Prioritizing the Maintenance and Replacement of Aging or Obsolete Intelligent Transportation Systems Infrastructure

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Ross Powers

AUTHOR

The thesis has been read and approved by the examining committee:

Dr. Brian L. Smith

Advisor

Dr. Byungkyu Park

Dr. John S. Miller

Accepted for the School of Engineering and Applied Science:

Dean, School of Engineering and Applied Science

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ABSTRACT

Many Intelligent Transportation Systems (ITS) are aging, experiencing significant maintenance needs, or becoming functionally obsolete. The primary output of this thesis is a methodology for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure. The methodology is structured such that existing ITS are prioritized according to the need for their obsolescence to be addressed and such that candidate interventions for those ITS are ranked. The methodology is designed to be practical to implement and widely applicable to disparate ITS technologies and is based on certain principles of transportation asset management and multi-criteria decision analysis methods from systems engineering. The major research contribution is thus a new application of existing techniques. This thesis includes a case study that applies part of the methodology to 31 Variable Message Signs on the outer loop of the Interstate-64 beltway in the Hampton Roads metropolitan area of Virginia. The assets are ranked using historical work order data from maintenance records and traffic volume data. The major recommendation is the implementation of the methodology in the form of an automated system that continuously receives data and updates asset priority to inform obsolescence management decisions. It is recommended that the system eventually be integrated into a comprehensive, automated ITS asset management system and that the maintenance data gathered for existing ITS be used for predicting life cycle costs of future ITS investments.

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CHAPTER 1 – INTRODUCTION

1.1 – PROBLEM STATEMENT AND PROJECT GOALS

Many Intelligent Transportation Systems (ITS) are aging, experiencing significant maintenance needs, or becoming functionally obsolete. Wochinger et al (2010) reports that participants of the U.S. Department of Transportation (U.S. DOT) ITS Evaluation Workshop on September 20, 2010 emphasized that "Evaluating the operations and maintenance of ITS projects over time distinguishes between the technologies and techniques that continue to provide benefits from those that have reached the end of their useful life" (p. 8). The goal of this project is to develop a formal methodology for systematically prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure for recommendation to state departments of transportation (DOTs), particularly the Virginia Department of Transportation (VDOT). Stated another way, the goal of this project is to establish a repeatable procedure for continuously prioritizing the management of ITS infrastructure obsolescence.

During the literature search, which is detailed in Chapter 2, no case studies or formal written methodologies applying formal decision processes to the specific problem of managing the obsolescence of ITS assets were found. The lack of findings has two major implications. Firstly, the gap in knowledge is especially problematic because ITS equipment and systems, unlike other transportation assets, are subject to the rapid pace of technological change, age more quickly than other transportation assets, and in many cases become functionally obsolete in a short time frame. Secondly, the prioritization methodology that this thesis presents aims to be comprehensive and widely applicable but also straightforward and simple to understand so as to provide a firm foundation for further research and improvement. The methodology is also meant to lay the groundwork for, or inform the selection of, an automated system for use by agency analysts and decision-makers to enable the making of well-informed ITS asset management prioritization decisions. The methodology applies multi-criteria decision analysis as well as principles of transportation asset management (TAM) to the problem of prioritizing the management of ITS obsolescence.

It is anticipated that the divisions of VDOT and local agencies concerned with ITS obsolescence management will ultimately implement the methodology and recommendations presented in this thesis or a future improvement upon them. The capacity to make well-informed ITS asset management decisions will help agencies make wise use of limited transportation funds on the highest priority ITS infrastructure and projects and maximize the return on investment when it comes to ITS expenditures. The data gathered in maintenance evaluations of existing ITS will be helpful in predicting life cycle costs of future ITS investments.

1.2 – SCOPE OF PROJECT

This project approaches ITS decision-making from the standpoint of existing ITS rather than from the standpoint of roadway sections that have never had ITS and on which ITS could be implemented in the future. As discussed in the literature review in Chapter 2, multiple methods exist for evaluating new ITS project alternatives, but this project focuses on improving ITS through addressing existing ITS and considering replacement of the existing ITS with new ITS as only one of a large number of candidate actions.

Two aspects of the systems engineering process are emphasized in this thesis. The first is multi-criteria decision analysis. The second is the setting of system boundaries for which ITS to analyze in a single prioritization. Proper definition of which ITS devices any particular "system" of ITS devices includes may require substantial technical understanding of the specific ITS systems involved. It was thus decided for this project that detailed technical descriptions of every ITS system, technology, and trend in the world is beyond the scope of this project. The methodology is intended to be applicable to a wide range of ITS devices and systems. The focus of this project is the methodology and sound decision-making, while the details of the different technologies are secondary.

Some of the literature reviewed, particularly Ozbay et al (2009), emphasized environmental goals of ITS maintenance. Indeed, the criteria recommended for consideration in the methodology outlined in Chapter 4 of this thesis could be expanded to include measures such as reductions in greenhouse gas emissions and reductions in airborne pollutants. However, the decision was made to exclude them from the lists of criteria in Chapter 4 in order to narrow the focus of the project. It is assumed that improvements to the operation of the surface transportation system brought on by better management of ITS help improve environmental performance of the system. Improved environmental performance of the surface transportation system is an incentive for implementing the recommendations of this thesis, but this issue could be integrated more explicitly into the methodology in future research.

1.3 – THESIS ORGANIZATION

The subsequent chapters in this thesis are as follows:

- Chapter 2 provides a summary of the literature review. The literature review was done in two phases. The first phase focused on establishing the need for the project as well as searching for existing methodologies, while the second phase involved gaining knowledge about the field of systems engineering.
- Chapter 3 provides a summary of the survey that was sent to contacts at state DOTs. The survey supplemented the literature review by providing insight into the state of the practice in ITS obsolescence management. Responses to the surveys are documented and discussed.
- Chapter 4 presents the ITS obsolescence management prioritization methodology developed for this project. The methodology has two parts. Part I focuses on determining which ITS should be top-priority for receiving obsolescence management attention, while Part II ranks alternative interventions for those ITS.
- Chapter 5 demonstrates Part I of the methodology developed in Chapter 4 by applying it to a case study of 31 Variable Message Signs on the outer loop of the Interstate-64 beltway in the Hampton Roads metropolitan area of Virginia. Data is analyzed from a Hampton Roads Transportation Operations Center database.
- Chapter 6 summarizes the recommendations of this study and suggests possibilities for further research.

CHAPTER 2 – LITERATURE REVIEW

2.1 – OVERVIEW OF LITERATURE REVIEW

The literature review, the first major task of this project, was performed in two phases. The first phase was performed early in the project and the second phase was performed late in the project. The first phase focused on corroborating the project proposal's assertion of the need for the project as well as searching for prioritization methodologies that had already been developed for the specific case of aging or obsolete ITS infrastructure. The first phase was successful in establishing a need for the project but mostly unsuccessful in discovering existing prioritization methodologies for the specific case of ITS obsolescence management. The one such methodology that was discovered, the Hampton Roads Smart Traffic Center Obsolescence Management Plan (VDOT, 2007a), discussed further in sections 2.2 and 4.3, was helpful as a starting point for creating a more robust methodology and as an explanation of the problems that a more robust methodology could solve. However, it was far from a comprehensive guide for creating such a methodology, whether for managing ITS obsolescence or for managing any large-scale complex system. The second phase of the literature review, however, provided the guidance necessary for creating and partially applying a comprehensive methodology for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure.

The second phase of the literature review focused on two aspects of the systems engineering methodology: system boundary definition and multi-criteria decision analysis. A major shift in understanding of the project was brought on by the acquisition of knowledge of the field of systems engineering and its problem solving methods. This shift in understanding occurred very late in the project and enabled the formulation of the methodology developed in Chapter 4 and the application of Part I of the Chapter 4 methodology in a case study in Chapter 5. It became clear that the development of a widely applicable comprehensive methodology for prioritizing the maintenance and replacement of aging and obsolete ITS infrastructure would be possible in the time remaining only if these two aspects of the systems engineering process were applied. In fact, it became apparent that the large research area of transportation asset management (TAM), including this project's focus on the special case of ITS asset management, is essentially one of an unlimited number of possible applications of the systems engineering process.

Steps in the analysis of any large-scale complex system include setting goals for the system, defining system boundaries, generating a list of alternatives, formulating indices of performance, and evaluating and ranking the alternatives in terms of the chosen indices of performance so as to reveal the optimal solution and enable decision makers to make informed decisions (Gibson et al, 2007). Multi-criteria decision analysis methodology stresses the importance of coming up with indices of performance, or metrics, that allow for apples-to-apples comparisons of even the most disparate alternatives (Gibson et al, 2007). Guidance for establishing commensurate comparisons is especially needed for ITS prioritization because ITS refers to an extremely diverse array of technologies and applications and, when implemented, tends to be physically and geographically large-scale and complex. The metrics chosen to evaluate alternatives should serve to capture the degree to which each alternative fulfills the ITS project's goals, which should be tied to the organization's mission (Gibson et al, 2007). Strong et al (1999) states that ITS “devices should be prioritized for repair not on the basis of a particular technology but on the basis of how critical it is to the mission” of the agency (p. vi).

The connection between the obsolescence risk ranking methodology in the Hampton Roads Smart Traffic Center Obsolescence Management Plan (VDOT, 2007a) and the multi-criteria decision analysis techniques within the systems engineering process was not established until late in the project. As a result, it was possible for VDOT (2007a) to be even more helpful as a starting point in the formulation of the methodology presented in Chapter 4 of this thesis. VDOT (2007a) is discussed further in sections 2.2 and 4.3. The two phases of the literature review are presented in Sections 2.2 and 2.3, respectively.

2.2 – LITERATURE REVIEW PHASE I: ESTABLISHING THE NEED FOR THE PROJECT AND SEARCHING FOR EXISTING METHODOLOGIES

The first phase of the literature review was performed early in the project. It focused on corroborating the project proposal’s assertion of the need for this project as well as searching for prioritization methodologies that had already been developed for the specific case of aging or obsolete ITS infrastructure.

Technological obsolescence is not unique to ITS. Any electronic devices or systems that are produced in low volumes or customized for specific applications and that are intended for decades-long operation are prone to obsolescence and shortened life spans due to rapid technological advancement (Josias et al, 2004; Rojo et al, 2012). Once demand for a low-volume device or system disappears with the emergence of superior equivalents and replacement parts, it is no longer economical to continue production of the older version (Josias et al, 2004; Rojo et al, 2012). Ensuring the long-term viability of such technologies requires being proactive in managing their obsolescence from the system level down to the component level, especially if failures have severe consequences (Josias et al, 2004; Rojo et al, 2012).

The first accomplishment of this project was establishing the connection between the problem of ITS obsolescence and TAM in general. The focus of this thesis on prioritizing ITS obsolescence management activities is merely one component of ITS asset management that may contribute to the development of comprehensive ITS asset management practice and integrated systems. The need for ITS strategic management and asset management is well documented in the literature (Anjuman, 2009; Anjuman et al, 2011; Martin, 2002). Martin (2002) emphasizes the need for the collection and analysis of data in order to support present and future ITS decision-making, and the methodology developed in Chapter 4 of this thesis calls for inputs of large amounts of data. Anjuman (2009) develops a methodology for evaluating ITS asset management tools and software according to metrics such as spatial visualization and analysis capabilities, ease of retrieving data, quality of the user interface, remote access capabilities, and enterprise capability in order to help agencies decide which tool is best for them. ITS asset management tools that have been developed include OSPInSight, FiberTrak, and NexusWorx, while other possibilities are enterprise-based GIS and Microsoft Access (Anjuman, 2009). Anjuman (2009) helps show that developing methodologies for prioritizing the maintenance and replacement of ITS is merely one of many important components in the long-term development of comprehensive, successful ITS asset management practice and integrated systems.

Ozbay et al (2009) identifies many problems resulting from mismanaged ITS that signal a need for better ITS maintenance prioritization practices. Improper maintenance increases the frequency of ITS malfunctions, which degrades traffic flow and roadway safety, inefficiently consumes maintenance funds, and shortens the useful life-spans of the ITS equipment (Ozbay et al, 2009). Ozbay et al (2009) calls for “a cost-effective approach to inspecting, maintaining, upgrading, and operating physical assets, such as ITS equipment on roadways” (p. 5) and identifies prioritization as a needed component. Walton and Crabtree (2004) identifies prioritizing maintenance as a critical best practice in ITS management and has as a final recommendation the establishment of “guidelines for determining priorities for ITS maintenance” (p. 37).

It is well documented that deferred or insufficient maintenance negatively affects the operational performance of ITS devices and systems (CDOT, 2008; Ozbay et al, 2009; VDOT, 2007A), just as deferred or insufficient maintenance negatively affects the operational performance of any transportation asset. However, there is a fundamental difference between the management of traditional transportation assets, such as pavement and bridges, and the management of ITS. The difference lies in the fact that ITS involves electronic equipment and communications systems, the rapid pace of technological advancement and obsolescence of ITS, and thus the time frames relevant for management and planning (Anjuman, 2009; Anjuman et al, 2011; Mizuta et al, 2013; VDOT, 2007a). VDOT (2007a) identifies the fact that ITS equipment is subject to rapidly accelerating technological change in addition to the environmental wear and tear that all transportation assets, traditional and electronic, are subject to. FDOT (2011) points out that ITS devices and systems generally must remain in operation nonstop at all times every day of the year. The rapidly accelerating changes that ITS devices are constantly subject to include the following (VDOT, 2007a):

- Original manufacturers of devices and spare parts going out of business
- Specific makes and models of devices going out of production
- Manufacturers ceasing device and software support for specific makes, models, and software versions
- Specific software versions being superseded by newer ones
- Communications protocols constantly changing

The challenges identified in VDOT (2007a) regarding rapid technological change make the development of a methodology for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure very important. Yet as a result of the fundamental difference between traditional asset management and ITS asset management, asset management practitioners have comparatively limited experience in managing technologically advanced systems like ITS assets (Faquir & Mastascusa, 2008; QGDTMR, 2002). In fact, responsibility for the management of ITS assets tends to be in the hands of ITS practitioners, who work in agency divisions that run traffic operations centers (TOCs) or traffic management centers (TMCs), rather than asset managers (VDOT, 2007a). The fact that there is a gap in experience and knowledge regarding the management of electronic surface transportation equipment and systems strongly suggests that there is a need for research into ITS asset management methods, including prioritizing ITS for receiving obsolescence management attention. This project aims to contribute to increasing ITS practitioners' expertise by providing a foundation in prioritizing ITS maintenance and replacement activities.

The need for prioritizing ITS obsolescence management activities was recognized at least as early as 1999. Strong et al (1999) developed a list of 13 "strategic recommendations for ITS maintenance" (p. xi). The recommendations, which are addressed to a large extent in this project, include the following (Strong et al, 1999):

- Formulating guidelines for prioritizing ITS maintenance
- Establishing a spare parts inventory for all ITS devices
- Establishing ITS maintenance performance metrics, such as down time
- Incorporating maintenance planning into ITS strategic planning
- Determining the costs and benefits of contracting out ITS maintenance services to reduce ITS life cycle costs

The fifth point regarding outsourcing maintenance of new ITS devices and systems to third-party contractors who can more easily adapt to rapid technological advancement is a direction that VDOT has been moving towards (VDOT, 2012c; VDOT, 2013a). FDOT (2011) also describes efforts to procure ITS maintenance contracts. Outsourcing of ITS obsolescence management services to private entities means that the unique challenges of ITS regarding accelerating technological change can be managed more efficiently (FDOT, 2011; VDOT, 2012c). The past procurement of vast amounts of ITS equipment and attempting to manage and maintain it all in-house led to VDOT owning a large inventory of increasingly unreliable and unsupportable ITS equipment, as the device inventory and descriptions in VDOT (2007A) indicate. VDOT (2012c) explains that VDOT's goal is to "leverage private sector innovation and expertise" (p. 15) in order to help "replace current field device maintenance with a consistent method for maintaining ITS field devices across the Commonwealth" (p. 31). VDOT (2012c) explains that the contractor must "routinely reassess the priority level of each ITS field device to ensure the device priority meets the demands of the operation, and delivers the expected results" (p. 31). ITS obsolescence management prioritization in Virginia will thus be a collaborative effort between each TMC and the contractor (N. Reed, personal communication, April 22, 2013). VDOT's outsourcing of ITS and TOC management is discussed further the Chapter 5 case study, which applies Part I of the Chapter 4 methodology to a specific case of ITS devices in the Hampton Roads metropolitan area. Part I of the methodology developed in Chapter 4, which provides guidance on prioritizing ITS according to needed obsolescence management attention, can help agencies such as VDOT determine device priority. The general alternatives formulated in Part II of the Chapter 4 methodology for addressing ITS identified as needing obsolescence management attention include the option of outsourcing maintenance services. For example, the priority of a device or system of devices could change if application of the methodology developed in Chapter 4 shows the device or system to be increasingly strategically important and yet unable to perform as well as intended.

VDOT (2007a) contains a simple method for ranking ITS assets on obsolescence. The ranking is established according to four metrics. Metrics are discussed further in Section 2.3. The first of the four metrics is age, condition, and use. The second metric is ease of replacement, which considers the statuses of the manufacturer, model, and software. The third metric is the technology curve, which considers the status of the technology in the market as a whole. The fourth metric is whether or not the equipment has already undergone a service life extension via upgrades or replacement. This method is lacking in that it does not account for a comprehensive list of metrics, such as those recommended in Section 4.3, and does not visibly link the ranking of devices to actual data. Part I of the methodology established in Chapter 4 addresses these shortcomings. In particular, VDOT (2007a) has a simple ranking scheme in which an ITS asset's score in each metric is a simple integer (i.e., 1, 2, 3, or 4 for the first three metrics and -4, -3, -2, -1, or 0 for the fourth metric) based on qualitative descriptions rather than quantitative analysis. The Chapter 4 methodology calls for the collection and analysis of data in addition to analysis based on qualitative metrics such as asset condition.

Another shortcoming of VDOT (2007a) is that an obsolescence ranking is established for each make and model of ITS device without also providing information on which ITS devices in the field at which locations are which makes and models (HRTOC, 2013; VDOT, 2007a). The lack of such information is indicative of an ITS inventory containing incomplete data. In keeping with the principles of TAM, the first step in prioritizing existing ITS for obsolescence management attention is to finish inventorying all ITS assets in the relevant geographical area (FHWA, 2008). ITS asset rankings that are based on incomplete lists of assets or incomplete data on already-inventoried assets are not guaranteed to result in optimal decisions. The maintenance management system (MMS) that the VDOT Hampton Roads operations region currently uses has an ITS device inventory in which very few of the deployed devices have information on make and model (HRTOC, 2013). Part I of the methodology as outlined in this chapter calls for readily retrievable asset-specific information regarding make and model.

VDOT (2007b) provides information, particularly details on retrofit and replacement options, necessary for addressing those ITS already “identified as critical obsolescence risks” (p. 1) in VDOT (2007a). However, VDOT (2007b) also does not reference data detailing which deployed ITS in which exact locations are which makes and models. VDOT (2007c) demonstrates the recommendation to provide a timely alert to appropriate staff when there has been a newly determined change in the obsolescence risk of any ITS.

Johnston et al (2006) explains a method for prioritizing ITS using risk analysis and provides a case study that applies the method to variable message signs (VMS), just as the case study presented in Chapter 5 of this thesis investigates VMS. However, Johnston et al (2006) focuses on prioritizing roadway segments for deployment of new ITS rather than prioritizing existing ITS devices and systems for consideration of intervention alternatives. The methodology presented in Chapter 4 of this thesis, on the other hand, does focus on prioritizing existing ITS for invention consideration and then evaluating intervention alternatives. It should be noted, though, that choosing an intervention for an existing ITS may involve similar considerations and metrics as deciding where to implement new ITS, as shown by the moderate similarity in metrics between Johnston et al (2006) and Section 4.4 of this thesis. Thus this project adds to Johnston et al (2006) in that it prioritizes ITS from the standpoint of existing ITS rather than roadway segments that do not yet have ITS. The ITS Deployment Analysis System (IDAS), a tool developed by FHWA for quantifying the costs and benefits of ITS alternatives, is another ITS evaluation mechanism that focuses on new ITS investments rather than obsolescence management of existing ITS (Cambridge Systematics, n.d.; FHWA, 2013c; Ogle, 2007; Wang, 2005). Studies that apply IDAS to predicting the impacts of alternative ITS investments include Sadek & Baah (2003) and Wang (2005). Other planning-level or sketch-planning tools that can help in the evaluation of new ITS deployment alternatives include the ITS Options Analysis Model (ITSOAM) that was developed for New York DOT (Thill et al, 2004) and the Florida ITS Evaluation Tool (FITSEVAL) (Xiao et al, 2013). Clearly there is a need for methodologies for prioritizing the obsolescence management of existing ITS.

2.3 – LITERATURE REVIEW PHASE II: SYSTEMS ENGINEERING

Rausch et al (2007) defines the *systems engineering process* as “a methodology and tool for managing a system’s life cycle starting with concepts and ending with the system’s retirement” (p. 4). It is compelling that the literature reviewed in Section 2.2 either does not mention or does not emphasize the systems engineering process. Figure 2-1 shows the Systems Engineering “V” Model for ITS from Rausch et al (2007). This focus of this project is on the last three, post-deployment stages of the systems engineering process “V” model for ITS from Rausch et al (2007) shown in Figure 2-1: Operations and Maintenance, Changes and Upgrades, and Retirement/Replacement. Figure 2-1 is a visual that helps place this project within a broader context. Gustafson (2013) emphasized that it is critical for VDOT to apply the systems engineering process in its operation and management of ITS statewide. This thesis improves upon previous literature by providing an explicit link between the topic of ITS obsolescence management prioritization and the systems engineering process, which U.S. DOT has emphasized for ITS (Rausch et al, 2007; FHWA, 2009), particularly with regard to system boundary definition and multi-criteria decision analysis. The essential link to the systems engineering process allows this project to act as a strong foundation for further research in ITS obsolescence management prioritization. The link also allows this project to act as a reminder to practitioners involved in other stages of the systems engineering process of the benefits of incorporating planning for obsolescence management into their activities.

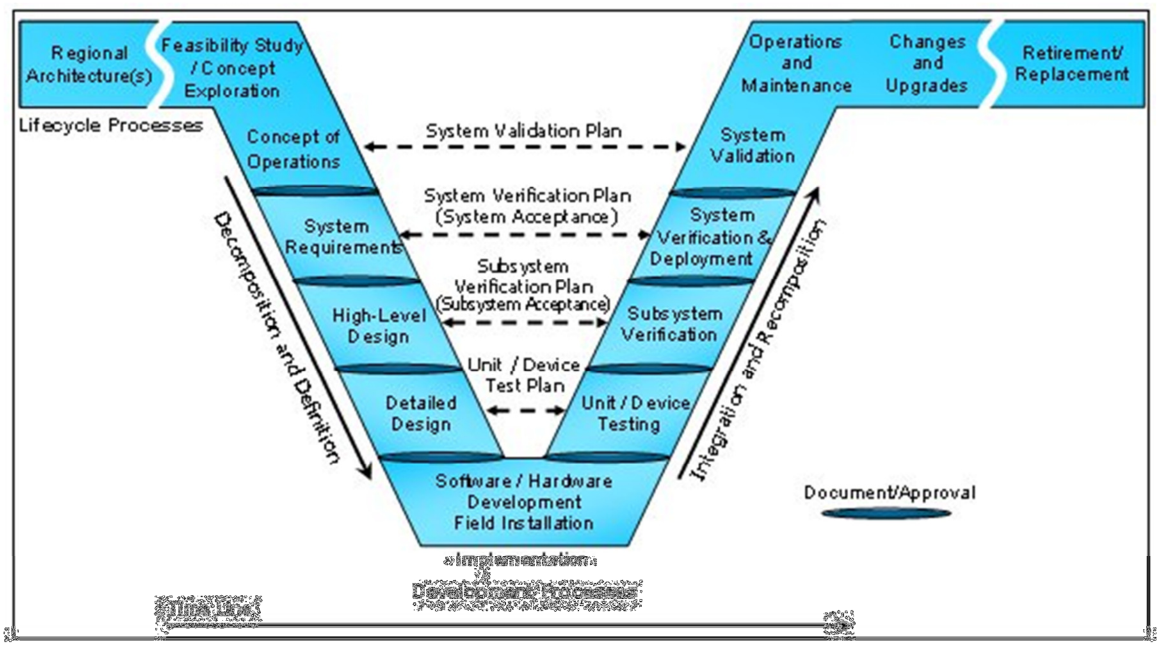

Figure 2-1: The Systems Engineering "V" Model for ITS (Rausch et al, 2007)

FHWA (2009) also makes use of the Systems Engineering "V" Model for ITS and describes certain "cross-cutting activities" (p. 109) that support all stages of the systems engineering process, including the final three stages relevant to this project. One of the most foundational cross-cutting activities in FHWA (2009) is referred to as "metrics" (p. 109). Metrics are measures that help monitor large-scale systems and allow for problems to be corrected and improvements made in a timely manner (FHWA, 2009; Gibson et al, 2007). Ideally, metrics are measurable, objective, meaningful, and understandable (FHWA, 2009; Gibson et al, 2007; Sallman et al, 2012). Aspects of the Metrics activity in FHWA (2009) include defining and tracking technical metrics, identifying and addressing issues accordingly, determining which metrics are key, and making informed decisions, all of which are addressed in Chapters 4 and 5 of this thesis for the case of ITS obsolescence management. FHWA (2009) includes technical guidance on how to compare ITS alternatives in terms of multiple metrics. For example, since metrics may have different units and magnitudes, data collected for metrics must be normalized to a common scale to allow for commensurate comparisons of the disparate metrics (FHWA, 2009). Then, weights must be assigned to each metric according to their relative importance, and the weights must add up to 1 (FHWA, 2009). These ranking analysis guidelines in FHWA (2009) also appear in Gibson et al (2007) and many other sources on systems engineering. It is acknowledged that ranking analysis is only a small topic within the field of systems engineering. The guidelines are the focus of the methodology created in Chapter 4 and the case study reported in Chapter 5 as a starting point for possible future efforts in applying more advanced decision analytics to this line of research.

Multiple literature sources on multi-criteria decision analysis were found that explain different aspects of the ranking analyses presented in Chapter 4 and applied in Chapter 5 and are cited accordingly throughout this paper. Beroggi (1999), Buede (2000), de Neufville and Stafford (1971), and Gibson et al (2007), are textbooks that explain the systems analysis process of choosing metrics, choosing alternatives, and evaluating alternatives, including details such as weights, value functions, and sensitivity and scenario analysis. Multiple academic papers in the decision analysis literature were able to elucidate many of the details, enabling the ranking analyses in this project. Triantaphyllou et al (1998) adds many important details to the textbooks' introductions to the decision analysis process and provides alternative methods. The paper by Drobne and Lisec (2009) contains the clearest explanation of how to normalize data. Decancq and Lugo (2013) helps explain how marginal rates of substitution can help determine metric weights. Triantaphyllou and Sánchez (1997) explain more precisely how to perform sensitivity analysis by varying one weight at a time in order to rank metrics according to criticality of accurate weight determination. Baker & Powell (2005), Butler et al (1997), and Comes et al (2005) provide additional explanation about scenario analysis, particularly the systematic variation of multiple weights and the selection of worst-case and best-case weighting scenarios.

Also, although the details vary greatly, multi-criteria decision analysis is generally a common tool used in transportation studies, as shown in other literature reviewed for this project such as Chowdhury et al (2010) and Anjuman (2009). Vanier et al (2006), "Decision Models to Prioritize Maintenance and Renewal Alternatives," makes great use of decision analysis methods from systems engineering and helps demonstrates that such methods, particularly multi-criteria ranking analysis, are appropriate for prioritizing the maintenance of public infrastructure.

CHAPTER 3 – SURVEY OF PRACTICE IN THE STATES

3.1 – SURVEY OVERVIEW

The second major task of this project was to gain insight into the state of the practice regarding ITS infrastructure assessment and obsolescence management through the composition and distribution of a survey to contacts at various state DOTs. The intent of the survey was to determine current and emerging practices among state agencies in order to complement the findings of the first phase of the literature review and help provide direction for the project. The first phase of the literature review focused on corroborating the project proposal's assertion of the need for the project as well as searching for prioritization methodologies that had already been developed for aging or obsolete ITS infrastructure. It is not certain whether the survey succeeded in determining the state of the practice because only seven responses representing five states were received out of the 24 states represented in the contact list used, which is detailed in Section 3.2. Five of the seven responses that did come in mostly indicated a continued prevalence of reactive management of ITS obsolescence and a lack of robust methodologies and long-term planning to ensure the future sustainability of ITS devices and systems. Of the other two responses, one provided almost no additional details and the other is discussed in Section 3.2. No respondents sent any documents detailing ITS obsolescence management prioritization methodologies or practices in response to requests for such documents throughout the survey. Thus the survey did not discover any written material that the literature review did not find. One possible conclusion is that the practice is in its infancy or that such documentation has not been created yet and thus any current research into ITS infrastructure assessment and prioritization is both timely and needed greatly. Another possible conclusion is that the survey simply failed to find such methodologies because it did not garner enough responses, it did not ask the right questions, or both. For the sake of moving forward with the project, the former conclusion was assumed to be the right one. Therefore the methodology developed in Chapter 4 and partially applied in Chapter 5 was written as a foundation for more advanced or specialized methodologies and as a foundation for further research.

It is acknowledged, however, that the survey that was written for this project has significant flaws. It must be noted that the survey was composed and distributed in summer 2012 before the acquisition of knowledge about the systems engineering process, which effectively expanded the literature review to a second phase, as explained in Chapter 2. The survey was also done long before any work was done on the case study, which was performed using the knowledge gained about the systems engineering process. Completing the case study provided an understanding of how ITS infrastructure is presently managed in Virginia that piloting the survey with VDOT regional operations directors (RODs) and regional traffic operations managers (RTOMs) did not provide. The present state of ITS infrastructure management in Virginia is discussed in Chapter 5. Such an understanding is valuable for writing a survey that asks staff at other DOTs to explain how ITS infrastructure is managed in their respective states. To be sure, the whole idea of including a survey component in this project was to find information not yet known, specifically information about how prioritization is done elsewhere. However, it helps to have the right pre-existing knowledge for asking the right questions, eliciting the right information from respondents, interpreting responses, and acting on the responses. Therefore, the end of this chapter includes some possible additional survey questions that a future research initiative could use to gain better information on the state of the practice of ITS infrastructure management in the United States. The whole survey is attached in Appendix B.

3.2 – SURVEY RESPONSES

After piloting the survey by sending it to Virginia Center for Transportation Innovation and Research (VCTIR) and VDOT staff (i.e., RODs and RTOMs) for feedback, the finalized survey was entered into Survey Monkey and sent out to the states through the Traffic Management Center Pooled-Fund Study (TMCPFS) contact list. TMCPFS is a program administered by the Federal Highway Administration (FHWA) Office of Research, Development, and Technology with the goal of facilitating collaboration between TMCs nationwide (FHWA, 2013b). TMCPFS presently has 28 members representing 24 state DOTs, including VDOT, as well as FHWA and other organizations (FHWA, 2013a). Only seven responses were received as a result of emailing the survey to all representative members of TMCPFS. Three of the responses were from California DOT (each responding for a different district), and Utah, Oklahoma, Missouri, and Idaho DOTs accounted for one response each, as summarized in Table 3-1. “N/A” in Table 3-1 means that the respondent chose to answer the survey for the whole state. Most of the questions on the survey included space for optional or required open-ended responses. No robust quantitative analysis of the survey results was performed because of the importance of open-ended responses in this survey and because of the small number of responses. This section includes discussion about questions for which there were multiple important responses, particularly open-ended-responses. The only respondent who responded positively and with additional details to most of the questions asking about ITS obsolescence management prioritization and long-term plans was the one from the TMC in Kansas City, MO.

Table 3-1 Summary of States that Responded to Survey

Response No.	State DOT	Region/District
1	Utah	N/A
2	Oklahoma	N/A
3	California	3
4	California	9
5	California	6
6	Missouri	Kansas City
7	Idaho	N/A

Question 4 of the survey inquired about current approach to ITS obsolescence management in terms of standardization across the state and formality of approach.

4. Which of the following best describes your agency's approach to ITS obsolescence management?

a) A formal statewide program has been developed with written policies and procedures.

b) Regions have their own local plans and procedures, but there is no consistent statewide program.

c) Decisions are made on a project by project basis, and there is no formal statewide or regional approach.

d) Other

Table 3-2 shows the responses to Question 4. The responses generally indicate inconsistent decision-making and a lack of statewide standardization. The two open-ended responses indicate continued reactive management and a lack of existing plans for long-term physical sustainability of ITS.

Table 3-2: Summary of Responses to Question 4

State DOT	Region/District	Response	Open-Ended Response
Utah	N/A	c	
Oklahoma	N/A	c	"Working more on reactive mode currently, trying to develop a replacement program but not there yet."
California	3	c	
California	9	c	"There are not plans or policies for long term maintenance of ITS elements. The districts must secure state funding for large scale repair/replacement projects as needed. However this process takes several years to complete from the initiation phase to the construction phase."
California	6	b	
Missouri	Kansas City	b	[Respondent explains that option c) is accurate too]
Idaho	N/A	c	

Inventories that are complete and full of actionable information are a vital first step towards asset management for any class of assets. For Question 5 all seven respondents answered "Yes" to whether or not their organization has at least a partial inventory of ITS assets, as summarized in Table 3-3. The common thread among the few responses received is that complete inventories of ITS assets are common in states with TMCs but that there is room for improvement regarding the tracking of data items, such as the ones recommended in Section 4.3, that are useful for ITS obsolescence management prioritization. The Utah respondent, when contacted by phone and asked about the asset management system under development for ITS at Utah DOT, said that the initiative was high-priority but had barely begun and that no work had been completed yet (B. Lucas & R. Clayton, personal communication, November 2012).

Table 3-3: Summary of Responses to Question 5

Question 5: Does your agency have at least a partial inventory of ITS assets?			
State DOT	**Region/District**	**Response**	**Open-Ended Response**
Utah	N/A	Yes	"We are working on developing an asset management system."
Oklahoma	N/A	Yes	"We have a comprehensive inventory [for] every item valued $50 or more. We include maintenance records for each item, and location, and sub-locations. GIS inventory for point and linear data such as fiber optic strands."
California	3	Yes	"Our district (electrical Systems Branch) maintains a file maker pro based inventory. This varies by district. There is a statewide inventory that has been recently implemented. The maintenance program has an inventory for their charging purposes but it is not as complete and has proved more difficult to add elements as needed."
California	9	Yes	"We have a complete inventory of our field elements."
California	6	Yes	"District 6 keeps a full inventory of ITS assets - active, inactive, in repair, planned, in construction, etc."
Missouri	Kansas City	Yes	"Complete list of assets. Repair history location and operational status"
Idaho	N/A	Yes	

In Question 9, respondents were asked whether their organizations had developed a method for establishing the best option (e.g., keep as is, maintain, repair/rehabilitate, replace, remove, abandon, etc.) for any given mature ITS asset. Determination of the best option for any given ITS asset is addressed as Part II of the Chapter 4 methodology (i.e., Section 4.4). In Table 3-4 positive responses from Kansas City TMC and Utah DOT are reported.

Table 3-4: Summary of Responses to Question 9

Question 9: Your agency has developed a method for establishing the best option for any given mature ITS asset.			
State DOT	**Region/District**	**Response**	**Open-Ended Response**
Utah	N/A	Disagree	
Oklahoma	N/A	Disagree	"Not a policy, it is determined by the item, on an individual basis. Sometimes by groups if we replace all batteries in the 332 cabinets in groups or all together."
California	3	Strongly Disagree	"No method has been developed."
California	9	Disagree	
California	6	Disagree	
Missouri	Kansas City	**Agree**	
Idaho	N/A	**Agree**	

Question 10 was an open-ended follow-up question for respondents who answered positively to Question 9. Question 10 asked: "Regarding your agency's method for establishing the best option for any given mature ITS asset: What criteria are used in the method for establishing the best option?" The criteria mentioned by the respondents and summarized in Table 3-5 were considered during the process of creating the lists of recommended prioritization metrics in both Part I and Part II of the methodology developed in Chapter 4.

Table 3-5: Summary of Responses to Question 10

Question 10: Regarding your agency's method for establishing the best option for any given mature ITS asset: What criteria are used in the method for establishing the best option?		
State DOT	**Region/District**	**Open-Ended Response**
Missouri	Kansas City	Cost, life cycle, network compatibility, integration effort needed, warranty support
Idaho	N/A	Reliability and compatibility with current control software

Similar to Question 9, Question 13 asked respondents if their organizations had developed protocol for prioritizing projects addressing mature ITS assets. The question did not specify whether "projects" referred to ITS determined to be in need of attention but whose exact intervention solution had not yet been determined, or ITS for which the best intervention option had already been determined. Part I of the Chapter 4 methodology focuses on determining which ITS should be top-priority for receiving attention, while Part II focuses on determining the best intervention option for each top-priority device. The responses to Question 13 are summarized in Table 3-6 and show once again that Kansas City TMC and Idaho DOT are the most advanced of the seven respondents regarding ITS obsolescence management.

Table 3-6: Summary of Responses to Question 13

Question 13: Your agency has developed protocol for prioritizing projects addressing mature ITS assets.			
State DOT	**Region/District**	**Response**	**Open-Ended Response**
Utah	N/A	Disagree	
Oklahoma	N/A	Disagree	"Handled by project by project basis."
California	3	Strongly Disagree	"There is no formal protocol for addressing mature ITS needs. The district is programming major projects for replacement of ITS elements to replace those that are reaching the end-of-life."
California	9	Disagree	
California	6	Disagree	
Missouri	Kansas City	**Strongly Agree**	
Idaho	N/A	**Agree**	

Question 14 was an open-ended follow-up question for respondents who answered positively to Question 13. Question 14 asked: "Regarding your agency's protocol for prioritizing projects addressing mature ITS assets: What criteria are used in the protocol for prioritizing the projects?" The criteria mentioned by the respondents and summarized in Table 3-7 were considered during the process of creating the lists of recommended prioritization metrics in both Part I and Part II of the methodology developed in Chapter 4. Idaho's response of "asset performance" is not very specific but was considered in the writing of the Part I metric list. Other than "cost," Kansas City TMC's response was more along the lines of general considerations, such as whether or not a project fits in with short-term and long-term transportation plans and available funding, rather than specific metrics ready for data to be gathered for. However, the simple fact that Kansas City TMC has a formal long term transportation plan and considers it in planning ITS obsolescence management activities is noteworthy. After all, an important aspect of the systems engineering process is ensuring that projects serve a purpose that is traceable to the organization's stated plans and goals (Gibson et al, 2007).

Table 3-7: Summary of Responses to Question 14

Question 14: Regarding your agency's protocol for prioritizing projects addressing mature ITS assets: What criteria are used in the protocol for prioritizing the projects?		
State DOT	**Region/District**	**Open-Ended Response**
Missouri	Kansas City	Cost; STIP planning and yearly budget; Maintenance; Long term transportation plan
Idaho	N/A	Asset performance

Question 17 asked respondents if their organizations track the effectiveness of its project identification and prioritization procedures addressing mature ITS assets, and only Kansas City TMC answered favorably (i.e., "Agree"). Question 18 then asked the respondent to describe how the tracking is done and to include a list of any performance metrics used. Questions 17 and 18 were meant to refer to whether the prioritization efforts have been improving management outcomes, such as reducing maintenance costs, relative to the time before the organization started prioritizing ITS in the current manner. It is not known whether the metrics that Kansas City TMC listed in its response to Question 18, shown in Table 3-8, are metrics used in addition to those in Table 3-7 for doing the prioritizing, for tracking whether the prioritizations have been improving management outcomes, or both. However, the judgment was made for this project that the metrics in Table 3-8 are useful for doing the prioritizing and thus were considered during the process of creating the lists of recommended prioritization metrics in the methodology developed in Chapter 4, especially Part I. In follow-up Questions 19-25, Kansas City TMC indicated that its ITS obsolescence prioritization efforts and tracking of their effects on management outcomes have been shown to reduce operations costs, reduce maintenance costs, and mitigate traffic congestion, though no associated documentation or data was provided.

Table 3-8 Summary of Responses to Question 18

Question 18: Please describe how your agency evaluates or tracks the effectiveness of its project identification and prioritization procedures addressing mature ITS assets. Please include a list of the performance measures used.		
State DOT	**Region/District**	**Open-Ended Response**
Missouri	Kansas City	Years in service; Cost of maintenance and product support from manufacturer; Device uptime; Compatibility with network and software system; Device repair history; Cost of repairs for single device; Location of device

The respondents provided important information regarding agency staffing for managing ITS obsolescence. Question 26 asked for responses on the agree-disagree spectrum to the following statement: "Your agency has enough staff for managing ITS obsolescence." The responses to Question 26 are summarized in Table 3-9. California DOT's response that "failing ITS elements create a strain on resources for both Operations and Maintenance personnel in order to determine remedial action" indicates that efforts to determine which ITS need attention and what kinds of attention to give requires sufficient human resources. California DOT District 3's response to Question 26 and Kansas City TMC's responses to Questions 19-25 indicate tradeoffs between personnel costs and maintenance and operations costs. Specifically, improving ITS obsolescence management outcomes over time requires an investment in additional personnel, whether in-house or contract, up front.

Table 3-9: Summary of Responses to Question 26

Question 26: Your agency has enough staff for managing ITS obsolescence.			
State DOT	**Region/District**	**Response**	**Open-Ended Response**
Utah	N/A	Disagree	
Oklahoma	N/A	Disagree	"We seem to [be] always reactive not proactive yet."
California	3	Strongly Disagree	"Failing ITS elements create a strain on resources for both Operations and Maintenance personnel in order to determine remedial action."
California	9	**Agree**	"We don't have a large ITS inventory."
California	6	Disagree	
Missouri	Kansas City	Disagree	
Idaho	N/A	**Agree**	

Question 27 asked about the existence of plans to improve or expand management of ITS obsolescence, and responses are summarized in Table 3-10. Responses to previous questions show that five of the seven respondents are still managing ITS obsolescence reactively and with a lack of existing plans for long-term physical sustainability of ITS infrastructure. However, two of those five respondents, Utah DOT and California DOT District 6, indicated current efforts towards addressing the problem. Utah DOT, as discussed above, has future plans to create an asset management system for ITS. Kansas City TMC's responses to Questions 27 and 26 indicate that they are planning to make further improvements but do not have the ideal number of staff for doing so, respectively. Kansas City TMC's response to Question 29, shown in Table 3-12, also cites insufficient staffing as an impediment.

Table 3-10: Summary of Responses to Question 27

Question 27: Your agency has plans to improve and/or expand its program of managing ITS obsolescence.			
State DOT	**Region/District**	**Response**	**Open-Ended Response**
Utah	N/A	**Strongly Agree**	
Oklahoma	N/A	Disagree	
California	3	Strongly Disagree	"There have been no discussion[s] to my knowledge on any formal program to address obsolescence."
California	9	Disagree	
California	6	**Agree**	"This issue has been identified and is being addressed to some extent."
Missouri	Kansas City	**Strongly Agree**	"Always seeking to find better and cheaper ways to deliver the best ITS system to the Kansas City region."
Idaho	N/A	Disagree	

Question 28 asked about the degree to which each organization is developing policies, developing long-term strategies, or carrying out visioning exercises to help proactively adapt its management of ITS obsolescence to future technology trends and operations needs. Question 28 was asked in recognition of the fact that the rapid pace of technological advancement and obsolescence of ITS, and thus the time frames relevant for management and planning, makes ITS different from other classes of transportation assets, as discussed in Chapter 2. VDOT's recent solution, discussed more fully in Chapter 5, has been to outsource ITS and TMC management to a single private contractor statewide (VDOT, 2012c; VDOT, 2013a). None of the seven respondents to this survey indicated anything about private contracting. The responses to Question 28 are shown in Table 3-11.

Table 3-11: Summary of Responses to Question 28

Question 28: Your agency is developing policies, developing long term strategies, or carrying out visioning exercises to help proactively adapt its ITS obsolescence management program to future technology trends and operations needs.			
State DOT	**Region/District**	**Response**	**Open-Ended Response**
Utah	N/A	**Strongly Agree**	
Oklahoma	N/A	Disagree	"When we have time."
California	3	Strongly Disagree	"The solution at this time is to defer maintenance."
California	9	Disagree	
California	6	Disagree	
Missouri	Kansas City	**Strongly Agree**	
Idaho	N/A	Disagree	

Question 29 was an open-ended question asking respondents to explain any problems that their agencies have encountered in developing an ITS obsolescence management program. The problems reported, summarized in Table 3-12, include insufficient staffing, insufficient funds, lack of time, and lack of practical replacement options. The responses to Question 29 are another indicator that improving ITS obsolescence management over time requires an up-front investment in resources.

Table 3-12: Summary of Responses to Question 29

Question 29: What problems have you encountered in your agency in developing an ITS obsolescence management program?		
State DOT	**Region/District**	**Open-Ended Response**
Utah	N/A	"We have not had enough staff to develop any plans or programs. We have only focused on issues as they come up."
Oklahoma	N/A	"Time"
California	3	"There has been no effort to develop a plan. There are limited resources in the Operations program and Maintenance has had to redirect resources to other areas."
California	9	"Not developing a program."
California	6	"Budgets and available replacement options also play a big role. An ITS element may be obsolete, but you may not have the money or infrastructure in place to upgrade."
Missouri	Kansas City	"Staffing time for research and testing of new technologies; Staff time to fully document all maintenance activities."
Idaho	N/A	

Question 30 was an open-ended question asking respondents to explain any lessons that their agency has learned about managing ITS obsolescence, and responses are summarized in Table 3-13. Utah DOT's response echoes the experience of the Hampton Roads metropolitan area explained in VDOT (2007A) regarding lack of availability of replacement parts, expired contracts with vendors, and general lack of prior planning for ITS maintenance. Utah DOT's response includes advice to consider ITS technology alternatives that do not require intrusive maintenance procedures and to avoid equipment such as in-pavement detectors that require intrusive, disruptive maintenance. California DOT District 3's response reveals that the lack of ITS obsolescence management practice is also caused by lack of communication vertically within the organization regarding the need for such practice. California DOT District 9's response explains that ITS obsolescence "can be on a component or system basis," and the Chapter 4 methodology is built to reflect that. California DOT District 9 also confirmed that the life cycles of ITS equipment is much shorter that those of other transportation assets. California DOT District 6's response that "technology adapts to change faster than bureaucracy" is a fact that VDOT has recognized and responded to accordingly by outsourcing ITS and TMC management to a single private contractor statewide (VDOT, 2012c; VDOT, 2013a), as discussed further in Chapter 5. ITS obsolescence management prioritization in Virginia will thus be a collaborative effort between each TMC and the contractor (N. Reed, personal communication, April 22, 2013).

Table 3-13: Summary of Responses to Question 30

Question 30: Please describe any lessons that your agency has learned about managing ITS obsolescence.		
State DOT	**Region/District**	**Open-Ended Response**
Utah	N/A	"It has been difficult to get parts to maintain devices because they have been discontinued or our contracts have expired and new contracts were awarded to a new vendor (lack of planning for maintenance). We are moving toward non-intrusive devices as much as is practical to avoid impacts from pavement maintenance projects."
Oklahoma	N/A	
California	3	"Need to engage upper management to the longer term needs of ITS elements."
California	9	"Obsolescence can be on a component or system basis. The current technology life cycle is 3-5 years and is much shorter than other DOT equipment."
California	6	"Technology adapts to change faster than Bureaucracy."
Missouri	Kansas City	
Idaho	N/A	

3.3 – FUTURE SURVEY QUESTIONS

This section includes a list of some additional survey questions that could be used on a future survey of state DOTs in a future research initiative in this research area. Some of the questions could be used as follow-up e-mail or telephone correspondence questions instead. The questions are intended as guidance on what information to seek from respondents and thus can be reformulated according to how the researcher wishes to write and administer the survey. These questions have been written in light of having gained knowledge about the systems engineering process and having completed the Hampton Roads case study in Chapter 5.

- Approximately what percentage of deployed ITS devices in your state or district are in disrepair, functionally obsolete, or both?

- How many TMCs or traffic operations centers (TOCs) or does your agency have?
- Does each TMC/TOC operate independently or in an integrated/interoperable fashion when it comes to ITS field device and system maintenance and obsolescence management?
- Either statewide or in each region/district, are ITS field device and system maintenance and obsolescence management performed in-house, under a private contract, or some combination? If a private contractor is involved, what is the nature of the agreement? For each contractor involved in these activities statewide, would it be possible to send VDOT a copy of the contract documents, including the request for proposal and the final contract?
- Does your agency use maintenance management system (MMS) software or asset management software for ITS? If so, what software and version? If the computer system was developed in-house, please provide as much information as possible on how the system works.
- What data, criteria, or metrics does your agency track for ITS devices and systems, either within or outside of its MMS?
- Would it be possible to send VDOT a copy of your agency's ITS inventory and database of ITS maintenance and obsolescence management data to be accessed and researched by VDOT in a secure fashion?
- Does your agency rank ITS according to how much maintenance or obsolescence management attention it needs, and what data, criteria, or metrics are used for each type of ITS?

    - The idea is not to use an MMS just to keep accurate and detailed maintenance records but to actively use that high quality data for making informed obsolescence management decisions. Conversely, if the data is not accurate or detailed, then even if the data is actively used for prioritization and decision-making, informed decisions are not ensured.

- What assumptions or findings has your agency made about the relative importance of the different data sets, criteria, or metrics used for prioritizing ITS for obsolescence management?
- Does your agency routinely apply sensitivity and scenario analysis to its decision-making process for ITS obsolescence management? If so, has your agency gained experience and knowledge about which data items or metrics are generally the most critical for indicating the obsolescence management priority of a given ITS device or system?

CHAPTER 4 – DEVELOPMENT OF A GENERALIZED METHODOLOGY

4.1 – SELECTING THE TYPE OF METHODOLOGY

This chapter establishes a methodology for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure. The U.S. DOT's national ITS program is based heavily on the principles of systems engineering (Rausch et al, 2007; FHWA, 2009; RITA, 2012a; RITA, 2012b). The methodology developed in this chapter focuses on two aspects of the systems engineering process, namely system boundary definition and multi-criteria decision analysis, to address the problem of ITS obsolescence. Decision analysis is the application of analytical methods to the problem of making decisions in an environment in which bad decisions can have far-reaching negative consequences (Gibson et al, 2007). The multi-criteria decision analysis aspect of the systems engineering process, as explained in de Neufville and Stafford (1971) and Gibson et al (2007), includes six key steps:

1) Setting a goal
2) Establishing a list of alternative means of meeting the goal
3) Choosing a set of non-duplicative performance metrics that is comprehensive enough to measure the full anticipated effects of each alternative on progress towards the goal
4) Establishing quantitative estimations of the relative importance of each metric
5) Evaluating the alternatives by ranking them in terms of the metrics chosen
6) Iterating as appropriate

The metrics indicate the data requirements for the project. After the necessary data is collected, the alternatives are ranked or prioritized according to the chosen metrics with their chosen weights, and as a result, the making of informed decisions is possible. Multi-criteria decision analysis is recommended for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure.

4.2 – SUMMARY OF METHODOLOGY

Instead of analyzing and ranking an unmanageably large set of alternatives and metrics all at once, the methodology presented in this paper is broken into two main parts, each involving different sets of alternatives and metrics. The methodology strives to establish and recommend metrics that enable comprehensive apples-to-apples comparisons between as many kinds of ITS devices and systems as possible. Part I is similar to VDOT (2007a) in that it focuses on establishing which ITS devices or systems need obsolescence management attention the most. Part II is similar to VDOT (2007b) in that it considers intervention options for ITS already established to be in greatest need of obsolescence management attention. The methodology is grounded in, while significantly building on, early ITS obsolescence plans in Hampton Roads, namely VDOT (2007a) and VDOT (2007b).

4.2.1 Part I: Identification of ITS in Need of Obsolescence Management Attention-Summary

Part I provides a guiding framework for analyzing existing ITS devices or systems and prioritizes them according to needed obsolescence management attention. In other words, Part I calls for gathering data on certain obsolescence-related metrics in order to rank existing ITS devices or systems according to how much attention they need. This part is designed to be more accurate than Part II in that its focus is on metrics that use historical and present information rather than forecasting. Nothing more intensive than straightforward algebraic extrapolation is intended for the example metrics in Part I that call for forecasting. Devices and systems can be ranked according to which ones need the most attention so as to address ITS obsolescence in a worst-first manner, or according to which ones need the least attention so as to help kick-start ITS asset management and avoid major technology obsolescence problems in the future. Part I is demonstrated in a case study in Chapter 5.

4.2.2 Part II: Determination of Optimal Solutions for ITS in Need of Obsolescence Management Attention – Summary

Part II provides a guiding framework for determining the optimal solution for any ITS identified in the Part I ranking as being in need of obsolescence management attention. Part II analysis could be applied to any subset of ITS from Part I, but in most cases the subset chosen would be ITS that ranked highly in Part I. The number of ITS from Part I that are chosen for further analysis under Part II (i.e., the size of the subset) would depend on agency resources. Part II calls for establishing alternative courses of action for the ITS in Part I that were selected for further analysis. Those alternatives are then ranked according to metrics having to do with future costs and benefits, such as life cycle accounting costs and projected effects on traffic flow, travel time, delay, and throughput. It is recommended that existing methods of life cycle cost analysis (LCCA), travel demand forecasting, and traffic simulation be used for estimating the future costs and benefits. The amount of resources that it is appropriate to spend on such analyses would depend on the particular ITS device or system and its Part I priority, as well as the analysis resources available. The result will be a number-one-ranked alternative, or optimal solution, for each ITS from the Part I ranking that was chosen for further analysis. All the optimal solutions are specific projects ready for implementation. In fact they can be combined into a final ranking that prioritizes the optimal projects.

The rationale for separating Part II from Part I is that LCCA, travel forecasting, and traffic simulation require extra resources to perform. The resources required for prioritizing the maintenance and replacement of ITS infrastructure can be minimized by allowing agency decision-makers to decide which, if any, ITS from the ranking in Part I to spend resources applying the Part II methodology to. If insufficient resources are available for analyzing all ITS from Part I with Part II, the agency could either decide not to do Part II or substitute a simpler decision making technique for any or all ITS from Part I. Part II also emphasizes the need to enter into contracts that maximize long-term support for the system in order to reduce the occurrence of obsolescence problems in the future.

4.3 – METHODOLOGY PART I: IDENTIFICATION OF ITS IN NEED OF OBSOLESCENCE MANAGEMENT ATTENTION

The first task in prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure is to gather as much relevant information as possible about the ITS devices and systems in existing inventory. This section details information that is ideal to keep track of on existing ITS assets to ensure that well-informed decisions can be made regarding ITS obsolescence management project prioritization. The data collected can be used to establish a ranking of which devices and systems to focus maintenance and replacement efforts on.

4.3.1 Inventory, Data, and Documentation

The VDOT Hampton Roads Smart Traffic Center Obsolescence Management Plan (2007) contains a simple method for ranking ITS assets on obsolescence. The ranking is established according to four metrics. The first metric is age, condition, and use. The second metric is ease of replacement, which considers the statuses of the manufacturer, model, and software. The third metric is the technology curve, which considers the status of the technology in the market as a whole. The fourth metric is whether or not the equipment has already undergone a service life extension via upgrades or replacement. Part I of the methodology established in this paper expands greatly on the Hampton Roads method by increasing the number of metrics and improving upon the ranking scheme. The Hampton Roads method has a simple ranking scheme in which an ITS asset's score in each metric is a simple integer (i.e., 1, 2, 3, or 4 for the first three metrics and -4, -3, -2, -1, or 0 for the fourth metric) based on qualitative descriptions rather than quantitative analysis. Part I calls for the collection and analysis of data in addition to analysis based on qualitative metrics.

In keeping with the principles of transportation asset management (TAM), the first step is to finish inventorying all ITS assets in the relevant geographical area (FHWA, 2008). ITS asset rankings that are based on incomplete sets of alternatives or incomplete data on already-inventoried alternatives are not guaranteed to result in optimal decisions. For example, another shortcoming of the VDOT Hampton Roads Smart Traffic Center Obsolescence Management Plan (2007) is that an obsolescence ranking is established for each make and model of ITS device without also providing information on which ITS devices in the field at which locations are which makes and models (HRTOC, 2013; VDOT, 2007a). The maintenance management system (MMS) that the VDOT Hampton Roads operations region currently uses has an ITS device inventory in which very few of the deployed devices have information on make and model (HRTOC, 2013). Part I of the methodology as outlined in this chapter calls for readily retrievable asset-specific information regarding make and model. Section 5.2.1 further discusses the importance of such information as it relates to Hampton Roads in Virginia. New or cutting edge ITS infrastructure should be completely inventoried as well because they may age or become obsolete faster than expected due to the rapid pace of technological change. A full-scale ITS asset management system, which this methodology intends to be a precursor to, would especially require a complete and data-rich inventory in order to help prevent ITS equipment from aging excessively in the first place.

An important task in evaluating existing ITS architecture is locating as much of the original agency and manufacturer documentation for the devices and systems as possible as well as ensuring that the documentation is preserved electronically in an easily retrievable state. FHWA (2009) recommends locating documentation regarding requirements, design, verification, development, and support. Such documentation could provide valuable information for informing decision-making about long-term operations, maintenance, upgrades, expansion, and replacement (FHWA, 2009). Agency historical information on the assets, such as maintenance history and historical performance, as well as manufacturer data, should also be located.

4.3.2 Goals, Alternatives, Ranking Schemes, and Metrics

The goal behind Part I is for an agency to be able to expend resources performing obsolescence management only on the ITS devices and systems that need it most. In this case, the alternatives to be ranked are ITS devices and systems in existing inventory rather than alternative courses of action for particular individual projects, which Part II discusses. These inventory alternatives may be prioritized using two different ranking schemes, one scheme for systems (and systems of systems) of devices, and the other scheme for individual devices within any defined system of at least two devices. The scheme for ranking systems (and systems of systems) of devices is outlined first so that the ranking of ITS is outlined in a top-down manner from system level to device level.

Ranking Scheme #1: Systems (and Systems of Systems) of Devices

- All defined systems (or systems of systems) of devices within a geographical entity (e.g., state, region, district, corridor, or metropolitan area) can be ranked so as to determine which systems (or systems of systems) need the most attention.
- A system can be defined as consisting of either multiple devices or one device, and a system of systems is defined as consisting of multiple such systems.
- The metrics (listed below) account for physical condition, reliability, time in service, technological supportability, disruptiveness of maintenance activities, frequency of customer complaints, quality of the associated communications network, facility performance (in terms of travel reliability, mobility, and safety), and facility importance

Ranking Scheme #2: Individual Devices within Any Defined System of at Least Two Devices

- All individual devices defined as being part of a system of at least two devices can be ranked within that system.
    - In this part of the methodology, it is proposed that systems of ITS devices (whether around one location on a highway or spanning a larger area or longer distance) be broken down for analysis into as many individual devices as possible as long as the result is a list of devices that are reasonably commensurate in terms of the metrics chosen for ranking them. For example, using the metrics recommended below, in-pavement detectors (e.g., inductive loop detectors), would not be ranked as individual devices because they are not sufficiently comparable with other devices in terms of those metrics, which are recommended here for their applicability to a wide range of ITS devices and technologies. Instead, it is proposed here that they be treated as components of the closest device they support, such as the pull box or controller, as Figure 4-1 suggests is reasonable, rather than as devices themselves. In this case, the device to be ranked with the other devices in the defined system of devices would be the pull box or controller. For example, the list of ITS assets in the current MMS database of the Hampton Roads Transportation Operations Center in Virginia Beach, VA does not list in-pavement detectors as separate assets but rather as parts of associated controller cabinets (HRTOC, 2013). Another example would be electrical wires connecting

interdependent devices within a defined system of devices. It is not practical to inventory and collect data on every electrical wire at every location and within every geographical area. Inductive loop detectors, after all, are just wires. Therefore, if such a device as it is defined in this way ranks highly in terms of the recommended metrics, inspection could reveal the real problem to be with one of the associated in-pavement sensors.

- The metrics (listed below) account for only physical condition, reliability, time in service, technological supportability, and disruptiveness of maintenance activities

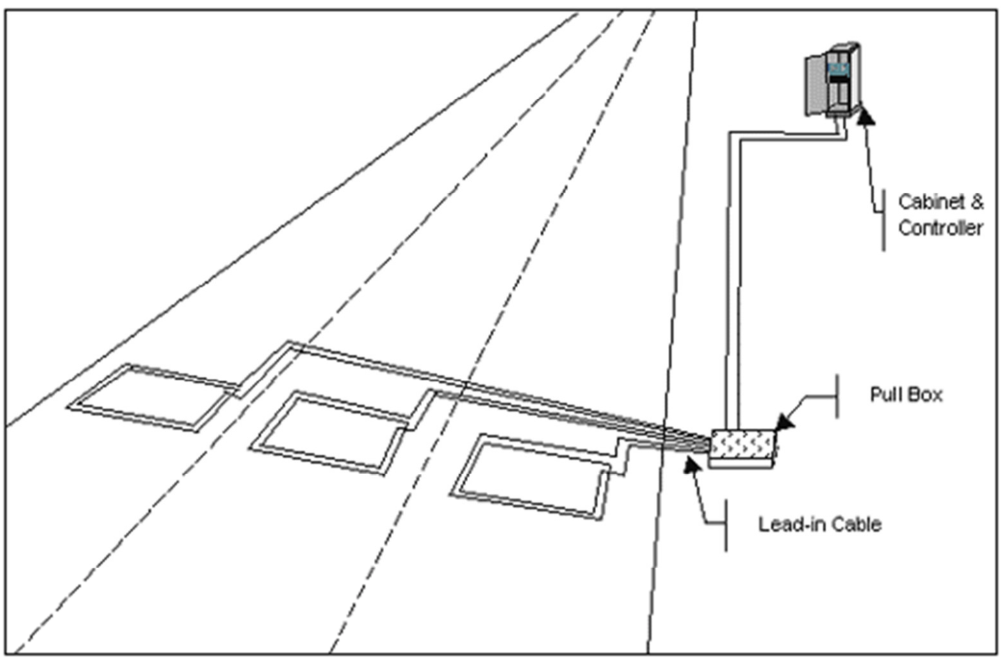

Figure 4-1: Neudorff et al (2003) "Figure 15-2: Inductive Loop Configuration Example" (Section 15.2.6.1), suggesting that an in-pavement detector could be treated as a component of an associated device it supports, such as the pull box or controller.

The definitions of a "system of devices" and a "system of systems of devices" are flexible. In fact, the definitions are flexible enough to take into account interdependencies between disparate individual devices (with the exception of in-pavement sensors, as explained above). The number of possible system boundaries is essentially unlimited, but some are better than others. Proper system definition requires substantial strategic and technical understanding of the specific ITS system, and detailed technical descriptions of every ITS system and technology in the world is beyond the scope of this project, although there is a case study in Chapter 5. The recommended metrics for Part I, outlined below, are meant to be more or less equally applicable to a wide range of ITS technologies and applications. A theoretical example of system (and system of systems) boundary definition is depicted in Figure 4-2.

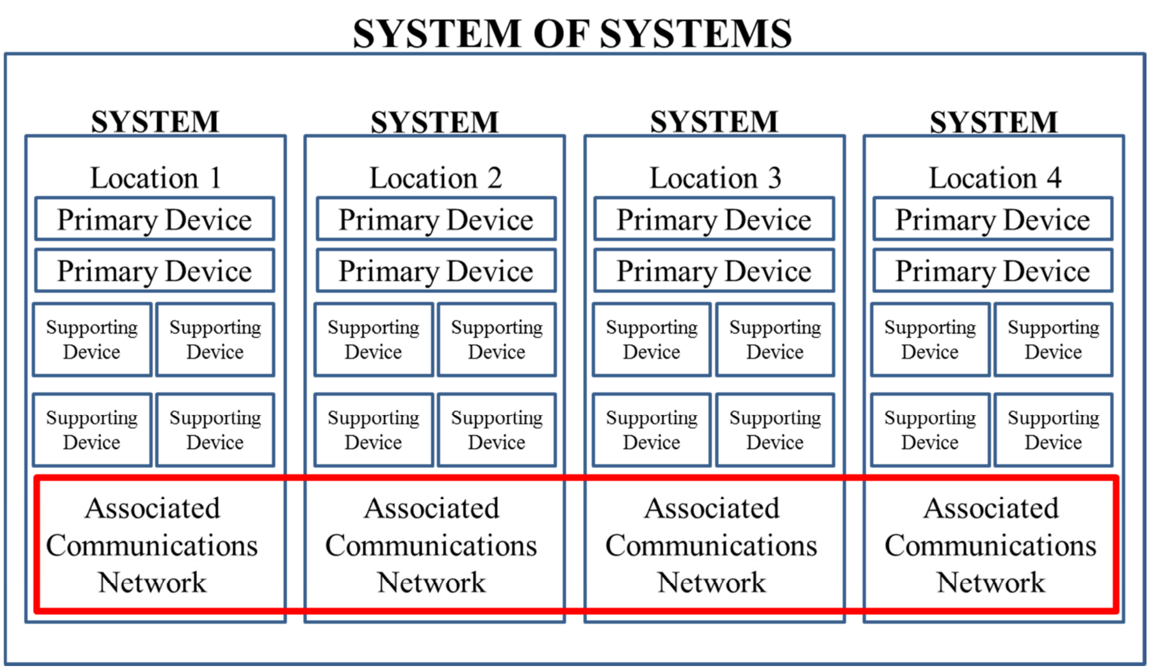

Figure 4-2: System Boundary Definition Theoretical Example. Multiple systems of systems can be ranked according to needed attention; within each system of systems, each system can be ranked according to needed attention; and within each system, each device can be ranked according to needed attention.

It is proposed that for purposes of analysis, there are two situations in which an individual device can be treated as a system of devices (i.e., a system of one device). Firstly, if there is truly only one device, it could be treated as a system of one device with associated communications infrastructure, whose relevant characteristics are accounted for as Metric #7 in Section 4.3.3. Thus the single device, treated as a system, can be commensurate with other systems elsewhere in the roadway network in terms of the same metrics. Secondly, if there are multiple devices in the system, but the decision maker wishes to account for the effect of each individual device, rather than (or in addition to) the effect of the system as a whole, on the performance of the facility (Metric #8 below), then individual devices should be treated as systems of one device.

4.3.3 Selection of Metrics

The device and system alternatives may be ranked according to metrics having to do with condition, time in service, technological supportability, quality of the associated communications network, facility performance (in terms of reliability, mobility, and safety), and facility importance. Recommended metrics are listed below, but the decision maker may change, add, or eliminate metrics within each ranking scheme according to agency needs or availability of resources as long as all metrics used are applicable to, and applied to, all alternatives being ranked together. The list is ambitious but appropriate given trends in maintenance management among state agencies, particularly VDOT, as discussed in Chapter 5. The metrics were developed through brainstorming unless specified otherwise. The recommended metrics for Ranking Scheme #2 are listed first so that the metrics are outlined this time in a bottom-up manner from device-level to system-level. The metrics are separated into categories and, in some cases, subcategories. Neil Reed, chief maintenance engineer at Hampton Roads Transportation Operations Center, reviewed these metrics both via email and during a site visit on April 22, 2013 and agreed with their usefulness for prioritization and appropriateness given future maintenance management trends in Virginia (N. Reed, personal communication, April 16 and 22, 2013).

Metrics for Ranking Scheme #2: Ranking Individual Devices within any Defined System of at Least Two Devices

1. Current Physical Condition
    a. Physical condition ratings of device itself or critical components of device (e.g., intensities of the pixels on LED displays, fraction of pixels whose intensities are zero or below a certain threshold, retro-reflectivity of variable message sign flip disks, dirt accumulation on critical components such as lenses, or any other measure applicable to all devices in the system [B. L. Smith, personal communication, July 24, 2013])
    b. Physical condition ratings of device housing (e.g., cracking, deformation, structural integrity, corrosion, or any other traditional non-technical measure applicable to all devices in the system)
    c. Physical condition ratings of mount and support structure (e.g., cracking, deformation, structural integrity, corrosion, or any other traditional non-technical measure applicable to all devices in the system)
2. Reliability
    a. Percent difference between the required accuracy and actual accuracy of the device's most critical output during peak periods
    b. Down time: frequency (FDOT, 2011; Strong et al, 1999)
        i. Frequency of failures or breakdowns
    c. Down time: duration and effect on the system

i. Total down time not caused by interdependent devices multiplied by the percentage of the larger system's critical functionality that the device supports

ii. Percentage of {Total down time multiplied by the percentage of the larger system's critical functionality that the device supports} occurring during peak periods

3. Time in Service

    a. Time since initial installation

    b. Time since last upgrades or major repair

    c. Time since last maintenance

4. Technological Supportability

    a. Sunk costs as a measure of (the rate of) obsolescence

        i. Present value of the sunk costs of all maintenance, repairs, and upgrades since initial installation

        ii. Historical average yearly change in costs (present value) of all maintenance, repairs, and upgrades since initial installation

        iii. Historical average yearly percent change in costs of all maintenance, repairs, and upgrades since initial installation

    b. Longest possible extension of service life, based on:

        i. Quantity of identical or compatible spare devices left in agency spare equipment inventory per deployed device

        ii. Quantity of the limiting-factor identical or compatible part (i.e., the critical part that would be most likely to run out first) remaining in agency spare equipment inventory per deployed device (e.g., based on historical rates at which each spare part has been consumed), not including parts attached to deployed devices or spare devices.

iii. Production of identical or compatible spare devices in the marketplace

a) Current rate of production per deployed device

b) Current rate of change of production per deployed device

iv. Production of the limiting-factor identical or compatible spare part (i.e., the critical part that would be most likely to become unavailable first) in the marketplace

a) Current rate of production per deployed device

b) Current rate of change of production per deployed device

c. Estimated future costs as a measure of (the rate of) obsolescence

i. Estimated present value of the cost associated with the longest possible service life extension

ii. Estimated average yearly change in costs (present value) associated with the longest possible service life extension

iii. Estimated average yearly percent change in costs associated with the longest possible service life extension

5. Disruptiveness of Maintenance Activities; Difficulty of Performing Maintenance

a. SUM[Fraction of roadway capacity eliminated $]_i$*[Duration of maintenance activity$]_i$ for all maintenance activities for the device over the previous year (assuming that the degree to which traffic must be blocked off for maintenance, and for how long, is directly related to the difficulty of the maintenance and therefore obsolescence)

Metrics for Ranking Scheme #1: Ranking Systems (and Systems of Systems) of Devices

1. Current Physical Condition
    a. Composite physical condition rating of all devices in the system
2. Reliability
    a. Percent difference between the required accuracy and actual accuracy of the most critical output of the system during peak periods
    b. Down time: frequency
        i. Frequency of critical failures or breakdowns within the system
    c. Down time: duration and extent
        i. SUM[Fraction of the system's critical functionality that is down]$_i$*[Duration of that down time]$_i$ for all instances of system down time over the previous year
        ii. Percentage of that SUM that occurred during peak periods
        iii. OR: Average system availability (%), total and peak-period
3. Time in Service
    a. Time since initial installation of system
    b. Time since last upgrades or major repair aimed at improving the system's critical functionality
4. Technological Supportability
    a. Sunk costs as a measure of (the rate of) obsolescence

i. Present value of the sunk costs of all maintenance, repairs, and upgrades since initial system installation
ii. Historical average yearly change in costs (present value) of all maintenance, repairs, and upgrades since initial system installation
iii. Historical average yearly percent change in costs of all maintenance, repairs, and upgrades since initial system installation

b. Longest possible extension of system service life, based on:
   i. Longest possible extension of the service life of the limiting-factor device in the system (i.e., the device from the Ranking Scheme #2 ranking with the shortest of the longest possible device service life extensions)
c. Estimated future costs as a measure of (the rate of) obsolescence
   i. Estimated present value of the cost associated with the longest possible system service life extension
   ii. Estimated average yearly change in costs (present value) associated with the longest possible system service life extension
   iii. Estimated average yearly percent change in costs associated with the longest possible service life extension

5. Disruptiveness of Maintenance Activities; Difficulty of Performing Maintenance
   a. SUM[Fraction of roadway capacity eliminated $]_i$*[Duration of maintenance activity$]_i$ for all maintenance activities for the system over the previous year (assuming that the degree to which traffic must be

blocked off for maintenance, and for how long, is directly related to the difficulty of the maintenance and therefore obsolescence)

6. Frequency of Customer Complaints
7. Quality of the Associated Communications Network (e.g., fiber optic cables, twisted-pair copper cables, or coaxial cables, as well as associated equipment such as routers, multiplexers, modems, switches, hubs, relay interfaces, and amplifier/repeaters) (FCI, 2011; VDOT, 2007a).
    a. Average peak period difference between required system-wide data throughput and actual system-wide data throughput
    b. Average age of all links relevant to the system
    c. Bit error rate
8. Facility (or System) Performance Gap Analysis
    a. Current percent differences between facility performance goals (either in general or solely ITS-driven) and actual facility performance for the relevant roadway segment in the following metrics:
        i. Reliability and Mobility
            1. Peak-period speed variance
            2. Peak-period average delay per person
            3. Peak-period person throughput
        ii. Safety
            1. Crash rates
                a) Property damage only
                b) Injury

c) Fatality

9. Importance of Location within the Facility or Segment

    a. Annual Average Daily Traffic (AADT), Annual Average Weekday Daily Traffic (AAWDT), Peak-Hour Volume (PHV), or associated person throughput for the relevant roadway location or segment

Ranking Scheme #1 can be applied to a system of systems by, for example, changing “the limiting-factor device in the system” in the service life extension metric to “the limiting factor system in the system of systems.”

If any metric is eliminated from any alternative for any reason, such as irrelevance or difficulty of finding data, it must be eliminated from all the other alternatives being ranked together with it. Consistency of metric definitions across all alternatives that are being ranked together is paramount. If the decision maker wishes to change or add any metrics, the changes or additions must be applied consistently across all device or system alternatives being ranked together.

4.3.4 Overlap between Metrics

An important aspect of ranking analysis is choosing metrics that are not related (i.e., are not duplicative) so as to avoid double-counting system attributes (Sallman et al, 2012). The metrics in Part I were chosen so as to be applicable to as wide a range of ITS technologies and applications as possible while minimizing overlap. However, it is acknowledged that there is not a perfect lack of overlap between the metrics and that the amount of overlap between the metrics could vary from case to case. For example, an objection could be raised regarding possible overlap between physical condition and time in service. After all, asset condition tends to worsen as time in service increases. However, both of these metrics are included in order to account for varying in-service environments. In other words, time in service does not necessarily say anything about the harshness of the in-service environmental conditions, while physical condition ratings clearly do. It is assumed here, on the other hand, that time in service is a better indicator of technological obsolescence than physical condition. After all, as discussed in Chapter 2, passing time is a much greater concern with ITS than it is with other transportation assets due to rapid technological change (Anjuman, 2009; Anjuman et al, 2011; VDOT, 2007a). Also, a newer and more technologically up-to-date ITS device could be in bad physical condition given a harsh in-service environment. However, possible overlap between the metrics is acknowledged. In practice it can be difficult to find metrics that have little overlap (W. T. Scherer, personal communication, June 7, 2013).

One way of measuring degree of independence or mutual information between metrics is correlation (W. T. Scherer, personal communication, July 22, 2013). Correlation of data sets is an indicator of degree of possible overlap between candidate metrics and can be measured with the Pearson product-moment correlation coefficient (de Neufville & Stafford, 1971; J. S. Miller, personal communication, July 22, 2013; W. T. Scherer, personal communication, June 7 and July 22, 2013). The result is the creation of a correlation matrix (W. T. Scherer, personal communication, June 7, 2013). The general form of the correlation matrix is shown in Table 4-1. The values on the diagonal are all 1 to reflect the perfect correlation that any data set has with itself (Green et al, 2005). Also, the upper and lower triangular matrices are the same (i.e., transposes of each other) because data set A correlated with data set B results in the same correlation value as data set B correlated with data set A.

Table 4-1: Correlation Matrix General Form (Green et al, 2005)

	Correlation Coefficients between Data Sets						
Metric	**1**	**2**	**3**	**.**	**.**	**.**	***n***
1	1						
2		1					
3			1				
.				.			
.					.		
.						.	
n							1

The correlation matrix can help guide decisions regarding what data should be used in evaluating the alternatives (W. T. Scherer, personal communication, June 7, 2013). The correlation values provide insight into the amount of possible overlap between the metrics for which data has been collected (Beroggi, 1999; de Neufville & Stafford, 1971). Ideally, correlations between metrics used together for ranking should be as low as possible to ensure that there is minimal over-accounting of particular contributions to the final scores of the alternatives (Sallman et al, 2012). Correlations between data sets can thus inform decisions regarding which metrics to use together for ranking and which not to use together. The exception in which a high correlation between metrics being used together is acceptable is if the high correlation is likely a random occurrence, as in between metrics that are unlikely to have a causal relationship (Beroggi, 1999; de Neufville & Stafford, 1971).

4.3.5 Discussion of the Quality of Associated Communications Network Metric

Chowdhury et al (2010) emphasizes that it is important for an ITS asset management system to be able to display “communication connectivity” (p. 126) such that, in the case of fiber optic networks, each fiber’s path within the network and its connections to other communications equipment as well as to the ITS devices can be displayed. As the methodology developed in this paper is intended to be both a precursor to and a potential component of a future ITS asset management system, existing literature on ITS asset management systems can provide insight on what metrics are important for ITS obsolescence management prioritization. Quality of the Associated Communications Network was therefore chosen as a metric for Part I. The Associated Communications Network may be defined differently depending on the case, but one example could be the network in place for moving data from the device or system of devices to the Traffic Operations Center or Traffic Management Center. Data throughput was chosen as the recommended metric because successful throughput of data is the result of communication connectivity, regardless of the how the connectivity is accomplished, the path the data takes, or the amount of redundancy in the network. This metric allows for commensurate comparison of different types of wired networks as well as wireless networks. In the case of fiber optic cables, an optical time-domain reflectometer (OTDR) can be used to measure optical losses over the lengths of the fibers and determine locations of any splices (Fluke Networks, 2013; N. Reed, personal communication, April 22, 2013). Regarding wireless communications, Chowdhury et al (2010) emphasizes the transition from wired to wireless communications as a current technological trend in ITS that is recommended for consideration when choosing replacement alternatives in Part II of the methodology in Section 4.4.

4.3.6 Normalizing the Data

For any given set of alternatives, after all the data is gathered, the data for each metric should be normalized to a common scale to allow for equivalent comparisons between the disparate metrics (Sallman et al, 2012). The recommended method for normalization of data is to normalize the data for each metric linearly into values between zero and 100 (Gibson et al, 2007), where zero corresponds to lowest priority for obsolescence management attention and 100 corresponds to highest priority for obsolescence management attention out of the alternatives being ranked together. For any given metric, if the judgment is made that high data values should contribute to higher priority for obsolescence management attention, then the normalized data values should be calculated using Eq. 4-1.

$$N_{ij} = \frac{x_{ij} - X_{min_i}}{R_i} \times 100 \qquad \text{Eq. 4-1}$$

Where:

N_{ij} = normalized data value for metric *i* for alternative *j*

x_{ij} = value in original data set for metric *i* for alternative *j*

X_{min_i} = minimum value in original data set for metric *i*

R_i = range of original data set for metric *i* (i.e., $X_{max_i} - X_{min_i}$)

Eq. 4-1 is the same as Equation 3 in Drobne and Lisec (2009). Likewise, for any given metric, if the judgment is made that high data values should contribute to lower priority for obsolescence management attention, then the normalized data values should be calculated using Eq. 4-2.

$$N_{ij} = \frac{X_{max_i} - x_{ij}}{R_i} \times 100 \qquad \text{Eq. 4-2}$$

Where:

N_{ij} = normalized data value for metric *i* for alternative *j*

x_{ij} = value in original data set for metric *i* for alternative *j*

X_{max_i} = maximum value in original data set for metric *i*

R_i = range of original data set for metric *i* (i.e., $X_{max_i} - X_{min_i}$)

As a result of Eq. 4-1 and Eq. 4-2, regardless of whether high *data* values are intended to contribute to higher or lower priority for obsolescence management attention, in both cases high *normalized* values are made to contribute to higher priority for obsolescence management attention. Eq. 4-1 and Eq. 4-2 are referred to as the two different directions of normalization (W. T. Scherer, personal communication, June 7, 2013).

Of the recommended metrics in Section 4.3.3, Metric #9, the metric regarding the importance of the location of the system of ITS devices within the whole facility or facility segment, is the only metric that is not assumed to be an indicator of ITS obsolescence. For example, it is assumed that measures such as traffic volumes and crash rates do not “age” or “become obsolete.” It is proposed here that high normalized values of facility importance metrics contribute to higher priority for obsolescence management attention whether it is intended for the ITS to be ranked in a worst-first manner or a best-first, asset-management manner.

Section 4.3.7 explains how to weigh each metric (and thus all the normalized values for each metric). After all the normalization and weighting has been performed, all the normalized values (multiplied by their weights) are added up for each alternative to determine a total score for each alternative (FHWA, 2009; Gibson et al, 2007). The ITS asset with the highest score is the device or system with the highest priority for obsolescence management attention and is thus the strongest candidate for expending resources performing further analysis under Part II of the methodology. If an alternative is removed from the set of alternatives after they have all been ranked together and doing so changes the range of original values for any metric, the whole ranking must be performed again.

4.3.7 Weighting Factors and Final Rankings

The fourth step defined in Section 4.1 in the ranking analysis aspect of the systems engineering process is establishing quantitative estimations of the relative importance of each metric and calculating metric weights accordingly (FHWA, 2009; Gibson et al, 2007; Triantaphyllou et al, 1998). Metric weights should not be chosen arbitrarily because they contain implicit value judgments regarding the relative importance of the metrics and thus degree to which data values for each metric increase the total score of each alternative (Decancq & Lugo, 2013; Gibson et al, 2007). Ratios of metric weights are in fact related to marginal rates of substitution and the data ranges of the two metrics, as shown in Eq. 4-16 and Eq. 4-17 (Beroggi, 1999; Decancq & Lugo, 2013; W. T. Scherer, personal communication, November 26, 2012). Given two metrics,

metrics A and B, the marginal rate of substitution is the amount of metric A the decision maker values, or is willing to give up, per additional unit amount of metric B (Beroggi, 1999; Decancq & Lugo, 2013). If it is determined via marginal rates assumptions that the weight of metric A is twice the weight of metric B, then implicitly the decision maker values five points on the 0-100 normalized scale under metric A the same as 10 such points under metric B. Expressed mathematically, the marginal rate of substitution is negative, since one quantity is subtracted while another is added (Beroggi, 1999). However, for simplicity, it is recommended that positive weight ratios are used while accounting for the positive or negative sign in the direction of normalization (W. T. Scherer, personal communication, June 7, 2013). Eq. 4-16 is the general weight ratio equation. Eq. 4-16 is derived starting with the assumption of a linear additive value function (Beroggi, 1999), also known as the weighted sum model (Triantaphyllou & Sánchez, 1997), for the metrics. The assumption of a linear additive value function is expressed as Eq. 4-3.

$$V_j(\vec{M}) = \sum_{i=1}^{n} v_j(m_i) \qquad \text{Eq. 4-3}$$

Where:

$\vec{M}$ = vector of metrics

$V_j(\vec{M})$ = value function for $\vec{M}$ for alternative j (i.e., total weighted score)

n = number of metrics in $\vec{M}$

m_i = metric i

$v_j(m_i)$ = value function for m_i for alternative j

The value function for m_i for alternative j, $v_j(m_i)$, is equal to the product of the normalized data value for m_i for alternative j and the weight of m_i, as shown in Eq. 4-4.

$$v_j(m_i) = N_{ij}w_i \qquad \text{Eq. 4-4}$$

Where:

$v_j(m_i)$ = value function for m_i for alternative j

N_{ij} = normalized data value for m_i for alternative j

w_i = weight of m_i

Eq. 4-4 can be expressed in terms of the original rather than normalized data value by substituting either Eq. 4-1 or Eq. 4-2, whichever is appropriate, for N_{ij}. Eq. 4-1 is chosen for this derivation, and the result is Eq. 4-5.

$$v_j(m_i) = \left(\frac{x_{ij} - X_{min_i}}{R_i} \times 100\right) w_i \qquad \text{Eq. 4-5}$$

Given two metrics, A and B, and assuming that Eq. 4-1 was used for direction of normalization in both cases, Eq. 4-5 can be written more specifically as Eq. 4-6 and Eq. 4-7, respectively.

$$v_j(m_A) = \left(\frac{x_{Aj} - X_{min_A}}{R_A} \times 100\right) w_A \qquad \text{Eq. 4-6}$$

$$v_j(m_B) = \left(\frac{x_{Bj} - X_{min_B}}{R_B} \times 100\right) w_B \qquad \text{Eq. 4-7}$$

Eq. 4-6 and Eq. 4-7 can be rewritten as Eq. 4-8 and Eq. 4-9, respectively.

$$v_j(m_A) = \left(\frac{x_{Aj}}{R_A} w_A \times 100\right) - \left(\frac{X_{min_A}}{R_A} w_A \times 100\right) \quad \text{Eq. 4-8}$$

$$v_j(m_B) = \left(\frac{x_{Bj}}{R_B} w_B \times 100\right) - \left(\frac{X_{min_B}}{R_B} w_B \times 100\right) \quad \text{Eq. 4-9}$$

The right-hand terms of Eq. 4-8 and Eq. 4-9 are constants. Thus the derivatives of $v_j(m_i)$ can be taken with respect to x_{ij}, resulting in

$$\frac{dv_j(m_A)}{dx_{Aj}} = \frac{w_A}{R_A} \times 100 \quad \text{Eq. 4-10}$$

$$\frac{dv_j(m_B)}{dx_{Bj}} = \frac{w_B}{R_B} \times 100 \quad \text{Eq. 4-11}$$

Given the definition of marginal rate of substitution, total value does not change (Beroggi, 1999), as depicted in Eq. 4-12.

$$dV_j\left(\vec{M}\right) = 0 \quad \text{Eq. 4-12}$$

It follows from Eq. 4-12 that the absolute values of the differential value functions for metrics A and B are equal (Beroggi, 1999), as depicted in Eq. 4-13.

$$\left|dv_j(m_A)\right| = \left|dv_j(m_B)\right| = dv_j \quad \text{Eq. 4-13}$$

Given Eq. 4-13, Eq. 4-10 and Eq. 4-11 can be combined to form Eq. 4-14.

$$dv_j = \left(\frac{w_A}{R_A} \times 100\right) dx_{Aj} = \left(\frac{w_B}{R_B} \times 100\right) dx_{Bj} \quad \text{Eq. 4-14}$$

Eq. 4-14 can be rearranged to form Eq. 4-15, which is rewritten as Eq. 4-16 to emphasize that the differential original data value *dx* applies to all alternatives rather than just one alternative *j*. Eq. 4-16 is the weight ratio equation. The weight ratio calculations in Chapter 5 are based on Eq. 4-16.

$$\frac{w_A}{w_B} = \frac{R_A}{R_B}\frac{dx_{Bj}}{dx_{Aj}} \qquad \text{Eq. 4-15}$$

$$\frac{w_A}{w_B} = \frac{R_A}{R_B}\frac{MR_B}{MR_A} \qquad \text{Eq. 4-16}$$

Where:

MR_A = marginal rate of metric A in terms of the scale and units of the original data set for metric A

MR_B = marginal rate of metric B in terms of the scale and units of the original data set for metric B

For example, under the technological supportability metric category, the agency may be willing to pay *X* additional dollars (Metric 4ci in Ranking Scheme #1) for each additional year of service life (Metric 4bi in Ranking Scheme #1). The ratio of weights is shown in Eq. 4-17.

$$\frac{w_{FutureCost}}{w_{AddedYears}} = \left(\frac{R_{FutureCost}}{R_{AddedYears}}\right)\frac{1\ AddedYear}{\$X\ FutureCost} \qquad \text{Eq. 4-17}$$

The analyst then makes similar educated judgments about the relative importance of all the other metrics before the alternatives can be evaluated and ranked. For cases in which the decision maker values any two given metrics as equally important and thus sets their marginal rates equal to each other, it can be deduced from Eq. 4-16 that equal importance does not translate into equal weights unless the data ranges of the two metrics are equal.

Legitimate objections can be raised about exact metric weights determined via some procedure (Butler et al, 1997), such as the procedure presented in this section. For example, agency analysts or decision-makers may not be able to agree on exact marginal rates between metrics (Butler et al, 1997). Also, determining exact marginal rates may require more resources than are justified for the size of the particular prioritization analysis (Butler et al, 1997). To be sure, documenting the research and assumptions behind the weights has advantages in transparency, which is important for public agencies. However, Section 5.3 of the case study demonstrates that deciding on marginal rates can require detailed research and assumptions even for a relatively simple example. Thus another option for choosing weights is to agree on a relative ordering of importance of the weights to help choose reasonable values for them (Butler et al, 1997).

For each ITS device or system being ranked together, the ranking is determined by multiplying each normalized metric value by its weight and then summing those products to determine a total weighted score (Beroggi, 1999; Buede, 2000; Gibson et al, 2007; Triantaphyllou & Sánchez, 1997), as formulated in Eq. 4-3, where higher score indicates higher priority. Again, the assumption is a linear additive value function (Beroggi, 1999; Buede, 2000; Gibson et al, 2007; Triantaphyllou & Sánchez, 1997). Other value functions are possible, but the linear additive model is recommended because of its simplicity and transparency (Gibson et al, 2007; Triantaphyllou & Sánchez, 1997).

The question can be raised regarding whether prioritizing ITS according to the methodology explained in this section leads to rankings that are significantly different from the order in which the organization would have addressed those ITS without applying this methodology. In other words, the organization may want to demonstrate the benefits of using this methodology relative to continuing on their present course of ITS obsolescence management before fully adopting the methodology. In this situation, the organization can rank a sample of ITS devices using this methodology and compare that ranking to a base-case ranking of those ITS devices that reflects the organization's current practice. It should be noted, however, that such analysis is not meaningful unless the metrics chosen for calculating the rankings according to this methodology are satisfactory metrics, such as the ones listed in Section 4.3.3.

4.3.8 Sensitivity Analysis and Scenario Analysis

Sensitivity analysis and scenario analysis involve analyzing the effect of changing certain inputs, such as metric weights, on the final ranking of the devices or systems (Butler et al, 1997; Gibson et al 2007). The goals of sensitivity analysis and scenario analysis are to help provide insight into which metrics are the most critical and to determine the confidence that can be had in a given ranking (Triantaphyllou & Sánchez, 1997) of ITS devices or systems. Insights regarding critical metrics and alternatives with sensitive ranks can help inform decisions about which metrics to include in the analysis and whether to spend extra effort and resources increasing the accuracy of the prioritization. Possible sensitivity-related questions that could be beneficial to answer, especially for decisions regarding devices or systems shown to be the most important or highest priority, include the following (Butler et al, 1997; Gibson et al, 2007; Triantaphyllou & Sánchez, 1997):

1. By what percentage would each metric weight have to change for the ranking to change if the weight of each metric were varied one at a time?

2. How does systematically varying multiple metric weights simultaneously effect the ranking?
3. How much would the original data values of a metric have to change for the ranking to change?
4. How much would other factors in the particular case study have to change for the ranking to change?

A sensitivity analysis can be performed on any ranking scenario in order to determine which metrics are more critical (Triantaphyllou & Sánchez, 1997). When the metrics are ranked according to criticality, they are ranked according to relative importance of determining an accurate weight and, therefore, according to relative amount of justification for expending resources determining an accurate weight (Triantaphyllou & Sánchez, 1997). Sensitivity analysis can be performed by varying each weight individually (i.e., by changing just one weight and leaving the others unchanged) until an effect on the final ranking is detected (Triantaphyllou & Sánchez, 1997). Thus it is recommended that the metrics chosen be ranked according to the degree to which their weights can change individually before the final ranking of devices or systems is affected. More specifically, it is recommended that the metrics be ranked according to difference between the percent increase in weight and percent decrease in weight needed to switch the rankings of any two of the devices or systems, as done in Triantaphyllou and Sánchez (1997). It should be noted that "higher weight" does not necessarily mean "more critical," as demonstrated in Section 5.4. For example, a ranking could be more sensitive to changes in a small weight but less sensitive to changes in a large weight. The case study in Chapter 5 provides a demonstration of sensitivity analysis applied to ITS obsolescence management prioritization.

Scenario analysis, which is a form of higher-dimensional sensitivity analysis (Butler et al, 1997), involves establishing a set of weighting scenarios in which multiple weights are varied simultaneously. Developing multiple weighting scenarios, rather than just one set of weights, for use with every set of alternatives recognizes the fact that the relative importance of each metric may vary with circumstances (Comes et al, 2009). There could be an unlimited number of possible weighting scenarios, but the scenario development may be limited to only a few critical scenarios that more or less span the range of possible scenarios (Comes et al, 2009). It is recommended that the set of scenarios include a primary or base-case scenario and a set of plausible contingency scenarios (Comes et al, 2009). The primary scenario could be, for example, the status-quo environment under which the agency is operating and the agency's corresponding values and strategic priorities. A contingency scenario could be, for example, that transportation funding or staffing is reduced by *X* percent and the agency must realign its values or strategic priorities accordingly. For example, perhaps such a scenario would reduce by *X* percent the amount of money the agency would be willing to pay for each additional year of service life extension, affecting the relative weights of those two metrics. It is recommended that Part I analysis, for any set of ITS devices or systems, show not only the ranking resulting from the base-case weighting scenario but also how the rankings would change, if at all, under the contingency weighting scenarios.

Similar to how sensitivity analysis allows for metrics to be ranked according to criticality, it is proposed here that scenario analysis can show which assets have rankings that are the most and least sensitive to systematic variations in the inputs. Such knowledge can provide insight into how much assurance that can be had that the relative priority of any given asset is correct. For example the agency could decide to spend extra effort increasing the accuracy of the input values if there is an asset that is ranked highly but whose ranking is shown to be particularly sensitive to systematic variations in the inputs.

4.3.9 Iteration

The sixth step of the ranking analysis process listed in Section 4.1 is iteration as appropriate. Gibson et al (2007) emphasizes that iteration is important in analyzing alternatives for any large-scale system. Embracing the fact that errors occur in analysis reduces perfectionism and thus prevents too much time from being spent on one run-through of an analysis (Gibson et al, 2007). The ranking analysis performed using the procedures outlined in Section 4.3 may provide insights that justify redoing (i.e., performing another iteration of) the analysis. For example, the iteration phase of a ranking analysis is the chance to change the weights as necessary in response to the sensitivity and scenario analysis from Section 4.3.8 and generate new rankings. Also, unexpected or nonsensical results may be grounds for iteration. For example, by looking at a visual aid, such as a stacked bar graph, that shows the contribution of each metric to the final score of each alternative, the analyst may notice that one metric is contributing an unreasonably high or low amount to the final scores of the alternatives. Such an observation would be grounds for changing the weights and redoing the rankings. The soundness of the original weight ratio assumptions can be easier to evaluate after they are used to generate rankings. Reapplication of the whole process by iterating can thus yield more accurate results for enabling better-informed decisions. If Part I of the methodology is coded into an automated system, new ranking results and sensitivity and scenario analysis results could be generated immediately just by entering the new weights.

Ideally, for each set of ITS devices or systems prioritized using Part I of the methodology, all iterations of the methodology should be preserved for purposes of record-keeping, keeping track of lessons learned, and transparency. To be sure, in practice such record-keeping may not be possible given limitations on data storage resources. The idea in this section, though, is to recognize that iteration is part of the ranking process rather than an indication that incompetent mistakes were made that should be covered up by deleting all iterations other than the final one.

4.4 – METHODOLOGY PART II: DETERMINATION OF OPTIMAL SOLUTIONS FOR ITS RANKED AS TOP PRIORITIES FOR OBSOLESCENCE MANAGEMENT ATTENTION

4.4.1 Generation of Project Alternatives

For each Part I ITS that has been chosen for further analysis with Part II, a custom set of alternative courses of action should be developed for a predetermined planning horizon. Part II addresses the need identified in the project proposal to determine the best replacement technology. Part II also addresses the question as to whether replacement is the best option at all. In fact, Part II is broad enough to encompass a wide range of alternative courses of action for each ITS that was identified in Part I to be in greatest need of obsolescence management attention. Such alternatives could include, but might not be limited to, alternative replacement technologies. The methodology therefore recognizes that different courses of action are better for different situations regardless of how state-of-the-art a technology is in general. Part II features a long comprehensive list of general ITS alternatives rather than attempting to list every conceivable specific alternative for every possible situation in which an existing ITS has been identified as obsolete and in need of being addressed. Coming up with specific alternatives for specific field contexts is best left to those who have not only strategic planning experience but also technical knowledge and expertise regarding different ITS technologies and manufacturers. Some generalized alternatives and generalized sub-alternatives that can serve as guidance for generating a more particular list of alternatives include the following:

Generalized Primary Alternatives:

1. Keep in current state (i.e., do nothing, whether it means abandoning a non-operational device or system, or allowing an operating device or system to continue operating without any maintenance or until failure)
2. Remove from facility and do not replace with anything
3. Keep current device or system and perform only reactive maintenance as needed
4. Keep current device or system and perform proactive maintenance on an optimal set schedule plus any needed reactive maintenance
5. Perform major repairs or upgrades on current device or system and perform only reactive maintenance as needed thereafter

6. Perform major repairs or upgrades on current device or system and perform proactive maintenance on an optimal set schedule plus any needed reactive maintenance thereafter
7. Replace with new device or system and perform only reactive maintenance, repairs, and upgrades on it as needed thereafter
   a. This alternative could be expanded into multiple alternatives for different candidate replacement technologies and/or manufacturers.
8. Replace with new device or system and perform proactive maintenance, repairs, and upgrades on an optimal set schedule plus any needed reactive maintenance thereafter
   a. This alternative could be expanded into multiple alternatives for different candidate replacement technologies and/or manufacturers.

Generalized Responsibility-Related Sub-Alternatives:

1. Perform maintenance, repairs, and upgrades in-house
2. Outsource maintenance, repairs, and upgrades services to a private contractor
3. Some combination of both in-house and outsourced maintenance, repairs, and upgrades

Generalized Quantity-Related Sub-Alternatives for Systems of Devices:

1. Keep number of devices the same and with the same spacing along the facility
2. Keep number of devices the same but with different spacing along the facility
3. Increase the number of devices
4. Decrease the number of devices

Generalized Sub-Alternatives for the Associated Communications Network:

1. Make no changes or upgrades to the associated communications network
2. Implement changes or upgrades to the associated communications network

Generalized Geographic Sub-Alternatives for Systems of Devices:

1. Keep geographical extent of system the same
2. Increase geographical extent of system
3. Decrease geographical extent of system
4. Different combinations of the above alternatives for different geographic portions of the system

Generalized Time-Related Sub-Alternatives:

1. Different combinations of the above alternatives for different time periods within the planning horizon

4.4.2 The Planning Horizon and Contracting: Ensuring Future Support for Deployed ITS Devices and Systems

Ideally an agency avoids implementing any ITS without some mechanism to ensure the long-term supportability of the system and avoid the obsolescence pitfalls explained in literature such as Josias et al (2004), Rojo et al (2012), and VDOT (2007A). For example, a transportation agency can benefit from avoiding entering into any contracts procuring any physical assets that will likely not be supportable later on. It is proposed here that all Part II alternatives involving replacing existing ITS with new ITS should specify the manufacturer or service provider, and ideally that manufacturer or service provider is a large, established company that is willing to enter into a long-term maintenance and support contract with the agency and that has a track record of profitability and bidding on and winning similar contracts. In addition, ideally there would exist multiple other similarly established companies that manufacture compatible equipment or provide similar services. Also, any Part II alternatives proposing to outsource maintenance, repairs, and upgrades services to a private management company should specify desired contractors or contractors that have expressed interest in responding to a request for proposals. Depending on the situation, suboptimal financial and contractual track records might be compensated for by the existence of multiple reliable redundant sources of long-term support for the system. The planning horizon chosen for Part-II analysis of any project that includes replacement and/or outsourcing alternatives should be linked to the associated contract durations, and those durations should be acceptable to the agency and likely to be accepted by qualified manufacturers or service-providing contractors. Inter-regional and interstate collaboration on standardizing choices of manufacturers and service contractors for each type of ITS, as well as adherence to proactive maintenance schedules to maintain demand for replacements and replacement parts, are essential for ensuring the long-term sustainability, viability, and public acceptance of ITS. In summer 2013 VDOT made major progress in addressing these concerns by awarding a contract to Serco, Inc. to provide integrated ITS and TOC management services statewide (VDOT, 2012c; VDOT, 2013a).

4.4.3 Establishment of Metrics for Ranking Project Alternatives

Regarding the determination of the best option for ITS identified in Part I as being high priority for receiving obsolescence management attention, this section lists widely used transportation project metrics that can be used to evaluate ITS alternatives from Section 4.4.1 in terms of life cycle costs and life cycle impacts. It is recommended that the metrics recommended in this section be evaluated in the same ways as the metrics in Part I in terms of analyzing correlation, determining weights, and performing sensitivity and scenario analysis.

Metrics for Ranking Project Alternatives:

1. Present value of projected life cycle accounting costs over the planning horizon
    a. Present value of capital costs, including integration into existing network
    b. Present value of O&M costs
    c. Present value of disposal costs
2. Present value of projected life cycle accounting revenues over the planning horizon (e.g., toll revenue from an electronic toll collection system)
3. Projected effect of implementing the given alternative on facility reliability and mobility over the planning horizon according to travel demand modeling and traffic simulation or other analysis
    a. Projected percent change in peak-period speed variance
    b. Projected percent change in peak-period average delay per person
    c. Projected change in peak-period person throughput

The amount of effort spent estimating the above metrics for each alternative, let alone whether all of them are included, should be appropriate for the magnitude of the alternative. For example, advanced travel demand forecasting and traffic simulation using advanced software may be warranted for major candidate projects addressing a large ITS system found to be high-priority in Part I. The ITS investment evaluation software IDAS can help in the evaluation of intervention alternatives in terms of the metrics above for ITS shown in Part I to be in greatest need of intervention (Cambridge Systematics, n.d.; FHWA, 2013c). IDAS has the ability to estimate future costs and benefits for over 60 types of ITS projects (Cambridge Systematics, n.d.). Other planning-level or sketch-planning tools that can help in the evaluation of new ITS deployment alternatives include ITSOAM and FITSEVAL, mentioned in Section 2.2. Cost estimates for ITS deployments can also be determined using the U.S. DOT ITS costs database (RITA, n.d.). On the other hand, such effort would probably not be warranted for evaluating alternative replacement parts for addressing a single ITS device.

4.4.4 Further Analysis and Program Continuation

The methods for analyzing correlations, normalizing data, calculating weights, developing scenarios, analyzing sensitivity and scenarios, and iterating explained in Part I apply to Part II as well. If winning alternatives from Part II are actually implemented, Part II can be applied continually to track the system's progress so far in terms of the given metrics. In fact, in the case of maintenance, repairs, and upgrades being outsourced to a private contractor, retrospective Part II analysis could be done to help determine the contractor's performance in managing the system and fulfilling the contract.

CHAPTER 5 – DEMONSTRATION OF METHODOLOGY IN A CASE STUDY

5.1 – SELECTION OF CASE STUDY

5.1.1 Case Study Selection Overview

This chapter provides a demonstration of the prioritization of ITS infrastructure in terms of needed obsolescence management attention using some of the methodology developed in Chapter 4. The goal was to select a system of ITS equipment that was located in Virginia and on which enough data could be found to demonstrate the methodology. VDOT's Smart Travel program features five Transportation Operations Centers (TOCs), each located in its own operations region (VDOT, 2012c). The five operations regions and associated TOCs are as follows (VDOT, 2012c):

- Northern Regional Operations (NRO): Northern Virginia (NOVA) TOC
- Eastern Regional Operations (ERO): Hampton Roads TOC
- Central Regional Operations (CRO): Richmond TOC
- Southwestern Regional Operations (SWRO): Salem TOC
- Northwestern Regional Operations (NWRO): Staunton TOC

Since VDOT (2007a), the Hampton Roads Obsolescence Management Plan, clearly details each type of ITS equipment deployed in the region and their statuses regarding obsolescence, Hampton Roads was chosen for the case study. A further benefit of selecting a system of ITS devices in the Hampton Roads metropolitan area was the presence of two Hampton Roads stakeholders on this project's Technical Review Panel (TRP): Neil Reed, chief maintenance engineer at Hampton Roads TOC (HRTOC), and Keith Nichols, senior transportation engineer at the Hampton Roads Transportation Planning Organization (HRTPO).

During the case study selection process, it became clear that it would not be possible to find anywhere close to the amount of data for any system of ITS devices in Virginia that Part I of the methodology developed in Chapter 4 calls for. This thesis recommends that agencies find ways to collect and store data for the metrics recommended in the Chapter 4 methodology so that decisions made on ITS maintenance and replacement are as well-informed as possible. However, if such data does not exist yet, as is the case in Virginia, an agency can at least prioritize ITS by applying the Part I methodology from Section 4.3 to whatever data is available as a preliminary exercise in preparation for greater data availability in the future. The demonstration presented in this chapter takes available data for a system of ITS devices in Hampton Roads and ranks them according to needed attention, or the need to expend agency resources evaluating alternative corrective actions for them. The obsolescence metrics used in this demonstration, numbers of work orders and time spent completing those work orders, are unsatisfactory metrics that are used due to current lack of readily available data on the metrics listed in Section 4.3. Thus the decision was made not to include a base case ranking. This case study does not apply the Part 2 methodology in Section 4.4.

The availability of data relevant to ITS obsolescence management prioritization in Hampton Roads is expected to change significantly in the near future (N. Reed, personal communication, April 22, 2013). HRTOC uses a maintenance management system (MMS) to manage the Hampton Roads metropolitan area's ITS devices and systems, but two major MMS changes are on the horizon (N. Reed, personal communication, April 22, 2013). The first change will be an upgrade from one software version of the current MMS to another at HRTOC only, and the second change will be the adoption of an entirely new MMS at all five TOCs in Virginia including HRTOC (N. Reed, personal communication, April 22, 2013).

The MMS software that HRTOC currently uses is called MicroMain XM, and the upgrade will be from Version 6 to Version 7.5 (N. Reed, personal communication, April 22, 2013). HRTOC uses MicroMain for not only inventory management and ITS preventative and corrective maintenance but also fleet and facility maintenance and management as well as IT software and hardware support (N. Reed, personal communication, May 15, 2012). HRTOC originally selected MicroMain XM for its MMS in 1998 because it was affordable and because the company provided the source code as well as support in making changes to it that could then be rolled into the next version of the software if desired (N. Reed, personal communication, April 22, 2013). Unfortunately, the initial adoption of the software was rushed in that the critical step of performing all the proper front-loading of data, information, and control and integrity processes was largely skipped (N. Reed, personal communication, April 22, 2013). As a result, MicroMain XM Version 6, as it stands currently at HRTOC, does not lend itself very well to prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure. HRTOC plans to migrate to Version 7.5 during summer 2013 and to significantly improve its inventory of ITS devices and systems with it in preparation for migration to the entirely new MMS that will be adopted statewide (N. Reed, personal communication, May 29, 2013). However, HRTOC will stop short of actually using Version 7.5 to manage maintenance in favor of waiting for the statewide upgrade (N. Reed, personal communication, May 29, 2013).

The second major change regarding maintenance management at HRTOC will be the adoption of an entirely new MMS at every TOC in Virginia including HRTOC in order to standardize operations across all five regions and TOCs (N. Reed, personal communication, April 22, 2013). This change will be occurring as a result of VDOT's effort, explained in the Literature Review in Chapter 2, to move towards outsourcing the management of ITS to private contractors in order to take advantage of the efficiencies and innovative solutions possible in the private sector (VDOT, 2012c). As detailed in VDOT (2012c)), in July 2012 VDOT issued a request for proposals (RFP) from qualified companies to formulate a contract to provide the following statewide services (p. 15):

- Safety Service Patrol
- TOC Floor Operations
- ITS Infrastructure and Field Network Maintenance
- A Statewide Advanced Traffic Management System (ATMS) Solution and Technology Support
- Program Management
- General Support Services

On May 15, 2013, VDOT awarded the contract to Serco, Inc in the form of a $355-million, six-year contact (VDOT, 2013a). As a part of the contractor's responsibility to provide a statewide ATMS solution, the contractor is required to provide an automated MMS (VDOT, 2012c). Because of the importance of an MMS to the ability of an agency to prioritize the maintenance and replacement of ITS infrastructure, the exact language from the May 2012 RFP regarding the MMS is reproduced here (VDOT, 2012c):

> The Contractor shall include as part of its Statewide ATMS Solution an automated Maintenance Management System (MMS), to provide corrective and preventive maintenance services support for all systems, subsystems and components of the Statewide ATMS Solution. The maintenance

> assets may include facilities, hardware and software, field devices (including supporting structures), communication infrastructure and other associated elements. This system will be required to provide the full range of systems maintenance functions including but not limited to scheduling, resource allocation, preventive and corrective maintenance activity tracking, control, analysis and reporting. (p. 34)

ITS obsolescence management prioritization will then be a collaborative effort between the TOC and the contractor (N. Reed, personal communication, April 22, 2013).

The MMS that Serco will be providing is IBM Maximo Asset Management, or "Maximo" for short (IBM, 2013; N. Reed, personal communication, May 29, 2013). Ideally, this case study would not be done until after the transition to Serco's TOC management and the Maximo MMS, but this project must adhere to "Rule 6: Meet the Time Deadline and the Cost Budget" of the 10 Golden Rules of Systems Analysis in Gibson et al (2007, p. 310). The fact that the transition to Maximo will not occur until after this project is complete highlights the difference between the theoretical, such as in Chapter 4 and developing a methodology, and the practical, such as in regard to time constraints, and the need to reconcile them as best as possible.

3.1.2 Selection of ITS Equipment for Analysis

In order to select a system of ITS devices in Hampton Roads to do a case study on, it was necessary to gain access to HRTOC's current MicroMain XM Version 6 MMS. Accordingly, a special trip was taken to HRTOC on April 22, 2013 for a site tour and meeting with staff. HRTOC staff introduced MicroMain's interface, reporting capabilities, and data as well as provided a Microsoft Access database file containing of all the raw data on CD for later analysis. After looking through the available data, a system of 31 Variable Message Signs (VMS) on a 35.8-mile stretch (Google, 2013; VDOT, 2013b) of the outer loop of the Interstate-64 beltway (i.e., I-64 westbound [WB]) in the Hampton Roads metropolitan area in southeastern Virginia was selected. The 35.8-mile stretch of I-64 westbound from the junction of I-64, I-264, and I-664 in Chesapeake, VA through the cities of Chesapeake, Virginia Beach, Norfolk, and Hampton to the junction of I-64 and I-664 in Hampton, VA with the VMS locations is shown in Figure 5-1. There are 31 VMS at 28 VMS locations because three of the locations have two VMS (Google, 2013; HRTOC, 2013).

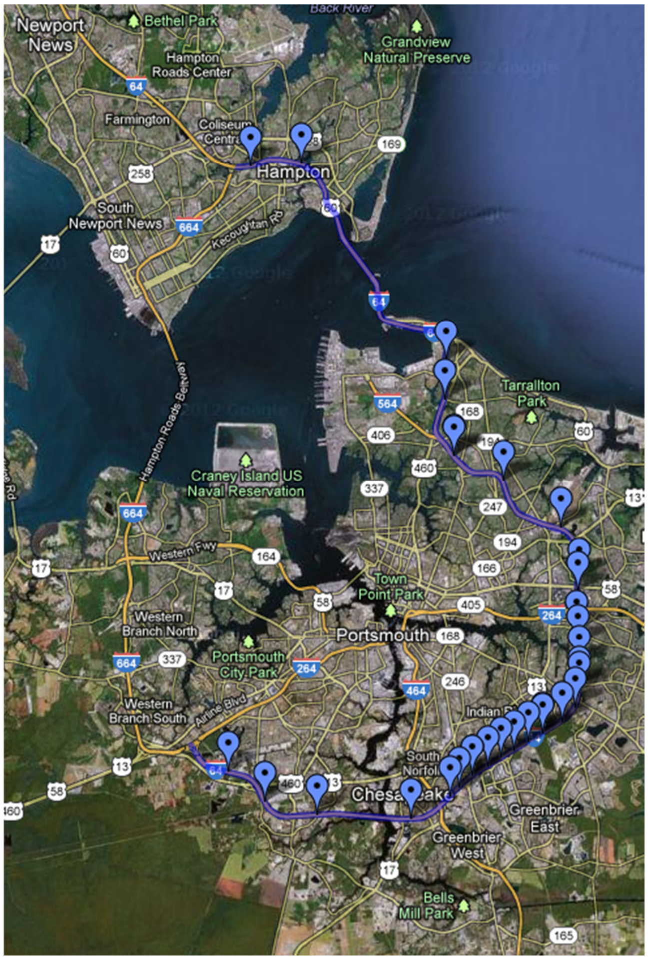

Figure 5-1: 31 VMS at 28 Locations on the Outer Loop of I-64 in the Hampton Roads Metropolitan Area of Virginia

HRTOC's database names assets according to route, direction, and number in the group of similar assets (HRTOC, 2013). For example, asset 64-o1 is the first VMS in a series of many on the outer loop (i.e., "o" stands for "outer loop") of I-64 (HRTOC, 2013). This stretch of interstate includes the I-64 Reversible Roadway, an 8.2-mile reversible-flow HOV facility entirely within the City of Norfolk (VDOT, 2012b; VDOT, 2013b) whose direction of flow, as well as whether it is open to any traffic at all, depends on the time of day (VDOT, 2012a). Figure 5-5 shows the Reversible Roadway as well as the rest of the HOV system in the vicinity. The Reversible Roadway has only one VMS, asset 64-o22, and it is for WB traffic (Google, 2013; HRTOC, 2013); hence it will be included in the analysis. VMS 64-o22 is attached to the same overhead span as VMS 64-o21, which is over the general purpose WB lanes at that location, which is one of the three locations with two VMS (Google, 2013; HRTOC, 2013). Table 5-1 shows which of the 31 VMS are located within each I-64 link as defined in VDOT's Statewide Planning System (SPS) (VDOT, 2013b). Table 5-1 also shows the 2011 combined AADTs for both directions (VDOT, 2013b) as well as the WB AADT from VDOT's TMS website (VDOT, 2013c) under the assumption that the traffic volume passing by a VMS is a good indicator of the number of people benefiting from information posted on the VMS. Using the WB AADT from VDOT (2013c) vs. using the two-way AADT from SPS (VDOT, 2013b) is discussed in the metric correlation analysis in Section 5.3.2. The most recent year of traffic volume data in SPS is 2012 (VDOT, 2013b), but 2011 data for AADT is used for this case study because 2011 was the most recent year of AADT data in VDOT (2013c) at the time the data was retrieved. It is acknowledged that AADT for a freeway is by definition one-directional, but in this chapter "WB AADT" is specified to differentiate it from the two-way AADTs that were entered into SPS for planning-level applications.

Table 5-1: Locations of the 31 VMS and Their Associated SPS Links and AADTs (Google, 2013; HRTOC, 2013; VDOT, 2013b)

City	VDOT Statewide Planning System (SPS) Link	Length (mi)	VMS 64-o…	2011 WB AADT	2011 Two-Way AADT
Chesapeake	I-264/I-664 - Military Hwy	2.31	1	34351	70798
Chesapeake	Military Hwy - GW Hwy	1.46	2	33455	69844
Chesapeake	GW Hwy - I-464	4.31	3, 4	36668	76193
Chesapeake	I-464 - Battlefield Blvd	1.22	4A-B	51848	96918
Chesapeake	Battlefield Blvd - Greenbrier Pkwy	1.49	4C-E, 5	51848	96918
Chesapeake	Greenbrier Pkwy - VA Beach CL	0.98	6-9	59490	119844
VA Beach	Chesapeake CL - Indian River Rd	1.34	10, 11	59490	119844
VA Beach	Indian River Rd - Norfolk CL	1.58	12-14	67791	137276
Norfolk	VA Beach CL - I-264	1.34	15, 16	67791	137276
Norfolk	I-264 - Northampton Blvd	1.55	17, 18	79716	158516
Norfolk	Northampton Blvd - Military Hwy	1.38	19	67873	130931
Norfolk	Norview Ave - Chesapeake Blvd	1.00	20	68065	131038
Norfolk	Tidewater Dr - Little Creek Rd	0.67	21	58149	105931
Norfolk	I-64 Reversible Roadway	N/A	22	10846	21566
Norfolk	New Gate Rd - Bay Ave	1.09	23	41700	84691
Norfolk	Bay Ave - 4th View St	1.30	24	37999	75879
Hampton	Settlers Landing Rd - King St N.	1.22	25	47610	88988
Hampton	Armistead Ave/Lasalle Ave - I-664	0.77	26	56877	112424
Total mileage of links without VMS (not shown)		10.77			
Total mileage of study segment		35.78			

All 31 VMS have controller cabinets associated with them. Thus one possibility would be to include the controller cabinets in the analysis. One option for accounting for the controller cabinets would be to designate the 31 VMS as primary devices and their associated controller cabinets as secondary devices in the manner of Figure 4-2. Figure 5-2 shows one definition of system boundaries that would be appropriate for these VMS and controller cabinets in the manner of Figure 4-2. A more realistic possibility for this case study would be to establish system boundaries as shown in Figure 5-2 but without

including the associated communications network, since appropriate communications network data was not retrievable for this case study.

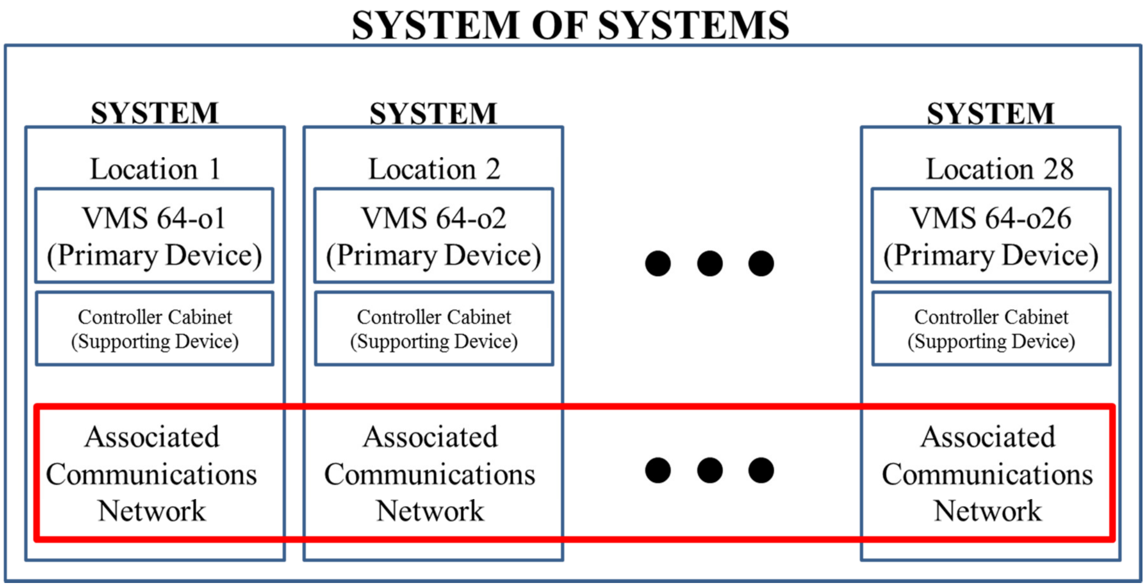

Figure 5-2: System Boundary Definition for 31 VMS and Associated Controller Cabinets as Ideally Applied to Figure 4-2

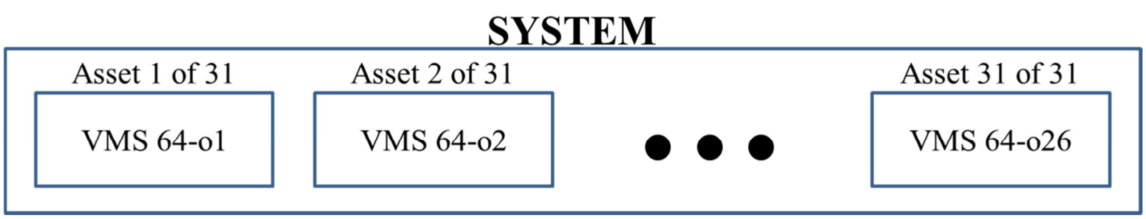

Figure 5-3: Simplified System Boundary Definition Used for Case Study Given Current Lack of Data and for Greater Simplicity

However, the decision was made not to include the controller cabinets in the analysis either, and the resulting system boundary diagram is shown in Figure 5-3. Section 5.2.2 discusses the selection of number of work orders and work order completion times as metrics for use in this case study because they were the only obsolescence-related metrics for which complete data could be found in the MMS. The number of work orders per year varies greatly for the 31 VMS, but the number of work orders is two for every full year of recorded data for every controller cabinet, and they are performed on the same or almost the same two dates every year (HRTOC, 2013). The consistency of two work orders per year for the controller cabinets is likely explained by the fact that all of them are labeled in the MMS as preventive maintenance rather than some form of reactive maintenance (HRTOC, 2013). On the other hand, all of the VMS work orders are labeled as some form of reactive maintenance, such as "corrective" or "demand" maintenance (HRTOC, 2013). The consistency and lack of entries for reactive maintenance for the controller cabinets suggests that maintenance of VMS controller cabinets on I-64 WB in Hampton Roads is an example of scheduled preventive maintenance preventing problems and reducing reactive maintenance. When it comes to determining which ITS asset, VMS or controller cabinet, is higher priority for obsolescence management attention at any given VMS location, the question arises as to whether preventive work orders and reactive work orders are commensurate. In other words, the question arises as to whether it is acceptable for preventive and reactive work orders to be counted in the same data set under the metric "number of work orders" or if they should be counted in separate data sets as different metrics. The same question can thus be asked about time spent completing preventive work orders and time spent completing reactive work orders. In order to simplify this case study and keep the number of metrics manageable so that ranking tables can fit on individual pages, the issue is done away with by including only the 31 VMS, the primary devices whose work orders are all reactive, in the analysis. The ranking analyses in this chapter, however, could be expanded in future research to include the controller cabinets. Including the controller cabinets would entail doubling the number of work-order-related metrics and ranking the two disparate ITS devices, the VMS and its controller cabinet, at each VMS location, as shown in general in Table 5-2. The zeros in Table 5-2 apply to this case study but could be nonzero in other cases. Weights would have to be established between preventive and reactive.

Table 5-2: Method for Ranking Primary Devices and Supporting Devices in a System of ITS Devices as Customized for the Data Available for This Case Study

	Work-Order-Related Metric No.						Total Weighted Score
	1		2		3		
Asset	Prev.	React.	Prev.	React.	Prev.	React.	
VMS	0		0		0		
Cabinet		0		0		0	

5.2 – SELECTION OF METRICS

5.2.1 Unavailability of Data on Installation Date and Manufacturer

The database of raw MicroMain data provided contains 99 tables, but only two of them, the table of assets and the table of work orders, contain sufficient data for obsolescence prioritization (HRTOC, 2013). The table of assets (dbo_tblAsset) includes data on asset name, ID, location, and description (HRTOC, 2013). The table of assets also contains numerous columns such as manufacturer, supplier, model number, and installation date that are either entirely blank or almost entirely blank and thus impossible to take advantage of for prioritizing assets for obsolescence management (HRTOC, 2013). The manufacturer and installation date columns, if they were filled in, would be particularly useful for prioritization because they would allow assets to be compared in terms of age and future reliability of manufacturer support. Time since initial installation was identified as an important item under metric category 3, time in service, in Section 4.3. Also, metric category 4b in Ranking Scheme #2, longest possible extension of service life based on various manufacturer-related technological supportability metrics, could be used in a case study given availability of asset-specific data on make and model. The problem is not a lack of a complete asset inventory or a lack of information on manufacturers and the ITS equipment that HRTOC has procured from them in the past. Instead, there is currently a lack of information linking the two. VDOT (2007a) details every make and model of ITS device that HRTOC has deployed, including information on number deployed, construction phase, year of procurement, number of spares available, availability of manufacturer support, status of the manufacturer, and production status. In addition, HRTOC has an electronic knowledge portal containing more detailed information on each make and model, most of which is available only to VDOT staff. However, the database of assets that HRTOC provided for this project identifies the manufacturer for only a very small number of assets (HRTOC, 2013). In fact, not a single one of the 31 VMS chosen for the case study has its manufacturer identified in the database (HRTOC, 2013). Once the transitions to MicroMain XM Version 7.5 and then Maximo are complete, this information gap will no longer exist (N. Reed, personal communication, May 7, 2013), but this information is not available for this case study. The VMS prioritization analysis that follows in this chapter is performed using the limited data available in order to demonstrate the Part I methodology from Section 4.3, not to recommend that decisions be made based on unsatisfactory metrics.

Despite the lack of asset-specific data on manufacturers, some detective work was done in an attempt to deduce which VMS at which locations were which make and model. For example, Google Maps Street View reveals that five of the 31 VMS (i.e., 64-o13, 64-o14, 64-o15, 64-o17, and 64-o18) were made by Daktronics, as evidenced by the "DAKTRONICS" name written on the lower right hand corner of the VMS, such as on the VMS shown in Figure 5-4 (Google, 2013). VDOT (2007A) shows that the Daktronics VMS were procured in 1993, that VDOT has no spares left, that no replacements or retrofit options are available from Daktronics, and that no suitable replacement components are available from any suppliers. If desired, additional research could then be done in order to obtain enough information to be able to account for some or all of the metrics recommended under metric category 4b in Ranking Scheme #2 in Section 4.3. Unfortunately, it was not possible to identify with any certainty the manufacturer of any of the other VMS in the 31 selected. Therefore, neither asset age nor any metrics that knowledge of the make and model would provide data for were included as metrics in this case study.

5.2.2 Work Order Counts and Completion Times

The table of work orders (dbo_tblWO) includes data on work order number, date, time, ITS service, status, type (e.g., corrective or preventive), asset ID, and asset name, as well as the number of hours it took to complete the work order (HRTOC, 2013). All work orders for every one of the 31 VMS were listed as "corrective" (HRTOC, 2013), indicating that asset management principles have never been applied to the maintenance of those VMS. The table of work orders also contains numerous columns such as down time, cost of labor, cost of replacement parts, miscellaneous costs, and total costs that are entirely blank, almost entirely blank, entirely filled with zeros, or almost entirely filled with zeros (HRTOC, 2013) and thus are impossible to take advantage of as metrics for ranking the VMS. Data on the time required to complete the work order, however, was filled in for every recorded work order for all 31 VMS (HRTOC, 2013) and was thus included as a metric

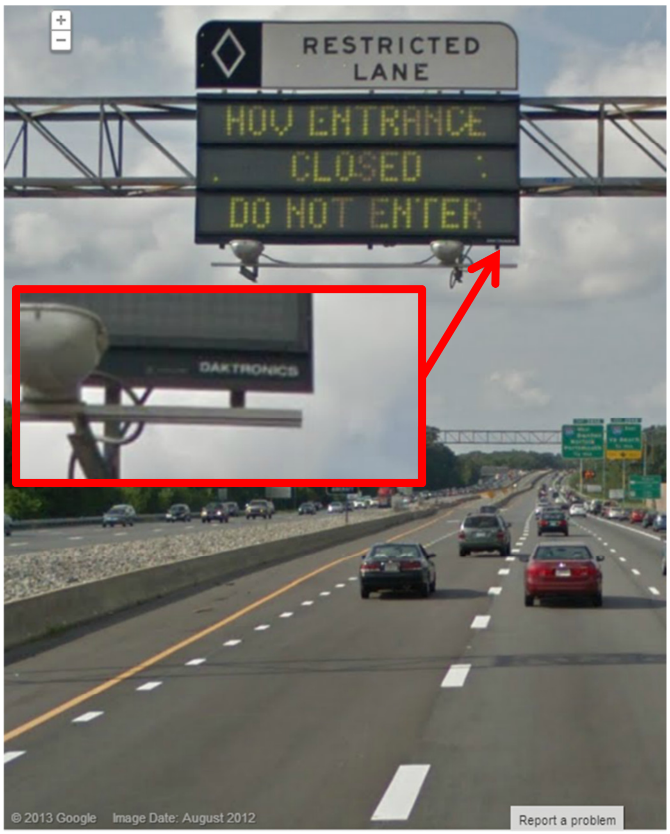

Figure 5-4: Daktronics VMS 64-o15 at Entrance to Eastern End of Reversible Roadway Alerting Motorists that the Reversible Roadway is not Currently Open to WB Traffic (Google, 2013; HRTOC, 2013; VDOT, 2007a)

category for ranking the VMS. No further details on exactly how the work order completion time was spent are provided. The total time through 2012 spent completing work orders for an asset, the average time spent completing work orders for an asset per year, and the average yearly change in time spent completing work orders for an asset per year are used in this analysis as indicators of asset age, average maintenance-intensiveness of an asset, and speed of asset obsolescence, respectively. The premise is that assets that are older, more maintenance-intensive, and deteriorating at higher rates require attention sooner and should be higher-priority regarding expending agency resources evaluating alternative corrective actions for them.

Total time spent completing work orders is actually only a dubious indicator of asset age because the number of years of work order data on which the total time value is based may or may not be related to the actual age of the asset. Although the 31 VMS were installed gradually between 1993 and the present (VDOT, 2007a), and although HRTOC has been using MicroMain since 1998, the earliest recorded work order for any of the 31 VMS is 2004 (HRTOC, 2013). However, the key consideration is that the year of the earliest recorded work order in the database varies greatly among the 31 VMS, namely between 2004 and 2012 (HRTOC, 2013). As a result, if just the average time spent completing work orders per year for each VMS were considered, information about the number of years over which each average was taken would be lost. It is assumed that that information has some real meaning other than that, for example, work order data mistakenly did not start getting entered until 2004 and only for some VMS and then for gradually more VMS as the years went on. It is presumed that asset age is at least part of the meaning. A supporting example is the fact that VMS 64-o4A, 64-o4B, 64-o4C, 64-

o4D, and 64-o4E, whose names in relation to the other 26 VMS suggest that they are very recent additions, have only from zero to two years of work order data as opposed to eight or nine (HRTOC, 2013). In conclusion, for any given asset, it is possible but by no means certain that total time spent completing work orders is an indicator of asset age.

However, for the purposes of the ranking demonstration in this case study, it is assumed that the number of years of work order data present in the database for each asset correlates well with the actual age of the asset. The premise is that, if an assumption had to be made about asset age given only data on total time spent completing work orders, the assumption would be that assets with higher values of total work order time are older. The other two metrics, average time spent on work orders per year and average yearly change in time spent on work orders per year, are accounted for because in reality there is a lack of correlation (i.e., Pearson's r = 0.460) between the total number of years of work order data provided and total time spent completing work orders among the 31 VMS (HRTOC, 2013). There is a similar lack of correlation (i.e., Pearson's r = 0.448) between the total number of years of work order data provided and the total number of work orders (HRTOC, 2013). HRTOC (2013) contains some 2013 work order data, but only data through 2012 was considered because it is the most recent complete year of data.

The 31 VMS can also be ranked according to total number of work orders through 2012, average number of work orders per year, and average yearly change in the number of work orders per year, which likewise are used in this analysis as indicators of asset age, average maintenance-intensiveness of an asset, and speed of asset obsolescence, respectively. The same discussion that was applied to total time spent completing work orders regarding asset age can be applied to total number of work orders. In Section 5.3, the three metrics regarding number of work orders are not used for ranking together with the three metrics regarding time spent completing work orders because they are assumed in this case study to be indicators of the same thing. For example, Table 5-6 in Section 5.3.2 shows a reasonably high correlation between total time spent completing work orders and total number of work orders.

During the site visit to HRTOC, Neil Reed explained that number of work orders and work orders per unit time tend to correlate well with maintenance costs (personal communication, April 22, 2013). However, the metric categories of number of work orders and time spent completing work orders do not provide a full picture of the maintenance reality. It is strongly recommended that better metrics, such as the example metrics listed in Section 4.3, have data collected for them and used instead. The metric categories of number of work orders and time spent completing work orders are used as surrogate metric categories in this case study in the absence of data on the costs associated with completing each work order and other metrics. Number of work orders and time spent completing work orders are used in this case study solely for purposes of demonstrating the methods in Section 4.3 in anticipation of better data being available later in light of the inventory, MMS, and data improvements underway at HRTOC. Data on work order costs, for example, would provide much more information than data on work order duration and number of work orders.

5.2.3 Traffic Volume

Inclusion of a traffic volume metric satisfies metric category #9, importance of facility location or associated segment, in Section 4.3. For this case study it is assumed that the traffic volume passing by a VMS is a good indicator of the number of people benefiting from information posted on the VMS. The premise is that the number of people benefiting from information posted on a given VMS is a good indicator of the relative importance of that VMS and that the importance of a VMS to the traveling public should be a factor in determining obsolescence management priority. For example, if VMS A is in a slightly better state of repair than VMS B but VMS A has higher traffic volumes, it might be better to expend agency resources determining the optimal intervention option (as well as carrying out that intervention) for VMS A first. In fact, since VMS A is in slightly better repair, Section 4.4 Part-II analysis might show the optimal solution to the problem with VMS A to be slightly less expensive than the optimal solution to the problem with VMS B.

Table 5-1 shows which of the 31 VMS are located within each I-64 link as defined in SPS as well as the 2011 two-way AADT (VDOT, 2013b) and the 2011 WB AADT (VDOT, 2013c). An alternative to using AADT is to use peak hour volume (PHV) such that the VMS are compared in terms of public benefit during the peak hour. PHV is not considered in this demonstration, however, because at the time the data was retrieved there were too few segments with enough data available for determining WB PHV, either continuous-count or not continuous-count, especially for the recent years of 2011 and 2012 (VDOT, 2012c). The most recent year of traffic volume data in SPS is 2012 (VDOT, 2013b), but AADT data from 2011 is used for this case study because 2011 was the most recent year of one-directional AADT data available in VDOT (2013c) at the time the data was retrieved.

AADT is an adequate but not ideal metric to use for determining VMS obsolescence management rankings. Presumably it is essentially impossible to quantify accurately the public benefits that result from the presence of a VMS or from any given message posted on it. It is probably not the case that everyone who passes by a VMS with a message written on it sees the message, and presumably it is not the case that the message is both relevant and helpful to everyone who does see it. Also, public benefits resulting from VMS information is likely to be uncertain given the variety of messages that can be posted. Johnston et al (2006) explains that the effects of VMS are difficult to estimate. For the purposes of this case study, however, the more important consideration is potential public benefit, as measured by the estimated maximum number of people who have the opportunity to see and benefit from the VMS and its messages, rather than actual public benefit.

5.2.4 Importance to Reversible Roadway Operation

Google Maps Street View reveals that six of the 31 VMS (i.e., 64-o12, 64-o13, 64-o14, 64-o15, 64-o17, and 64-o18) have either a white "Restricted Lane" sign (with a white diamond on a black square on the left side) posted above (i.e., 64-o13, 64-o14, 64-o15, 64-o17, and 64-o18) or just a small black sign with a white diamond posted to the left (i.e., 64-o12) (Google, 2013), as depicted in Figure 5-4. It is assumed for this analysis that these six VMS are critical to the operation of the Reversible Roadway based on their accompanying HOV-related signage, their placement leading up to Reversible Roadway access points, and the variable messages regarding the status of HOV entrances such as the one shown in Figure 5-4. Also, other than the stretch of the 35.8-mile study segment with the 8.2-mile Reversible Roadway in the middle, there is a 5.7-mile stretch (starting at Battlefield BLVD) with a single regular HOV lane leading up to the Reversible Roadway, as shown in Figure 5-5, and none of the VMS in that stretch have associated HOV signage (Google, 2013; VDOT, 2012b).

VMS 64-o22 receives special consideration in the ranking analysis in Section 5.3 because it is the only VMS in the Reversible Roadway. Particularly, the AADT of the Reversible Roadway is much smaller than the AADTs of the general purpose lanes (VDOT, 2013b) but should be considered as similar in magnitude to the AADTs of the general purpose lanes because of the elevated status and exclusivity of the Reversible Roadway as a right-of-way-separated express HOV facility. If the methodology used for case study were applied to a system or systems of ITS devices spanning more than just two roads (i.e., in this case the I-64 outer loop and the Reversible Roadway), a more detailed study might be warranted to determine the relative status of each road in the context of the regional network and adjust all AADTs accordingly.

5.2.5 Summary of Metrics

Table 5-3 shows a summary of the metrics discussed in this Section. Not all metrics are accounted for in each instance of ranking the 31 VMS. For the work order completion time metric category in Table 5-3, the time unit was not specified in HRTOC (2013), but it is assumed to be hours. The unit does not actually matter, though, as long as the same unit is used consistently for each metric because the 31 VMS are being compared relative to one another, but the units are specified anyway in Table 5-3.

Table 5-3: Summary of Metrics

Metric No.	METRIC CATEGORY	METRIC	UNIT	INDICATOR OF
1	Number of Work Orders	Total number of work orders through 2012	#	Asset age; Total sunk costs
2	Number of Work Orders	Average number of work orders	#/yr	Ave. maintenance-intensiveness
3	Number of Work Orders	Average change in number of work orders	#/yr/yr	Rate of obsolescence
4	Work Order Completion Time	Total time spent completing work orders through 2012	hr	Asset age; Total sunk costs
5	Work Order Completion Time	Average time spent completing work orders	hr/yr	Ave. maintenance-intensiveness
6	Work Order Completion Time	Average change in time spent completing work orders	hr/yr/yr	Rate of obsolescence
7	Traffic Volume	2011 WB AADT	veh/day	Location importance; Public benefit
8	Traffic Volume	2011 AADT	veh/day	Location importance; Public benefit
9	Reversible Roadway Importance	Reversible-Roadway-critical?	binary	Importance to safe operation of Reversible Roadway
10	Reversible Roadway Importance	Reversible-Roadway-exclusive?	binary	Importance of whole facility

5.3 – RANKING OF ITS DEVICES

5.3.1 Overview of VMS Ranking Methodology

In this section the 31 VMS are ranked according to needed obsolescence management attention, or the need to expend agency resources evaluating alternative corrective actions for them, using very limited available relevant data from the HRTOC (2013) MMS database provided and the metrics identified in Section 5.2. In general, four sets of factors determine the final prioritization of devices, and all of them can be varied to influence the final ranking. The metrics established make up the first set of factors. In other words, varying which metrics are taken into account effects the ranking. The second set of factors are the weighting factors that measure the relative importance of the metrics used and that are calculated using various assumptions, which can be altered to produce new weights. The third set of factors are the particular data sets or data sources used for each chosen metric. The fourth consideration for each metric is whether higher data values should positively or negatively influence the ranking of any given alternative. Since the number of possible combinations of these factors (i.e., the number of possible scenarios) can be very large in general and indeed is large for this case study, this section fully documents the analysis of four sample ranking scenarios for the 31 VMS for purposes of demonstrating the type of methodology introduced in Section 4.3. The four sample scenarios are summarized in Table 5-4, and Section 5.4.2 analyzes two additional scenarios and explains the implications. As explained in Section 4.3.7, establishing a base case ranking with which to compare the rankings calculated using this methodology can be useful in determining the benefits of using this methodology. However, in this demonstration, unsatisfactory metrics are used due to lack of data on better metrics, and thus comparison to a base case would not yield meaningful insights. A base case should only be established and included in the analysis given a satisfactory group of metrics.

Table 5-4: Summary of Sample Ranking Scenarios Used for This Case Study

Sample Ranking Scenario	Management Approach	Primary Metric Category Used	Other Metrics Used
1	Worst-First	Number of Work Orders (Metrics 1,2,3)	7,9,10
2	Worst-First	Work Order Completion Time (Metrics 4,5,6)	7,9,10
3	Best-First	Number of Work Orders (Metrics 1,2,3)	7,9,10
4	Best-First	Work Order Completion Time (Metrics 4,5,6)	7,9,10

The “Management Approach” column in Table 5-4 specifies whether a transportation asset management (TAM) “best-first” approach is used or whether a conventional worst-first approach is used. “Best-first” management refers to the principle of TAM in which an agency saves money by performing continual maintenance on assets that are in relatively good condition in order to prevent them from deteriorating further and becoming far greater financial liabilities in terms of maintenance and rehabilitation costs in the future (AASHTO, 2009). “Worst-first” management refers to the conventional antithesis of TAM in which an agency uses its funds to address assets that have already reached more advanced states of deterioration or obsolescence (AASHTO, 2009). The worst-first approach is considered in this case study because this project focuses on ITS infrastructure that is aging or obsolete and thus already in advanced stages of deterioration and obsolescence. The best-first approach is demonstrated here too as a second option for how an analyst can prioritize any group of ITS devices for consideration of maintenance alternatives. In addition, for the example of the 31 VMS in this case study, one option for VDOT could be to address a certain number of the VMS rated as top-priority according to a worst-first ranking until the system of 31 VMS as a whole is improved to some minimum state of repair and obsolescence. After such a point is reached, VDOT could re-rank the assets in the best-first manner and then continue using the best-first ranking method on those 31 assets henceforth. The transition from worst-first management to best-first management is very difficult to make because worst-first management is a habit that is easy to fall into and challenging to break, but it is worth it in the long run (AASHTO, 2009).

In Table 5-4, the management approach indicated for each sample scenario applies only to the metrics in the primary metric category and not to metrics in the "Other Metrics Used" column. "Best" and "worst" refer to state of repair and obsolescence, which are indicated by metrics 1-3 or, alternatively, metrics 4-6 from Table 5-3. In a worst-first ranking, higher data values in metrics 1-6 correspond to higher priority, while in a best-first ranking, higher data values in metrics 1-6 correspond to lower priority. Higher traffic volume and greater relevance to Reversible Roadway operation, on the other hand, correspond to higher priority regardless of state of repair or obsolescence. If VMS A and VMS B are in the same state of repair and obsolescence but VMS A has a higher traffic volume flowing by it, it makes sense to address VMS A first. Traffic volume and importance to safety and operations, after all, do not "age" or "become obsolete" over time.

Metric 7, 2011 WB AADT, is chosen over metric 8, the full 2011 AADT, for the four sample ranking scenarios because in this case it was possible to find data for metric 7. However, in this case metric 8 could be used because there is little variation in the two data sets, as discussed in Section 5.3.2.

Both the list of metrics developed in Section 5.2 and the longer list of recommended metrics in Section 4.3 can be modified over time as the agency gains more data and experience. For example, data analyzed throughout a long-term program of ITS obsolescence prioritization and management may reveal that certain metrics are more mutually exclusive (i.e., have less overlap) than others and that certain metrics tend to influence final rankings of ITS assets more heavily than others. It is these metrics, which are discussed in Section 5.3.2 and Section 5.4, that are most important for prioritizing ITS according to needed obsolescence management attention.

5.3.2 Data Collected and Correlation Analysis

Table 5-5 shows the data compiled from HRTOC (2013) for all the metrics needed for the sample ranking scenarios (i.e., all metrics except metric 8, which will be considered in the sensitivity analysis in Section 5.4). Metrics 9 and 10, Reversible Roadway relevance, are yes-or-no metrics in which 1 means yes and 0 means no. The degree to which a 1 should increase the weighted score of any given asset is taken into account in the weights calculated for metrics 9 and 10. VMS 64-o22 is the only VMS that is located such that it applies only to vehicles that have already entered the Reversible Roadway (Google, 2013, HRTOC, 2013) and thus is the only VMS to have a 1 assigned to it for metric 10. The weights for each metric for each sample ranking scenario are calculated with assumptions fully documented in Sections 5.3.3-5.3.5. The minimum value, maximum value, and range of values are shown in the last three rows of Table 5-5 and are used to normalize the data so that commensurate comparisons can be made between the data sets provided for each metric. The data for each year for each asset is shown in Appendix A.

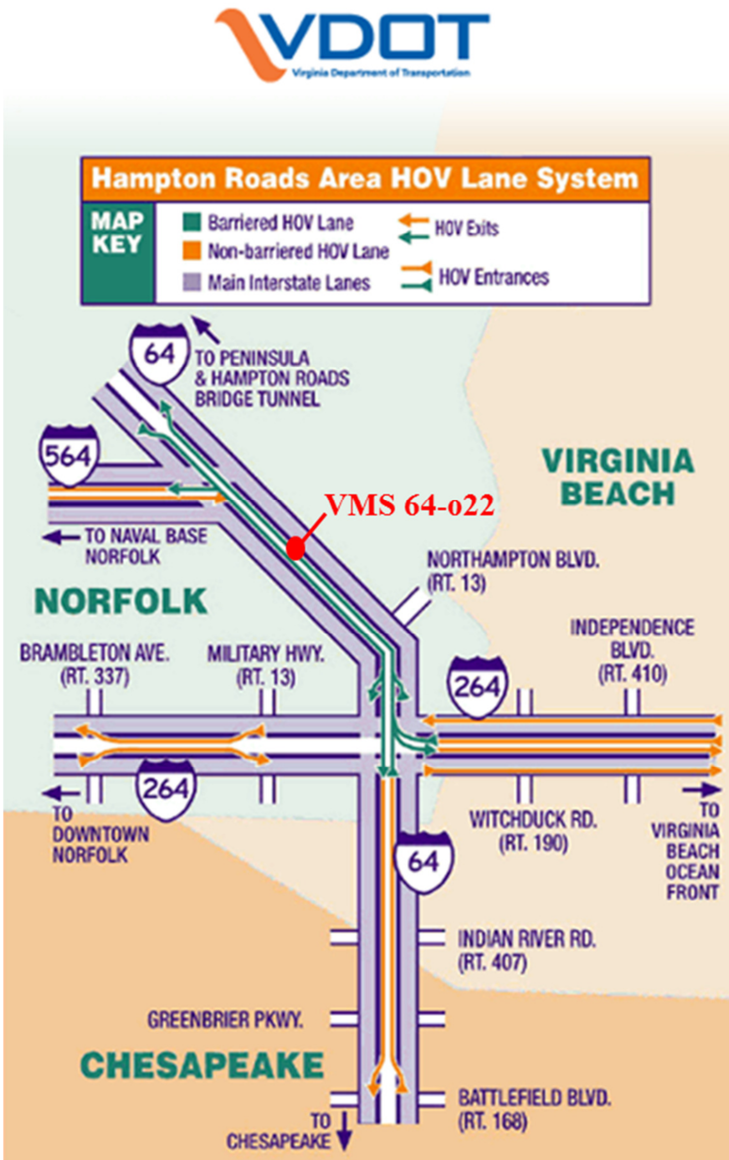

Figure 5-5: Hampton Roads Area HOV Lane System (VDOT, 2012b) with the VMS 64-o22 location (Google, 2013; HRTOC, 2013) superimposed. The Reversible Roadway is made up of the two "barriered" HOV lanes. In the I-64 WB direction, all traffic in the Reversible Roadway has entered before Northampton Blvd.

The 2011 AADT of the Reversible Roadway is 21,566 (VDOT, 2013b). The 2011 WB AADT of the Reversible Roadway, which is relevant to VMS 64-o22, was calculated not by dividing it by two but by multiplying it by the ratio of the 2011 WB AADT to the 2011 AADT of the segment of general purpose lanes between I-264 and Northampton Blvd, which is 79,716/158,516 (VDOT, 2013b; VDOT, 2013c). The assumption is that the ratio of WB AADT to full AADT in the Reversible Roadway is equal to the ratio of WB AADT to full AADT in the general purpose lanes segment where the last WB entrance to the Reversible Roadway is located, which Figure 5-5 shows is the segment between I-264 and Northampton Blvd (Google, 2013; VDOT, 2012b). It is possible to apply this information for estimating a 2011 WB AADT for VMS 64-o22 because WB traffic in the Reversible Roadway, all of which has entered the facility before Northampton Blvd, is confined to the facility until after it passes VMS 64-o22, as shown in Figure 5-5 (Google, 2013; VDOT, 2012b). The estimated 2011 WB AADT relevant to VMS 64-o22 is calculated in Eq. 5-1 to be 10,846 vehicles per day and is reflected in Table 5-5 for metric 7. 10,846 vehicles is used for the analysis even though it is only 63 vehicles greater than half of 21,566 (i.e., 10,783).

$$\text{64-o22 2011 WB AADT} = (21566)\left(\frac{79716}{158516}\right) = 10846\ \frac{veh}{day} \qquad \text{Eq. 5-1}$$

Table 5-5: Final Data Values Calculated for Use in This Case Study (HRTOC, 2013)

	Metric Nos. from Table 5-3											
	Data for Sample Ranking Scenarios 1 and 3						Data for Sample Ranking Scenarios 2 and 4					
Asset	**1**	**2**	**3**	**7**	**9**	**10**	**4**	**5**	**6**	**7**	**9**	**10**
64-o1	34	4.250	0.714	34351	0	0	99.90	12.488	4.071	34351	0	0
64-o2	87	10.875	1.714	33455	0	0	301.95	37.744	2.136	33455	0	0
64-o3	54	6.750	1.429	36668	0	0	184.85	23.106	7.471	36668	0	0
64-o4	19	2.375	0.286	36668	0	0	76.75	9.594	0.929	36668	0	0
64-o4A	4	4.000	0.000	51848	0	0	56.20	56.200	0.000	51848	0	0
64-o4B	3	3.000	0.000	51848	0	0	2.75	2.750	0.000	51848	0	0
64-o4C	5	2.500	1.000	51848	0	0	14.50	7.250	-9.500	51848	0	0
64-o4D	0	0.000	0.000	51848	0	0	0.00	0.000	0.000	51848	0	0
64-o4E	2	2.000	0.000	51848	0	0	2.25	2.250	0.000	51848	0	0
64-o5	24	2.667	0.250	51848	0	0	59.00	6.556	0.375	51848	0	0
64-o6	11	1.222	0.125	59490	0	0	61.00	6.778	1.938	59490	0	0
64-o7	16	2.000	0.857	59490	0	0	276.50	34.563	1.214	59490	0	0
64-o8	6	0.667	0.125	59490	0	0	13.00	1.444	-0.063	59490	0	0
64-o9	16	2.000	0.286	59490	0	0	35.85	4.481	-1.093	59490	0	0
64-o10	12	1.500	0.000	59490	0	0	18.50	2.313	0.214	59490	0	0
64-o11	30	3.333	0.125	59490	0	0	257.60	28.622	16.188	59490	0	0
64-o12	44	11.000	2.333	67791	1	0	87.50	21.875	4.917	67791	1	0
64-o13	17	2.833	0.400	67791	1	0	139.75	23.292	5.300	67791	1	0
64-o14	97	12.125	0.143	67791	1	0	413.55	51.694	-3.679	67791	1	0
64-o15	71	7.889	2.000	67791	1	0	270.45	30.050	7.650	67791	1	0
64-o16	13	2.167	0.600	67791	0	0	44.75	7.458	-2.000	67791	0	0
64-o17	91	10.111	2.875	79716	1	0	409.05	45.450	7.563	79716	1	0
64-o18	56	6.222	1.500	79716	1	0	161.75	17.972	3.594	79716	1	0
64-o19	24	3.000	0.143	67873	0	0	75.50	9.438	-2.321	67873	0	0
64-o20	19	2.111	0.125	68065	0	0	138.40	15.378	0.063	68065	0	0
64-o21	14	1.750	0.571	58149	0	0	54.00	6.750	-1.643	58149	0	0
64-o22	9	1.125	0.000	10846	0	1	31.00	3.875	-0.250	10846	0	1
64-o23	14	1.750	0.429	41700	0	0	37.30	4.663	-0.071	41700	0	0
64-o24	50	5.556	1.500	37999	0	0	167.55	18.617	4.406	37999	0	0
64-o25	13	1.625	-0.429	47610	0	0	73.00	9.125	-2.000	47610	0	0
64-o26	6	2.000	-1.000	56877	0	0	15.75	5.250	-5.250	56877	0	0
Min	0	0	-1	10846	0	0	0	0	-9.500	10846	0	0
Max	97	12.125	2.875	79716	1	1	413.55	56.2	16.188	79716	1	1
Range	97	12.125	3.875	68870	1	1	413.55	56.2	25.688	68870	1	1

Calculation of a correlation matrix for the data gathered is an important step in decision analysis, as explained in Section 4.3.4, because it provides insight into the amount of possible overlap between the metrics for which data has been collected (Beroggi, 1999; de Neufville & Stafford, 1971). Ideally, correlations between metrics used together for ranking should be as low as possible to ensure that there is minimal over-accounting of particular contributions to the final scores of the alternatives (Sallman et al, 2012), or in this case, minimal over-accounting of particular contributions to the amount of needed obsolescence management attention. Correlations between data sets can thus inform decisions regarding which metrics to use together for ranking and which not to use together (Beroggi, 1999; de Neufville & Stafford, 1971). The exception in which a high correlation between data sets is acceptable is if it is likely a random occurrence, as in between metrics that are unlikely to have a causal relationship. For example, it can be safely assumed that AADT and number of work orders do not have a causal relationship and thus do not raise concerns about overlap regardless of degree of data correlation.

In practice, however, for metrics intended to serve as indicators of different things, it can be difficult to find data with very low correlations (W. T. Scherer, personal communication, June 7, 2013). This practical limitation is pronounced in this case study given the limited number of relevant metrics for which data was reasonably retrievable. Table 5-6 is the correlation matrix that shows the Pearson's r correlation coefficient between the data sets in Table 5-5 for the metrics chosen for this demonstration. The lightly shaded cells in Table 5-6 are correlations relevant to the metrics used in sample ranking scenarios 1 and 3, while the darkly shaded cells are correlations relevant to the metrics used in sample ranking scenarios 2 and 4. Table 5-6 shows that some correlations relevant to the sample ranking scenarios are high even though ideally they would be low. For example, the correlation of 0.811 between the data for metrics 4 and 5 is high within sample ranking scenarios 2 and 4, and even more pronounced is the correlation of 0.917 between the data for metrics 1 and 2 within sample ranking scenarios 1 and 3. In addition, the fact that there are many low correlations in Table 5-6 that are not included in any of the four sample ranking scenarios suggests that there are other valid combinations of metrics. For example, for measuring maintenance intensiveness and rate of obsolescence, a case could be made for using metrics 2 and 6 (rather than 2 and 3), respectively, together based on their low correlation of 0.330, even though one is in the work order counts metric category and the other is in the work order time metric category.

Table 5-6: Correlation Matrix for Table 5-5 plus Metric 8

	Pearson's r Correlation Coefficients between Data Sets									
Metric	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	0.917	0.702	0.874	0.674	0.403	0.197	0.256	0.630	-0.126
2	0.917	1	0.715	0.756	0.720	0.330	0.209	0.259	0.675	-0.155
3	0.702	0.715	1	0.567	0.448	0.455	0.208	0.252	0.565	-0.128
4	0.874	0.756	0.567	1	0.811	0.484	0.272	0.327	0.558	-0.134
5	0.674	0.720	0.448	0.811	1	0.359	0.233	0.265	0.495	-0.150
6	0.403	0.330	0.455	0.484	0.359	1	0.086	0.143	0.315	-0.062
7	0.197	0.209	0.208	0.272	0.233	0.086	1	0.991	0.572	-0.549
8	0.256	0.259	0.252	0.327	0.265	0.143	0.991	1	0.611	-0.542
9	0.630	0.675	0.565	0.558	0.495	0.315	0.572	0.611	1	-0.089
10	-0.126	-0.155	-0.128	-0.134	-0.150	-0.062	-0.549	-0.542	-0.089	1

The upper triangular matrix of Table 5-6 is the same (i.e., the transpose) of the lower triangular matrix. For the completeness of Table 5-6, data for metric 8, total 2011 AADT, was also organized and compared with the other metrics to find R-squared values. The very high correlation of 0.991 between metrics 7 and 8 indicates that there is little difference in this case between using data for one versus the other. It thus indicates that one must be chosen over the other, and in this case metric 7 might as well be used, but metric 8 could be used if AADT data for individual directions were not available. Regardless of the degree of success in finding data sets with low correlation, inclusion of the correlation matrix is important for the transparency of the analysis.

5.3.3 Prioritizing the 31 VMS: Sample Ranking Scenario 1

Step 4 of the decision analysis methodology outlined in Section 4.1 is to establish quantitative estimations of the relative importance of each metric. Once data sets have been compiled for each metric, weighting factors that reflect assumptions about relative importance must be calculated, as explained in Section 4.3.7.

As discussed in Section 5.2, Metrics 1-3 are assumed for the purposes of this case study to be indicators of different things, but equations can be written to show how they are related. The relationship between Metrics 1 and 2 for any given asset is defined by Eq. 5-2.

$$W_o + \bar{W}\Delta t = W \qquad \text{Eq. 5-2}$$

Where:

W_o = the number of work orders that have been completed at some initial time

W = the number of work orders that have been completed at some final time

$\bar{W}$ = The average number of work orders per unit time between the initial time and final time

Δt = final time – initial time

The assumption is made that an agency wants to keep a system of ITS devices in the best condition possible and in the state that best serves the public with as little work as possible, and in this example, the amount of work done is measured by the number of work orders. An agency can use that assumption to make value judgments involving the relative importance of metrics. Regarding metrics 1 and 2, for any given asset, the agency could make the value judgment that it can tolerate W_o being larger by one as long as $\overline{W}$ is sufficiently smaller to yield the same W that would have resulted without W_o being larger by one, as depicted in Figure 5-6. Specifically, it is the time frame Δt that the agency can make a value judgment for. For example, if $\Delta t = 5$ years is chosen, then the agency is making the judgment that it values a marginally larger number of completed work orders to be offset within 5 years by a smaller average number of work orders per year. The judgment is expressed algebraically in Eq. 5-3 and Eq. 5-4.

$$W_o + \overline{W}_1 \Delta t = W \qquad \text{Eq. 5-3}$$

$$(W_o + 1) + \overline{W}_2 \Delta t = W \qquad \text{Eq. 5-4}$$

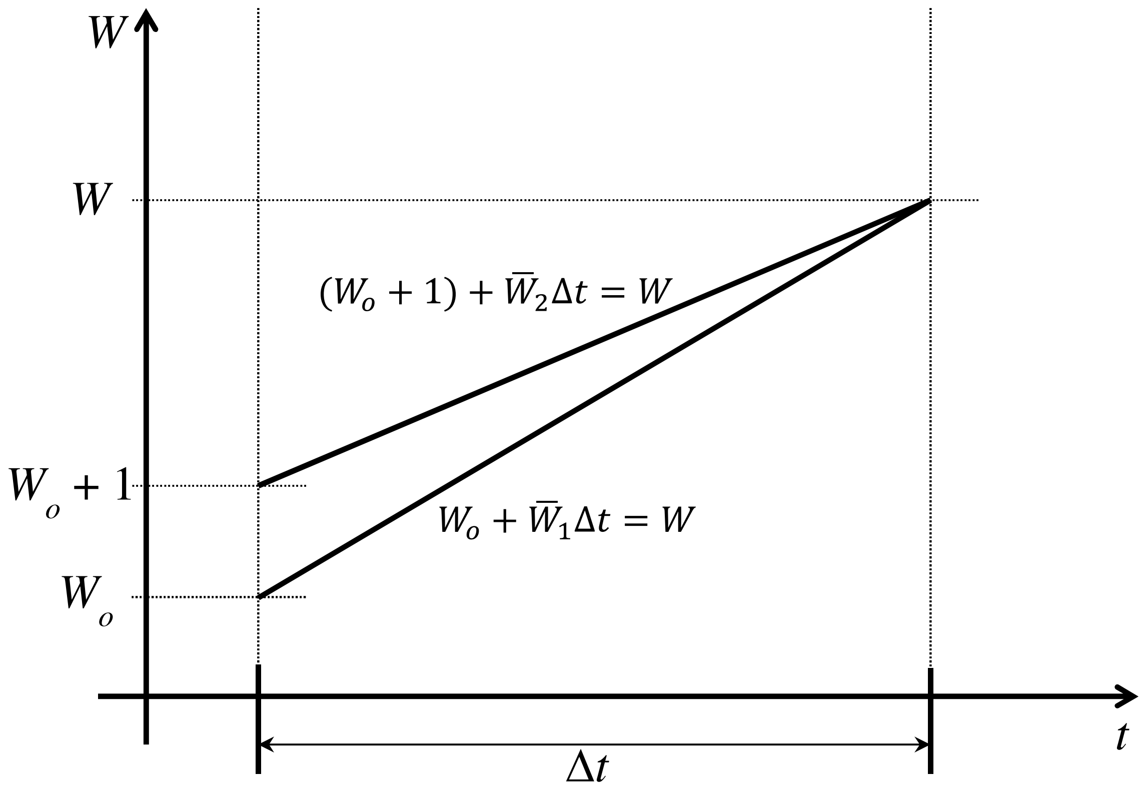

Figure 5-6: Graphical Depiction of the Assumptions behind the Weights for Metrics 1, 2, and 3

Eq. 5-3 and Eq. 5-4 are set equal to each other in Eq. 5-5 to find the marginal difference between $\overline{W_1}$ and $\overline{W_2}$ that is associated with a marginally larger W_o.

$$W_o + \bar{W}_1 \Delta t = (W_o + 1) + \bar{W}_2 \Delta t \qquad \text{Eq. 5-5}$$

After algebraic reduction of Eq. 5-5, it is determined that

$$\bar{W}_2 = \bar{W}_1 - \frac{1}{\Delta t} \qquad \text{Eq. 5-6}$$

Therefore, if the number of work orders is larger by one, the average number of work orders per year must be smaller by a margin of $1/\Delta t$ for the number of work orders after Δt to be the same as it would have been without the marginal increase of one. However, because metric weights should not be negative (W.T. Scherer, personal communication, June 7, 2013), only the absolute values of the marginal changes are considered for calculating the ratio of weights between metrics 1 and 2. In other words, for any given asset, the absolute values of the marginal changes of 1 and 1/Δ*t* for metrics 1 and 2, respectively, indicate the degree of relative importance of the two metrics. It is assumed in all four sample ranking scenarios that Δ*t* = 5 years and thus 1/Δ*t* = 0.2. Using Eq. 4-16, the weight ratio equation from Section 4.3, the ratio of the weights for metrics 1 and 2 is calculated in Eq. 5-7.

$$\frac{w_1}{w_2} = \left(\frac{97\ Work\ Orders}{12.125\ \frac{Work\ Orders}{Yr}}\right)\left(\frac{0.2\ \frac{Work\ Orders}{Yr}}{1\ Work\ Order}\right) = \frac{1.600}{1.000} \qquad \text{Eq. 5-7}$$

Where:

w_1 = the weight of metric 1

w_2 = the weight of metric 2

The determination of relative importance and thus the derivation of ratio of weights between metrics 2 and 3 is the same. The relationship between Metrics 2 and 3 for any given asset is defined by Eq. 5-8.

$$\overline{W}_o + \overline{\overline{W}}\Delta t = \overline{W} \qquad \text{Eq. 5-8}$$

Where:

$\overline{W}_o$ = the average number of work orders per unit time at some initial time

$\overline{W}$ = the average number of work orders per unit time at some final time

$\overline{\overline{W}}$ = The average change in the number of work orders per unit time

Δ*t* = final time – initial time

Therefore, the marginal difference in $\bar{\bar{W}}$ associated with a marginally larger $\bar{W}_o$ is likewise 1/Δ*t*, or 0.2 assuming once again that Δ*t* = 5 years. Using Eq. 4-16, the ratio of the weights for metrics 2 and 3 is calculated in Eq. 5-9.

$$\frac{w_3}{w_2} = \left(\frac{3.875\ \frac{Work\ Orders}{yr^2}}{12.125\ \frac{Work\ Orders}{yr}}\right)\left(\frac{1\ \frac{Work\ Order}{yr}}{0.2\ \frac{Work\ Orders}{yr^2}}\right) = \frac{1.598}{1.000} \qquad \text{Eq. 5-9}$$

The weight for metric 7, 2011 WB AADT, can be determined by establishing a relationship between that metric and metric 2, average number of work orders per year. Since AADT is a measure of location importance and public benefit, the idea is to use the historical work order data for the system of 31 VMS to calculate an average number of vehicles per work order as a measure of how much additional AADT justifies the completion of one additional work order per year. In other words, the question is, on average over the system of 31 VMS, how much additional traffic justifies incrementally improving the system in the form of one additional work order per year to benefit the additional travelers. Using the historical work order data to estimate an answer to that question is not ideal because maintenance on the 31 VMS has always been reactive rather than proactive (HRTOC, 2013). In other words, the maintenance has not been performed according to the principles of TAM and thus is not necessarily well reflective of what work is actually justified.

However, the historical work order data combined with some assumptions is sufficient for this demonstration of the methodology. In particular, the traffic volumes used in this calculation are the 2011 WB AADTs minus the minimum regular-travel-lanes 2011 WB AADT of all the segments in the study corridor with VMS. The assumption is that only traffic volumes of a certain minimum magnitude would justify the installation of VMS in the first place for the particular public services that these 31 VMS provide. Regardless of traffic volume, if the traffic volume at a location is small enough not to justify the existence of a VMS there, it does not make any sense to install a VMS, let alone install a VMS and issue work orders for it and perform maintenance on it. It is assumed that the minimum one-directional AADT that justifies a VMS in the particular context of the I-64 outer loop in Hampton Roads is equal to the minimum regular-travel-lanes 2011 WB AADT of all the segments on the I-64 outer loop with VMS, which is 33,455 (VMS 64-o2) (HRTOC, 2013; VDOT, 2013c). The WB AADT of the Reversible Roadway, which is smaller than 33,455, is a special case and is thus not considered as the minimum in this instance. However, in calculating the average number of vehicles per work order, the WB AADT of the Reversible Roadway is accounted for in full without subtracting anything from it because the fact that it is an exclusive right-of-way-separated HOV facility is considered in this analysis to be the minimum threshold that justifies it having its own VMS (i.e., 64-o22). Also, VMS 64-o4D was not accounted for in calculating the average because it has zero work orders (HRTOC, 2013), leading to a division by zero. The final count of VMS accounted for in the calculation is thus 30. As discussed in section 5.2.3 regarding the selection of traffic volume as a metric for ranking, it is acknowledged that traffic volume is not the only consideration that factors into a decision about whether to install a VMS, but it is the factor accounted for in this demonstration of the methodology. Eq. 5-10 reports that on average, one additional work order is associated with 9,188 additional vehicles above the minimum traffic volume threshold for a VMS.

$$\frac{Vehicles}{Work\ Order} = \frac{1}{30}\sum_{i=1}^{30}\frac{(2011\ WB\ AADT)_i - 33455}{\bar{W}_i} = 9188 \qquad \text{Eq. 5-10}$$

The ratio of weights between metrics 2 and 7 is calculated in Eq. 5-11 to be 0.618/1.000.

$$\frac{w_7}{w_2} = \left(\frac{68870\ \frac{veh}{day}}{12.125\ \frac{Work\ Orders}{yr}}\right)\left(\frac{1\ \frac{Work\ Order}{yr}}{9188\ \frac{veh}{day}}\right) = \frac{0.618}{1.000} \qquad \text{Eq. 5-11}$$

In establishing a weight for metric 9, the judgment was made that AADT passing a VMS that is on the general purpose lanes but that is important for the operation of the Reversible Roadway is worth an additional magnitude equal to the 2011 WB AADT of the Reversible Roadway, which was calculated in Eq. 5-1 to be 10,846 veh/day. It is assumed to be justified to double-count the vehicles on the general purpose lanes that will be entering the Reversible Roadway for three reasons. Firstly, as discussed in Section 5.2.4, such signs appear to be critical to the safe operation of the Reversible Roadway in terms of complementing the gates to prevent WB and EB traffic from colliding head-on. Secondly, since the Reversible Roadway is an HOV-2 facility during rush hours (VDOT, 2012a), the average vehicle occupancy of cars entering the Reversible roadway is likely higher than that of the general purpose lanes, resulting in such a VMS having a larger public benefit per vehicle than a VMS with a zero for metric 9. Thirdly, the double-counting can be justified on the grounds that the Reversible Roadway has premier status within the metropolitan area's surface transportation system as an exclusive, right-of-way-separated, directionally flexible, express HOV facility. 10,846 veh/day is therefore assumed to be the marginal change in AADT associated with metric 9 having a value of one rather than zero. The weight for metric 9 is calculated to be 0.097 in Eq. 5-12 and Eq. 5-13.

$$\frac{w_9}{w_7} = \left(\frac{1}{WB\ AADT\ Range}\right)\left(\frac{WB\ AADT\ Reversible\ Roadway}{1}\right) \qquad \text{Eq. 5-12}$$

$$w_9 = \left(\frac{1}{68870\ \frac{veh}{day}}\right)\left(\frac{10846\ \frac{veh}{day}}{1}\right) \times 0.618 = 0.097 \qquad \text{Eq. 5-13}$$

Another way to account for the extra significance attributed to the traffic entering the Reversible Roadway would have been not to take into account metric 9 separately and instead just to add 10,846 veh/day to the 2011 WB AADTs of Reversible-Roadway-critical VMS. This option leads to the same ranking results, but treating the extra significance as a separate metric can make the analysis clearer.

The weight for metric 10 happens to apply to only one VMS in this particular case study, 64-o22, which is exclusively for traffic already on the Reversible Roadway (Google, 2013; HRTOC, 2013). In determining the weight for metric 10, the traffic on the Reversible Roadway can be over-counted for the same reasons used to justify the double-counting of vehicles entering the Reversible Roadway in the weight determination for metric 9. The assumption is that if a stretch of general purpose lanes had a one-directional AADT of only 10,846 veh/day, it would not be enough to justify a VMS, at least relative to the unique context of ITS on interstate highways in Hampton Roads. Therefore, it can be assumed that the Reversible Roadway has a premier status that can be accounted for in many ways, including treating its traffic volumes as higher than they really are. One option is to increase the 10,846 veh/day 2011 WB AADT of the Reversible Roadway to a magnitude similar to that of the vicinity of the sign locations where the Reversible Roadway entrances split off from the general purpose lanes. For example, the average 2011 WB AADTs of VMS 64-o12, 64-o13, 64-o14, 64-o15, 64-

o17, and 64-o18, all of which are located before Northampton Blvd (and are assumed to be Reversible-Roadway critical), is 71,766 veh/day. The 10,846 veh/day AADT for VMS 64-o22 is thus treated as 71,766 veh/day for metric 10 in this demonstration as a reflection of the premier status of the facility. 71,766 veh/day minus 10,846 veh/day, which is 60,920 veh/day, is therefore assumed to be the marginal change in AADT associated with metric 10 having a value of one rather than zero. The weight for metric 10 is calculated to be 0.547 in Eq. 5-14 and Eq. 5-15.

$$\frac{w_{10}}{w_7} = \left(\frac{1}{WB\ AADT\ Range}\right)\left(\frac{Marginal\ Change\ in\ AADT}{1}\right) \quad \text{Eq. 5-14}$$

$$w_{10} = \left(\frac{1}{68870\ \frac{veh}{day}}\right)\left(\frac{60{,}920\ \frac{veh}{day}}{1}\right) \times 0.618 = 0.547 \quad \text{Eq. 5-15}$$

The prioritization of the 31 VMS for sample ranking scenario 1, whose management approach is worst-first and whose primary metric category is number of work orders, is summarized in Table 5-7. All the data is normalized in the worst-first manner using Eq. 4-1 such that higher values of all metrics indicate higher priority for consideration of intervention alternatives. The relative weights determined using the assumptions and analysis in this section are normalized as well such that they all add up to 1. In Table 5-7, for each asset, each metric's normalized value is multiplied by the normalized weight of that metric, and the sum of those products is the total weighted score. Figure 5-7 shows the score contribution of each metric to the total weighted score of each asset for sample ranking scenario 1. VMS 64-o17, with a total weighted score of 85.13/100, is the number-one ranked asset by a large margin of 17.74/100.

Table 5-7: Prioritization of the 31 VMS According to Sample Ranking Scenario 1

Sample Ranking Scenario 1 (# of Work Orders, Worst-First) - Normalized Data								
Metrics from Table 5-2		**1**	**2**	**3**	**7**	**9**	**10**	**Total Weighted Score**
ASSET RANK	Relative Weight	1.600	1.000	1.598	0.618	0.097	0.547	
	Normalized Weight	0.293	0.183	0.293	0.113	0.018	0.100	
1	**64-o17**	**93.81**	**83.39**	**100.00**	**100.00**	**100.00**	**0.00**	**85.13**
2	64-o14	100.00	100.00	29.49	82.68	100.00	0.00	**67.39**
3	64-o15	73.20	65.06	77.42	82.68	100.00	0.00	**67.16**
4	64-o2	89.69	89.69	70.05	32.83	0.00	0.00	**66.92**
5	64-o12	45.36	90.72	86.02	82.68	100.00	0.00	**66.22**
6	64-o18	57.73	51.32	64.52	100.00	100.00	0.00	**58.30**
7	64-o3	55.67	55.67	62.67	37.49	0.00	0.00	**49.09**
8	64-o24	51.55	45.82	64.52	39.43	0.00	0.00	**46.84**
9	64-o1	35.05	35.05	44.24	34.13	0.00	0.00	**33.50**
10	64-o13	17.53	23.37	36.13	82.68	100.00	0.00	**31.13**
11	64-o11	30.93	27.49	29.03	70.63	0.00	0.00	**30.59**
12	64-o7	16.49	16.49	47.93	70.63	0.00	0.00	**29.88**
13	64-o19	24.74	24.74	29.49	82.80	0.00	0.00	**29.79**
14	64-o16	13.40	17.87	41.29	82.68	0.00	0.00	**28.64**
15	64-o5	24.74	21.99	32.26	59.54	0.00	0.00	**27.46**
16	64-o4C	5.15	20.62	51.61	59.54	0.00	0.00	**27.13**
17	64-o20	19.59	17.41	29.03	83.08	0.00	0.00	**26.83**
18	64-o21	14.43	14.43	40.55	68.68	0.00	0.00	**26.52**
19	64-o9	16.49	16.49	33.18	70.63	0.00	0.00	**25.56**
20	64-o4	19.59	19.59	33.18	37.49	0.00	0.00	**23.28**
21	64-o23	14.43	14.43	36.87	44.80	0.00	0.00	**22.73**
22	64-o22	9.28	9.28	25.81	0.00	0.00	100.00	**21.98**
23	64-o6	11.34	10.08	29.03	70.63	0.00	0.00	**21.66**
24	64-o4A	4.12	32.99	25.81	59.54	0.00	0.00	**21.54**
25	64-o10	12.37	12.37	25.81	70.63	0.00	0.00	**21.44**
26	64-o4B	3.09	24.74	25.81	59.54	0.00	0.00	**19.73**
27	64-o8	6.19	5.50	29.03	70.63	0.00	0.00	**19.31**
28	64-o4E	2.06	16.49	25.81	59.54	0.00	0.00	**17.92**
29	64-o25	13.40	13.40	14.75	53.38	0.00	0.00	**16.74**
30	64-o4D	0.00	0.00	25.81	59.54	0.00	0.00	**14.29**
31	64-o26	6.19	16.49	0.00	66.84	0.00	0.00	**12.40**

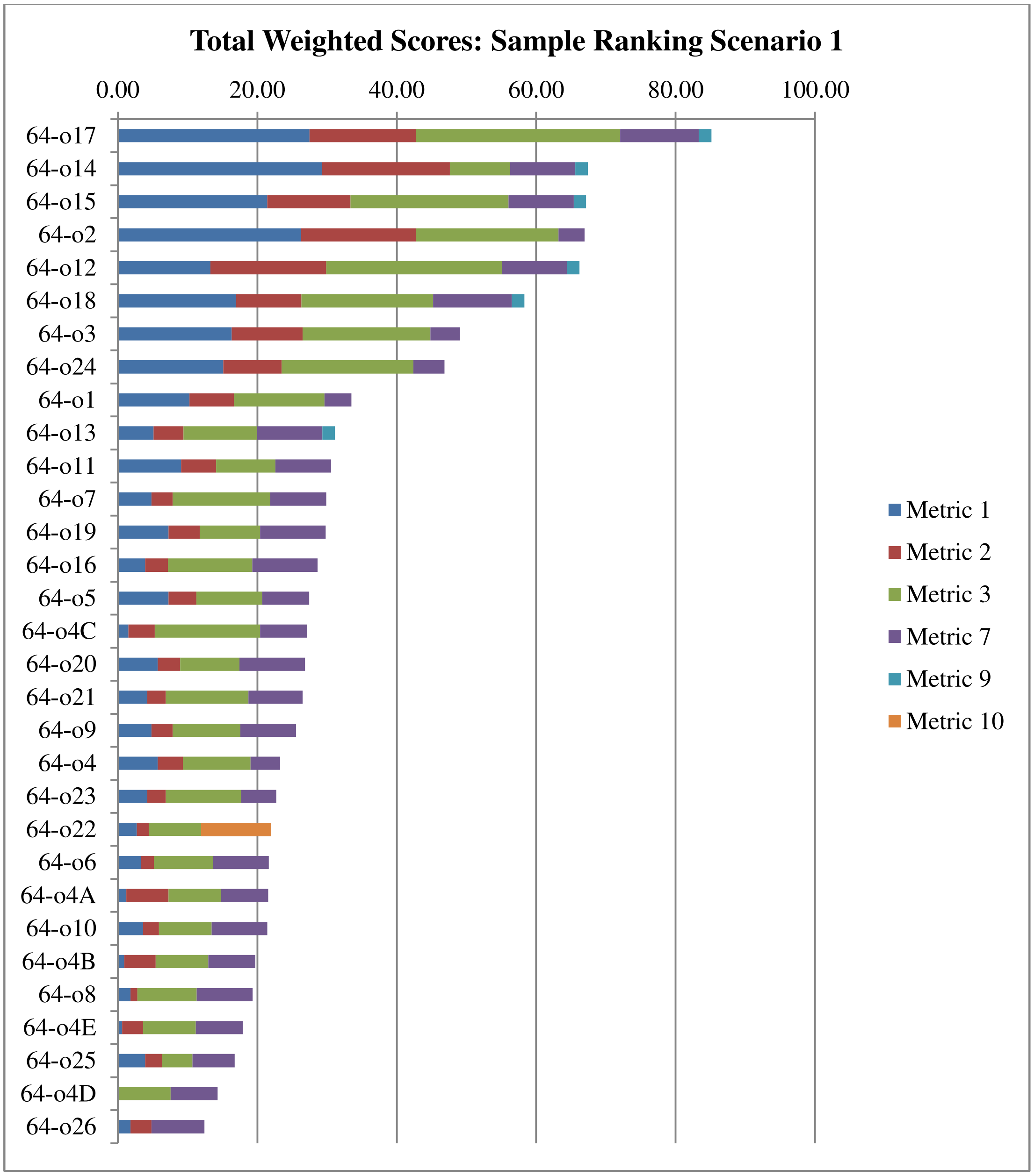

Figure 5-7: Score Contribution of Each Metric to the Total Weighted Score of Each Asset for Sample Ranking Scenario 1

5.3.4 Prioritizing the 31 VMS: Sample Ranking Scenario 2

The relative weights for metrics 4-6 having to do with work order completion times can be determined in the same way as the relative weights for metrics 1-3 were determined. The relationship between metrics 4 and 5 for any given asset is defined in Eq. 5-16, similar to Eq. 5-2.

$$T_o + \bar{T}\Delta t = T \quad \text{Eq. 5-16}$$

Where:

T_o = the total time spent completing work orders at some initial time

T = the total time spent completing work orders at some final time

$\bar{T}$ = The average amount of time spent completing work orders per unit time between the initial time and final time

Δt = final time – initial time

Just as with metrics 1 and 2, Eq. 5-17 and Eq. 5-18 (similar to Eq. 5-3 and Eq. 5-4, respectively) can be set equal to each other to arrive at Eq. 5-19 (similar to Eq. 5-6) and determine that the marginal difference between $\bar{T}_1$and $\bar{T}_2$ that is associated with a marginally larger T_o is $1/\Delta t$.

$$T_o + \bar{T}_1\Delta t = T \quad \text{Eq. 5-17}$$
$$(T_o + 1) + \bar{T}_2\Delta t = T \quad \text{Eq. 5-18}$$

$$\bar{T}_2 = \bar{T}_1 - \frac{1}{\Delta t} \quad \text{Eq. 5-19}$$

Just as in the calculation of the weight ratio between metrics 1 and 2, it is assumed that Δt = 5 years and thus $1/\Delta t$ = 0.2. Using Eq. 4-16, the ratio of the weights for metrics 4 and 5 is calculated in Eq. 5-20, similar to Eq. 5-7.

$$\frac{w_4}{w_5} = \left(\frac{413.55\ hr}{56.2\ \frac{hr}{yr}}\right)\left(\frac{0.2\ \frac{hr}{yr}}{1\ hr}\right) = \frac{1.472}{1.000} \quad \text{Eq. 5-20}$$

Likewise, the relationship between Metrics 5 and 6 for any given asset is defined by Eq. 5-21, similar to Eq. 5-8.

$$\bar{T}_o + \bar{\bar{T}}\Delta t = \bar{T} \quad \text{Eq. 5-21}$$

Where:

$\bar{T}_o$ = the average time spent completing work orders per unit time at some initial time

$\bar{T}$ = the average time spent completing work orders per unit time at some final time

$\bar{\bar{T}}$ = the average change in the time spent completing work orders per unit time

Δt = final time – initial time

The ratio of the weights for metrics 5 and 6 is calculated in Eq. 5-22, similar to Eq. 5-9.

$$\frac{w_6}{w_5} = \frac{w_6}{1.000} = \left(\frac{25.688\ \frac{hr}{yr^2}}{56.2\ \frac{hr}{yr}}\right)\left(\frac{1\ \frac{hr}{yr}}{0.2\ \frac{hr}{yr^2}}\right) = \frac{2.285}{1.000} \qquad \text{Eq. 5-22}$$

The weight for metric 7, 2011 WB AADT, can be determined by establishing a relationship between that metric and metric 5, average time spent completing work orders per year, that is similar to the relationship that was established in Section 5.3.3 between metrics 7 and 2. The difference is that instead of using historical data on the number of work orders completed, the historical data on the time spent completing those work orders is used. Since AADT is a measure of location importance and public benefit, the idea is to use the historical work order completion time data for the system of 31 VMS to calculate an average number of vehicles per hour of time spent completing work orders as a measure of how much additional AADT justifies spending one additional hour of time completing work orders per year. In other words, the question is, on average over the system of 31 VMS, how much additional traffic justifies incrementally improving the system in the form of one additional hour spent completing work orders per year to benefit the additional travelers. Eq. 5-23, similar to Eq. 5-10, reports that on average, one additional hour spent completing work orders is associated with 3,171 additional vehicles above the minimum traffic volume threshold for a VMS discussed in Section 5.3.3.

$$\frac{Vehicles}{Hour\ of\ Work} = \frac{1}{30}\sum_{i=1}^{30}\frac{(2011\ WB\ AADT)_i - 33455}{\bar{T}_i} = 3171 \qquad \text{Eq. 5-23}$$

The ratio of weights between metrics 5 and 7 is calculated in Eq. 5-24 (similar to Eq. 5-11) to be 0.386/1.000.

$$\frac{w_7}{w_5} = \frac{w_7}{1.000} = \left(\frac{68870\ \frac{veh}{day}}{56.2\ \frac{hr}{yr}}\right)\left(\frac{1\ \frac{hr}{yr}}{3171\ \frac{veh}{day}}\right) = \frac{0.386}{1.000} \qquad \text{Eq. 5-24}$$

Metric 9 is calculated in Eq. 5-25 for sample ranking scenario 2 as it was in Eq. 5-13 for sample ranking scenario 1.

$$w_9 = \left(\frac{1}{68870\ \frac{veh}{day}}\right)\left(\frac{10846\ \frac{veh}{day}}{1}\right) \times 0.386 = 0.061 \qquad \text{Eq. 5-25}$$

Metric 10 is calculated in Eq. 5-26 for sample ranking scenario 2 as it was in Eq. 5-15 for sample ranking scenario 1.

$$w_{10} = \left(\frac{1}{68870\ \frac{veh}{day}}\right)\left(\frac{60{,}920\ \frac{veh}{day}}{1}\right) \times 0.386 = 0.342 \qquad \text{Eq. 5-26}$$

The prioritization of the 31 VMS for sample ranking scenario 2, whose management approach is worst-first and whose primary metric category is work order completion time, is summarized in Table 5-8. All the data is normalized in the worst-first manner using Eq. 4-1 such that higher values of all metrics indicate higher priority for consideration of intervention alternatives. The relative weights determined in this section are normalized such that they all add up to 1. Figure 5-8 shows the score contribution of each metric to the total weighted score of each asset for sample ranking scenario 2. VMS 64-o17, with a total weighted score of 76.26/100, is the number-one ranked asset by a margin of 4.42/100, which is smaller than the margin by which VMS 64-o17 was the number one ranked asset in sample ranking scenario 1 by 13.32/100.

Table 5-8: Prioritization of the 31 VMS According to Sample Ranking Scenario 2

Sample Ranking Scenario 2 (Work Order Time, Worst-First) - Normalized Data								
Metrics from Table 5-2		**4**	**5**	**6**	**7**	**9**	**10**	
	Relative Weight	1.472	1.000	2.285	0.386	0.061	0.342	
ASSET RANK	Normalized Weight	0.265	0.180	0.412	0.070	0.011	0.062	**Total Weighted Score**
1	**64-o17**	**98.91**	**80.87**	**66.42**	**100.00**	**100.00**	**0.00**	**76.26**
2	64-o11	62.29	50.93	100.00	70.63	0.00	0.00	**71.84**
3	64-o15	65.40	53.47	66.76	82.68	100.00	0.00	**61.36**
4	64-o14	100.00	91.98	22.66	82.68	100.00	0.00	**59.32**
5	64-o2	73.01	67.16	45.30	32.83	0.00	0.00	**52.44**
6	64-o7	66.86	61.50	41.71	70.63	0.00	0.00	**50.94**
7	64-o3	44.70	41.11	66.07	37.49	0.00	0.00	**49.11**
8	64-o13	33.79	41.44	57.62	82.68	100.00	0.00	**47.04**
9	64-o18	39.11	31.98	50.97	100.00	100.00	0.00	**45.21**
10	64-o12	21.16	38.92	56.12	82.68	100.00	0.00	**42.62**
11	64-o24	40.52	33.13	54.14	39.43	0.00	0.00	**41.78**
12	64-o4A	13.59	100.00	36.98	59.54	0.00	0.00	**41.02**
13	64-o20	33.47	27.36	37.23	83.08	0.00	0.00	**34.94**
14	64-o1	24.16	22.22	52.83	34.13	0.00	0.00	**34.56**
15	64-o6	14.75	12.06	44.53	70.63	0.00	0.00	**29.36**
16	64-o4	18.56	17.07	40.60	37.49	0.00	0.00	**27.34**
17	64-o5	14.27	11.66	38.44	59.54	0.00	0.00	**25.88**
18	64-o19	18.26	16.79	27.95	82.80	0.00	0.00	**25.16**
19	64-o22	7.50	6.90	36.01	0.00	0.00	100.00	**24.23**
20	64-o25	17.65	16.24	29.20	53.38	0.00	0.00	**23.36**
21	64-o16	10.82	13.27	29.20	82.68	0.00	0.00	**23.06**
22	64-o21	13.06	12.01	30.59	68.68	0.00	0.00	**23.02**
23	64-o10	4.47	4.11	37.82	70.63	0.00	0.00	**22.43**
24	64-o9	8.67	7.97	32.73	70.63	0.00	0.00	**22.15**
25	64-o23	9.02	8.30	36.70	44.80	0.00	0.00	**22.14**
26	64-o8	3.14	2.57	36.74	70.63	0.00	0.00	**21.36**
27	64-o4B	0.66	4.89	36.98	59.54	0.00	0.00	**20.45**
28	64-o4E	0.54	4.00	36.98	59.54	0.00	0.00	**20.25**
29	64-o4D	0.00	0.00	36.98	59.54	0.00	0.00	**19.39**
30	64-o26	3.81	9.34	16.55	66.84	0.00	0.00	**14.17**
31	64-o4C	3.51	12.90	0.00	59.54	0.00	0.00	**7.40**

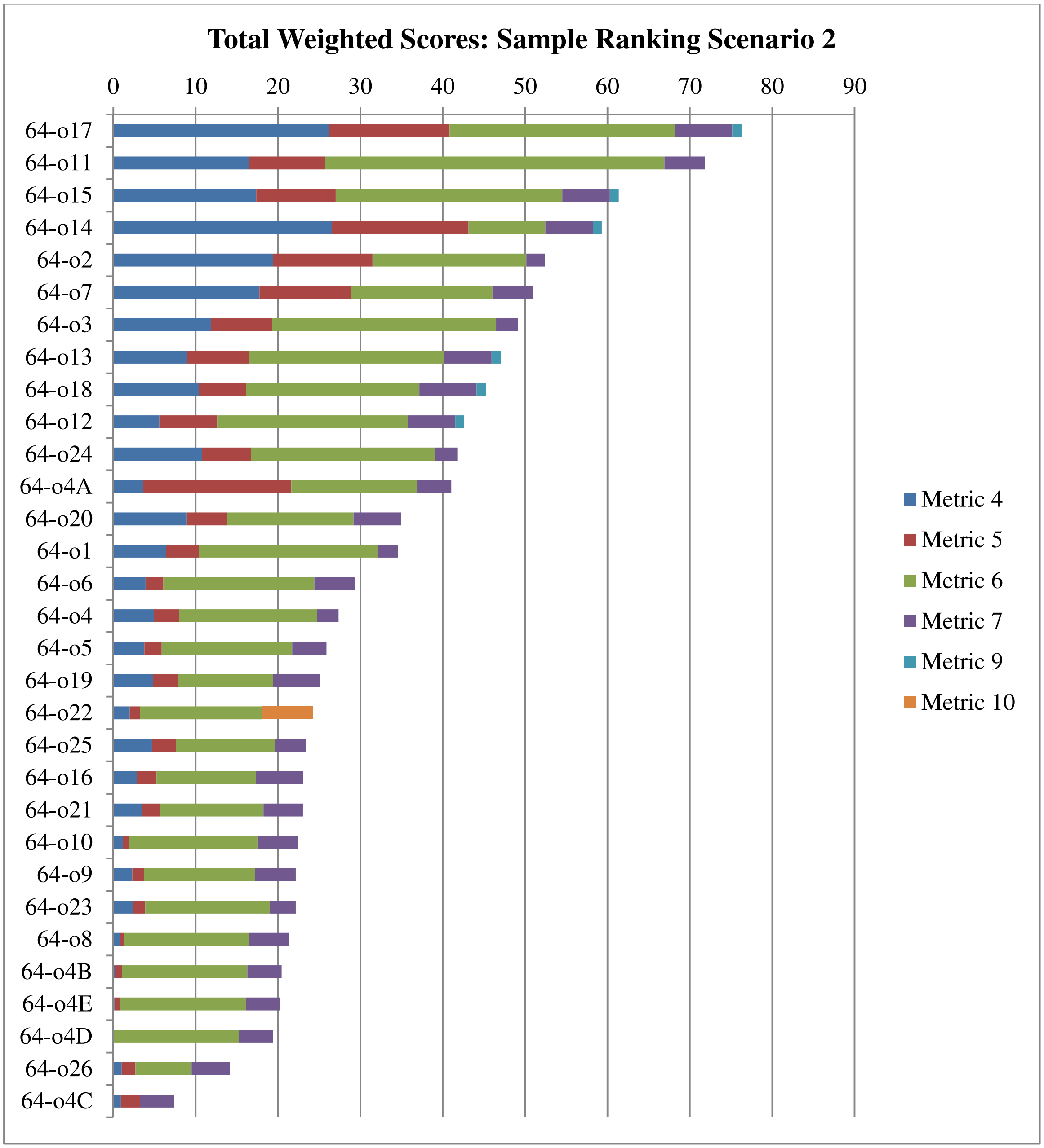

Figure 5-8: Score Contribution of Each Metric to the Total Weighted Score of Each Asset for Sample Ranking Scenario 2

5.3.5 Prioritizing the 31 VMS: Sample Ranking Scenario 3

The prioritization of the 31 VMS for sample ranking scenario 3, whose management approach is best-first and whose primary metric category is number of work orders, is summarized in Table 5-9. The data for metrics 1-3 is normalized in the best-first normalization direction using Eq. 4-2 such that lower values of the data for metrics 1-3 indicate higher priority for consideration of intervention alternatives. The same relative weights that were used in sample ranking scenario 1 are used in sample ranking scenario 3, and they are normalized such that they all add up to 1. Figure 5-9 shows the score contribution of each metric to the total weighted score of each asset for sample ranking scenario 3. In this case VMS 64-o26, with a total weighted score of 79.61/100, is the number-one ranked asset by a margin of 3.54/100.

Table 5-9: Prioritization of the 31 VMS According to Sample Ranking Scenario 3

Sample Ranking Scenario 3 (# of Work Orders, Best-First) - Normalized Data								
Metrics from Table 5-2		**1**	**2**	**3**	**7**	**9**	**10**	
	Relative Weight	1.600	1.000	1.598	0.618	0.097	0.547	
ASSET RANK	Normalized Weight	0.293	0.183	0.293	0.113	0.018	0.100	**Total Weighted Score**
1	**64-o26**	**93.81**	**83.51**	**100.00**	**66.84**	**0.00**	**0.00**	**79.61**
2	64-o4D	100.00	100.00	74.19	59.54	0.00	0.00	**76.07**
3	64-o22	90.72	90.72	74.19	0.00	0.00	100.00	**74.93**
4	64-o8	93.81	94.50	70.97	70.63	0.00	0.00	**73.56**
5	64-o4E	97.94	83.51	74.19	59.54	0.00	0.00	**72.44**
6	64-o25	86.60	86.60	85.25	53.38	0.00	0.00	**72.23**
7	64-o10	87.63	87.63	74.19	70.63	0.00	0.00	**71.43**
8	64-o6	88.66	89.92	70.97	70.63	0.00	0.00	**71.21**
9	64-o4B	96.91	75.26	74.19	59.54	0.00	0.00	**70.63**
10	64-o20	80.41	82.59	70.97	83.08	0.00	0.00	**68.86**
11	64-o4A	95.88	67.01	74.19	59.54	0.00	0.00	**68.82**
12	64-o13	82.47	76.63	63.87	82.68	100.00	0.00	**68.04**
13	64-o9	83.51	83.51	66.82	70.63	0.00	0.00	**67.31**
14	64-o16	86.60	82.13	58.71	82.68	0.00	0.00	**66.96**
15	64-o21	85.57	85.57	59.45	68.68	0.00	0.00	**65.92**
16	64-o19	75.26	75.26	70.51	82.80	0.00	0.00	**65.84**
17	64-o23	85.57	85.57	63.13	44.80	0.00	0.00	**64.29**
18	64-o4C	94.85	79.38	48.39	59.54	0.00	0.00	**63.23**
19	64-o7	83.51	83.51	52.07	70.63	0.00	0.00	**63.00**
20	64-o5	75.26	78.01	67.74	59.54	0.00	0.00	**62.90**
21	64-o11	69.07	72.51	70.97	70.63	0.00	0.00	**62.28**
22	64-o4	80.41	80.41	66.82	37.49	0.00	0.00	**62.09**
23	64-o1	64.95	64.95	55.76	34.13	0.00	0.00	51.11
24	64-o18	42.27	48.68	35.48	100.00	100.00	0.00	**44.79**
25	64-o24	48.45	54.18	35.48	39.43	0.00	0.00	**38.97**
26	64-o3	44.33	44.33	37.33	37.49	0.00	0.00	**36.28**
27	64-o12	54.64	9.28	13.98	82.68	100.00	0.00	**32.94**
28	64-o15	26.80	34.94	22.58	82.68	100.00	0.00	**32.00**
29	64-o14	0.00	0.00	70.51	82.68	100.00	0.00	**31.78**
30	64-o17	6.19	16.61	0.00	100.00	100.00	0.00	**17.96**
31	64-o2	10.31	10.31	29.95	32.83	0.00	0.00	**17.39**

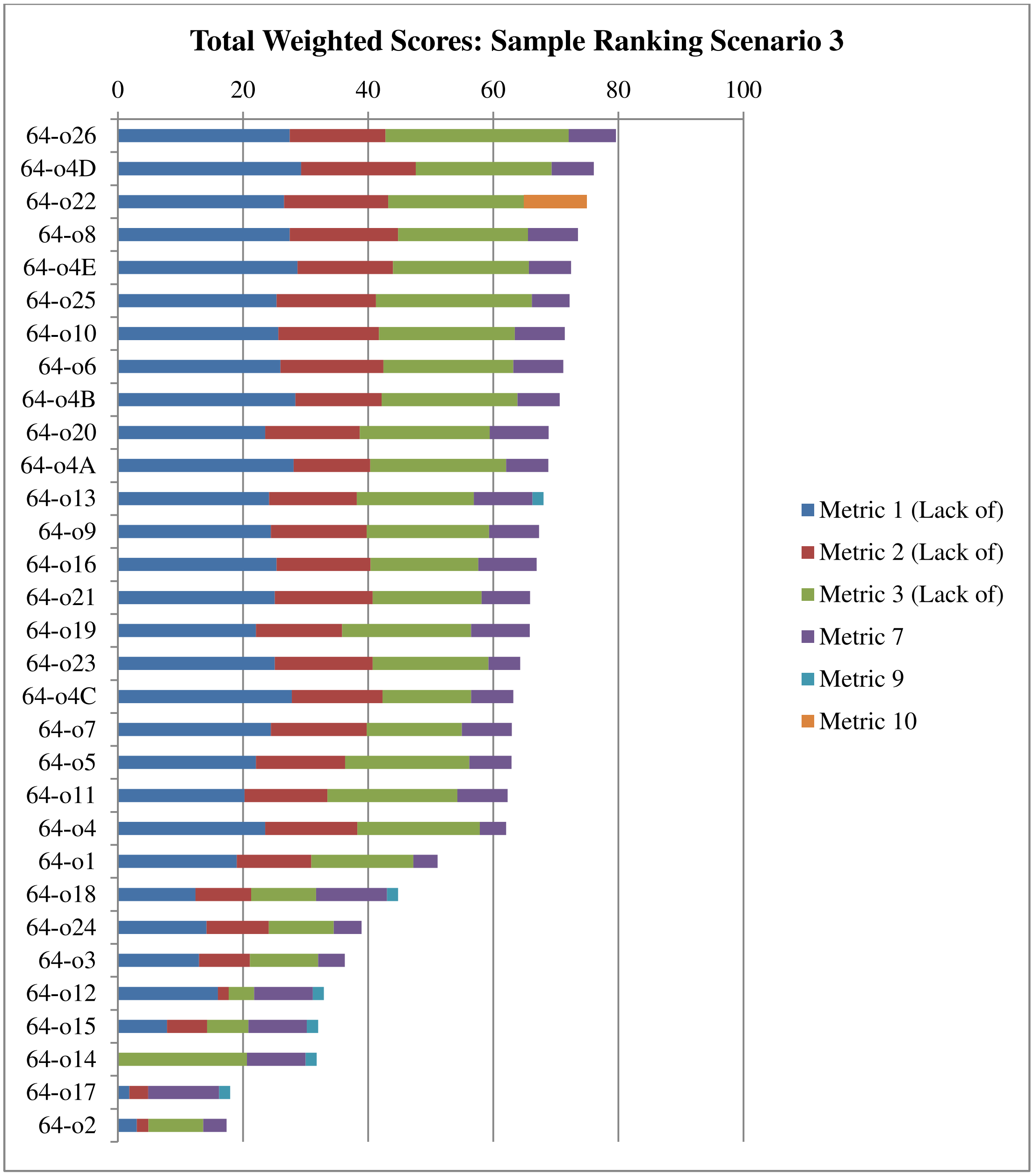

Figure 5-9: Score Contribution of Each Metric to the Total Weighted Score of Each Asset for Sample Ranking Scenario 3

5.3.6 Prioritizing the 31 VMS: Sample Ranking Scenario 4

The prioritization of the 31 VMS for sample ranking scenario 4, whose management approach is best-first and whose primary metric category is work order completion time, is summarized in Table 5-10. The data for metrics 4-6 is normalized in the best-first normalization direction using Eq. 4-2 such that lower values of the data for metrics 4-6 indicate higher priority for consideration of intervention alternatives. The same relative weights that were used in sample ranking scenario 2 are used in sample ranking scenario 4, and they are normalized such that they all add up to 1. Figure 5-10 shows the score contribution of each metric to the total weighted score of each asset for sample ranking scenario 3. In this case VMS 64-o4C, with a total weighted score of 86.66/100, is the number-one ranked asset by a margin of 5.74/100.

The Reversible-Roadway-critical VMS are ranked as having very low priority in the best-first ranking in Table 5-10, which may not reflect the importance of keeping those VMS in good condition. Thus one option for VDOT could be to begin addressing the 31 VMS using a worst-first ranking and not switch from using worst-first rankings to using best-first rankings until at least after all the RR-critical VMS have been addressed.

Table 5-10: Prioritization of the 31 VMS According to Sample Ranking Scenario 4

Sample Ranking Scenario 4 (Work Order Time, Best-First) - Normalized Data								
Metrics from Table 5-2		**4**	**5**	**6**	**7**	**9**	**10**	
	Relative Weight	1.472	1.000	2.285	0.386	0.061	0.342	
ASSET RANK	Normalized Weight	0.265	0.180	0.412	0.070	0.011	0.062	**Total Weighted Score**
1	**64-o4C**	**96.49**	**87.10**	**100.00**	**59.54**	**0.00**	**0.00**	**86.66**
2	64-o26	96.19	90.66	83.45	66.84	0.00	0.00	**80.92**
3	64-o4D	100.00	100.00	63.02	59.54	0.00	0.00	**74.68**
4	64-o8	96.86	97.43	63.26	70.63	0.00	0.00	**74.26**
5	64-o16	89.18	86.73	70.80	82.68	0.00	0.00	**74.24**
6	64-o22	92.50	93.10	63.99	0.00	0.00	100.00	**73.86**
7	64-o4E	99.46	96.00	63.02	59.54	0.00	0.00	**73.81**
8	64-o4B	99.34	95.11	63.02	59.54	0.00	0.00	**73.62**
9	64-o9	91.33	92.03	67.27	70.63	0.00	0.00	**73.47**
10	64-o10	95.53	95.89	62.18	70.63	0.00	0.00	**73.18**
11	64-o21	86.94	87.99	69.41	68.68	0.00	0.00	**72.32**
12	64-o19	81.74	83.21	72.05	82.80	0.00	0.00	**72.15**
13	64-o23	90.98	91.70	63.30	44.80	0.00	0.00	**69.88**
14	64-o25	82.35	83.76	70.80	53.38	0.00	0.00	**69.85**
15	64-o5	85.73	88.34	61.56	59.54	0.00	0.00	**68.19**
16	64-o6	85.25	87.94	55.47	70.63	0.00	0.00	**66.26**
17	64-o4	81.44	82.93	59.40	37.49	0.00	0.00	**63.65**
18	64-o20	66.53	72.64	62.77	83.08	0.00	0.00	**62.41**
19	64-o12	78.84	61.08	43.88	82.68	100.00	0.00	**56.87**
20	64-o18	60.89	68.02	49.03	100.00	100.00	0.00	**56.69**
21	64-o1	75.84	77.78	47.17	34.13	0.00	0.00	**55.96**
22	64-o4A	86.41	0.00	63.02	59.54	0.00	0.00	**53.04**
23	64-o13	66.21	58.56	42.38	82.68	100.00	0.00	**52.45**
24	64-o24	59.48	66.87	45.86	39.43	0.00	0.00	**49.49**
25	64-o7	33.14	38.50	58.29	70.63	0.00	0.00	**44.68**
26	64-o3	55.30	58.89	33.93	37.49	0.00	0.00	**41.89**
27	64-o14	0.00	8.02	77.34	82.68	100.00	0.00	**40.17**
28	64-o15	34.60	46.53	33.24	82.68	100.00	0.00	**38.13**
29	64-o2	26.99	32.84	54.70	32.83	0.00	0.00	**37.91**
30	64-o17	1.09	19.13	33.58	100.00	100.00	0.00	**25.64**
31	64-o11	37.71	49.07	0.00	70.63	0.00	0.00	**23.78**

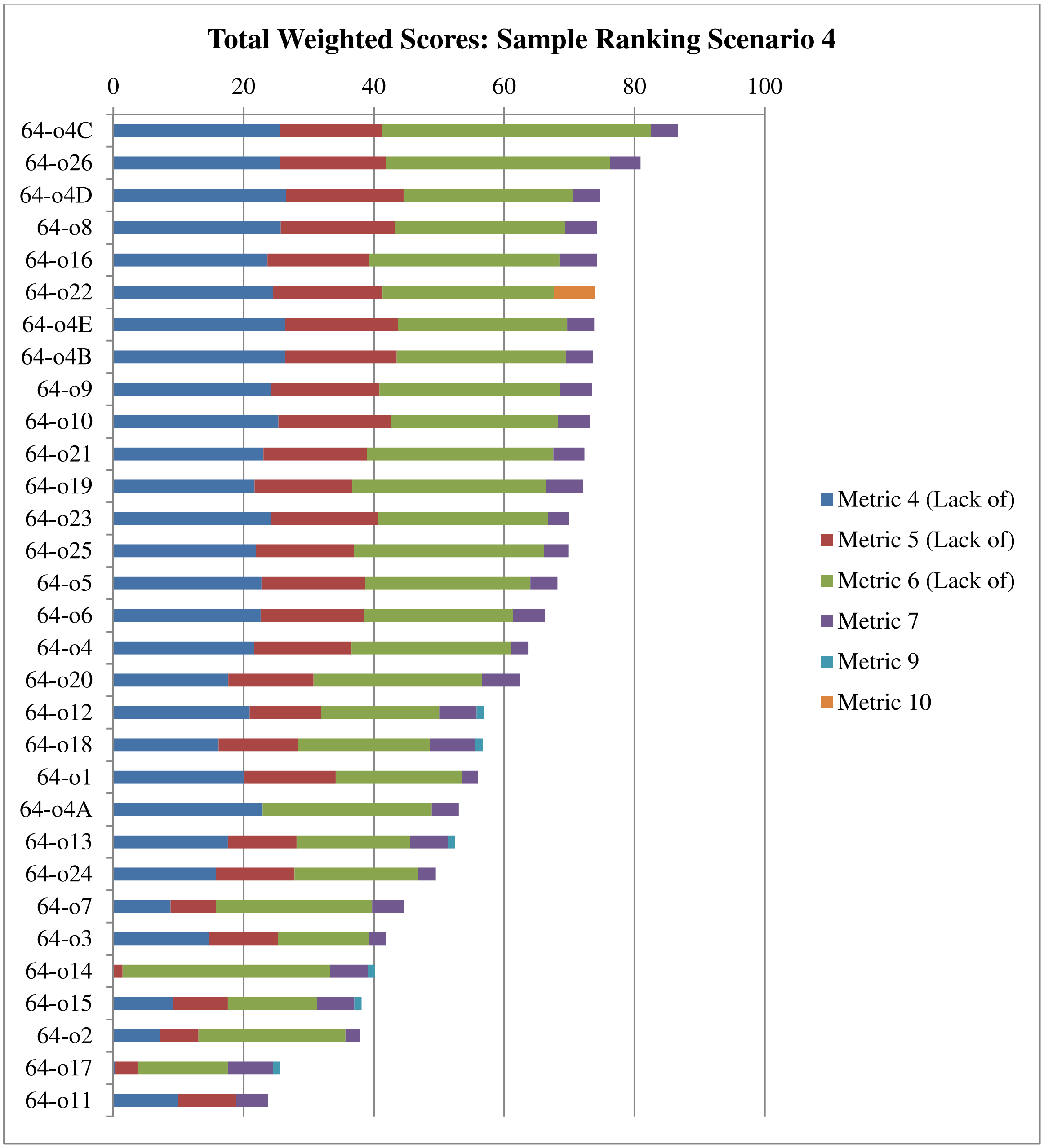

Figure 5-10: Score Contribution of Each Metric to the Total Weighted Score of Each Asset for Sample Ranking Scenario 4

5.3.7 Summary of Sample Ranking Scenarios

Table 5-11 summarizes which assets have which rankings in which sample ranking scenarios. Sample ranking scenarios 1 and 2 are worst-first and sample ranking scenarios 3 and 4 are best-first. The shaded cells show that the top-priority VMS in the worst-first scenarios are much lower priority in the best-first scenarios, and vice versa.

Table 5-11: Summary of Sample Ranking Scenarios 1-4

Asset Rank	Sample Ranking Scenario			
	1	2	3	4
1	**64-o17**	**64-o17**	**64-o26**	**64-o4C**
2	64-o14	64-o11	64-o4D	64-o26
3	64-o15	64-o15	64-o22	64-o4D
4	64-o2	64-o14	64-o8	64-o8
5	64-o12	64-o2	64-o4E	64-o16
6	64-o18	64-o7	64-o25	64-o22
7	64-o3	64-o3	64-o10	64-o4E
8	64-o24	64-o13	64-o6	64-o4B
9	64-o1	64-o18	64-o4B	64-o9
10	64-o13	64-o12	64-o20	64-o10
11	64-o11	64-o24	64-o4A	64-o21
12	64-o7	64-o4A	64-o13	64-o19
13	64-o19	64-o20	64-o9	64-o23
14	64-o16	64-o1	64-o16	64-o25
15	64-o5	64-o6	64-o21	64-o5
16	64-o4C	64-o4	64-o19	64-o6
17	64-o20	64-o5	64-o23	64-o4
18	64-o21	64-o19	64-o4C	64-o20
19	64-o9	64-o22	64-o7	64-o12
20	64-o4	64-o25	64-o5	64-o18
21	64-o23	64-o16	64-o11	64-o1
22	64-o22	64-o21	64-o4	64-o4A
23	64-o6	64-o10	64-o1	64-o13
24	64-o4A	64-o9	64-o18	64-o24
25	64-o10	64-o23	64-o24	64-o7
26	64-o4B	64-o8	64-o3	64-o3
27	64-o8	64-o4B	64-o12	64-o14
28	64-o4E	64-o4E	64-o15	64-o15
29	64-o25	64-o4D	64-o14	64-o2
30	64-o4D	64-o26	64-o17	64-o17
31	64-o26	64-o4C	64-o2	64-o11

Figure 5-11 and Figure 5-12 show the work order counts through 2012 and work order completion times through 2012, respectively, for top priority VMS in each of the four sample ranking scenarios. Figure 5-11 and Figure 5-12 emphasize the contrast in terms of work order counts and work order completion times between assets that are top-priority according to a worst-first management approach and assets that are top-priority according to a best-first management approach.

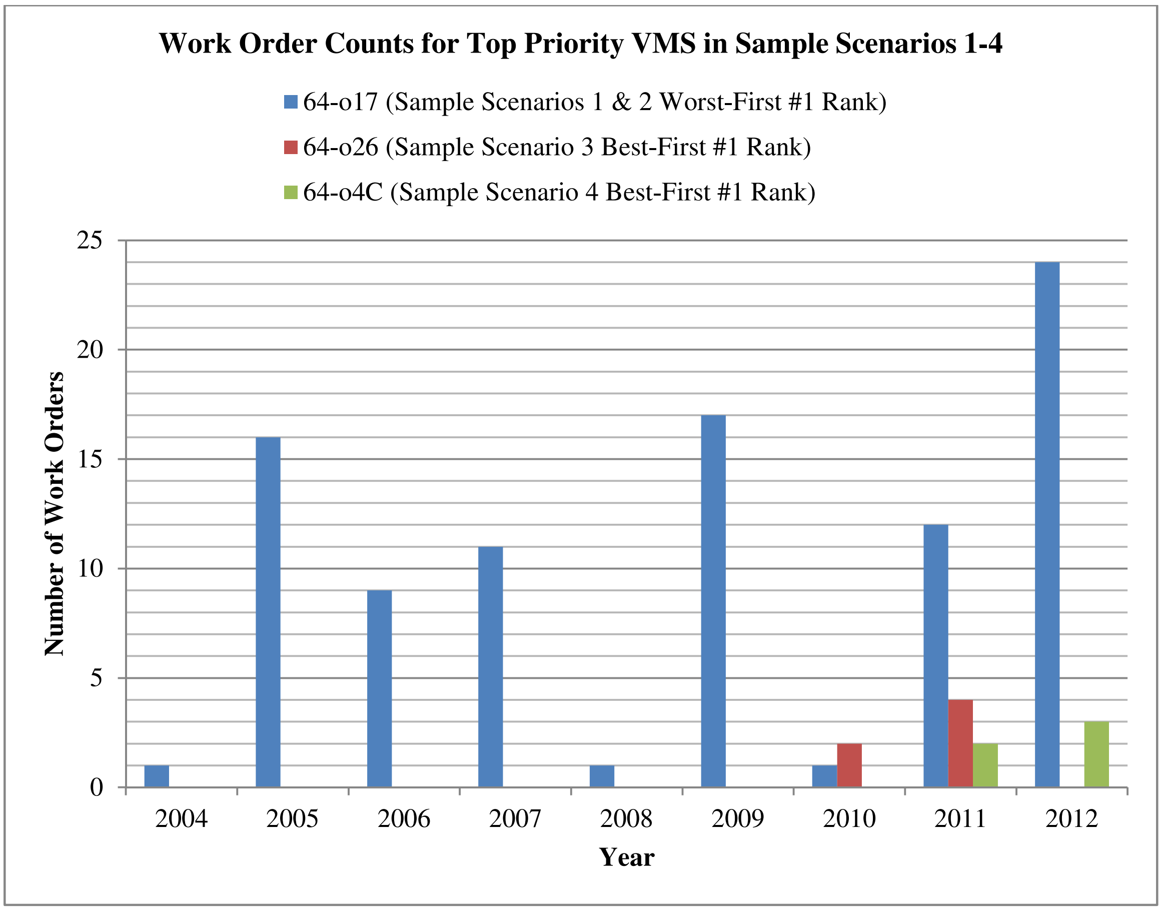

Figure 5-11: Yearly Work Order Counts for Top Priority VMS in Sample Ranking Scenarios 1-4 (HRTOC, 2013)

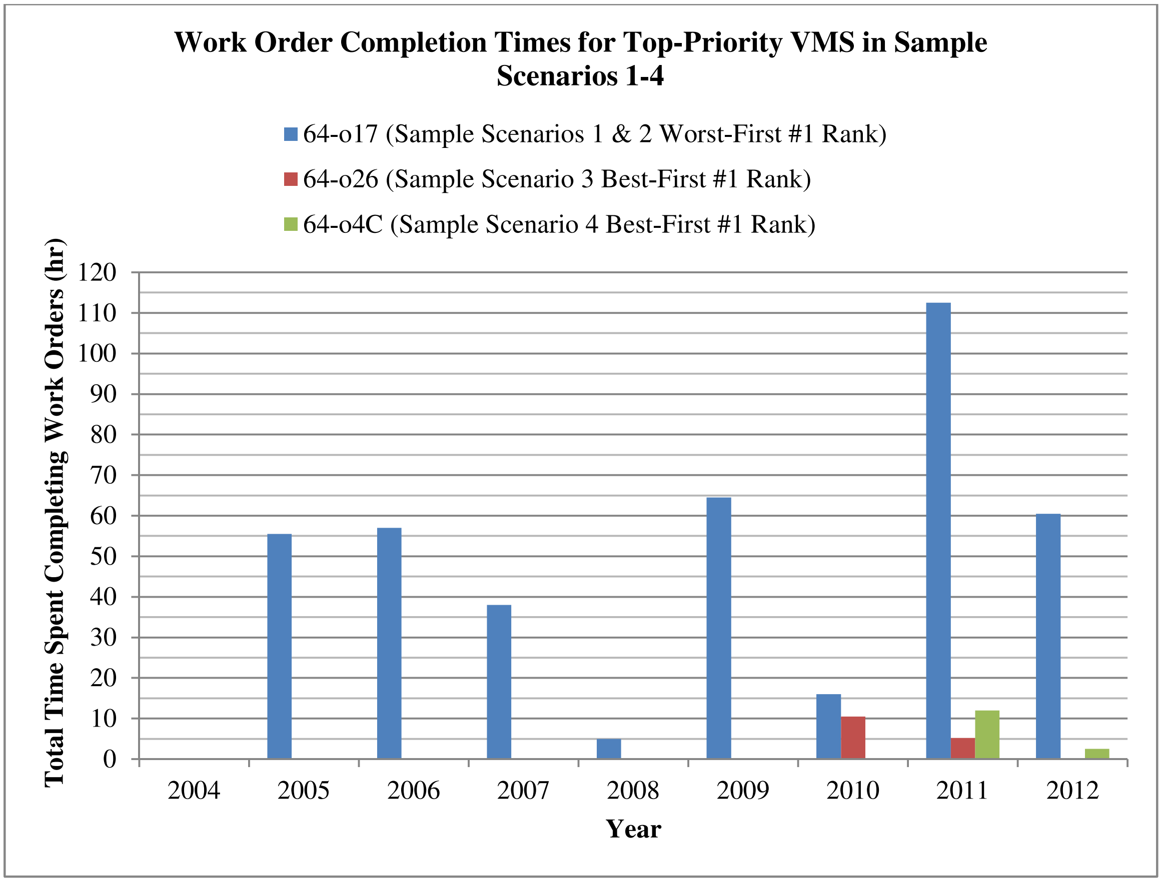

Figure 5-12: Yearly Total Times Spent Completing Work Orders for Top-Priority VMS in Sample Ranking Scenarios 1-4 (HRTOC, 2013)

Figure 5-13 graphically summarizes the rankings for the 31 VMS in the four sample ranking scenarios. The point of Figure 5-13 and Figure 5-14 is to help show the difference in the device rankings between calculating best-first rankings by switching the normalization direction of metrics 1-6 and calculating best-first rankings simply by taking the inverse of the worst-first rankings. Figure 5-14 graphically depicts what Figure 5-13 would look like if the best-first rankings are calculated simply by inverting the worst-first rankings. As described in Section 5.3.1, traffic volume and importance to safety and operations do not "age" or "become obsolete" over time.

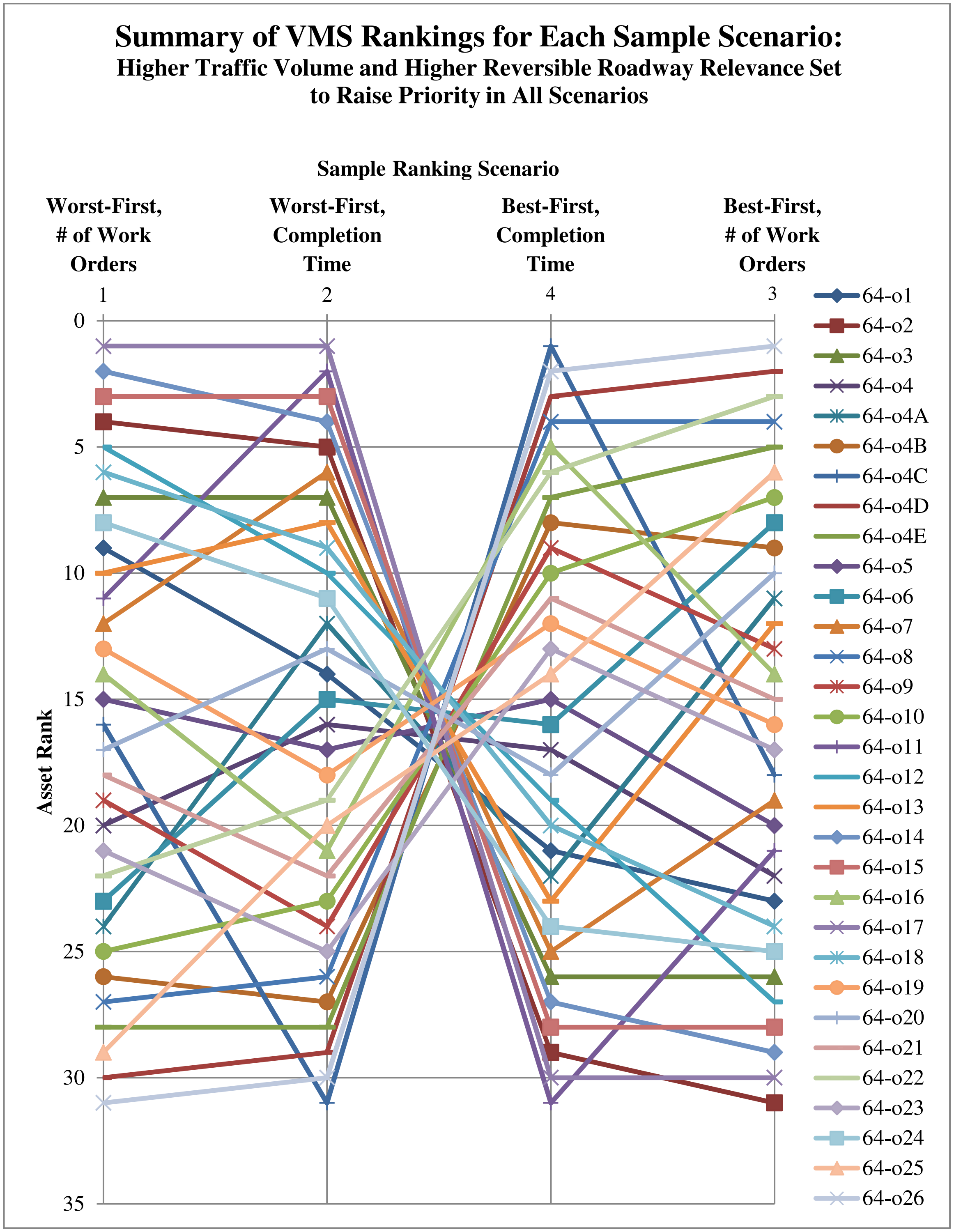

Figure 5-13: Graphical Depiction of All VMS Rankings for Each Sample Ranking Scenario with Higher Traffic Volume and Higher Reversible Roadway Relevance Set to Raise Asset Priority in All Scenarios.

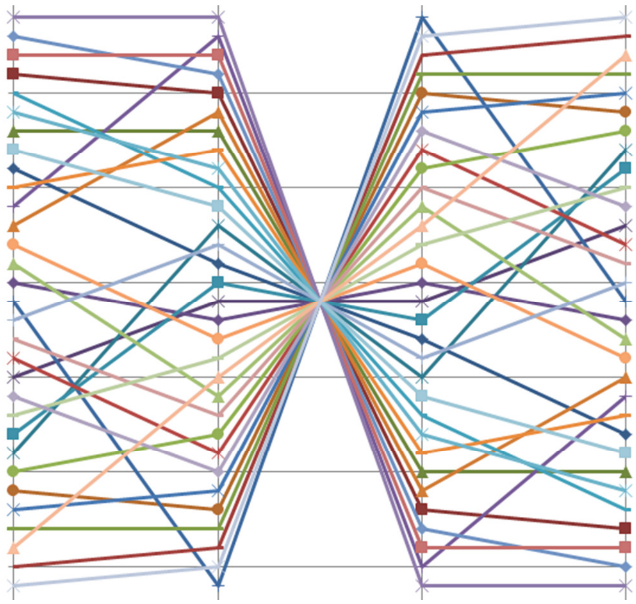

Figure 5-14: Depiction of What Figure 5-13 Would Look Like if the Best-First Rankings Were Calculated Simply by Inverting the Worst-First Rankings

5.3.8 Obsolescence Risk Assessment

Asset priority can also be evaluated by obsolescence risk. Risk assessment is not the main focus of this study, but a simple example of obsolescence risk analysis is provided in this section using sample ranking scenario 1. A primary method of determining risk is by multiplying the probability of occurrence of some event by the severity of the event (FAA, 2007; FHWA, 2009). Obsolescence risk, in turn, is determined by relating some measure of obsolescence or probability of obsolescence to criticality or importance of the asset (Rojo et al, 2012). In this case study, metrics 1-3 (or 4-6) are obsolescence-related and 7, 9, and 10 are criticality- or importance-related. In Figure 5-15 the relative obsolescence risk of each of the 31 VMS is depicted by plotting the total weighted score of metrics 1-3 against the total weighted score of metrics 7, 9, and 10. In Figure 5-15 risk increases from the lower left to the upper right, and the top six VMS from sample ranking scenario 1 are labeled. Figure 5-15 provides a visual representation of the relative obsolescence risk of each asset as an aid for decision-making. Figure 5-15 does not necessarily show which assets are most critical and least critical on an absolute scale because the 31 VMS are being compared only with each other in the present example. NAMS (2006) explains that "failure will and should occur for non-critical assets" (p. 3.105). However, ranking analysis of a much larger array of ITS devices and systems in Hampton Roads would be necessary to determine if, for example, the VMS in the lower left region of Figure 5-15 are indeed non-critical.

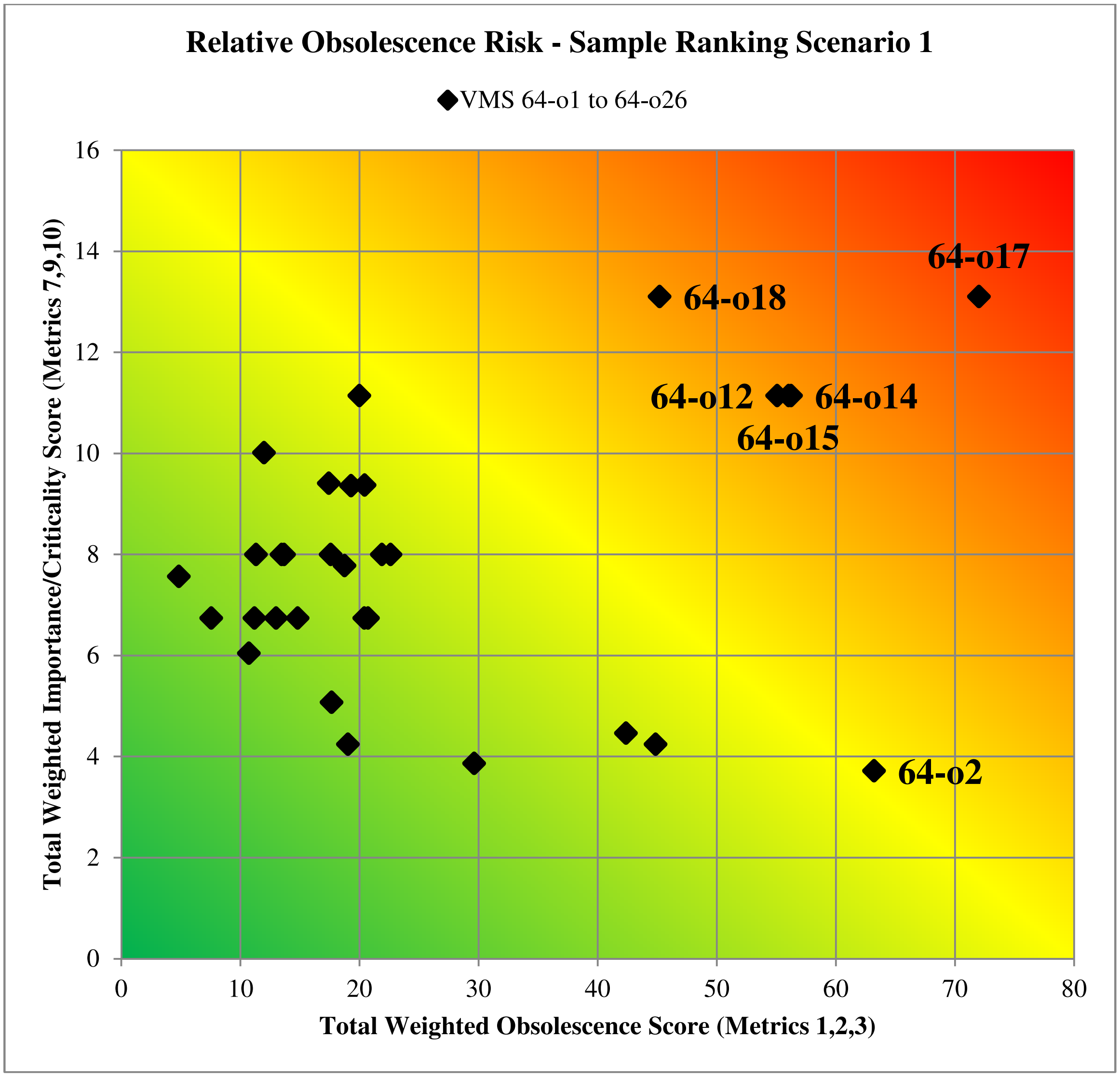

Figure 5-15: Relative Obsolescence Risk of the 31 VMS According to Sample Ranking Scenario 1

Another way to determine the total weighted score of each asset is to multiply rather than add the weighted scores of each metric (Triantaphyllou & Sánchez, 1997; Triantaphyllou et al, 1998). Such scoring is recommended for ranking assets according to obsolescence risk in that the total weighted score (determined additively) for the obsolescence metrics is multiplied by the total weighted score (determined additively) for the criticality or importance metrics. On the graph in Figure 5-15, the obsolescence risk of a given point representing one VMS would thus be the product of the horizontal and vertical components. Multiplying rather than adding the two total weighted scores may result in a different ranking of assets. For this case it just so happens that the six VMS ranked as top priority in the purely additive sample ranking scenario 1 are also ranked in the top six in the risk assessment version of the scenario but in different order. This method of obsolescence risk ranking is an improvement over the obsolescence risk ranking in VDOT (2007A), but further research into applying risk analysis techniques to prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure is warranted.

5.4 – SENSITIVITY AND SCENARIO ANALYSIS

5.4.1 Sensitivity Analysis

A sensitivity analysis is performed on each of the four sample ranking scenarios from Section 5.3 in order to determine which metrics are more critical. When the metrics are ranked according to criticality, they are ranked according to relative importance of determining an accurate relative weight and, therefore, according to relative amount of justification for expending resources determining an accurate weight (Triantaphyllou &

Sánchez, 1997). The sensitivity analysis in this section is performed by varying each relative weight individually (i.e., by changing just one relative weight and leaving the others unchanged) until an effect on the final VMS ranking is detected. The metrics are ranked according to the degree to which their relative weights can change individually before the final VMS ranking is affected. More specifically, the metrics are ranked according to difference between the percent increase in relative weight and percent decrease in relative weight needed to switch the rankings of any two of the 31 VMS. The relative weights, varied individually, both lower than and higher than the base case relative weights from Section 5.3, that result in a switch in the final rankings of any two of the 31 VMS are summarized in Table 5-12 for each sample ranking scenario. Table 5-13 complements Table 5-12 by summarizing the minimum percent changes in relative weights (varied individually) needed to switch the rankings of any two VMS and by ranking the metrics in terms of criticality (i.e., according to difference between the positive and negative percent changes) for each sample ranking scenario. Comparison of Table 5-12 and Table 5-13 confirms the expectation that higher weight does not necessarily mean more critical. The final VMS ranking could be more sensitive to changes in a small weight but less sensitive to changes in a large weight. For example, for sample ranking scenario 1, Table 5-13 shows that metric 2 is more critical than metric 1 while Table 5-12 shows that metric 2 has a lower relative weight than metric 1.

Table 5-12: Relative Weights (Varied Individually) that Result in a Switch in the Final Rankings of Any Two VMS

Sample Ranking Scenario	Metric	Relative Weights (Varied Individually)		
		Base Case	To Change Rankings of Any Two VMS	
			Low	High
1	1	1.600	1.553	1.670
	2	1.000	0.972	1.029
	3	1.598	1.571	1.624
	7	0.618	0.591	0.644
	9	0.097	0.084	0.136
	10	0.547	0.529	0.588
2	4	1.472	1.316	1.562
	5	1.000	0.840	1.063
	6	2.285	2.041	2.300
	7	0.386	0.384	0.445
	9	0.061	0.014	0.176
	10	0.342	0.293	0.394
3	1	1.600	1.560	1.616
	2	1.000	0.984	1.135
	3	1.598	1.360	1.624
	7	0.618	0.608	0.647
	9	0.097	0.066	0.141
	10	0.547	0.472	0.610
4	4	1.472	1.458	1.512
	5	1.000	0.990	1.057
	6	2.285	2.125	2.300
	7	0.386	0.362	0.392
	9	0.061	0.048	0.094
	10	0.342	0.339	0.363

Table 5-13: Minimum Percent Changes in Relative Weights (Varied Individually) to Switch the Final Rankings of Any Two VMS

Sample Ranking Scenario	Criticality Rank	Metric	Minimum Percent Changes in Relative Weights (Varied Individually) to Change Rankings of Any Two VMS		
			Low (%)	High (%)	Delta (%)
1	1	3	-1.686	1.631	3.317
	2	2	-2.800	2.900	5.700
	3	1	-2.937	4.375	7.313
	4	7	-4.400	4.174	8.573
	5	10	-3.262	7.528	10.789
	6	9	-13.720	39.692	53.412
2	1	6	-10.693	0.640	11.333
	2	7	-0.635	15.150	15.785
	3	4	-10.580	6.135	16.715
	4	5	-16.000	6.300	22.300
	5	10	-14.288	15.257	29.546
	6	9	-76.997	189.185	266.182
3	1	1	-2.500	1.000	3.500
	2	7	-1.650	4.659	6.309
	3	2	-1.600	13.500	15.100
	4	3	-14.890	1.631	16.521
	5	10	-13.685	11.551	25.236
	6	9	-32.208	44.828	77.036
4	1	4	-0.931	2.738	3.669
	2	5	-1.000	5.700	6.700
	3	10	-0.832	6.189	7.021
	4	6	-7.017	0.640	7.657
	5	7	-6.328	1.435	7.763
	6	9	-21.131	54.451	75.582

Figure 5-16, Figure 5-17, Figure 5-18, and Figure 5-19 are inverse tornado charts that show the metrics used in each sample ranking scenario ranked according to difference between positive and negative percent change in weight needed to switch the rankings of two of the 31 VMS when only one weight is varied at a time. The metric at the top with the shortest bar is the metric whose weight the final VMS ranking is most sensitive to, and the metric at the bottom with the longest bar is the metric whose weight the final VMS ranking is least sensitive to. Metrics 1-3 and 4-6 are calculated using Δt and metrics 7, 9, and 10 are calculated using various traffic volumes, as discussed in Section 5.3.

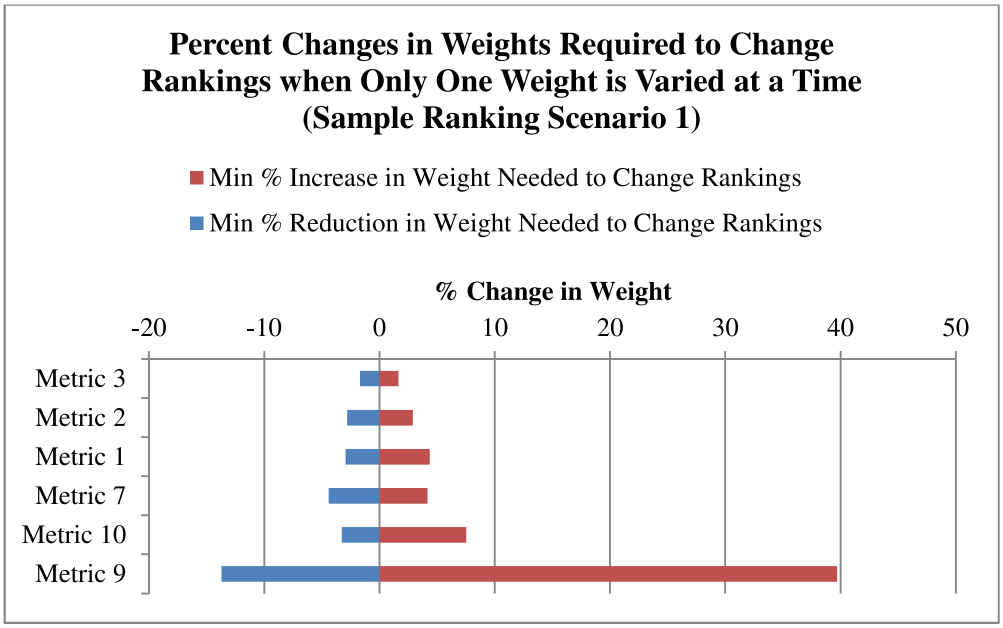

Figure 5-16: Metrics Ranked According to Criticality of Accurate Weight Determination (Sample Ranking Scenario 1)

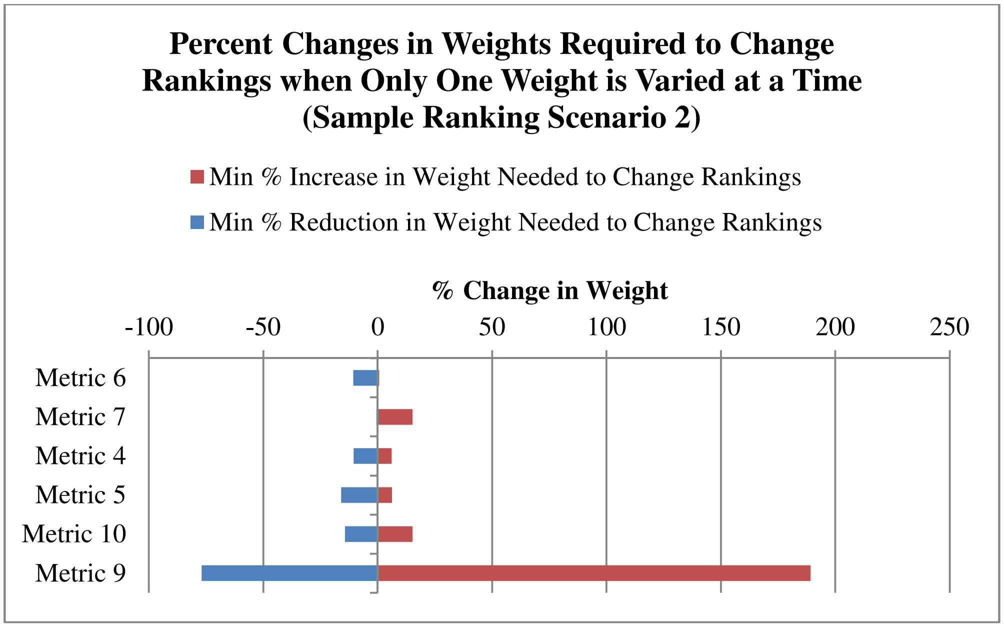

Figure 5-17: Metrics Ranked According to Criticality of Accurate Weight Determination (Sample Ranking Scenario 2)

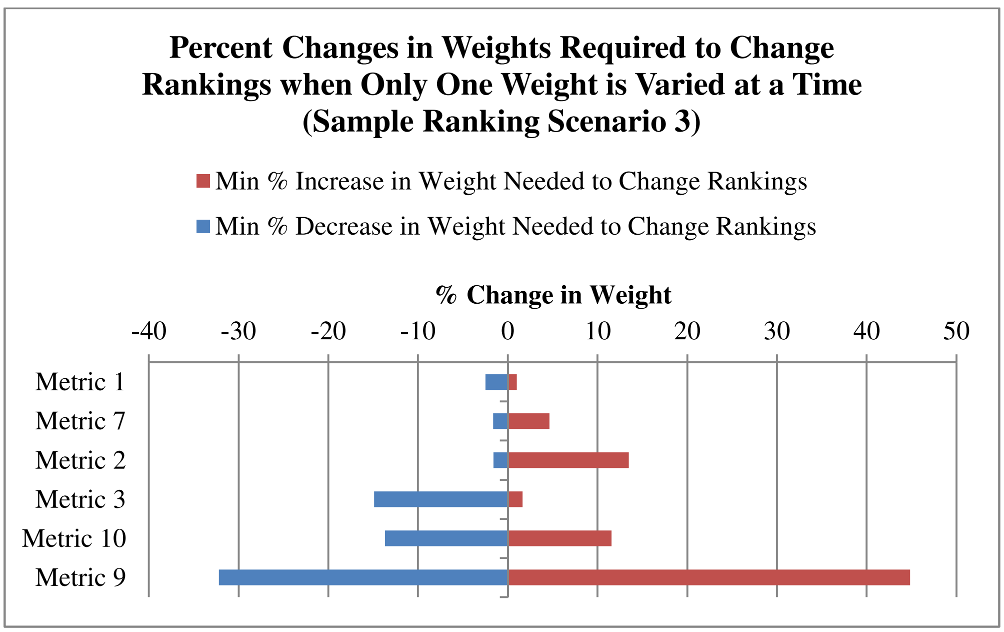

Figure 5-18: Metrics Ranked According to Criticality of Accurate Weight Determination (Sample Ranking Scenario 3)

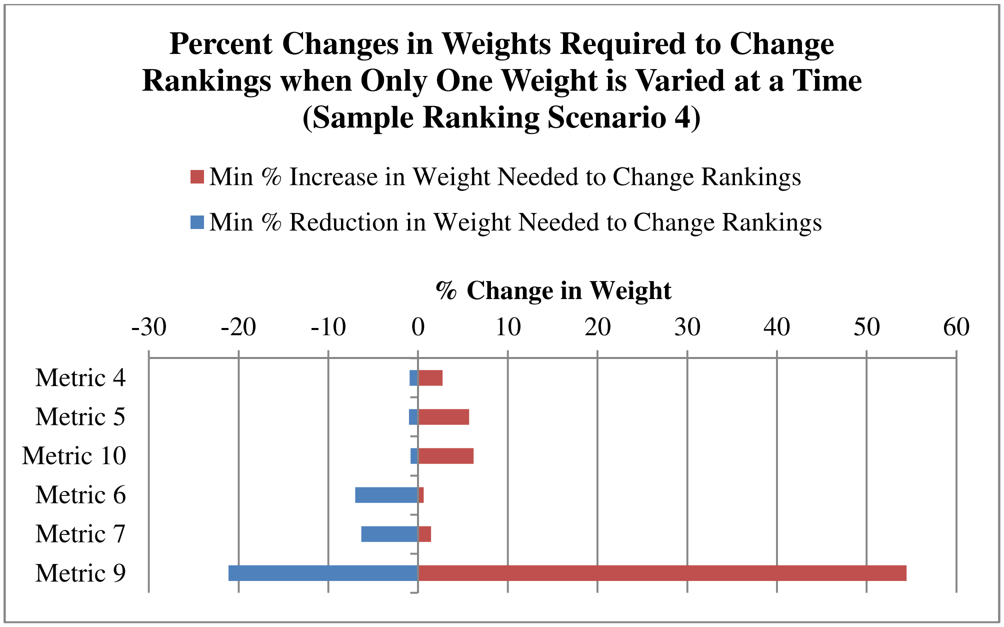

Figure 5-19: Metrics Ranked According to Criticality of Accurate Weight Determination (Sample Ranking Scenario 4)

The differences between the positive and negative percent changes of the Δt and AADT values (used to calculate the base-case metric weights) that are associated with the metrics in Figure 5-16, Figure 5-17, Figure 5-18, and Figure 5-19 are the same and thus not shown here. They are the same because of the proportionality, either direct or inverse, between the Δt or AADT inputs and the weights they are used to calculate. The absolute Δt and AADT values associated with Table 5-12 and the inverse tornado charts are shown in Table 5-14.

Table 5-14 Variable Values Associated with Table 5-12 and Table 5-13

Sample Ranking Scenario	Criticality Rank	Metric	Type of Variable Used to Calculate Weight	Associated Variable Values		
				Base Case	To Change Rankings of Any Two VMS	
					Low	High
1	1	3	Δt (hr)	5.000	4.916	5.082
	2	2	Δt (hr)	5.000	4.860	5.145
	3	1	Δt (hr)	5.000	4.790	5.151
	4	7	AADT (veh/day)	9188	8820	9611
	5	10	AADT (veh/day)	60920	58933	65506
	6	9	AADT (veh/day)	10846	9358	15151
2	1	6	Δt (hr)	5.000	4.465	5.032
	2	7	AADT (veh/day)	3171	2754	3191
	3	4	Δt (hr)	5.000	4.711	5.592
	4	5	Δt (hr)	5.000	4.200	5.315
	5	10	AADT (veh/day)	60920	52216	70215
	6	9	AADT (veh/day)	10846	2495	31365
3	1	1	Δt (hr)	5.000	4.950	5.128
	2	7	AADT (veh/day)	9188	8779	9342
	3	2	Δt (hr)	5.000	4.920	5.675
	4	3	Δt (hr)	5.000	4.255	5.082
	5	10	AADT (veh/day)	60920	52583	67957
	6	9	AADT (veh/day)	10846	7353	15708
4	1	4	Δt (hr)	5.000	4.867	5.047
	2	5	Δt (hr)	5.000	4.950	5.285
	3	10	AADT (veh/day)	60920	60413	64690
	4	6	Δt (hr)	5.000	4.649	5.032
	5	7	AADT (veh/day)	3171	3126	3385
	6	9	AADT (veh/day)	10846	8554	16752

Determining the relative criticalities of the metrics chosen for the analysis can offer guidance for improving future analysis of both the present system of ITS devices and other systems of ITS devices. After HRTOC has transitioned to MicroMain Version 7.5 and then on to Serco's management and the Maximo MMS, and then once enough data has been collected on a wider range of metrics, a more comprehensive prioritization analysis will be possible. However, given more luxuries regarding data availability, metric criticality analysis will be even more important in order to avoid wasting resources collecting and analyzing data on metrics that consistently do not matter. A combination of engineering judgment and continual sensitivity analysis can guide continual improvement of an agency program of prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure.

Relative criticalities of metrics can have another, different interpretation. For example, it can be seen in Figure 5-16, Figure 5-17, Figure 5-18, and Figure 5-19 that in every sample ranking scenario, metric 9, the importance of a VMS to the safe and orderly operation of the Reversible Roadway, has by far the lowest criticality in terms of the final VMS ranking's sensitivity to changes in its weight. One possibility is that the metric does not matter very much and should either receive less attention when it comes to expending effort to determine its weight or be discarded entirely in future prioritizations. However, another possibility is that the weight chosen for the metric is far too low and that therefore the assumptions that led to that weight being chosen are unsound. This is a distinct possibility in the particular case of metric 9. Figure 5-7, Figure 5-8, Figure 5-9, and Figure 5-10 show that metric 9, as weighted using the assumptions in Section 5.3, contributes very little to the total weighted scores of the assets to which it applies. Because the six relevant VMS serve a distinct safety-related purpose, it would not be good judgment to discard metric 9, in opposition to the primary interpretation of the inverse tornado charts. The original assumption from Section 5.3 assigned an additional 10,846 veh/day, which is equal to the 2011 WB AADT of the Reversible Roadway, as the marginal change in AADT merited if a VMS is a safety-related Reversible-Roadway-critical VMS. It is true that the Reversible-Roadway-critical VMS are of secondary importance to the physical access-control gates at the entrances to the facility, which actually block traffic from entering into head-on conflicts (Adams, 2009). Thus if a Reversible-Roadway-critical VMS fails while the relevant gate is in the down position, the gate will still block opposing traffic from entering. However, in a second iteration of the methodology, the 10,845 veh/day margin could be raised anyway to increase the weight of metric 9 on safety-related grounds and because of the exclusive status of the Reversible Roadway discussed in Section 5.3. Such a possibility is investigated in the scenario analysis in Section 5.4.2, although a second iteration of the whole analysis was not performed in this demonstration due to time constraints. A second iteration of the whole analysis in which the weight of metric 9 is increased would yield higher priorities (i.e., lower ranks) for the relevant six VMS as well as final rankings that are more sensitive to changes in the weight of metric 9 in all four sample ranking scenarios. It must be emphasized that problems discovered with the first iteration, no matter how glaring, does not justify erasing the first iteration from memory or spending excessive time on first iterations in future ranking analyses out of fear of making errors (Gibson et al, 2007). The systems analysis process is by nature an iterative process in which errors can be detected and fixed (Gibson et al, 2007), and not covering up the fact that iterations were warranted helps keep the process transparent, as discussed in Section 4.3.9.

It is acknowledged that the weights are interrelated according to how they were calculated in Section 5.3 and thus changing one weight affects the others. It is true that a sensitivity analysis could be performed by manually varying one weight at a time but also letting the other weights change according to the relationships established in Section 5.3.

However, according to Triantaphyllou and Sánchez (1997), standard procedure for determining critical metrics is to change each weight individually while leaving the other weights unchanged. Also, it is possible that the relationship established between any two metrics in Section 5.3 according to the assumptions discussed is not accurate. In fact, it is possible that the relationship between two metrics could be made to be more accurate by changing the ratio by a factor that the sensitivity analysis shows to change the final VMS ranking. Relative criticalities between metrics indicate which metrics it is justified to expend greater effort determining accurate relative weights for, not which relative weights have already been calculated the most accurately. It is also conceivable that it could be justified for two pairs of metrics interrelated by the same variable, such as in the cases of metrics 1 and 2 (or 4 and 5) and 2 and 3 (or 5 and 6) being related by Δt, to be calculated using different values of that variable. For example, the value of Δt relating metrics 3 and 2 could be set lower than the value of Δt relating metrics 1 and 2 if the analyst wants rate of obsolescence, as measured by metric 3, to contribute more heavily to determining obsolescence management priority than age, sunk costs, or average maintenance intensiveness, as measured by metrics 1 and 2.

The metrics could also be ranked according to the degree to which they can change individually before the number-one-ranked VMS changes. Triantaphyllou and Sánchez (1997) explain that sensitivity analysis is also commonly performed on just the number-one-ranked alternative. However, the goal of this case study is to demonstrate a methodology that can address all ITS devices in a defined system of devices and for that methodology to be able to act as an ongoing program of ITS obsolescence management. The goal is not to address the top-ranked asset and do nothing to address the other assets.

In general, after a number-one-ranked device is determined using the general Part I methodology, such as in this case study, and addressed using the general Part II methodology, its status in terms of its data can be changed according to the degree to which it was addressed. Then all assets in the system can be re-ranked and the program continued. In the specific example of this case study, it is acknowledged that the complete historical record of work orders is not a good set of data to use for continuing the prioritization program. One option is to reduce the work order count of a VMS in proportion to the degree to which it is addressed. For example, the work order count of the VMS could be reduced by half if its condition is improved halfway to new, reset to zero if it is replaced entirely, and so on. The degree to which an asset is addressed after it has deteriorated can be expressed visually using a deterioration curve such the one used in Zhang et al (2010) for pavement management.

5.4.2 Scenario Analysis

This section demonstrates how to evaluate the effect of varying multiple inputs simultaneously on the final VMS rankings. In this section the different sets of inputs used are referred to as scenarios. Analysis of the effects of using different input scenarios can show which assets have rankings that are the most and least sensitive to systematic variations in the inputs. Such knowledge can provide insight into how much assurance that can be had that the relative priority of any given asset is correct. The agency could decide to spend extra effort increasing the accuracy of the input values if there is an asset that is ranked highly but whose ranking is shown to be particularly sensitive to systematic variations in the inputs. For demonstration purposes, instead of establishing and evaluating a large number of scenarios, only two scenarios are established and evaluated relative to a single base case scenario, as Comes et al (2009) explains is common practice. The base case scenario chosen for this demonstration is sample ranking scenario 1 from Section 4.3. The first scenario's input values are set arbitrarily far from the base scenario's input values in one direction, and the second scenario's input values are set similarly far from the base scenario's input values in the opposite direction. Although there is nothing "bad" or "good" about the two scenarios, they are similar to "bad" and "good," or "best-case" and "worst-case," scenarios used in scenario analysis for other applications (Baker & Powell, 2005; Comes et al, 2009). Although the input values chosen for the two scenarios are arbitrary, they are sufficient to allow for insight be gained about the relative sensitivities of the ranks of the assets to systematic variations in the inputs.

The first scenario, Scenario 1A, is a combination of inputs that are more "strict" than the base inputs used for sample ranking scenario 1. Firstly, regarding the weights for metrics 1-3, $\Delta t = 3$ years is used rather than 5 years, meaning that the agency values a marginally larger number of completed work orders to be offset within only 3 years by a smaller average number of work orders per year. As a result, relative to the base weights, the weight of metric 1 goes up and the weight of metric 3 goes down. Secondly, regarding the weight for metric 7, 9,188 additional vehicles per day justifying the completion of one additional work order per year is reduced by 50 percent to 4,594 vehicles per day. The assumption is that it is a "stricter" work order stipulation to assume that only 4,594 rather than 9,188 additional AADT is needed to justify improving the asset by a margin of one work order per year. As a result, the weight of metric 7 goes up relative to its base weight. Thirdly, regarding the weight for metric 9, the inflation of the

AADT figure for VMS assumed to be Reversible-Roadway-critical is increased fourfold from 10,846 to 43,384 in light of the finding in Section 4.4 that metric 9's weight could justifiably be increased. The assumption is that increasing the importance of vehicles entering the Reversible Roadway is a "stricter" approach to safety. The weight of metric 10 is left unchanged. The input values and associated new weights for Scenario 1A are summarized in Table 5-15 and Table 5-16, respectively.

The second scenario, Scenario 1B, is a combination of inputs that are more "lenient" than the base inputs used for sample ranking scenario 1. Firstly, regarding the weights for metrics 1-3, Δt = 10 years is used rather than 5 years, meaning that the agency accepts a marginally larger number of completed work orders being offset within 10 years by a smaller average number of work orders per year. As a result, relative to the base weights, the weight of metric 1 goes down and the weight of metric 3 goes up. Secondly, regarding the weight for metric 7, 9,188 additional vehicles per day justifying the completion of one additional work order per year is increased by 50 percent to 13,782 vehicles per day. The assumption is that it is a more "lenient" work order stipulation to assume that 13,782 rather than 9,188 additional AADT is needed to justify improving the asset by a margin of one work order per year. As a result, the weight of metric 7 goes down relative to its base weight. Thirdly, in light of the finding in Section 4.4 that metric 9's weight could justifiably be increased, the inflation of the AADT figure for VMS assumed to be Reversible-Roadway-critical is not decreased from the base input, unlike the other input values for this scenario. Instead of increasing the AADT inflation fourfold (as in Scenario 1A), it is only doubled this scenario, namely from 10,846 to

21,692. The weight of metric 10 is left unchanged. The input values and associated new weights for Scenario 1B are summarized in Table 5-15 and Table 5-16, respectively.

Table 5-15: Summary of "Strict," Base-Case, and "Lenient" Scenarios

Scenario	Input Set	Δt (yr)	(Vehicles per Day) per (Work Order per yr)	AADT Inflation for Reversible-Roadway-Critical VMS
1A	Strict	3	4594	43384
1	Base	5	9188	10846
1B	Lenient	10	13782	21692

Table 5-16: Summary of Relative Weights Associated with the "Strict," Base-Case, and "Lenient" Scenarios

Scenario	Input Set	Relative Weights for Scenario Analysis					
		Metric 1	Metric 2	Metric 3	Metric 7	Metric 9	Metric 10
1A	Strict	2.667	1.000	0.959	1.236	0.779	1.094
1	Base	1.600	1.000	1.598	0.618	0.097	0.547
1B	Lenient	0.800	1.000	3.196	0.412	0.130	0.365

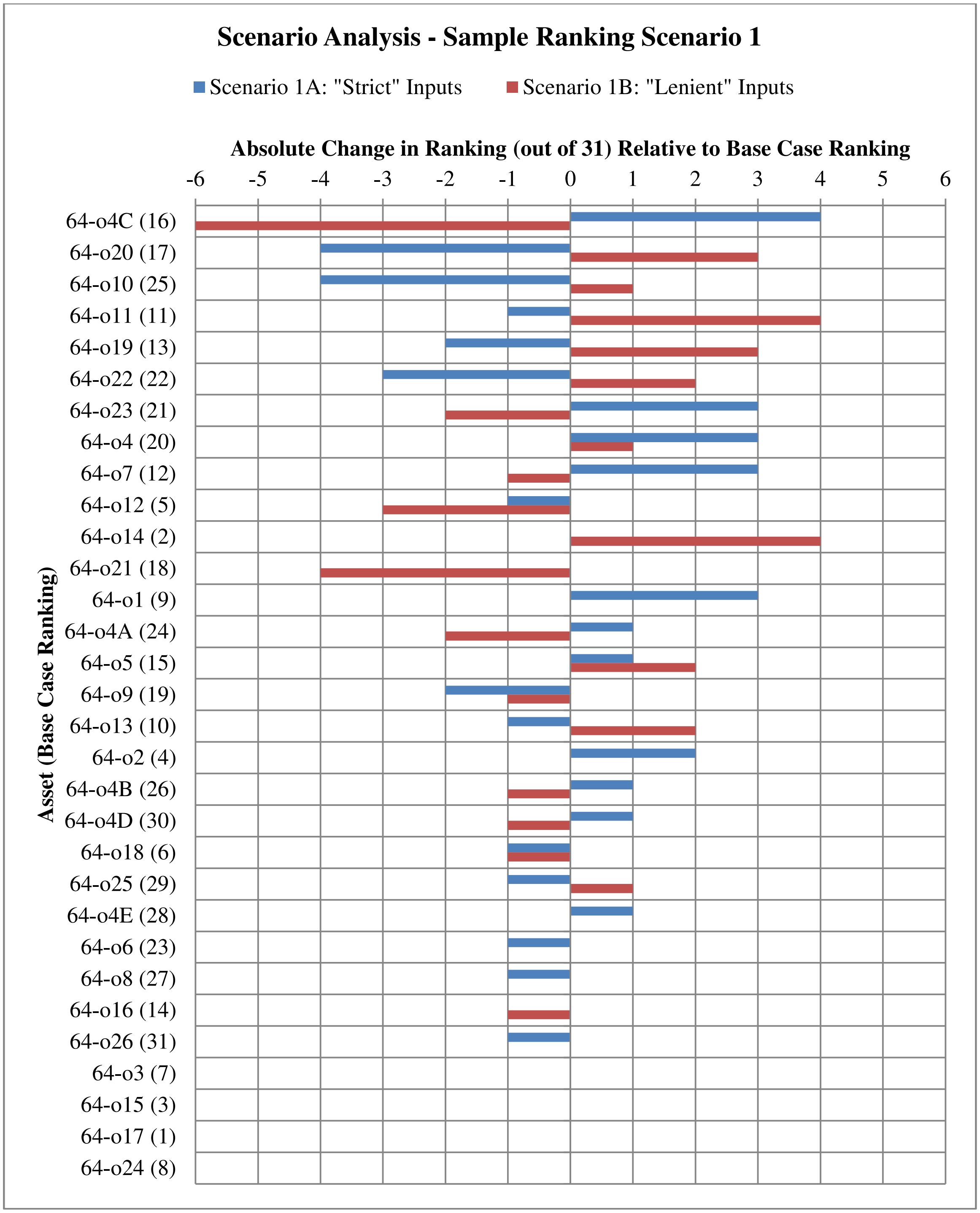

Figure 5-20: 31 VMS Ranked According to Absolute Change in Final Rankings in the “Strict” and “Lenient” Scenarios Relative to the Base-Case Scenario (Sample Ranking Scenario 1)

The absolute change in rank (out of the 31 ranking slots) relative to the base scenario rank for each of the 31 VMS in response to the two different systematic variations in input values, Scenarios 1A and 1B, are summarized in the tornado chart in

Figure 5-20 in order of most sensitive to least sensitive from top to bottom. The base scenario rankings are shown in parentheses for each asset on the vertical axis. Negative absolute changes in ranking indicate that priority becomes higher, while positive changes indicate that priority becomes lower. Figure 5-20 suggests that VMS 64-o4C is the asset whose ranking from sample ranking scenario 1 is the most sensitive to systematic variations in the input values, as well as that VMS 64-o3, -o15, -o17, and o-24 are the assets whose rankings are the least sensitive.

Figure 5-20 shows the top-ranked asset from sample ranking scenario 1, VMS 64-o17, to be insensitive to multiple large variations in input values. In other words, based on the scenario analysis performed, assurance that VMS 64-o17 should indeed be given top priority for obsolescence management attention is increased. In this case the increase in assurance that VMS 64-o17 deserves top-priority status is not surprising given the fact that its total weighted score was over 17 points higher on the 100-point scale than the second-ranked VMS in Table 5-7. However, scenario analysis can provide additional value to decision-makers in cases where assuredness of the ranking of any given asset is not as obvious. Differences in total weighted scores between adjacently ranked assets do not necessarily correspond to relative sensitivities of the ranks to systematic variations in the inputs. For example, Table 5-7 shows that VMS 64-o15 is ranked third with a total weighted score of 67.16 that is nestled between the scores of 67.39 and 66.92 for the assets ranked second and fourth, respectively, and thus its rank would be expected to be sensitive. However, Figure 5-20 reveals its rank to be insensitive. It is also reassuring that, as summarized in Figure 5-20, many of the VMS with the most sensitive ranks according to this scenario analysis were not highly ranked in the base scenario. Such assets would be unlikely to be top priorities for spending extra effort gaining additional assurance of the accuracy of their ranks.

CHAPTER 6 – CONCLUSIONS, RECOMMENDATIONS, AND FURTHER RESEARCH

6.1 – CONCLUSIONS

Many Intelligent Transportation Systems (ITS) are aging, experiencing significant maintenance needs, or becoming functionally obsolete, but there is a gap in experience and knowledge regarding the management of ITS. The research done for this thesis suggests that the systems engineering process, particularly system boundary definition and multi-criteria ranking analysis, is a useful framework for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure. Also, the research suggests that the principle of best-first management within the practice of transportation asset management should be considered as an option in developing obsolescence risk rankings for ITS, at least once a system of ITS devices has been brought up to some minimum state of repair.

The research done for this thesis suggests there are two key considerations in choosing metrics for ITS obsolescence management. The first consideration is the fundamental difference between technical obsolescence for electronic equipment and physical deterioration of traditional assets such as pavement and bridges. In particular, ITS infrastructure is subject to the rapid pace of technological change, faster aging than other transportation assets, and quicker functional obsolescence than other transportation assets. ITS infrastructure is constantly subject to changes in the status of manufacturers of devices and spare parts, changes in production of specific models, changes in software versions and communications protocols, and changes in the availability of device and software support. ITS infrastructure can be managed effectively by tracking those changes and continually using multi-criteria prioritization to help respond to them in the right order and in the right way. Traditional metrics considered for pavement or bridge management systems, such as surface roughness, cracking, deformation, deflection, and structural strength (Li & Kazmierowski, 2004), are insufficient or inadequate for ITS infrastructure. Metrics to consider for ITS infrastructure are listed in Section 4.3 as well as under Recommendation C in Section 6.2. A physical condition metric category is included but a much broader range of metrics related to technical obsolescence is appropriate for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure. The principles of ITS asset management are similar to the principles of asset management for traditional assets such as pavement and bridges, but the information technology challenges of ITS, particularly technical obsolescence, are what is new.

The second key consideration in choosing metrics for ITS obsolescence management is the cost of data collection. Continual monitoring of data being collected for prioritization can yield information about criticality of, and degree of mutual information between, metrics. For example, if monitoring shows that two metrics consistently contain a high degree of mutual information, the agency is more empowered to make the well-informed, cost-effective decision of ceasing data collection for one of them and dropping it from future applications of the methodology. Also, if a certain metric has a weight that was soundly determined but that many applications of the methodology over time shows rankings to be very insensitive to, data collection can likewise be ceased.

Obsolescence risk rankings of ITS devices and systems depend on the relative degrees of importance that the agency attaches to each chosen metric. In other words, priorities are based on value judgments, and the value judgments should be those of the agency and the public that the agency serves.

In order to address aging and obsolete ITS infrastructure, analysis must be performed to define which existing ITS devices and systems are aging or obsolete and thus in need of intervention. Agency resources should not be spent predicting the future costs and benefits of alternative intervention options for existing ITS devices and systems that do not need intervention. Resources should instead be spent ranking alternative interventions for existing ITS devices and systems that have already been determined to be high priority in terms of need for intervention. A two-part methodology was established in this thesis in recognition of the difference between deciding which assets need to be addressed the most and deciding how to address those assets.

6.2 – RECOMMENDATIONS

The research done for this thesis suggests that a state DOT, particularly VDOT, would find the following elements of a process for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure desirable:

A. The adoption of a maintenance management system (MMS) that integrates and standardizes ITS obsolescence management throughout the state, either via in-house means or via outsourcing ITS maintenance management services
    a. VDOT is currently implementing this recommendation via the outsourcing option with Serco, Inc (VDOT, 2012c; VDOT, 2013a).

B. The building and continuous updating of a complete inventory of ITS devices, either in a MMS or in a separate database that can be linked to the MMS

    a. HRTOC is currently improving its inventory in preparation for the statewide transition to the Maximo MMS under the new TOC management contract with Serco, Inc. (N. Reed, personal communication, May 29, 2013).

C. The tracking of asset-specific data and associated system-level data on metrics relevant to ITS obsolescence risk ranking analysis, such as those listed in Section 4.3, which are summarized more concisely here:

    a. Physical condition ratings
    b. Accuracy of most critical output
    c. Down time or system availability
    d. Frequency of user complaints
    e. Dates and costs of original installation
    f. Dates, times of day, durations, and costs of past maintenance and repair activities, as well as what proportion of lanes were blocked off, if any, and for how long
    g. Quantities of identical or compatible spare devices and parts available that are already in the agency's possession
    h. Estimated availabilities or rates of production of identical or compatible spare devices and parts in the marketplace

i. Estimated longest reasonably possible extension of service live based on items g) and h)
j. Estimated future costs based on item i)
k. Performance of the associated communications network, such as the fiber optic network (e.g., age and condition of links, optical loss, and desired vs. actual data throughput)
l. Data on improvements to mobility, travel-time reliability, and safety that can reasonably be attributed to the presence of the ITS device or system of devices
m. Importance of location within the facility or segment as measured by traffic volume or person throughput

D. The defining of systems (and systems of systems) of ITS devices for prioritization

E. The continuous analysis of the correlations of data between metrics and the adding or deleting of metrics in prioritization analyses accordingly.

F. The establishment of relative weights between the metrics using reasonable assumptions for marginal rates of substitution (i.e., tradeoffs)

G. The ranking of ITS devices and systems in each defined system of ITS devices or systems

H. The continuous updating of ITS device and system rankings as more data comes in and as ITS projects, whether on the scale of a spare part replacement or the scale of a corridor-wide replacement of a legacy ITS system with a new and different ITS system, are completed

I. The continuous monitoring of ranking sensitivity to percent changes in individual weights, and the increase or decrease in effort expended towards ensuring accurate weights accordingly

J. The establishment of contingency weighting scenarios in preparation for events that would prompt major changes in agency values or strategic direction such as a major reduction in funding allocated for ITS management

K. The establishment of alternate weighting scenarios for helping to determine the confidence that can be had in the ranks of high-priority ITS devices and systems

L. The systematic consideration, via prediction of life-cycle costs and benefits metrics, of alternative interventions for ITS devices and systems determined to be high priority for receiving obsolescence management attention
    a. Sketch-planning tools such as IDAS can help quantify the costs and benefits of alternative ITS projects

M. The incorporation of historical maintenance data and results of historical prioritizations into ITS strategic planning and prediction of life-cycle costs and benefits of future ITS investments.

It is, however, not recommended that obsolescence ranking analysis be performed using number of work orders as a primary metric category except as a preliminary exercise in applying the methodology in preparation for greater data availability on the metrics listed under Recommendation C in the near future.

The recommendations listed in this section suggest that the implementation of this methodology in the form of an automated system that continuously receives data, updates asset priority to inform obsolescence-related decisions, and analyzes the priorities to alert staff to issues, is warranted. It is recommended that the system eventually be integrated into a comprehensive, automated ITS asset management system and that the maintenance data gathered for existing ITS be used for predicting life cycle costs of future ITS investments.

6.3 – FURTHER RESEARCH

The scenario analysis performed in Section 5.4 provides a fundamental demonstration of scenario analysis, but an even better scenario analysis would be to systematically vary the weights a very large number of times using Monte Carlo simulation (Gibson et al, 2007). An ITS asset management system that performs Monte Carlo simulation on each set of final rankings could be set to provide alerts to appropriate staff that the criticality of a metric or the rank of a high-priority device is uncertain. Monte Carlo simulation would be able to show analysts the effects that different assumptions about marginal rates of substitution would have on final ITS device and system priority. Depending on the size of the prioritization and the assets involved, changes in inputs could affect which ITS assets and projects, and thus which roadway segments and geographical areas, get funding first. The geographical distribution of funding for transportation improvements has socio-economic and political implications.

One shortcoming of this study is a lack of financial analysis. For example, budget constraints are not factored into the mathematical framework. Vanier et al (2006) incorporates optimization techniques from the study of operations research within the field of systems engineering to account for financial limitations. Another component to financial analysis of ITS obsolescence management prioritization not considered in this project is quantifying how much money is worth spending for prioritization analysis given the benefits of any particular prioritization analysis. Gibson et al (2007) emphasizes that the cost of the system study should not outweigh the predicted benefits from implementing the system study's recommendations.

As mentioned in Section 5.3.8, further research on risk analysis is warranted for the case of ITS obsolescence. The example provided in Section 5.3.8 is a basic obsolescence risk assessment that further research could improve upon. Other than Section 5.3.8, this project did not explicitly consider probabilistic methods. However, such methods are worthy of study given the risks involved in actions taken or not taken with ITS infrastructure.

6.4 – RESEARCH SUMMARY

This thesis provided a foundational methodology for prioritizing the maintenance and replacement of aging or obsolete ITS infrastructure using the principles of transportation asset management and multi-criteria decision analysis methods within the field of system engineering. The research completed for this project addresses the problem of ITS aging, experiencing significant maintenance needs, and becoming functionally obsolete by applying existing management and decision analysis techniques to the specific research area of ITS asset management. The methodology could be made more robust with better financial and risk analysis as well as additional and more advanced decision methods from systems engineering. Also, further refinement would be necessary for integration into an automated ITS asset management system.

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APPENDIX A – YEARLY DATA

Table A-1: Number of Work Orders in MMS Database (HRTOC, 2013)

Asset	Number of Work Orders in MMS Database										
	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total (Data for Metric 1)	Average (Data for Metric 2)
64-o1		4	7	1	3	0	5	5	9	34	4.250
64-o2		5	10	10	12	4	6	23	17	87	10.875
64-o3		3	3	5	9	3	7	11	13	54	6.750
64-o4		3	1	0	1	0	3	6	5	19	2.375
64-o4A									4	4	4.000
64-o4B									3	3	3.000
64-o4C								2	3	5	2.500
64-o4D										0	0.000
64-o4E									2	2	2.000
64-o5	1	3	2	1	0	5	1	8	3	24	2.667
64-o6	1	1	2	0	1	1	1	2	2	11	1.222
64-o7		1	0	0	0	2	2	4	7	16	2.000
64-o8	1	0	1	1	0	0	0	1	2	6	0.667
64-o9		2	0	1	0	1	2	6	4	16	2.000
64-o10		1	1	0	0	4	2	3	1	12	1.500
64-o11	1	2	2	5	5	8	2	3	2	30	3.333
64-o12						5	3	24	12	44	11.000
64-o13		1	10	0	1	2	3			17	2.833
64-o14		6	4	22	35	9	5	9	7	97	12.125
64-o15	4	12	4	5	4	1	6	15	20	71	7.889
64-o16				3	0	0	0	4	6	13	2.167
64-o17	1	16	9	11	0	17	1	12	24	91	10.111
64-o18	3	6	6	4	6	2	4	10	15	56	6.222
64-o19		3	1	4	1	8	2	1	4	24	3.000
64-o20	1	5	1	2	1	4	3	0	2	19	2.111
64-o21		2	0	2	0	2	2	0	6	14	1.750
64-o22		1	0	2	1	1	3	0	1	9	1.125
64-o23		1	2	1	2	0	0	4	4	14	1.750
64-o24	1	9	11	9	0	1	1	5	13	50	5.556
64-o25		4	1	0	1	1	2	3	1	13	1.625
64-o26							2	4	0	6	2.000

Table A-2: Change in Number of Work Orders from Previous Year (HRTOC, 2013)

Asset	Change in Number of Work Orders from Previous Year									
	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average (Data for Metric 3)
64-o1			3	-6	2	-3	5	0	4	0.714
64-o2			5	0	2	-8	2	17	-6	1.714
64-o3			0	2	4	-6	4	4	2	1.429
64-o4			-2	-1	1	-1	3	3	-1	0.286
64-o4A										0.000
64-o4B										0.000
64-o4C									1	1.000
64-o4D										0.000
64-o4E										0.000
64-o5		2	-1	-1	-1	5	-4	7	-5	0.250
64-o6		0	1	-2	1	0	0	1	0	0.125
64-o7			-1	0	0	2	0	2	3	0.857
64-o8		-1	1	0	-1	0	0	1	1	0.125
64-o9			-2	1	-1	1	1	4	-2	0.286
64-o10			0	-1	0	4	-2	1	-2	0.000
64-o11		1	0	3	0	3	-6	1	-1	0.125
64-o12							-2	21	-12	2.333
64-o13			9	-10	1	1	1			0.400
64-o14			-2	18	13	-26	-4	4	-2	0.143
64-o15		8	-8	1	-1	-3	5	9	5	2.000
64-o16					-3	0	0	4	2	0.600
64-o17		15	-7	2	-11	17	-16	11	12	2.875
64-o18		3	0	-2	2	-4	2	6	5	1.500
64-o19			-2	3	-3	7	-6	-1	3	0.143
64-o20		4	-4	1	-1	3	-1	-3	2	0.125
64-o21			-2	2	-2	2	0	-2	6	0.571
64-o22			-1	2	-1	0	2	-3	1	0.000
64-o23			1	-1	1	-2	0	4	0	0.429
64-o24		8	2	-2	-9	1	0	4	8	1.500
64-o25			-3	-1	1	0	1	1	-2	-0.429
64-o26								2	-4	-1.000

Table A-3: Total Time Spent Completing Work Orders in MMS Database (HRTOC, 2013)

Asset	Total Time Spent Completing Work Orders in MMS Database (hr)										
	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total (Data for Metric 4)	Average (Data for Metric 5)
64-o1		7.50	22.40	2.00	11.50	0.00	11.00	9.50	36.00	99.90	12.488
64-o2		69.50	33.75	14.25	16.25	11.50	29.25	43.00	84.45	301.95	37.744
64-o3		10.25	5.50	16.50	28.80	5.25	18.00	38.00	62.55	184.85	23.106
64-o4		4.50	2.00	0.00	21.00	0.00	19.75	18.50	11.00	76.75	9.594
64-o4A									56.20	56.20	56.200
64-o4B									2.75	2.75	2.750
64-o4C								12.00	2.50	14.50	7.250
64-o4D										0.00	0.000
64-o4E									2.25	2.25	2.250
64-o5	0.75	3.50	16.75	2.00	0.00	11.00	3.25	18.00	3.75	59.00	6.556
64-o6	0.75	1.50	25.50	0.00	10.50	2.00	2.00	2.50	16.25	61.00	6.778
64-o7		1.00	0.00	0.00	0.00	6.00	29.00	231.00	9.50	276.50	34.563
64-o8	1.00	0.00	4.00	0.50	0.00	0.00	0.00	7.00	0.50	13.00	1.444
64-o9		11.00	0.00	0.50	0.00	1.00	6.00	14.00	3.35	35.85	4.481
64-o10		1.00	0.25	0.00	0.00	5.50	4.00	5.25	2.50	18.50	2.313
64-o11	2.00	37.25	4.35	12.50	35.25	7.75	6.00	21.00	131.50	257.60	28.622
64-o12						6.50	8.00	51.75	21.25	87.50	21.875
64-o13		12.00	80.75	0.00	6.00	2.50	38.50			139.75	23.292
64-o14		99.75	10.05	62.75	120.50	15.00	18.00	13.50	74.00	413.55	51.694
64-o15	13.80	35.75	48.90	17.00	7.25	16.00	31.00	25.75	75.00	270.45	30.050
64-o16				16.00	0.00	0.00	0.00	22.75	6.00	44.75	7.458
64-o17	0.00	55.55	57.00	38.00	5.00	64.50	16.00	112.50	60.50	409.05	45.450
64-o18	11.00	7.50	7.75	15.75	25.25	7.50	9.00	38.25	39.75	161.75	17.972
64-o19		20.00	2.00	8.25	4.50	21.50	13.50	2.00	3.75	75.50	9.438
64-o20	2.00	59.65	5.00	15.50	13.00	15.25	25.50	0.00	2.50	138.40	15.378
64-o21		19.50	0.00	1.25	0.00	21.75	3.50	0.00	8.00	54.00	6.750
64-o22		2.00	0.00	13.50	3.00	0.25	12.00	0.00	0.25	31.00	3.875
64-o23		4.00	2.80	0.50	4.00	0.00	0.00	22.50	3.50	37.30	4.663
64-o24	1.00	56.35	28.95	25.00	0.00	3.00	5.00	12.00	36.25	167.55	18.617
64-o25		18.00	1.00	0.00	0.00	2.00	24.00	24.00	4.00	73.00	9.125
64-o26							10.50	5.25	0.00	15.75	5.250

Table A-4: Change in Total Time Spent Completing Work Orders from Previous Year (HRTOC, 2013)

	Change in Total Time Spent Completing Work Orders from Previous Year									
Asset	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average (Metric 6)
64-o1			14.90	-20.40	9.50	-11.50	11.00	-1.50	26.50	4.071
64-o2			-35.75	-19.50	2.00	-4.75	17.75	13.75	41.45	2.136
64-o3			-4.75	11.00	12.30	-23.55	12.75	20.00	24.55	7.471
64-o4			-2.50	-2.00	21.00	-21.00	19.75	-1.25	-7.50	0.929
64-o4A										0.000
64-o4B										0.000
64-o4C									-9.50	-9.500
64-o4D										0.000
64-o4E										0.000
64-o5		2.75	13.25	-14.75	-2.00	11.00	-7.75	14.75	-14.25	0.375
64-o6		0.75	24.00	-25.50	10.50	-8.50	0.00	0.50	13.75	1.938
64-o7			-1.00	0.00	0.00	6.00	23.00	202.00	-221.50	1.214
64-o8		-1.00	4.00	-3.50	-0.50	0.00	0.00	7.00	-6.50	-0.063
64-o9			-11.00	0.50	-0.50	1.00	5.00	8.00	-10.65	-1.093
64-o10			-0.75	-0.25	0.00	5.50	-1.50	1.25	-2.75	0.214
64-o11		35.25	-32.90	8.15	22.75	-27.50	-1.75	15.00	110.50	16.188
64-o12							1.50	43.75	-30.50	4.917
64-o13			68.75	-80.75	6.00	-3.50	36.00			5.300
64-o14			-89.70	52.70	57.75	-105.50	3.00	-4.50	60.50	-3.679
64-o15		21.95	13.15	-31.90	-9.75	8.75	15.00	-5.25	49.25	7.650
64-o16					-16.00	0.00	0.00	22.75	-16.75	-2.000
64-o17		55.55	1.45	-19.00	-33.00	59.50	-48.50	96.50	-52.00	7.563
64-o18		-3.50	0.25	8.00	9.50	-17.75	1.50	29.25	1.50	3.594
64-o19			-18.00	6.25	-3.75	17.00	-8.00	-11.50	1.75	-2.321
64-o20		57.65	-54.65	10.50	-2.50	2.25	10.25	-25.50	2.50	0.063
64-o21			-19.50	1.25	-1.25	21.75	-18.25	-3.50	8.00	-1.643
64-o22			-2.00	13.50	-10.50	-2.75	11.75	-12.00	0.25	-0.250
64-o23			-1.20	-2.30	3.50	-4.00	0.00	22.50	-19.00	-0.071
64-o24		55.35	-27.40	-3.95	-25.00	3.00	2.00	7.00	24.25	4.406
64-o25			-17.00	-1.00	0.00	2.00	22.00	0.00	-20.00	-2.000
64-o26								-5.25	-5.25	-5.250

APPENDIX B – SURVEY

Methods for Managing ITS Obsolescence
Survey of the State DOTs

Virginia Department of Transportation (VDOT)
Virginia Center for Transportation Innovation and Research (VCTIR)

THIS SURVEY

- **Deals with ITS obsolescence management**
- **Seeks answers to two main questions…**

1. **How does your agency decide what to do with mature ITS* assets?** [PROJECT IDENTIFICATION]
   Possible choices might include:
   - ❖ Keep as is
   - ❖ Maintain
   - ❖ Repair/Rehabilitate
   - ❖ Replace (If so, determine the best new technology)
   - ❖ Remove
   - ❖ Abandon
2. **How does your agency rank or prioritize approved projects addressing mature ITS* assets?** [PROJECT PRIORITIZATION]

   *****"Mature ITS" here refers to any older or legacy ITS experiencing significant maintenance needs or becoming functionally obsolete.
   *****Includes ITS assets that might be managed by a traffic operations center, **not including traffic signals**.

INSTRUCTIONS – PLEASE READ

- ➢ **Please use the text boxes in this survey to provide as much supporting information as possible, including URLs.**
  - ❖ **Please send supporting documents to ross.powers@vdot.virginia.gov.**
    - ▪ For example, if a question asks if your agency has a program for managing ITS obsolescence, and your agency has documentation or URLs regarding that program, please provide those information sources. This research project has found very little information about ITS obsolescence management. This survey is our primary means of filling that critical information gap.
    - ▪ Some questions have strongly agree, agree, disagree, and strongly disagree as answer choices to accommodate varying degrees of

yes/no, comprehensiveness, and consistency. Please justify your answer by providing as much supporting information as possible.

- **This survey asks about your state DOT as a whole, but it is acknowledged that methods for managing ITS obsolescence might vary between regions/districts within your state. If so, please do one or both of the following:**
  - Explain the situation in your responses.
  - Distribute this survey to the appropriate regional staff and provide their contact information.

SECTION 1: Preliminary Questions

1. What state DOT are you affiliated with? {DROP DOWN MENU}

2. Are you answering this survey for your state as a whole or for a region or district?
   a. State as a whole
   b. Region/District

   Please specify your region/district if applicable. Also use this space for any further explanation you wish to provide.

3. What groups or offices in your agency are involved in ITS obsolescence management? Briefly describe their roles.

4. Which of the following best describes your agency's approach to ITS obsolescence management?
   a. A formal statewide program has been developed with written policies and procedures.
   b. Regions have their own local plans and procedures, but there is no consistent statewide program.
   c. Decisions are made on a project by project basis, and there is no formal statewide or regional approach.
   d. Other

   Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

5. Does your agency have at least a partial inventory of ITS assets?
   a. Yes
   b. No.

Please provide any comments or explanation here.

6. {If answer to Question 5 is Yes} What is a good estimate of the percentage of your state's ITS assets that are accounted for in your agency's inventory?
   a. 80-100%
   b. 60-80%
   c. 40-60%
   d. 20-40%
   e. 0-20%

   Please provide any comments or explanation here.

7. {If answer to Question 5 is Yes} How often does your agency update its inventory of ITS assets?

8. Does your agency have a computer system for managing ITS assets beyond simple inventory?
   a. Yes
   b. No

   Please provide any comments or explanation here.

SECTION 2: Questions about Project Identification

9. Your agency has developed a method for establishing the best option for any given mature ITS asset:
   - Keep as is
   - Maintain
   - Repair/Rehabilitate
   - Replace (If so, determine the best new technology)
   - Remove
   - Abandon

   a. Strongly agree
   b. Agree
   c. Disagree
   d. Strongly disagree

   Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

10. {If answer to Question 9 is Strongly agree or Agree} Regarding your agency's method for establishing the best option for any given mature ITS asset: What criteria are used in the method for establishing the best option?

11. {If answer to Question 8 is Yes and if answer to Question 9 is Strongly agree or Agree} Is your agency's method for establishing the best option for any given mature ITS asset built into your agency's computer system for managing ITS assets?
    a. Yes
    b. No

    Please provide any comments or explanation here.

12. {If answer to Question 9 is Strongly agree or Agree} Has your agency applied in practice its method for establishing the best option for any given mature ITS asset?
    a. Yes
    b. No

    Please provide any comments or explanation here.

SECTION 3: Questions about Project Prioritization

13. Your agency has developed protocol for prioritizing projects addressing mature ITS assets.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

14. {If answer to Question 13 is Strongly agree or Agree} Regarding your agency's protocol for prioritizing projects addressing mature ITS assets: What criteria are used in the protocol for prioritizing the projects?

15. {If answer to Question 8 is Yes and if answer to Question 13 is Strongly agree or Agree} Is your agency's protocol for prioritizing projects addressing mature ITS assets built into your agency's computer system for managing ITS assets?
    a. Yes
    b. No

    Please provide any comments or explanation here.

16. {If answer to Question 13 is Strongly agree or Agree} Has your agency applied in practice its protocol for prioritizing projects addressing mature ITS assets?
    a. Yes
    b. No

    Please provide any comments or explanation here.

SECTION 4: Questions about Tracking Total Effectiveness

17. Your agency evaluates or tracks the effectiveness of its project identification and prioritization procedures addressing mature ITS assets.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree
    e. Not Applicable (i.e., no such procedures exist)

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

18. {If answer to Question 17 is Yes} Please describe how your agency evaluates or tracks the effectiveness of its project identification and prioritization procedures addressing mature ITS assets. Please include a list of the performance measures used.

19. {If answer to Question 17 is Yes} Tracking the procedures' effectiveness has shown improvements in performance as measured by the performance measures that you listed in the previous question.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

20. {If answer to Question 17 is Yes} Does your agency quantify the effect of its project identification and prioritization procedures addressing mature ITS assets on OPERATIONS COSTS?
    a. Yes
    b. No

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

21. {If answer to Question 20 is Yes} Your agency's project identification and prioritization procedures addressing mature ITS assets have been shown to be effective in REDUCING OPERATIONS COSTS.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

22. {If answer to Question 17 is Yes} Does your agency quantify the effect of its project identification and prioritization procedures addressing mature ITS assets on MAINTENANCE COSTS?
    a. Yes
    b. No

Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

23. {If answer to Question 22 is Yes} Your agency's project identification and prioritization procedures addressing mature ITS assets have been shown to be effective in REDUCING MAINTENANCE COSTS.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

24. {If answer to Question 17 is Yes} Does your agency quantify the effect of its project identification and prioritization procedures addressing mature ITS assets on TRAFFIC CONGESTION?
    a. Yes
    b. No

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

25. {If answer to Question 24 is Yes} Your agency's project identification and prioritization procedures addressing mature ITS assets have been shown to be effective in MITIGATING TRAFFIC CONGESTION.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

SECTION 5: Further Questions about ITS Obsolescence Management

26. Your agency has enough staff for managing ITS obsolescence.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

27. Your agency has plans to improve and/or expand its program of managing ITS obsolescence.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

28. Your agency is developing policies, developing long term strategies, or carrying out visioning exercises to help proactively adapt its ITS obsolescence management program to future technology trends and operations needs.
    a. Strongly agree
    b. Agree
    c. Disagree
    d. Strongly disagree

    Please use this box to provide as much information as possible related to the question or supporting your answer to the question. Please compose or paste text and/or provide URLs. Also, documents can be sent to ross.powers@vdot.virginia.gov.

29. What problems have you encountered in your agency in developing an ITS obsolescence management program?

30. Please describe any lessons that your agency has learned about managing ITS obsolescence.

31. Would you like a copy of the final report of this research project?
    a. Yes
    b. No
32. Thank you very much for taking this survey for the Virginia Department of Transportation (VDOT) and the Virginia Center for Transportation Innovation and Research (VCTIR). So that we may contact you later if we have further questions, and/or so that we may send you a copy of the final report, please enter your name and contact information here. If others in your organization can be contacted for future questions as well, please enter their contact information too.

If you have questions about this survey, please contact:

Ross Powers
Graduate Research Assistant
Virginia Center for Transportation Innovation and Research
Virginia Department of Transportation
Ross.Powers@VDOT.Virginia.gov
703.350.8599