the thorough review and evaluation of different budget allocation models, Chapter 6 explores the impact of accounting for multiple funding categories and project eligibility restrictions on pavement performance. This chapter demonstrates how certain policies associated with the "siloed" budgets in highway planning can actually lead to a lower performance of the network. Most of the contents in this chapter is a reprint from the accepted publication: **France-Mensah, J., O'Brien, W. J., Khwaja, N. (2019) "Impact of multiple highway funding categories and project eligibility restrictions on pavement performance" Journal of Infrastructure Systems, 25(1), 04018037.** Following this chapter, Chapter 7 presents on the development of a shared ontology for supporting the integrated planning of highway projects. The content of this section in the manuscript is currently under review at the Journal of Advanced Engineering Informatics (Elsevier). Next, Chapter 8 presents on the use and validation of the decision support tool built on the proposed ontology. Lastly, Chapter 9 presents a synthesized conclusion of the research study and delineates the intellectual and practical contributions to the body of knowledge. The potential future research directions are also discussed.

Chapter 2 Background Review

The need to develop defensible and effective M&R policies has led to the development and proposal of several methods in the literature for budget planning and budget allocation. For several agencies, these investment decisions tend to be a hybrid of subjective qualitative and quantitative approaches. However, there have been growing concerns about the pragmatism, fairness, and objectivity in the use of some subjective measures in making decisions on budget allocation for highway infrastructure using tax-payer dollars (Kulkarni et al. 2004). Furthermore, the planning of M&R projects needs to be integrated with the programs of other highway construction projects for more effective planning. Thus, this review highlights prior studies in the domain of infrastructure management as well as challenges with integrated highway planning.

2.1 HIGHWAY M&R BUDGET ALLOCATION

Major approaches for budget allocation include the use of ranking methods (like the "Worst-First" approach, cost-benefit analysis (CBA), analytic hierarchy process (AHP)) and mathematical optimization models (Hong et al. 2017). CBA and the Worst-First approach are well documented in practice with AHP and the mathematical optimization models still being in an emerging phase for practical use by SHAs (Wiegmann and Yelchuru 2012). Ranking methods usually involve developing and assigning weights to certain key indicators as an approach to the optimal selection of eligible M&R candidate projects for funding (Farhan and Fwa 2011). This is usually done by creating and rating candidate treatments or projects based on a set of indicator parameters. The analysis usually depends on the expert judgment, pavement-related data (condition states), or economic analysis (Torres-Machí et al. 2014). More often than not, decision-makers tend to employ a hybrid of the above-mentioned approaches. A key demerit of the ranking methods especially the Worst-First approach is that the funds tend to be allocated to pavement sections that are most severely damaged and hence, seldom leads to the optimal benefit of the entire pavement network. Even for more robust ranking methods like the AHP, the consistency metric introduced does not address the precision problem with ranking-based methods (Ahmed et al. 2017). On the flip side, ranking methods are easy to understand, and are usually indicative of the intended pavement maintenance policies of the respective highway agency (Farhan and Fwa 2011). They can also be easily tailored to the specific needs of different highway agencies, who tend to have different short term, long term or strategic goals due to varying levels of traffic, network dynamics, and available M&R funding levels.

On the other hand, the use of mathematical optimization approaches has received increasing attention in transportation investments and policy-setting decisions in the past two decades (France-Mensah and O'Brien 2018; Wu et al. 2012a). This has been primarily driven by the need for more data-driven and performance-based approaches to allocating limited highway funds to select projects. Furthermore, decision-makers are being mandated by federal and state legislative requirements to demonstrate the efficiency of their infrastructure management plans via objective and measurable metrics for their respective networks. Mathematical optimization models address this need and more by providing optimal decisions for network performance based on select evaluation metrics as prioritized by the decision-making agency (Farhan and Fwa 2011). The most frequently used methods include the linear, non-linear, integer, and dynamic programming models (Boyles et al. 2010; De La Garza et al. 2011; Gao and Zhang 2009; Ng et al. 2011). Details of the merits and demerits of these methods are documented in the comparative analysis of budget allocation models in Chapter 5.

These methods notwithstanding, there still remains a gap between the mathematical optimization models developed in the literature and the practice of allocating M&R funds. This is evidenced by the slow adoption of optimization models in the M&R decision-making process of many SHAs. Primary reasons for this slow rate of adoption include inadequate data to run models, bespoke models which are not generally applicable in other decision-making contexts, resistance based on organizational culture, a lack of technological expertise, and a deficiency of practical considerations in models (Augeri et al. 2010; Duncan and Schroeckenthaler 2017; Harrison 2005).

Furthermore, the isolated planning of M&R projects without accounting other highway construction projects which occur jointly or independently on the same pavement network can lead to the scheduling of potentially redundant M&R projects. For instance, if a pavement section is scheduled for a capacity expansion project in a few months, it may be inefficient to fix minor distresses or execute other maintenance activities within a short time interval. Thus, it is important to perform integrated planning for M&R projects and other highway construction projects like mobility, and safety projects among others. A preliminary study of this issue suggests that there are complex inter-relationships that need to be considered as part of the M&R planning process. This is discussed further in the next section.

2.2 INTEGRATED HIGHWAY PLANNING

Transportation professionals still face the onerous task of organizing highway data into suitable forms to support decisions concerning highway maintenance, rehabilitation, traffic control, highway monitoring, and projects prioritization. There are challenges associated with fragmented databases, multiple incompatible models, redundant data acquisition efforts, and sub-optimal coordination between the various agencies or departments operating on the same highway facilities (Chi et al. 2013; Ziliaskopoulos and Waller 2000). To compound this problem, multiple independent legacy information systems usually co-exist within the same agency (Chi et al. 2013; Thill 2000). Accordingly, both practitioners and researchers have questioned the efficiency of data programs in meeting the needs of users for highway infrastructure planning purposes (Flintsch and Bryant 2006; Woldesenbet et al. 2015). These issues have given rise to a surge in the demand for effective practices, frameworks, and tools that can integrate, manage, and analyze highway data in a format that can better support the achievement of the short- to long-term goals of the decision-making agency (Parida and Aggarwal 2005).

The need for such systems and tools has grown for metropolitan areas since they have significantly more lane-miles of on-system highways under their responsibility and consequently, more projects in various phases of development. The funding mechanism for maintaining, rehabilitating, and upgrading the existing system is complex. It has become further complicated since, for many SHAs, funding is dependent on revenue from multiple sources with different permissible uses. Moreover, the planning process is fiscally-constrained at the category level; the amount of funding available determines the number of projects that can be planned within specific categories. Furthermore, there are instances when existing roadways that were not expected to be rehabilitated within the planning horizon, have to be rehabilitated owing to faster deterioration in condition. This leads to reactive maintenance to maintain safety and pushing lesser priority projects down the list. The combined effect of these factors (and many more) creates a need for an integrated planning process leveraging modern data management, and visualization tools which will allow the integration of temporal and spatial projects data for effective review, and convenient updates of projects data in a dynamic setting (France-Mensah et al. 2017a). This means that it is important to connect planning information to the projects coordination tasks in order to ensure that the network-wide goals and logic of projects' selection are being integrated into the decision-making process (France-Mensah and O'Brien 2019a).

Although most pavement engineers have to contend with these aforementioned issues, different approaches are often employed to address these issues based on the decision-making entity's practices, experience, and/or resources. For this reason, such issues are better explored within a practical context of the problem with "real world" examples of typical M&R planning decisions made towards the achievement of the strategic goals of an SHA. Hence, to demonstrate a typical decision-making context which reveals these challenges with integrated highway projects planning, a motivational case study is presented in the next section.

Chapter 3 Motivation – M&R Planning (TxDOT)

The contents of this chapter were reprinted from the publication: France-Mensah, J., O'Brien, W. J., Khwaja, N., and Bussell, L. C. (2017a). "GIS-based visualization of integrated highway maintenance and construction planning: a case study of Fort Worth, Texas." Visualization in Engineering, 5(1), 7**.** The corresponding author (Jojo France-Mensah) designed the research approach, performed the data collection and analysis, and wrote the manuscript.

In order to better understand the status quo of the M&R planning process of a typical highway agency, the planning practices of the Fort Worth District of the Texas Department of Transportation (TxDOT) were studied as a motivational case study. This agency is responsible for nine (9) counties and approximately 9,000 highway lane miles within its boundary. The district oversees nearly $4 billion investment in construction projects and over $100 million annual expenditure on preventative, routine, and rehabilitative maintenance operations (TxDOT 2016b). As part of the case study, there were interviews, analysis of documents, and observations to document the agency's practices and decision-making process. The interviewees consisted of Directors of the maintenance and transportation planning functional groups of the district. Additionally, more interviews were conducted for four Directors of the operations, maintenance, transportation planning functional groups of the Austin and Dallas districts. The documents reviewed included multi-year plans for the Unified Transportation Program (UTP), the Legislative Appropriations Request, TxDOT funding sources, and other relevant publications from the Center for Transportation Research at the University of Texas at Austin.

3.1 Transportation plans

Rider 55 of the TxDOT's appropriations bill requires TxDOT to provide the Legislative Budget Board (LBB) and the Governor with a district-specific analysis plan for the use of highway funds. The plan includes pavement score targets and the performance impact of the proposed maintenance spending on the state of the highway infrastructure network (Liu et al. 2012). This plan allows districts and regional entities to appropriately allocate resources through long-term planning to achieve the state-wide goals set by the agency. Accordingly, each district develops a 4-year projection of M&R expenditures based on the anticipated funds from state budgets.

Consequently, TxDOT prepares the 4-year Pavement Management Plan (PMP) which includes financial constraints for all categories of highway M&R treatments (routine maintenance, preventive maintenance, and rehabilitation projects). Although the PMP involves the use of funding for M&R projects, it does not include construction expenditures from the state highway fund (Fund 6); which receives funds from state and federal taxes and fees. Hence, the PMP is actually a part of a more extensive plan for the entire transportation network of the State of Texas. Beyond the PMP, there are plans for construction expenditures in the form of rehabilitation and preventive maintenance projects from "Category 1" of the Unified Transportation Program (UTP). The UTP is a 10-year snapshot of planned projects and activities intended to fulfill the long-term goal for the transportation network of Texas. Similarly, the State Transportation Improvement Plan (STIP) contains projects scheduled to be undertaken in the next 4 years while the 2-year letting schedule is for projects that have already been funded for the near term. Figure 3-1 shows the 10-year UTP, the 4-year STIP, and the 2-year letting schedule by TxDOT. This case study examined the 4-year plan (STIP) focusing on the highway projects scheduled for those fiscal years.

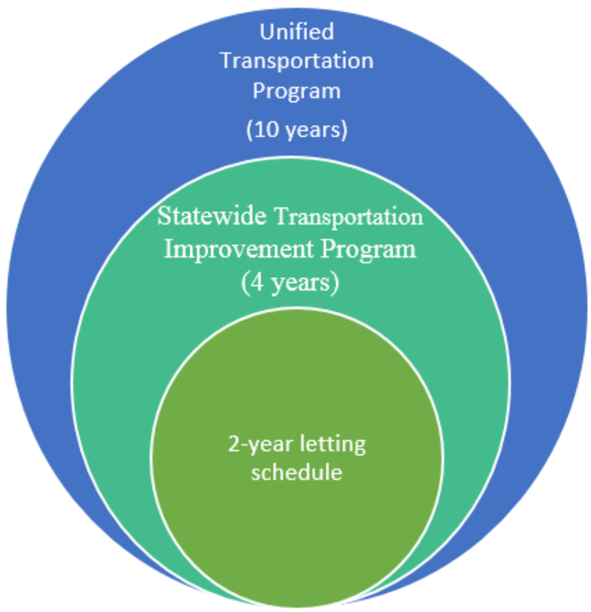


Figure 3-1. 3-tier TxDOT transportation development plans.

3.2 State of practice (TxDOT)

Two of TxDOT's stated goals and objectives consist of "*delivering the right projects by implementing effective planning and forecasting processes to deliver the right projects on time, and on budget*, and *preserving its assets through preventive maintenance of the system and capital assets*" (TxDOT 2016b). In order to meet these and additional goals, TxDOT's complex portfolio of projects consists of maintenance, rehabilitation, safety, bridge, widening, capacity-addition, and several other project types delivered by its district offices responsible for multi-county geographical regions of Texas. The simpler maintenance projects can either be done with in-house workforce or through contractors. Maintenance projects can cover both roadway and roadside maintenance tasks. Normally these projects are handled by the maintenance functional group of a district office. These projects are programmed in TxDOT's Maintenance management information system (referred to as the COMPASS system) and can have very short planning time associated with them.

On the other hand, several M&R projects require planning and design effort with associated lead time and a formal process of letting to achieve cost-efficiencies. These projects are planned, programmed, and generally developed by the Transportation Planning and Development (TPD) group of a district. They are managed within the Design and Construction Information System (DCIS) which is the department's primary system of record for design and construction projects. On the farther end, there are capacity addition and reconstruction projects managed by the TPD that take years to plan, design, and fund for construction. These capital construction projects often involve several iterations of proposals and feedback from a wide variety of stakeholders before they are approved for execution. Furthermore, such projects require complex processes like ROW acquisitions, legislative approvals, environmental assessments, funds appropriation, public buy-in, and other legally mandated tasks.

3.2.1 Network-Level Project Selection

For most districts, the development of the PMP starts with identifying pavement sections in the PMIS that call for urgent attention. This could be pavement sections with extremely low condition scores or sections with good scores but exhibit trends of relatively fast deterioration rates. A list of candidate projects is prepared by the Area Office Engineers (AOE) and submitted to the district office for consideration. This is followed by an elaborate field investigation to confirm the current condition of the selected pavement section(s) for the proposed projects. The District Maintenance Engineer (DME), in collaboration with AOEs, then prioritizes projects based on the pavement condition, deterioration rate, traffic volume, project costs, available funding, and other local considerations. Prior to this, a project-level analysis is carried out to determine which treatment strategy is the most suitable for the identified pavement sections over the planning period based on historical data and the experiential knowledge of pavement engineers.

Due to the use of some federal funding sources for M&R projects, the TPD Director also coordinates with the DME to ensure that M&R projects eligible for federal funding are also allocated effectively. Hence, at the district-level, budget allocation is often an iterative process that requires collaborative planning and negotiations between the Maintenance and the TPD functional groups of TxDOT. Developing plans consisting of projects that undergo “starts” and “stops” during their varied development phases is a continual challenge faced by the district staff. The district’s maintenance and TPD functional groups have different challenges and processes for planning, design, funding, and delivery. This is primarily due to the type of projects within their purview and the associated expectations and funding constraints. In order to gain synergy between the plans of these functional groups, the district leadership depends on effective communication and collaboration among multiple stakeholders (Sankaran et al. 2016). However, the above-described processes can benefit from emerging tools and techniques to save time and enhance effectiveness. Accordingly, a GIS-based tool was developed to visualize projects data residing in disparate legacy systems to support integrated planning. Details of this task are presented next.

3.3 GIS-BASED VISUALIZATION

To address disparities in information systems and data access barriers which exist due to the "siloed" approach to highway projects planning, the use of a GIS-based platform was employed. This was done via the development of an integrated GIS-based tool to fuse all the projects' information from the TPD and Maintenance functional groups of the district. The proposed framework includes 3 major components; data extraction from the database systems, a middleware –processing platform, and the output in the form of active maps and reports (Figure 3-2). The first step was to identify the relevant data sources and data types required for developing the GIS-based tool. The sources used could be broadly grouped as GIS shapefiles (County boundaries and road network), highway inventory data, DCIS projects data, and COMPASS projects data. The GIS data were accessed primarily from the Transportation Planning and Programming (TPP) division of TxDOT and the Texas Natural Resources Information System (TNRIS). After identifying and obtaining the required data sources, the next step of this project was to process the data to ensure that all the records contained accurate spatial attribute values in a GIS-compatible format.

Processing took place in two steps—data processing and geoprocessing using GIS. Data processing was conducted in a spreadsheet environment for the extracted projects data. This comprised data cleaning, data validation, and sorting. Most of the data-processing tasks involved data cleaning. A new field was also created to query the highway inventory database for GIS-compatible linear reference values for project records. The projects' data were also validated using a "set of validation rules" to ensure that project attributes and spatial data were consistent across all records in the databases. The second step involved data fusion in a geospatial environment. Route event layers were created using the highway network shapefile and the processed projects data. ESRI's ArcGIS software was used for geospatial operations because that was the default GIS application used by TxDOT at the time of the tool's development.

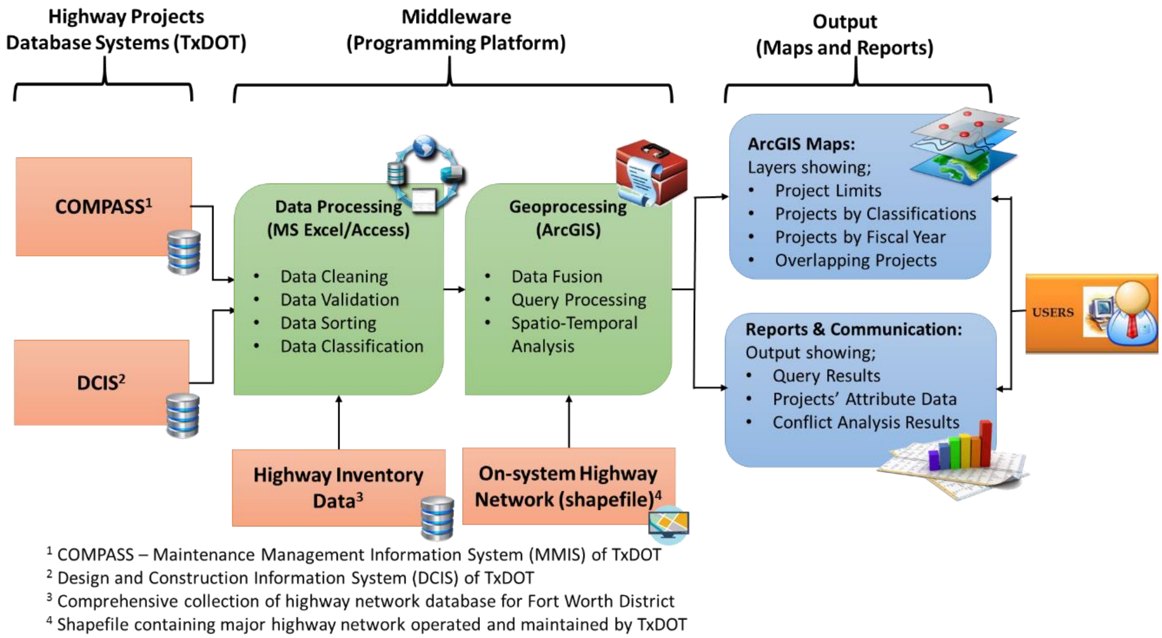


Figure 3-2. The conceptual framework for a GIS-based tool developed for the case study

Finally, projects data were visualized as feature layers according to the County, project type, and fiscal year. Figure 3-3 shows a visual of the 4-year PMP for the district according to the fiscal year as displayed in the tool. It also includes some projects from the 10-year UTP from the long-term plan for highway construction projects in DCIS. In addition to this, intra-database and inter-database analyses were also performed and added as layers to the tool.

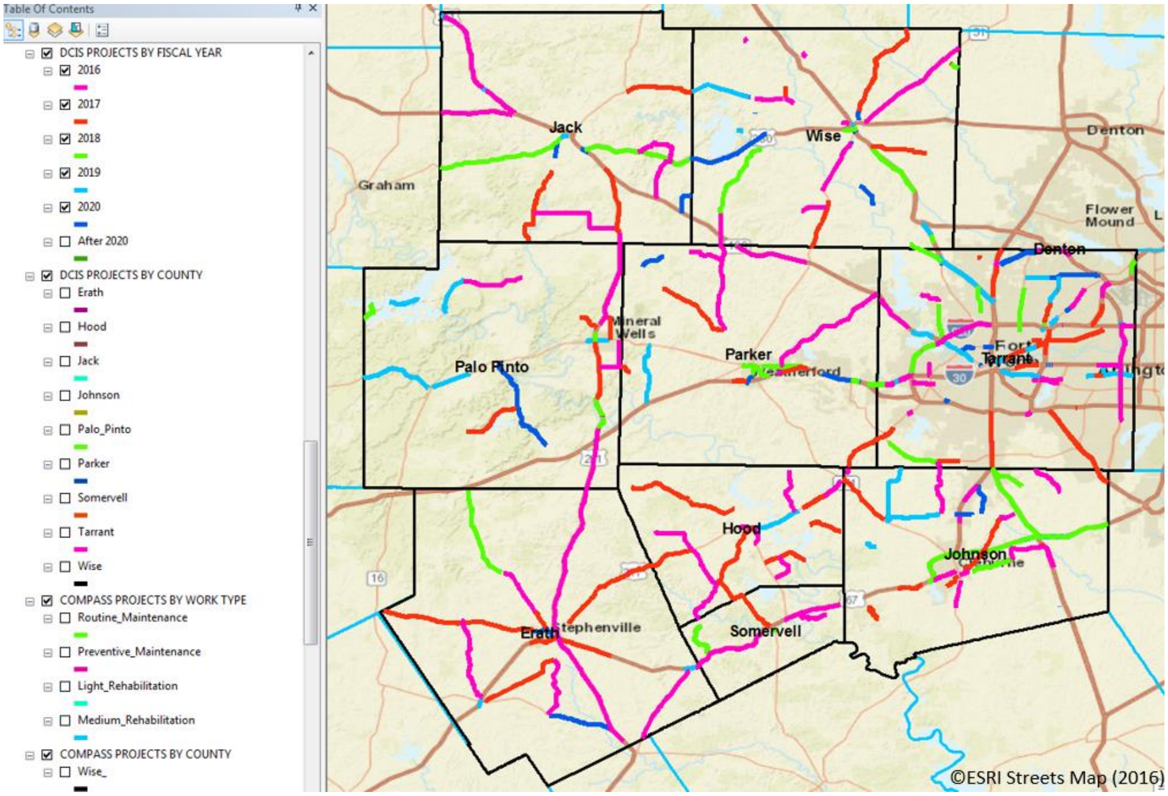


Figure 3-3. Screenshot of 4-year DCIS (construction) projects in Fort Worth (in 2016)

Intra-database analysis refers to the identification of sections of highway pavement sections that are scheduled to receive annual or biennial projects in the same database (DCIS or COMPASS). These were referred to as “overlaps.” Included in this category, for example, would be a road pavement with a rehabilitation project scheduled to take place continuously for 3 consecutive fiscal years. On the other hand, inter-database analysis refers to the identification of pavements sections that have both capital construction and maintenance projects scheduled to take place in the same fiscal year. For example, a road section that has a “widen freeway to three lanes” project (DCIS) and a “Seal Coat” project (COMPASS) scheduled within the same fiscal year has an “inter-project conflict.” Figures 3-4 and 3-5 show visual examples of conflicting project layers for projects across databases and road sections receiving repetitive annual M&R treatments respectively.

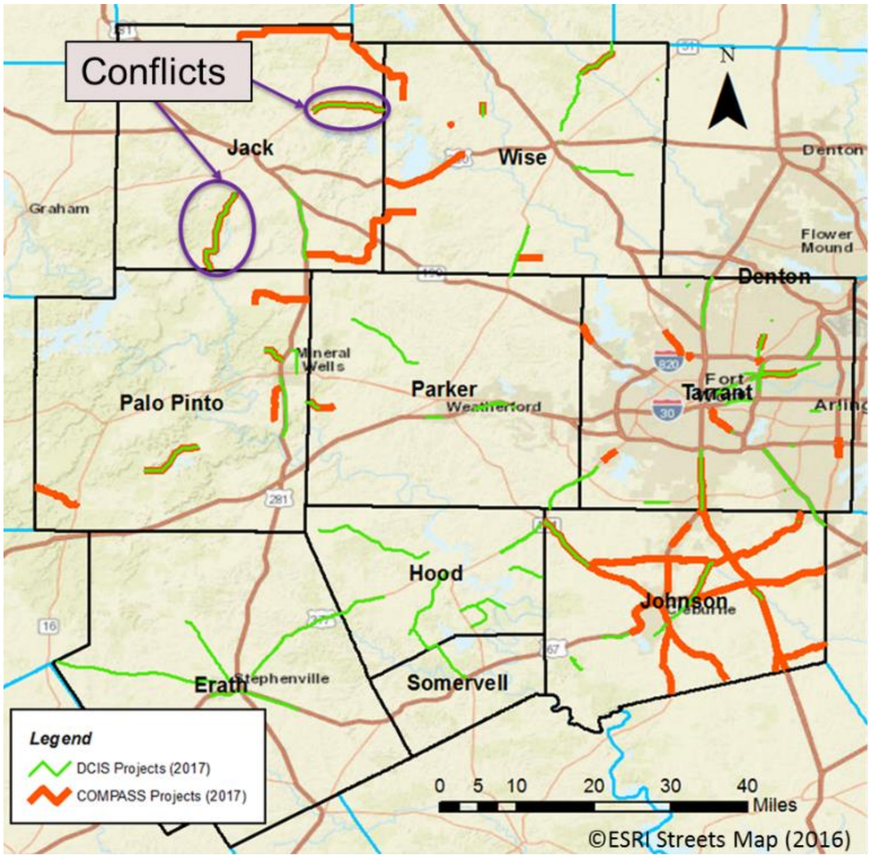


Figure 3-4. Conflicting highway projects on the same pavement section in the fiscal year, 2017

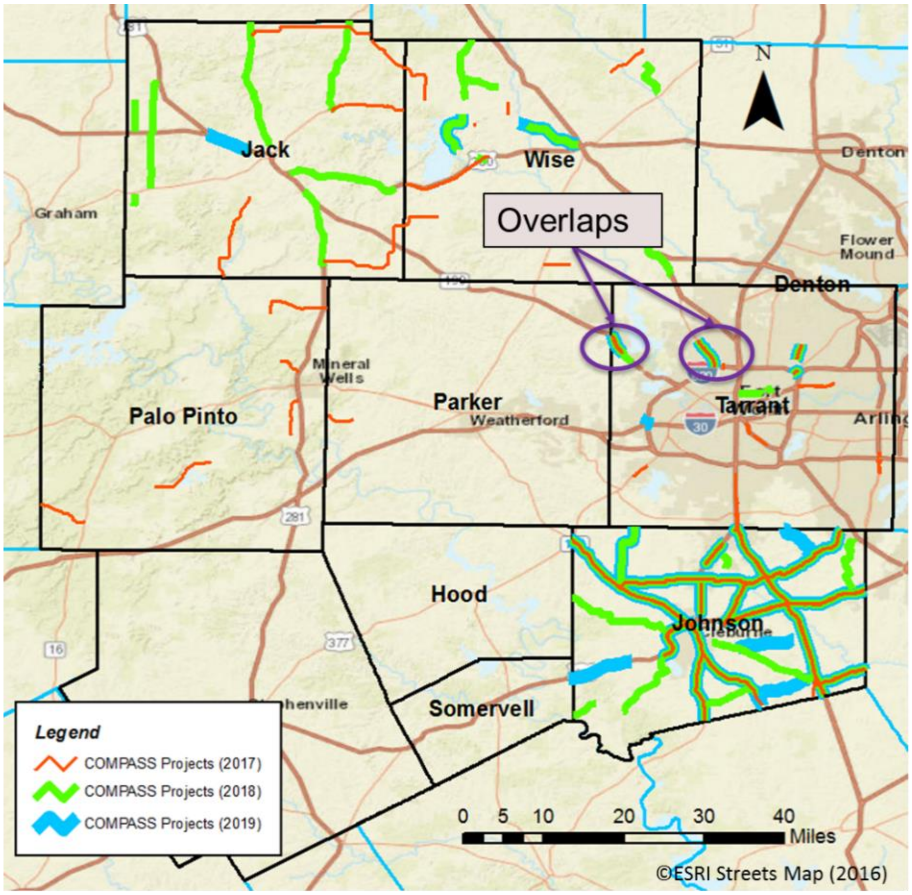


Figure 3-5. Multi-year COMPASS projects that take place on the same pavement section

3.3.1 Key Issues

Based on the preliminary work on GIS-based visualization of highway projects in this district, some issues identified earlier are confirmed. Furthermore, other issues not previously discussed arises. These include;

- The repetitive scheduling of M&R projects on the same pavement section raises concerns about the M&R programming approach and the efficiency of the current budget allocation process employed by decision-makers (as shown in Figure 3-5).

- Interviews with relevant decision-making personnel confirmed that there is no formalized analytical approach for assessing the efficiency of the existing projects prioritization and subsequent budget allocation approach being implemented by the agencies.
- The existing state of integrated highway planning is at risk of scheduling projects whose scope of work may be conflicted or rendered redundant by other highway projects by different functional groups working on the same asset (as shown in Figure 3-4).
- Currently, there no formalized approaches or representations to aid in conducting standardized spatial-temporal conflict analysis of highway projects which are proposed by multiple but often functionally disjoint groups in SHAs.

These issues, planning challenges, and critical literature review were used in conjunction to extract salient gaps in the extant research which if addressed, can have significant value to the body of knowledge and relevant domain of practice.

3.4 RESEARCH GAPS

The literature offers a significant number of methods to aid pavement engineers in budget planning and budget allocation processes. In most of these studies, however, the authors do not objectively compare or evaluate various alternative models proposed for resource allocation. In the few instances of such comparisons, researchers implement allocation methods based on different contexts (location, scale, or level of decision making) on the same network. This can lead to biased results that are not representative of the pragmatic context of the proposed models. Furthermore, when comparative studies are done, the usual performance criteria and metrics focus solely on effectiveness without simultaneously accounting for other criteria like equity and the strategic goal(s) of the agency. From a pragmatic standpoint, several highway agencies have strategic goals about the percentage of pavement sections that are expected to be in a specified condition state (score) for each year or over a pre-determined planning horizon. Furthermore, addressing disparities in performance in condition states of individual pavement sections is also standard practice by pavement engineers in highway agencies. This ensures that poorly performing sections of the network do not fall below acceptable standards which can lead to expensive rehabilitation projects later on. Accordingly, there is the need to conduct comparative studies of representative budget allocation methods in a pragmatic context to demonstrate how selected methods perform in effectiveness, equity, and the degree to which they satisfy the strategic goals of the decision-making entity.

Additionally, a critical pragmatic consideration of highway budgets which is absent from most M&R budget allocation models is the multiplicity of highway funding categories and project eligibility constraints. Most approaches to budget allocation in M&R programming assume one central source of funding with no restriction on the different types of projects that are eligible for funding. Nonetheless, especially for metropolitan agencies, there are often multiple funding categories with specific restrictions on which types of M&R projects are eligible for different funding categories. Little research has been done to understand how the existence of multiple funding categories can affect network-level M&R treatment decisions. In order to understand the multiplicity in the budget funding categories and how significant it is, to account for this characteristic in budget allocation models, a new approach to formulating budgetary constraints is required. This will enable the implementation of such new constraints in typical highway networks for the evaluation of the impact of this aspect of highway funding on the network performance and the resulting M&R decisions.

Moreover, beyond M&R programming, it is also important to integrate the schedules of M&R projects with the programs of other construction projects like mobility and safety. Given the differences in practice, information systems, and data repositories for maintenance and capital construction projects, it is pertinent to develop formalized knowledge representations and frameworks that will serve as a standardized platform to integrate planning and projects data to avert potential spatial-temporal conflicts that could occur. Furthermore, infrastructure and highway projects data usually experience changes in response to variations in the funds available, traffic volume (truck traffic surge), asset conditions, land use change patterns, and political influence among others. This means that asset information used to guide decision-making as well as earlier project selection decisions taken, often change in response to demand. Thus, such changes in the planned projects need to account for the planning knowledge which underpins the project selection decisions. However, little research has been done to link the representation of asset, planning, and projects information. Consequently, there is a need for a shared representation to support the integrated planning of highway projects

These gaps in the literature form the basis for the objectives of this study.

Chapter 4 Research Objectives and Methodology

To address the research gaps identified in the literature and supported by the motivational case study, this section formally lays out the three main objectives and questions. Conceptually, the objectives deal with the comparison of budget allocation methods, accounting for budgetary restrictions in budget allocation models, and developing an ontology capable of supporting integrated planning of highway projects. The first two objectives provided key lessons and information requirements for the third objective. Figure 4-1 shows the objectives, proposed methodology, and the anticipated outcomes from these objectives.

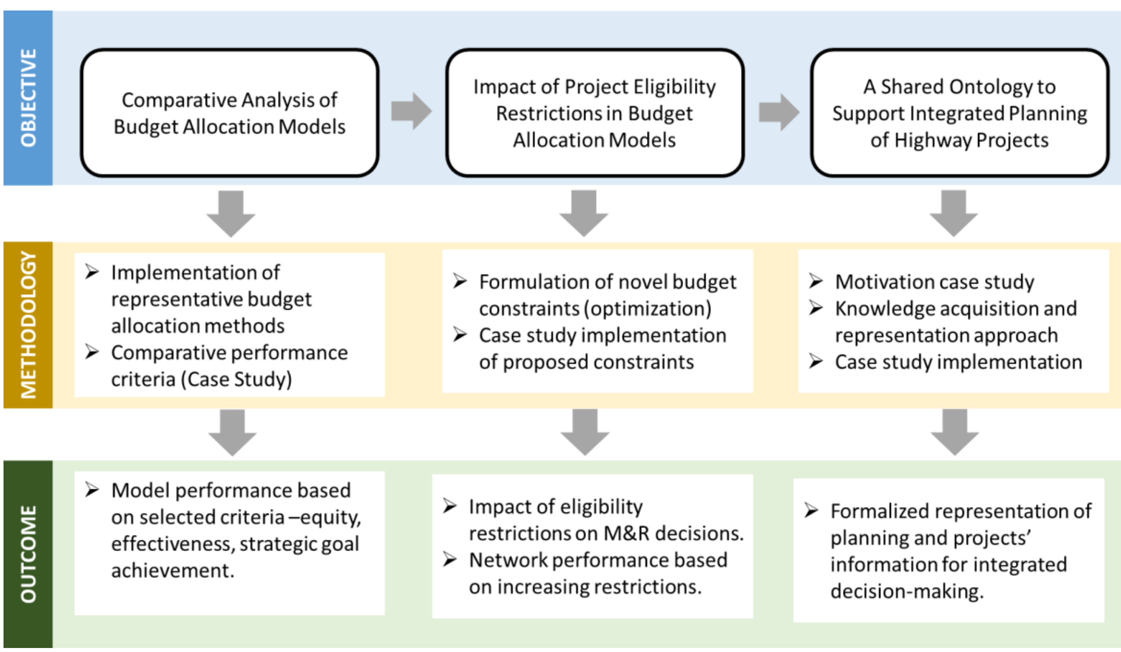


Figure 4-1. Overview of research objectives and methodology

Research Question 1: How can the comparative performance of different budget allocation approaches in Pavement Maintenance and Rehabilitation (M&R) programming be conducted?

RQ 1.1: What evaluation criteria can be used to assess the performance of different methods for M&R budget allocation? What are the metrics under these criteria?

RQ 1.2: How do representative budget allocation models perform based on these criteria?

This research question is based on the need to first understand the existing approaches in the literature that have been applied to budget allocation in pavement management. It further explores how some select representative methods perform in terms of the overall network condition, equity considerations, and the degree to which each method achieves a common strategic goal of many State Highway Agencies in pavement management. The study documents in detail the merits and demerits of using ranking-based, mathematical optimization, and data mining approaches for pavement management decisions. For the comparative analysis, the methods compared included cost-benefit analysis, an integer-linear optimization program, and a hybrid "Decision tree + Worst-First" method. Each method was implemented in a numerical case study with the same parameters to provide a common pavement network for the analysis. A consolidated summary of the findings from this paper is presented in Chapter 5.

Research Question 2: What is the impact of project eligibility restrictions in multiple M&R budgets on pavement network performance?

RQ 2.1: How can budget allocation models be formulated to account for project eligibility restrictions in pavement budget allocation?

RQ 2.2: How does this formulation affect the projected network-level performance, M&R network-level project selections, and the achievement of the strategic goals of decision-making entities?

To further investigate how to build more pragmatic funding characteristics in budgetary constraints, this objective explores an approach to accounting for multiple funding categories with project eligibility constraints. This was addressed by formulating the budgetary constraints to account for funding categories and their corresponding funding restrictions. The model is explored through the lens of a typical objective that SHAs tend to aim for. This is the optimal improvement of the average network pavement condition score over the planning horizon. The study also investigates how this formulation of budget constraints affects network-level project selections. The proposed models are implemented on a subset network in a numerical case study to demonstrate the pragmatic implementation of the model. The impact of increasing distinct funding categories is discussed to provide insights into how important it is to account for this aspect of highway funding when formulating budget allocation problems in pavement management. The major findings from this study are presented in detail in Chapter 6.

Research Question 3: How can highway planning and projects information be formally represented to support integrated planning practices?

RQ 3.1: What are the relevant asset and planning information requirements for developing M&R projects?

RQ 3.2: How can functionally different highway projects information be formally represented to support inter-project coordination?

RQ 3.3: How can inter-project conflicts between highway projects of different functional groups be represented for effective coordination?

This research question aims at addressing issues with integrated planning for M&R projects and other projects like mobility, and safety. After developing M&R programs, the resulting M&R projects has to be coordinated with other projects developed by mobility planners, safety engineers, and other functional groups within the same agency. Current approaches to integrating this planning process are informal and do not account for lapses or spatial-temporal conflicts in the projects proposed by different functional groups working on the same asset within the same agency. Thus, this study is driven by the need to integrate all these projects data in a common collaborative environment to improve communication and the conduct of spatial-temporal conflict analysis. Furthermore, the planning information needed to make changes in the planned projects is also connected to the project's information. This is because whenever there are changes in funding or new unanticipated projects have to be added to the list of projects, planning information is crucial towards the re-prioritization of planned projects. To achieve this integrated representation, it was first important to identify and formalize the relevant attributes that can be used to support integrated projects planning and coordination. Following this, a shared ontology was developed to capture domain knowledge related to integrated planning and projects' coordination to support decision-making. This was followed by a case study implementation for a TxDOT district to demonstrate its practical usefulness. The proposed approach can be used to obviate costly planning errors associated with "siloed" planning practices by the different functional groups in SHAs. The major findings from this study are presented in detail in Chapter 7 with a corresponding implementation tool presentation in Chapter 8.

Chapter 5 Comparative Analysis of Budget Allocation Models for Pavement Maintenance and Rehabilitation: A Case Study

The contents from this chapter were extracted from the publication: France-Mensah, J., and O'Brien, W. J. (2018). "Budget Allocation Models for Pavement Maintenance and Rehabilitation: Comparative Case Study." ASCE Journal of Management in Engineering, 34(2), 05018002. The corresponding author (Jojo France-Mensah) designed the research approach, performed the data collection and analysis, and wrote the manuscript.

This chapter presents the objective comparison of three methods for budget allocation—cost-benefit analysis, integer-linear programming, and a "decision tree + needs-based" allocation. The study first presents a review of the major resource allocation approaches in the extant literature. It then implements, through a numerical case study, a representative method from each allocation approach. These are implemented on a subset pavement (50 sections) network for project prioritization and budget allocation. The results indicate that, in comparison to the optimization model, both the cost-benefit analysis and the "decision tree + needs-based" allocation methods lead to faster declines (over the planning horizon) in average network condition scores (1% annually). However, this result arises due to both models inherently considering more "equity in outcome," evidenced by a decreasing gap between the individual condition scores of pavement sections over time. The method leading to the highest average network performance (0.30% decrease annually) is the integer-linear program. This method, though, performs the worst in equity considerations. The findings from this study highlight the important dynamics of “equity-effectiveness” trade-offs inherent in different budget allocation methods for M&R programming. This paper also supports the need to develop more hybrid approaches capable of leveraging the merits of different resource allocation approaches. For practitioners, this work presents a consolidated view of the strengths and weaknesses of major resource allocation methods which can aid in the transition that many highway agencies are making towards the use of more formalized analytical models for M&R budget allocation.

5.1 INTRODUCTION

In modern society, transportation infrastructure plays a key role in the economics and mobility of goods and human resources (Boyles et al. 2010). Highway infrastructure planners are tasked with addressing mobility, safety, accessibility, and economic development issues for multi-modal corridors that have different functional classifications and networks that stretch for thousands of miles (Chen et al. 2015). This work is increasingly challenging due to limited funds allocation coupled with the rapid deterioration of pavement infrastructure over time (Arif et al. 2015; Ismail et al. 2009; Lamptey et al. 2008b). Contributing to the fast deterioration of infrastructure is urbanization and the pressure it puts on highway facilities. Another level of complexity in highway planning is the consideration of multiple and often conflicting stakeholder objectives (Caldas et al. 2011; Chen et al. 2015; Podgorski and Kockelman 2006). Consequently, a major concern of highway agencies is the development of effective maintenance and rehabilitation (M&R) plans which account for the constraints of available funding as well as the differing objectives of relevant stakeholders (Ashuri and

Mostaan 2015; Gao and Zhang 2008). Due to the constrained availability of resources, highway agencies managing large-scale road networks can execute pavement treatments each year only on small sections of their network. It is thus critical that pavement engineers make the most cost-effective choices while achieving the best time efficiencies across the highway network and among project alternatives (Gao and Zhang 2013a).

In M&R programming, transportation engineers must also consider issues such as the strategic goals of the central body, the network management objectives of regional authorities, conditions of the highway network, and other political or administrative constraints not easily quantified (Augeri et al. 2010). This problem can be divided into two main categories—budget allocation and budget planning (Gao et al. 2012). A budget planning problem is a network-level analysis that attempts to minimize the total M&R cost over a specified planning horizon, such that a selected condition requirement is satisfied. This is usually done at a higher level in the decision-making process and leads to the proposal of a minimal budget required to meet specific state-wide agency goals. The budget allocation problem, on the other hand, attempts to maximize the effectiveness of M&R treatments and/or minimize the user cost, while accounting for specified budget constraints (Gao et al. 2012). In recent studies, however, the emphasis has shifted towards the bi-objective optimization of agency costs and user costs alike (Gao and Zhang 2013a; Labi and Sinha 2005; Li and Madanu 2009).

Accordingly, Pavement Management Systems (PMSs) were developed by state highway agencies (SHAs) to aid in maintenance and rehabilitation decision-making tasks. The information contained in typical PMSs includes roadway condition history, treatment history, traffic volume data like the Annual Average Daily Traffic (AADT), and many other functional pavement characteristics (Woldesenbet et al. 2015). PMSs help agency staff in making decisions concerning pavement sections which need interventions, the appropriate maintenance treatment option to apply, and the optimal scheduling periods (Shah et al. 2014). For every PMS, the appropriate agency needs to identify and specify the relevant data attributes, the main objectives of the M&R program, and the resource allocation logic. There are several studies that have proposed models, frameworks, and different approaches for M&R programming. Still, many SHAs today continue to use a hybrid of engineering judgment, needs-based, and/or performance-based condition assessments to guide the allocation of highway funds to M&R projects (Wiegmann and Yelchuru 2012). Current studies in the literature have mostly focused on the effectiveness (objective function) of proposed models in conducting comparative analyses of different methods. However, for many agencies considering a transition to more analytical frameworks and models, there is a need for a more holistic comparative analysis of the existing budget allocation models in a pragmatic context. Such analyses would inform decision makers of the caveats, strengths, and weaknesses of different methods which can guide the development of an effective budget allocation framework.

The remaining sections of this chapter are organized as follows. The next section provides a detailed description of the general M&R planning practices of a major SHA as a motivating case. This is followed by an overview of the major approaches to budget allocation models. The representative methods for the analysis are then introduced and implemented in a numerical case study. The case study implementation results are then discussed. Finally, the conclusion section presents key findings, study limitations, and future research work.

5.2 M&R PLANNING IN TEXAS

Districts within the Texas Department of Transportation (TxDOT) are aiming to attain "90% or better state-maintained pavements in good or better conditions." As part of this effort, they are required to submit a 4-year Pavement Management Plan (PMP). This plan contains the anticipated budgets to meet the agency goals for the network (Zhang et al. 2009), including estimated construction costs for maintenance (routine and preventive) projects and for rehabilitation projects to be executed over the planning horizon (Chi et al. 2013). This district-specific plan is expected to include pavement score targets and the performance impact of the proposed maintenance spending on the highway infrastructure network (Liu et al. 2012).

Complicating the planning process is the fact that TxDOT's funding is dependent on revenue from multiple sources (state and federal) with stringent project funding eligibility constraints (France-Mensah et al. 2017a). Additionally, Metropolitan Planning Organizations' (MPO) policy boards have oversight over certain funding categories that also require concurrence with TxDOT. Recent studies suggest that the current levels of funding for TxDOT will be insufficient to keep the network-level pavement condition at the desired performance and service levels (Zhang et al. 2010). In order to prevent the pavement network from falling to unacceptable (minimum) standards with the projected levels of funding, it is imperative for the agency to make sound and defensible data-driven decisions on the best short- to long-term M&R projects.

To collect, store, and aid in the analysis of pavement-related data, TxDOT developed the Pavement Management Information System (PMIS). Implemented in 1993, PMIS contains annual data on pavement condition trends, treatment history, traffic information, structural attributes, and potential problem areas for 0.81-km (0.5-mile) sections of the pavement network. The primary metric for measuring the functional and structural condition of Texas pavements is the PMIS condition score (CS). This is a product of the utility score value for ride quality (comfort and safety oriented) and the assessed distress score rating (Figure 5-1). For flexible pavements, distress score ratings are based on data collected on failures, flushing, raveling, shallow rutting, deep rutting, alligator cracking, block cracking, traverse cracking, and longitudinal cracking. A distress score is assigned to a pavement section based on the utility values of some of the aforementioned distress-related data according to conversion charts developed by TxDOT. Similarly, the ride score is also awarded based on the ratings for the ride quality of each pavement section. These metrics guide pavement engineers in the screening and shortlisting of pavement sections for potential M&R projects.

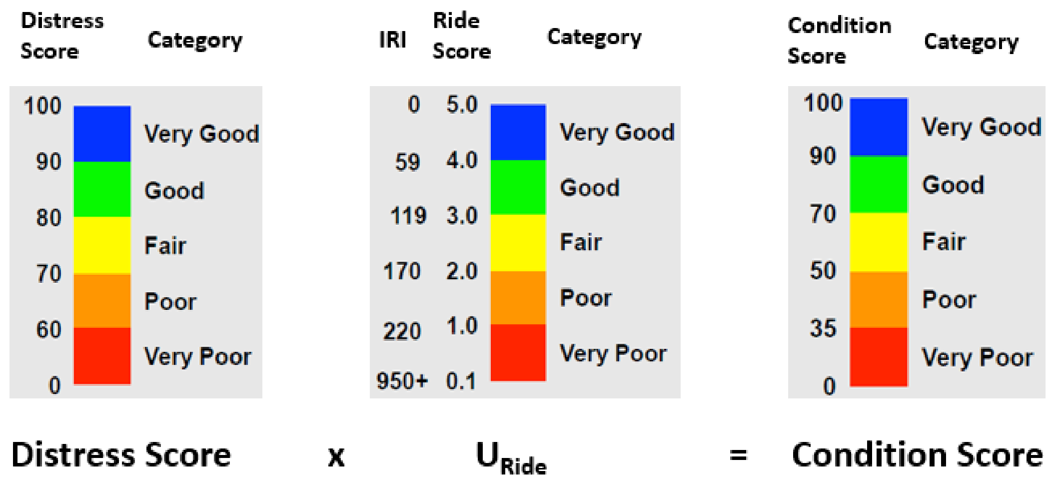


Figure 5-1. PMIS condition score composition (modified from Goehl, 2013)

About 93% of all the pavement sections in Texas are flexible. Hence, the treatment categories discussed in this section concern flexible pavements. As depicted in Figure 5-2, TxDOT has five primary M&R treatment options—no maintenance, preventive maintenance (PM), light rehabilitation (LR), medium rehabilitation (MR), and heavy rehabilitation (HR). PM is usually applied to sections with minor stresses like traverse and longitudinal cracking. It typically involves the application of seal coats or overlays less than 51 mm (2 in.). LR is moderately expensive and typically includes thicker overlays between 51 – 76 mm (2-3 in.), repairs to potholes and pavement edges, and performing pavement level-up activities. MR involves a structural overlay between 76 – 127 mm (3-5 in.), base repair, replacing the surface layer, and milling off the worn-out surface layer. Finally, HR (also known as reconstruction) involves the total replacement of the existing pavement section. This is the most expensive treatment option and is usually applied to sections with major distresses like deep rutting to restore the section to its original structural and functional condition (Chi et al. 2013; Gharaibeh et al. 2014a).

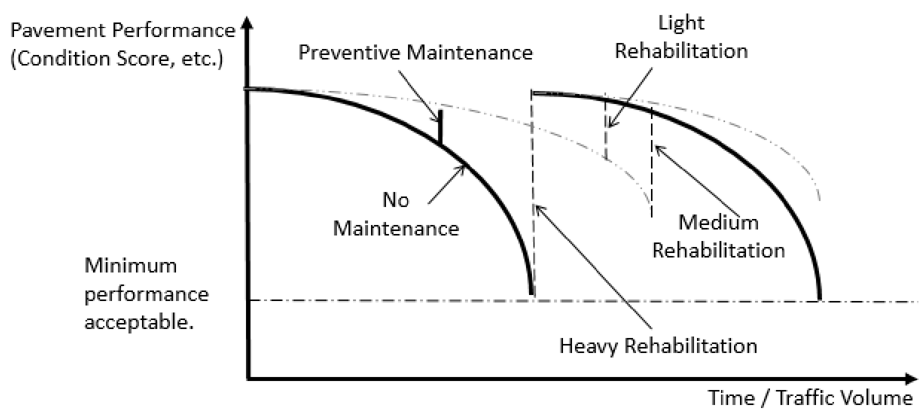


Figure 5-2. Different M&R treatments performed by TxDOT

5.2.1 Network-Level Project Selection

For most districts, the development of the PMP starts with identifying pavement sections in the PMIS that call for urgent attention. This could be pavement sections with extremely low condition scores or sections with good scores but exhibit trends of relatively fast deterioration rates. A list of candidate projects is prepared by the Area Office Engineers (AOE) and submitted to the district office for consideration. This is followed by an elaborate field investigation to confirm the current condition of the selected pavement section(s) for the proposed projects. The District Maintenance Engineer (DME), in collaboration with AOEs, then prioritizes projects based on the pavement condition, deterioration rate, traffic volume, project costs, available funding, and other local considerations. Prior to this, a project-level analysis is carried out to determine which treatment strategy is the most suitable for the identified pavement sections over the planning period based on historical data and the experiential knowledge of pavement engineers.

Due to the use of some federal funding sources for M&R projects, the Transportation Planning and Development (TPD) Director also coordinates with the DME to ensure that M&R projects eligible for federal funding are also allocated effectively. Hence, at the district-level, budget allocation is often an iterative process that requires collaborative planning and negotiations between the Maintenance and the TPD functional groups of TxDOT. Previous research has suggested that this process of network-level selection is still conducted via a hybrid of qualitative and quantitative approaches that rely heavily on pavement condition evaluations and the engineering judgment of pavement engineers (Chi et al. 2013). The literature provides numerous quantitative budget allocation models, yet few districts have fully transitioned to using such models (Wu et al. 2012a). With increasing urbanization and a growing gap between available funds and M&R needs, it is becoming increasingly important to develop defensible approaches for effective allocation of limited budgets. For some districts, there is still is no formal and consistent analytical/quantitative approach in the selection and funding of M&R projects at the network-level. However, this is not limited to TxDOT. Several SHAs have still not fully transitioned from the needs-based approach of projects prioritization for budget allocation (Wiegmann and Yelchuru 2012).

5.3 FUNDS ALLOCATION APPROACHES

The first part of this study involves a discussion of the existing major approaches to M&R programming. This section presents brief descriptions and enumerates the merits and demerits of the different methods of each approach.

5.3.1 Ranking-based Methods

One approach to solving M&R fund allocation problems is via ranking-based methods. This often involves developing and assigning weights to certain key indicators as an approach to the optimal selection of eligible M&R candidate projects for funding (Farhan and Fwa 2011). This is usually done by creating and rating candidate treatments or projects based on a set of indicator parameters. The analysis usually depends on expert judgment, pavement-related data (condition states), or economic analysis (Torres-Machí et al. 2014). More often than not, decision-makers tend to employ a hybrid of the aforementioned approaches. The methods include cost-benefit analysis (Li and Madanu 2009), analytic hierarchy process (Farhan and Fwa 2009; Li and Sinha 2004), and other multi-criteria decision-making methods (Sabatino et al. 2015; Zietsman et al. 2006). Figure 5-3 indicates a general framework of M&R programming based on ranking-based approaches.

The ranking approach to selecting M&R treatments has several drawbacks. First, the budget tends to be allocated to pavement sections that are most severely damaged and hence, seldom leads to the optimal benefit of the entire pavement network (Visintine et al. 2016). The parameters that are selected do not always lead to an optimal solution for achieving a given objective (for instance, maximizing network performance or minimizing M&R agency costs). Other studies have gone a step further to critique the relative importance or weights of parameters that are considered vital versus other parameters that are considered trivial (Farhan and Fwa 2011). Furthermore, given the fact that experts usually provide their opinion on the relative importance of the indicators in the model, there is a tendency for some experts to hype or overestimate the importance of certain variables to the performance and functionality of the highway pavement network (Wu et al. 2008). To address subjective inconsistencies in the factor weights, other studies (Ahmed et al. 2017; Porras-Alvarado et al. 2017) have employed and modified the AHP approach for M&R projects prioritization. This involves a multi-criteria approach which ensures internal consistency (via the consistency index) in the pairwise comparisons of attributes by the respective decision makers.

More importantly, when highway agencies use such prioritization schemes or ranking methods, they rarely develop well-defined criteria to assess the effectiveness of chosen methods in achieving certain strategic goals for the highway pavement network. Farhan and Fwa (2011) addressed this by demonstrating the loss in optimality when decision makers choose to go with certain prioritized activities in the M&R program. Furthermore, most ranking methods ignore multi-year analysis (Torres-Machí et al. 2014). This is particularly important because a lower ranked project not selected in one year may lead to an expensive rehabilitation project in a year or two. This drawback makes it unsuitable for medium- to long-range M&R plans.

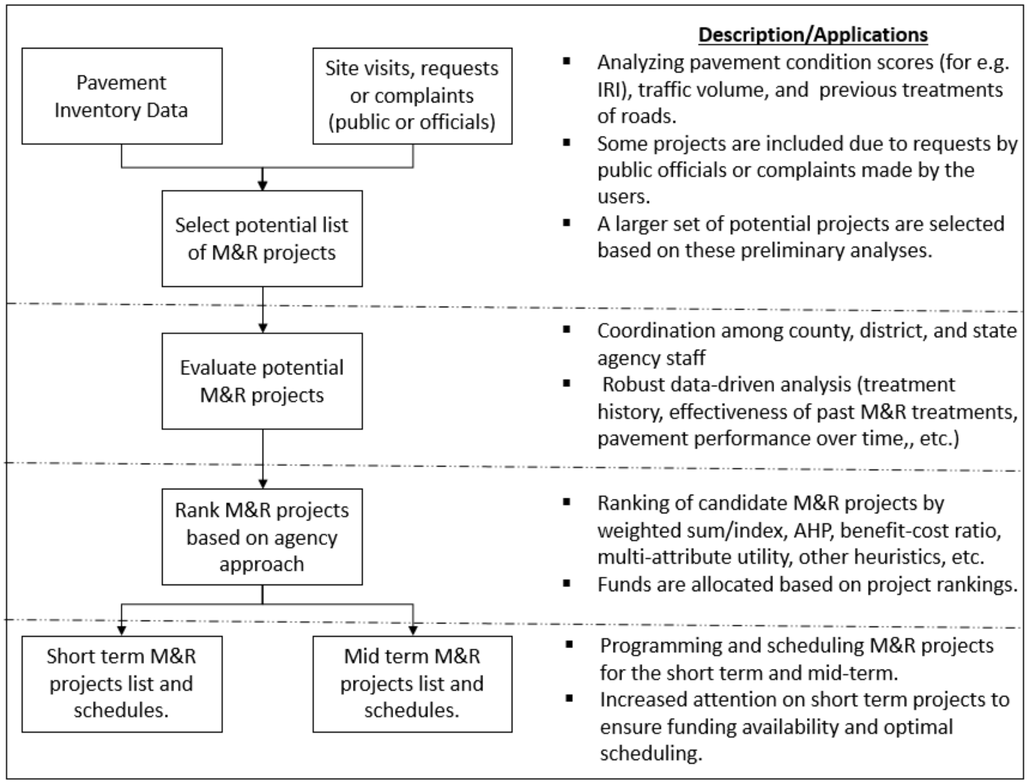


Figure 5-3. General framework for funds allocation via ranking-based methods (modified from Chi et al. 2013; Gharaibeh et al. 2014)

On the flip side, ranking methods are easy to understand and are usually indicative of the intended pavement maintenance policies of the respective highway agency (Farhan and Fwa 2011). They can also be easily tailored to the specific needs of different highway agencies; since, each agency tends to have different short-term, long-term, or strategic goals due to varying levels of traffic volume, network dynamics, and available M&R funding levels. Given the importance of transparency to the M&R planning process for highway agencies and the ease of understanding and implementation of such methods, the ranking method logically tends to be an attractive option for highway pavement engineers.

5.3.2 Mathematical Optimization and Metaheuristics

In the domain of pavement management, the mathematical optimization methods usually employed are linear, integer, non-linear, and dynamic programming (Torres-Machí et al. 2014). A defining characteristic of mathematical optimization methods is that they often lead to optimal solutions within the construct of the pavement management problem definition and formulation. Linear programming (LP) usually involves dividing the road network into groups of pavement sections that have similar traits; these traits can be road class, distress type, pavement condition range, traffic volume, or any combination of the above-listed classifications. Based on this, a resource allocation problem is formulated and solved with the output being the M&R treatments that are selected for the pavement groups created. Accordingly, LP models are relatively tractable and allow users to perform sensitivity analyses of the input parameters (De La Garza et al. 2011). The demerit of LP models is that the solutions provided apply only to a group of pavement sections rather than individual pavement sections (De La Garza et al. 2011; Gao and Zhang 2013b). In practice, however, pavement engineers are also interested in M&R project-selection at the network level. Providing treatments to a group of pavements leaves decision makers with an extra decision—selecting which pavement sections in the group should receive the proposed treatment (project-selection problem).

Now in areas where linear programming fails, the integer programming (IP) approach thrives. IP models can provide exact information regarding M&R activities scheduling and individual project selections for the optimal performance of the pavement network. However, IP models tend to require more computational power, especially when implemented on large-scale networks (Gao and Zhang 2013b). Even for single-objective functions, an M&R scheduling problem that has integer decision variables is an NP-hard problem (Gao et al. 2012). On the other hand, dynamic programming (DP) can be used to solve discrete problems having an optimal substructure and overlapping sub-problems. This means that the problems formulated should be solvable sequentially and components of the optimal solution should also facilitate the solving of sub-problems (Boyles et al. 2010). Also, DP is often used for accounting for uncertainty in infrastructure maintenance policies (Madanat et al. 2006; Medury and Madanat 2013a). The work by Powell (2007) on the use of approximate dynamic programming (ADP) demonstrated that ADP models can be conveniently applied to heterogeneous networks of facilities (Kuhn 2009). Finally, non-linear programming models have their objective(s) and at least some of their constraints formulated as curvilinear (Bryce et al. 2014). Studies that have employed non-linear programming suggest that it is more reflective of the distribution of the selected input variables especially for variables related to pavement performance (Abaza 2006; Gao et al. 2010).

As indicated by Wu et al. (2012), no single mathematical optimization approach is universally superior in terms of computational requirements, the availability of the required information, ease of use, and transparency. In general, mathematical programming methods are not suitable for application in large networks. The inclusion of a large number of decision variables in such optimization models leads to increased complexity of the formulated problems and geometrically increases the computing time (Torres-Machí et al. 2014). Beyond this, some of the parameters in such models are often poorly defined, making it challenging to adapt proposed models to different case scenarios (Augeri et al. 2010).

On the other hand, meta-heuristics are high-level iterative procedures that guide the selection of heuristic processes to explore the solution space to find near-optimal solutions (Blum and Roli 2003). Here again, while mathematical optimization models are not suitable for large networks (due to combinatorial explosion), metaheuristics provide "acceptable" close approximations or near-optimal solutions, in a shorter time period, for problems that have a high polynomial complexity (Lee and Madanat 2015). While there are global search and local search metaheuristics, applications in M&R programming often involve global search heuristics (usually population-based) like genetic algorithms (GA), particle swarm optimization, ant colony optimization, and evolutionary programming. A thorough review of related works in the literature reveals a disproportionately high number of works employing GAs for solving M&R resource allocation problems (Chootinan et al. 2006a; Jha and Abdullah 2006). Two major demerits of metaheuristics are that convergence to the true global value is still unclear and their computation approach can be complex. Fuzzy logic-based programming has also been used in numerous studies (Mellano et al. 2009; Moazami et al. 2011). Fuzzy logic is an approach to expressing the membership of individual entities as a continuum of probability values ranging from 0 to 1 (Sundin and Braban-Ledoux 2001). It is usually applied in conjunction with other mathematical optimization methods, heuristics, or ranking-based methods.

5.3.3 Artificial Intelligence and Data Mining

Artificial Neural Networks (ANNs) are used to replicate decision-making patterns but do not necessarily define one on their own. Consequently, if the training dataset of "decisions" contains sub-optimal decisions, those decisions will be reflected in the output by the ANN. Fwa and Chan (1993) demonstrated the feasibility of using neural networks to replicate the decisions of pavement engineers in prioritizing pavement maintenance needs. Comparing ANNs to the traditional weighted sum method of ranking, the authors argued that the former lacked consistency in application and failed to reflect the thought process of pavement engineers. ANNs, however, are the subject of the "black-box" critique, making them unattractive for application in M&R resource allocation problems. On the other hand, decision tree algorithms are "white-box" methods, which pavement engineers typically employ to support engineering judgments. In a study by Chi et al. (2013), decision tree classifiers were used to develop a network-level project prioritization method for a district in Texas. Based on the qualitative input from pavement engineers and historical pavement performance data, a list of candidate M&R projects was proposed for a 4-year pavement plan for a district.

5.3.4 Need for Comparative Analysis

The literature thus offers a significant number of methods to aid pavement engineers in budget planning, project prioritization, and budget allocation processes. In most of these studies, however, the authors do not objectively compare or evaluate proposed resource allocation models with other extant methods. In the few instances of such comparisons, researchers implement allocation methods based on different contexts (location, scale, or level of decision making) on the same network. This can lead to biased results that are not representative of the pragmatic construct of the proposed models. Furthermore, when comparative studies are done, the usual performance criteria and metrics focus solely on effectiveness without simultaneously accounting for other measures like equity and the strategic goal(s) of the agency. From a pragmatic standpoint, most SHAs have strategic goals about the percentage of pavement sections that are expected to be in a specified condition state (score) for each year or over a pre-determined planning horizon. Furthermore, addressing performance gaps in condition states of individual pavement sections is also standard practice by pavement engineers in highway agencies. This ensures that poorly performing sections of the network do not fall below acceptable standards which can lead to expensive rehabilitation projects later on. In the current study, the methods chosen for comparison have all been previously implemented on a subset pavement network in Texas. They have common pavement assessment measures (condition scores, etc.) and the same implementation context. This allows for the objective evaluation of different methods to demonstrate each method's pragmatic merits and demerits in budget allocation for M&R programming. Furthermore, the cost-benefit analysis, needs-based approach and the integer-linear programming methods have been reported to be used by several highway agencies in nationwide studies by Wiegmann and Yelchuru (2012) and Cambridge Systematics (2009).

Thus, the primary objective of this study is to compare methods from the identified major approaches to M&R programming—ranking-based approaches, mathematical optimization models, and data mining. The corresponding methods are cost-benefit analysis, integer-linear programming, and a combination of a "decision tree classifier (data mining approach) + needs-based" allocation method. All the methods (hitherto implemented on a portion of the Texas highway network) are applied in a numerical case study representative of a subset pavement network in Texas. The models are evaluated based on the average network condition score (effectiveness), inherent equity considerations, and their ability to meet the prime strategic goal set by a highway agency (in this case, TxDOT).

5.4 Budget Allocation Methods

This section provides a description of the three methods implemented in the numerical case study. The section highlights the major assumptions, the resource allocation logic, and the parameters that were used in each method for the case implementation and comparison.

5.4.1 Cost-Benefit Analysis

One often used method for prioritizing M&R projects for budget allocation is the Cost-Benefit Analysis (CBA). Menendez et al. (2013) proposed and implemented a CBA approach in a TxDOT district to develop multi-year M&R plans for different budgetary scenarios. The decision-making process occurred at two levels—project and network. At the project level, the metric used for treatment selection was the treatment cost to added life (CAL_m) ratio. At the network level, projects were prioritized based on the relative importance of the shortlisted projects on the expected improvement of the network. Concerning the former, pavement sections with a condition score lower than 70 (CS_{net}) were eligible for an M&R treatment. An eligible M&R treatment for a pavement section had to be able to increase the CS to at least 70 or more. The added life (AL_m) of each eligible pavement section was calculated based on non-linear pavement performance models developed and used by TxDOT (Equation 5.1). The equation was based on consideration of the estimated additional years added to the life of the pavement section before it fell below the threshold value (CS_{net} of 70). The CAL_m was then calculated, as shown in Equation 5.2, as the ratio of the unit treatment cost (C_m) and the added life (AL_m). The treatments with the lowest CAL_m ratio were then chosen as the optimal project alternatives for the shortlisted pavement sections. All the pavement performance modeling parameter values were, as presented in Menendez et al. (2013), based on the treatment option and the traffic classification categories (low, medium, or high).

$$AL_m = \frac{\rho_{pm}}{\left[-\ln\left(1 - \frac{CS_{net}}{\min(CS_B + \Delta CS_{pm}, 100)}\right)\right]^{\frac{1}{\beta_{pm}}}} \tag{5.1}$$

Where ρ_{pm} and β_{pm} are curve parameters for traffic level p and treatment option m (Table 5-1), CS_B is the condition of the section prior to the application of the treatment while ΔCS_{pm} is the estimated improvement in the CS based on the traffic level p and treatment option m.

$$CAL_m = \frac{C_m}{AL_m} \tag{5.2}$$

Considering the network-level prioritization of projects, these were conducted based on how important the shortlisted projects were to the expected improvement on the network. Prior to this stage, all the eligible pavement sections in the network have an assigned project (based on the CAL ratio). Hence, the problem being addressed here is which project to fund based on a limited budget. The proposed approach was to calculate the benefit of each section *i* ($Benefit_i$) by calculating a product of the AADT, section length, and the area between the performance curve ($AUPC_i$) and the threshold value. This was followed by calculating the total cost ($Cost_i$) of the project as a product of the length, number of lanes, and unit cost of the selected M&R project (Equation 5.3). Pavement sections were then ranked in order of descending benefit-to-cost ratios (BCR_i) and allocated funds until the M&R budget for each year was exhausted.

$$BCR_i = \frac{Benefit_i}{Cost_i} = \frac{AADT_i \times AUPC_i \times L_i}{C_m \times L_i \times N_i} \tag{5.3}$$

Table 5-1. Curve parameters for additional pavement life model (Menendez et al. 2013)

	β_{pm}			ρ_{pm}		
M&R Option	Low traffic	Medium Traffic	High Traffic	Low traffic	Medium Traffic	High Traffic
PM	2.3	1.5	1.7	9.3	9.0	10.6
LR	2.4	1.5	1.5	11.0	12.5	12.4
MR	2.4	1.6	1.3	12.9	14.8	14.7
HR	2.5	1.6	1.2	16.1	19.4	17.1

5.4.2 Integer-Linear Programming

Integer-linear programming (ILP) models provide quantitative solutions on the selection (0- not selected, 1- selected) of specific projects to be undertaken throughout a network to optimize specified objectives under constraints. SHAs usually need to choose an optimal set of projects from a pool of candidate projects for multiple years. Hence, the ILP approach was chosen because it is one of the most employed models for budget allocation due the specificity in its solutions providing details on the timing, treatment type, and location (Gao and Zhang 2013b). For this model, the current work presents a novel integer-linear program which builds on studies by Al-Amin (2013), Wang et al. (2003), and Lee and Madanat (2015). Table 5-2 displays the notations for the parameters and decision variables of the model.

Table 5-2. Notations of the integer-linear program

Symbol	Definition
$AADT_i$	Average annual daily traffic of pavement section *i*
$AADTT_i$	Average annual daily truck traffic of pavement section *i*
B_t	Available budget for M&R at period *t*
C_{im}	Unit cost of applying treatment *m* to pavement section *i*
CS_{i0}	Initial condition score for pavement section *i*
CS_{it}	Condition Score for pavement section *i* at period *t*
CS_{max}	Maximum possible condition score for each pavement section in the network
CS_{min}	Least allowable condition score for each pavement section in the network
DC_m	Travel time delay costs per AADT for treatment option, *m*
d_i	Constant pavement deterioration rate for pavement section *i*
e_{im}	Improvement in condition score for pavement section *i* for M&R treatment option, *m*
L_i	Length of pavement section *i* (in miles)
N_i	Number of lanes of pavement section, *i*
OC_1	Marginal operating cost of a passenger car
OC_2	Marginal operating cost of a truck
RS_i	Ride score of pavement section *i*
TDC_{im}	Travel time delay costs for pavement section *i* for treatment option *m*
VOC_i	Vehicle operating costs for pavement section *i*
Wc	Adjustment factor - average cost of adding one additional unit of condition score
X_{imt}	Whether or not to select pavement section *i*, for treatment *m*, in year *t* (binary variable 0:not selected or 1: if selected)

Objective Functions

The objectives of the model include the maximization of pavement condition improvements and the minimization of road user costs. The first objective (Z_1) is constructed as the summation of the product of the number of lane-km (lane-miles), improvement in condition scores, and decision variable for each pavement section, maintenance treatment chosen, and specific time period (Equation 5.4).

$$max\ Z_1 = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{t=1}^{T}(N_i L_i\ e_{im})x_{imt} \tag{5.4}$$

Šelih et al. (2008) demonstrated that, in comparison to M&R agency costs, indirect costs like road user costs are significant even when the actual user costs are underestimated. Accordingly, the second objective of this model was to account for the road user costs which are usually borne by the public and the state as a whole. The primary components of road user costs are the vehicle operating cost, crash cost, and the travel delay cost (Gao and Zhang 2013a). This model accounts for the most valuable and measurable components of user costs—travel-delay and vehicle operating costs (Lee and Madanat 2015). Crash costs are difficult to evaluate and are thus often not accounted for in the formulation of road user cost models. These are shown in Equations 5.5 to 5.7.

$$min\ \ Z_2 = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{t=1}^{T}(VOC_i + TDC_{im})x_{imt} \tag{5.5}$$

Where,

$$VOC_i = \left(OC_1 * (AADT_i - AADTT_i) + OC_2 * (AADTT_i)\right) * RS_i \tag{5.6}$$

$$TDC_{im} = AADT_i * DC_m \tag{5.7}$$

The weighted sum approach was used to form a composite function (Z_3) of the two conflicting objectives (Equation 5.8). Furthermore, the weighting factors allow different highway agencies to assign different factors to the level of importance that improvements to infrastructure conditions have in relation to user costs. Given the difference in units of the functions, a conversion factor (W_c) was introduced to objective function (Z_1) to ensure that both functions were in equivalent dollar values. W_c was calculated by finding the average marginal cost of improving a pavement section by one unit (condition score). This value was assessed to be $7,705/lane-km/unit CS ($12,400/lane-mile/unit CS) in this study. For purposes of comparison, W_1 was chosen as 0.9 and hence (1- W_1) was 0.1 for Z_2. This is based on the argument that agency costs are physically and directly borne by SHAs while user costs are not as "visible" (Khurshid et al. 2009).

$$max\ Z_3 = [W_1 * W_c * Z_1 + (1 - W_1) * -Z_2] \quad (5.8)$$

Constraints

To reflect the pragmatic programming constraints and practices by pavement engineers in a typical highway agency (TxDOT), a number of constraints were formulated. First, the total cost of performing all the M&R projects for each year should not exceed the budget allocation for each time point (Equation 5.9). It is also important to account for the changes in the condition score from year to year based on the applied M&R project and pavement deterioration based on traffic and other factors. This transition equation is based on a study by (Wang et al. 2003a), as shown in Equation 5.10.

$$\sum_{i=1}^{I}\sum_{m=1}^{M} N_i L_i C_{im} x_{imt} \leq B_t \qquad \forall t \in T \tag{5.9}$$

$$CS_{it} = CS_{i0}(1-d_i)^t + \sum_{m=1}^{M}\sum_{t*=1}^{T} x_{imt} e_{im} (1-d_i)^{t-t*} \qquad \forall t \in T \quad \forall i \in I \tag{5.10}$$

Where t* is a previous discrete time point (t* ≤ t) at which an M&R treatment was applied to the pavement section. This confirms that the model takes into account the impact of previous M&R treatments.

The next set of constraints ensures that the minimum and maximum condition score values are satisfied (Equation 5.11). Finally, the model also accounted for constraints on the number of treatments that each pavement section can receive per year and the total number of treatments which a specific pavement section can receive over the planning horizon (Equation 5.12). For Texas pavements, sections were limited to one treatment option (can be no maintenance) per year, so four treatments per section over the development of the 4-year PMP.

$$CS_{min} \leq CS_{it} \leq CS_{max} \qquad \forall t \in T \quad \forall i \in I \tag{5.11}$$

$$\sum_{m=1}^{M} x_{imt} = 1, \qquad \forall t \in T \quad \forall i \in I \tag{5.12}$$

Other Parameter Values

For this study, a pavement condition score deterioration rate of 5% was assumed. The present value of operating costs used for the model were $0.0547/lane-km/unit ride score ($0.0881/lane-mile/unit ride score) for passenger cars and $0.1861/lane-km/unit ride score ($0.2995/lane-mile/unit ride score) for trucks (Gao and Zhang 2013a). The allowable minimum and maximum condition scores were also constrained at 50 and 100 respectively. Table 5-3 shows the assumed values for other relevant parameters that were used for the implementation of this model.

Table 5-3. Condition score improvements, travel delay costs, and M&R treatment costs

M&R Option	**Treatment Cost ($ per lane-mile)**	**PMIS Condition Score Improvement**	**Travel Delay Costs ($/AADT/lane-mile)**
NM	0	0	0
PM	34,000	3	0
LR	202,000	15	0.5
MR	277,000	25	1
HR	517,000	40	1.35

5.4.3 Decision-Tree + Needs-based allocation

As the name suggests, the "Decision-Tree + Needs-based allocation" (DTN) method is a combination of two methods. A general description of this method is outlined below;

- Assembly of pavement-related data on the condition trends of the pavement sections in the network.
- Selection of representative attributes from the list of pavement attributes which can influence the decision to select a pavement section for a project.

- Assignment of class labels (project eligibility) based on experiential knowledge of pavement engineers.
- Setting up and execution of decision trees or rule-based algorithms to predict class labels.
- Selection and implementation of best performing classifiers to prioritize pavement sections.
- Application of "Worst First" approach on the prioritized list of pavement sections.

The decision tree algorithm used in this study is based on a study by Chi et al. (2013). The main objective of that decision tree was to aid in the efficient screening of network-level candidate projects for a district in TxDOT. The attributes (features) used for the derivation of the decision tree in that study were the current CS, the condition score deterioration (CSD) from the previous year, and the condition of the adjacent pavement sections in the network. The project selection algorithm used these input features to classify candidate projects as one of the following: a potential immediate project, a vigilance project, or an isolated project. The classification was carried out in two phases. The first classification algorithm (J48 class for creating a pruned or unpruned C4.5 decision tree), which was implemented in *Weka* (data mining software developed by Witten et al. 1999), was used to decide if a pavement section should be a project (Yes), not be a project (No), or be closely monitored for future intervention (Vigilance). The next phase involved addressing the problem of having "isolated" projects and the prioritization of consolidated projects based on the number of contiguous pavement sections needing M&R intervention (Yes and Vigilance) and a project-ranking matrix.

In this study, the method described above was slightly modified. The projects eligibility decision tree generated by the J48 class was used in conjunction with a needs-based (Worst-First) allocation logic (typically used by pavement engineers) for M&R budget allocation. The decision tree (in Figure 5-4) was used as a guide to shortlist the number of pavement sections that should, in the current planning year, have an M&R project (Yes and/or Vigilance). After the shortlist, a traditional Worst-First (WF) approach was employed to assign funds to suitable M&R projects until the allocated budget for each year was depleted. Based on the structure of the tree, pavement sections with "bad" condition scores were funded first followed by other pavement sections classified as "Yes" and then "Vigilance" if there were still more funds available. For the feature categories, the CS for each pavement section was grouped as follows: bad ($CS \leq 70$), fair ($70 < CS \leq 80$), and good ($80 < CS \leq 100$). Similarly, the CSD were also categorized as slow ($-5 \leq CSD$), medium ($-15 \leq CSD < -5$), and fast ($CS < -15$). This is consistent with the groupings for the second test set of the original study which yielded higher prediction accuracies for the test data.

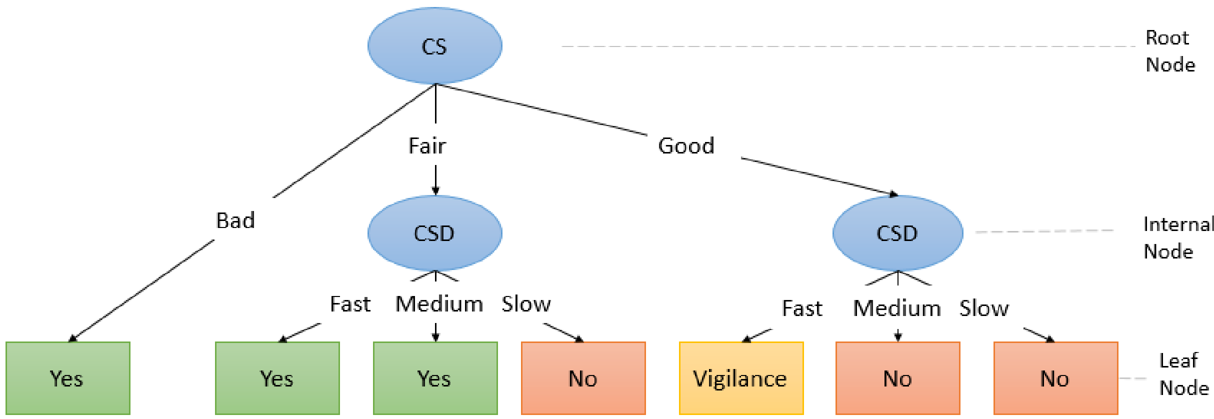


Figure 5-4. Decision tree for shortlisting pavement sections (modified from Chi et al. 2013)

5.5 CASE STUDY

5.5.1 Preamble

The models were implemented on a network size of 50 flexible pavement sections, representative of a subset network in Texas. The pavement attributes were retrieved from PMIS; Table 5-4 presents a summary statistical description of the salient attributes of the network. Considering a typical PMP, a 4-year planning horizon was chosen for the case study implementation. All the selected pavement sections were 0.81-km (0.5-mile) in length with 2 lanes. The budget for the 4-year plan was $2 million (assumed to be in constant dollars). For other cost parameter values retrieved from earlier studies, a discount rate of 4% was used to adjust previous values to present worth (Lamptey et al. 2008b). For the Integer-linear model, the model was formulated and solved within the General Algebraic Modeling System (GAMS) software environment. While GAMS has a number of solvers for mixed integer programming (MIP), the solver "branch and cut

(CBC)” originally developed by Computational Infrastructure for Operations Research (COIN-OR) was used. The CBC algorithm for solving MIP models is an extension of the “branch-and-bound” method with cutting planes to constrain the relaxations of linear programming (Mitchell 2002). The other approaches (cost-benefit analysis and decision tree + needs-based allocation) were implemented in a traditional worksheet (Microsoft Excel®) environment with formulas and Visual Basic for Applications (VBA). Given the scope of the problem (network size), there were no significant differences in the computational times between the approaches employed.

Table 5-4. Summary statistics of the model pavement network (50 sections)

Attribute	Mean	Median	Minimum	Maximum	Standard Deviation
AADTT*	118.86	102.00	14.00	350.00	91.55
AADT**	2253.50	1168.50	167.00	6807.00	2161.88
Ride Score	3.04	3.00	2.00	4.00	0.49
Current Condition Score	76.40	76.50	51.00	98.00	12.79
Previous Condition Score	78.84	82.00	45.00	99.00	14.42

* Annual Average Daily Truck Traffic (AADTT)

** Annual Average Daily Traffic (AADT)

5.5.2 Performance Evaluation

The three approaches to projects prioritization and budget allocation were assessed via three measures—the concepts of effectiveness, equity, and the achievement of a strategic goal synonymous to one set by TxDOT. Effectiveness was measured by the computation of the average network condition score at the end of each plan year. Furthermore, after the implementation of the different methods, a final network condition score (in the 4th year) was also assessed as an indication of the "residual" value of the network. Equity is a largely subjective measure; it is important then to clearly define it for the context of this study. The notion of equity used in this paper is not "social equity." Equity is defined in this study as the fair distribution of M&R funds according to pavement sections in need of interventions. This concept for measuring the fairness of the distribution of limited resources is often used in the performance evaluation of resource allocation in other areas (Mishra et al. 2015). For many mathematical models developed for M&R programming in the extant literature, though, researchers neglect equity considerations or fail to specifically account for them during problem formulation. In a network-level study by Boyles (2015), it was suggested that more funding tends to go to urban areas than rural areas which is "arguably unfair and politically infeasible." Since equity theory was not the focus of the paper, the authors did not specifically account for equity in the constraints of the integer-linear program (in order to reflect the status quo of most models in the literature). Given the importance of the impact of M&R strategies on the resulting condition of the network, the metrics used to assess equity focused on "equity in outcome" of the condition scores. This study focused on equity by examining how an allocation method widened or reduced the gap in condition scores for the different pavement sections in the network. Hence, assigning funds to pavements sections which had lower condition scores was perceived as more "equitable." The specific metrics used in this study include the range (the difference between the minimum and maximum values) and the standard deviation of the condition scores of the pavement network for each plan (fiscal) year. The last measure of assessment is the percentage of pavement sections that qualified as being in a "good or better" condition. This was based on TxDOT's statewide condition goal of having 90% of pavement lane miles in a "good or better" condition.

5.6 RESULTS AND DISCUSSION

5.6.1 Effectiveness

Over the planning horizon (4 years), the average network condition score dropped continually for all the methods compared. This could be indicative of an allocated budget ($2 million) that is insufficient to maintain the infrastructure network at its current functional and structural condition. The integer-linear programming approach emerges as the most "effective" budget allocation approach since it leads to the slowest annual decline in average network condition score (Figure 5-5). With an average decline in network condition score of 0.3% per year, the ILP method significantly outperformed the CBA and DTN methods, which had average declines of 1.17% and 1% per annum. The difference between the ILP method and other methods becomes increasingly conspicuous with an average network condition score of 75.42 in the 4th year in comparison to 72.94 and 73.42 for CBA and DTN respectively. Hence, from a "residual value" perspective, ILP also leaves the network with the highest asset value. This happens because, for the latter models, pavements in "very good" and "good" conditions seldom receive M&R treatments or projects. This often leads to faster declines in the condition scores of such pavement sections since deterioration occurs over longer periods of time leading to a geometric compound impact.

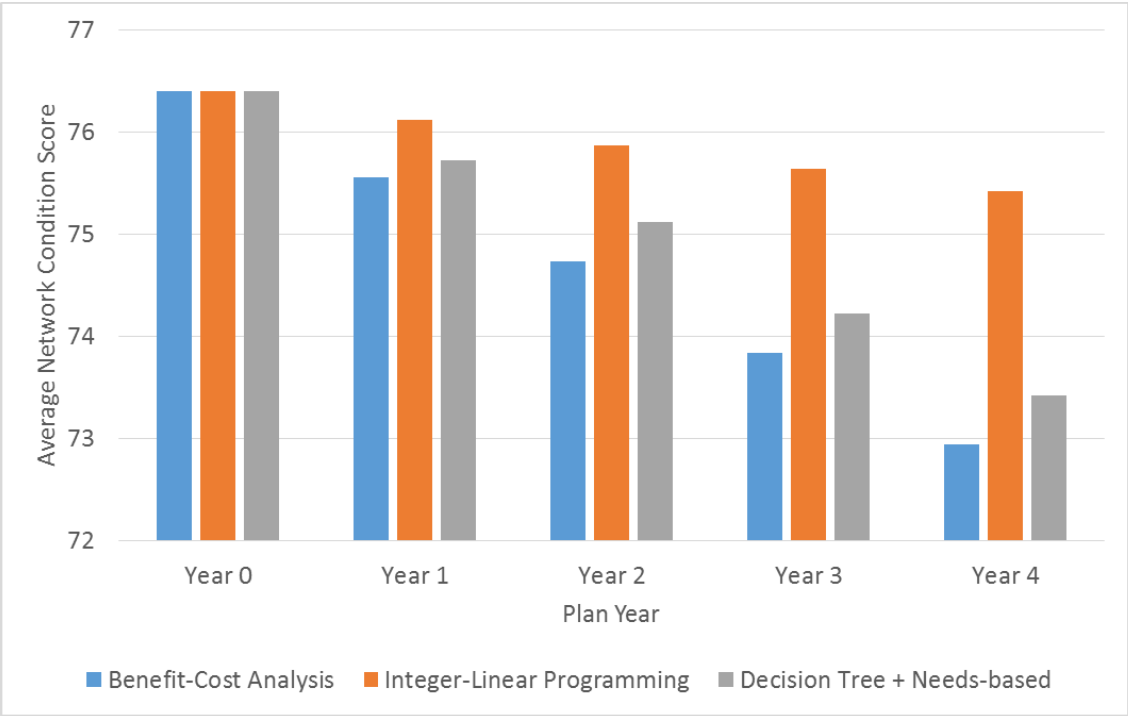


Figure 5-5. Results of the average network condition score

5.6.2 Equity

Given the lack of standardized measures in the assessment of equity in M&R budget allocation outcomes, this study chose the conventional statistical metrics—range and standard deviation of the condition scores. For both metrics, CBA and DTN performed better than ILP. There was practically no difference in the measure of dispersion between the CBA and DTN methods which were within 0.28 standard deviation points of the condition score of individual pavement sections throughout the planning period. The trend is similar for the range values in individual pavement condition scores for both methods. Furthermore, over the fiscal years of planning, both methods continually reduced the level of disparity between the condition scores of individual sections (Figure

5-6). Conversely, the ILP method appeared to maintain the initial level of disparity (standard deviation around 12) in the condition scores of the pavement network for each time period. Accordingly, it does not necessarily reduce or increase the difference in the condition scores of the pavement sections.

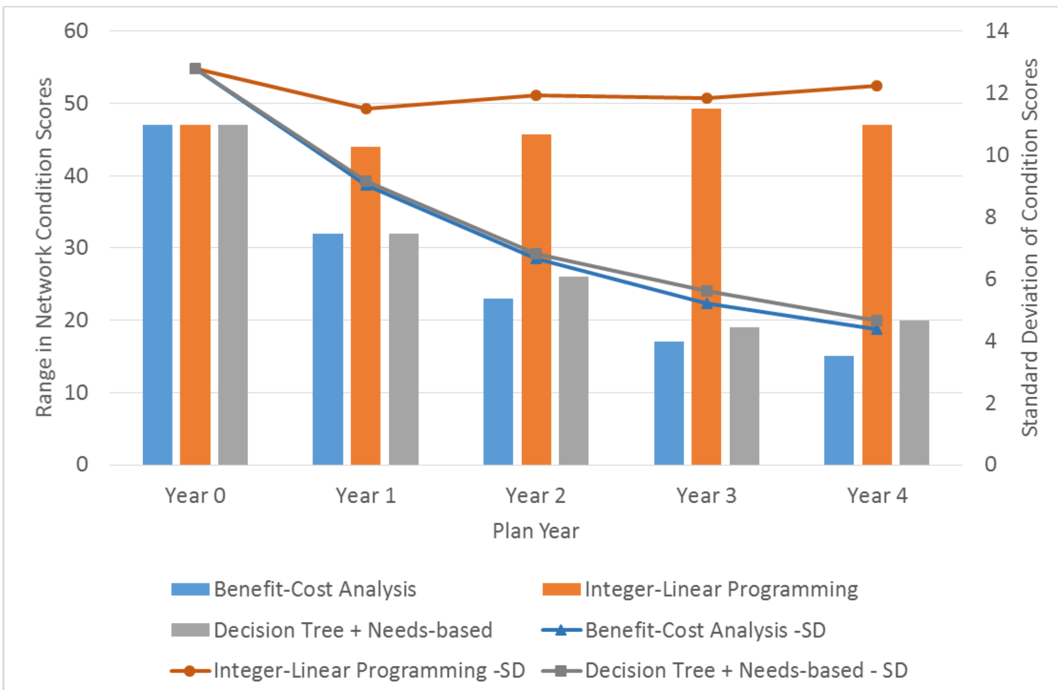


Figure 5-6. Results of range and spread of network condition scores

5.6.3 Strategic Goal (% Good or Better)

Different agencies have varying strategic goals based on different decision-making levels (state, district, and local/area). However, for this performance measure, a variation of TxDOT's statewide goal was used. DTN starts out in the first year with the most (76%) pavement sections in a "good or better" condition but consistently declines to 68% (4th year) over the remaining time periods (Figure 5-7). On the other hand, CBA shows an up-and-down movement trend that declines over time, ranging from 68% (lowest in year 4) to 72% (highest in year 1). The ILP model follows a similar trend with generally higher percentages of pavement sections in a good or better condition. In the third and fourth years, ILP also emerges as the most consistent approach with the highest number (72%) of good pavement sections in the network. Accordingly, the authors argue that the ILP approach is the best and most consistent method of achieving the strategic statewide goal of TxDOT.

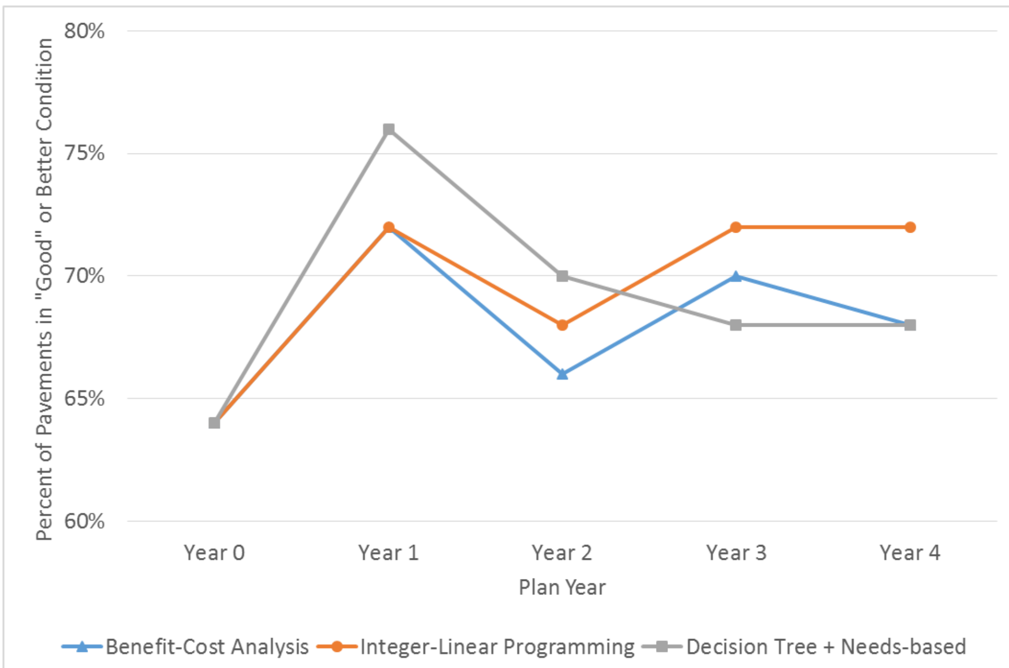


Figure 5-7. Percentage of pavement sections in at least good condition

5.6.4 Key Inferences

The CBA method is used by highway agencies because it is able to measure and contrast the performance benefits versus treatment costs on a pavement section; thereby providing a neutral metric for performance evaluation of M&R treatments. At the network-level, accounting for AADT in the prioritization of M&R projects also helps partially account for the relevance of a particular pavement section to the highway network. In this study, it was found that in spite of these considerations, the CBA method employed was not the most effective. A key demerit of this method is that it does not account for “good or better” pavement sections that may be rapidly deteriorating. As Labi and Sinha (2005) pointed out, even for pavements in a good condition, a preventive maintenance project can retard the onset of significant deterioration of the section, potentially obviating the need for a more expensive future M&R project. Another observation during implementation was that, since this particular CBA approach recommends treatment options with the least cost to added life ratio, selected projects were more likely to lead to the minimally acceptable impact. Beyond the second year, most of the suggested projects were PM or LR, which is not reflective of practical decision-making choices. On the other hand, the CBA method has strong inherent equity considerations, which leads to better equity in outcome results. This is reflected by the decreasing standard deviation in network condition scores over time.

In this study, it was found that of the three methods implemented, ILP is the most effective. This is consistent with previous studies that did comparative analyses of other mathematical optimization methods and other judgment-based methods like the Worst-First approach (Visintine et al. 2016). It also outperformed the other approaches in leading to a network in the best condition at the end of the planning horizon as well as in better achieving the strategic goal of the agency. At the same time, in equity considerations, it performed the worst. Certainly, the ILP model can be formulated to account for better equity in outcome. However, as indicated earlier, most models in the literature do not specifically account for equity in outcome concerns. Hence, this study also demonstrates this gap in problem formulation. This notwithstanding, it is important to note that it would also be unrealistic to make the minimization of the difference in condition scores of pavement sections an optimization objective instead of a flexible model constraint. Different highway agencies have varying levels of "equity in outcome" expectations that are acceptable while simultaneously accounting for the network-wide effectiveness of proposed models. Furthermore, there appears to be an inverse relationship between increasing "effectiveness" and improving "equity" as confirmed by an earlier study by Castells and Solé-Ollé (2005). Accordingly, an area for further research could be investigating the balance between these measures when both concepts are incorporated in the same optimization model and implementation context.

The DTN method is a hybrid approach that fuses the project-screening function of decision trees (based on data mining) and a needs-based (Worst-First) allocation approach. The results of its implementation suggest that its performance is similar to that of the CBA approach. DTN has similar, strong equity considerations because it prioritizes pavement sections in "fair" or worse condition to be eligible to receive M&R projects. Furthermore, it also accounts for pavement sections that are in "good" condition but deteriorating at a "fast" rate. This possibly explains the marginal advantage that DTN has over CBA in having higher average network condition scores over the planning period. While the decision tree used for this study is based on a previous study on Texas pavements, other SHAs can perform a similar analysis for their state networks and benefit from the balance in "equity" and "effectiveness" that DTN offers. The most important merit of using decision trees in practice is that they are white-box analysis techniques, which provide a consistent approach to making experience-based decisions (Chi et al. 2013). Accordingly, it would be easier for practitioners to adopt this method in conjunction with the Worst-First Approach—a method pavement engineers are already familiar with.

5.7 CONCLUSION

Findings from this study support the widely-held claim that optimization models are generally more effective than other approaches (DingXin Cheng et al. 2010). First, this paper has presented a consolidated review of the major approaches to budget allocation in the extant literature. Second, this work conducted a comparative analysis of select methods within each major approach on a numerical example illustrative of a subset network in Texas. The models were assessed based on three performance measures (equity, effectiveness, and strategic goal achievement) of a smaller scope pavement management plan typically developed by a highway agency. The method achieving the highest average network condition score was the ILP budget allocation, though at the expense of a deficiency in equity considerations over the planning horizon. On the other hand, CBA and DTN both performed better in equity measures, with DTN slightly outperforming CBA in effectiveness.

The primary contribution of this paper is that it demonstrates the effectiveness, equity considerations, and strategic goal performance of select methods of ranking-based, mathematical optimization, and data-mining approaches to budget allocation. The extant literature contains several methods that are not assessed based on established, comprehensive, and well-defined criteria for model performance. Previous comparative studies have often focused on just evaluating the effectiveness (functional or structural performance of pavement network) of methods without accounting for the equity considerations and the degree to which different methods achieve typical agency goals. By performing a well-defined comparative analysis and simple but useful evaluation of different methods, the findings from this study provide useful information for pavement engineers who are considering a transition to a more formal analytical approach to budget allocation. Furthermore, this work has proposed a novel network-level project selection ILP model that was assessed to be the most "effective" approach among the CBA and DTN methods. This ILP model can also be formulated to accommodate both equity and effectiveness concepts and allows decision-makers the flexibility of choosing the specific network-wide goals to be achieved. As demonstrated in this study, there appears to be an "equity-effectiveness" trade-off based on the different methods employed. This concept needs to be accounted for in the decision by any SHA to employ any of the above-implemented methods. Future research can explore the equity–effectiveness Pareto frontier and possibly make recommendations for model modifications and adaptation based on specific agency goals, M&R practices, and other relevant factors. This could drive the proposal of more hybrid approaches that could leverage the advantages of different methods for M&R budget allocation.

Chapter 6 Impact of Multiple Highway Funding Categories and Project Eligibility Restrictions on Pavement Performance

Most of the contents in this chapter is a reprint from the accepted publication: France-Mensah, J., O'Brien, W. J., Khwaja, N. (2019) "Impact of multiple highway funding categories and project eligibility restrictions on pavement performance" ASCE Journal of Infrastructure Systems, 25(1), 04018037. The corresponding author (Jojo France-Mensah) designed the research approach, performed the data collection and analysis, and wrote the manuscript.

In maintenance and rehabilitation (M&R) programming, most budget allocation models in literature often assume one principal budget that can be used for funding all the different projects undertaken by the decision-making entity. For most agencies, this is rarely the case. This study explores the impact of formulating the M&R budget allocation problem with multiple funding categories (or budgets) having stringent project eligibility constraints. For state highway agencies (SHAs), there are often several federal, state, and local funding sources for highway projects. There are also agency norms and regulations that restrain the eligible projects under each funding category. This study presents an integer-linear programming model that accounts for funding restrictions in M&R budgets to assess changes in network performance and M&R decisions for pavement assets. The model is implemented in a numerical case study representing a subset network consisting of 500 pavement sections. Findings from this study suggest that the projected performance of the M&R program is overestimated when there is the assumption of one “central” budget with no project eligibility constraints. This may lead to an increase in unplanned expenditures towards reactive M&R projects to meet performance targets. Furthermore, the findings also suggest that increasingly restrictive budgets lead to a lower network performance for the same aggregate budget. The sensitivity analyses conducted confirm that the results obtained are robust against variations in key input variables used in the model. These findings contribute to ongoing efforts towards incorporating pragmatic constraints in optimization models to enhance their utility for effective decision-making.

6.1 Introduction

An efficient maintenance and rehabilitation (M&R) policy is key for the development and sustenance of a safe and functionally effective transportation infrastructure (Ng et al. 2011). Planning for transportation infrastructure involves complex decisions concerning Right-of-Way (ROW) acquisitions, funds allocation, public engagement, setting strategic goals, and the development of short-to-long term plans for the expansion and preservation of highway assets (France-Mensah et al. 2017a; O’Brien et al. 2012). This process is challenged by the rapid deterioration rate of highway infrastructure resulting from exposure to adverse environmental conditions and an increase in urbanization in the United States (Anani and Madanat 2010; Sahin et al. 2014). Furthermore, the M&R planning process also involves managing multiple and often conflicting stakeholder objectives at the federal, state, and local agency levels (Chen et al. 2015; Sankaran et al. 2016; Torres-Machí et al. 2014). Decisions on highway development and maintenance can lead to significant impacts on the safety, ease of transportation, and socio-economic development of the respective jurisdictions of the decision-making entity (Boyles et al. 2010).

After the initial phase of the mass construction and development of the interstate system, State Highway Agencies (SHAs) gradually transitioned from expansion to the preservation of highway infrastructure assets (Dong et al. 2013; Mild and Salo 2009b). The focus on the maintenance of highway infrastructure has been primarily driven by an increase in the funding gap between maintenance needs and available budgets, stringent government regulations, sustainability considerations, growing travel demand, and increased accountability concerning the allocation of highway funds (Shah et al. 2014; Torres-Machi et al. 2017; Wu et al. 2012a). With a grade of "D" in the current "Infrastructure Report Card" for roads, the American Society of Civil Engineers (ASCE) estimates that the funding gap (for "improvements") in surface transportation infrastructure will be about $1.1 trillion (constant 2015 dollars) over the next decade (2016 –2025). M&R projects account for an estimated $420 billion out of this total funding deficit (ASCE 2017). These concerns about increasing gaps in funding highway infrastructure have led to legislative proposals geared towards increasing strategic data-driven decision-making and the implementation of asset management principles (D'Ignazio et al. 2015; France-Mensah et al. 2017a). The Moving Ahead for Progress in the 21st Century Act (MAP-21), introduced in 2012, emphasized the need to make highway funding decisions more safety-focused, more sustainable (in protecting the environment), and performance-driven (France-Mensah et al. 2017b; Saha and Ksaibati 2015b).

The need to develop defensible and effective M&R policies has led to the development of several approaches in the literature for budget planning and budget allocation. Accordingly, for several agencies, these investment decisions tend to be a hybrid of qualitative and quantitative approaches. However, there have been growing concerns about the fairness and objectivity in the use of such subjective measures in supporting the decisions on budget allocation for highway infrastructure using tax-payer dollars (Kulkarni et al. 2004). Consequently, in the past few decades, there has been a push for the use of objective mathematical optimization models in driving M&R decisions to ensure optimal decisions concerning highway infrastructure performance and to achieve the best "value for money" in highway investments (Wiegmann and Yelchuru 2012). Mathematical optimization models provide policy makers with the option of optimizing multiple objectives while considering constraints that different decision-making agencies have to contend with (Farhan and Fwa 2011). This notwithstanding, the practical adoption of optimization techniques for highway asset management has still been slow, due in part, to the critique of inadequate pragmatic considerations in models (Wu et al. 2012a).

One such pragmatic consideration which is absent from most optimization models for M&R budget allocation is the multiplicity of highway funding categories and their respective project eligibility constraints. Most approaches to budget allocation in M&R programming assume one central source of funding with no restriction on the different types of projects that are eligible for funding. However, especially for metropolitan agencies, there are often multiple funding categories with specific restrictions on which types of pavement M&R projects that are eligible for funding per category. This study aims to assess the impact of multiple funding categories with eligibility constraints on budget allocation decisions by formulating an integer-based optimization model which accounts for multiple funding categories. Through the proposed model, this paper addresses an important characteristic of M&R budgets in pavement management decision-making and extends the state-of-the-art understanding of highway budgeting dynamics in the literature.

The remaining sections of the chapter are organized as follows. The background review discusses relevant studies on the use of optimization models in budget allocation and highway funding sources for M&R. Subsequently, the research approach is presented followed by the problem formulation consisting of the objective function and alternate budgetary constraints. Next, the model implementation is demonstrated through a numerical case study along with a discussion of the results. The key conclusions are then presented together with future directions for the study.

6.2 BACKGROUND REVIEW

Highway asset management involves the utilization of business-oriented approaches to strategically and systematically operate, maintain, upgrade, and expand physical highway assets throughout their lifecycle (Porras-Alvarado 2016). A key part of this process is the allocation of resources to highway programs and projects in a way that significantly improves the performance of highway networks in a cost-effective manner (Cambridge Systematics 2009). For many Departments of Transportation (DOTs) and other highway agencies in the U.S., the funding available for highway planning is constrained by legislative and managerial constraints which makes the budget allocation process complex (France-Mensah et al. 2017a). For this reason, agency decision-makers need to account for these complex funding restrictions and budgetary constraints as part of the process of developing short to long-term highway asset management plans. To further explore these funding dynamics that most highway agencies need to contend with, a brief overview of funding sources and such typical funding constraints are discussed next.

6.2.1 Review of Highway Funding Sources

The Federal Highway Trust Fund (HTF) was created in 1956 with the passing of the "Federal-Aid Highway Act of 1956: Creating the Interstate System." This is one of the major legislations which led to the planning and development of the interstate system from gasoline and diesel fuel taxes which the federal government had started collecting in 1932 (Small et al. 2012). Today, every SHA receives highway funding from the Federal HTF and each State's own receipts of applicable taxes and fees. Federal funds are mostly given to SHAs as reimbursements for eligible highway planning and construction projects already being undertaken by the respective agencies. For such projects, the federal funds are used to fund about 80% to 90% of the highway project costs. Depending on the agency, state highway funds can also include user taxes, oil production taxes, vehicle registration fees, licensing fees, surplus toll revenues, local funds, bond programs, and special legislative appropriations by the respective State's legislative body or Metropolitan Planning Organizations as shown in Figure 6-1 (Porras-Alvarado et al. 2015; Small et al. 2012).

Furthermore, these sources are usually allocated to legislatively mandated categories of funding for pre-approved types of projects. Hence, there could be categories for pavement maintenance, rehabilitation, bridges, operations, safety projects, mobility enhancements, and other strategically classified categories based on the respective SHA's goals and objectives. For example, the State Highway Account of the California Department of Transportation is used to fund 8 major funding categories including expenditures on major damage restoration, corridor mobility improvement, roadway preservation, collision reduction, and bridge preservation, among others (California Department of Transportation 2015). Furthermore, within these funding categories, there can also be area/district-level constraints on how much funds can be allocated to specific types of projects and whether certain projects are performed in-house or contracted out. This trend in budget divisions and different funding categories often applies to several SHAs as well as their respective district- and area-level entities. However, most models in the literature ignore this characteristic of funding in the formulation of the budget allocation problem for pavement M&R programming. Accordingly, a review of the current resource allocation models in the literature is presented to provide a theoretical context for the study.

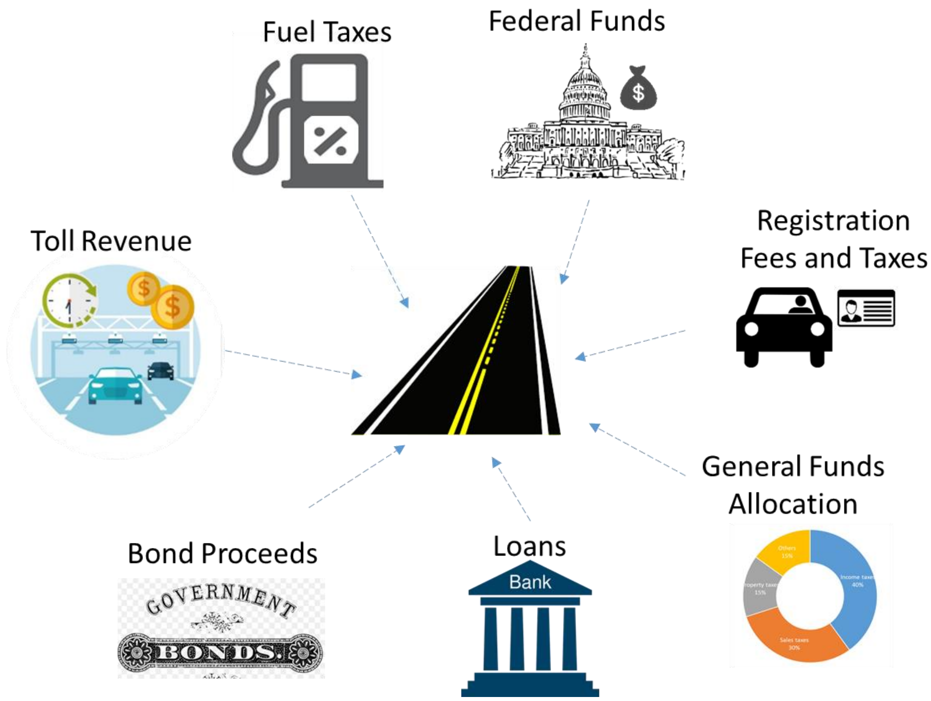


Figure 6-1. Transportation funding and finance sources

6.2.2 Review of Resource Allocation Models

Resource allocation approaches in the literature can be categorized into three major clusters namely historical/formula allocations, performance or asset-based allocation, and optimization schemes (Fwa and Farhan 2012; Porras-Alvarado 2016). For pavement assets, the dominant techniques include the use of the "Worst-First" approach, cost-benefit analysis (CBA), analytic hierarchy process (AHP), and mathematical optimization models (Hong et al. 2017). While the latter two are still in an emerging phase in practice, the former two techniques are well-documented practices by decision-makers in highway agencies (Wiegmann and Yelchuru 2012). The worst-first approach involves the prioritization and selection of projects based on the current condition of the pavement sections in the network. Accordingly, pavement sections in the "worst" conditions receive the most immediate and expensive projects (Menendez et al. 2013). Conversely, the cost-benefit analysis method is based on the projected performance benefits and the associated costs of M&R treatments over a multi-year period. According to Almalki et al. (2016), SHAs were reported to be using CBA more than the worst-first approach in prioritizing projects for potential funding. Relatively new to decision-making in highway asset management, AHP is a structured hierarchy which employs a mathematical approach for multi-criteria decision-making by aiding decision-makers in making the most rational choice(s) from among a set of alternatives. It addresses the weakness of traditional ranking methods like the "weighted sum" by introducing a consistency index to check for the consistency in the subjective pair-wise comparisons of decision-makers (Porras-Alvarado et al. 2017). Ranking of the relevant attributes by experts are solely based on experience and hence, does not necessarily reflect objective decision-making based on the physical condition of the asset. Furthermore, the consistency metric ensures precision in results but does not necessarily address accuracy concerns in subjective judgments. Ahmed et al. (2017) attempted to bridge this gap by validating AHP results with data analysis of observed data.

Several mathematical optimization models have been applied to network-level highway budget planning and budget allocation. Most studies in the literature employ linear programming (De La Garza et al. 2011; Medury and Madanat 2013b), mixed integer programming (Abaza and Ashur 2009; Gao and Zhang 2008; Ng et al. 2011), and dynamic programming (Boyles et al. 2010; Gao and Zhang 2009; Kuhn 2009; Medury and Madanat 2013a) to decide on the optimal timing and types of M&R treatments to keep a pavement network in an acceptable functional and physical condition. However, in spite of the presence of these models in the literature, the extent of their usage in practice has been limited (Wu et al. 2012a). Some of the modeling limitations reported in the literature include the combinatorial explosion problem, inadequate pragmatic considerations, and inadequate data for the parameters required to run proposed optimization models (Dekker 1996; Torres-Machí et al. 2014). Accordingly, recent works have endeavored to improve the practical aspects of models proposed in the literature.

Concerning data requirements, more SHAs are investing in data collection and archival due to increased legislative requirements and an emphasis on data-driven decision-making (Chi et al. 2013). There have also been extensive efforts to transition from legacy systems (which often contain “siloed” planning data) towards integrated information systems which enable the life-cycle collection and utilization of data on infrastructure networks (Harrison 2005). Furthermore, the combinatorial explosion problem which is usually associated with integer-based programming models is being addressed using meta-heuristic approaches; which give near-optimal results for a fraction of the computing time costs when implemented on a full-scale network model. Most M&R programming studies using meta-heuristics have employed genetic algorithms (Chootinan et al. 2006b; Morcous and Lounis 2005; Yang et al. 2015), ant colony optimization (Shoghli and De La Garza 2016; Terzi and Serin 2014), particle swarm optimization (Tayebi et al. 2013), and gradient descent techniques (Tsunokawa et al. 2006; Van Hiep and Tsunokawa 2005).

Pragmatic considerations in models also suggest the need to account for variability in key input variables like the budget, M&R unit costs, projected pavement performance, and other relevant factors. Accordingly, recent studies have applied several techniques including Markov Decision Processes (MDP) and Bayesian methods to model the uncertainty in M&R actions and the resulting improvement in the condition of a pavement section (Medury and Madanat 2013b; Seyedshohadaie et al. 2010). Li and Madanu (2009) also incorporated risk assessment in a pavement plan by accounting for uncertainties in the unit cost of M&R treatments and budget availability. The issue with the heterogeneity in deterioration rates of different pavement sections in the network is also addressed by Sathaye and Madanat (2012) and Zhang et al. (2017) via employing a segment-level "bottom-up" approach towards developing optimal pavement management strategies. Lamptey et al. (2008) also accounted for the projected traffic growth and the discount rate in the budget and M&R costs in modeling preventive maintenance schedules for a lifecycle performance model.

6.2.3 Research Gap

These studies notwithstanding, an important pragmatic consideration in M&R budgets that is often neglected is that highway funding budgets often have strict project eligibility constraints (France-Mensah et al. 2017a). Some studies have attempted to account for this funding characteristic in models for M&R programming but with different research objectives. For example, Lee and Madanat (2017) studied the impact of different budgetary scenarios on the greenhouse gas (GHG) emissions from highway users and maintenance, rehabilitation and reconstruction (MR&R) activities. In that study, the budget splits were based on the M&R activities budget and a capital budget for reconstruction. Similarly, Menendez et al. (2013) studied the efficiency of two projects prioritization models for different scenarios of the maintenance budget and a rehabilitation budget. In both studies, the budget splits yielded significantly different results from the traditional combined budget scenario. Few studies have elaborately studied why the multiplicity in funding categories and project eligibility restrictions is an important aspect of the budget allocation problem. Prior studies have mostly acknowledged the existence of this funding dynamic without making a case for why it is important.

Accordingly, little research has been done to explore the impact that multiple budgets with stringent project eligibility restrictions have on the projected network condition and project selection decisions for pavement networks. There are competing funding demands from a large pool of M&R projects for limited highway funding. The increasing gap between the need and availability of funds is further challenged by continuous changes in funding availability and constant changes in the pavement condition. This often leads to changes in the scope of M&R projects and a ripple effect on funds available in different categories for other M&R projects in the same plan. Accordingly, the dominant approach of modeling budget allocation problems with only one budget is thus, not flexible enough to address these changes that often occur as a result of funding shortfalls, urbanization, and/or legislative restrictions. In order to address this gap in problem formulation and more importantly, assessing its impact on the projected network performance of pavement assets, this paper proposes and implements a budget allocation model that accounts for these pragmatic funding restrictions in M&R budgets.

6.3 RESEARCH APPROACH

The principal objective of this paper is to demonstrate the impact of funding restrictions in multiple funding categories on the projected performance of pavement networks. The focus of this study will be on the utilization of optimization models for budget allocation as applied to maintenance and rehabilitation of pavement assets. Hence, the scope of this study excludes funding categories involving mobility improvement and bridge projects. This study builds on prior research by (Ng et al. 2011; Wang et al. 2003b). For these studies, the budget used for the formulation of the problem is assumed to be a combined budget amount with no funding restrictions or project eligibility constraints. Thus, first, this study builds on the budget allocation problem formulation to account for multiple pavement M&R categories and their funding restrictions. Secondly, this formulation is used to assess the impact of these funding restrictions on the projected network performance of the pavement assets. The proposed model is an integer-linear model which improves on a "base case" network-level budget allocation model formulated in (Ng et al. 2011; Wang et al. 2003b).

The choice of an integer-linear programming (ILP) model is due to the specificity in its solutions providing detailed information on the specific M&R treatment to execute in each year and on each pavement section throughout the network (France-Mensah and O'Brien 2018). Moreover, the ILP model is flexible in representing mathematical relationships, is easy to evaluate, and has several solution methods to choose from (Chu and Huang 2018). Accordingly, to be able to study network-level project selections, an integer-linear program is more suitable. In this study, the selected objective function is the maximization of the average network condition score of the pavement network. This objective is widely used in the extant literature and is usually employed as a measure of the overall performance of the network (Wu and Flintsch 2009). Multiple scenarios are created to represent instances from one funding category or budget (base case) to K (multiple) funding categories; where K represents the total number of M&R funding categories with strict project eligibility constraints (Figure 6-2). This is achieved by formulating the budget constraints to reflect the multiple M&R funding categories that most highway agencies have to contend with as part of the pavement management decision-making process. The proposed models are then implemented in a numerical case study network representative of a subset network in Texas. Based on the model solution results, there is an analysis of the impact of the formulation of budgetary constraints and how M&R decisions change as the funding categories increase with more stringent requirements for each funding category. Additionally, the model is implemented in a network with a lower average initial condition score to study the differences in M&R decisions in an alternate case network. Finally, a sensitivity analysis is performed to check for the robustness of the model solutions obtained based on key model parameters like the budget size, deterioration rate, and the different M&R unit costs.

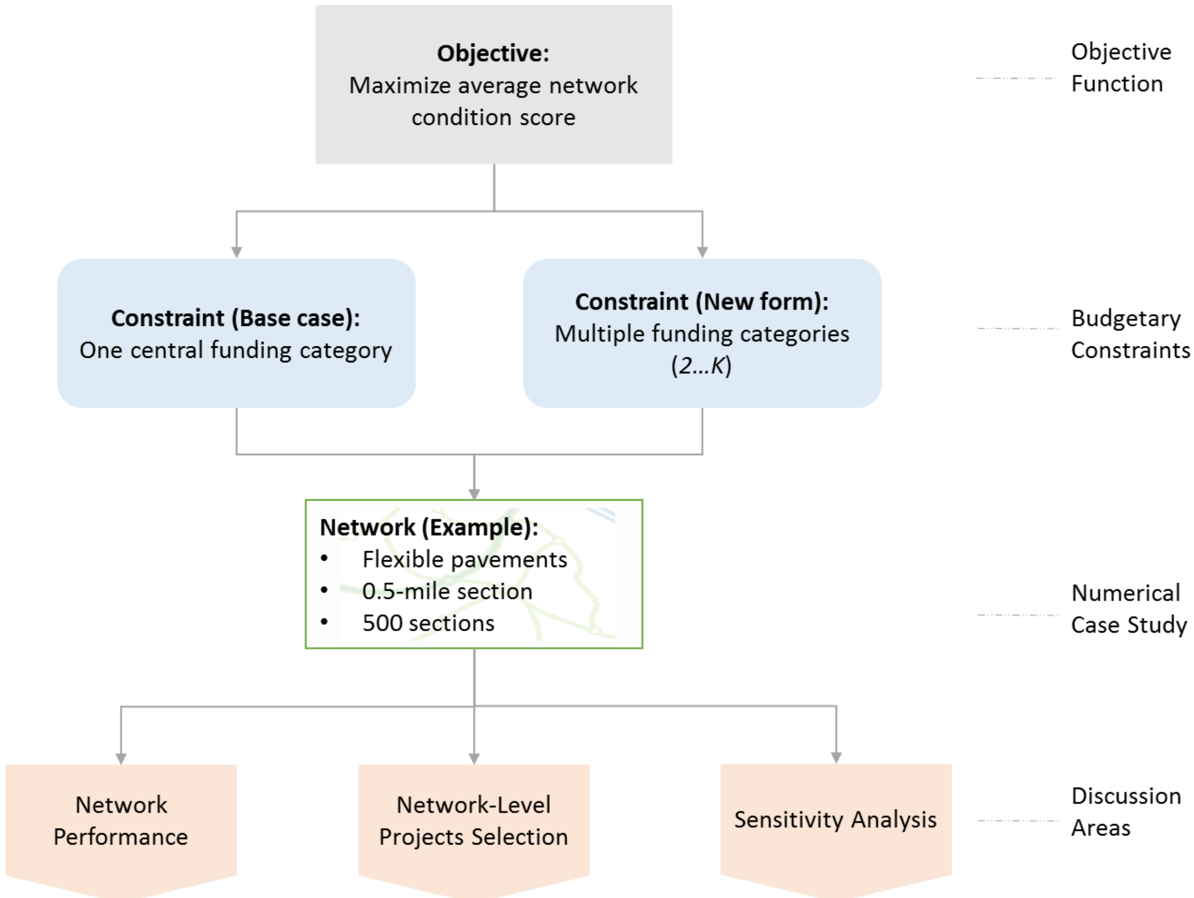


Figure 6-2. Budget allocation objective and funding restriction scenarios

6.3.1 Problem Formulation

Based on the methodological description, the integer-linear model is presented in detail below. However, it is worth pointing out that some of the model constraints were modified from prior studies and have been duly noted where applicable.

Objective Function

In many cases, agencies need to decide if a performance measure must be included in an objective function, constraint, or both. Whether or not a particular objective is included as the main function to optimize depends on the engineering judgment of decision-makers, the scale of the problem, urban versus rural jurisdictions, and/or other influential factors (Wu and Flintsch 2009). In this study, the objective (*Z*) considered is the maximization of the overall network condition. This was formulated as maximizing the total network condition score over a specified planning horizon, *T* (Equations 6.1 and 6.2). The total network condition score was formulated as a summation of the average network condition scores for each year over the planning period.

$$max\ \ Z = \sum_{t=1}^{T} \overline{S_t} \tag{6.1}$$

where $\overline{S_t}$ is the average condition score of the network for each year. $\overline{S_t}$ can be formulated as shown below;

$$\overline{S_t} = \frac{\sum_{i=1}^{I} S_{it} L_i}{\sum_{i=1}^{I} L_i}, \qquad \forall\ t\ \in T \tag{6.2}$$

where S_{it} is the condition score for a pavement section, *i* in the time period, *t* and L_i is the length of the pavement section in lane-km (or equivalent lane-miles).

Constraints (Base Case)

Constraints provide pragmatic bounds and considerations for the decision-making context of budget allocation in pavement management. In this model, the constraints are as follows.

Budget

Each maintenance and rehabilitation project will have an associated unit cost. Accordingly, the total cost of executing selected M&R projects cannot exceed the total highway budget allocation for each plan period. The base case budget constraint only reflects one funding category as indicated earlier and presented in Equation 6.3.

$$\sum_{i=1}^{I}\sum_{p=1}^{P} x_{ipt} L_i C_p \leq B_t \qquad \forall t \in T \tag{6.3}$$

where, x_{ipt} is the decision variable as to whether or not M&R treatment, p is applied to a pavement section, i, in the plan period, t. It is a binary decision variable which equals 1 for a specific combination of i,p,t and zero otherwise; C_p is the unit cost of treatment, p; and B_t is the budget for each time period, t.

Condition Scores and Other Constraints

The condition scores of the pavement sections change from one plan period to another. This condition score transition equation was obtained from the model by Ng et al. (2011). Accordingly, the cumulative impact of previous decisions in the prior periods (j) to a given time, t, have an impact on the current condition score of each pavement section. Even when, no M&R activities take place over the planning period, the deterioration rate has a compound effect of reducing the condition score from one plan period to another (Equation 6.4). Furthermore, there is usually theoretical or practical limits (maximum and minimum) to the condition score of the pavement sections in the network (Equation 6.5). In some cases, certain pavement sections may have higher thresholds based on their significance to the functionality of the entire network. Furthermore, the proposed model also ensures that a decision is made on each pavement section for each time period

(Equation 6.6). Lastly, it is important to restrict the number of M&R treatments that take place on the same pavement section within the planning period. Accordingly, a threshold value is placed on the maximum number of M&R treatments that can be performed on each pavement section (Equation 6.7). Additionally, these values vary depending on the intensity of the treatment option with the least structural treatment option having the highest maximum value.

$$S_{it} = S_{i0}\gamma_i^t + \sum_{j=1}^{t}\sum_{p=1}^{P} x_{ipj} e_{ip} \gamma_i^{(t-j)} \qquad \forall i \in I \qquad \forall t \in T \tag{6.4}$$

$$U_i^{min} \leq S_{it} \leq U_i^{max} \qquad \forall i \in I \qquad \forall t \in T \tag{6.5}$$

$$\sum_{p=1}^{P} x_{ipt} = 1, \qquad \forall i \in I \qquad \forall t \in T \tag{6.6}$$

$$\sum_{t=1}^{T} x_{ipt} \leq V_p, \qquad \forall p \in P \qquad \forall i \in I \tag{6.7}$$

where S_{i0} is the initial condition score of pavement section i at the beginning of the first period of the planning horizon; γ_i is the average deterioration rate of pavement section, i, with a range definition, $0 \leq \gamma_i \leq 1$; x_{ipj} refers to all the decision variable values for all the past decisions from previousa time, j until the current time, t; e_{ip} is the expected improvement to the condition score of section, i as a result of the application of a specific

M&R treatment option, p. U_i^{min} and U_i^{max} are the minimum and maximum acceptable condition scores for pavement section, i. Lastly, V_p is the maximum number of allowable treatments for a specific M&R treatment type, p. It is also worth pointing out that γ_i is used as a fractional multiplier to reflect the drop in pavement condition score from one plan period to another.

Alternate Constraint (Multiple Funding Categories)

The proposed alternate constraint will replace the budget limit constraint as shown earlier in Equation 6.3. To reformulate this constraint, an understanding of how funding categories are constructed is relevant to the decision-making context. Traditionally, funding categories may be based on M&R treatment type, project classification, project costs, the relevance of the project to the network, the jurisdiction of the proposed project, or other pre-defined criteria by the decision-making agency (Duncan and Schroeckenthaler 2017). This implies that there can be several ways of formulating the budget constraint to reflect the existence of multiple funding categories and their respective project eligibility constraints. However, the dominant criteria for constructing funding categories are often consistent with or can be related to the M&R treatment options to be undertaken on select pavement sections (Lee and Madanat 2017; Menendez et al. 2013). Accordingly, the authors chose to formulate this constraint as a function of the M&R treatment options. Thus, it is assumed that there are K funding categories that can fund at least one M&R treatment option exclusively. Hence, a funding category, k, can only fund eligible M&R treatment(s), $\ddot{p}$ (as shown in Equation 6.8).

$$\sum_{i=1}^{I}\sum_{\ddot{p}=1}^{P} x_{i\ddot{p}t} L_i C_{i\ddot{p}} \leq B_{kt} \qquad \forall k \in K \qquad \forall t \in T \tag{6.8}$$

where $\ddot{p}$ refers to the M&R treatments or project types which are eligible to receive funding from category, k.

6.4 Numerical case study

This case study is used to demonstrate the practical implementation of the model and the impact of funding restrictions on the resulting pavement network performance. The metrics assessed include the average network condition score and the percentage of pavements in a good or better ("good" and "very good" condition scores) condition. The proposed model was implemented in a numerical example involving pavement sections representative of a subset network in Texas. The network consisted of 500 [0.81-km (0.5-mile) long] sections with 2 lanes each leading to a total of 805 lane-km (500 lane-miles) of pavement sections. This corresponds to between 4% to 12.5% of a typical network size of on-system highway under the jurisdiction of a Texas Department of Transportation (TxDOT) district (Hong et al. 2017). The average initial "condition score" of the network at the beginning of the fiscal year is 76.4 with a standard deviation of 12.8. The model is also implemented on an alternate case network with a lower network condition score (66.4) but a similar standard deviation. However, the results from the base case network are mostly presented. Results from the alternate case network are only presented in the discussion of M&R project selection decisions where the results and trends observed were significantly different. The condition scores information required for the model were obtained from the Pavement Management Information System (PMIS) of TxDOT. Additionally, other assumptions of parameter values were based on engineering judgment and/or previous literature on the implementation of budget allocation models on Texas pavements.

The condition score metric used is a combination of the distress score (DS) and ride score (RS) of a pavement section as defined and assessed by the pavement engineers at TxDOT. TxDOT collects distress-related data on raveling, flushing, failures, rutting (shallow and deep), and cracking (block, alligator, longitudinal, and traverse) on flexible pavements. Based on this information, a distress score derived from corresponding utility values of the visual distress ratings is assigned to each pavement section in the network ranging from 0 to 100. On the other hand, the ride score is used as a metric to assess the smoothness or ride quality of a pavement section. It is similar in definition to other more widely recognized metrics like the present serviceability rating (PSR) and international roughness index (IRI). However, while an increasing IRI indicates decreasing ride quality, the reverse holds true for the PMIS ride score of TxDOT. RS ranges from 0.1 to 5 and is also based on the corresponding utility values and the different traffic volume classifications (low, medium, high) of the agency. Lastly, the condition score of a pavement section is calculated as the product of the distress score and the utility factor for ride quality of each pavement section. The qualitative descriptions and ranges for all three metrics described above are presented in Figure 6-3. The TxDOT funding situation is presented next to provide a practical guide for the choice of budget constraints and justification of the decision to use the M&R treatment options as the project eligibility constraints criteria.

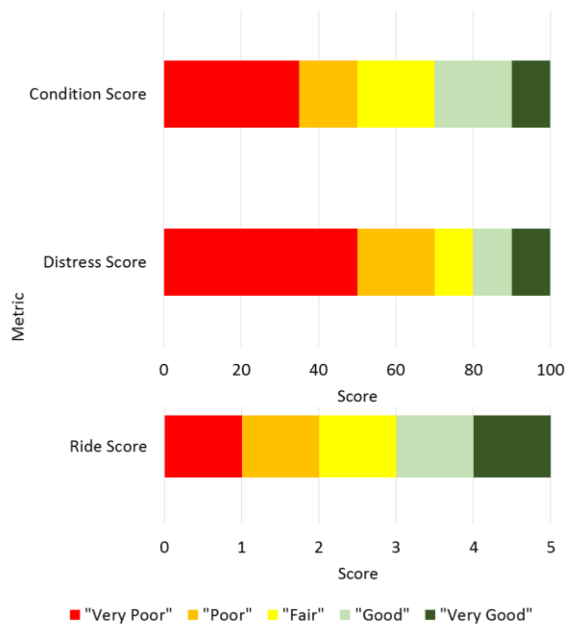


Figure 6-3. Qualitative categories for pavement condition metrics (adapted from Texas Department of Transportation 2014)

6.4.1 TxDOT Funding

For M&R of pavement assets, TxDOT has 2 major budgets namely the Maintenance and the Unified Transportation Program (UTP) budgets. The Maintenance budget is usually used for funding routine maintenance, preventive maintenance, and light rehabilitation projects. The UTP is a 10-year, mid-range document used by TxDOT to guide the development of transportation projects in the State. It has 12 major funding categories with Category 1 dedicated to “Preventive Maintenance and Rehabilitation.” UTP is often used to fund the more intensive and expensive M&R projects like medium and heavy rehabilitation and occasionally, to supplement funding for preventive maintenance projects.

In this study, the authors studied the impact of budget categories based on the maintenance budget and the UTP budget. The maintenance budget, as pointed out earlier, can also be sub-divided into the in-house funding category, also referred to as “Strategy 105” and the contract funding category also referred to as “Strategy 144.” To provide more scenarios for comparison, the study also hypothetically divides the UTP (Category 1) budget into 2 categories with one category funding medium rehabilitation projects and the other funding heavy rehabilitation projects. This is to further demonstrate how more funding restrictions affect M&R decisions and network performance. The breakdown of different scenarios is presented in Figure 6-4 together with the percentage splits for the various budget categories; which were calculated based on a study by Gharaibeh et al. (2014). The percentage allocation of funds is based on a historical precedent from the Gharaibeh et al. (2014) study and is only used to represent a base case distribution of funds. Accordingly, this case constraint is only to be viewed as an initialization of a potential budget split for different M&R budgets. These percentages may pragmatically differ depending on the funding sources and legislative appropriations for the decision-making agency.

The M&R treatment options considered include the option to do nothing (DN), preventive maintenance (PM), light rehabilitation (LR), medium rehabilitation (MR), and heavy rehabilitation (HR). Only flexible pavement sections are considered in this case study since the majority of pavement sections in Texas are asphalt-based. The detailed scope definitions and related works that fall under these respective M&R treatments are as outlined in studies by (Gharaibeh et al. 2014b; Menendez and Gharaibeh 2017). PM primarily consists of chip seal coats and thin overlays. On the other hand, the rehabilitation activities often involve overlays (over 2 inches), mill and inlay, and other treatments with the most intensive treatment being a complete restoration or reconstruction (which applies for the HR option).

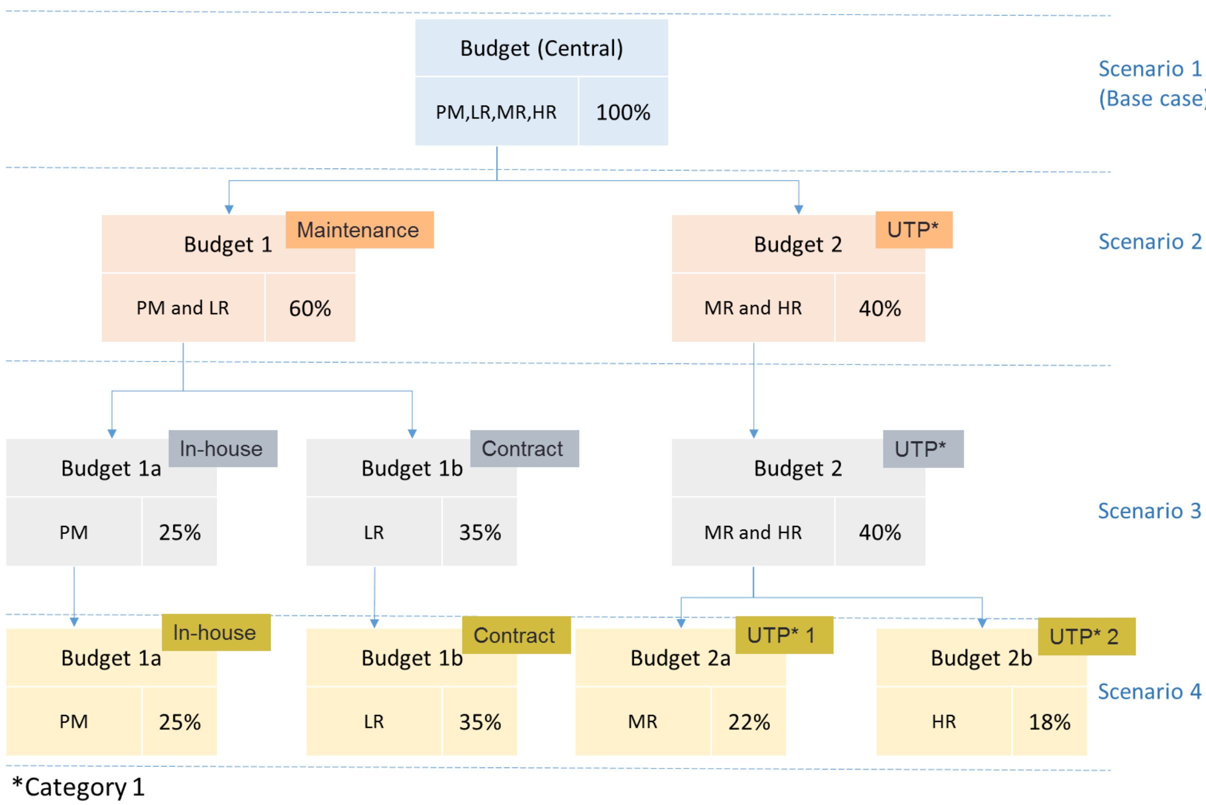


Figure 6-4. Case study scenarios for multiple funding categories

6.4.2 Implementation (Parameters)

The planning horizon considered for this case study is 4 years. This is consistent with the 4-year Pavement Management Plan (PMP) developed by TxDOT prior to the beginning of each fiscal year. Accordingly, the selection of a 4-year period for analysis is consistent with the practices of this SHA. More broadly, this planning horizon is also aligned with the 4 to 6-year Statewide Transportation Plan (STIP) which is mandated as a transportation plan by several state and federal laws. Additionally, this period is consistent with when many decision-making agencies have the most certainty concerning the network funding needs as well as the legislatively-mandated funds available. For practical purposes, the minimum and maximum condition scores were constrained to 50 and 100 respectively. The deterioration rate (reduction factor) as modeled in Equation 6.4 was assumed to be 95% (Ng et al. 2011).

An aggregate budget of $20 million is assumed for each fiscal year (as reflected in the base case scenario). Accordingly, for scenario 2, budget 1 has $12 million (60%) for PM and LR projects with budget 2 having $8 million (40%) for MR and HR projects. These budget amount calculations are consistent with other branches (scenarios) of the tree as depicted in Figure 6-4. On the other hand, the M&R unit costs range from $21,130/lane-km ($34,000/lane-mile) for PM projects to $321,250/lane-km ($517,000/lane-mile) for HR projects (Table 6-1). Accordingly, the condition score improvement also ranges from 3 (PM projects) to 40 (HR projects). The M&R unit costs were obtained from an earlier work by Liu et al. (2012); which involved the development of a statewide PMP for TxDOT in 2012. Those unit costs were converted to the current year (2017) equivalent costs using a discount rate of 4% (Lamptey et al. 2008b). However, during the planning horizon (relatively short period), all the costs and budget amounts were assumed to be in constant dollars and hence, compound calculations of the "time value of money" were not implemented in the model. An observation in Table 6-1 is that LR appears to be the least cost-effective treatment. This may be because LR tends to have high fixed costs (mobilization, equipment, and ancillary items) relative to the improvements in the condition score of the target pavement section. Finally, a pavement section could only receive the PM treatment twice (maximum) and rehabilitation treatments (LR, MR, and HR) once, during the 4-year planning horizon.

Table 6-1. M&R unit costs and condition score improvements

M&R action	Unit cost ($/lane-mile)	Mean condition score improvement	Unit cost ($)/unit condition score increase
DN	0	0	0
PM	34,000	3	11.33
LR	202,000	15	13.47
MR	285,000	25	11.40
HR	517,000	40	12.93

6.4.3 Model Solution

The proposed integer-linear program was programmed and solved using the General Algebraic Modeling System (GAMS) integrated development environment (IDE). The solver used was the "CBC (COIN-OR Branch and Cut)" algorithm developed by Computational Infrastructure for Operations Research (Bussieck and Vigerske 2010). The CBC algorithm employs the "branch-and-cut" method for solving mixed integer programming problems. This algorithm combines the concepts of "branch-and-bound" and cutting planes. Essentially, the algorithm solves a linear programming relaxation of the problem and then tightens the relaxations by adding additional valid constraints, or splits the problem into two or more sub-problems recursively (Mitchell 2002). The optimization model was run on a desktop computer equipped with 3.33GHz of Intel Core i7 CPU with a RAM size of 24 GB. All the scenarios took between 70 to 200 seconds run (wall clock) time.

6.5 Results and discussion

First, an analysis of the impact of multiple funding categories according to the different scenarios of funding implemented in the model is discussed based on the average network condition score and the strategic goal of TxDOT. This is followed by a discussion concerning the differences in M&R network-level projects selection for different scenarios. Additionally, the results of the sensitivity analyses are discussed to demonstrate the robustness of the findings in the study and assessing the impact of incremental changes in key input parameters on the analysis outcomes produced by the optimization model.

6.5.1 Network Performance

The scenario analysis was first assessed based on the average network condition score over the planning horizon. In Figure 6-5, it is evident that the system-wide performance of the pavement sections declines with increasing project eligibility constraints. Here again, the gap in network performance appears to widen over the planning period with increasing consideration of more funding categories. This implies that formulating optimization models for budget allocation in M&R programming without accounting for this aspect of budgeting can lead to an over-estimation of the projected performance of the network. Consequently, highway agencies may end up having higher unanticipated expenditures towards reactive maintenance needs which can lead to rapid exhaustion of

M&R contingency funds. Furthermore, this finding is consistent with the study by Porras-Alvarado (2016) which found that the “siloed” traditional approach to funds allocation leads to an inefficient network performance situation. This study demonstrates that the network performance for the extreme scenarios (1 and 4) is significantly different and the performance gap also continues to grow over the planning horizon. If this trend continues, this can also be an indication that for long-term M&R plans, the projected network performance gap will be even more pronounced.

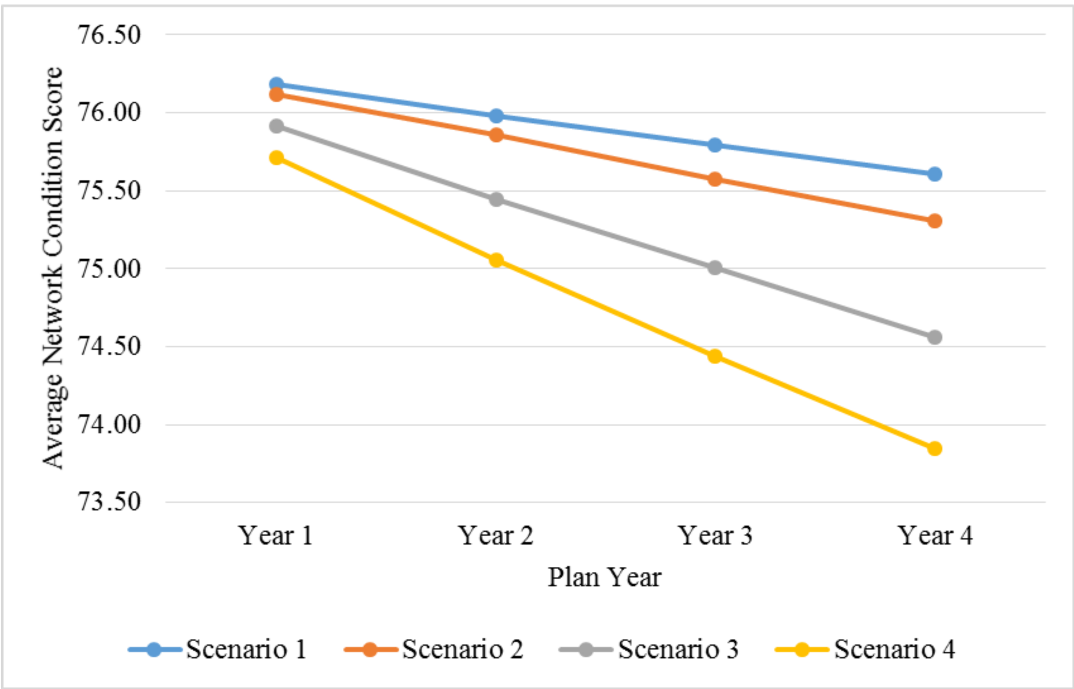


Figure 6-5. Average condition score of different scenarios

Furthermore, an assessment of the different scenarios also indicates that accounting for more funding categories leads to lower proportions of the network pavement sections in a good or better condition (Figure 6-6). This assessment metric was also chosen because several SHAs have the strategic goal of achieving a proportion of the pavement network (in lane-km or equivalent lane-miles) in a good or better condition. Similarly, TxDOT has the strategic goal of having 90 percent or more of the network lane-miles in a good or better condition. In this case study, prior to the implementation of the optimization model, the initial proportion of network lane-miles in a good or better condition was 64 percent. The qualitative descriptions of pavement conditions were limited to fair, good, and very good because the constraints in the optimization model prevent the condition score from falling below 50 (which is the lowest condition score limit of a 'fair' pavement condition). While in scenarios 1 and 2, an overall increase in the proportion of good pavement sections is observed, the reverse holds true for scenarios 3 and 4. Hence, in the latter two scenarios, the restrictions on funding actually led to a decreasing proportion of sections in the network that are at least in a good condition. Hence, while formulating the budget allocation problem with one central budget yields about 70% good or better pavement sections in the fourth year, the extreme case (scenario 4) in this study yields about 61% of the network in at least a good condition; which is worse off than the initial proportion (64%) of network sections which were good or better. Here again, this study's finding suggests that the degree to which a proposed M&R program affects the achievement of the strategic goal of an agency is significantly different between the extreme cases (scenarios 1 and 4).

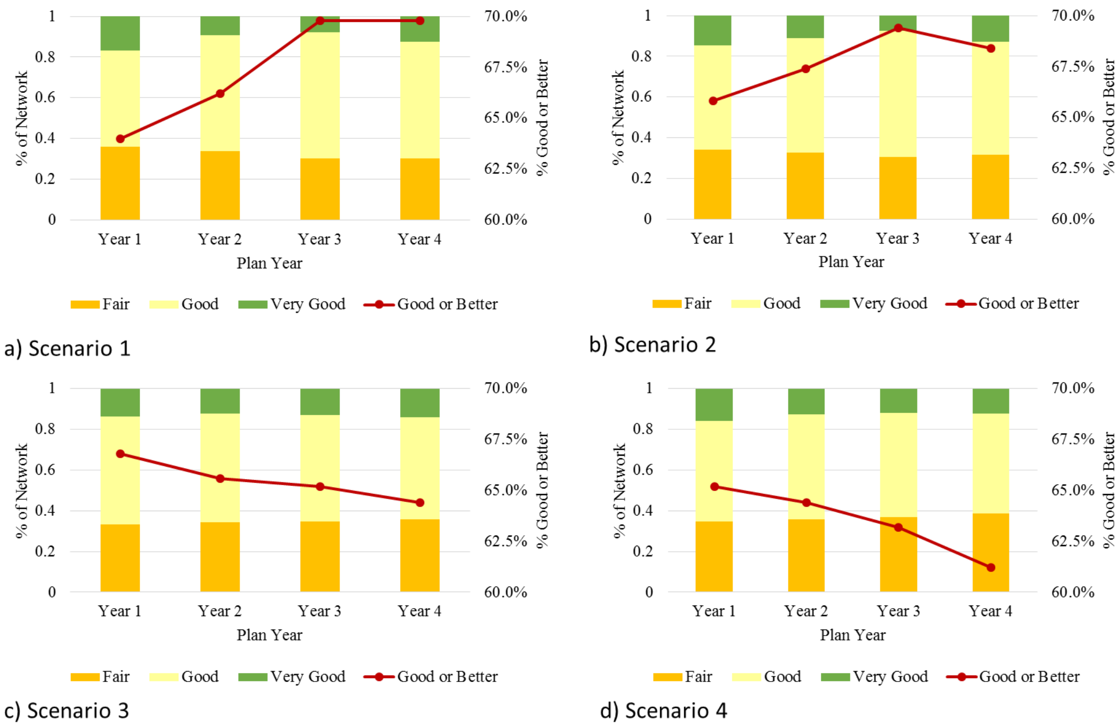


Figure 6-6. Percentage of the network in different conditions for (a) scenario 1 to (d) scenario 4

6.5.2 Network-level Projects Selection

A closer look at the selected M&R activities in the different scenarios also suggests that proposed solutions (M&R decisions) in scenarios 1 and 2 are noticeably not pragmatic (Figure 6-7a). It is unrealistic to administer that many PM treatments to pavement sections in the network over the entire planning horizon. It is worth noting that the model has already accounted for multiple recurring PM treatments on the same pavement section over the planning horizon. However, what appears to be happening is that the optimization model is prioritizing the treatments with the lowest unit cost per unit improvement in the condition score (Table 6-1). Hence, since PM and MR have the least costs ($11.33 and $11.40 respectively) per unit improvement in condition score, they are prioritized in the budget allocation process ahead of LR and HR treatments. Moreover, PM treatments are by far the least expensive M&R option. This explains why in scenario 1 (base case), most of the M&R treatments suggested were PM and MR projects and similarly, in the case of scenario 2, PM projects (mostly selected from budget 1) and MR projects (mostly selected from budget 2) dominated the decisions. Furthermore, from a modeling standpoint, the budget assumed appears to be relatively small. This is evidenced by the declining pavement performance for all the scenarios under consideration. Accordingly, this factor together with the cheap costs of PM corroborates the trends observed in Figure 6-7.

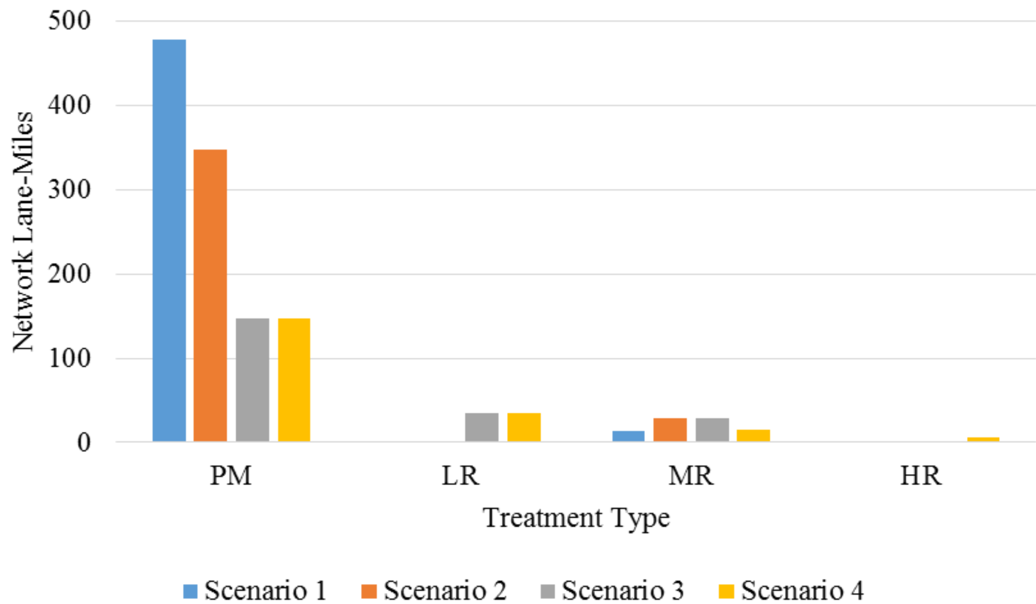
This notwithstanding, the cost-effectiveness of PM treatments are well documented in the extant literature (Chen et al. 2017; Labi and Sinha 2005). This supports the observed trend of majority PM projects in most of the model scenarios. Furthermore, several other studies have had similar (only two recommended M&R treatments) results for network-level optimization problems (Wang et al. 2003b; Wu and Flintsch 2009). For instance, the multi-objective model formulated by Wu and Flintsch (2009) recommended PM treatments for 80% of the network pavement sections and corrective maintenance (akin to MR) treatments for the remaining pavement sections even though there were other M&R treatment options. These prior results suggest that there could be a deficiency in how such network-level problems are formulated. This is evidenced by the models' solutions since choosing only the most cost-effective solutions is not feasible in a pragmatic decision-making context.

On the other hand, scenarios 3 and 4 appear more pragmatic since they have a realistic distribution of the different M&R treatments as would be applied to a typical pavement network by an agency's pavement engineers. Hence, this result also indicates that it may be necessary to introduce such budgetary constraints to better reflect a proportionate application of different M&R actions for the applicable pavement distress types throughout the network. This is more consistent with practice since different pavement distress types require varying degrees of M&R actions by decision-makers (Hong et al. 2017; Lamptey et al. 2008b).

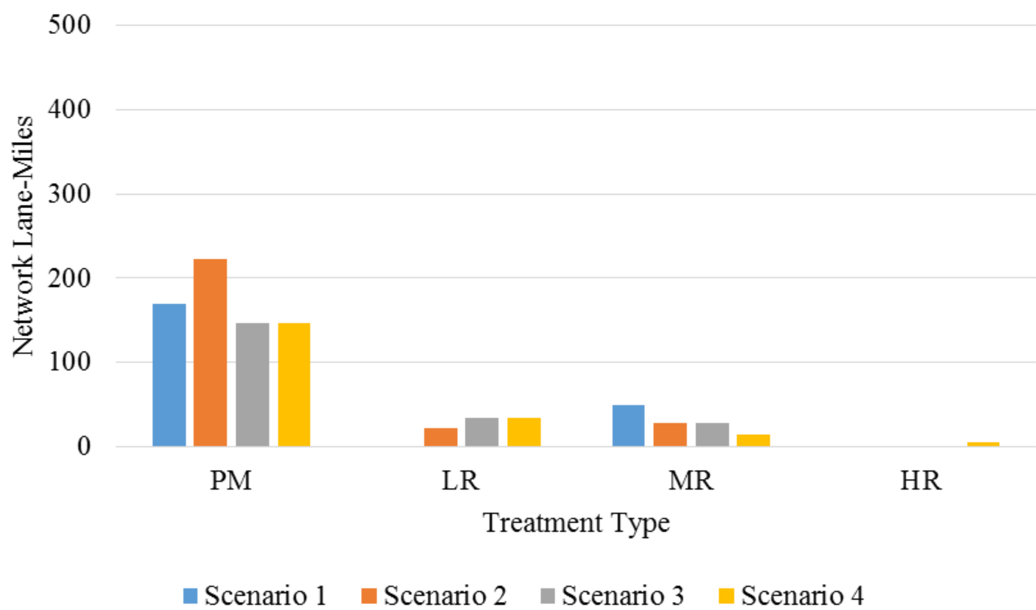
However, for a pavement network in a "good" initial condition (like the base case network), pavement engineers may be incentivized to be more proactive in scenario 1 (suggesting a high number of PM treatments). Nonetheless, for the same condition pavement network, scenario 4 may encourage a reactive maintenance policy by decision-makers (by necessitating MR and HR treatments and limiting the number of PM treatments needed). Conversely, in the case of a pavement network in a lower initial condition (alternate case network), the reverse is more likely. There will be the need to have more MR and LR treatments to meet the minimum condition thresholds of specific individual pavement sections in the network. This can be observed in the difference in the proposed M&R treatments for Figures 6-7a and 6-7b. Noticeably, in Figure 6-7b, scenarios 1 and 2 experience a significant reduction in the number of PM treatments because a lower condition network requires more intensive M&R treatments. Accordingly, a general increase in MR and LR treatments are observed in that case network. The M&R programming decisions were not shown for subsequent years (in

Figure 6-7) because it was observed that the aggregate sum of different M&R actions selected (by the optimization model) from one plan year to another did not significantly differ.

Moreover, another area of discussion was the level of funds utilization for the different funding categories. To clarify, since the objective of the proposed model was to maximize the average network condition score over the planning horizon, the model was incentivized to spend as much of the funds that were available in each funding category to improve the condition of the network. Accordingly, the authors did not include additional constraints concerning a minimum percentage of the budgets to be spent in each year. Nonetheless, it was observed that more funds were left unallocated for increasing levels of project eligibility restrictions. The simple reason is that for different M&R project types, an additional project requires a minimum amount of funds for another project to be added to the plan. Hence, for funding categories requiring a higher minimum threshold (in terms of funding), more funds will be left unallocated. In this study, the average unallocated funds for scenarios 2 to 4 was around $360,000 per annum (across multiple categories). This is in contrast to scenario 1's average unallocated funds of $11,000 per annum. This observation suggests that, in the pragmatic funding situation where multiple budgets are preset, it is possible to have more funds going towards certain types of M&R treatments at the detriment of other much needed M&R treatment types.



a) Base case network condition (average good condition)



b) Lower network condition (average fair condition)

Figure 6-7. Network lane-miles receiving M&R actions for different scenarios (Year 1): (a) base case network; (b) alternate case network

6.5.3 Sensitivity Analysis

Given the deterministic nature of the input variables used for this model, it is important to further investigate how variations in the input variables under the different scenarios discussed above can impact the network performance. Accordingly, these sensitivity analyses provide useful information to 1) assess potential instances where the model results could change significantly for different scenarios and 2) assess how sensitive network performance is to some of the input variables which are susceptible to variability. In this study, the sensitivity analysis was conducted for scenarios 1 and 4 since they represent the most lenient and restrictive budgetary scenarios respectively. Variations in the deterioration rate, aggregate budget, and M&R unit costs were studied to determine their impact on the projected network-wide condition performance. These variables were chosen because prior studies (Lamptey et al. 2008b; Menendez and Gharaibeh 2017; Torres-Machi et al. 2017) have investigated the impact of these variables on network performance. The deterioration rate was allowed to vary from 1% to 7%; beyond which the model was infeasible. Similarly, the aggregate budget availability was allowed to vary by ±10% with 5% step increments. The M&R unit costs were also allowed to vary by ±20% with 10% step increments. The performance metric used was the 4-year average network condition score since it was observed earlier that there was a consistent linear trend in the periodical network condition scores for different scenarios. Accordingly, Figure 6-8 shows how variations in these input variables affected the 4-year average network condition score for scenarios 1 and 4.

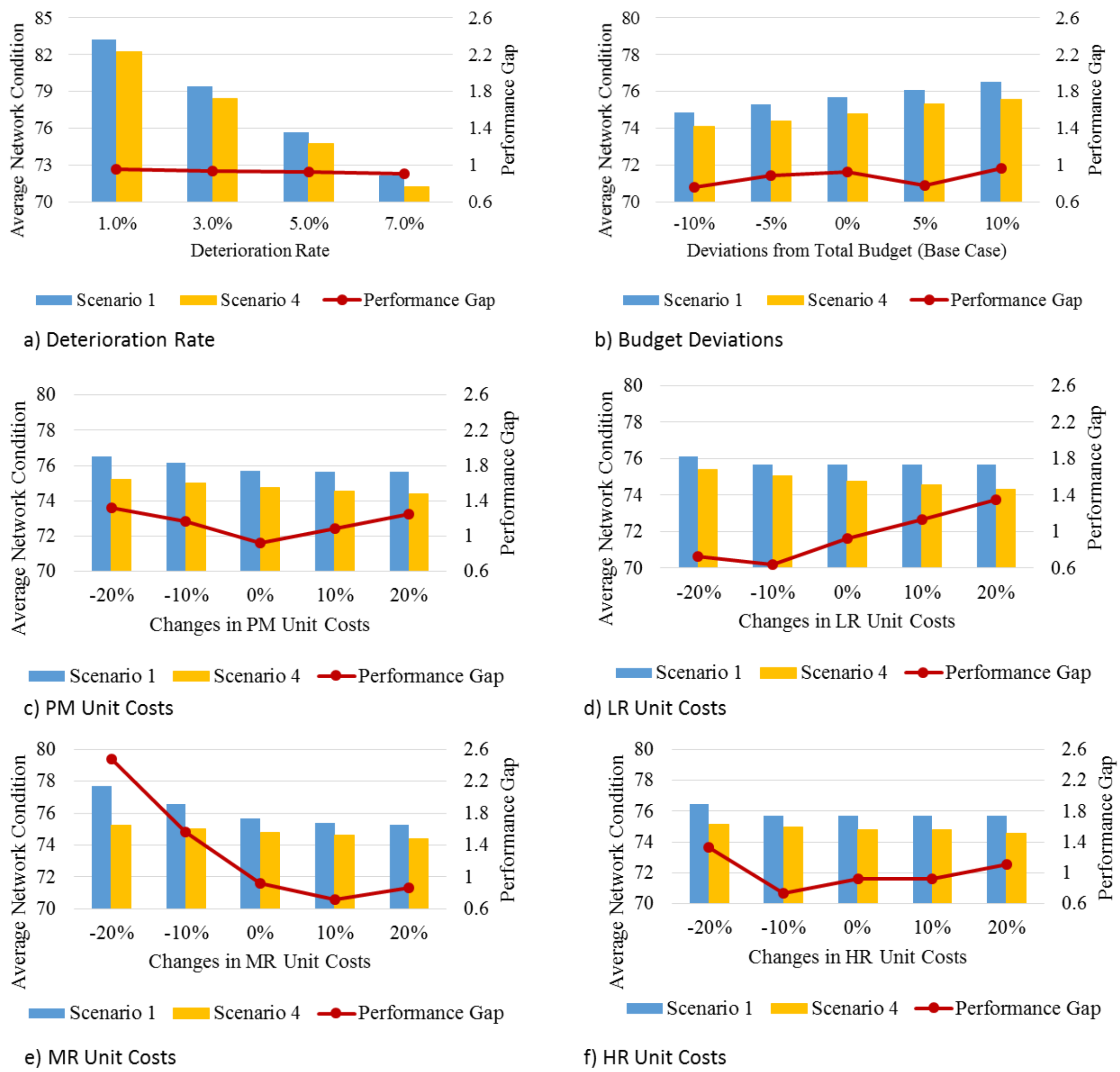


Figure 6-8. Sensitivity analysis of input variables

To begin with, variations in all six input variables indicates that network performance for scenario 1 is always higher than scenario 4. However, the degree to which scenario 1 outperforms scenario 4 varies significantly depending on the variable under study. To quantify this, the "performance gap" metric in Figure 6-8 is calculated as the difference in the projected 4-year average network condition scores between scenario 1 and scenario 4. Thus, based on the observed performance gap in Figure 6-8a, the deterioration rate appears to be the least sensitive variable in the model. Furthermore, an increase in the available budget does not necessarily lead to an increasing performance gap although, for both scenarios, the network performance continually improves (as shown in Figure 6-8b). On the other hand, the results suggest that the performance gap is most sensitive to the MR unit costs. This could be due to the condition score improvement value assigned to the MR treatment option. There is also a consistent trend in the performance gap for the four M&R unit costs (Figure 6-8c-f); with all of them reaching a minimum performance gap and then rising steadily afterward (bearing similarity to a convex function shape). This can be interpreted as justification that scenario 1 will always perform better than scenario 4 in terms of the average condition of the pavement network. These trends were also confirmed in the implementation of the model in the alternate case network with a lower average initial condition score. Accordingly, the sensitivity analysis results suggest that even if there are variations in the assumed input variables studied for this budget allocation problem, the model with more stringent funding restrictions will always lead to a lower network performance than the most lenient (one budget) case.

6.5.4 Model Limitations

Although the current formulation of the model is sufficient for fulfilling the objective of this paper, there are still a number of limitations in the model that can be addressed in future models. First, the consideration of a single objective versus a multi-objective function could have added more information about the impact of this funding dynamic on other objectives. Secondly, the model does not consider network interdependencies of individual sections and assumes a homogenous deterioration rate for pavement sections in the network. Furthermore, the deterioration models for the network could have been more complex to capture the impact of age, traffic loading, and other exogenous spatial-temporal factors. However, this would unnecessarily complicate the model and have little impact on the results given the span of the planning horizon. Condition trigger values could have also been included in the model. Lastly, cost savings which can be accrued from clustering M&R treatments on neighboring sections are also not considered. This notwithstanding, these complexities were assessed to be non-consequential towards the key findings of the inter-scenario analysis of the impact of this funding dynamic on the pavement network's condition performance.

6.6 CONCLUSION

For pavement engineers to employ mathematical optimization models in pavement M&R programming, there have to be incremental efforts to build practical constraints in such models. Accordingly, several studies have explored practical issues like the need to account for variability in key parameters (including M&R budgets) for pavement management decision-making. However, the fact that decision-makers have to draw from several funding categories (with restrictions) to fund M&R pavement projects has not been adequately addressed in the extant literature. The primary contribution of this study is the demonstration of the impact of multiple funding categories and their respective project eligibility constraints on budget allocation decisions and the projected network-level performance of proposed M&R programs. First, an integer-linear programming model was formulated to account for the multiplicity of funding categories and their respective funding constraints based on M&R treatment options. Secondly, the impact of different funding restrictions on the projected network performance and M&R decisions were studied.

Findings from the implementation of the model suggest that failing to account for this characteristic of M&R funding can lead to an overestimation of the projected network performance by optimization models. Consequently, this may lead to increased unplanned expenditures (related to reactive maintenance) which can lead to a faster depletion of contingency funds. On the other hand, this study's results also suggest that more stringent funding restrictions of M&R budget categories can be inefficient. These restrictions may lead to a lower performing M&R program with the same available pooled budget amount. Therefore, this study's findings suggest that there is value in allowing funds transfer across "silo" funding categories in lieu of multiple funding budgets with stringent funding restrictions. These findings are particularly relevant for highway decision-making entities that are responsible for managing high volume road networks in urban regions. Such agencies tend to receive funding from more diverse sources including federal sources; which tend to have very stringent requirements for project eligibility. By demonstrating the inefficiencies in having multiple budgets with restrictions, this study provides insights useful for highway budgeting dynamics. From a policy perspective, this study's findings can incentivize the elimination or reduction of funding restrictions around M&R budgets. Future research can explore the network impact of having multiple budgets via other methods like the cost-benefit analysis, worst-first approach, or AHP. Furthermore, although, the percentage splits (combined budget) are initialized as a historical precedent in the case study, a prior (first) stage optimization model can be implemented to find the optimal split percentages before this study's subsequent analysis is executed.

Chapter 7 A Shared Ontology for Integrated Highway Planning

The content of this chapter in the manuscript is currently under review at the Journal of Advanced Engineering Informatics (Elsevier). Additionally, the contents of this ontology can be publicly accessed at the following link:

https://github.com/Francemens/Integrated-Highway-Planning-Ontology

Many highway agencies have several functional groups responsible for planning for safety, maintenance and rehabilitation (M&R), mobility, and other functions. The functional nature of State Highway Agencies (SHAs) can result in a siloed approach to planning. Such efforts are further challenged by functional groups utilizing legacy systems which lack interoperability. In practice, this leads to redundant planning efforts and potential spatial-temporal conflicts in the projects proposed by the different groups over a planning period. There is a need for an integrated approach to planning supported by information systems. However, the existing literature on formalized knowledge representation fails to adequately account for the level of information needed for cross-functional planning of projects scheduled for the same network. Hence, this study presents an ontology for integrating information to support the cross-functional and spatial-temporal planning of highway projects. The Integrated Highway Planning Ontology (IHP-Onto) is a shared representation of knowledge about pavement assets, M&R planning, and inter-project coordination. Sources of the knowledge acquired included expert interviews, a review of nation-wide studies, and previously published ontologies. The implementation phase included a case study demonstration of the ontology by answering relevant competency questions via SPARQL queries. Based on the data-driven evaluation of the ontology, the precision and recall rates obtained were 97% and 92% respectively. The study findings indicate that IHP-Onto sufficiently represents domain knowledge capable of supporting inter-project conflict analysis affiliated with integrated highway planning.

7.1 INTRODUCTION

The highway system is a key infrastructure network in modern society (Boyles et al. 2010). Billions of dollars are spent annually on maintenance, rehabilitation, capital projects (mobility), and short-term operational tasks (American Society of Civil Engineers 2017; France-Mensah et al. 2017a). With such large investments in highway infrastructure, the need for effective planning practices cannot be overemphasized. Highway planning is executed at three major decision-making tiers including the project, network, and strategic levels (Wang et al. 2003b). However, in line with several studies in infrastructure management, this study focuses on the network-level (De La Garza et al. 2011; Dehghani et al. 2013; Fwa and Farhan 2012). At this level, there are usually multiple funding categories with stringent project eligibility constraints for the types of projects that can be performed on the different asset classes (France-Mensah et al. 2018). Accordingly, the planning processes for these tasks are often performed by several functional groups in the same State Highway Agency (SHA), but with different group priorities and funding constraints. This context for decision-making can be a barrier to collaborative planning resulting in inefficient practices like repetitive information generation, a deficiency in decisions made across siloed information, and missed opportunities for developing or bundling synergistic projects (Halfawy 2010; Porras-Alvarado 2016). An ideal approach would be to perform network-level integrated planning across multiple functional groups with the seamless integration of relevant data and information systems employed for decision-making.

In making incremental efforts to achieve this goal, this study focuses on integrated planning in two main dimensions at this level of decision-making. The first dimension is the integration of planning and projects coordination information of a functional group (phase-wise dimension). The other area is in integrating projects information from multiple functional groups working on the same highway network (cross-functional dimension). Taken together, the planning process and the cross-functional inter-project coordination process are interdependent. The planning process leads to the highway projects that are selected but after approval, there can be unanticipated changes in the planning information (budget, etc.) that can trigger changes in the projects to be performed. Such changes can also have cross-functional implications on other scheduled projects. Thus, there needs to be a formal approach to synchronizing changes in asset information, planning decisions and constraints, and inter-project coordination information. However, integrated planning is challenged by the technological (data and information systems) setup among functional groups in highway agencies (Woldesenbet Asregedew et al. 2016).

The technological challenge is primarily driven by functional groups in SHAs using fragmented databases and multiple incompatible legacy systems which lack interoperability and integration capabilities (Ziliaskopoulos and Waller 2000). There are two main components of this challenge. First, there is heterogeneity in the data and information systems used in terms of structure (schema), syntax, and semantics (Seedah et al. 2015). The second challenge involves dynamic data updates in common information items that support tasks performed by several functional entities within an agency. After an initial management plan, there are often variations in the funds available, traffic volume (truck traffic surge), asset conditions, land use patterns, and political influence among others (Lamptey et al. 2008a; Menendez and Gharaibeh 2017). This means that asset information used to guide decision-making as well as earlier project selection decisions taken, often change in response to demand. For example, a change in the anticipated highway funding amount can imply a change in the mix of projects that are scheduled in a pavement management plan.

These challenges are exacerbated by the dynamic nature of transportation planning and maintenance activities. For example, a sudden increase in commerce in a geographical area can lead to a rapid decline in the condition of the current network necessitating additional unplanned M&R projects (Meerow and Newell 2017). For many agencies, road users can also report hazardous road conditions and be advised by political authorities to take action on a perceived high priority project (Wang and Guo 2016). When SHAs act on such unplanned requests, this leads to a change in the list of approved projects and consequently affects the available budget for the hitherto planned projects. In light of this, when integrated planning is not implemented as part of these changes, there is the risk of multiple functional groups planning spatial-temporally conflicting highway projects on the same asset. This can result in redundant projects and ultimately inefficient use of public funds. Accordingly, representing knowledge in a formalism for addressing these challenges is needed to support a more data-driven, integrated, and cross-functional planning process.

Current studies in the domain on infrastructure management have mostly focused on representing construction information, highway asset information, safety planning, sustainability, and risk management (Katsumi and Fox 2018; Le et al. 2018; Le and Jeong 2016; Tessier and Wang 2013). However, a review (Katsumi and Fox 2018) of the scope of existing literature suggests that there are limited formalized representations (El-Diraby and Osman 2011; El-Gohary and El-Diraby 2010; Le and Jeong 2016) that are designed to aid the cross-functional planning of highway projects. In particular, the literature is silent about cross-functional planning under dynamic conditions (such as shifting funding constraints and priorities). In order to address this gap in representation, this paper describes a shared ontology representing asset information, M&R planning, and inter-project coordination knowledge. The developed ontology will aid in proactive, integrated planning by supporting an iterative approach that links planning knowledge with project data.

The remaining sections of the paper are presented below. A motivating scenario is presented to better describe the challenges and constraints facing SHAs. A background review follows which discusses prior studies on formalized representations related to the built environment. The research approach is then presented with details on the ontology development and validation processes. Subsequently, the ontology is presented and demonstrated by a case study implementation. Next, the ontology validation comprising of multiple evaluation approaches is described. Lastly, the conclusion synthesizes the major findings of the study, study limitations, and directions for future work.

7.2 MOTIVATING SCENARIO

As noted by Uschold and Gruninger (1996), the development of ontologies can be motivated by practical applications. More specifically, motivating scenarios serve as a guide for delineating the ontology scope as well as the potential semantics of major classes and their relationships. In this study, the motivating scenario is based on an earlier case study by France-Mensah et al. (2017a) on the visualization of highway project data from disparate information systems of an agency.

A typical urban district for the Texas Department of Transportation (TxDOT) is responsible for over 600 highway projects over a 4-year planning horizon. Projects range from major new construction or re-construction/renewal to minor maintenance. Information about these projects is put in multiple information systems designed to address the individual requirements of the different functional groups. In the above-mentioned study (France-Mensah et al. 2017a), projects from the maintenance and capital planning functional groups of a district were visually displayed in a Geographic Information System (GIS)-enabled tool that was built. Project data from two disparate database systems (for each functional group) were processed and manually integrated prior to visualization. Due to inconsistencies in the semantics and data format, it was also necessary to integrate information from other sources like the highway inventory data.

For example, each functional group within the same district used a different spatial referencing system for planned projects. Thus, developers had to manually cross-reference projects to attain a common GIS-compatible spatial attribute for all projects.

Building on this visualization (as shown in Figure 7-1), inter-database conflicts were identified across highway projects residing in different information systems via geospatial analysis. An inter-database conflict was defined as a spatial-temporal overlap between highway projects residing in different databases. There were over 30 inter-database conflicts identified over 58 miles of the highway network. The projects involved in inter-database conflicts had a total estimated cost of $19.8 million and constituted about 8.5% of the maintenance and capital projects scheduled. Additionally, the study also examined intra-database conflicts which included spatial-temporal overlaps in highway projects in the same database. This visual analysis also yielded 100 miles of projects that were scheduled to occur on overlapping pavement sections within a 4-year planning horizon. For intra-database conflicts involving capital construction, there were 23 overlapping projects with a total estimated cost of $148 million. The scale and magnitude of these identified spatial-temporal conflicts point to a deficiency in the current integrated planning approach or the lack thereof. While this case is demonstrated using a district in TxDOT, a review of the organizational/functional structure and list of scheduled highway projects by other SHAs suggests that this is a general problem affecting many agencies (Wu et al. 2012a).

Without a formalized representation of integrated planning and project information from different functional groups, there is always the risk of scheduling and funding potentially redundant highway projects on the same network. This notwithstanding, visualization alone does not provide enough information to aid in effective integrated planning. For example, only one attribute can be visualized at a time (year, project type, etc.) when multiple attributes are needed for cross-functional inter-project analysis. Furthermore, the proposed data integration framework and resulting tool from the above-mentioned study is primarily based on a manual integration (ad-hoc basis) of systems and lacks a shared representation of planning and project information. Additionally, there was no formal representation proposed for documenting and resolving the spatial-temporal conflicts that were visually identified among the highway projects. To discuss the existing formal representations in infrastructure management and allied domains, a detailed background review is presented next.

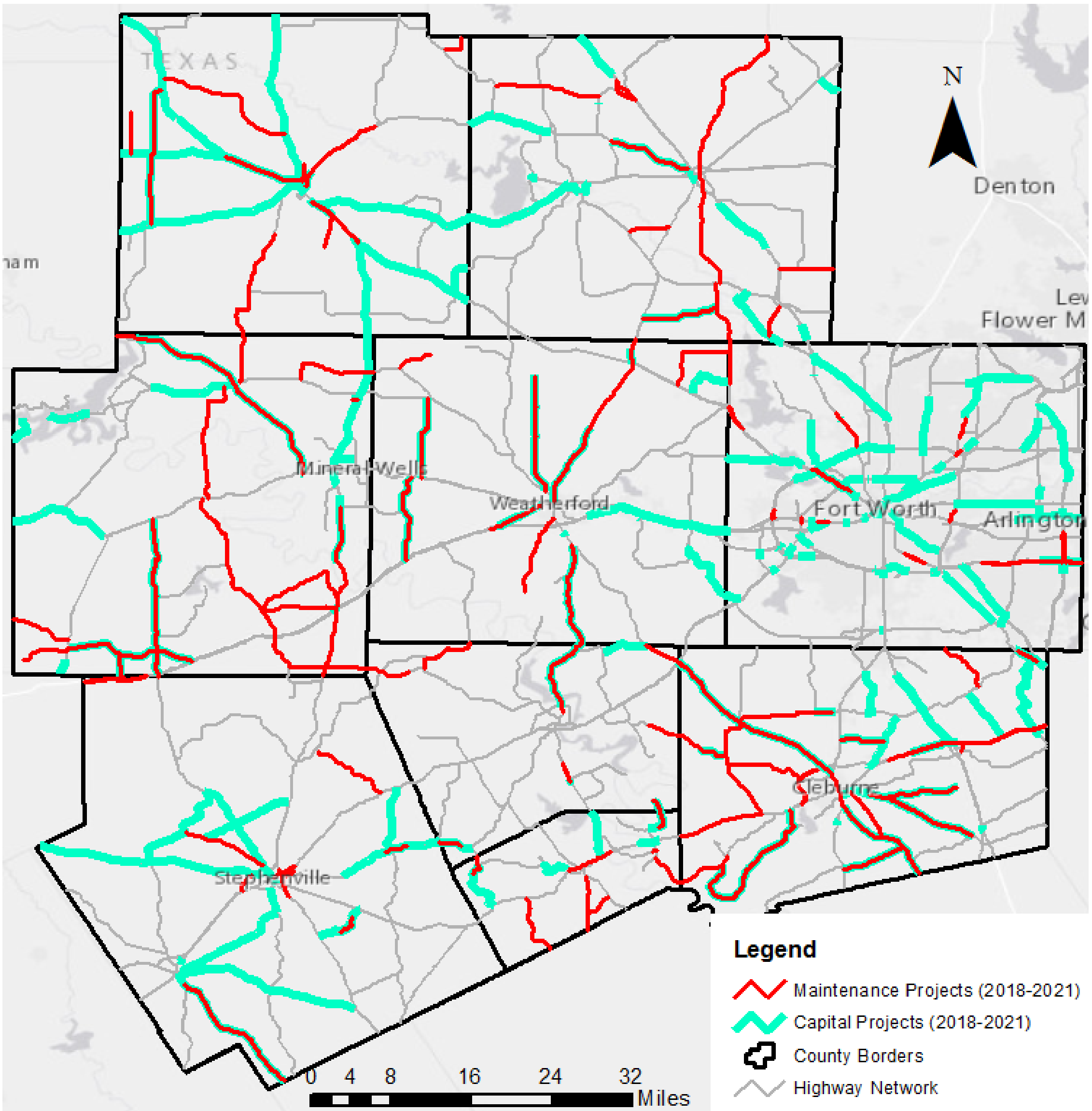


Figure 7-1. Spatial conflicts of highway projects on a pavement network

7.3 Background Review

As noted in the motivating scenario above, the SHA currently operates multiple information systems developed for different tasks. Such systems can have mismatched structures, syntax, and semantics. This results in limited interoperability, poor communication, repetitive data generation efforts, and ultimately, inefficient use of limited resources (Halfawy 2010; Uschold and Gruninger 1996). An approach to solving this problem is by developing formalized knowledge representations which can act as a unifying framework to reduce the terminological confusion in vocabulary (Uschold and Gruninger 1996). In order to provide a common format that is machine-readable, a standardized knowledge representation of domain knowledge is necessary (Seedah et al. 2015). An ontology is a representation which provides an “explicit specification of a conceptualization” (Gruber 1995). Concepts, terminologies, and relationships that are known in a particular domain constitute a “conceptualization” (Gruber 1995). Thus, the objective of an ontology is to capture and represent a shared understanding of knowledge in a specific domain in a machine-readable format (Guo and Goh 2017).

In the Architectural, Engineering, and Construction (AEC) domain, numerous ontologies have been developed to facilitate data integration, data transfer, natural language processing, and information extraction (Liu and El-Gohary 2017; Zhang and El-Gohary 2017; Zhou and El-Gohary 2017). Specific to the construction sector, there have been a number of data standards which typically employ Extensible Markup Language (XML) or object-oriented modeling methods (Le and Jeong 2016). Prime examples of these standards include agcXML, e-COGNOS (Lima et al. 2003), aecXML, the industry foundation classes (IFC), and many others (France-Mensah and O’Brien 2019a). IFC is a well-known standard format for the exchange of project information in the construction industry (Karan et al. 2015). The development of IFC enabled the transfer of building object data between custom software applications by different vendors and better collaborative planning (Vossebeld and Hartmann 2016). Building on this schema, several studies have developed representations that are IFC compliant for design, construction, sustainability, safety, project management, and asset management applications (Liu et al. 2016; Solihin et al. 2016; Venugopal et al. 2015; Zhang et al. 2015). The aecXML schema also covers documents, building components, projects information, professional services, and organization information. The concepts represented in aecXML are more geared towards construction activities as well as facilitating communication between project team members (Weng and Zhu 2001). Similarly, the e-COGNOS ontology was developed to provide an interlinked and content-oriented representation comprising of resources, actors, processes, and products relevant for lifecycle business processes in the building construction domain (Lima et al. 2003; Wetherill 2003).

In comparison to the building sector, domain knowledge representations in the transportation sector have been slower to develop (Le et al. 2018). Notable studies in this domain include ontologies developed by El-Diraby and other collaborators for highway construction (El-Diraby and Kashif 2005), processes in infrastructure construction (El-Gohary and El-Diraby 2010), and urban infrastructure products (El-Diraby and Osman 2011; Osman and Ei-Diraby 2006). In addition to these studies, there have been a number of industry-wide XML-based schemas proposed. TransXML is a well-known representation schema which was developed for the various development stages of transportation infrastructure. Developed by the National Cooperative Highway Research Program, it aims at providing an extensive framework for data exchange among different parties working within the transportation domain (Ziering 2007). Major elements of this schema focus on the design, construction, and safety of highway infrastructure. On a larger scale, the CityGML schema was also developed to address the growing interest and need for virtual city representations (Kolbe 2009). CityGML represents multi-scale topological, geometrical, and semantic descriptions of a virtual city model (Kolbe et al. 2005). It accounts for and delineates buildings, environmental objects, and transportation infrastructure at different levels of detail.

In spite of these aforementioned representation efforts, a majority of these representations focus solely on data exchange standards as part of efforts to improve software interoperability (El-Diraby and Osman 2011). XML-based schema utilizes XML language to support standard data exchange. However, this schema is unable to aid in formalized knowledge reasoning which is essential for the decision-making process of highway projects (France-Mensah and O'Brien 2019a; Niknam and Karshenas 2017). This inadequacy can be addressed by the development of application-specific ontologies which leverage the semantic web. The semantic web utilizes the Web Ontology Language (OWL) and the Resource Description Framework (RDF) as standard data models for representing and sharing knowledge in a computer-interpretable and human-readable form (Karan et al. 2015). OWL is a semantic language for developing and sharing ontologies on the World Wide Web. It adds rich semantic expressions (additional vocabulary) to ontologies by building on the RDF representation schema (McGuinness and Van Harmelen 2004; Zhang et al. 2008). RDF, in conjunction with OWL, provides a rich framework to describe resources and address syntactic and semantic heterogeneity issues across information silos. In line with these strengths of the semantic web, some studies have leveraged semantic web-based ontologies to address transportation asset management problems in specific application contexts. These studies are discussed further in the next section.

7.3.1 Application Ontologies (Transportation Asset Management)

Primary application areas for ontology development in transportation asset management have included formalizing communications (Zeb and Froese 2012, 2016), data visualization (Darter et al. 2008), data transformation (Le et al. 2018; Zhang et al. 2008), and improving software integration (Le and Jeong 2016) between asset lifecycle phases. Zeb and Froese (2012) developed the Trans_Dom_Onto to represent communication activities between parties involved in infrastructure asset management. Darter et al. (2008) employed ontologies to support the geo-visualization of transportation assets. The use of the semantic web in that study enabled the use of spatial and semantic queries in constructing layers in the Google Earth environment. Le et al. (2018) added more asset information to the spatial representation of transportation assets and focused on how to transfer project-oriented data to asset-oriented systems for transportation infrastructure management. That study provided project data handover requirements and demonstrated an important link between project information and updates to asset information. Focusing on highway assets, another study (Le and Jeong 2016) by the same authors accounted for information on facility management decisions to be taken as part of asset management. That study developed an ontology that linked highway design, construction events, and condition survey information about the highway asset network.

While these two latter studies made significant strides in connecting project information to asset information (through updates), there remain two major limitations. First, there is incomplete information to support network-wide planning decisions on highway project selection (France-Mensah and O'Brien 2019a; Le and Jeong 2016). This is because most of these representations are focused on transferring completed projects information to asset information without accounting for the planning process of those projects involved. Examples of key information from the planning process that is omitted from these studies include the funding categories (budgets), network performance metrics, and prior projects completed among others. Secondly, these studies fail to adequately consider the cross-functional dimension of highway planning (France-Mensah et al. 2017a; France-Mensah and O'Brien 2019a). Cross-functional planning requires recognition of different metrics and priorities as well as constraints such as budgets across functional groups, multiple funding categories with specific spending limitations, program-specific performance metrics, as well as the possibility of spatial-temporal conflicts in the projects proposed by the different functional groups.

7.4 Research approach

A review of the existing literature and the motivating scenario demonstrate that existing representations fail to adequately account for the interrelationship between planning information and inter-project coordination information. Furthermore, the deficiency in the integrated planning processes by SHAs can lead to spatial-temporal project conflicts and yet, knowledge about such conflicts have not been formally represented in the extant literature. Based on the issues raised in the motivating scenario and the research gap, the principal objective of this study is to develop an ontology to aid in cross-functional inter-project coordination of highway projects. To achieve this, the research approach includes ontology specification, knowledge acquisition, conceptualization, implementation, and evaluation. The methodology employed for ontology development is a hybrid framework which leverages the "methontology" approach (Fernández-López et al. 1997) and the "Uschold and Gruninger" ontology building approach (Uschold and Gruninger 1996). The Uschold and Gruninger approach provides detailed information for delineating the purpose and scope, ontology formalization, evaluation, and documentation. On the other hand, the methontology approach provides a more nuanced approach towards knowledge acquisition, conceptualization, and implementation (Fernández-López et al. 1997). Figure 7-2 demonstrates a step-by-step research approach towards developing the ontology and the pragmatic implementation of the ontology in a case study.

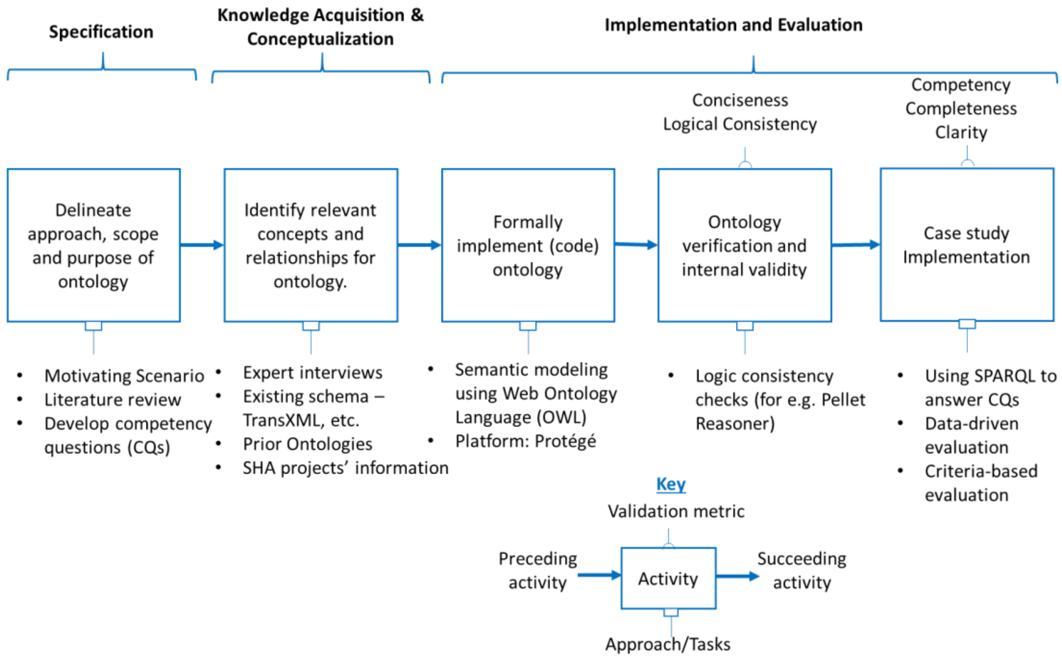


Figure 7-2. Research framework for ontology development and implementation

Based on the framework presented in Figure 7-2, it was first important to define what the scope and purpose of the ontology should be. This was executed via developing and answering ontology specification questions and the anticipated use cases for the ontology. This was followed by knowledge capture and abstraction of relevant terms and their relationships. Beyond this stage, the ontology was formally coded using RDF/OWL to make it computer-interpretable. The coded ontology then underwent internal logical checks and was implemented afterward in a case study. Further validation of the case study results was then conducted via data-driven evaluation and criteria-based evaluation. Details of the different stages in the research framework are presented below.

7.4.1 Ontology Specification

The aim of ontology requirements specification is to produce a formal or informal description of the rationale behind the development of the ontology and what its potential uses could be (Fernández-López et al. 1997). This can be done by documenting this information in natural language, using specification questions, and/or developing intermediate representations. In this study, a set of specification questions from Fernández-López et al. (Fernández-López et al. 1997) is used. This is augmented by a use case diagram in response to the "intended use" question.

What is the purpose? This ontology was developed to provide representation that can be used to support integrated planning tasks in highway asset management. This includes the formalization and re-use of planning and inter-project coordination knowledge from different functional groups working in a highway agency.

What is the scope? The ontology will include information on pavement assets, M&R planning constraints, and inter-project coordination relevant to integrated planning tasks. The ontology will exclude detailed information on the Right-Of-Way acquisition process, environmental review, new project design process, and traffic control plans among others. While all projects are considered in the inter-project coordination component of the ontology, only the M&R planning information is included in the planning component. The reason for this is that changes to M&R projects are easier to implement than for capital mobility projects.

Who are the intended end users? The users include highway agency personnel and functional groups within SHAs that are engaged in the planning of maintenance, rehabilitation, reconstruction, and new construction projects on pavement assets.

What is the intended use? The anticipated use cases of the ontology are presented in Figure 7-3.

The major use cases include the ability to support performing network-level M&R project selection, documenting projects information, and performing inter-project conflicts coordination. Inter-project conflict coordination refers to performing a spatial-temporal analysis of planned projects and documenting the resulting conflicts between these highway projects. As part of prioritizing projects, it is important to be able to access asset information and identify decision-making constraints (for e.g. budgets for different funding categories). It is also pertinent to have a representation of evaluation measures to be able to make a comparative analysis of alternative M&R programs. This is followed by the documentation of projects' information which entails a standardized representation of highway projects proposed by different functional groups. This use case allows all the functional groups in an agency to integrate their planned projects in a standard format. Finally, the last use case includes representing information on spatial-temporal conflicts and the actions taken to resolve them.

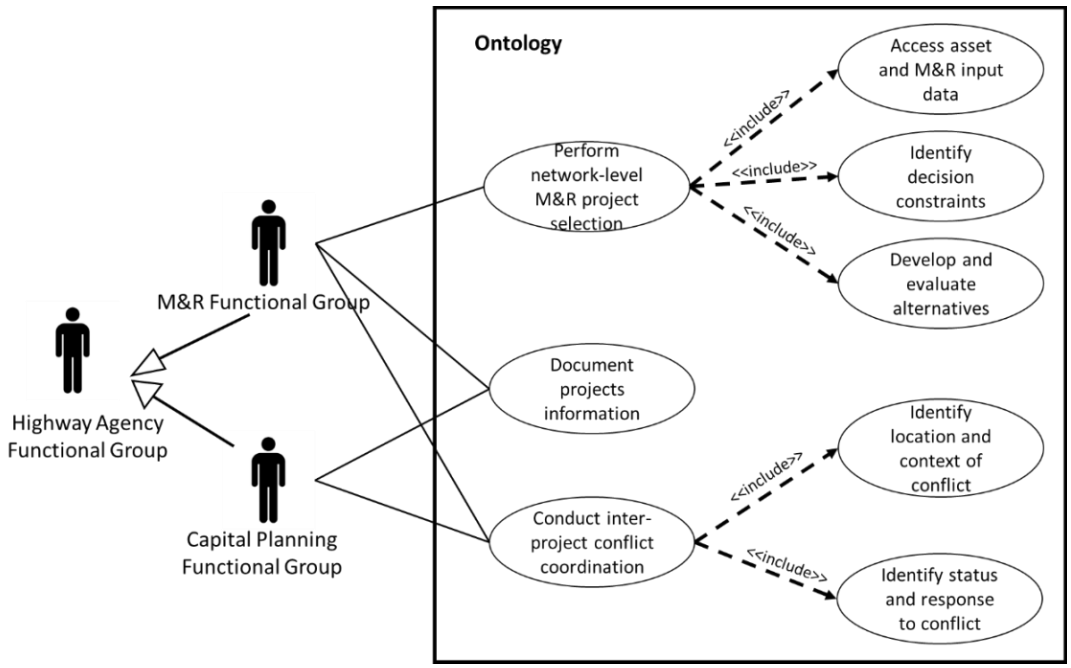


Figure 7-3. Use case diagram for the ontology

7.4.2 Knowledge Acquisition & Conceptualization

After defining the ontology requirements specification, the next step is to describe how domain knowledge for the ontology was acquired and formalized. The major steps in this phase include listing the relevant terms in the ontology, defining a class hierarchy, defining class properties, and specifying the range and domain of the properties (Noy and McGuinness 2001). In RDF triples, the domain is the class at the tail end of the property (predicate) arrow. The class or data type at the opposite end (target node) of the property is also called the range. The property arrow or line can be an object property or a datatype property. As their names suggest, the object property has a class as its range while the data type property has a data type as its range. These terms are demonstrated in Figure 7-4 with three levels of abstraction. Below the standard RDF triple, an abstract level ontology involves having high-level concepts which can have instances to represent knowledge. In Figure 7-4, the pavement section is an abstract class which has an instance "Section_1."

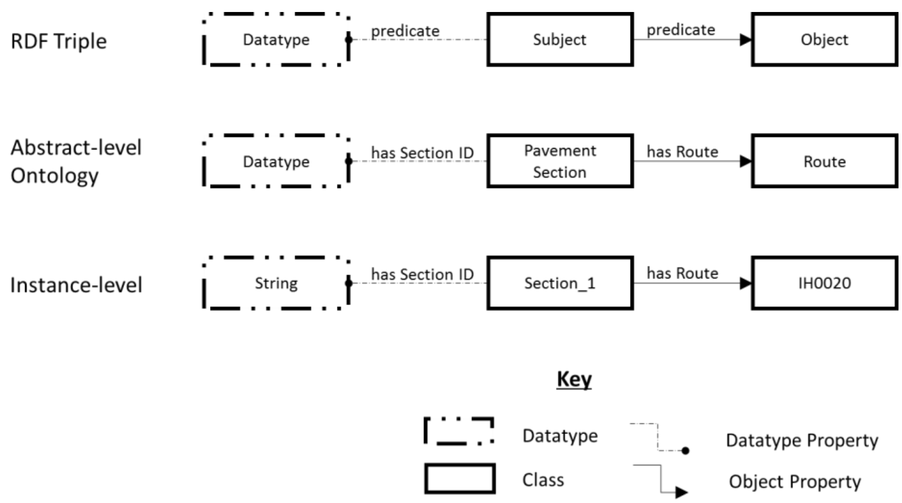


Figure 7-4. Example ontology using RDF triples

To guide the identification of relevant terms, a set of sample competency questions and answer examples are presented in Table 7-1. These questions were also used as part of a set of evaluation questions to confirm if the ontology covered the representation of salient knowledge needed for supporting integrated planning tasks. Accordingly, the competency questions focus on information concerning asset information, planning, and inter-project coordination knowledge.

Table 7-1. Sample competency questions and answer examples

Competency Questions	Potential Answers
When was the last treatment on a pavement section and in what fiscal year?	Seal Coat in Fiscal Year (FY) 2017
What is the available budget for a funding category?	$20 million in Maintenance Category
What is a performance metric for evaluating an M&R program?	Average network condition score
Which functional group is responsible for the execution of a maintenance project in the highway projects plan?	Maintenance Planning Division
Which route is the proposed highway project located on?	Interstate 20 (IH0020)
What are the projects involved in this identified spatial-temporal conflict?	Overlay project and Widen freeway project
How is an identified spatial-temporal conflict resolved?	Remove/reschedule the overlay project
What is the resolution status of an identified spatial-temporal conflict in a highway plan?	Resolved; Unresolved

Relevant knowledge for the ontology was first acquired by conducting interviews with seven highway agency personnel with each interviewee having extensive experience and knowledge in infrastructure management. The job titles of interviewees included “Director of Maintenance”, “Director of Transportation Planning and Development”, “Director of Operations” and “Pavement Engineer.” Six of the interviewees were Directors of their functional groups with each having over 15 years’ experience in the infrastructure management domain. The Pavement Engineer had over 8 years’ experience in the domain of interest. Interview questions covered knowledge about the M&R decision-making process, planning constraints, the status quo on inter-project coordination practices, and opportunities for improved collaborative planning among several groups working within an agency. The interviews lasted an average of 1 hour per person with follow-up questions for clarification if needed. The interview phase was followed by a detailed review of existing studies concerning ontologies for infrastructure management. The literature reviewed included NCHRP (nationwide) studies, prior ontologies in the literature, project documents, and online highway projects information (with details in Table 7-2).

Table 7-2. Literature sources for ontology knowledge

Major Ontology Components	Attribute Examples	Sources of Information and Knowledge (Literature)
Pavement asset information	Condition rating, pavement distress, pavement type	(El-Diraby and Osman 2011; El-Gohary and El-Diraby 2010; Le et al. 2018; Le and Jeong 2016; Lima et al. 2003; Osman 2012; Yuan et al. 2017; Ziering 2007)
M&R planning	M&R treatment type, treatment cost, treatment benefit, available M&R budget	(Cambridge Systematics 2006, 2009; France-Mensah et al. 2018; France-Mensah and O'Brien 2018; Hall 2015; Harrison 2005; Neumann 1997; Neumann and Markow 2004; Šelih et al. 2008; Wetherill 2003; Ziering 2007)
Inter-project coordination	Project let date, authorized amount, project description, project start point, responsible functional group	(Cambridge Systematics 2009; France-Mensah et al. 2017b; Le et al. 2018; Le and Jeong 2016; Neumann 1997; Weng and Zhu 2001; Ziering 2007)

As a precursor for accounting for completeness in the ontology, the interviews and review of the literature were stopped after data saturation had taken place. Data saturation is reached when no new information is being attained with additional data collection efforts (Fusch and Ness 2015). To illustrate how this was achieved in this study, data saturation for the inter-project coordination component of the ontology is presented in Figure 7-5. From this figure, it can be observed that there is a diminishing return trend (or plateau) in the number of unique information attributes (used to construct concepts) identified from project data of over 30 SHAs. After the 23rd agency, no additional unique information item was identified for that component of the ontology. This is consistent with data saturation practices conducted in earlier studies (Malterud et al. 2016; O'Reilly and Parker 2013).

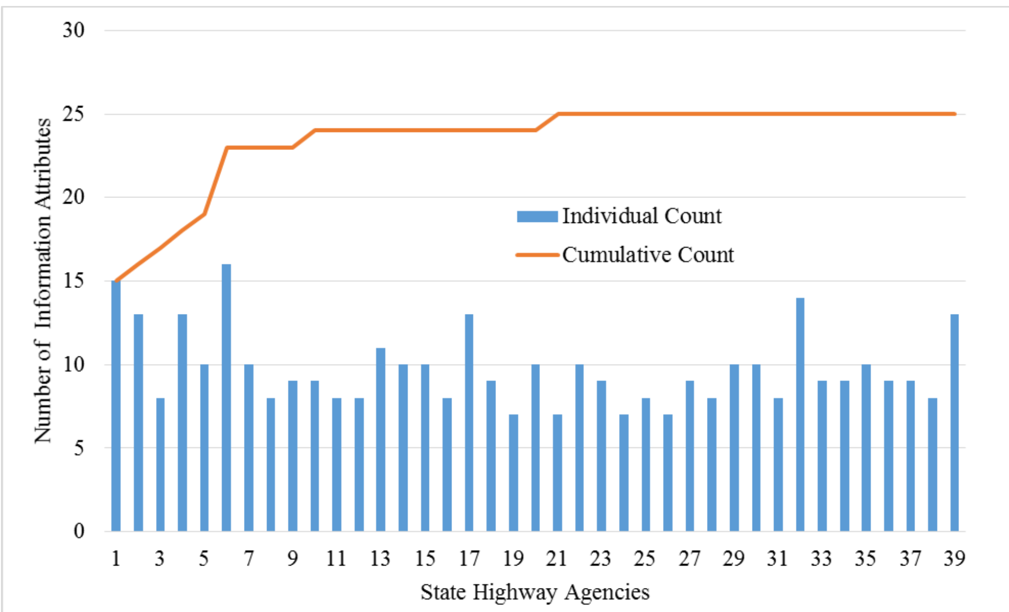


Figure 7-5. Cumulative count of information attributes used by SHAs

7.4.3 Implementation and Evaluation

In order to make the ontology machine-readable, it is important to implement it in a formal language (Fernández-López et al. 1997). The ontology was implemented using OWL/RDF in the Protégé environment (Guo and Goh 2017; Horridge et al. 2004). A snapshot of the implementation of the ontology in Protégé software environment can be seen in Figure 7-6. Furthermore, the ontology evaluation consisted of automated consistency checking (ontology verification), task-based, data-driven, and criteria-based evaluations (as shown in Figure 7-7). The case study implementation was then used to demonstrate the practical application of the ontology and as the basis for executing SPARQL queries in response to typical decision-making questions by the intended users. The information in Figure 7-7 also indicates the key metrics that are covered in the evaluation approaches selected for the validation of the ontology. Automated consistency checks evaluate the internal consistency of the ontology via description logic. The task-based evaluation demonstrates the pragmatic use of the ontology in satisfying the purpose and objectives of the ontology. Additionally, the data-driven approach aids in testing the coverage of the ontology while the criteria-based evaluation focuses on completeness, clarity, and the conciseness of the ontology. Further details on the description, limitations, and choice of the evaluation approaches are provided in the ontology evaluation section.

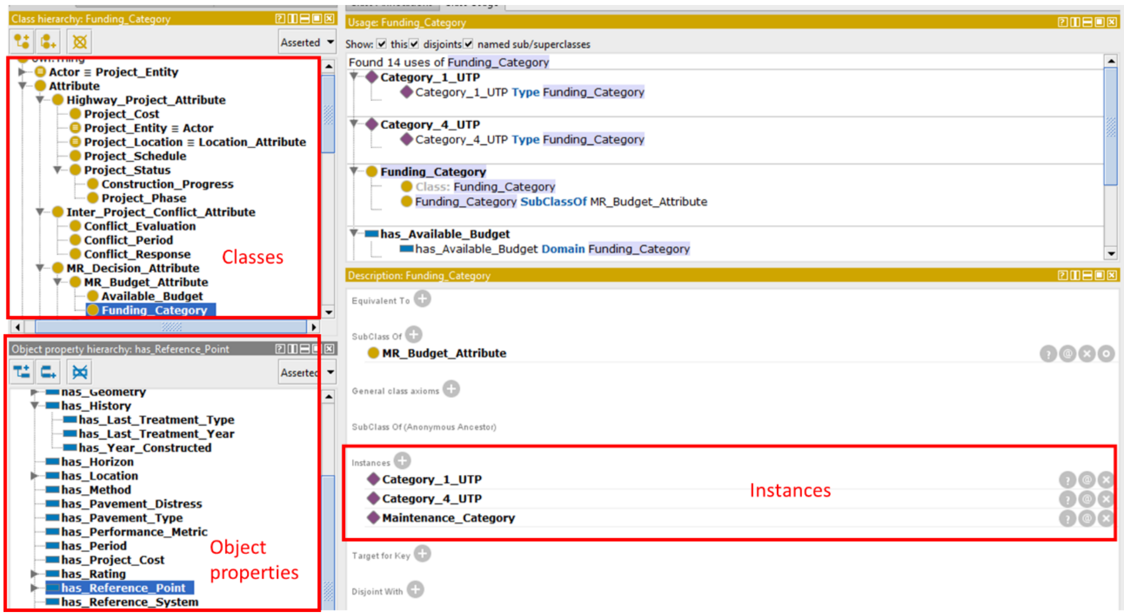


Figure 7-6. Screenshot of implementation in Protégé Ontology Editor Environment

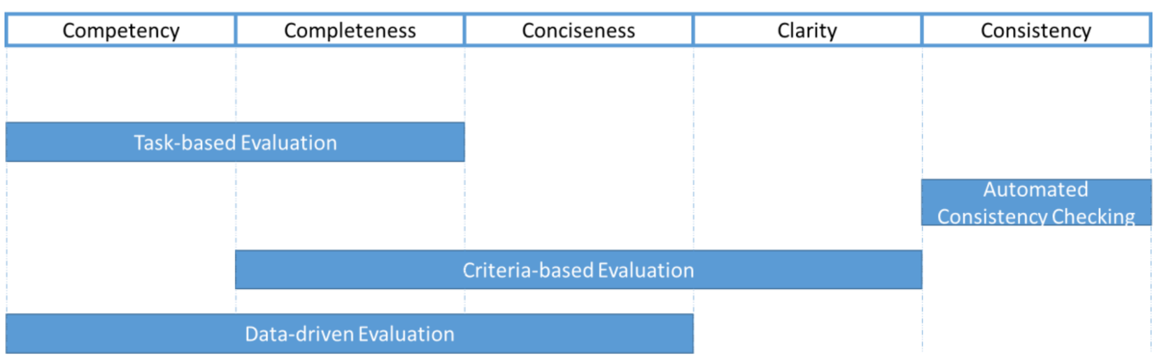


Figure 7-7. Metrics covered by the selected evaluation approaches

7.5 INTEGRATED HIGHWAY PLANNING ONTOLOGY (IHP-ONTO)

In this section, IHP-Onto is presented in detail. However, before its components are presented, an ontological model which is "flexible, simple, but also deep enough" (El-

Diraby and Osman 2011) to represent the knowledge needed for integrated planning is presented.

7.5.1 Ontological Model

Ontologies are developed to be reused. Accordingly, it is important that before a new ontology is built, reusable concepts from prior ontologies are integrated as much as possible. This practice of building on prior ontologies is consistent with the ontology building principles by Fernández-López et al. (Fernández-López et al. 1997) and Holsapple and Joshi (Holsapple and Joshi 2002). Furthermore, it is important to map the ontology to an upper-level abstraction model which will allow future integration with other models in the target domain. Thus, building on prior ontologies, a modified e-COGNOS ontological model is employed in this study. This model is similar to the Actor-Process-Product-Attribute model used by several domain ontologies developed for transportation infrastructure management (El-Diraby and Osman 2011; El-Gohary and El-Diraby 2010; Lima et al. 2003). While there have been different variations of this model for diverse applications, the main concepts remain mostly the same. Hence, from Figure 7-8a, this model suggests that an "Actor" can perform a "Process" that can lead to a "Product." The Product is a "Decision Action, Knowledge Item, or Physical Product." Thus, the description of the ontology in this study can be presented as follows (in Figure 7-8b). Information about *Pavement Sections* (Product | Physical Product) is input for network-level *M&R Project Selection* (Process). This selection process leads to an output in the form of an *M&R Projects Program* (Product | Decision Action) which in turn serves as input information for *Conflicts Analysis* (Process). The *Capital Projects Program* (Product | Decision Action) from another process is also input information for the analysis. The output of the *Conflict Analysis* is an *Inter-Project Conflict* (Product | Knowledge Item). However, knowledge of the conflict means there has to be a change in the *M&R Projects Program* due to projects that have to be eliminated or rescheduled. This decision cycle continues until there are no conflicts. Furthermore, an *Agency Division* (Actor) is responsible for performing the *M&R Project Selection* and the *Conflicts Analysis* processes. These statements above demonstrate how IHP-Onto was constructed to fit into a high-level abstraction model which is often employed in the infrastructure management domain. In addition to the four major abstract concepts, mechanisms and constraints were also added. Mechanisms represent all concepts related to guides, methods, and measures that can be used to support the work of actors performing processes. Constraints, on the other hand, refer to applicable laws, codes, specifications, and user requirements that govern the work processes of actors (El-Diraby and Osman 2011).

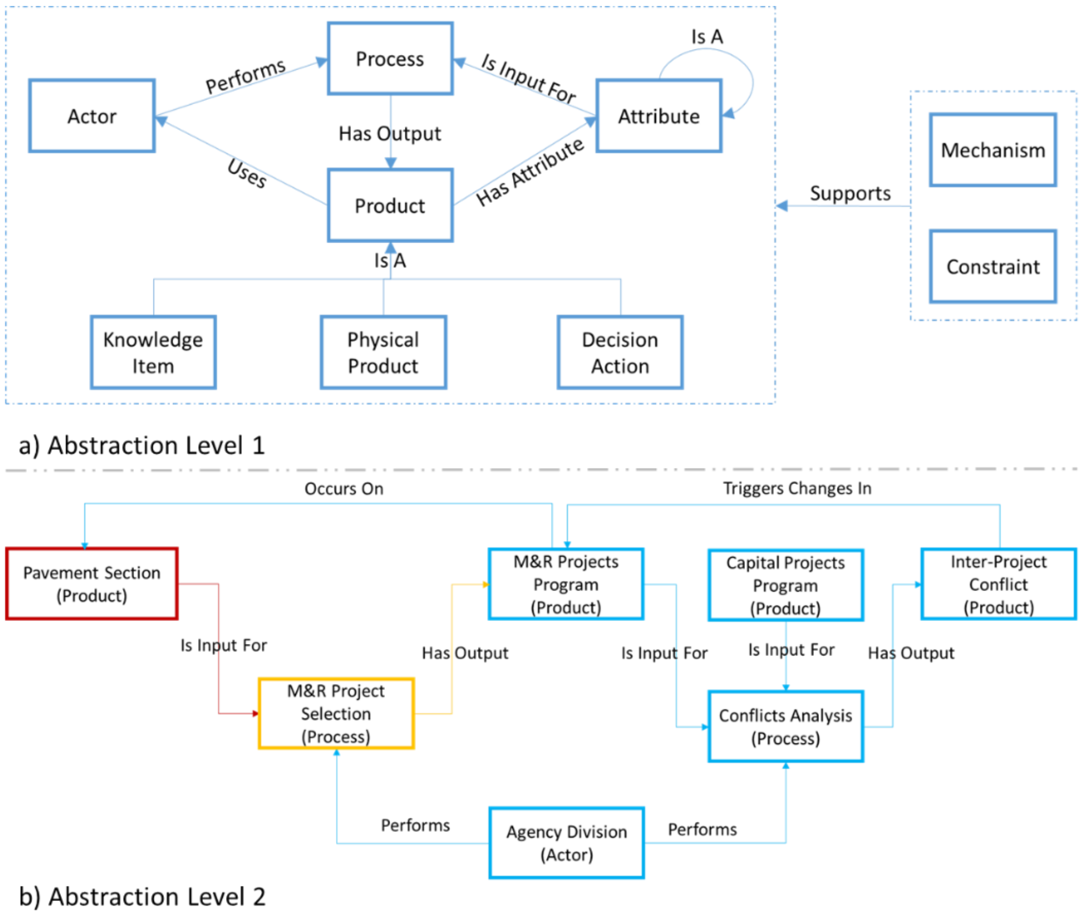


Figure 7-8. Ontological model of IHP-Onto (a) level 1 (b) level 2

Beyond the ontological model, IHP-Onto can be sub-divided into three major components. These include the pavement asset, M&R planning, and the inter-project coordination components (in Figure 7-9). These three components are linked through the location concept (Figure 7-9b) which is related to the route, roadway direction, a start, and an end reference point for each pavement section. The location is also based on a Linear Referencing System (LRS) which is considered a mechanism for locating linear highway assets and by extension, highway projects. LRS is a system where features (points and lines) are localized by measure along a linear asset. Notable LRSs utilized by SHAs include the Milepoint, Milepost, and other state-specific systems (Le et al. 2018). Often times, the same agency may have multiple LRSs being used by its individual functional groups. Accordingly, a formal representation for the location of pavement sections allows a structured documentation of different referencing systems and provides a basis for comparison between LRSs of projects from the agency functional groups.

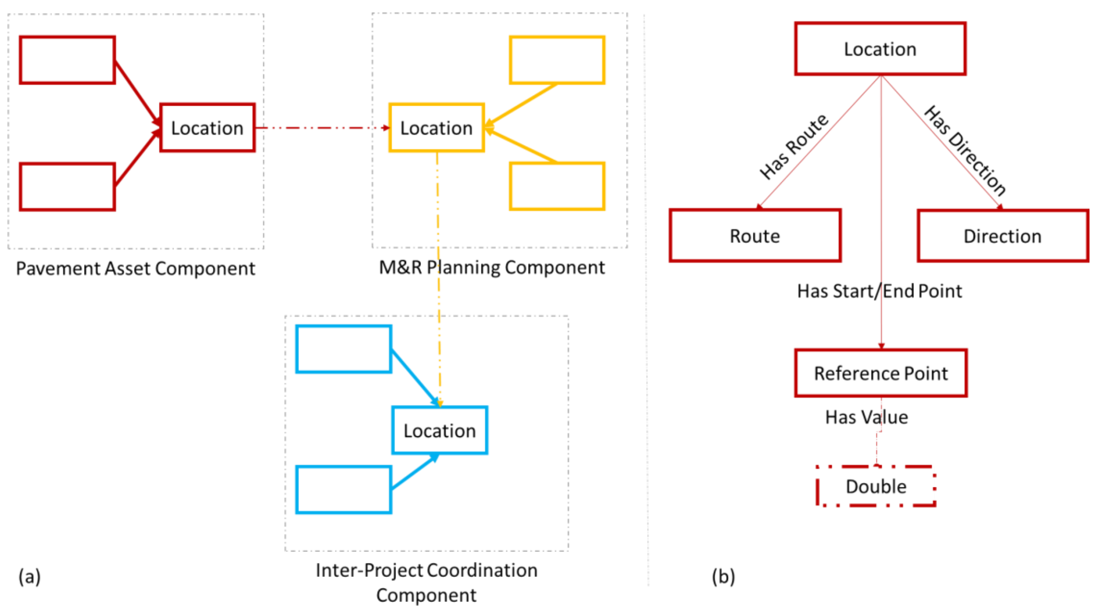


Figure 7-9. Components of IHP-Onto (a) inter-connected components (b) *Location* class

7.5.2 Pavement Asset Information

The main classes of the asset information component are the pavement section, location, traffic volume, condition rating, geometric information, pavement distress, and treatment history. Reused concepts in this component of the ontology include the section, pavement distress, and some location attributes (Le and Jeong 2016). Figure 7-10 shows an abstract level representation of this component in the upper part of the ontology (depicted as the red color). To begin with, the *Geometric Information* of a pavement section provides information on pavement thickness, lane width, the number of lanes and the section length. The *Traffic Volume* of pavement sections have implications for funding eligibility, the rate of deterioration, the minimum acceptable condition of the pavement section, and priority rankings during M&R project selection. Furthermore, the *Condition Rating* is one of the primary criteria for shortlisting pavement sections for potential projects to be funded. Closely linked to *Condition Rating*, the *Pavement Distress* is useful in proposing candidate M&R projects for pavement sections in the network. This information can help decision-makers in understanding why a specific treatment was chosen and guide decisions about whether it is feasible to postpone or remove projects if there are changes in the funds available or a conflict with another project exists. Moreover, the inclusion of the *Treatment History* provides information on the last time a treatment or project was done on the pavement section, the last treatment that was applied to the section, and information on the pavement age (as computed using year constructed/re-constructed). This information can play a vital role in discovering if highway engineers have been applying too many treatments in a short amount of time (which may be inefficient). This historical information is one of the unique aspects of IHP-Onto that can lead to significant savings for SHAs but as yet has not been formally represented in the existing literature.

7.5.3 M&R Planning

The M&R planning component primarily centers on the M&R Project Selection Analysis (as depicted with the yellow color in Figure 7-10). The pavement asset component connects to the M&R planning component as input information for network-level project selection analysis. The major classes cover information on budgets/funding categories, M&R treatments, M&R program evaluation, and the allocation method. First, the *Available Budget* for each *Funding Category* specifies the amount available for pavement M&R projects as well as the restrictions on the respective highway funds (allocated for different types of projects). As pointed out in earlier studies (France-Mensah et al. 2018; Lee and Madanat 2017), there can be separate highway budgets for new construction, rehabilitation, and maintenance projects. Accordingly, it is also important to clearly delineate the eligible types of M&R treatments used by the agency. The detailed treatments usually differ from SHA to SHA but the main classes can be classified as *Preventive Maintenance, Rehabilitation, and Reconstruction*. Preventive maintenance (PM) usually involves the application of low-cost treatments to pavements in good condition to retard future deterioration on the target sections. It can be used to correct some minor defects on the section but it does not contribute significantly to the structural capacity of the pavement (Lamptey et al. 2008a). Rehabilitation projects can be referred to as treatments that significantly improve the structural capacity of the pavement section in response to structural pavement distresses. In this study, rehabilitation treatments are synonymous to the designation "3R" (used to represent resurfacing, restoration, and rehabilitation) projects as used by the Federal Highway Administration (Grile et al.

2005). On the extreme end of rehabilitation is reconstruction. Reconstruction is essentially a new construction of a pavement section without significantly changing the existing road alignment. It often involves a full-depth replacement of the pavement section with over 5 inches of asphalt overlay (France-Mensah and O'Brien 2018). In addition to the agency-administered classes of treatments, the *M&R Treatment Costs* and *M&R Treatment Benefits* are also represented. While it is the convention to focus on *Agency Costs* in decision-making, IHP-Onto also represents information regarding *Environmental Costs* and *Road User Costs* as well. The consideration of these costs will provide a more holistic view of the costs associated with the different M&R treatments selected as projects. Conversely, there are benefits associated with the application of these M&R treatments. The obvious benefit is a jump in the condition rating or extension of the service life that a pavement section gains after a treatment is applied (Lamptey et al. 2008a). Moving on, the outcome of the M&R project selection analysis process is the M&R program for a given planning period. This program is evaluated by performance metrics which can have a score for comparison of alternate M&R programs. Performance metrics can include the average network condition score, the percentage of pavement sections within a "good condition," or the Greenhouse gas (GHG) emissions savings among others (France-Mensah and O'Brien 2019b). Lastly, an M&R program will consist of a number of *M&R Projects* (which have a subsumption (Is A) relationship with the *Highway Project* class). This is one way that the M&R planning component is connected to the inter-project coordination component.

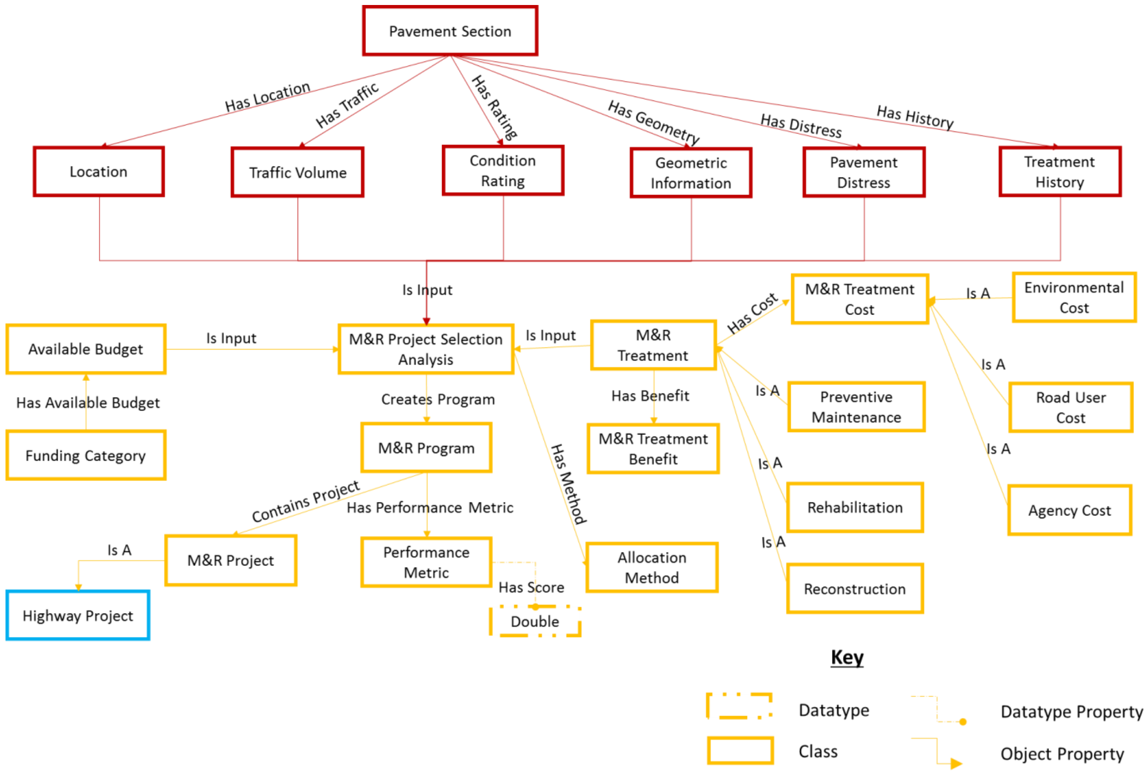


Figure 7-10. Pavement asset and M&R planning components of IHP-Onto

7.5.4 Inter-Project Coordination

The inter-project coordination component of IHP-Onto is designed to be able to represent projects information from M&R functional groups as well as other functional groups proposing safety projects and other capital-intensive projects like mobility. This component comprises two main sub-components. The first is a formal structure for documenting highway projects while the second sub-component comprises the documentation of inter-project conflicts between projects proposed by agency functional groups. In Figure 7-11, the first part of the component has the highway project class as its central focus. Every *Highway Project* has a unique identifier (*has Project ID*) and description (*has Description*). Other major classes in this component include information on the spatial-temporal characteristics of the project, cost, status, and the responsible actors for the execution of the project (Figure 7-11). The project location is a derivative of the initially described *Location* concept (as shown in Figure 7-9) with references to the *Route*, *Direction,* and ending/starting *Reference Points*. The *Linear Referencing System* concept is also represented to make sure that there is consistency across the LRSs used for proposing projects by functional groups within an agency. Details about the project schedule include the fiscal year that the project is taking place, the letting date, and the start/end dates of the project. For the project cost, a distinction is drawn between the *Authorized Amount* and the *Engineering Estimate*. When the project is programmed but has not yet been let, agency personnel may know an estimate of works to be outsourced (estimate) and how much funds have been currently allocated to that project (authorized amount). However, those values may not be the same. Furthermore, being able to link the project costs to the *Funding Category* can allow decision-makers to assess available funds for different categories if some projects are eliminated or modified later. This information is important because, for some funding categories, funds left unused will not be rolled over to the next planning cycle. Additionally, in the next cycle, the higher-level agency (State or Federal) disbursing the funds can reduce the amount allocated to a District or County if the funds allocated to them are not fully utilized. Where available, it is also important to represent the *Project Status* of a highway project. This information will inform decision-makers of the different phases of development of a project and guide the decision as to when it is too late to eliminate a project from the projects' plan. As an example, the phases of a mobility project may include the preliminary feasibility studies, initial design, detailed design, and construction phases. Depending on the agency practices and the proposed delivery strategy for each project, the project phases may vary for different SHAs. Lastly, it is important to represent the project *Actors* who will be responsible for the execution of each project. These *Actors* may include the responsible *Agency Division, Agency Personnel,* and *Contractor*. Not all highway projects are performed using external forces. Thus, for some projects that are executed using in-house forces, a contractor may not be a relevant *Actor*. It is also worth stating that while "Division" is used in this ontology in reference to state-level functions, this term is semantically synonymous to "Functional Groups" for applications at lower-levels of decision making.

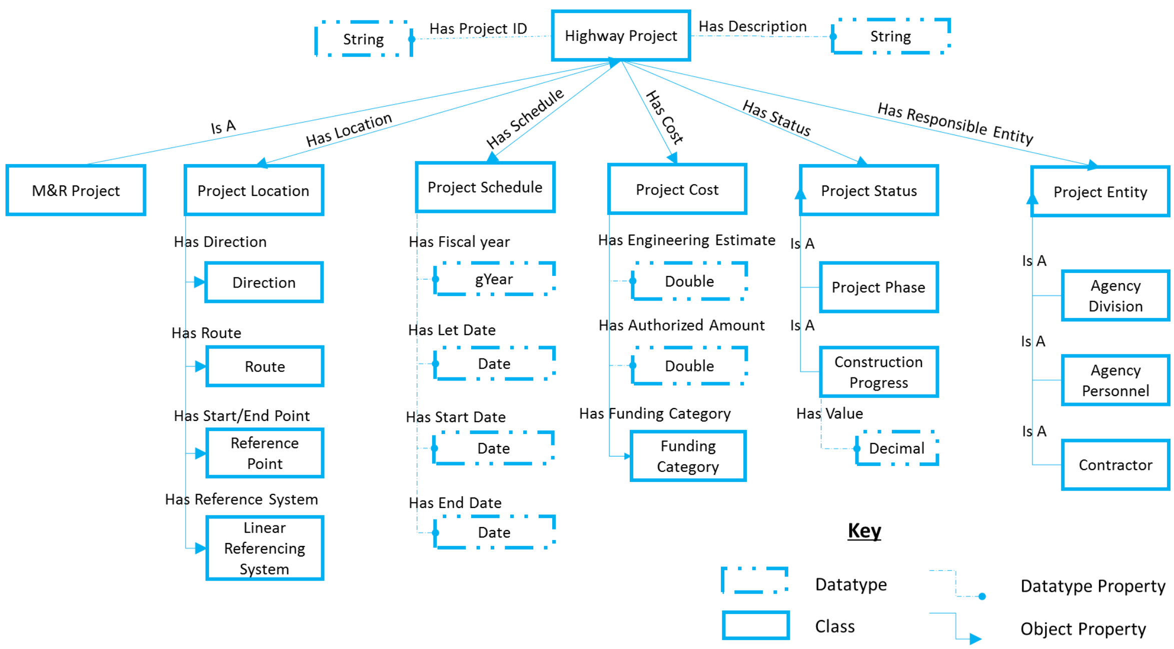


Figure 7-11. Inter-project coordination component of IHP-Onto (Highway Project focus)

Inter-project conflicts detection process

A key part of integrated planning is conducting inter-project conflicts analysis between the projects proposed by the different functional groups in an agency. Thus, the formal representation of the *Highway Project* concept presented earlier offers a standard format to support the spatial-temporal conflict analysis of highway projects. The principal steps in the conflicts analysis include; 1. Converting all planned highway pavement projects into a uniform semantic and syntactic form; 2. Performing spatial checks to identify spatial overlaps in projects proposed by different functional groups; 3. Checking for spatially conflicting projects that have a "close" temporal sequence; 4. Evaluating the spatial-temporal conflicts identified; 5. Proposing a resolution action, tracking the status of the resolution, and assigning a responsible division for the management of the conflict identified. This is, however, an iterative process. Thus, if the list of projects or the details of existing highway projects changes (due to funding cuts, emergency projects, political influence, etc.), this spatial-temporal analysis would have to be conducted again to make sure that there are no new conflicts introduced in the plan (as depicted in Figure 7-12). The relevant information represented in Figure 7-12 also demonstrates why it is important to represent inter-project conflict information for effective response and management.

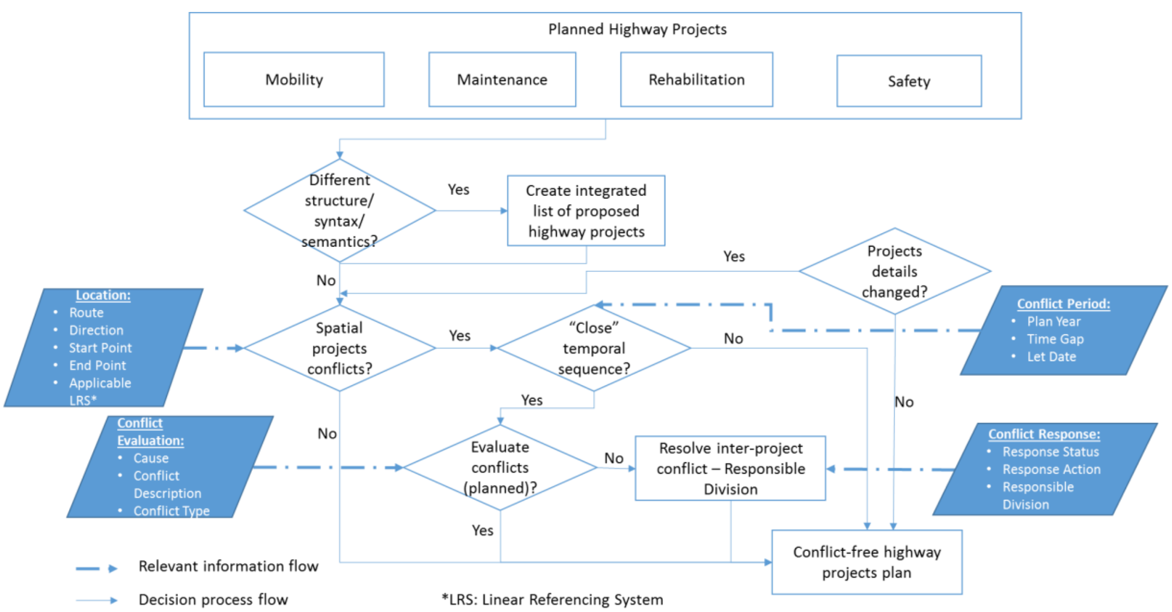


Figure 7-12. Conflicts detection process flow in highway projects plan

In line with documenting the spatial-temporal conflicts identified among planned highway projects, IHP-Onto includes a formalized representation for managing an *Inter-Project Conflict*. The major classes related to conflicts include information on the affected projects, the overlapping location of the conflict, the relevant timeline of the affected projects, the evaluation, and how to respond or manage the conflicts (as seen in Figure 7-13). To begin with, it is important to detect the projects that are involved in spatial-temporal project conflicts. The link between the *Conflicting Project* class and the *Highway Project* class ensures that the respective projects' information can be used during the conflict analysis. For instance, identifying that a PM project is clashing with a mobility project will suggest that, if there are no immediate safety implications, it would be easier to eliminate or reschedule the PM project. This is because mobility projects tend to take a longer time to plan, can be funded from multiple funding categories, and often have legislative restrictions which limit the ease of making changes to those projects. Furthermore, the *Funding Category* information related to projects can also aid in assessing the extra funds available for different categories after changes are made in response to conflicts identified. The time gap data (related to the "*has Time Gap*" property) refers to the temporal gap between the timelines of a pair of projects scheduled to occur on the same section. The *Conflict Evaluation* class includes information about the cause, type, and description of the conflict. This set of information will aid the responsible division in deciding how to respond to the inter-project conflict. Lastly, the *Conflict Response* class provides a standard format for documenting the proposed response action, the status of that action, and who is responsible for taking the action. This component of IHP-Onto ensures accountability in conflict management and provides a structured approach to tracking identified inter-project conflicts.

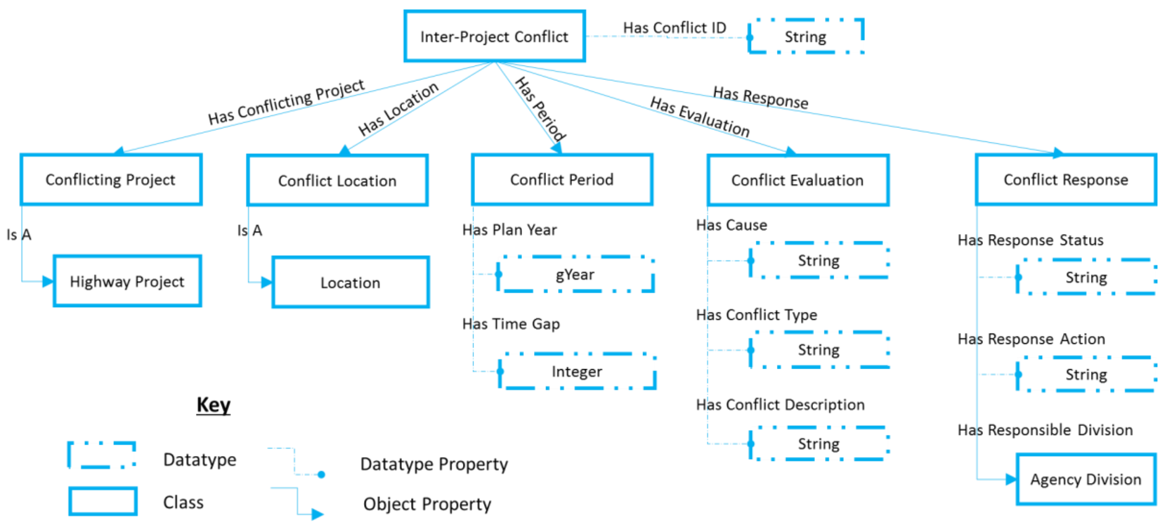


Figure 7-13. Inter-project coordination component of IHP-Onto (Inter-Project Conflict focus)

7.6 Implementation Case Study

The ontology was implemented in a real-world case to demonstrate its practical use in supporting integrated planning tasks. A knowledge base is constructed in this case study by adding instances to the classes defined in the ontology. Noy and McGuinness (Noy and McGuinness 2001) defined a knowledge base as a repository of information that is built on ontologies to capture, organize, and share information about a domain. In this study, it also acts as a pragmatic context to use SPARQL statements for queries in response to user questions related to integrated planning.

The Texas Department of Transportation (TxDOT) was chosen as the SHA for this case study because of information availability and the fact that it oversees the largest highway network in the United States by lane-miles (France-Mensah et al. 2017a).

Hence, a subset of the Texas highway network was used as the target asset network. More specifically, a stretch of the Interstate 35 West (IH0035W) highway section was selected. For the M&R planning constraints, the information used in the knowledge base is from earlier studies on objectives, planning constraints, and alternatives analysis associated with pavement asset decision-making in Texas (France-Mensah and O'Brien 2018; Menendez and Gharaibeh 2017; Wang et al. 2003b). The source of the projects input data was the Maintenance Management Information System (MMIS) and the Design and Construction Information system (DCIS) of TxDOT. Details of the evaluation of IHP-Onto as demonstrated via this case study is presented in the evaluation section.

7.7 Ontology Evaluation

Evaluating informatics ontologies can be very challenging partly because many assume that ontologies need to be a universal standard of knowledge for the target domain (El-Diraby and Osman 2011). However, for application ontologies, the emphasis has to be placed on the competency of the ontology towards addressing the problem identified in the motivating scenario (Grüninger and Fox 1995). In general, ontology evaluation approaches can include the task-based, gold standard, criteria-based, data-driven, and automated consistency checking evaluations (Brewster et al. 2004; Guo and Goh 2017; Haghighi et al. 2013). Detailed explanations of the scope, strengths, and limitations of these approaches are presented in studies by Guo and Goh (2017) and Haghighi et al. (2013). Most studies tend to use a combination of two or more approaches to test different metrics of an ontology because of the limitations of a single evaluation approach. The gold standard is not an option in this case since a benchmark “gold standard” does not exist in the literature. Accordingly, the authors conducted automated consistency checking, task-based evaluation, a data-driven evaluation, and criteria-based evaluation. This choice in evaluation methods is supported by a study by El-Diraby (2014) which proposed validation guidelines for ontologies that focus on the Artificial Intelligence (AI) dimension. Thus, the “fundamental” (El-Diraby 2014) aspects of the developed ontology to be tested should include the formal logic, internal error checks (through automated consistency checks via reasoners), and competency questions (through answers to queries executed as part of performing tasks).

7.7.1. Automated consistency checking

Consistency checking investigates an ontology to confirm that there are no contradictory facts based on Description Logic (DL). IHP-Onto was evaluated using the in-built DL reasoner in Protégé known as the Pellet reasoner. Pellet is a complete open-source OWL-DL reasoner with reasoning support for individuals (instances), cardinality restrictions, user-defined datatypes, sub-property axioms, reflexivity restrictions, symmetric properties, and disjoint properties (Sirin et al. 2007). This reasoner checks for implied subclass relationships based on user-defined class relationships. From a development standpoint, Pellet also provides debugging support for the iterative process of designing and coding an ontology which is free of DL errors. Errors in the ontology were pointed out via error messages and inconsistent classes were marked “red” for review. For example, subsumed child classes cannot inherit from multiple disjoint parent classes.

Thus, instances, where these inconsistencies were found in the ontology, prompted a review of the subsumption relationships of the child classes with the affected parent (supertype) classes. This checking exercise was repeated until the final version of the ontology was devoid of DL errors.

7.7.2. Task-based evaluation

The aim of this evaluation is to assess how the ontology can be used to accomplish certain tasks. Thus, a description of how the ontology fulfills the use cases is presented. This may be based on a software program application or a use-case scenario (Niknam and Karshenas 2017; Zhang et al. 2015). The latter is employed in this paper. The use cases included the ability to support decision-makers in performing network-level M&R project selection, documenting projects information, and performing inter-project conflicts analysis (as depicted in Figure 7-3). In the case study, three M&R projects were scheduled to take place on the selected network in the *2018* fiscal year. The selection of the projects was based on a prior planning process which leveraged, among other information, the condition score ratings, the last treatment, last treatment year and the costs of applying these treatments on the respective pavement sections (in Figure 7-14a). In addition to the M&R projects, the *Capital Planning Division* also proposed a "*Widen Freeway*" mobility project. Thus, it can be observed in Figure 7-14b that four projects with their respective location attributes, fiscal year, cost estimates, and funding categories are presented. A closer inspection (visually) of the start and end points of the proposed projects reveal that the projects with IDs "*35-2-2*" and "*35-01M*" both occur between

DFO_2 and *DFO_4* reference points. For context, *"DFO"* refers to the "Distance from Origin" LRS which is one of the state-specific LRSs of Texas. The spatial-temporal overlap is indicative of an inter-project conflict since both projects occur on the same sections and in the same fiscal year (visually shown by a red box in the GIS map in Figure 7-14b). After the inter-project conflicts were identified, the conflicts were documented by using the inter-project coordination component. Thus, Figure 7-14c shows the results of SPARQL statements in response to questions about the inter-project conflict's information. The conflict information indicates that conflict ID "*C0001*" is scheduled to occur in the fiscal year *2018*. Furthermore, it is documented that the decision to be taken was to *re-schedule the seal coat project* and the status of the action was that it had been *resolved* by the *Maintenance Planning Division*. These query results demonstrate that IHP-Onto provides a representation of planning and inter-project coordination knowledge that is capable of accomplishing the use cases defined earlier (under the ontology requirements specification section).

(a) Pavement asset information

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-ontology#>

SELECT ?Section ?Route ?Start_Point ?End_Point (STR(?Combined_Rating_Value) AS ?Combined_Rating) ?Last_Treatment_Type ?Last_Treatment_Year
    WHERE {  ?Section           iponto:has_Route                 ?Route.
             ?Section           iponto:has_Start_Point           ?Start_Point .
             ?Section           iponto:has_End_Point             ?End_Point.
             ?Section           iponto:has_Combined_Rating       ?combined_rating.
             ?combined_rating   iponto:has_Rating_Value          ?Combined_Rating_Value.
             ?Section           iponto:has_Last_Treatment_Type   ?Last_Treatment_Type.
             ?Section           iponto:has_Last_Treatment_Year   ?Last_Treatment_Year }
```

Section	Route	Start_Point	End_Point	Combined_Rating	Last_Treatment_Type	Last_Treatment_Year
Section_8	IH0035W	DFO_8	DFO_9	"70.0"	Overlay_4inch	FY2017
Section_10	IH0035W	DFO_10	DFO_11	"80.0"	Mill_and_Overlay	FY2016
Section_1	IH0035W	DFO_1	DFO_2	"87.0"	Seal_Coat	FY2016
Section_6	IH0035W	DFO_6	DFO_7	"76.0"	Thin_Overlay	FY2011
Section_5	IH0035W	DFO_5	DFO_6	"81.0"	Seal_Coat	FY2017
Section_3	IH0035W	DFO_3	DFO_4	"70.0"	Seal_Coat	FY2006
Section_9	IH0035W	DFO_9	DFO_10	"58.0"	Thin_Overlay	FY2006
Section_7	IH0035W	DFO_7	DFO_8	"75.0"	Microsurfacing	FY2006
Section_4	IH0035W	DFO_4	DFO_5	"94.0"	Mill_And_Inlay	FY2016
Section_2	IH0035W	DFO_2	DFO_3	"77.0"	Microsurfacing	FY2017

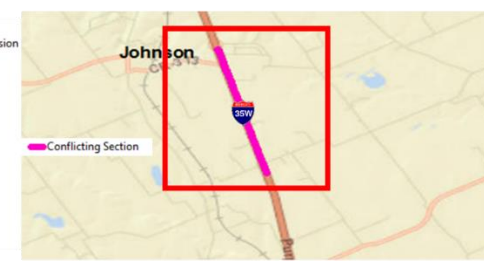
(b) Projects information

```
SELECT (STR(?ID) AS ?Project_ID) (STR(?Project_Desc) AS ?Project_Description) ?Route ?Start_Point ?End_Point (STR(?Year) AS ?Fiscal_Year)
(STR(?Let_Date) AS ?Project_Let_Date) (STR(?Engineering_Estimate) AS ?Project_Estimate) ?Funding_Category ?Responsible_Division

    WHERE {  ?Project        iponto:has_Project_ID              ?ID.
             ?Project        iponto:has_Description             ?Project_Desc.
             ?Project        iponto:has_Route                   ?Route.
             ?Project        iponto:has_Start_Point             ?Start_Point.
             ?Project        iponto:has_End_Point               ?End_Point.
             ?Project        iponto:has_Schedule                ?Schedule.
             ?Schedule       iponto:has_Fiscal_Year             ?Year.
             ?Schedule       iponto:has_Let_Date                ?Let_Date.
             ?Project        iponto:has_Project_Cost            ?Project_Cost.
             ?Project_Cost   iponto:has_Engineering_Estimate    ?Engineering_Estimate.
             ?Project_Cost   iponto:has_Funding_Category        ?Funding_Category.
             ?Project        iponto:has_Responsible_Division    ?Responsible_Division }
```

Project_ID	Project_Description	Route	Start_Point	End_Point	Fiscal_Year	Project_Estimate	Funding_Category
"35-6-3"	"1.5 inch HMA thin overla	IH0035W	DFO_6	DFO_9	"2018"	"150000.0"	Maintenance_Category
"35-9-1"	"4-inch overlay on main l	IH0035W	DFO_9	DFO_10	"2018"	"250000.0"	Category_1_UTP
"35-2-2"	"Seal coat for main lanes	IH0035W	DFO_2	DFO_4	"2018"	"100000.0"	Maintenance_Category
"35-01M"	"Widen freeway to 3 lan	IH0035W	DFO_2	DFO_4	"2018"	"3000000.0"	Category_4_UTP

(c) Conflicts information

```
SELECT (STR(?ID) AS ?Project_ID) ?Conflicting_Project_1 ?Conflicting_Project_2 (STR(?Plan_Year) AS ?Conflict_Year)
(STR(?Cause) AS ?Conflict_Cause) (STR(?Action) AS ?Response_Action) (STR(?Status) AS ?Response_Status) ?Responsible_Division

    WHERE {  ?Conflict     iponto:has_Conflict_ID              ?ID.
             ?Conflict     iponto:has_Conflicting_Project_1    ?Conflicting_Project_1.
             ?Conflict     iponto:has_Conflicting_Project_2    ?Conflicting_Project_2.
             ?Conflict     iponto:has_Period                   ?Period.
             ?Period       iponto:has_Plan_Year                ?Plan_Year.
             ?Conflict     iponto:has_Evaluation               ?Evaluation.
             ?Evaluation   iponto:has_Cause                    ?Cause.
             ?Conflict     iponto:has_Response                 ?Response.
             ?Response     iponto:has_Response_Action          ?Action.
             ?Response     iponto:has_Response_Status          ?Status.
             ?Response     iponto:has_Responsible_Division     ?Responsible_Division}
```



Project_ID	Conflict_Year	Conflict_Cause	Response_Action	Response_Status	Responsible_Division
"C0001"	"2018"	"Clashing schedules"	"Re-schedule seal coat project"	"Resolved"	Maintenance_Planning_Division

Figure 7-14. SPARQL statements, results and visualization for select competency questions

7.7.3 Data-driven evaluation

This evaluation approach does a comparative analysis of the developed ontology against a pre-defined set of knowledge items by counting the related terms that appear between a set of knowledge items and the ontology (Guo and Goh 2017). The primary metrics chosen for the evaluation of IHP-Onto with regards to information retrieval is *precision* and *recall*. *Precision* refers to the amount of knowledge that is accurately detected in comparison to all the knowledge items that are represented in the ontology (Brewster et al. 2004). Conversely, *recall* reflects the amount of knowledge that is accurately detected in comparison to all the knowledge items that it should identify (from the pre-defined set) (Brewster et al. 2004). The frame of reference (corpus) is a set of answers to questions that were extracted from expert interviews concerning the type of information that is required to support integrated planning tasks. Forty-five questions covering the asset information, M&R planning, and inter-project coordination were used for the evaluation. The questions were manually annotated to extract the main concepts needed to answer them. Then, SPARQL queries were developed in response to the annotated questions by utilizing the entities (concepts and relations) in the developed ontology. Thus, *relevant entities* include information items needed to answer a query whether or not it exists in the ontology. However, *retrieved entities* include information items in the ontology that could be used implicitly or explicitly to answer questions using SPARQL statements. Accordingly, per these definitions, answers to some questions may require implied knowledge extracted from the explicit definitions of the concepts and relations in IHP-Onto. For example, the conflicting project length or the distance over which two conflicting projects are scheduled to take place can be computed by performing algebraic operations in SPARQL using the start and end *Reference Points*. From Equations 7.1 and 7.2, the "knowledge that is accurately detected" corresponds to the intersection of the *relevant entities* and the *retrieved entities*.

The performance (recall and precision rates) of IHP-Onto was then compared with the performance of TransXML (Ziering 2007) and with an earlier study by Le and Jeong (Le and Jeong 2016) (as shown in Table 7-3). The two latter studies were chosen because they were assessed to have a partial overlap in the intended scope of IHP-Onto. The results of the precision and recall rates highlight three main points. First, the low recall rates by TransXML and Le and Jeong (2016) reiterates the limitations of existing ontologies and further underscores the need for IHP-Onto for supporting integrated planning. Secondly, the high performance of IHP-Onto demonstrates that it contains a high percentage of the *relevant* entities (Recall = 92.40%) for supporting integrated planning. Thirdly, the precision rate (97.48%) of IHP-Onto indicates that a high percentage of the knowledge items are applicable for providing information useful in integrated planning. This supports the conciseness of the ontology.

$$Precision = \frac{|\{relevant\ entities\} \cap \{retrieved\ entities\}|}{|\{retrieved\ entities\}|} \tag{7.1}$$

$$Recall = \frac{|\{relevant\ entities\} \cap \{retrieved\ entities\}|}{|\{relevant\ entities\}|} \tag{7.2}$$

$$F\ measure = 2 \times \frac{Precision\ \times Recall}{Precision + Recall} \tag{7.3}$$

Table 7-3. Precision and recall rates for comparing ontologies

Ontologies	**Precision**	**Recall**	**F-measure**
IHP-Onto	97.48%	92.80%	95.08%
TransXML	73.08%	45.60%	56.16%
Le and Jeong (2016)	81.82%	50.40%	62.38%

7.7.4 Criteria-based evaluation

This evaluation uses several criteria for assessing the validity of an ontology. Based on prior validation studies, the dominant evaluation criteria include competency, consistency, conciseness, completeness, clarity, coverage, correctness, and expandability (Guo and Goh 2017; Haghighi et al. 2013). One of the limitations of this approach is that some of the criteria are not easily quantifiable and thus, require a manual inspection of the ontology (Yu et al. 2007). In this study, the five criteria chosen include competency, consistency, completeness, clarity, and conciseness. These selected criteria are based on the recommendations in the "Validity Roadmap" by El-Diraby (2014). The consistency and competency criteria were primarily demonstrated via automated consistency checking and task-based evaluation respectively. The data-driven evaluation also demonstrates satisfactory performance for conciseness via the precision analysis. Hence, this section focuses on addressing the completeness and clarity criteria.

Completeness: Proving that an ontology is complete is not feasible. However, completeness can be demonstrated (Yu et al. 2007). In ontology development, completeness is demonstrated by first checking the information that the concepts claim to define. They must be representations of their real-world equivalents. Secondly, another check is conducted for those concepts not explicitly defined; they should be capable of being implicitly derived from the existing information defined (Gómez-Pérez 1996). Accordingly, three major steps were taken. First, the authors checked the ontology to identify classes that were over-specified or imprecise. This check also included classes that did not reflect real-world concepts. Secondly, checks were conducted to ensure that the domain and ranges of the object properties and datatype properties were complete within the class hierarchy of the ontology. Thirdly, checks were conducted to ensure that there were no missing properties or cardinality errors and that the entity classes did not have any properties that it was unable to have in the real world (Gómez-Pérez 1996). The data saturation trend demonstrated in Figure 7-5 and the recall rate further demonstrate the completeness of IHP-Onto.

Clarity: In determining the clarity of an ontology, the critical question to ask is if knowledge items in the ontology have an unambiguous meaning (El-Diraby 2014). Thus, clarity is concerned with an ontology communicating the intended meaning of classes and their relationships (Guo and Goh 2017). Clarity is better addressed at the initial stage of ontology development by benchmarking the user-defined terms against standards or dominant terms in the literature. In this study, the terms used for the components of the ontology were extracted from NCHRP studies (Cambridge Systematics 2006, 2009; Hall 2015; Harrison 2005; Neumann 1997) on infrastructure management. NCHRP studies are generally seen as authorities in this domain and hence, fulfills the clarity requirement of IHP-Onto.

In summary, four approaches were employed to evaluate IHP-Onto. First, the automated consistency checking approach ensures that the ontology is internally consistent. Secondly, the task-based evaluation demonstrated that IHP-Onto was capable of achieving the competency tasks earlier defined via competency questions. Thirdly, the data-driven evaluation rigorously tests the completeness and conciseness in the ontology by demonstrating its comparative performance with prior ontologies. Finally, the criteria-based evaluation further addresses the clarity and completeness metrics of the ontology. Thus, IHP-Onto was assessed to be competent, consistent, concise, clear, and demonstrated completeness. The performance of tasks to ensure compliance with these criteria was mostly iterative and thus, the ontology went through several versions before a final evaluated version was implemented.

7.8 CONCLUSION

The functional nature of highway agencies can result in a siloed approach to planning. Usually, there are several functional groups in the same highway agency but each utilizing group-specific information systems and processes. The net result is that there are often spatial-temporal conflicts in the highway projects that are proposed by functional groups working on the same network, ultimately leading to inefficiencies and undue expenses. Resolutions of such conflicts and, more generally, better use of public funds necessitate a cross-functional or integrated approach to coordination. There needs to be an iterative approach to synchronizing changes in asset information, planning decisions and constraints, and inter-project coordination information.

To support a more integrated approach to planning, this paper presents an ontology (IHP-Onto) which can act as a unifying framework for data sharing across functional groups and their associated data systems. The knowledge elicited for the development of the ontology included interviews with domain experts, project information from SHAs, and prior ontologies in the literature. IHP-Onto was also implemented and demonstrated in an implementation case which included the planning and documentation of projects and inter-project conflicts on a highway pavement asset network. The integrated information retrieval performance of IHP-Onto was also tested via precision and recall rates which exceed benchmarks for prior studies in the domain of interest.

IHP-Onto contributes to the body of knowledge by providing an integrated view of information that can be used to support various applications in infrastructure management. There are two aspects to these contributions to the body of knowledge. To begin with, the ontology developed provides a formalized knowledge representation for M&R planning constraints and its relationship with pavement asset information. Secondly, the developed machine-readable ontology can be utilized by computers and domain experts in inter-project coordination across multiple functional groups working on the same asset network. These contributions add to the state-of-the-art understanding of how cross-functional highway agencies can improve decision-making by generating integrated highway information that can support cost-effective decisions made during inter-project coordination.

While extensive, there are areas for future expansion of the ontology. In particular, IHP-Onto could be expanded to represent safety planning tasks and as well as further aspects of mobility planning. This can include the representation of information concerning the Right-Of-Way acquisition process, environmental review, new project design process, and traffic control plans. Further work can also build on the ontology to support more reasoning and decision support tasks. For example, research can elicit and formalize explicit and implicit rules on integrated planning practices via the Semantic Web Rule Language (SWRL). IHP-Onto provides a basis from which new applications in integrated planning can be developed, tested, and deployed to support improvements in the transportation planning process.

Chapter 8 Decision Support Tool for Integrated Planning

A decision support tool (DST) for implementing the proposed ontology in Chapter 7 is presented in this chapter. Figure 8-1 shows the four major stages followed in this study. Chapter 7 addressed the scope specification and the elicitation of the knowledge needed to develop the ontology. Following this, an ontology was developed by formalizing the knowledge elicited and building on prior ontologies. The proposed ontology was implemented in the Protégé knowledge management environment and validated using multiple approaches including but not limited to data-driven and task-based evaluations. As part of extending the task-based evaluation to enable input from users and subject-matter experts, a DST tool was developed. The primary objective of this tool is to enable a more efficient integrated planning process of highway projects by linking highway information. This entails the provision of a structured format for documenting planned highway projects, performing inter-project conflict analysis, and linking M&R planning information to projects information. The tool was developed in the Microsoft Excel environment using Visual Basic (VBA) as the primary programming language for functions. Additionally, a GIS-based component of the tool was also developed to enable decision-makers visualize the results of different scenarios of budget allocation and projects coordination. The detailed use cases of the tool are presented in Figure 8-2. After the development of the tool, the DST was evaluated by using the Charrette test and validation by Subject-Matter Experts (SMEs).

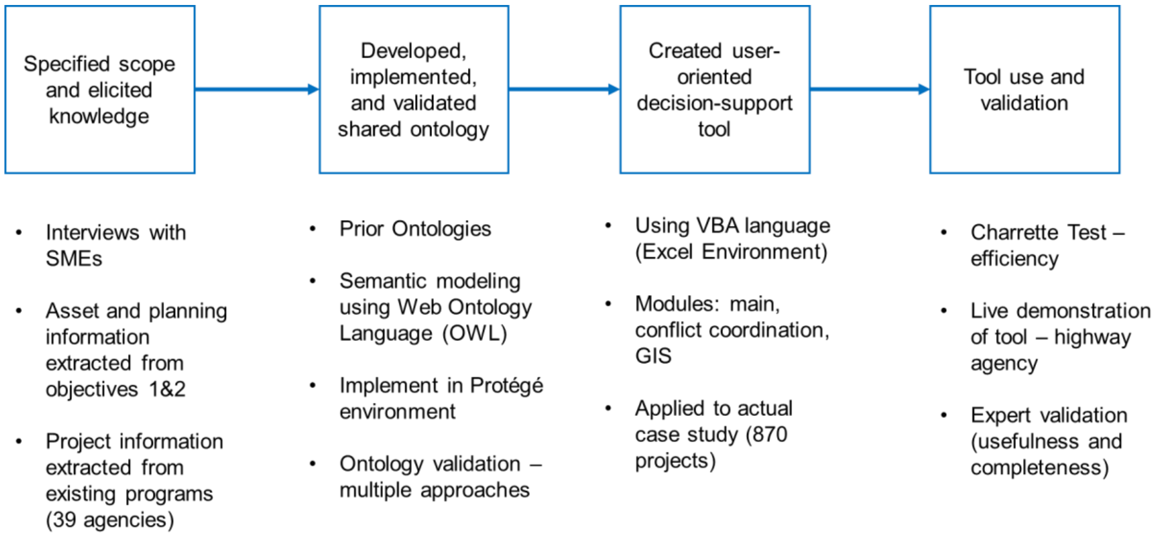


Figure 8-1. Research study plan for the decision support tool.

The rest of this chapter is presented as follows; the underlying need for the tool from practice and research-oriented perspectives are presented. This is followed by a detailed description of the modules in the tool and what their functions are. An application scenario is then presented with a description of practical contexts for making decisions about inter-project conflicts or responding to changes in the planned projects. Finally, a Charrette test and a synthesis of answers to validation questions are presented based on feedback from a group of SMEs from TxDOT.

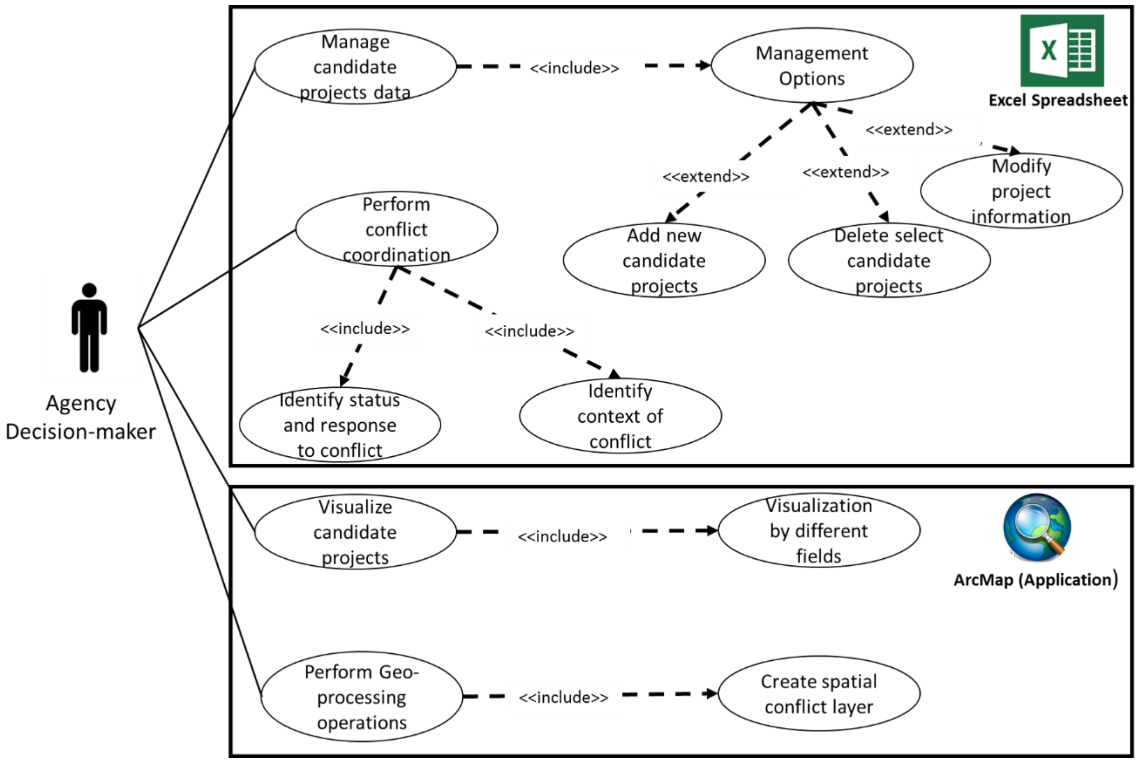


Figure 8-2. Detailed use case diagram for the decision support tool.

8.1 NEED FOR TOOL

Based on interviews with six Directors of different functional groups at three districts, integrated planning is necessary to avoid redundant projects and improve the effectiveness of pavement management plans. However, there is no formal approach to conducting a cross-functional analysis of projects proposed by the different functional groups in the same SHA. More specifically, there is no structured format for capturing the context and status of inter-project conflicts in the proposed projects by multiple functional groups. In addition to this, more often than not, there is an inadequate connection between the planning information (funding categories, project eligibility restrictions, asset condition ratings, etc.) and projects information. This is important because unanticipated changes in the funding or asset conditions can trigger a review of the projects list. Accordingly, being able to link planning and projects information can allow a dynamic response to these changes.

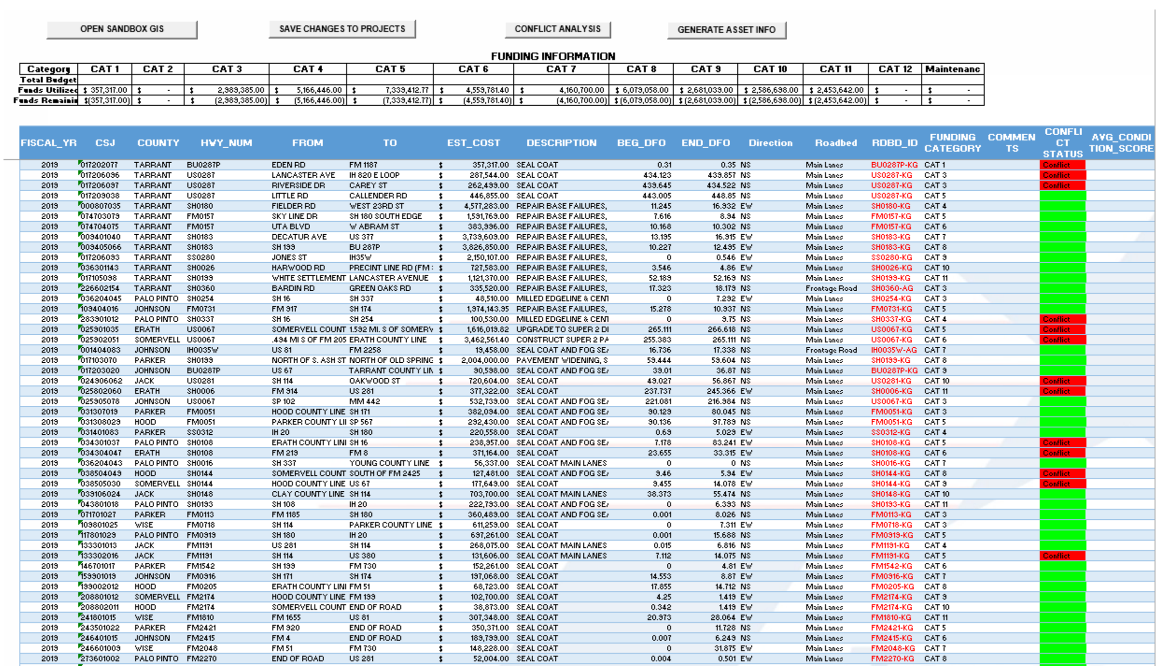
8.2 Decision support tool

The decision support tool (DST) contains three major modules including the main module, the conflicts coordination module, and the GIS module. Detailed explanations of the functions and potential operations in each module are presented next.

8.2.1 Main Module

The main module contains a combined list of projects from all the relevant functional groups in a decision-making agency. The representation of project information includes attributes like the fiscal year, unique project identifier, highway number, estimated project costs, and a general description of the project. Other attributes include the spatial limits (from and to reference points), the roadbed (main lanes or frontage road), and the corresponding funding category or categories that the project is drawing from. Accordingly, the budgetary limits for each funding category and the remaining funds based on the planned projects in the list are also presented in this module. Figure 8-3 shows a screenshot of the main module displaying a list of planned projects information.

In addition to the aforementioned attributes, the main module also has a number of functionalities including the “Conflict Analysis” button and the “Generate Asset Info” button. First, the latter function allows users to query for condition score data from the Pavement Management Information System (PMIS). This condition score information retrieved is pivotal towards confirming that some of the planned projects are scheduled to occur/cover "critical" pavement sections with low PMIS scores. Secondly, the inter-project conflict analysis function allows users to conduct inter-project conflict analysis of all the projects that have been aggregated in the list. The results of the conflict analysis are published in the second tab in the Excel sheet labeled the "Conflicts Coordination" tab or module. The information in the conflicts coordination tab is presented next.



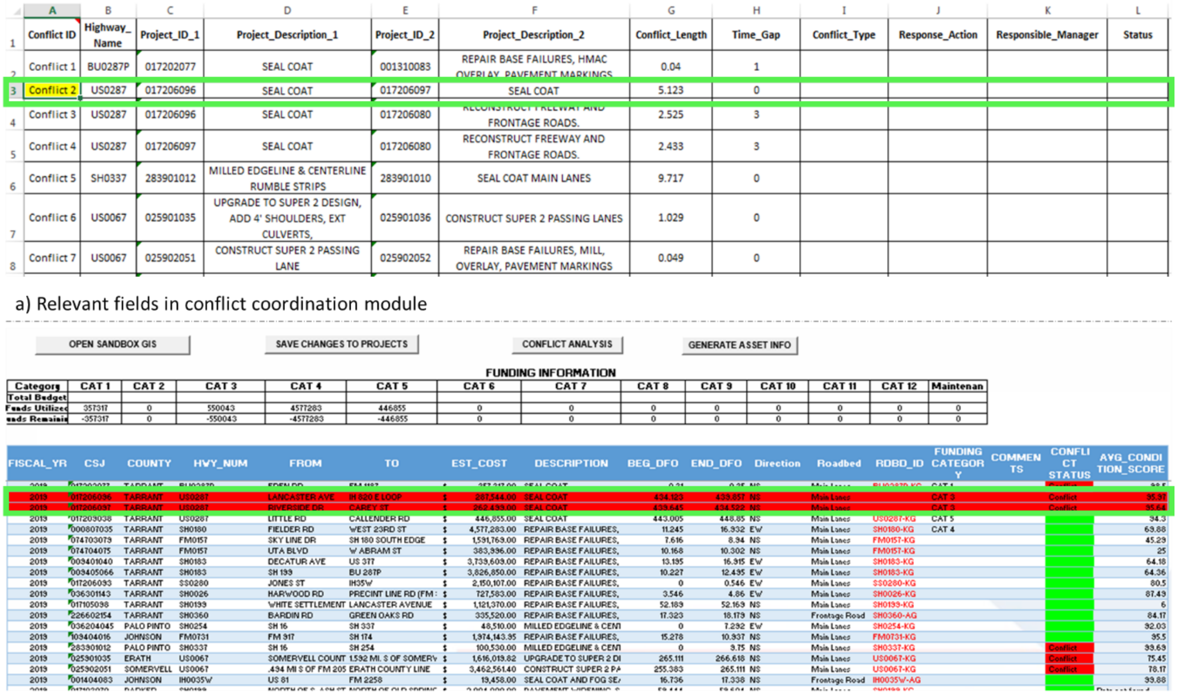
Category	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5	CAT 6	CAT 7	CAT 8	CAT 9	CAT 10	CAT 11	CAT 12	Maintenanc
Total Budget													
Funds Utilized	$ 357,317.00	$ -	$ 2,989,385.00	$ 5,166,446.00	$ 7,339,412.77	$ 4,559,781.40	$ 4,160,700.00	$ 6,079,058.00	$ 2,681,039.00	$ 2,586,698.00	$ 2,453,642.00	$ -	$ -
Funds Remainin	$(357,317.00)	$ -	$ (2,989,385.00)	$ (5,166,446.00)	$ (7,339,412.77)	$ (4,559,781.40)	$ (4,160,700.00)	$ (6,079,058.00)	$ (2,681,039.00)	$ (2,586,698.00)	$ (2,453,642.00)	$ -	$ -

FISCAL_YR	CSJ	COUNTY	HWY_NUM	FROM	TO	EST_COST	DESCRIPTION	BEG_DFO	END_DFO	Direction	Roadbed	RDBD_ID	FUNDING CATEGORY	COMMENTS	CONFLICT STATUS	AVG_CONDITION_SCORE
2019	017202077	TARRANT	BU0287P	EDEN RD	FM 1187	$ 357,317.00	SEAL COAT	0.31	0.35	NS	Main Lanes	BU0287P-KG	CAT 1		Conflict	
2019	017206096	TARRANT	US0287	LANCASTER AVE	IH 820 E LOOP	$ 287,544.00	SEAL COAT	434.123	439.857	NS	Main Lanes	US0287-KG	CAT 3		Conflict	
2019	017206097	TARRANT	US0287	RIVERSIDE DR	CAREY ST	$ 262,499.00	SEAL COAT	439.645	434.522	NS	Main Lanes	US0287-KG	CAT 3		Conflict	
2019	017209038	TARRANT	US0287	LITTLE RD	CALLENDER RD	$ 446,855.00	SEAL COAT	443.005	448.85	NS	Main Lanes	US0287-KG	CAT 5			
2019	000807035	TARRANT	SH0180	FIELDER RD	WEST 23RD ST	$ 4,577,283.00	REPAIR BASE FAILURES,	11.245	16.932	EW	Main Lanes	SH0180-KG	CAT 4			
2019	074703079	TARRANT	FM0157	SKY LINE DR	SH 180 SOUTH EDGE	$ 1,591,769.00	REPAIR BASE FAILURES,	7.616	8.94	NS	Main Lanes	FM0157-KG	CAT 5			
2019	074704075	TARRANT	FM0157	UTA BLVD	W ABRAM ST	$ 383,996.00	REPAIR BASE FAILURES,	10.168	10.302	NS	Main Lanes	FM0157-KG	CAT 6			
2019	009401040	TARRANT	SH0183	DECATUR AVE	US 377	$ 3,739,609.00	REPAIR BASE FAILURES,	13.195	16.915	EW	Main Lanes	SH0183-KG	CAT 7			
2019	009405066	TARRANT	SH0183	SH 199	BU 287P	$ 3,826,850.00	REPAIR BASE FAILURES,	10.227	12.495	EW	Main Lanes	SH0183-KG	CAT 8			
2019	017206093	TARRANT	SS0280	JONES ST	IH35W	$ 2,150,107.00	REPAIR BASE FAILURES,	0	0.546	EW	Main Lanes	SS0280-KG	CAT 9			
2019	036301143	TARRANT	SH0026	HARWOOD RD	PRECINT LINE RD (FM :	$ 727,583.00	REPAIR BASE FAILURES,	3.546	4.86	EW	Main Lanes	SH0026-KG	CAT 10			
2019	017105098	TARRANT	SH0199	WHITE SETTLEMENT	LANCASTER AVENUE	$ 1,121,370.00	REPAIR BASE FAILURES,	52.189	52.169	NS	Main Lanes	SH0199-KG	CAT 11			
2019	226602154	TARRANT	SH0360	BARDIN RD	GREEN OAKS RD	$ 335,520.00	REPAIR BASE FAILURES,	17.323	18.179	NS	Frontage Road	SH0360-AG	CAT 3			
2019	036204045	PALO PINTO	SH0254	SH 16	SH 337	$ 48,510.00	MILLED EDGELINE & CENT	0	7.292	EW	Main Lanes	SH0254-KG	CAT 3			
2019	109404016	JOHNSON	FM0731	FM 917	SH 174	$ 1,974,143.95	REPAIR BASE FAILURES,	15.278	10.937	NS	Main Lanes	FM0731-KG	CAT 5			
2019	283901012	PALO PINTO	SH0337	SH 16	SH 254	$ 100,530.00	MILLED EDGELINE & CENT	0	9.75	NS	Main Lanes	SH0337-KG	CAT 4		Conflict	
2019	025901035	ERATH	US0067	SOMERVELL COUNT	1.592 MI. S OF SOMERV	$ 1,616,019.82	UPGRADE TO SUPER 2 DI	265.111	266.618	NS	Main Lanes	US0067-KG	CAT 5		Conflict	
2019	025902051	SOMERVELL	US0067	.494 MI S OF FM 205	ERATH COUNTY LINE	$ 3,462,561.40	CONSTRUCT SUPER 2 PA	255.383	265.111	NS	Main Lanes	US0067-KG	CAT 6		Conflict	
2019	001404083	JOHNSON	IH0035W	US 81	FM 2258	$ 19,458.00	SEAL COAT AND FOG SE/	16.736	17.338	NS	Frontage Road	IH0035W-AG	CAT 7			
2019	017103070	PARKER	SH0199	NORTH OF S. ASH ST	NORTH OF OLD SPRING	$ 2,004,000.00	PAVEMENT WIDENING, S	59.444	59.604	NS	Main Lanes	SH0199-KG	CAT 8			
2019	017203020	JOHNSON	BU0287P	US 67	TARRANT COUNTY LIN	$ 90,598.00	SEAL COAT AND FOG SE/	39.01	36.87	NS	Main Lanes	BU0287P-KG	CAT 9			
2019	024906062	JACK	US0281	SH 114	OAKWOOD ST	$ 720,604.00	SEAL COAT	49.027	56.867	NS	Main Lanes	US0281-KG	CAT 10		Conflict	
2019	025802060	ERATH	SH0006	FM 914	US 281	$ 377,322.00	SEAL COAT	237.737	245.366	EW	Main Lanes	SH0006-KG	CAT 11		Conflict	
2019	025905078	JOHNSON	US0067	SP 102	MM 442	$ 532,739.00	SEAL COAT AND FOG SE/	221.081	216.984	NS	Main Lanes	US0067-KG	CAT 3			
2019	031307019	PARKER	FM0051	HOOD COUNTY LINE	SH 171	$ 382,094.00	SEAL COAT AND FOG SE/	90.129	80.045	NS	Main Lanes	FM0051-KG	CAT 3			
2019	031308029	HOOD	FM0051	PARKER COUNTY LII	SP 567	$ 292,430.00	SEAL COAT AND FOG SE/	90.136	97.789	NS	Main Lanes	FM0051-KG	CAT 5			
2019	031401083	PARKER	SS0312	IH 20	SH 180	$ 220,558.00	SEAL COAT	0.69	5.029	EW	Main Lanes	SS0312-KG	CAT 4			
2019	034301037	PALO PINTO	SH0108	ERATH COUNTY LINI	SH 16	$ 238,957.00	SEAL COAT AND FOG SE/	7.178	83.241	EW	Main Lanes	SH0108-KG	CAT 5		Conflict	
2019	034304047	ERATH	SH0108	FM 219	FM 8	$ 371,164.00	SEAL COAT	23.655	33.315	EW	Main Lanes	SH0108-KG	CAT 6		Conflict	
2019	036204043	PALO PINTO	SH0016	SH 337	YOUNG COUNTY LINE	$ 56,337.00	SEAL COAT MAIN LANES	0	0	NS	Main Lanes	SH0016-KG	CAT 7			
2019	038504049	HOOD	SH0144	SOMERVELL COUNT	SOUTH OF FM 2425	$ 127,481.00	SEAL COAT AND FOG SE/	9.46	5.94	EW	Main Lanes	SH0144-KG	CAT 8		Conflict	
2019	038505030	SOMERVELL	SH0144	HOOD COUNTY LINE	US 67	$ 177,649.00	SEAL COAT	9.455	14.078	EW	Main Lanes	SH0144-KG	CAT 9		Conflict	
2019	039106024	JACK	SH0148	CLAY COUNTY LINE	SH 114	$ 703,700.00	SEAL COAT MAIN LANES	38.373	55.474	NS	Main Lanes	SH0148-KG	CAT 10			
2019	043801018	PALO PINTO	SH0193	SH 108	IH 20	$ 222,793.00	SEAL COAT AND FOG SE/	0	6.393	NS	Main Lanes	SH0193-KG	CAT 11			
2019	071701027	PARKER	FM0113	FM 1185	SH 180	$ 360,489.00	SEAL COAT AND FOG SE/	0.001	8.026	NS	Main Lanes	FM0113-KG	CAT 3			
2019	109801025	WISE	FM0718	SH 114	PARKER COUNTY LINE	$ 611,259.00	SEAL COAT	0	7.311	EW	Main Lanes	FM0718-KG	CAT 3			
2019	117801029	PALO PINTO	FM0919	SH 180	IH 20	$ 697,261.00	SEAL COAT	0.001	15.688	NS	Main Lanes	FM0919-KG	CAT 5			
2019	133301013	JACK	FM1191	US 281	SH 114	$ 268,075.00	SEAL COAT MAIN LANES	0.015	6.816	NS	Main Lanes	FM1191-KG	CAT 4			
2019	133302016	JACK	FM1191	SH 114	US 380	$ 131,606.00	SEAL COAT MAIN LANES	7.112	14.075	NS	Main Lanes	FM1191-KG	CAT 5		Conflict	
2019	146701017	PARKER	FM1542	SH 199	FM 730	$ 152,261.00	SEAL COAT	0	4.81	EW	Main Lanes	FM1542-KG	CAT 6			
2019	159901019	JOHNSON	FM0916	SH 171	SH 174	$ 197,068.00	SEAL COAT	14.553	8.87	EW	Main Lanes	FM0916-KG	CAT 7			
2019	199002012	HOOD	FM0205	ERATH COUNTY LINI	FM 51	$ 68,723.00	SEAL COAT	17.855	14.712	NS	Main Lanes	FM0205-KG	CAT 8			
2019	208801012	SOMERVELL	FM2174	HOOD COUNTY LINE	FM 199	$ 102,700.00	SEAL COAT	4.25	1.419	EW	Main Lanes	FM2174-KG	CAT 9			
2019	208802011	HOOD	FM2174	SOMERVELL COUNT	END OF ROAD	$ 38,873.00	SEAL COAT	0.342	1.419	EW	Main Lanes	FM2174-KG	CAT 10			
2019	241801015	WISE	FM1810	FM 1655	US 81	$ 307,348.00	SEAL COAT	20.973	28.064	EW	Main Lanes	FM1810-KG	CAT 11			
2019	243501022	PARKER	FM2421	FM 920	END OF ROAD	$ 350,371.00	SEAL COAT	0	11.728	NS	Main Lanes	FM2421-KG	CAT 5			
2019	246401015	JOHNSON	FM2415	FM 4	END OF ROAD	$ 189,799.00	SEAL COAT	0.007	6.249	NS	Main Lanes	FM2415-KG	CAT 6			
2019	246601009	WISE	FM2048	FM 51	FM 730	$ 148,228.00	SEAL COAT	0	31.875	EW	Main Lanes	FM2048-KG	CAT 7			
2019	273601002	PALO PINTO	FM2270	END OF ROAD	US 281	$ 52,004.00	SEAL COAT	0.004	0.501	EW	Main Lanes	FM2270-KG	CAT 8			

Figure 8-3. Screenshot of the main module

8.2.2 Conflicts Coordination Module

After the conflict analysis is executed in the main module, the results of the inter-project conflicts identified are presented in this module. The major fields in this module include a unique conflict identifier (Conflict ID), highway name, the IDs, and the description of the conflicting projects. Additional information is allowed for what the response action should be, who should take that action (Responsible Division/Manager) and what the status of the conflict is (as seen in Figure 8-4a). Thus, based on the description of the conflicting projects and other information like the time gap, the agency staff can input information on the responsible action and division. Another feature of this module is that it allows users to select the Conflict ID and check the main module for additional information on the conflicting projects (highlighted in red in Figure 8-4b). Accordingly, the users can make changes in the main module like deleting a conflicting project or modifying its information. Modifying a project's information can include changing the spatial limits of the project, the planned fiscal year, project description, and/or estimated costs. However, such changes may also lead to other conflicts in the plan and should prompt a re-run of the conflict analysis function to ensure that no new conflicts were introduced. Thus, this spatial-temporal conflict analysis process is a continuous, dynamic, and iterative process.



Conflict ID	Highway_Name	Project_ID_1	Project_Description_1	Project_ID_2	Project_Description_2	Conflict_Length	Time_Gap	Conflict_Type	Response_Action	Responsible_Manager	Status
Conflict 1	BU0287P	017202077	SEAL COAT	001310083	REPAIR BASE FAILURES, HMAC OVERLAY, PAVEMENT MARKINGS	0.04	1				
Conflict 2	US0287	017206096	SEAL COAT	017206097	SEAL COAT	5.123	0				
Conflict 3	US0287	017206096	SEAL COAT	017206080	RECONSTRUCT FREEWAY AND FRONTAGE ROADS.	2.525	3				
Conflict 4	US0287	017206097	SEAL COAT	017206080	RECONSTRUCT FREEWAY AND FRONTAGE ROADS.	2.433	3				
Conflict 5	SH0337	283901012	MILLED EDGELINE & CENTERLINE RUMBLE STRIPS	283901010	SEAL COAT MAIN LANES	9.717	0				
Conflict 6	US0067	025901035	UPGRADE TO SUPER 2 DESIGN, ADD 4' SHOULDERS, EXT CULVERTS,	025901036	CONSTRUCT SUPER 2 PASSING LANES	1.029	0				
Conflict 7	US0067	025902051	CONSTRUCT SUPER 2 PASSING LANE	025902052	REPAIR BASE FAILURES, MILL, OVERLAY, PAVEMENT MARKINGS	0.049	0				

a) Relevant fields in conflict coordination module

b) Corresponding pair of conflicting projects in main module

Figure 8-4. Screenshot of example conflicts identified in conflicts coordination module (a) relevant fields (b) selected pair of conflicting projects.

8.2.3 GIS Module

The primary purpose of the GIS module is to visualize the planned projects within a spatial context of the highway infrastructure network. Users will be able to visualize scenarios of planned projects in the ArcMap component of ArcGIS (as shown in Figure 8-5). The visualization functionality serves two major purposes. First, it allows users to confirm the spatial extents of the planned projects in the main module. For example, if the limits of a planned highway project indicated that it was in another county other than where it was supposed to be, the user can quickly ratify this error in spatial information. Secondly, the overlay of the planned projects with other information like the PMIS condition score of the network can aid decision-makers in assessing if critical (low PMIS score) sections have been accounted for throughout the network. This feature of the GIS module does not only ensure the minimum acceptable score of the network but also leads to improved safety for those sections. Furthermore, joint visualization with information like the last treatment year on a pavement section can enable decision-makers assess if the current list of preventive maintenance projects are covering target pavement sections which have not been resurfaced for a long period.

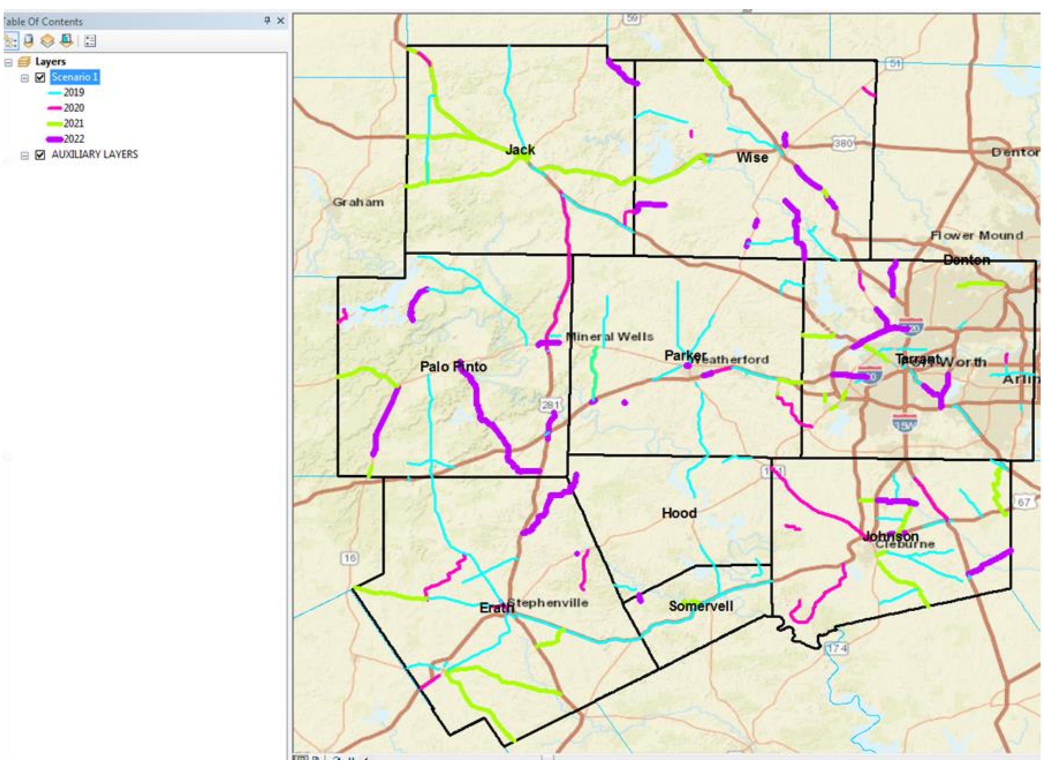


Figure 8-5. Screenshot of the GIS module showing a select scenario of planned projects by fiscal year in the Fort Worth district.

8.3 APPLICATION SCENARIOS

This section describes the application of the developed tool to a select case study involving the Fort Worth District of TxDOT. The network for this district includes nine counties and a total network size of approximately 9,000 lane-miles. The scenario includes a spatial-temporal conflict analysis of projects proposed by the Maintenance functional group and the Transportation Planning, and Development (TP&D) functional group working in the District. To focus on the depth of the discussion, a subset of the projects is presented in detail for the scenarios described. The results of the scenarios further confirm the competency of the tool in being able to support typical integrated planning tasks in a pragmatic setting.

8.3.1 Overview of Conflict Analysis

For this application scenario, there were about 340 projects proposed by the TP&D functional group and over 530 projects proposed by the Maintenance functional group. The projects proposed by the latter group included planning activities like the application of seal coats, pavement leveling, milling, base repair, crack sealing, edge maintenance, and pothole repairs. On the other hand, the TP&D group proposed projects involving widening pavement sections, thick overlays, constructing interchanges, replacing bridges, construction of ramps, and new construction in general. There are some common projects in the preventive maintenance category which can be funded by both functional groups under Category 1 of the 12 standard functional categories approved for the Unified Transportation Plan of TxDOT. Examples of such projects include seal coats, thin overlays, and micro-surfacing treatments. The current practice of integrated planning involves members of both functional groups having meetings to go over the projects for finalization and potential conflicts. However, given the scale of the projects described above (over 800 projects), it is statistically possible that some spatial-temporal conflicts are not identified or addressed appropriately. More importantly, changes in asset data and planning information often leads to unanticipated changes in highway projects information. To address this, the developed tool allows agency personnel to accurately identify such inter-project conflicts within their individual plans and the combined plan. The output from using the tool is further discussed below.

8.3.2 Tool Results of Conflict Analysis

After the conflict analysis is run in the tool, a total of 39 inter-project conflicts were identified in the plan. The inter-project conflicts include information on the pairs of projects that were assessed to be having a spatial overlap in the plan. Relevant information provided include the project description, project IDs, and the highway name of each pair of conflicting projects. To provide additional information for the response to the conflicts, the conflict length, and the time gap information is also presented. As explained earlier, the time gap information is an algebraic computation of the difference in the fiscal years of the conflicting pair of projects. Thus, it can be observed in Figure 8-6 that *Conflicts 2 and 5* have conflicting projects that are scheduled to occur in the same fiscal year. The conflict length information about *Conflict 1* also suggests that the spatial overlap in projects may too small (0.04 mile) to consider it a “structural” inter-project conflict.

From a decision-making standpoint, *Conflict 3* provides an interesting case for a deeper dive. It can be observed from Figure 8-6 that this conflict is between a seal coat project and a reconstruction project. On the M&R spectrum of projects, a seal coat project is a preventive maintenance project while the reconstruction project is a major capital project synonymous with the “Heavy Rehabilitation” designation by TxDOT. It can also be observed that the spatial overlap in projects is about 2.53 miles and this pair of projects are scheduled 3 fiscal years apart. The crucial question here for decision-makers is;

“Is it worth doing a Seal Coat project on a 2.5-mile road if that project is scheduled for a Reconstruction project in 3 years?”

To answer this question, decision-makers need to assess if there are immediate safety concerns with not doing the seal coat project in the scheduled fiscal year. This may require a complementary safety assessment to ascertain. A part of this safety assessment may include the generation of the condition score or skid score of the affected pavement sections. A secondary consideration is the availability of funds to undertake the scheduled project. To elaborate, if there are funding shortfalls or new unanticipated projects that need to be added to the projects’ plan, other previously planned projects will need to be eliminated. In such a scenario, the knowledge of the details of *Conflict 3* can prompt decision-makers to eliminate the planned seal coat project to make way for other much-needed projects.

On the other hand, *Conflict 5* involves a spatial-temporal conflict between a project description of "milled edgeline & centerline rumble strips" and a "seal coat project" on the main lanes. Here, this conflict can be an "intentional" one representing a set of complementary projects that have been scheduled for the same section in the same fiscal year. In this case, the rumble strips are installed on the pavement section after the application of the seal coat project. This means that these complementary tasks need to be synchronized to ensure the timely application of the rumble strips after the seal coat application. Thus, not only does this analysis identify "unintentional" conflicts like *Conflict 3* but it can also help in scheduling complementary projects in a timely manner.

Conflict ID	Highway_Name	Project_ID_1	Project_Description_1	Project_ID_2	Project_Description_2	Conflict_Length	Time_Gap	Conflict_Type
Conflict 1	BU0287P	017202077	SEAL COAT	001310083	REPAIR BASE FAILURES, HMAC OVERLAY, PAVEMENT MARKINGS	0.04	1	
Conflict 2	US0287	017206096	SEAL COAT	017206097	SEAL COAT	5.123	0	
Conflict 3	US0287	017206096	SEAL COAT	017206080	RECONSTRUCT FREEWAY AND FRONTAGE ROADS.	2.525	3	
Conflict 4	US0287	017206097	SEAL COAT	017206080	RECONSTRUCT FREEWAY AND FRONTAGE ROADS.	2.433	3	
Conflict 5	SH0337	283901012	MILLED EDGELINE & CENTERLINE RUMBLE STRIPS	283901010	SEAL COAT MAIN LANES	9.717	0	

Figure 8-6. Detailed information on a select list of conflicts in the integrated plan of projects

8.4 CHARRETTE TEST

The goal behind doing a Charrette test is to determine whether a process is performed better by using a proposed set of tools or by using a status quo set of tools or processes. It is a "comparative empirical method" that has been applied for the evaluation of formalizations as part of the design process (Clayton et al. 1998). The new set of tools can be either computer-aided or manual, and the hypothesis is that the new tool should be able to outperform the existing practices or set of tools. More often than not, the speed and quality of completing tasks or making decisions are used as proxies for measuring the effectiveness of the proposed set of tools. In this exercise, the inter-project coordination component is what was tested by participants.

8.4.1 Exercise Summary

The main task of this exercise is the cross-functional analysis of conflicts between highway projects proposed by the Maintenance and Capital Planning functional groups of a district in TxDOT. The specific tasks will be performed twice. First, by using an existing set of tools (normal spreadsheets) and a second time, by using the developed Excel-based tool based on the ontology. Specific tasks to be executed include;

1. The identification of spatial-temporal conflicts between pairs of highway projects in a 4-year plan. The specific attributes will be the conflicting project IDs, the project description, and the highway name or number on which the conflict will occur.
2. Computation of the conflicting pavement section length (i.e. the overlapping section over which both projects are scheduled to occur)
3. Computation of the time gap (i.e. the difference in the fiscal years of the pair of projects that are spatially conflicting)

Information made available: Two sets of proposed highway projects, each by the Maintenance and Capital Planning functional groups were made available to the test-takers (students with industry experience). A total of 100 highway projects were provided to the test participants. This was to simulate the scale of decision-making of a typical SHA district while accounting for a reasonable time to be able to complete the exercise.

Target Group: The target group was graduate students in the Civil, Architectural, and Environmental Engineering Department at the University of Texas at Austin with industry experience in project management. Ten (10) students with a total sum of 38 years of industry experience in project management participated in the exercise. This sample size is in accordance with prior studies that have conducted Charrette tests on the use of tools for supporting decision-making in the infrastructure management domain (Kim et al. 2018; Koo et al. 2007).

Implementation environment: In the first experiment, the participants were required to complete the aforementioned tasks in a general Microsoft (MS) Excel environment using any commands or functions that they were familiar with. In the second round, the participants completed the exercise by using the developed tool for performance comparison.

8.4.2 Evaluation Measures

As pointed out earlier, the major measures for conducting a Charrette test include speed and accuracy. In this test, speed was measured as the amount of time it took to complete the aforementioned tasks by using the existing set of tools and by using the developed tool. On the other hand, accuracy was measured as the percentage of supplementary information (conflict length, and time gap information) that the test-takers were able to accurately document or compute. The three hypotheses tested in this exercise are shown below;

<u>Hypothesis 1:</u>

H_0: there is no significant difference between the time it takes for participants to perform the tasks with or without the developed tool.

H_1: there is a significant difference in time

<u>Hypothesis 2:</u>

H_0: there is no significant difference between the number of conflicts identified by participants with or without the developed tool.

H_1: there is a significant difference in the conflicts identified.

<u>Hypothesis 3:</u>

H_0: there is no significant difference between the accuracy of supplementary information computed by participants with or without the developed tool.

H_1: there is a significant difference in the accuracy of supplementary information

Since the hypotheses described above refer to repeated measures of the same tasks by using two different sets of tools, the paired samples t-test was used for evaluating the statistical significance of the differences observed in the study. This test requires three assumptions to hold true to be used. First, the repeated observations in the dependent variable must be independent of one another. Secondly, the dependent variable has to be ordinal or ratio-scale data with no outliers. Finally, the dependent variable has to be normally distributed. The first two assumptions hold true based on the design of the test and the random selection of test participants. A violation of the normality assumption (using the Shapiro-Wilk Test) led to a change in the test to be conducted in hypotheses 2 and 3. The Wilcoxon signed-rank test is a non-parametric test that can be used to test the median difference in related samples and does not require a normal distribution in the dependent sample.

8.4.3 Results and Discussion

This section details the raw scores from the tests as well as the subsequent statistical analysis done to test the three hypotheses specified above. In Table 8-1, the raw results of the test are presented. First, it can be observed that the time taken to complete the exercise without the tool is significantly higher than the time it takes to use the tool for the exercise. On average, participants took 38.63 minutes without the tool versus an average of 1.02 minutes while using the tool to perform the same tasks. Secondly, the conflicts identified had a consistent accuracy with the tool whiles participants' performance without the tool had a higher variability (7 to 10). Similarly, the computed (supplementary) information about the conflicts varied significantly with some participants miscalculating as much as 50% of the supplementary information needed for characterizing the conflicts. These results suggest that the developed tool can be more efficient than the status quo of performing these tasks manually. However, to confirm statistical significance, the results of the hypotheses are presented next.

Table 8-1 Raw results of the Charrette test

Participant ID	Time in minutes (without tool)	Time in minutes (with tool)	Conflicts identified (without tool)	Conflicts identified (with tool)	Computed information (without tool)	Computed information (with tool)
1	43.68	1.82	9	10	16	20
2	36.57	1.08	9	10	17	20
3	30.5	0.92	7	10	13	20
4	26.43	1.5	9	10	18	20
5	59.12	1.5	8	10	10	20
6	41.05	0.5	10	10	20	20
7	27.64	0.5	10	10	20	20
8	42.75	0.55	8	10	10	20
9	46.5	1.33	8	10	14	20
10	32.05	0.49	10	10	20	20

The three hypotheses tested all yielded statistically significant results which translated to the rejection of the three respective null hypotheses. Accordingly, the results for hypothesis 1 suggests that the test participants were significantly faster at completing the exercise with the tool than otherwise. This finding is supported by the response to the feedback question about the difficulty of both approaches. Most participants commented that the exercise without the tool was laborious and time-consuming. This makes it error-prone. For SHAs that have limited human resources and consequently, limited man-hours to spare, this finding suggests that this tool can be used to make integrated planning more efficient. Furthermore, the statistical result of hypothesis 2 suggests that participants were significantly identifying more conflicts with the tool than without the tool. The result has direct implications of the economic value of the tool towards decision-making. The identification of conflicts before projects are executed means that more projects that are redundant can be identified and eliminated resulting in tax-payer dollar savings. Finally, the statistical result of hypothesis 3 suggests that supplementary information that can be used to guide decision-making concerning the conflicts identified were more accurately computed using the tool than otherwise. This is further supported by comments by participants about how the fatigue of the process could lead to errors in computation or visual judgment errors.

In conclusion, the three hypotheses tested demonstrate that the tool is effective and time-efficient. This is further supported by an average usefulness rating of 5 (on a scale of 1: least useful to 5: most useful) given by the participants after the exercise. The participants intimated that this tool was specifically useful in identifying, structuring, and providing supplementary information to support the inter-project conflict process of highway projects while accounting for decision constraints.

Table 8-2 Hypothesis test results for the Charrette test

Hypothesis	**Significance (p-value)**	**Interpretation (With an alpha level of 5%)**
Hypothesis 1	0.001	Reject the null hypothesis
Hypothesis 2	0.016	Reject the null hypothesis
Hypothesis 3	0.018	Reject the null hypothesis

8.5 Expert Validation

For this validation phase, a face-to-face meeting with a group of 6 SMEs was arranged for the demonstration of the tool on an actual set of highway projects. The projects were proposed by different functional groups in the same agency (a TxDOT district). A smaller set of 20 projects equally split between the maintenance and capital planning functional groups was used for this exercise. The SMEs present at the meeting had an average of 16 years of industry experience in transportation planning and development (TP&D), maintenance, safety, and highway asset operations. The titles of the experts included Director of Maintenance, Director of TP&D, Advanced transportation planning Director, GIS Planning Coordinator, and Pavement Engineer. The perspectives of the SMEs were elicited before, in between, and at the end of the case demonstration described above. Overall, the SMEs found the tool to be useful, easy-to-use, intuitive, and complete (in terms of the information required). A detailed discussion of the evaluation questionnaire is included below for more details.

What are the potential benefits of this tool?

The panel of experts intimated that there were a number of relevant uses of the tool within the context of integrated planning. All the SMEs agreed the tool was useful for identifying inter-project conflicts in the proposed projects by the functional group, confirming intentional conflicts for complementary projects (for e.g. a “level-up” preceding a “seal coat” project), and visual confirmation of the spatial limits of proposed projects. More importantly, the tool allowed a more comprehensive response to the conflicts identified by integrating information from the relevant asset and other planning information. Next, five SMEs pointed out that this tool could be useful in bundling conflicting projects where possible to save on mobilization costs. This would mean that if a pair of projects were planned to occur on the same section around the same time period, decision-makers can consider the possibility of letting those projects together as one contract.

Furthermore, other benefits identified by 3 or more SMEs include checks to ensure that critical (poor condition) pavement sections are covered in the proposed program as well as confirming that proposed highway projects were funded from their eligible budgets or funding categories. It was also pointed out that the tool can be used to ensure that proposed projects from different area (local) offices were combined in a more efficient manner. Additionally, the SMEs explained that local offices could check for conflicts in their list of projects before submitting it to the District office for inclusion in the district-wide plan.

At what stage(s) in the planning cycle will the tool be used?

Based on the responses on the benefits of the tool, the SMEs pointed out that the tool will be most frequently used during two stages. First, the tool will be used for the consolidation of all candidate projects coming from the local (area) engineers and other functional groups. Secondly, the tool will be used for the confirmation and approval of candidate projects for inclusion in the project information management systems. Given the dynamic nature of highway planning, two SMEs also pointed out that the tool would be used frequently during the course of the plan year to reflect potential changes in projects information. Changes in projects information can be due to changes in funds, asset information, user complaints, or other political factors. These implementation stages pointed out by SMEs align strongly with the purpose of the tool and reinforce the need for a proactive, cross-functional, and dynamic highway planning process.

What additional information has to be added to make the tool effective? Any relevant information missing?

The goal of this question was to evaluate the completeness of the information provided in the tool. In general, all of the SMEs agreed that this tool had most of the information items that were needed to perform integrated planning tasks. Additional information that was suggested by one of the SMEs was the inclusion of the funding agency behind the funds to be spent. For example, there can be funds from the Safety Division (at the State-level) for projects that qualified for safety improvement. However, this concern is addressed by the ontology and the resulting tool since it represents the different funding categories which are usually tied to the source agency.

On a scale of 1(least useful) to 5 (very useful), how useful is the tool for supporting integrated planning? Any comments on the degree of usefulness or otherwise?

Three SMEs assigned a score of 4.0/5.0 for the usefulness rating and the other three assigned a score of 5.0/5.0 for the usefulness rating. These ratings yielded an average rating of 4.5/5.0 which is an indication that the tool is generally considered useful for the performance of integrated planning tasks. One SME commentated that “it is a very useful tool to be utilized by different users managing different portfolios or programs.” As part of the discussions with the SMEs, it was also pointed out that it will be prudent for every functional group or local area office to use this tool before lists of candidate highway projects are submitted for review.

What will be some of the challenges with using this tool? (Data management, resources needed, organizational culture, the definition of roles)

Issues with data management and assigning responsibility dominate the responses of SMEs to this evaluation question. More specifically, five SMEs pointed out that the resources needed issue was the premier challenge associated with using this tool. Resources needed may include the personnel hours, software costs, training costs, and other costs related to the deployment, operation, and update of the tool developed. Furthermore, four SMEs raised issues with data management practices and the definition of roles and ownership. For data management practices, specific issues included access to up-to-date data, data processing, and data versioning concerns. For the definition of roles and ownership, SMEs intimated that it will be important to assign specific personnel for the update and maintenance of the tool. This will ensure that the tool has the most up-to-date data to be able to better support integrated planning decisions.

What additional features can be added to the functionality of the tool? (Future scope)

While the SMEs were generally satisfied with the current features of the tool, a number of additional features were proposed for future implementation. First, one expert suggested a funding dashboard according to the county or political entity. Another expert proposed the creation of a "live" link to project information systems of the agency. Lastly, it was suggested that spatial conflicts could be expanded to account for projects that are not located on the same route but have close spatial proximity. An example can be projects that take place on adjacent roads. All these features can be explored in subsequent versions of the tool.

8.6 CONCLUSION

In summary, it has been demonstrated that the developed ontology can be used in actual integrated planning contexts to improve decision-making. This chapter also demonstrates the competency and usability of the tool via the Charrette test involving multiple users. The developed DST tool currently aids decision-makers in identifying inter-project conflicts across different functional groups and provides contextual information to guide the response actions to be taken by the user. Linking the project information to the asset and funding information also allows the users to account for planning constraints in order to understand the rationale behind the selection of projects. This linked information will enable decision-makers make more cost-efficient decisions concerning highway projects thus saving limited tax-payer dollars for other much-needed projects. While the tool was implemented for a 4-year plan, long range plans of highway projects can also be analyzed by the tool.

Chapter 9 Conclusion and Future Research

This research study contributes to ongoing debates on how to build pragmatic constraints in budget allocation models and furthers the state-of-art understanding on how to improve the integrated planning of highway maintenance, rehabilitation, and capital construction projects. This section highlights the major contributions to the body of knowledge and the relevant domain of practice.

9.1 Intellectual contribution

- This study comprehensively provides a formalized and consolidated analysis of the weaknesses and strengths of the different budget allocation approaches to guide the decision-making process of highway agencies. Moreover, the study also provides an approach to evaluating the performance of different budget allocation methods employed for M&R budget allocation decisions.
- This research also proposes an approach to formulating budgetary constraints to reflect pragmatic funding constraints that influence the decision-making context of M&R programming. This contribution is relevant towards assessing the impact of accounting for this funding characteristic to network-level performance and M&R treatment decisions suggested by optimization models. The findings highlight the inefficiencies in the network performance due to funding restrictions in M&R budget categories.
- Moreover, the study proposes a shared ontology capable of supporting the integrated spatial-temporal planning of highway projects. The proposed ontology links planning information to highway projects information which addresses the interdependent relationship between them. Thus, this representation can enable a structured approach

to knowledge elicitation and information capture concerning the integrated planning of highway projects and inter-project conflict analysis.

9.2 CONTRIBUTION TO PRACTICE

- For SHAs looking to transition to more formalized budget allocation frameworks, this study can serve a relevant source of information concerning the performance of different budget allocation methods according to effectiveness, equity, and the degree to which it aids in the achievement of a strategic goal of the agency.
- By demonstrating the sub-optimal network performance that occurs as a result of projects eligibility constraints, this study's findings point out potential inefficiencies introduced by budgetary restrictions in funding categories. This can incentivize the adoption of more flexible policies which allow funds transfer from different budget categories to improve the overall pavement network performance.
- The data integration framework can serve as a collaborative platform for the maintenance and capital planning functional groups in SHAs to improve the integrated and cross-functional planning of maintenance and capital construction projects. This will enable the identification of spatial-temporal projects conflicts for the obviation of potentially redundant M&R projects.
- Finally, the shared representation of planning information on assets will enable changes in planned projects to be executed in a more efficient process which accounts for the rationale behind projects' selection.

9.3 Future research

This research study has explored pragmatic approaches to improving the budget allocation models for M&R programming and developed formalized representations to aid in the integrated planning of highway projects. The findings from this study contribute to infrastructure management knowledge and stress the need for more effective cross-functional practices in highway agencies. In spite of these contributions to the body of knowledge and practice, future directions in this research area can include;

- The budget allocation models developed for achieving research objective 1 and 2 do not account for social equity and sustainability considerations in developing M&R programs. As pointed out by Campbell (1996), sustainable development should be reflected in the triple bottom line of environmental conservation, economic prosperity, and social equity. Thus, it is important to develop M&R programs that enable the society to improve the built environment without "compromising the integrity and availability of natural, economic, and social assets for future generations (Hendricks et al. 2018)." Nonetheless, like most studies in the literature, this study overlooks the consideration of equitable service in the preservation of highway infrastructure. Future research can develop more sustainable and comprehensive models which provide reliable proxies for capturing social equity and sustainability considerations in budget allocation models.
- Furthermore, there are a number of practical limitations in the budget allocation models developed that can be better addressed in further studies. First, the models

fail to account for non-linear pavement performance behavior as part of modeling asset deterioration. Secondly, the deterioration trends for sections in the network can be heterogeneous and interdependent. However, the inclusion of non-linearity and complex interdependencies in the model will lead to Mixed Integer Non-Linear Programming (MINLP) problems which are NP-hard and computationally expensive. Thus, the application of near-optimal methods like genetic algorithms, ant colony optimization, particle swarm optimization, and other evolutionary algorithms to such problems can be explored.

- Based on the shared ontology for the integrated planning study, rules can be elicited and implemented in the ontology via the SWRL rules. These reasoning rules will provide more efficient ways of executing integrated planning tasks for projects' selection and projects coordination. For instance, currently, conflicts identified can be "intentional" or otherwise. The development of reasoning rules based on relevant parameters of a conflict can semi-automate the process of identifying "unintentional conflicts" and focus the agency's limited time and resources on addressing such conflicts. In line with this, the exploration of data mining algorithms of prior planning decisions or a set of labeled conflicts can provide insights on the different types of inter-project conflicts and the appropriate responses to such identified conflicts.
- Finally, the use of the proposed tool from the ontology can be further validated with multiple cases from other SHAs. While the development of the ontology accounted for generic terms and vocabulary in the infrastructure management

domain, the application contexts may differ from SHA to SHA, and hence, potentially lead to the development of more use cases for integrated planning.

List of Appendices

APPENDIX A: INTERVIEW GUIDE FOR IMPLEMENTATION OF BUDGET ALLOCATION MODELS BY HIGHWAY AGENCIES

Introduction

Highway agencies are tasked with addressing mobility, safety, accessibility, and economic development issues for multi-modal corridors stretching thousands of miles. This task is increasingly challenging due to limited funds allocation coupled with the rapid deterioration of pavement infrastructure over time driven by increasing urbanization. There have been numerous approaches proposed for M&R budget planning (higher-level) and budget allocation. In an attempt to make marginal gains in bridging the gap between theory and practice, this interview seeks to;

Objectives for Questions:

- Understand the status quo of how Maintenance and Rehabilitation (M&R) budget allocation is conducted for different highway agencies.
- Identify practical issues which affect the use or otherwise of different approaches to budget allocation in M&R programming.
- Identify and assess practical constraints which are not captured in existing optimization models and other M&R budget allocation approaches.
- Elicit suggestions to address or ameliorate the challenges identified.

Note: The information collected in this interview will be solely used to support an academic study for the doctoral dissertation of the interviewer.

<u>Demographic Information</u>

Work Title/Position:

Number of work experience years in M&R planning:

What is the name of your highway agency?

Which functional group do you work in? Maintenance, Transportation planning and programming, Strategic planning, Design, and/or Construction.

Highway agency [State (Central Office), District or County]

<u>Budget Allocation Approach</u>

Can you please provide a brief overview of the M&R budget allocation process employed by your agency? Whichever option below is applicable.

- State-Level
- District-Level
- County-Level

What pavement-related data attributes are generally used to guide M&R budget allocation decisions made by your agency?

Is there a decision support system(s) that provides an allocation method to aid in selecting and prioritizing M&R projects?

If yes, what software or decision support system (DSS) does your agency use?

What are the primary functions of the existing Decision Support System(s) used in M&R budget allocation or budget planning purposes?

- Develop pavement performance models
- Cost-benefit analysis
- Needs assessment
- Prioritization of candidate M&R projects
- Others:

What are the major sources of M&R funds for your agency? What are their respective amounts (percentage splits)?

Which division (s), functional group(s) or section(s) is/are responsible for allocating highway funds to maintenance and rehabilitation activities/projects?

What budget allocation model approach is used by your agency (in the DSS or M&R planning personnel) for M&R programming and budget allocation?

- Engineer's judgment (experiential)
- Ranking-based approach: weighted sum, multi-attribute utility theory, etc.
- Mathematical optimization approach: linear programming, dynamic programming, etc.
- Others: Artificial Intelligence (Artificial neural networks), etc.

How do you measure the effectiveness or efficiency of your agency's approach to M&R funds allocation for projects? Any measurement metrics? Approach to soliciting lessons learned?

M&R Planning Constraints

Are there constraints on eligible projects for different funding sources?

If yes, what are examples of such different M&R funding sources and constraints?

Are there usually some M&R projects that are pre-prioritized to receive funding before the general budget allocation framework is applied?

If yes, what are instances of such types of projects?

Why are these projects pre-prioritized before the general budget allocation framework is applied?

Are there projects that are funded by multiple funding sources i.e. one project funded by more than one funding source? How frequently does this happen (estimated % of projects)? Why?

In a typical year, when (period range – multiple possible) does your agency usually conduct most of its M&R programming (project selection for funding)?

Is there a secondary period of M&R programming? When does this occur?

Does your agency receive additional M&R funds after the traditional planning period for the fiscal year?

If yes, what sources and why do they flow in after the traditional planning period?

How many times in a fiscal year will you receive such funds? For e.g. after 6 months post first planning period?

How does your agency allocate additional funds that flow in after the initial planning period?

Does your agency conceptually set limits on how many M&R treatments can take place on a given section of pavement per fiscal year or during the planning horizon? Examples?

If yes what is the rationale behind this? If not, reasons why?

Does your agency compare M&R projects schedules to capital construction projects schedules?

If yes, how is this done? At what stage is it done? If not, reasons why?

<u>Challenges and Proposed Solutions</u>

What are some of the barriers to the practical implementation of budget allocation approaches (ranking, mathematical optimization, and meta-heuristics) to M&R programming?

- Transparency issues (black box critique)
- Computational Complexity (scalability)
- Inadequate data, excessive data requirements or data accuracy concerns.
- Flexibility (ability to change parameters and objectives)
- Practicality considerations (usefulness)
    - Pavement performance models
    - Multiple funding sources and constraints
    - Strategic projects or forced projects
- Allocation of unexpected or additional M&R funding allocation
- Budget fluctuations
- Others

APPENDIX B: INTERVIEW GUIDE FOR INTEGRATED MAINTENANCE AND CONSTRUCTION PLANNING (CONFLICT ANALYSIS)

Objectives for Questions

- Understand the status quo of how scheduling conflicts for maintenance and construction projects are identified by TxDOT district.
- Investigate data requirements and practical constraints to the performance of integrated planning.

Demographic Information

Work Title/Position:

Number of work experience years in M&R planning:

What is the name of your highway agency?

Which functional group do you work in? Maintenance, Transportation planning, and programming, Strategic Planning, Design, and/or Construction.

Highway agency [State (Central Office), District or County]

Current Planning Process

What is the current process of checking for potential conflicts in the planning of maintenance and construction projects being performed on the same pavement section within a short period of time?

How do agency staff coordinate to ensure that a "complementary" maintenance project is performed prior to a construction project?

What information items are needed to identify conflicts among planned projects?

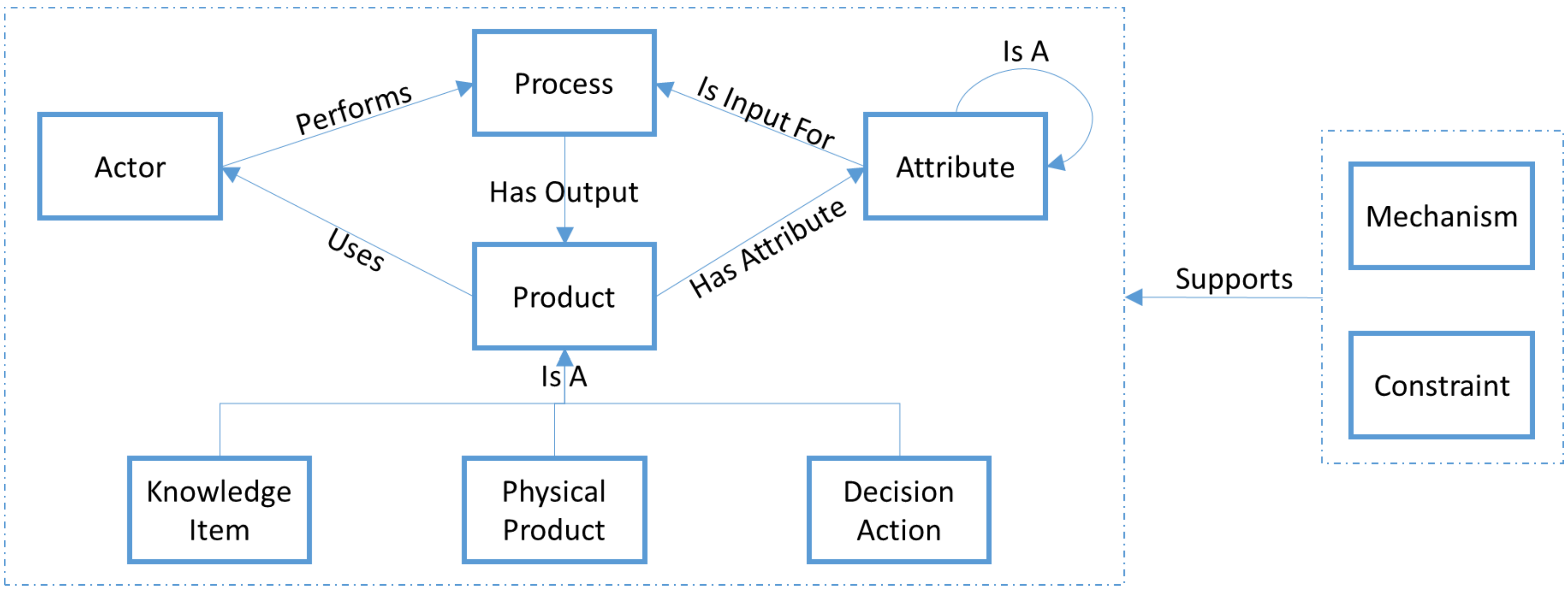
Is there a tool or platform which is used for different scenario analysis of potential spatial-temporal conflicts among candidate projects?

Are such complementary projects (maintenance and construction) performed by the same party (in-house or contracted)? If yes, how does agency staff ensure smooth scheduling and execution of such projects among multiple parties?

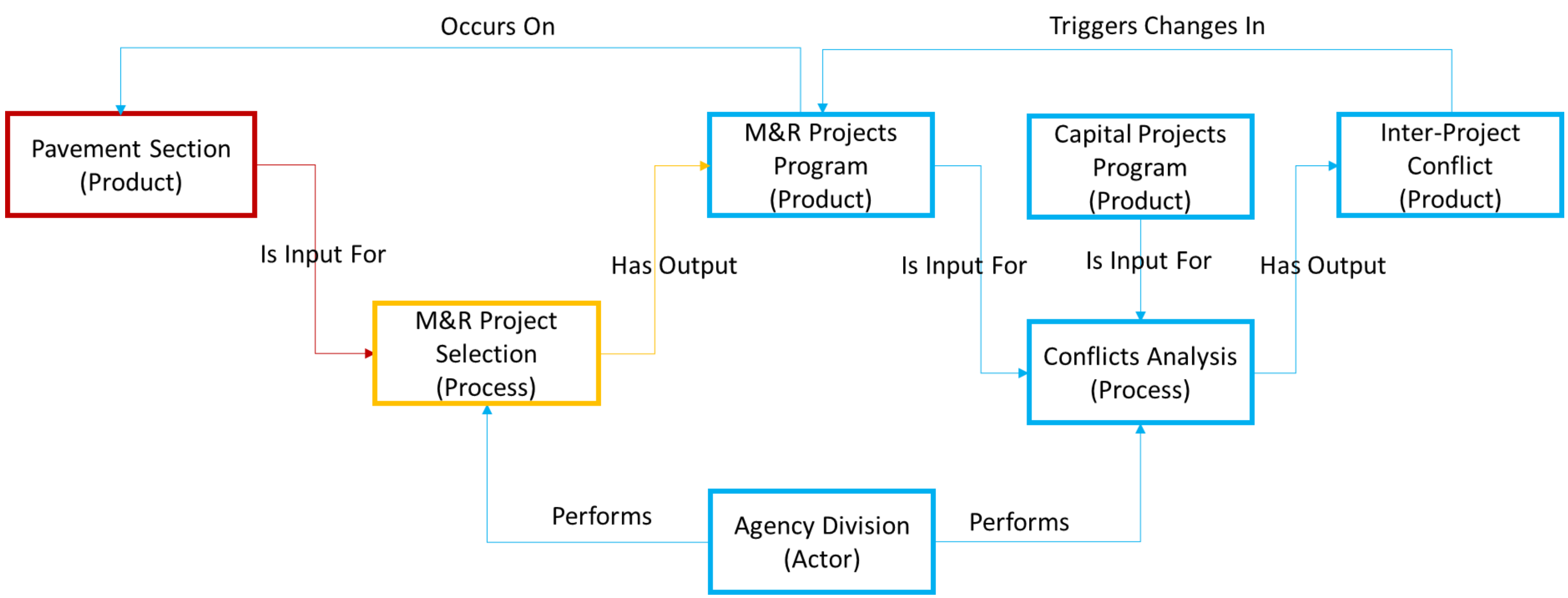
Have there been close-calls or instances where maintenance projects should have been delayed for a more intensive construction project? How often does this happen? What are examples of such incidences?

APPENDIX C: DETAILED IHP-ONTO REPRESENTATION AND IMPLEMENTATION

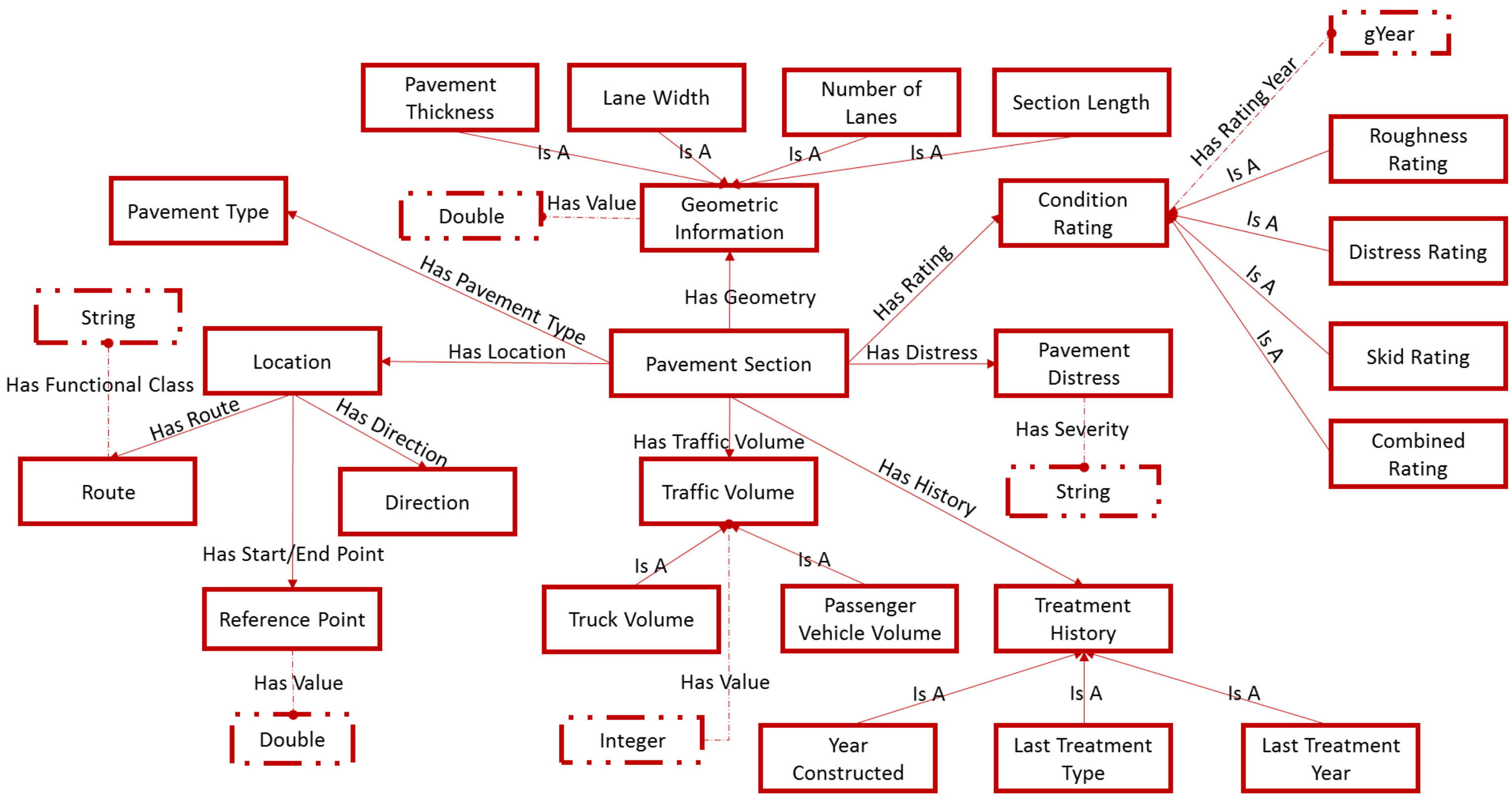
Representation of integrated planning information (Abstraction Level 1)



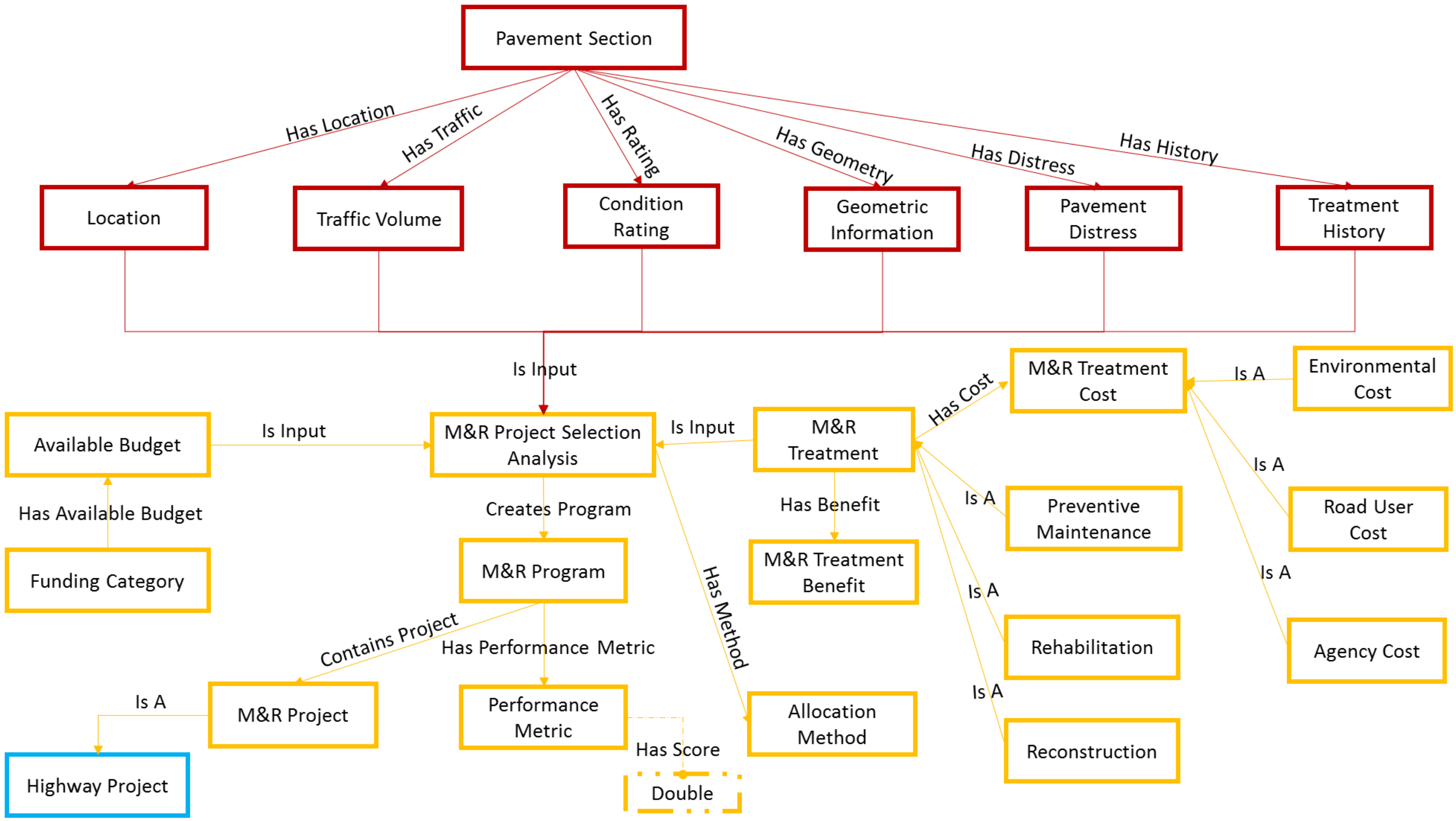
Representation of integrated planning information (Abstraction Level 2)



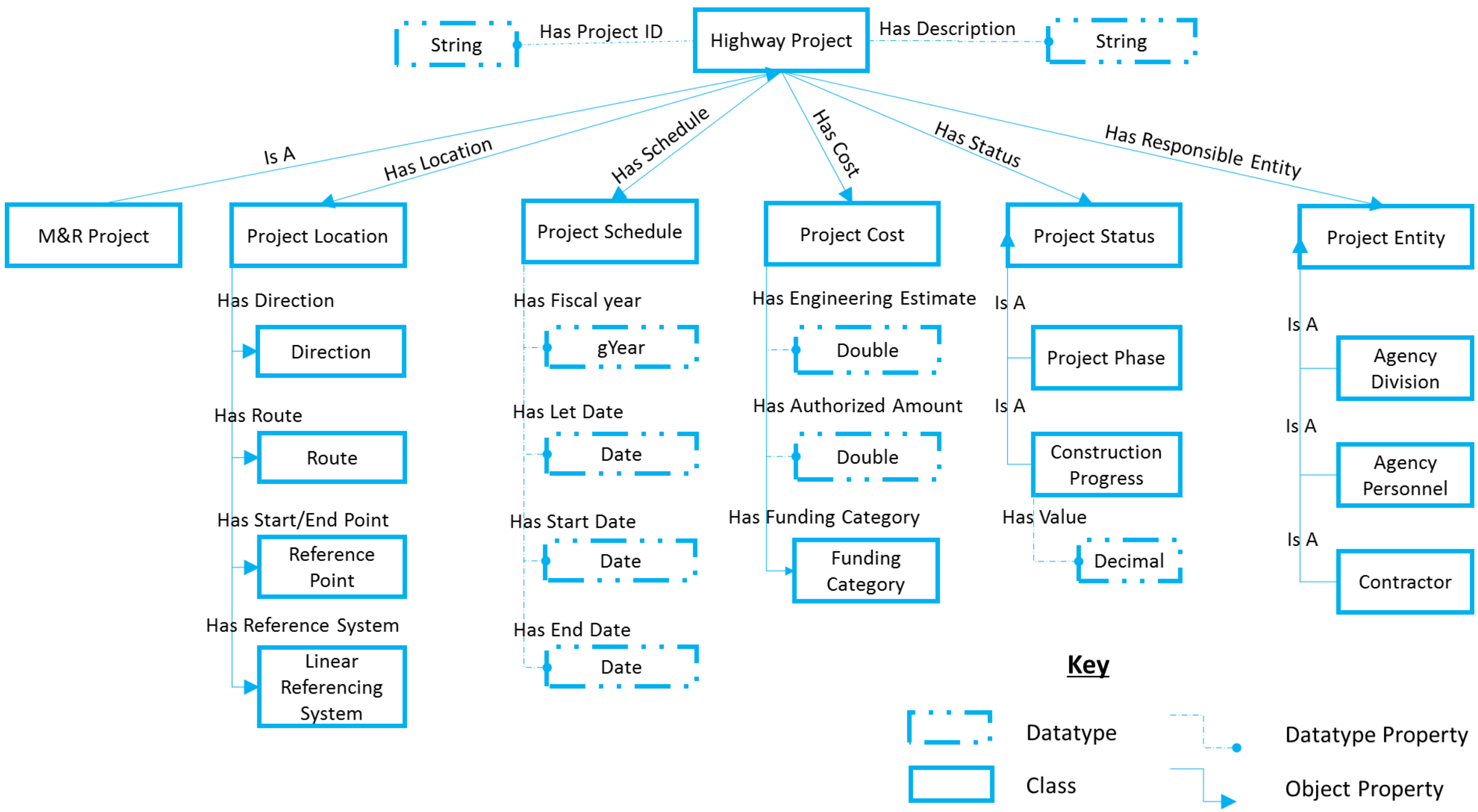
Representation of asset information



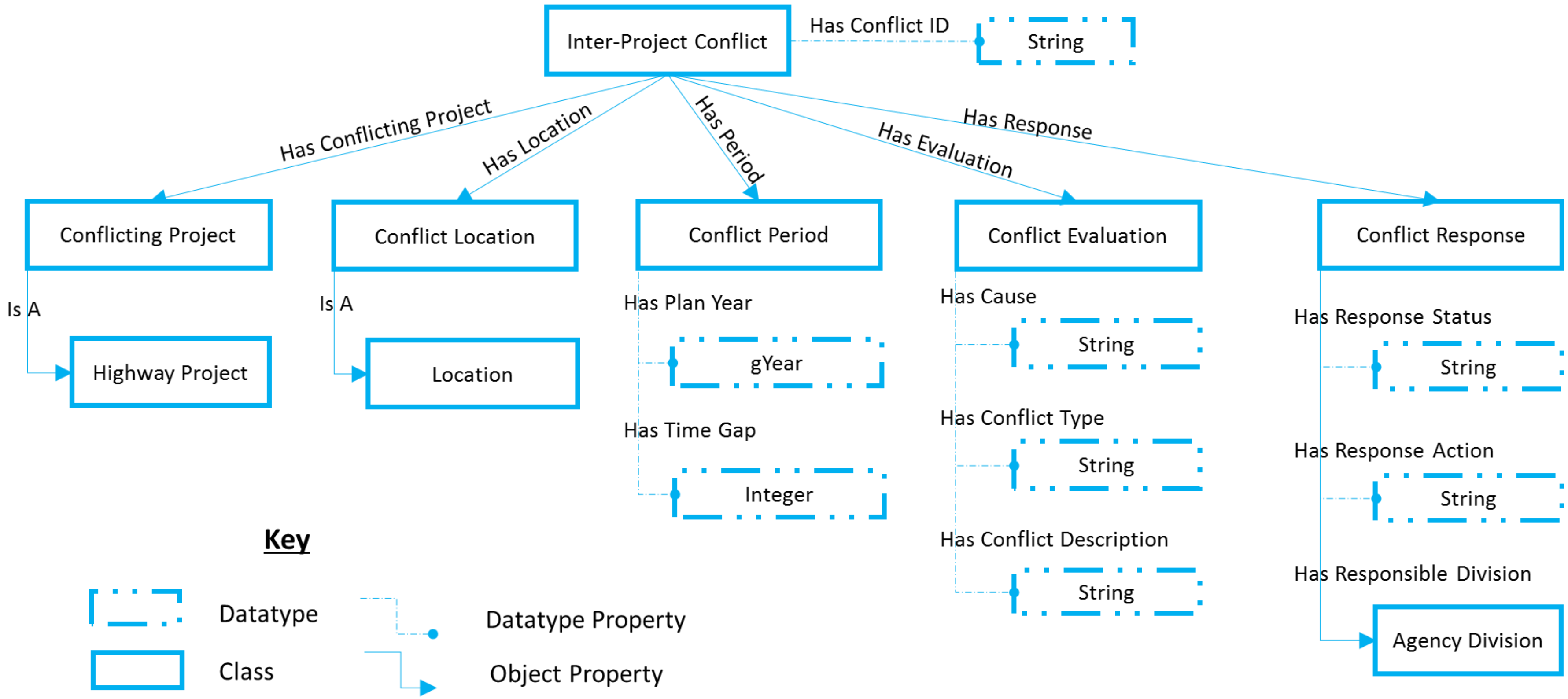
Representation of linked asset and planning information



Representation of linked highway project information

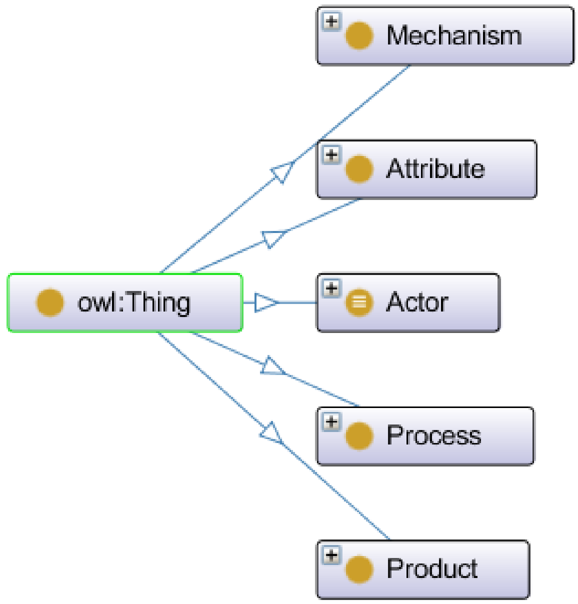


Representation of link to inter-project conflict information

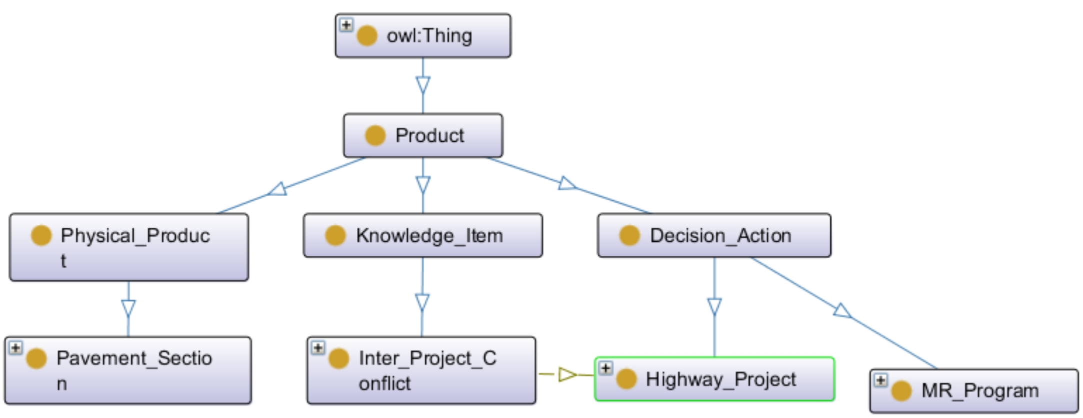


Inter-Project Conflict
Has Conflict ID
String
Has Conflicting Project
Has Location
Has Period
Has Evaluation
Has Response
Conflicting Project
Conflict Location
Conflict Period
Conflict Evaluation
Conflict Response
Is A
Highway Project
Is A
Location
Has Plan Year
gYear
Has Time Gap
Integer
Has Cause
String
Has Conflict Type
String
Has Conflict Description
String
Has Response Status
String
Has Response Action
String
Has Responsible Division
Agency Division
Key
Datatype
Class
Datatype Property
Object Property

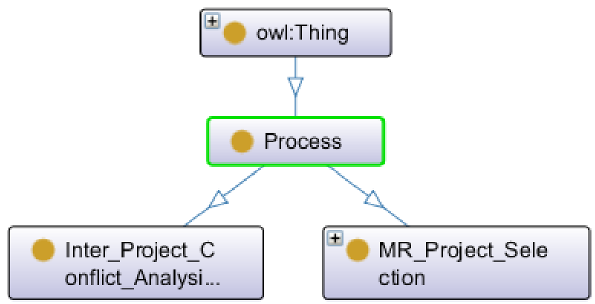
Screenshot of Protégé Implementation (Abstraction Level 1)



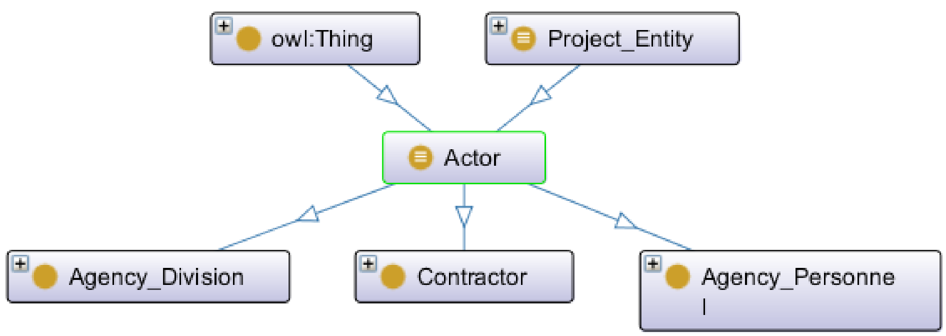
Screenshot of Protégé Implementation (Product Class Relationships)



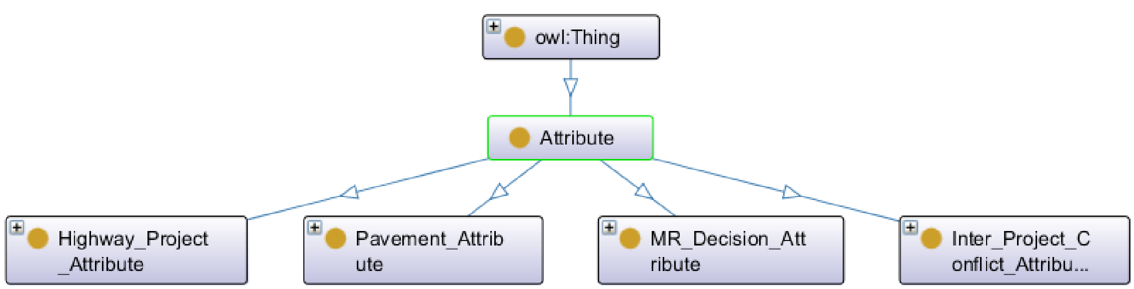
Screenshot of Protégé Implementation (Process Class Relationships)



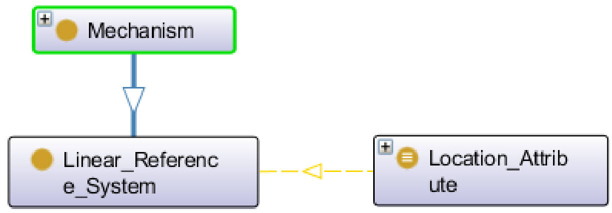
Screenshot of Protégé Implementation (Actor Class Relationships)



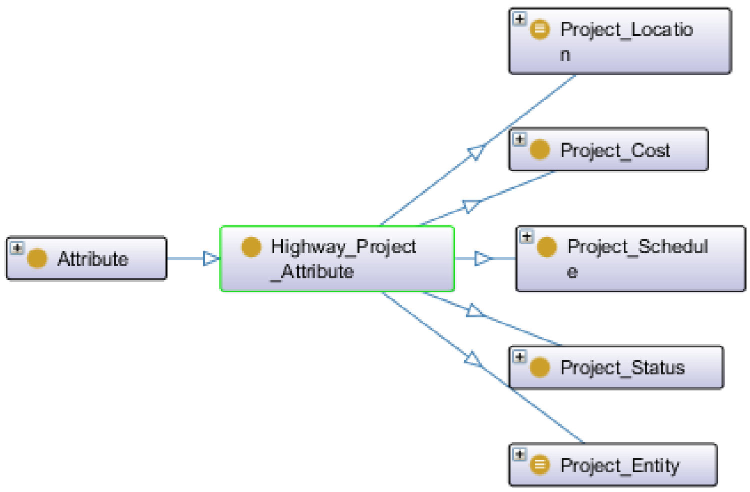
Screenshot of Protégé Implementation (Attribute Class Relationships)



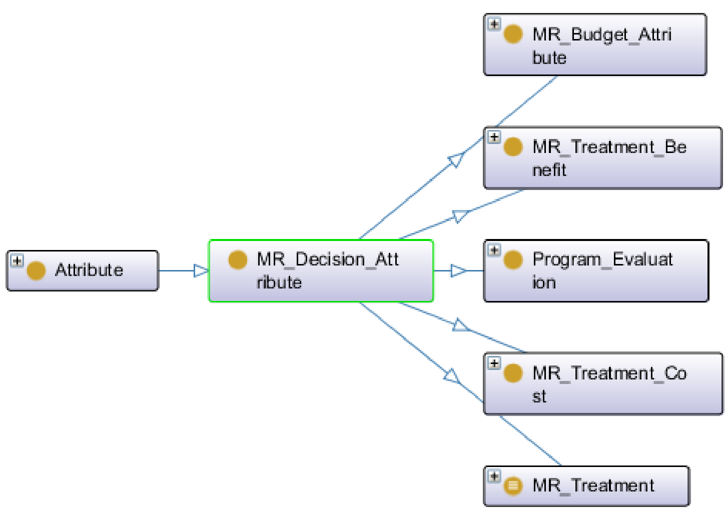
Screenshot of Protégé Implementation (Mechanism Class Relationships)



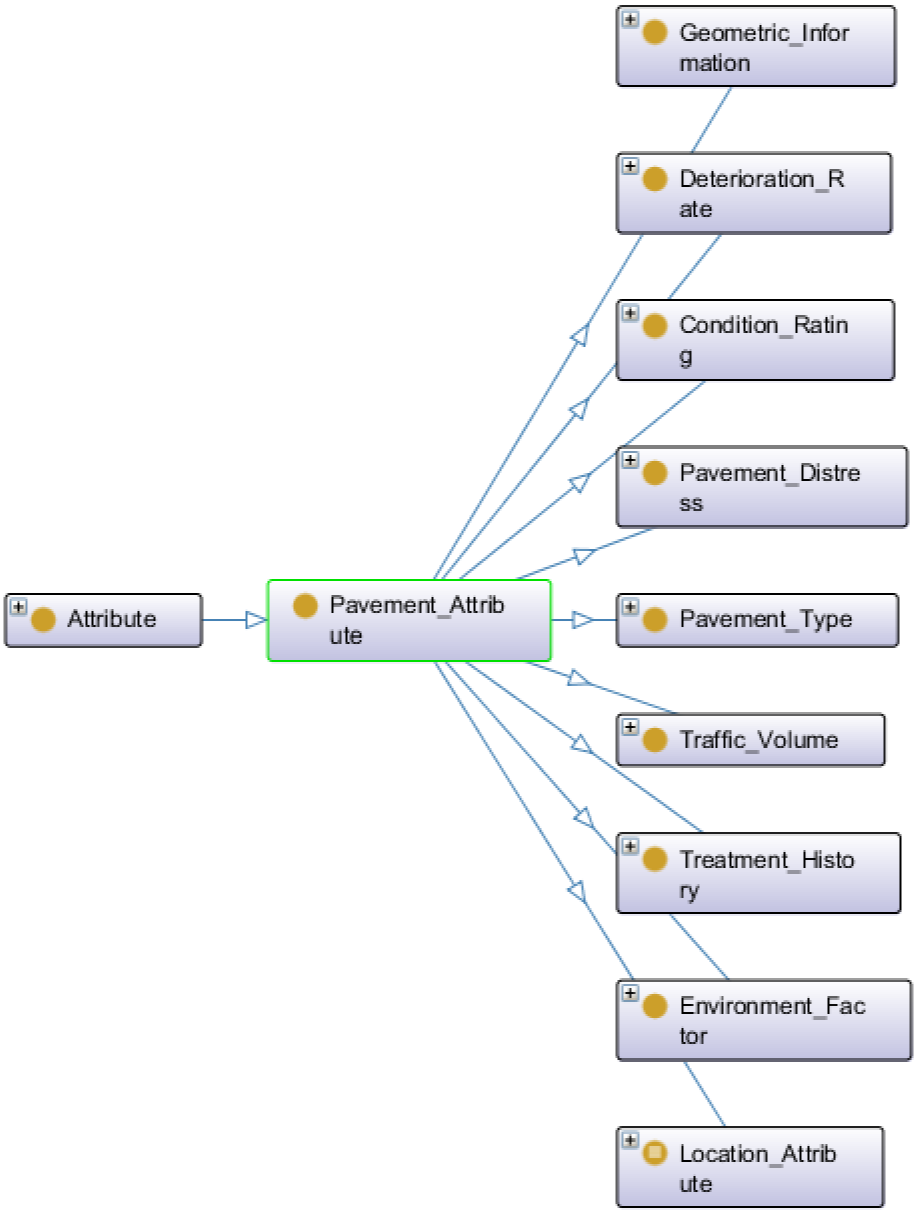
Screenshot of Protégé Implementation (Highway Project Attribute Class Relationships)



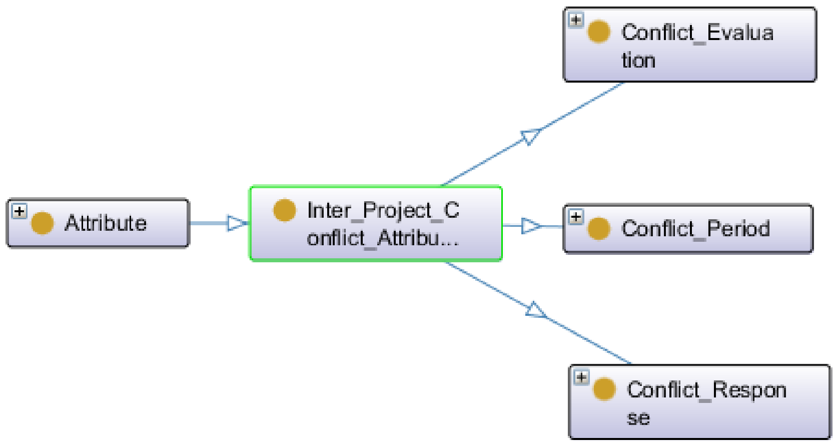
Screenshot of Protégé Implementation (M&R Decision Attribute Class Relationships)



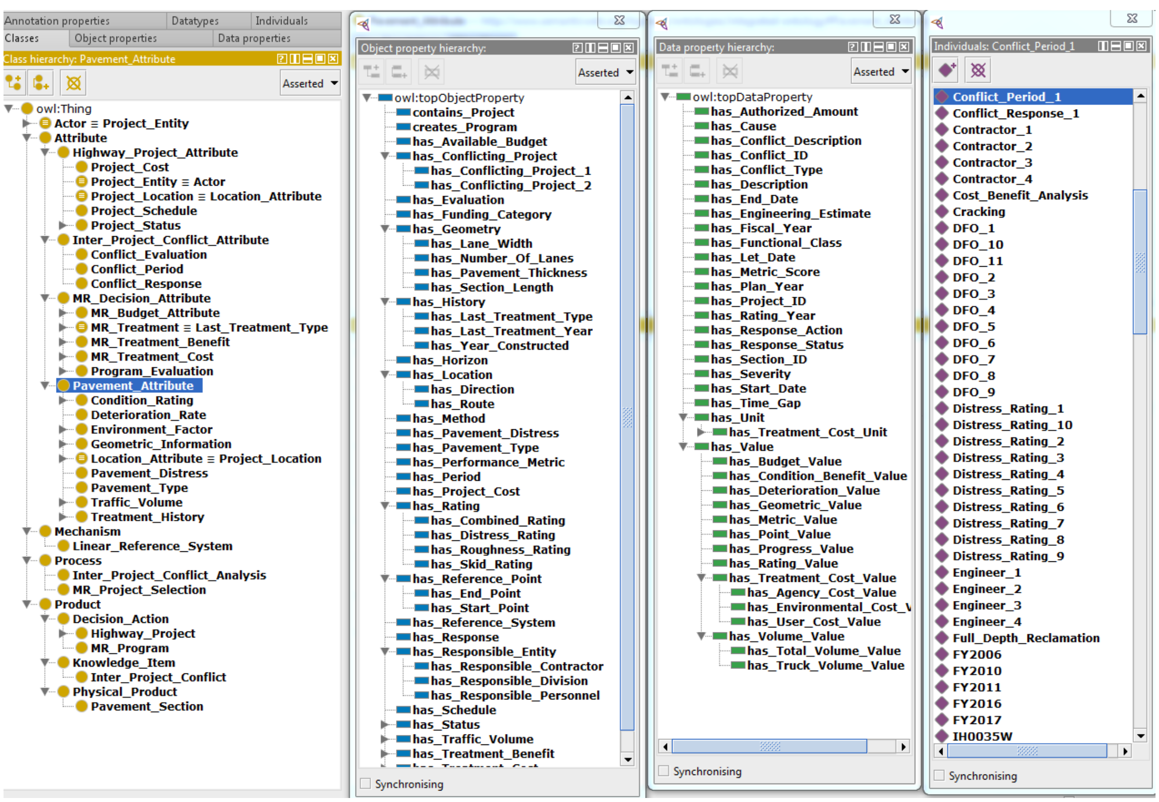
Screenshot of Protégé Implementation (Pavement Attribute Class Relationships)



Screenshot of Protégé Implementation (Inter-Project Attribute Class Relationships)



Screenshot of Protégé Implementation (Classes, Properties, and individuals)



APPENDIX D: ANNOTATED INTEGRATED PLANNING QUESTIONS CORPUS

This section includes a list of questions that were used to validate the competency and completeness of the proposed ontology. Table A-1 indicates questions that were extracted from answers given in the interviews and also presents the relevant entities needed to answer these questions.

Table D-1. Table of annotated questions with corresponding relevant entities

Questions extracted from Interviews	Relevant Entities
1. In what year was the last treatment on a pavement section on IH35?	Last treatment year, section, route
2. What was the last treatment that was administered on the pavement section on IH20 between two reference points?	Last treatment, section, route, start and end reference points
3. What is the functional classification of a route associated with a select pavement section?	Functional class, route, section
4. What is the current condition rating on a select pavement section?	Condition rating, section
5. What was the prior condition rating on a select pavement section?	Rating year, condition rating, section
6. What are the pavement sections in a "poor" state?	Qualitative rating, condition rating, sections
7. What pavement sections have a high traffic volume (above 10,000 AADT)?	Section, route, reference points (start and end), traffic volume
8. Which pavement sections have a high-speed limit?	Section, route, reference points (start and end), speed limit
9. In what year was the pavement section constructed/re-constructed?	Section, year constructed
10. What was the change in condition rating from the previous year for a select section?	Condition score, rating year, section
11. What is the severity of a pavement distress on a select section?	Section, pavement distress, severity
12. What is the pavement type of a select section?	Pavement type, Section

Table D-1. Table of annotated questions with corresponding relevant entities (continued)

Questions extracted from Interviews	Relevant Entities
13. What M&R projects also qualify for safety funds?	Funding category, M&R project, Eligible projects
14. How long can a pavement asset go without a treatment?	Section, minimum time untreated, last treatment year
15. What are the average agency costs of a preventive maintenance treatment?	Treatment cost, MR treatment
16. What are the average road user costs of a rehabilitation treatment?	Treatment cost, MR treatment
17. What is the unit of an M&R treatment cost?	Treatment cost unit, MR Treatment
18. What is the effective life of an M&R treatment?	MR treatment, effective life
19. What percent of the network is covered by the seal coat?	Network coverage (percent), MR treatment
20. What is the size of the maintenance budget?	Budget, funding category
21. How effective is a proposed M&R program?	Performance measures, metrics, MR program
22. What are the effectiveness metrics of a proposed program?	Performance measures, metrics, MR program
23. What is the planning horizon of an M&R program?	MR program, planning horizon
24. What is the M&R fund's allocation approach?	Allocation approach, MR program
25. Which functional groups are responsible for administering the M&R budgets?	Responsible functional groups, Budget, Funding category
26. Which pavement sections have upcoming Preventive Maintenance projects?	Section, MR project, Project schedule
27. Which pavement sections have upcoming mobility projects?	Section, highway project, Project schedule
28. Which pavement sections are receiving PM projects and mobility projects within the planning horizon?	Conflicting projects, conflict location, sections, planning horizon,
29. What is the authorized amount for a selected project?	Highway project, Authorized amount

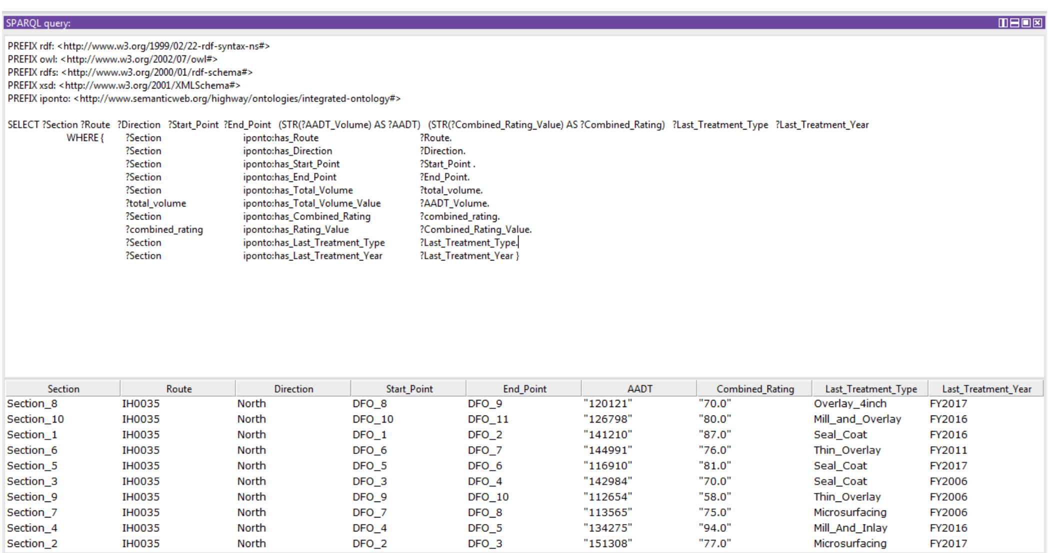
Table D-1. Table of annotated questions with corresponding relevant entities (continued)

Questions extracted from Interviews	Relevant Entities
30. What is the deficit between the engineer's estimate the authorized amount for a project?	Highway project, Authorized amount, Engineer's estimate
31. Who is the agency personnel responsible for a select project?	Agency personnel, Highway project
32. What is the description of the inter-project conflict identified?	Conflict evaluation, Inter-project conflict
33. How many identified conflicts in the plan year 2019?	Conflict period, inter-project conflict
34. What types of projects are conflicting in an identified inter-project conflict?	Conflicting project, inter-project conflict
35. What are the descriptions of the conflicting projects?	Highway project, Project description, conflicting projects
36. What are the source funding categories of the conflicting projects?	Funding category, highway project, conflicting projects
37. How far apart are the start dates of a set of conflicting projects?	Time gap, conflicting projects
38. What Is the overlap in distance between a set of conflicting projects	Conflicting projects, overlap distance, reference points (start and end)
39. What is the proposed response to an identified conflict?	Response Action, Inter-project conflict, conflict evaluation
40. What is the status of the proposed response to an identified conflict?	Response status, conflict response, inter-project conflict
41. What type/level of severity of the conflict identified?	Conflict type, conflict evaluation, inter-project conflict
42. Who is responsible for executing the changes in the project's information in the project's plan?	Responsible Division, inter-project conflict, conflict response
43. What caused the conflict identified?	Conflict cause, conflict evaluation, inter-project conflict
44. Which conflicting projects can be bundled together for savings in cost?	Conflicting projects, funding categories, project compatibility (bundling)
45. What is the available funds in the different categories after modifying projects information in the pavement management plan	Available funds, funding category, MR projects

APPENDIX E: SAMPLE SPARQL CODES IN PROTÉGÉ ENVIRONMENT

Pavement information:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-
ontology#>

SELECT ?Section ?Route   ?Direction   ?Start_Point  ?End_Point
(STR(?AADT_Volume) AS ?AADT)   (STR(?Combined_Rating_Value) AS
?Combined_Rating)   ?Last_Treatment_Type   ?Last_Treatment_Year
    WHERE {     ?Section                iponto:has_Route                ?Route.
            ?Section            iponto:has_Direction            ?Direction.
            ?Section            iponto:has_Start_Point                  ?Start_Point .
            ?Section            iponto:has_End_Point            ?End_Point.
            ?Section            iponto:has_Total_Volume                 ?total_volume.
            ?total_volume iponto:has_Total_Volume_Value         ?AADT_Volume.
            ?Section            iponto:has_Combined_Rating?combined_rating.
            ?combined_rating    iponto:has_Rating_Value
    ?Combined_Rating_Value.
            ?Section            iponto:has_Last_Treatment_Type
    ?Last_Treatment_Type.
            ?Section            iponto:has_Last_Treatment_Year
    ?Last_Treatment_Year }
```



SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-ontology#>

SELECT ?Section ?Route  ?Direction  ?Start_Point  ?End_Point  (STR(?AADT_Volume) AS ?AADT)  (STR(?Combined_Rating_Value) AS ?Combined_Rating)  ?Last_Treatment_Type  ?Last_Treatment_Year
        WHERE {   ?Section          iponto:has_Route                  ?Route.
                  ?Section          iponto:has_Direction              ?Direction.
                  ?Section          iponto:has_Start_Point            ?Start_Point .
                  ?Section          iponto:has_End_Point              ?End_Point.
                  ?Section          iponto:has_Total_Volume           ?total_volume.
                  ?total_volume     iponto:has_Total_Volume_Value     ?AADT_Volume.
                  ?Section          iponto:has_Combined_Rating        ?combined_rating.
                  ?combined_rating  iponto:has_Rating_Value           ?Combined_Rating_Value.
                  ?Section          iponto:has_Last_Treatment_Type    ?Last_Treatment_Type.
                  ?Section          iponto:has_Last_Treatment_Year    ?Last_Treatment_Year }
```

Section	Route	Direction	Start_Point	End_Point	AADT	Combined_Rating	Last_Treatment_Type	Last_Treatment_Year
Section_8	IH0035	North	DFO_8	DFO_9	"120121"	"70.0"	Overlay_4inch	FY2017
Section_10	IH0035	North	DFO_10	DFO_11	"126798"	"80.0"	Mill_and_Overlay	FY2016
Section_1	IH0035	North	DFO_1	DFO_2	"141210"	"87.0"	Seal_Coat	FY2016
Section_6	IH0035	North	DFO_6	DFO_7	"144991"	"76.0"	Thin_Overlay	FY2011
Section_5	IH0035	North	DFO_5	DFO_6	"116910"	"81.0"	Seal_Coat	FY2017
Section_3	IH0035	North	DFO_3	DFO_4	"142984"	"70.0"	Seal_Coat	FY2006
Section_9	IH0035	North	DFO_9	DFO_10	"112654"	"58.0"	Thin_Overlay	FY2006
Section_7	IH0035	North	DFO_7	DFO_8	"113565"	"75.0"	Microsurfacing	FY2006
Section_4	IH0035	North	DFO_4	DFO_5	"134275"	"94.0"	Mill_And_Inlay	FY2016
Section_2	IH0035	North	DFO_2	DFO_3	"151308"	"77.0"	Microsurfacing	FY2017

M&R Planning information:

M&R Costs

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-
ontology#>

SELECT ?MR_Treatment    (STR(?MR_Agency_Cost) AS ?Treatment_Agency_Cost)
(STR(?MR_Agency_Cost_Unit) AS ?Agency_Cost_Unit)   (STR(?MR_User_Cost) AS
?Treatment_User_Cost)  (STR(?MR_User_Cost_Unit) AS ?User_Cost_Unit)
(STR(?MR_Environmental_Cost) AS ?Treatment_Environmental_Cost)
(STR(?MR_Environmental_Cost_Unit) AS ?Environmental_Cost_Unit)

    WHERE {    ?MR_Treatment            iponto:has_Agency_Cost
    ?Agency_Cost.
        ?Agency_Cost        iponto:has_Agency_Cost_Value
    ?MR_Agency_Cost.
        ?Agency_Cost        iponto:has_Agency_Cost_Unit
    ?MR_Agency_Cost_Unit.
        ?MR_Treatment            iponto:has_Road_User_Cost  ?User_Cost.
        ?User_Cost               iponto:has_User_Cost_Value
    ?MR_User_Cost.
        ?User_Cost               iponto:has_User_Cost_Unit
    ?MR_User_Cost_Unit.
        ?MR_Treatment            iponto:has_Environmental_Cost
    ?Environmental_Cost.
        ?Environmental_Cost
    iponto:has_Environmental_Cost_Value      ?MR_Environmental_Cost.
        ?Environmental_Cost
    iponto:has_Environmental_Cost_Unit       ?MR_Environmental_Cost_Unit}
```

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-ontology#>

SELECT ?MR_Treatment    (STR(?MR_Agency_Cost) AS ?Treatment_Agency_Cost)    (STR(?MR_Agency_Cost_Unit) AS ?Agency_Cost_Unit)   (STR(?MR_User_Cost) AS ?Treatment_User_Cost)  (STR(?MR_User_Cost_Unit) AS ?User_Cost_Unit)
(STR(?MR_Environmental_Cost) AS ?Treatment_Environmental_Cost)    (STR(?MR_Environmental_Cost_Unit) AS ?Environmental_Cost_Unit)

        WHERE {   ?MR_Treatment          iponto:has_Agency_Cost                  ?Agency_Cost.
                  ?Agency_Cost           iponto:has_Agency_Cost_Value            ?MR_Agency_Cost.
                  ?Agency_Cost           iponto:has_Agency_Cost_Unit             ?MR_Agency_Cost_Unit.
                  ?MR_Treatment          iponto:has_Road_User_Cost               ?User_Cost.
                  ?User_Cost             iponto:has_User_Cost_Value              ?MR_User_Cost.
                  ?User_Cost             iponto:has_User_Cost_Unit               ?MR_User_Cost_Unit.
                  ?MR_Treatment          iponto:has_Environmental_Cost           ?Environmental_Cost.
                  ?Environmental_Cost    iponto:has_Environmental_Cost_Value     ?MR_Environmental_Cost.
                  ?Environmental_Cost    iponto:has_Environmental_Cost_Unit      ?MR_Environmental_Cost_Unit}
```

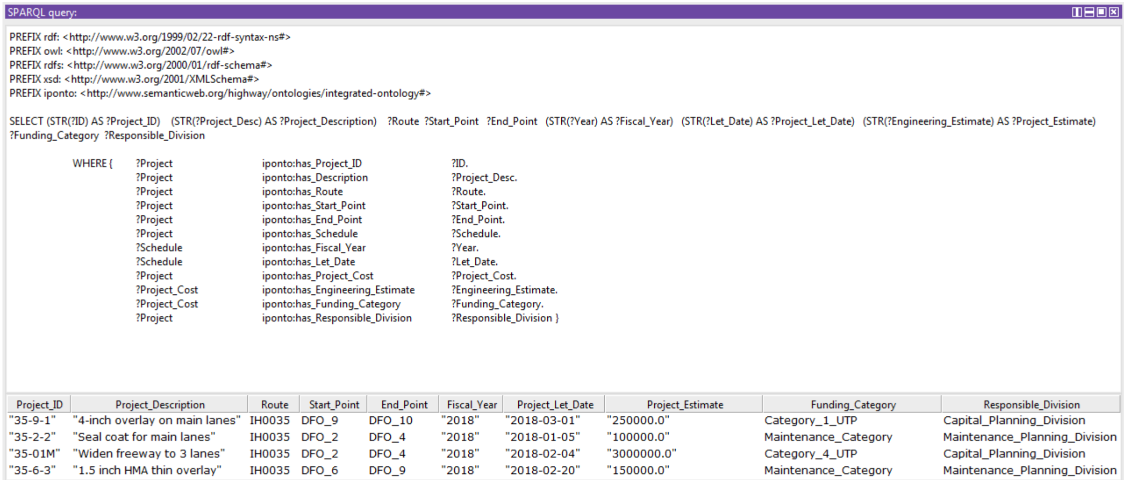
MR_Treatment	Treatment_Agency_Cost	Agency_Cost_Unit	Treatment_User_Cost	User_Cost_Unit	Treatment_Environmental_Cost	Environmental_Cost_Unit
Thin_Overlay	"50000.0"	"$/lane-mile"	"0.0"	"$/AADT/lane-mile"	"5715.0"	"kg CO2eq/lane-mile"
Overlay_6inch	"520000.0"	"$/lane-mile"	"1.35"	"$/AADT/lane-mile"	"57150.0"	"kg CO2eq/lane-mile"
Overlay_4inch	"250000.0"	"$/lane-mile"	"0.75"	"$/AADT/lane-mile"	"22860.0"	"kg CO2eq/lane-mile"

Projects Coordination information:

<u>Highway project information</u>

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-
ontology#>

SELECT (STR(?ID) AS ?Project_ID)   (STR(?Project_Desc) AS ?Project_Description)
?Route  ?Start_Point  ?End_Point  (STR(?Year) AS ?Fiscal_Year)  (STR(?Let_Date)
AS ?Project_Let_Date)  (STR(?Engineering_Estimate) AS ?Project_Estimate)
?Funding_Category  ?Responsible_Division

    WHERE {     ?Project            iponto:has_Project_ID            ?ID.
        ?Project            iponto:has_Description
    ?Project_Desc.
        ?Project            iponto:has_Route             ?Route.
        ?Project            iponto:has_Start_Point            ?Start_Point.
        ?Project            iponto:has_End_Point         ?End_Point.
        ?Project            iponto:has_Schedule          ?Schedule.
        ?Schedule           iponto:has_Fiscal_Year            ?Year.
        ?Schedule           iponto:has_Let_Date          ?Let_Date.
        ?Project            iponto:has_Project_Cost           ?Project_Cost.
        ?Project_Cost       iponto:has_Engineering_Estimate
    ?Engineering_Estimate.
        ?Project_Cost       iponto:has_Funding_Category
    ?Funding_Category.
```

```
            ?Project                    iponto:has_Responsible_Division
        ?Responsible_Division }
```



SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-ontology#>

SELECT (STR(?ID) AS ?Project_ID)   (STR(?Project_Desc) AS ?Project_Description)   ?Route  ?Start_Point  ?End_Point  (STR(?Year) AS ?Fiscal_Year)  (STR(?Let_Date) AS ?Project_Let_Date)  (STR(?Engineering_Estimate) AS ?Project_Estimate)
?Funding_Category  ?Responsible_Division

        WHERE {   ?Project         iponto:has_Project_ID              ?ID.
                  ?Project         iponto:has_Description             ?Project_Desc.
                  ?Project         iponto:has_Route                   ?Route.
                  ?Project         iponto:has_Start_Point             ?Start_Point.
                  ?Project         iponto:has_End_Point               ?End_Point.
                  ?Project         iponto:has_Schedule                ?Schedule.
                  ?Schedule        iponto:has_Fiscal_Year             ?Year.
                  ?Schedule        iponto:has_Let_Date                ?Let_Date.
                  ?Project         iponto:has_Project_Cost            ?Project_Cost.
                  ?Project_Cost    iponto:has_Engineering_Estimate    ?Engineering_Estimate.
                  ?Project_Cost    iponto:has_Funding_Category        ?Funding_Category.
                  ?Project         iponto:has_Responsible_Division    ?Responsible_Division }
```

Project_ID	Project_Description	Route	Start_Point	End_Point	Fiscal_Year	Project_Let_Date	Project_Estimate	Funding_Category	Responsible_Division
"35-9-1"	"4-inch overlay on main lanes"	IH0035	DFO_9	DFO_10	"2018"	"2018-03-01"	"250000.0"	Category_1_UTP	Capital_Planning_Division
"35-2-2"	"Seal coat for main lanes"	IH0035	DFO_2	DFO_4	"2018"	"2018-01-05"	"100000.0"	Maintenance_Category	Maintenance_Planning_Division
"35-01M"	"Widen freeway to 3 lanes"	IH0035	DFO_2	DFO_4	"2018"	"2018-02-04"	"3000000.0"	Category_4_UTP	Capital_Planning_Division
"35-6-3"	"1.5 inch HMA thin overlay"	IH0035	DFO_6	DFO_9	"2018"	"2018-02-20"	"150000.0"	Maintenance_Category	Maintenance_Planning_Division

<u>Inter-Project Conflict Information</u>

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-
ontology#>

SELECT (STR(?ID) AS ?Project_ID)  ?Conflicting_Project_1  ?Conflicting_Project_2
(STR(?Plan_Year) AS ?Conflict_Year)   (STR(?Time_Gap) AS ?Time_Gap_Months)
(STR(?Cause) AS ?Conflict_Cause)   (STR(?Action) AS ?Response_Action)
(STR(?Status) AS ?Response_Status) ?Responsible_Division

        WHERE {     ?Conflict              iponto:has_Conflict_ID                 ?ID.
            ?Conflict              iponto:has_Conflicting_Project_1
        ?Conflicting_Project_1.
            ?Conflict              iponto:has_Conflicting_Project_2
        ?Conflicting_Project_2.
            ?Conflict              iponto:has_Period              ?Period.
            ?Period                iponto:has_Plan_Year           ?Plan_Year.
            ?Period                iponto:has_Time_Gap            ?Time_Gap.
            ?Conflict              iponto:has_Evaluation          ?Evaluation.
            ?Evaluation            iponto:has_Cause               ?Cause.
            ?Conflict              iponto:has_Response            ?Response.
```

```
        ?Response               iponto:has_Response_Action ?Action.
        ?Response               iponto:has_Response_Status  ?Status.
        ?Response               iponto:has_Responsible_Division
    ?Responsible_Division }
```

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX iponto: <http://www.semanticweb.org/highway/ontologies/integrated-ontology#>

SELECT (STR(?ID) AS ?Project_ID)  ?Conflicting_Project_1  ?Conflicting_Project_2   (STR(?Plan_Year) AS ?Conflict_Year)   (STR(?Time_Gap) AS ?Time_Gap_Months)   (STR(?Cause) AS ?Conflict_Cause)   (STR(?Action) AS ?Response_Action)
(STR(?Status) AS ?Response_Status) ?Responsible_Division

        WHERE {    ?Conflict        iponto:has_Conflict_ID                ?ID.
                   ?Conflict        iponto:has_Conflicting_Project_1      ?Conflicting_Project_1.
                   ?Conflict        iponto:has_Conflicting_Project_2      ?Conflicting_Project_2.
                   ?Conflict        iponto:has_Period                     ?Period.
                   ?Period          iponto:has_Plan_Year                  ?Plan_Year.
                   ?Period          iponto:has_Time_Gap                   ?Time_Gap.
                   ?Conflict        iponto:has_Evaluation                 ?Evaluation.
                   ?Evaluation      iponto:has_Cause                      ?Cause.
                   ?Conflict        iponto:has_Response                   ?Response.
                   ?Response        iponto:has_Response_Action            ?Action.
                   ?Response        iponto:has_Response_Status            ?Status.
                   ?Response        iponto:has_Responsible_Division       ?Responsible_Division

                                                                                    }
```

Project_ID	Conflicting_Project_1	Conflicting_Project_2	Conflict_Year	Time_Gap_Months	Conflict_Cause	Response_Action	Response_Status	Responsible_Division
"C0001"	MR_Project_1	Mobility_Project_1	"2018"	"1"	"Clashing schedules"	"Re-schedule seal coat project"	"Resolved"	Maintenance_Planning_Division

APPENDIX F: SAMPLE GAMS SOURCE CODE (BUDGET ALLOCATION – SCENARIO 1)

```
Sets
* These are the sets for pavement sections, maintenance treatment options, and planning periods

    i  pavement sections in network     /P1*P500 /
    m  M&R treatment options            /NM, PM, LR, MR, HR /
    t  planning periods                 /t1*t4/
    q(m) Preventive maintenance    /PM /
    r(m) rehabilitation            /LR, MR, HR /

alias(tt,t);


Parameters
    c(m)  Unit cost of applying m treatment option per lane mile
    /   NM     0
        PM     34000
        LR     202000
        MR     285000
        HR     517000 /



    dc(m)  Travel time delay costs per AADT per mile for treatment option m
    /   NM     0
        PM     0
        LR     0.5
        MR     1
        HR     1.35 /

    CSin(i)  Initial condition score of pavement section i
    /   P1     97
        P2     88
        P3     92
        P4     70
        P5     98
        P6     88
        P7     51
        P8     76
        P9     60
        P10    65
        P11    92
```

P12	68
P13	82
P14	80
P15	78
P16	74
P17	61
P18	56
P19	65
P20	65
P21	94
P22	88
P23	92
P24	73
P25	91
P26	81
P27	57
P28	76
P29	65
P30	69
P31	84
P32	83
P33	91
P34	79
P35	91
P36	82
P37	61
P38	66
P39	80
P40	75
P41	97
P42	88
P43	92
P44	65
P45	58
P46	77
P47	61
P48	76
P49	63
P50	59
P51	97
P52	88
P53	92
P54	70

P55	98
P56	88
P57	51
P58	76
P59	60
P60	65
P61	92
P62	68
P63	82
P64	80
P65	78
P66	74
P67	61
P68	56
P69	65
P70	65
P71	94
P72	88
P73	92
P74	73
P75	91
P76	81
P77	57
P78	76
P79	65
P80	69
P81	84
P82	83
P83	91
P84	79
P85	91
P86	82
P87	61
P88	66
P89	80
P90	75
P91	97
P92	88
P93	92
P94	65
P95	58
P96	77
P97	61

P98	76
P99	63
P100	59
P101	97
P102	88
P103	92
P104	70
P105	98
P106	88
P107	51
P108	76
P109	60
P110	65
P111	92
P112	68
P113	82
P114	80
P115	78
P116	74
P117	61
P118	56
P119	65
P120	65
P121	94
P122	88
P123	92
P124	73
P125	91
P126	81
P127	57
P128	76
P129	65
P130	69
P131	84
P132	83
P133	91
P134	79
P135	91
P136	82
P137	61
P138	66
P139	80
P140	75

P141	97
P142	88
P143	92
P144	65
P145	58
P146	77
P147	61
P148	76
P149	63
P150	59
P151	97
P152	88
P153	92
P154	70
P155	98
P156	88
P157	51
P158	76
P159	60
P160	65
P161	92
P162	68
P163	82
P164	80
P165	78
P166	74
P167	61
P168	56
P169	65
P170	65
P171	94
P172	88
P173	92
P174	73
P175	91
P176	81
P177	57
P178	76
P179	65
P180	69
P181	84
P182	83
P183	91

P184	79
P185	91
P186	82
P187	61
P188	66
P189	80
P190	75
P191	97
P192	88
P193	92
P194	65
P195	58
P196	77
P197	61
P198	76
P199	63
P200	59
P201	97
P202	88
P203	92
P204	70
P205	98
P206	88
P207	51
P208	76
P209	60
P210	65
P211	92
P212	68
P213	82
P214	80
P215	78
P216	74
P217	61
P218	56
P219	65
P220	65
P221	94
P222	88
P223	92
P224	73
P225	91
P226	81

P227	57
P228	76
P229	65
P230	69
P231	84
P232	83
P233	91
P234	79
P235	91
P236	82
P237	61
P238	66
P239	80
P240	75
P241	97
P242	88
P243	92
P244	65
P245	58
P246	77
P247	61
P248	76
P249	63
P250	59
P251	97
P252	88
P253	92
P254	70
P255	98
P256	88
P257	51
P258	76
P259	60
P260	65
P261	92
P262	68
P263	82
P264	80
P265	78
P266	74
P267	61
P268	56
P269	65

P270	65
P271	94
P272	88
P273	92
P274	73
P275	91
P276	81
P277	57
P278	76
P279	65
P280	69
P281	84
P282	83
P283	91
P284	79
P285	91
P286	82
P287	61
P288	66
P289	80
P290	75
P291	97
P292	88
P293	92
P294	65
P295	58
P296	77
P297	61
P298	76
P299	63
P300	59
P301	97
P302	88
P303	92
P304	70
P305	98
P306	88
P307	51
P308	76
P309	60
P310	65
P311	92
P312	68

P313	82
P314	80
P315	78
P316	74
P317	61
P318	56
P319	65
P320	65
P321	94
P322	88
P323	92
P324	73
P325	91
P326	81
P327	57
P328	76
P329	65
P330	69
P331	84
P332	83
P333	91
P334	79
P335	91
P336	82
P337	61
P338	66
P339	80
P340	75
P341	97
P342	88
P343	92
P344	65
P345	58
P346	77
P347	61
P348	76
P349	63
P350	59
P351	97
P352	88
P353	92
P354	70
P355	98

P356	88
P357	51
P358	76
P359	60
P360	65
P361	92
P362	68
P363	82
P364	80
P365	78
P366	74
P367	61
P368	56
P369	65
P370	65
P371	94
P372	88
P373	92
P374	73
P375	91
P376	81
P377	57
P378	76
P379	65
P380	69
P381	84
P382	83
P383	91
P384	79
P385	91
P386	82
P387	61
P388	66
P389	80
P390	75
P391	97
P392	88
P393	92
P394	65
P395	58
P396	77
P397	61
P398	76

P399	63
P400	59
P401	97
P402	88
P403	92
P404	70
P405	98
P406	88
P407	51
P408	76
P409	60
P410	65
P411	92
P412	68
P413	82
P414	80
P415	78
P416	74
P417	61
P418	56
P419	65
P420	65
P421	94
P422	88
P423	92
P424	73
P425	91
P426	81
P427	57
P428	76
P429	65
P430	69
P431	84
P432	83
P433	91
P434	79
P435	91
P436	82
P437	61
P438	66
P439	80
P440	75
P441	97

P442	88
P443	92
P444	65
P445	58
P446	77
P447	61
P448	76
P449	63
P450	59
P451	97
P452	88
P453	92
P454	70
P455	98
P456	88
P457	51
P458	76
P459	60
P460	65
P461	92
P462	68
P463	82
P464	80
P465	78
P466	74
P467	61
P468	56
P469	65
P470	65
P471	94
P472	88
P473	92
P474	73
P475	91
P476	81
P477	57
P478	76
P479	65
P480	69
P481	84
P482	83
P483	91
P484	79

```
        P485      91
        P486      82
        P487      61
        P488      66
        P489      80
        P490      75
        P491      97
        P492      88
        P493      92
        P494      65
        P495      58
        P496      77
        P497      61
        P498      76
        P499      63
        P500      59 /

      L(i)   Mileage per pavement section i
   /     P1*P500 0.5 /



  B(t)      budget for the year t
  /      t1      20000000
         t2      20000000
         t3      20000000
         t4      20000000 /

 e(m)   Addition to condition score based on applying m treatment option
  /      NM      0
         PM      3
         LR     15
         MR      25
         HR      40/ ;


Scalar Nim Number of projects on a pavement section for horizon /4/;

Scalar CSmin Min. condition score per year per pavement section /50/;
```

```
Scalar CSmax Max. condition score per year per pavement section /100/;

Scalar dp constant detrioration rate per year /0.05/;

Scalar CSminet Minimum condition score for the entire network /65/;



Variables
    x(i,m,t)  Whether or not to select pavement section i trmt m year t
    z1        total M&R condition score improvement
    z2        total M&R user cost
    z3        Grand total
    CS(i,t)    condition score transition
    ACS(t)     average condition score per year;

* Decision variable is a binary (0 or 1) choice

Binary Variable x ;

Equations
    condscore         define objective function 1
    budget(t)         observe budget limit at each year t
    mainten1(i)       treatment cap for PM
    mainten2(i)       treatment cap for Rehabilitation
    treatcap(i)       satisfy treatment options cap planning horizon
    cap(i,t)          satisfy one treatment on a section each year
    conscotrans(i,t)  condition score transition
    avgcondscore(t)   average condition score per year
    condscorenet(t)   network condition score per year minimum
    minscore(i,t)     satisfy minimum condition score each section per year
    maxscore(i,t)     satisfy maximum condition score each section per year;

condscore .. z1  =e=  sum((t), ACS(t)) ;

conscotrans(i,t) .. CS(i,t) =e= CSin(i) * ((1 - dp)**ord(t)) + sum((m,tt)$(ord(tt)
le ord(t)), (e(m) *x(i,m,tt)* ((1 - dp)**(ord(t)-ord(tt)))));

avgcondscore(t) ..  ACS(t)=e= (sum(i,CS(i,t)*2*L(i))/(sum(i,2*L(i))));

condscorenet(t) ..  ACS(t) =g= CSminet;

budget(t) .. sum((i,m), 2*L(i)*c(m)*x(i,m,t)) =l= B(t) ;
```

```
 mainten1(i).. sum((q,t), x(i,q,t)) =l= 2 ;

 mainten2(i).. sum((r,t), x(i,r,t)) =l= 1 ;

 treatcap(i) .. sum((m,t), x(i,m,t)) =l= Nim ;

 cap(i,t) .. sum((m), x(i,m,t)) =e= 1 ;

 minscore(i,t) .. CS(i,t) =g= CSmin ;

 maxscore(i,t) .. CS(i,t) =l= CSmax ;

option limrow = 1000;
option limcol = 1000;
option optcr = 5E-5;

 Model Maintenance /all/;

 Solve Maintenance using mip maximizing z1 ;

 Display x.l;
 Display z1.l;
 Display Cs.l;
 Display ACS.l;
 Display budget.l;
```

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Vita

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