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**THE APPLICATION OF SENSORS ON GUARDRAILS FOR THE PURPOSE OF
REAL TIME IMPACT DETECTION**

THESIS

Matthew D. Sturtevant, Captain, USAF

AFIT/GEM/ENV/12-M20

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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AFIT/GEM/ENV/12-M20

THE APPLICATION OF SENSORS ON GUARDRAILS FOR THE PURPOSE OF
REAL TIME IMPACT DETECTION

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Engineering Management

Matthew D. Sturtevant, B.S.

Captain, USAF

March 2012

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THE APPLICATION OF SENSORS ON GUARDRAILS FOR THE PURPOSE OF
REAL TIME IMPACT DETECTION

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Captain, USAF

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Abstract

The United States roadway system has deteriorated over time due to its age, increasing delays in completing preventative maintenance, and the lack of timely repairs following damage to the infrastructure. The seriousness of this issue has motivated the US Department of Transportation and Transportation Research Board to develop and deploy new methods and technologies that can provide cost effective management of transportation infrastructure. Proper asset management drives the need for generalized methods to integrate new sensing capabilities into existing Intelligent Transportation Systems in a time efficient and cost effective manner.

In this thesis, we present a methodology for the deployment of new sensors into an existing ITS system. The proposed methodology employs a three phase approach that incorporates data modeling, spatial analysis in Geographic Information Systems, and cost optimization to provide enhanced decision support when deploying new sensing capabilities within an existing ITS. Additionally, we also demonstrate the usefulness of computing while integrating these new sensors using a guardrail sensor case study and focusing on data modeling. The results of the three phase methodology demonstrate an effective means for planning new sensor deployments by analyzing tradeoffs in equipment selection yielding the minimum cost solution for a given set of requirements. Furthermore, the results of the data models demonstrate necessary considerations that must be made with a systems engineering method. The data models accomplish this while accounting for asset management principles taking a systematic approach and incorporating engineering principles.

To wife and son who, together, are my source of strength.

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I would like to express my sincere appreciation for my thesis advisor, LtCol William Sitzabee for his diligent guidance and mentorship. I would also like to thank the other members of my thesis committee, Dr. Michael R. Grimaila and LtCol Tay Johannes. Dr. Grimaila has provided invaluable guidance in how to approach the issues raised in this thesis, most extensively the data modeling. In addition, he provided countless hours of guidance in the execution of modeling the intelligent transportation system. I would also like to thank members of the Ohio Department of Transportation, Mr. George Saylor and Bryan Comer, who have spent a great deal of time providing details of the ODOT ITS network. The information they've provided has been the basis of the data modeling. The ODOT ITS is intended to be the model for this thesis and they've made it a reality. Additionally, I want to thank 1 Lt Grant Jordan from the Air Force Research Labs Center for Rapid Product Development. He has, on multiple occasions, demonstrated the detailed workings of his motion activated sensors. His efforts have opened my eyes to what's possible in the transportation industry. Lastly, I want to thank my family. My wife and son are my reason for living and have sacrificed a great deal so that I might complete my master's education at AFIT. I am forever in your debt.

Matthew D. Sturtevant

Table of Contents

	Page
Abstract	iv
Dedication	v
Acknowledgments	vi
Table of Contents	vii
List of Figures	ix
List of Tables	x
I. Introduction	1
Background	1
Problem Statement	3
Research Objectives	5
Methodology	6
Assumptions and Limitations	7
Preview	9
II. Conference Paper	10
Abstract	10
Introduction	11
Development of ITS	13
Asset Management	15
Guardrail Systems	18
Combing ITS and guardrails	20
Conclusion	23
References	25
III. Scholarly Article	27
Abstract	27
Introduction	28
An Asset Management Based Methodology for Integrating Sensors into an Existing ITS	30
Example Application of the Methodology	35
Conclusions	54

	Page
References	57
Figure Captions List.....	59
IV. Scholarly Article	62
Abstract	62
Introduction	63
Background	65
Methodology	70
Results	76
Conclusions	79
Key Findings	80
References	83
Figure Captions List.....	85
V. Conclusions	90
Key Findings	95
Future Research.....	95
Appendix A – Expanded Literature Review	98
Appendix B – Preliminary Methodology.....	113
Vita.....	127

List of Figures

	Page
Figure 1: ODOT SV-1 Systems/Services Interface Description.....	60
Figure 2: ODOT DIV-2 “Logical Data Model.”.....	61
Figure 1: SV-1 or systems view of the network.	86
Figure 2: Data flow view (DIV-2).	87
Figure 3: Entity Relationship Diagram (ERD).	88
Figure 4: Operational view (OV-6C) displaying operational activity.	89

List of Tables

	Page
Table 1: DODAF Version 2.0 Viewpoints (DoDAF, 2010).....	32
Table 2: Selected guardrail coordinates for the guardrail sensor network.....	42
Table 3: Concord TSP solution for guardrail midpoint connections	46
Table 4: Number of sensors per guardrail and cost	48
Table 5: Communication media types with costs and ranges	51
Table 6: Required communication media for each guardrail link	52
Table 7: Total estimated cost per guardrail over 30 year lifecycle.....	53

THE APPLICATION OF SENSORS ON GUARDRAILS FOR THE PURPOSE OF REAL TIME IMPACT DETECTION

I. Introduction

Background

The history of transportation dates to the Egyptian Pharaohs, Roman Legions and Chinese Dynasties; however, the history of intelligent transportation systems (ITS) is far more recent (Wootton, 1995). The US Department of Transportation (DOT) started a program called Mobility 2000 in 1987, which eventually became the Intelligent Vehicle-Highway System (IVHS) in 1988. IVHS then became part of public law by Congress to be part of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. Since then the committee known as IVHS America has been advising the U.S. DOT while it meets the requirements set forth in the ISTEA.

The need for IVHS and Intelligent Transportation Systems has arisen out of a need to manage and maintain the current highway infrastructure as the construction of roads is now considered to be complete (Wootton, 1995). By definition, ITS refers to efforts to improve the overall efficiency of transportation systems and infrastructure using modern computing and communication and data processing technologies (Tarko and Roupail, 1997). Transportation industry officials are trying to improve our roadways and increase the safety and usability of our roads without the need to build new ones.

In addition to the roles ITS plays, there is now a need for the improvement of the nation's transportation infrastructure. The systems are deteriorating due to age and

increased stress. The result is an increased need for new technology which will bridge the gap between outdated, unsafe infrastructure and longer lasting, smart systems that will work for the departments of transportation across the country. The Transportation Research Board and U.S. DOT Research and Innovative Technology Administration both recognized this need and responded by collaborating on a conference to discuss improvements to these systems (Schofer et al., 2010). Out of the conference came the recognition of several needs. Two items of note include continued development of infrastructure condition and performance sensors as well as methods for rapid testing of new materials and designs. These two topics encourage the development of technologies, like remote sensors attached to the guardrails, to both monitor life cycle and signal when damage occurs (Schofer et al., 2010).

Not only do infrastructure systems, which include guardrail systems, need updating due to increased stresses caused by aging, but the safety of those on the road plays a part as well. Approximately 90 percent of guardrail impacts go unreported. Approximately, six percent of the total impacts result in injuries or fatalities (Michie and Bronstad, 1994). Not much is known about the 90 percent that go unreported, but most likely some of these resulted in injuries as well. Regardless of the personal injury incurred during the accident, the guardrail damage still costs the taxpayer. Either one of these factors is reason for concern. Furthermore, studies show of the six percent of accidents resulting in injuries or fatalities many involve guardrails that are out of date, incorrectly constructed, inadequately maintained, or involve accidents that are outside the design range of modern guardrail systems (Michie and Bronstad, 1994). For these

reasons the US DOT and Transportation Research Board want to improve highway infrastructure that may be causing traffic related injuries or fatalities. The need for improved guardrails, the need for improving the safety of those on the highway, and the affixing of sensors to guardrails are relevant research areas.

It can be argued that guardrails containing sensors could be used both for safety purposes and as monitors for the health of the guardrail system itself. The need for improved guardrails is evident from the conference of the Transportation Research Board and U.S. DOT and the data regarding guardrail related traffic accidents. The next step is to further develop the implications new technology has on the current network architecture while accounting for asset management (AM) principles. AM by definition "is a systematic process of maintaining, upgrading, and operating physical assets cost effectively...AM provides a framework for handling both short- and long-range planning" (FHWA, 1999). To account for proper AM and develop the concept of integrating guardrail sensors into an existing ITS network, a methodology has been developed for new technologies. Additionally, demonstrating the importance of computing during this integration process is also developed.

This thesis explores in more detail the importance of asset management and how to account for it while systematically incorporating new technology such as guardrail sensors into an existing ITS network.

Problem Statement

Currently, the ITS is comprised of thousands of systems covering multiple sensor applications and video feeds. The current sensor networks include everything from

bridge condition monitoring to traffic flow detection via doppler radar. The video feeds monitor traffic lights, accidents, and congestion as well as road condition. The systems in use today across the US vary by state, but the need to improve on the road systems is always present.

Available technologies are a means to improve the aging and stressed transportation infrastructures of today. It is important that the existing infrastructure does not deteriorate to the point that it's unusable; it is important also to create the technology to make transportation safer, faster, and easier (Schofer et al., 2010).

It's apparent that building on the already important issue of applying sensors to guardrails is a next logical step in the improvement of transportation infrastructure. Incorporating sensor technology into the guardrails will enable state and local DOTs to alleviate the stress the current infrastructure is experiencing across the US, stress caused by the ever-increasing number of vehicles on the road, the increase in variation of size of individual vehicles on the road, and the age of the existing infrastructure. Guardrails are no exception to this wear and tear on current assets and the infrastructure of roadways. More specifically the w-beam guardrail, which is the most widely used guardrail in the country, currently serves only as a roadside barrier (Tabiei, 2000).

There is currently no integration of guardrails with existing ITS systems in use today. It has however been researched and a sensor developed by Jiao et al. They researched the feasibility of guardrail sensors in Beijing China and developed a working sensor (Jiao et al., 2008). As sensors have not been integrated yet, the only way to know if a guardrail requires repair or replacement is for personnel to survey guardrails in the

area. This is a process that wastes valuable time, money and resources. Safety features on the road today, such as the guardrail, could be aging at a rate faster than they are being maintained. A much more efficient way to accomplish surveying guardrails would be to add small motion activated sensors to them; these could notify both the DOT and law-enforcement agencies that an impact has occurred and that not only is maintenance required, but that someone needs help. The main issue addressed in this thesis involves examining the methodology for applying a new sensor on an existing ITS network and how the use of computing can enable that process. This is accomplished while keeping AM principles at the forefront of the research.

Research Objectives

The overarching research objectives are first, what is the most effective methodology for tying new sensors to an existing ITS network for the purposes of safety and maintenance? Second, how can computing be used to accomplish this? Third, how can this be done while considering asset management principles such as cost-effectiveness with short and long-range planning? Within those primary questions several other questions need to be answered before the concept of applying sensors on guardrails is investigated. The first question would be which guardrail design should be looked at first, before a sensor is built. The guardrail type will be the w-beam since it's the most prevalent across the U.S (Tabiei, 2000). The research accomplished here can help DOTs across the country in a wide variety of scenarios from small two-lane roads to larger highways with four or more lanes.

The next question is how will it be determined that the existing network can even accept additional sensor input with the already burdensome task of managing the current sensors? The burden from the addition of a new data source (guardrail sensor) on an existing ITS network needs to be determined before optimal locations and costs are determined. This burden from the additional data on the network will be discussed further within the methodology, but by modeling the network it can be investigated whether or not a new sensor would fit into ODOT's network. The state of Ohio has an extensive ITS network. Working with the ODOT office allows for a better understanding in terms of what's required to tie into these types of systems and even what sensors are more appropriate in terms of durability, lifespan and cost.

Methodology

Two separate methodologies are required for determining how to integrate a guardrail sensor into an existing network, and be able to collect information from that sensor when the guardrail is impacted. Each methodology is described in detail in respective papers. The first methodology includes a three phase approach proposed in order to explain the integration process. Developing the sensor that allows for the collection of impact data, will be accomplished notionally within this methodology. The three phases of this methodology will first include data modeling to demonstrate how the guardrail sensor will tie into the existing ODOT ITS network. The second phase will include Geographic Information Systems (GIS) to determine the optimum location of a sensor across a predetermined area. GIS is a class of information systems that keep track of events, activities and various geographical data as well as where these events and

activities occur allowing traffic accidents in Montgomery County Ohio to be modeled (Longley, 2011). Lastly, in the third phase the information garnered from existing sensors will be used to determine the optimum mix of cost and performance through a cost optimization formula.

The second methodology entails data modeling to describe the importance of computing in the integration process. The data modeling will be used to develop a blueprint of how the guardrail sensor network would tie into the existing network used at the Ohio Department of Transportation (ODOT). The data modeling methodology proposes two separate approaches and based on the requirements the most appropriate is chosen. These two approaches are Longley et al.'s GIS approach and the DoD systems engineering approach and based on the requirements the most appropriate is chosen.

Assumptions and Limitations

In regards to the assumptions being made, a critical one would be “all models are wrong, some are useful” (George Box, 1979). A model can never actually consider every event that really occurs. The extent to which modeling will be utilized for this thesis excludes factors, otherwise present in reality, out entirely. Looking at the issue of attaching sensors to guardrails from a user standpoint, it's critical to consider DOT employees. It is assumed that these personnel would be willing to work with the additional influx of information and strain on their individual networks or operating systems. The amount of information that Ohio DOT employees need to consider within the Ops Center is already immense. Another sensor sending even more data and also requiring some evaluation on a daily basis may overload the working capacity of

personnel. Another limitation to the modeling will occur when utilizing a cost model for determining the optimum cost for a guardrail sensor network. The sensor is built only hypothetically and so actual costs are subject to vary. These assumptions make the models developed within this thesis even more important if and when the argument is made to ODOT that this is a useful and necessary system. Further assumptions include the current model assuming the portion of how to accurately place sensors throughout individual guardrails has already been addressed or will be addressed later by someone else. Also, the cost for the links between guardrails is a function of distance. So as the length between links increases as does the cost. Limitations include the data utilized. Only 10% of the accident data garnered from the Ohio Public Safety database have locations assigned to them. This meant only the locations of 10% of the accidents were analyzed in the spatial analysis of Phase II. Also, some of the accidents have the same location listed multiple times meaning that the location was most likely recorded falsely and as such the accident data does not completely represent where the majority of vehicle accidents may have occurred. Further limitations include there are less accidents in rural areas and therefore harder to identify locations to place the sensors in those areas. Lastly, guardrail lengths were calculated using decimal degrees and then converted into radians accounting for the curvature of the earth, rather it is an estimate of length by changing the coordinates to radians. Correcting for the curvature of the earth would not however greatly affect the length of the guardrails and since a completely accurate measurement of guardrail length is not the focus of this research this is an acceptable limitation.

Preview

The remaining four chapters are the conference paper on the connection between AM and ITS in Chapter 2, a paper on the integration of the sensors methodology Chapter 3, a paper on the consideration for computing while integrating a sensor into an existing ITS network in Chapter 4, and the conclusions in Chapter 5. The literature review and previous methodology will be listed in the appendix. Each paper took an asset management approach in the respective research incorporating principles such as cost effectiveness, short and long-range planning and systematically approaching problems.

II. Conference Paper

Presented at the Annual Inter-University Symposium for Infrastructure Management (sites.google.com/site/aisimseven/)

Intelligent Transportation Systems and Asset Management

Matt D. Sturtevant, William E. Sitzabee, Peter Feng

Abstract

The need for Intelligent Transportation Systems (ITS) has arisen out of a need to manage and maintain the current highway infrastructure as the construction of major U.S. roads is now considered to be complete (Wootton, 1995). Due to the age and stress on current roads there's an increased need for new technology that will work for the departments of transportation across the country. Given the factors in safety, the prevalence of guardrails on today's highways and the strong urge by the U.S. DOT and other organizations, incorporating ITS into guardrails makes sense. Looking at the maintenance as well as safety standpoint, the lifecycle of the guardrails can be extended by incorporating new technologies. The 911 emergency systems and maintenance systems could be tied into a series of guardrail networks for any one area. The system would monitor for impacts at the guardrails and alert personnel when an incident occurs. The application of sensor systems on guardrails is a logical next step in ITS, the safety factors of collisions with guardrails, the systems already in use today and the fact that organizations such as the TRB and U.S. DOT are forging ahead with those in the transportation industry should be reason enough.

Introduction

The history of transportation dates back to the Egyptian Pharaohs, Roman Legions and Chinese Dynasties; however, the history of intelligent transportation systems (ITS) is far more recent. The U.S. Department of Transportation or DOT started a program called Mobility 2000 in 1987, which eventually became the Intelligent Vehicle-Highway System (IVHS) in 1988. IVHS then became part of public law by Congress to be part of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. Since then the committee known as IVHS America has been advising the U.S. DOT while meeting the requirements set forth in the ISTEA.

The need for IVHS and Intelligent Transportation Systems has arisen out of a need to manage and maintain the current highway infrastructure as the construction of roads is now considered to be complete (Wootton, 1995). By its very definition, ITS refers to efforts to improve the overall efficiency of transportation systems and infrastructure using modern computing, communication and data processing technologies (Tarko, 1997). Transportation industry officials are trying to improve our roadways and increase the safety and usability of our roads without the need to build new ones.

Asset management (AM) can be described as “a foundation from which to monitor the transportation system and optimize the preservation, upgrading , and timely replacement of highway assets through cost effective management, programming, and resource allocation decisions” (U.S. DOT, 2002). Given this, it should come as no surprise that ITS and asset management go hand in hand. In fact, ITS enables enhanced AM.

In addition to the roles ITS and asset management play, there is now a serious need for the improvement of the nation's transportation infrastructure. The systems are deteriorating due to age and increased stress. The result is an increased need for new technology which will bridge the gap between outdated, unsafe infrastructure and longer lasting, smart systems that will work for the departments of transportation across the country. The Transportation Research Board and U.S. DOT Research and Innovative Technology Administration both recognized this need and responded by collaborating on a conference to bring the very people together that can improve on these systems (Schofer, 2010). Out of the conference came the need for several items. Two items of note include continued development of infrastructure condition and performance sensors as well as methods for rapid testing of new materials and designs. These two topics alone encourage the development of technologies, like remote sensors attached to guardrails, to both monitor life cycle and signal when damage has occurred (Schofer, 2010).

Not only do infrastructure systems, which include guardrail systems, need to be updated due to age increased stresses, but the safety of those on the road plays a part as well. Approximately, 90 percent of guardrail impacts go unreported with only 10 percent of total accidents being reported (Michie, 1994). Only six percent of the total impacts are both reported and result in injury or fatality. Not much is known about the other 90 percent that go unreported. These are most likely not fatalities, but could be resulting in injuries. Regardless of the personal injury incurred during the accident, the guardrail damage still costs the taxpayer and no one is held liable. Either one of these factors are reason for concern. Furthermore, studies show that of the six percent of

accidents resulting in injuries or fatalities many involve guardrails that are out of date, incorrectly constructed, inadequately maintained, or involve accidents that are outside the design range of modern guardrail systems (Michie, 1994). It is for the exact same reasons the U.S. DOT and Transportation Research Board want to improve highway infrastructure that may be causing traffic related injuries or fatalities. Combine the need for improved guardrails with the need for improved safety related to highway traffic and the placement of sensors on guardrails becomes a relevant research area.

This paper explores in more detail the benefits and technologies associated with ITS, how asset management is applied to ITS, what guardrail systems exist today and finally how the technology can be combined with the existing guardrail systems on the road.

Development of ITS

Currently, ITS is comprised of thousands of systems covering multiple sensor applications and video feeds. The current sensor networks include everything from bridge condition health monitoring to traffic flow detection via bluetooth. The video feeds monitor traffic lights, accidents, and congestion as well as road condition. The systems in use today across the U.S. vary by state, but the need to improve on the road systems is always present.

The technologies currently available are a means to improve on the aging and stressed transportation infrastructure. When the U.S. DOT Research and Innovative Technology Administration sponsored a conference with the help from the Transportation Research Board (TRB), owners of the infrastructure and researchers discussed what can

be done to manage and preserve the nation's infrastructure. Four key research areas were identified that led to six research themes. The four key areas include,

1. Inventory and condition assessment.
2. Innovative and environmentally friendly materials for the preservation, restoration and reconstruction of the infrastructure.
3. Strategies for rapid repair and rehabilitation.
4. Methods to model the deterioration, estimate costs, and preservation.

These four overarching research areas can be further broken down into all their components, but for the purposes of the paper they are only mentioned. The idea behind all four areas is to successfully preserve and renew, as necessary, the current surface transportation infrastructure.

Schofer, et al define the six research themes that grew out of the four areas as:

1. Methods for rapid testing of new materials and designs.
2. Responsive and flexible standards and specifications for new materials and systems.
3. Updated inspection standards to support the new systems being utilized.
4. New methods to support infrastructure management processes.
5. Training and education.
6. Continued development of the sensors for condition and performance.

Funding and support remain critical to meet these ends. Without the proper financial needs met, the materials, hardware/software and staffing are not possible.

Wendell C. Lawther states that in order to be successful, the funds must be obtained year-

in and year-out to allow operations and maintenance to effectively continue (Sussman, 2005). Support from the U.S. DOT is clear and they have made great strides in getting the technology on the road.

Asset Management

Asset management is a basis to manage the transportation assets currently in use across the U.S. The assets include highway systems as well as airport systems and transit systems. It also does not only refer to inorganic components of all these systems, but to the human element involved in their management as well (U.S. DOT, 2002).

ITS is fundamental to asset management with literally thousands of separate systems across the U.S. all involving highway infrastructure components. Management of ITS as an asset is the basis for transportation infrastructure management. Typical infrastructure management systems involve pavement management, management of bridges, other structures aside from bridges, maintenance management, other DOT-maintained facilities and other modal facilities. It's under this structure that ITS and guardrails are currently managed. More specifically, ITS installations are under the category of the management of bridges and other structures where certain areas, i.e. - retaining walls and the ITS installations, are managed from. Guardrails are under other DOT-maintained facilities and features and while different from where the ITS installations are managed they are both considered a part of infrastructure management systems and both under the umbrella of asset management (U.S. DOT, 2002).

Developing performance measures is critical for a states DOT's in order for long range planning and program development. Similar to each state are the standards,

measures of deterioration, management philosophies, customer perceptions and data collection methods; however, there are major differences in the measures of performance for policy goals and objectives (U.S. DOT, 2002). The goal here is to propose useable measures based on the experience of experts from Washington States DOT.

The Washington State DOT recognized that planning and programming were weaknesses in the performance measure category for the asset management of ITS. The three primary categories they proposed were as follows;

1. Vertical integration and consistency throughout the planning and programming process.
2. Prioritization formulas and project selection criteria.
3. Performance-based planning.

To expand a little on each category, the vertical integration and consistency applies to policy guidance through the defining of the planning of service objectives. It also includes defining system performance measures as well as deriving prioritization formulas.

Prioritization formulas should be based on benefit to cost criteria supplemented by any additional considerations such as environmental impacts. The prioritization of formulas assists in rationalizing the distribution of money for state wide projects. The performance based planning is to use specific service objectives in every program area (U.S. DOT, 2002).

Typical management systems and performance measures applied to systems have now been covered. At this point, it's necessary to look closely at what facets needed to

be applied to ITS in order to ensure its efficient management. Recommended practices have been developed by over 500 people involved in the industry between 1994 and 1999. They concluded there are ten areas of concentration (Kraft, 1999).

1. System management practices, which emphasizes strong and effective working relationships across all agencies and disciplines involved.
2. Planning, which has been further developed into the need for two ITS plans including a regional strategic plan for the “big picture” vision for ITS and a strategic system plan that would serve as an operational strategy for particular agencies.
3. Funding and more specifically, it needs to be accounted for and estimated carefully in terms of recurring costs and is the responsibility of each agency to manage their funds.
4. Design in that agencies need a system design plan or design guide to aid in the development and use of any ITS components.
5. Procurement, which pertained to assignment of responsibilities, identification of performance measures and that procurement processes for necessary software might be different then processes for the system hardware.
6. Installation was another recommended practice making the suggestion that installation of ITS devices and systems be planned and coordinated by the appropriate personnel.

7. The computer systems piece of the recommend practices focused on the computer software to be used and ensuring its generally accepted software system practices and a program for long-term maintenance is utilized.
8. Resource sharing, joint operations and integrations involves primarily the close coordination between agencies with respect to planning and throughout each phase of any projects.
9. Staffing and training that addresses the need for qualified, experienced staff members that can also maintain a training program and not only that but a sufficient amount of staff members.
10. Operational issues in that operations plans, manuals and any documentation needs to be developed and maintained by the operating agencies.

These recommended practices serve as a guide to follow in the development of ITS systems and the application of proper asset management. That said, it makes sense that guardrails fit into this system of management as would any devices that worked with them to ensure proper management of that asset.

Guardrail Systems

There is a wide array of guardrail designs in use on roads across the U.S. The designs include w-beams (wood and steel post), thrie-beam, 3-strand cable barriers, Jersey barriers, steel backed wood rails, and so on. The above mentioned designs as well as a few others cover nearly every application that exists on the roads today. The most popular of these designs is the strong-post or steel post w-beam guardrail (Tabiei, 2000). That said, there is far more to consider when reviewing the above mentioned designs than

simply the basic appearance of individual types. Table 1 shows guardrail types by test level and installation cost by linear foot. The safety of the guardrail denoted by its test level helps determine what's appropriate for specific applications. Aside from these factors the effects of soil type on guardrail posts also requires consideration. Greg Patzner et al. showed soil type significantly influences the performance of guardrail systems during full-scale crash tests (Patzner, 1999).

In regards to the soil-post relationship, two systems are discussed. The first is a guardrail system encased in pavement mow strips and the second is a wood post type guardrail with terminal anchors. In the case of the system located in mow strips, the steel post type guardrail had the least amount of deflection (movement) in pavement mow strips, compared to steel and wood posts mounted in soil or wood posts mounted in mow strips (Seckinger, 2005). In the case of the wood post type guardrail with the anchoring, the tests were modeled via computers with LS-DYNA3D software; however, the results show a definite advantage to the structural capabilities of the guardrails in terms of crash resistance. Three post types were analyzed against soil weight, which increased with increasing amounts of moisture. The post referred to as Grade No. 2, which consisted of a timber material gave the best results. Across every test the Grade No. 2 post was successful and the only possible failure occurring at the most substantial soil weight of 21760 N/mm^3 (Patzner, 1999). The tests conducted specifically measured, which post design would successfully resist cable rupture at the terminal and used computer modeling versus full-scale crash tests. That said, No. 2 posts gave the guardrail the highest chance for success before failure.

The designs in use today vary greatly. Regardless of which system is used, the indications are clear that many combinations exist for successful applications of timber and steel posts. This is also an indication that more work can be done to improve on these designs, specifically that of the w-beam. Research and design can greatly improve the guardrails currently in use. For instance, Jersey barriers, as much as they are used, might be considered an effective design since so many organizations use them; however, their design could be further refined. Research has found the barriers shape (ramped at two angles) and height, actually hinder the vehicle and passengers safety when compared to a similar barrier with one solid side (one angle) instead of the traditional side (Beason, 1991). By having only one angle on the side of the barrier the vehicles are less likely to be forced upward when striking the barrier. Increasing this same single slope barrier from 32" to 42" tall (as measured from the ground) also greatly increased its effectiveness (Beason, 1991). Similarly, the w-beam guardrail has been shown to be more effective when its height is increased from 27" to 32" (measured from ground level) and the design is modified to a three-beam at the same time due to the increase in larger vehicles on the road today (Glauz, 1991). This leads into the discussion about the existing safety issues with current guardrail applications and possible resolutions.

Combining ITS and guardrails

Given the factors in safety, the prevalence of guardrails on today's highways and the strong urge by the U.S. DOT and other organizations to further develop new technologies and new methods to preserve and manage the transportation infrastructure, incorporating ITS into guardrails makes sense. Guardrails do not cover every linear mile

of roadway across the country, but rather a large portion of it. Certain systems can be tied into guardrails and take advantage of the frequent roadside safety feature. Taking a look at this from a maintenance as well as safety standpoint, it stands to reason that the lifecycle of the guardrails can also be extended by incorporating new technologies into them.

In regards to safety, the 911 emergency system could easily be tied into a series of guardrail networks for anyone particular area. The exact sensors have not yet been developed, but for the purposes of this paper an example can be laid out in a more broad sense. For instance, the "malfunction junction" as it is nicknamed in Dayton Ohio, could greatly benefit from having sensors on guardrails at the intersections of major highways like I-70. The system would monitor for impacts at the guardrails and when an incident occurs the sensor would send a signal via radio module (one on each sensor) to the closest 911 dispatch center alerting them of an accident and provide the location to within 300 meters (Layton, 2011). That same sensor could send a second signal to a DOT maintenance office, whereupon crews would be notified that damage had occurred and to send DOT staff out to assess both the severity of the damage and whether or not the integrity of the guardrail had been damaged. This is only an example of how an ITS system could benefit guardrails, but it is entirely achievable since it is within the realm of current technology and could greatly enhance the safety of the local residents and lifespan of the Dayton area infrastructure.

In regards to systems that are already in use today, a couple examples are the Collision Avoidance Support Systems (CASS), Advanced Driver Assistance Systems

(ADAS) and Advanced Vehicle Control Systems (AVCS) (Ortiz, 1995). The latter of three, although not in use right now, is very much like the other two concepts. These systems rely on sensors providing the driver information on not only the road ahead, but the environment around the vehicle as well, and the AVCS would be more tied into information systems within the surrounding infrastructure. AVCS specifically involves the use of a wide variety of sensors, computers and actuators to control the vehicles systems such as the engine, transmission, brakes and steering (Ortiz, 1995). CASS and ADAS are systems that incorporate sensors for functions like headway detection (rear end protection), proximity detection (lane change, backing up), lane position monitor (road departure, opposite direction), gap acceptance aid (intersection and crossing paths) and vision enhancement (in reduced visibility situations) (Klein, 2001). In regards to road transportation, CASS is one of the main fields of interest and research. ADAS and CASS are designed to detect oncoming collisions and warn the driver in time to make evasive maneuvers or reroute the vehicle automatically (Santa, 2010).

CASS, ADAS and AVCS are heavily researched fields and technologies that are in use already or are in the process of being developed could easily be integrated into the guardrails to communicate with vehicles and inform them of their proximity to the structure or whether a collision with the guardrail is imminent. It's not unrealistic to assume that this area of research would interest researchers if it's not already being studied.

Conclusion

Given that the application of sensor systems on guardrails is a logical next step in the work being done with ITS, the safety factors of collisions with guardrails, the systems already in use today and the fact that organizations such as the TRB and U.S. DOT are forging ahead with those in the transportation industry, there are factors that limit the incorporation of guardrails into ITS. The main hindrance or limiting factor is funding. In a nation that has insurmountable amounts of debt, funding more transportation projects such as applying sensors to guardrails may be too much to take on. The funding provides the staff, training, hardware, and so on for these systems and without it or with the funding going to other research in the ITS field, it's hard to say whether or not this would be possible. Another limiting factor is the changes to the vehicle industry. While maybe not on the first thing some may think of as an issue, the changes in the vehicle industry over the past five years are a concern. International mergers on the part of Daimler Chrysler and the bankruptcy of GM and Daimler Chrysler, slow the ITS movement down and make it more difficult for new technologies to be incorporated into the more popular vehicles in use today. Microsoft's part in the software industry could also create limiting factors in the ITS industry. Restructuring within the software industry with buyouts or mergers could impact ITS significantly (Sussman, 2005).

The country is already taking seriously the ITS movement and is actively seeking out new technologies. The key players, i.e.- FHWA, TRB and organizations like it, are advancing a rapidly growing industry. From here, the plans developed by the FHWA and TRB need to be managed and followed, new engineers in the transportation industry

need to be trained and those currently in the industry may need retraining. The emerging and changing systems of transportation infrastructure are far different than they were 30 years ago. Information is now readily available with enabling technologies such as the internet and far more information than ever before can be easily accessed (Sussman, 2005). AM policies or guidance needs to be continually followed up on as well. Policies and goals, planning and programming, program delivery, information and analysis all together comprise the framework for AM today and into the future. AM is the bigger piece of what ITS is a part of and without proper management of today's infrastructure assets, however unlikely this is, ITS will fall by the way side (U.S. DOT, 2002).

Again, incorporating guardrails into the existing ITS systems can not only provide that gap in the 90% of unreported guardrail collisions and speed up the response for 911 calls to the 6% of injuries and fatalities, but also add to the maintenance and preservation capabilities of communities across the country. The idea is to advance and preserve the highways across the country. New roads will not be constructed and as a result the current roads need to be managed appropriately and improved to provide a faster, easier, and safer means of travel.

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III. Scholarly Article

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An Asset Management-Based Methodology for Integrating Sensors into an Existing Intelligent Transportation System

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Abstract

In this paper, we present a generalized asset management-based methodology for the integration and deployment of new sensors into an existing Intelligent Transportation System (ITS). The methodology employs a three phase approach that incorporates data modeling, spatial analysis using Geographic Information Systems (GIS), and cost optimization to provide enhanced decision support when integrating new sensing capabilities into an existing ITS. The value of the proposed methodology is illustrated through an example integration of a guardrail sensor network in high collision segment of roadways in a metropolitan area of Montgomery, Ohio. The results demonstrate that the methodology provides an effective means for planning new sensor deployments by providing a structured approach to modeling the existing ITS, identifying optimal sensor placement, and analyzing cost and performance tradeoffs to yield the optimal solution for a given set of requirements.

Introduction

United States (US) roadways are deteriorating as a result of increased age and use (Schofer et al., 2010). Based upon this recognition, the US Department of Transportation (DOT) and Transportation Research Board (TRB) facilitated a meeting of infrastructure stakeholders to consider problems, needs, achievements and to define the direction for research to manage and preserve the nation's surface transportation infrastructure. The group identified three areas needing further research: the development of infrastructure condition and performance monitoring, the development of methods for the rapid testing of materials, and the investigation of new transportation infrastructure designs. This paper addresses the integration of new sensors used for infrastructure condition and performance monitoring into an existing Intelligent Transportation System (ITS).

An ITS can be used to both monitor the state of the infrastructure in real-time and to collect aggregate statistics over time of parameters related to the infrastructure life cycle (Schofer et al., 2010). The ITS concept was developed to leverage modern communication and computing technologies to improve the overall efficiency of transportation systems and infrastructure (Tarko and Roupail, 1997). ITS is not a new concept has been in existence for decades (Kraft, 1999). Modern ITSs collect information about environmental conditions, the volume and speed of traffic, and communicate information back to motorists via message boards. The need for ITS results from a shift from the construction of new highway infrastructure to managing and maintaining the current highway infrastructure as the construction of roads is now considered to be complete (Wootton, 1995).

Over the years, a number of improved sensing and data collection in the transportation infrastructure have been developed. While work continues on the development of new sensing capabilities for use in the transportation infrastructure, little discussion has focused upon an Asset Management (AM) view of planning and deploying new sensors. Asset Management (AM) can be described as “a foundation from which to monitor the transportation system and optimize the preservation, upgrading, and timely replacement of highway assets through cost effective management, programming, and resource allocation decisions” (FHWA, 1999). Asset management is a basis to manage the transportation assets currently in use across the U.S. The hasty implementation of new technologies without the proper life cycle planning can result in suboptimal deployment designs, poor performance, and excessive costs. What is needed is a structured methodology that can be applied for the planning and deployment of any new sensor into an existing ITS. The methodology should support an asset management-based decision making process for implementing new transportation assets. The methodology should specifically address issues including how to integrate new sensors into an existing ITS, how to select the optimal placement of sensors based upon geospatial information and statistics, how to select the optimal set of hardware equipment to link a network of sensors to the ITS at minimum cost, and how to evaluate tradeoffs in system design over a variety of time horizons.

In this paper, we present a generalized methodology that can be used for planning the deployment of any type of sensors into an existing ITS. The methodology leverages data modeling, spatial analysis in Geographic Information Systems (GIS), and cost

optimization to provide enhanced decision support when planning the deployment of new sensing capabilities within an existing ITS. The remainder of this paper is structured as follows: in the second section, we propose a three phase methodology for integrating new sensors into an ITS; in the third section, we apply the methodology to the integration of a guardrail sensor network located within a major metropolitan area in Montgomery county, Ohio into the Ohio Department of Transportation ITS and discuss the process in detail; and in the final section, we present our conclusions and discuss future research directions.

An Asset Management Based Methodology for Integrating Sensors into an Existing ITS

In this section, we present a three phase methodology for the deployment of a new sensor within an existing ITS. Each of the three phases is executed sequentially, and the result is a plan for the optimal deployment of the sensor network.

Phase I – Documenting the Existing Intelligent Transportation Systems (ITS)

The purpose of the first phase is to develop models to describe and document the ITS architecture which are necessary to understand when integrating a new sensor. Before modeling can begin it is necessary to understand what the existing system consists of including sensors, collection boxes, reach back systems and databases. In modeling the existing system, the requirements for a new component(s) become clear. Understanding all the system components allows the person doing the modeling to understand the

direction of flow of data, how much data are created and the type of data used. It also allows for an understanding of the organization of the data within the database(s).

The format for documenting the requirements can come from several different approaches. The format is largely impacted by the type of analysis required and the level of information available to fully understand the complexity of the system being modeled (Sitzabee et al., 2009; Longley et al., 2011). Longley et al. (2011) recommends performing the modeling, from a GIS standpoint, using four levels ranging from reality, which is the understanding of system and major components it is comprised of, to the physical model which is the portrayal of the actual computer implementation. Another approach from the systems engineering perspective is to describe the systems architecture using a series of products which describe the system from multiple viewpoints. Systems architecture is an essential tool in systems engineering because it provides a shared representation of the system from multiple perspectives that can be used by multiple stakeholders to assure consistency and clarity about the composition of the system. For example, the Department of Defense Architecture Framework (DoDAF) version 2.02 defines a set of products, categorized into eight different views that act as mechanisms for visualizing, understanding, and assimilating the broad scope and complexities of the system as shown in Table 1 (DoDAF, 2010). Each view has multiple products to describe the system in terms of the given viewpoint. It is important to note that only a subset of the full DoDAF views, those products which are relevant to system understanding, are typically created to document the system development.

Table 1: DODAF Version 2.0 Viewpoints (DoDAF, 2010)

Viewpoints	Purpose
All Viewpoint (AV)	Describes the overarching aspects of architecture context that relate to all viewpoints.
Capability Viewpoint (CV)	Articulates the capability requirements, the delivery timing, and the deployed capability.
Data and Information Viewpoint (DIV)	Articulates the data relationships and alignment structures in the architecture content for the capability and operational requirements, system engineering processes, and systems and services.
Operational Viewpoint (OV)	Includes the operational scenarios, activities, and requirements that support capabilities.
Project Viewpoint (PV)	Describes the relationships between operational and capability requirements and the various projects being implemented. The Project Viewpoint also details dependencies among capability and operational requirements, system engineering processes, systems design, and services design within the Defense Acquisition System process.
Services Viewpoint (SvcV)	Presents the design for solutions articulating the Performers, Activities, Services, and their Exchanges, providing for or supporting operational and capability functions.
Standards Viewpoint (StdV)	Articulates the applicable operational, business, technical, and industry policies, standards, guidance, constraints, and forecasts that apply to capability and operational requirements, system engineering processes, and systems and services.
Systems Viewpoint (SV)	Articulates, for Legacy support, the design for solutions articulating the systems, their composition, interconnectivity, and context providing for or supporting operational and capability functions.

The importance of performing data modeling can be summed up in the following statement; “In many highway agencies separate data management systems are often incompatible and data integration among these systems becomes impractical or expensive” (Sitzabee et al., 2009; Gharaibeh et al., 1999). An accurate understanding of existing systems is critical to integrate additional components and avoid issues in the future.

Phase II – Geospatial Analysis using a Geographic Information Systems (GIS)

The purpose of the second phase is to exploit spatial analysis using a geographic information systems (GIS) model to determine the best locations to place the sensors. GIS provides people with the information about where events have occurred (Longley et al., 2011). Knowing where events occur allows for better decisions to be made in regards to the location selection for new transportation infrastructure assets. Additionally, data about these events can also be embedded giving them context and in turn a deeper understanding of the events is gained (Longley et al., 2011). The use of GIS allows for locations to be selected for sensors based on events particular to the purpose of that sensor. For example, if traffic volume sensors are needed, GIS can be used to identify locations of high traffic. Utilizing GIS can save money by providing accurate locations for sensor placement.

The need for GIS comes from the need to solve practical transportation issues (Longley et al., 2011). An example of the use of GIS is the New York State DOT. The New York DOT uses GIS to integrate both pavement and bridge management project information. Symbols on a map representing bridge or pavement projects can be selected to open a window displaying detailed project information (FHWA, 1999). The information allows for the quick reference of projects to understand them spatially on a map as well as find the status of specific projects. GIS allows for the spatial representation of information and for that information to be analyzed (Esri, 2011). In terms of new transportation assets, information can be analyzed spatially on a map to choose optimal locations for the new asset. The use of spatial analysis tools allows for a

variety of analysis to be conducted such as transportation corridors and high incidents of vehicle accidents.

Phase III –Life Cycle Planning and Cost Optimization

The purpose of the third phase is to use cost optimization techniques to identify the minimum cost solution that satisfies the sensor deployment requirements. Information from all phases is used providing the insight necessary to determine the total cost of ownership. It's critical to understand that in order to have real-time sensing a reach back network must be in place. Taking this into consideration in determining cost as accurately as possible a model sensor system should be built including the sensor and any reach back equipment necessary. The model can be physical or notional, but by detailing the components of the system using the information garnered from phases I and II a more realistic cost can be developed for the sensor system. Phase I and II provide the requirements for the hardware necessary for the proposed sensor and optimal locations of network nodes. The hardware requirements provide an understanding of what specifically can be used for components and their respective costs. The network node locations provide the potential size of the system and the reach back that would be required. These two portions combine with the life cycle factors such as length of life of the system and present worth to provide an optimal cost. Present worth determines economic effectiveness and provides a conversion for the system cost each year of its life cycle into present dollars (Canada et al., 2005).

Life cycle cost analysis (LCCA) provides DOTs a responsible decision making tool and allows for proper asset management. Effective asset management means the

management of highway assets and integration of new assets requires economic responsibility and sound investment strategies (FHWA, 1999). In estimating life cycle costs, DOTs and the FHWA can forecast budget requirements and determine the feasibility of a new asset more accurately. LCCA is widely accepted as a useful project evaluation tool and estimates the users cost over the life of a project or system (FHWA, 1999).

LCCA represents an optimization tool that focuses on a critical aspect of AM. Total cost of ownership and the overall economic feasibility of employing new infrastructure assets can be determined with LCCA. Other optimization tools utilized in this research include GIS and data modeling. Each tool hones in on specific attributes of the sensor that must be known in order to integrate it responsibly into an existing ITS network.

Example Application of the Methodology

In this section, we demonstrate the value of the proposed methodology through the planning required for the deployment of a guardrail sensor network into the Ohio Department of Transportation (ODOT) ITS.

Motivation for a Guardrail Sensor Network

Research in the area of the active sensing of guardrail condition is limited (Michie and Bronstad, 1994). The ability to sense and record guardrail impacts can yield multiple benefits including real-time notification of impacts, reduced emergency service notification times, and reduced resources required for manual damage inspection.

Examples of this research include sensor development in similar areas, such as impact detection. Flanigan et al. (2010) discuss emergency response technology and integrated active transportation systems (IATS). They cite research being performed by the U.S. DOT to create a future transportation infrastructure that improves safety, congestion, energy and environment as well as the infrastructures productivity. One of the most promising technologies the authors studied and that is already in use today was the Advanced Automated Crash Notification Systems (AACN), which use in-vehicle sensors (accelerometers) to sense crash occurrence and characterize the crash severity. The vehicle senses the crash and places a cell phone call to a private telematics service provider (Flanigan et al., 2010).

An alternate strategy is to sense collisions on the guardrail itself. A group of researchers in China investigated guardrail sensing with a monitoring system specifically for vehicle impacts with guardrails (Jiao et al., 2008). Their research was motivated by the fact that in China, 55% of all the traffic accidents are on the expressway and 30% of those involve vehicle impacts with guardrails. In terms of fatal traffic accidents, one third each year are due to vehicle impacts with guardrails. As discussed earlier, approximately 90 percent of guardrail impacts in the US are unreported. As a consequence, the need for real-time guardrail sensing has never been more important. Jiao et al. (2008) designed and built a wireless sensor network to specifically monitor vibrations within a guardrail during a vehicle impact. The network is comprised of a series of three-axis accelerometers connected to a still image capturing unit via a short distance communication device and a remote control center. Once a vehicle has impacted the

guardrail, vibrations are carried to the sensor which then triggers the camera to capture images of what has occurred. While Jiao et al. (2008) concluded with the determination that a guardrail sensor network is both feasible and practical, they did not address the planning required for the deployment of a guardrail sensor network (e.g., deploying guardrail sensors on multiple guardrails in a given geographic area). In this example, we demonstrate how our methodology provides value in the planning required for the deployment of a guardrail sensor network in Montgomery County, Ohio that accounts for the integration with existing infrastructure, selection of which guardrails to be sensed, and the total costs involved with deployment over the life cycle of the system. Note that we focus our analysis on the planning rather than the specific technologies used to construct the guardrail sensor network. This is intentional as the proposed planning methodology is not tied to any specific technology, but instead relies on parameters of the underlying technology as variables (e.g., cost, range, battery life) needed to perform the analysis.

Phase I – Documenting the Existing ODOT Intelligent Transportation System

The ODOT ITS is comprised of 600 nodes and covers a geographical area of over 4,085 square miles of urban areas and forty-four thousand square miles total. Sensor information is communicated back from remote locations via Internet Protocol (IP) over existing local area networks or via cellular telephone. Each node has a distinct IP address and provides an aggregation point for multiple sensors within the immediate geographic area of the node. Each node has a small embedded microcontroller with auxiliary data

ports which can talk multiple communication protocols (e.g., Ethernet, RS-232, RS-422). This allows a cluster of sensors, each talking a separate protocol, to be queried and the results aggregated into an IP message that is sent back ODOT's central office located in Columbus, Ohio. Existing sensors within the ODOT ITS include video traffic cameras, road temperature sensors, traffic speed sensors, humidity sensors, railway warning systems, roadway weather systems as well as many others.

In our analysis, we make use of DODAF products discussed previously to document the ODOT ITS. For brevity, only the two views most relevant to the paper are shown as the remaining views are addressed in other research. Figure 1 shows the SV-1 view "Systems/Services Interface Description" for the existing ODOT ITS. The SV-1 depicts the systems that make up the ODOT network. While there are many remote nodes in the ODOT ITS, only one prototypical node is shown for clarity. A remote node contains a sensor cluster (e.g., one or more sensors) connected to the control box. The clusters vary and there are a number of configurations that comprise the different sensor combinations across the state; however, each cluster follows the same overall system structure. The distance between each sensor and control box is limited based upon specific data communications interface. For example, a cable carrying RS-232 operating at 9600 bits per second is limited to 500 feet (Bies, 2010). As a result, sensors must be located within these distance limits. The control box aggregates sensor data into IP packets and then communicates these back to the ODOT Control Node via cellular telephone, radio-frequency, or hardwire internet connections. Currently, all remote nodes are powered by dedicated power line run from nearby utilities. ODOT also purchases

services from Speed Info which owns their speed sensors and communication reach back capabilities as shown at the bottom of Figure 1.

<<INSERT FIGURE 1 HERE>>

Figure 1: ODOT SV-1 Systems/Services Interface Description

In order to integrate guardrail sensors into the ODOT ITS, the collected sensor data must be transmitted back to the ODOT Control Node for processing. From SV-1 view, we recognize that using the existing architecture would mean that only a limited number of guardrails, those in close proximity to the Remote Node, could be equipped with sensors to provide active guardrail sensing. For this reason, we consider a collection of guardrails, each equipped with a guardrail sensor control node located at the center of each guardrail that consists of one or more sensors, a microcontroller, a wireless radio, and a battery that are connected together to form a single guardrail sensor network. Each guardrail continuously monitors its sensors and communicates sensor data back on a periodic basis to its nearest neighbor, which in turn passes it to its nearest neighbor, until it arrives at the guardrail designated as the communication reach back node to the ODOT Control Node. The communication reach back can be accomplished by a guardrail that is collocated with an existing Remote Node or, in remote areas lacking power, by a special battery powered cellular telephone.

Figure 2 shows the DIV-1 view “Systems/Services Interface Description” for the existing ODOT ITS. The DIV-2 is the logical model displaying the data view of the ODOT ITS network. The flow of information is represented in this view as are the

measurements and information being collected by individual sensors. The ODOT server queries the sensors and each sensor provides the ODOT server with data on their respective measurements. The Speed Info sensor is a separate system and communicates directly with the ODOT server. The data, once at the ODOT server is then channeled into the individual database tables for each sensor collecting all the information listed on the sensor in addition to the time and location (of the sensor) that the data was collected. This model demonstrates that both being queried and providing data to the database are necessary functions of an ODOT sensor.

The DIV-2 view reveals that the ODOT ITS was built using standard relational database technologies. As such, any new sensor data can easily be integrated into the database once the sensor data is transported back to the ODOT Control Node via an existing Remote Node or via a new direct Cellular Telephone connection. Based upon this analysis, the addition of a guardrail sensor network will be relatively inexpensive to implement in terms of the hardware and software required at the ODOT Control Node. As we will see, the cost of a guardrail sensor network will be dominated by the costs associated with the deployment, operation, and maintenance of the guardrail sensor network.

<<INSERT FIGURE 2 HERE>>

Figure 2: ODOT DIV-2 “Logical Data Model”

In summary, the two DODAF system architectural views presented provide a detailed understanding of the system as it exists and how difficult it will be to integrate guardrail sensors into the ODOT ITS.

Phase II – Geospatial Analysis for Guardrail Sensing using Geographic Information Systems

A GIS density analysis was performed on state owned roads located within Montgomery County, Ohio to determine the optimum locations for guardrail sensors. The major state owned roads include interstates I-675, I-70 and I-75 as well as state routes US 35 and US 40. Narrowing it to those roads specifically, a map was built of these major roadways across Montgomery County (Saylor and Comer, 2011). Crash statistics garnered from the Ohio Department of Public Safety site were loaded into the GIS and used to determine which location along the major roads to focus on (ODOPS, 2011). A density analysis was conducted to determine the optimum location of the guardrail sensors in relation to the existing infrastructure.

Performing the Density Analysis within GIS identifies several areas of high significance based on the number of accidents in those areas. One of the areas of highest density is a longitudinal section outside of any traffic camera locations (second of the two highest incident locations within Montgomery County). Regardless of the absence of traffic camera's, it's an area of importance in terms of major accident locations and includes two major roads, I-70 and US 40. It is for that reason that this area was selected for placement of guardrail sensors. As identified in Phase I, ideally one of the guardrails contained in the guardrail sensor network would be colocated with an ODOT Remote

Node to provide a communications pathway back to the ODOT Control Node. However, in this case the geographic area selected for guardrail sensing does not contain an existing ODOT Remote Node. For this reason, the guardrail sensor network will have to make use of a battery operated cellular telephone at one of the guardrails in the network to provide the required communications reachback to the ODOT Control Node. Since all of the guardrails are equipped with batteries, it is vital to consider the power consumption of the sensor network and the operational and maintenance costs associated with the use of batteries for power. From the area of focus on I-70, 30 guardrails were selected. The latitude and longitude coordinates of each of the guardrails endpoints and midpoint is shown in Table 2.

Table 2: Selected guardrail coordinates for the guardrail sensor network

Guardrail	Endpoint 1		Endpoint 2		Midpoint	
	LAT	LONG	LAT	LONG	LAT	LONG
1	-84.264374	39.862381	-84.2652	39.86223	-84.264764	39.862305
2	-84.263947	39.862598	-84.2632	39.86274	-84.263592	39.862667
3	-84.267593	39.861736	-84.2684	39.86157	-84.26801	39.861656
4	-84.267067	39.862019	-84.2685	39.86166	-84.267776	39.861847
5	-84.26815	39.861496	-84.2684	39.86145	-84.268253	39.861474
6	-84.268112	39.861393	-84.2683	39.86136	-84.268205	39.861376
7	-84.270599	39.860806	-84.2692	39.86115	-84.269911	39.860977
8	-84.269363	39.861355	-84.2699	39.86124	-84.269626	39.861296
9	-84.269424	39.861458	-84.2748	39.86024	-84.272089	39.860856
10	-84.276283	39.859909	-84.2748	39.86024	-84.275518	39.860087
11	-84.274147	39.859985	-84.276	39.85952	-84.275088	39.859746
12	-84.280037	39.858875	-84.2794	39.85915	-84.279703	39.858991
13	-84.279869	39.858765	-84.279	39.859	-84.27943	39.858883
14	-84.280251	39.858398	-84.2814	39.85803	-84.280812	39.858215
15	-84.280365	39.858471	-84.2813	39.85822	-84.280849	39.858351
16	-84.280655	39.858692	-84.2812	39.85853	-84.280932	39.85861
17	-84.28196	39.858299	-84.2837	39.85778	-84.282827	39.858042

18	-84.291946	39.855705	-84.2923	39.85569	-84.292114	39.855695
19	-84.292511	39.855595	-84.2932	39.85558	-84.292853	39.855591
20	-84.311378	39.855083	-84.3117	39.85509	-84.311553	39.855087
21	-84.310509	39.855152	-84.3112	39.85516	-84.310879	39.855164
22	-84.310211	39.855293	-84.3112	39.85528	-84.310729	39.855287
23	-84.262794	39.863003	-84.264	39.86272	-84.26338	39.862861
24	-84.269279	39.86124	-84.2701	39.86107	-84.269708	39.861154
25	-84.27726	39.875397	-84.2792	39.87403	-84.278231	39.874714
26	-84.279205	39.874031	-84.289	39.86721	-84.284095	39.87062
27	-84.277191	39.875309	-84.2889	39.86714	-84.283057	39.871227
28	-84.290375	39.867386	-84.2898	39.86672	-84.29004	39.867087
29	-84.289742	39.867092	-84.2903	39.86757	-84.289979	39.867353
30	-84.297447	39.872097	-84.2979	39.87241	-84.297652	39.872255

A preliminary site survey of the location must be conducted to identify potential power and communication utilities, unusual geographic concerns, and any potential obstructions that would affect the range or difficulty in establishing communications links between guardrails. A failure to complete this step can have catastrophic consequences on the success of the project.

Phase III –Minimizing the Total Cost of Ownership of the Guardrail Sensor Network

When selecting among a large number of possible solutions for a given problem, it is essential to exploit optimization tools which select optimal, or near optimal, solutions based upon the problem formulation. In the context of this example, the locations of the 30 guardrails are fixed, but the selection of the hardware and associated costs over the lifecycle of the system must be considered. This requires the formulation of a cost optimization model to determine the optimum mix of hardware to meet the performance requirements while minimizing the Total Cost of Ownership (TCO) over the life cycle of

the system. This phase has been broken into three components: 1) determining the minimum distance required to connect all of the guardrails in the guardrail sensor network, 2) determining the number of sensors placed on each guardrail and their cost, and 3) selecting the communication media for each of the links between the guardrails that meets the performance requirements while minimizing the TCO.

Identification of Minimum Distance between Guardrail Midpoints

To accomplish the first component, we used the guardrail midpoint coordinates identified in Table 2 and formulated a Traveling Salesman Problem (TSP) to identify the minimum distance required to interconnect all 30 guardrails (Cook, 2011). The solution to the TSP identifies the 30 minimum distance links necessary to connect all the 30 guardrail midpoints in a closed loop given the constraint that each guardrail midpoint is only visited one time. Since it is not necessary to have a closed loop, we identify and eliminate the maximum length link which still assures all of the remaining guardrails are connected. We formulate the problem in TSPLIB format and used the Concorde software package for solving the TSP and some related network optimization problems (Groer, 2008; Cook, 2011). Collectively, the guardrail nodes form a network that will be connected together using the most cost effective combination of wired and wireless communications media. The Concord optimization required less than 5 seconds to complete on an Intel based PC running Windows 7 operating system with a 3 GHz dual core processor with 4GB RAM and a 500MB disk. The solution for the TSP formulated in the example is shown in Table 3. Note that link 19 which connects guardrails 19 and 22 has the maximum length of 1987.72 meters. Based upon this analysis, we eliminate

this link leaving the remaining 29 links necessary to form the guardrails sensor network.

The sum of the link distances is 1987.72 meters.

Table 3: Concord TSP solution for guardrail midpoint connections

Link	From Guardrail	To	Distance (m)
1	1	4	334.96
2	4	3	26.11
3	3	5	27.1
4	5	6	5.45
5	6	8	158.01
6	8	24	9.25
7	24	7	22.66
8	7	9	242.19
9	9	11	333.7
10	11	10	47.96
11	10	13	435.2
12	13	12	30.38
13	12	16	136.72
14	16	15	9.67
15	15	14	4.38
16	14	17	224.07
17	17	18	1032.99
18	18	19	82.18
19	19	22	1987.72
20	22	21	16.73
21	21	20	74.95
22	20	30	1557.29
23	30	28	848.34
24	28	29	7.39
25	29	26	655.27
26	26	27	115.62
27	27	25	538.02
28	25	23	1656.59
29	23	2	23.67
30	2	1	130.38

Within each guardrail, one or more sensors (based upon the length of the guardrail) collect data and following an impact sends it to the guardrail node located at the midpoint of the guardrail. The sensor data is then transmitted to its nearest neighbor

in a daisy chain manner until it reaches a guardrail that has a communications reach back capability to the ODOT Control Node.

Composition of a Guardrail Sensor Node

The life spans of each sensor were evaluated over a 30 year period and the total cost of each, over the 30 year period, are then converted into a present worth. The discount rate for determining the present worth of each option from the Office of Management and Budget (OMB) is 2.3% for a 30 year period, which is the real interest rate as opposed to the nominal interest rate (OMB, 2011). Using this discount rate, all four costs for the lifetime of each communication type can be evenly evaluated for a 30 year period. The output from this phase is the quantity of each communication type that will be used across all 29 connections and thus the total cost of a sensor cluster over their lifespan. Again, the reason for this phase of the methodology is to determine the optimum blend of performance considering the cost of the individual guardrail sensors and the power source utilized.

Determining the Number of Sensors per Guardrail and Cost

The costs for each guardrail sensor node are determined by specifying the main components including one or more accelerometer sensors, a microcontroller, the communications transceiver (wired or radio), and a battery. The selection of the communications transceiver is addressed in the next section. The number of sensors placed on each guardrail is a function of the length of the guardrail and the maximum sensing distance, *MaxRange*, for the sensors used to detect collision. The number of sensors required per guardrail is shown below in Equation 1:

$$CEIL\left[\left(\frac{GuardrailLength}{MaxRange}\right)\right]-1 = \#sensors \quad (1)$$

Equation 2 is used to determine the distance between the sensors along the guardrail:

$$\frac{GuardrailLength}{\#Sensors + 1} = D, \text{ where } D = \text{distance between sensors} \quad (2)$$

The endpoint coordinates from Table 2 are used to determine the overall length of the guardrails. The length of the guardrails determines the number of sensors required per guardrail and thus allows for the determination in the cost for sensing element for each guardrail. In this example, we assume that each sensor has a maximum vibration sensing range, *MaxRange*, equal to 50m. In this example, the cost for each sensor contained within a guardrail is assumed to be a fixed \$54 and accounts for the connection back to the microcontroller guardrail sensor node. Each guardrail incurs a fixed cost of \$29 to account for the required microcontroller. This information, together with Equations 1 and 2, yields Table 4 which shows the first four guardrails for the required number of sensors per guardrail and the cost for sensing in each guardrail.

Table 4: Number of sensors per guardrail and cost

Guardrail ID	Guardrail Length (m)	Number of Sensors	Wire Length (m)	Total Cost for Sensing
1	87.41	1	43.71	\$68.34
2	78.07	1	39.04	\$66.80
3	92.53	1	46.27	\$69.17
4	156.95	2	52.32	\$96.16
5	22.91	1	11.46	\$57.76
6	20.35	1	10.18	\$57.34
7	152.72	2	50.91	\$95.70

8	57.72	1	28.86	\$63.47
9	592.38	11	49.37	\$320.19
10	170.50	3	42.63	\$117.98
11	209.55	4	41.91	\$142.75
12	71.34	1	35.67	\$65.70
13	97.55	1	48.78	\$70.00
14	125.60	2	41.87	\$92.73
15	106.89	2	35.63	\$90.69
16	61.96	1	30.98	\$64.16
17	192.57	3	48.14	\$119.79
18	37.36	1	18.68	\$60.13
19	76.39	1	38.20	\$66.53
20	39.03	1	19.52	\$60.40
21	82.28	1	41.14	\$67.49
22	115.42	2	38.47	\$91.62
23	130.69	2	43.56	\$93.29
24	95.09	1	47.55	\$69.59
25	216.80	4	43.36	\$143.22
26	1090.22	21	49.56	\$570.25
27	1307.89	26	48.44	\$694.89
28	65.80	1	32.90	\$64.79
29	57.84	1	28.92	\$63.49
30	45.17	1	22.59	\$61.41

Communications Media Selection

The next step involves selecting the minimum cost communications media that satisfies the range requirements at the minimum cost. A Microsoft Excel spreadsheet was used to identify the minimum cost communications media needed to satisfy each of the required 29 guardrail network links. The four communication types include a hardwire cable connection, low power wireless radio, medium power wireless radio and high power wireless radio. Each communication type has a total cost and an effective range. The cost portion of this phase is developed for each communication type separately based

on the range of each sensor type, its power source, and its life span. If none of the guardrails is collocated with a Remote Node to provide communications back to the Control Node, a cellular modem must be added to the system components. Each of the guardrail sensor nodes consume a variable amount of power based upon the guardrail size (e.g., the number of sensors is a function of the guardrail length), the maximum distance to the next guardrail in the network, if it contains the cellular modem, and the communications protocols used. It is assumed in this paper that the communications protocols have already been optimized to reduce power consumption to extend battery life. If two or more communication types met that range requirement than the least costly type was selected. Table 5 shows the types, costs with installation, and ranges for each type of communication media. It is important to note that the battery size, and hence cost, required for each of the possible communication media accounts not only for communication power consumption but also for the sensing power consumption of each guardrail. This is reasonable because the power consumption for a guardrail sensing nodes is dominated by the communications media, with the sensing power consumption being a relatively fixed amount across all guardrails.

The hardwire option is derived from real world electrical contractors and what they would require to do a permanent cable line install and is a function of the length of the connection. Total costs per foot including conduit, electrical line cost per foot, and manpower are included. The costs associated with each communications type accounts for the initial cost and annual reoccurring costs required for maintenance. Note that the ranges are only estimates and are actually dependent upon obstructions between

transmitter and receiver. The ranges must be validated using the information collected during the preliminary site survey.

Table 5: Communication media types with costs and ranges

Communication Type	Initial Cost (Install + Sensor)	Annual Maintenance Cost	Installation Cost per Meter	Maximum Range (meters)
Hardwire	\$279	\$15	\$1.53	150
Low Power Radio	\$40	\$20	N/A	90
Medium Power Radio	\$45	\$20	N/A	305
High Power Radio	\$52	\$20	N/A	1600
Cellular Modem	\$211	\$20	N/A	35000

Inspection of Table 3 reveals that there are communications links longer than 1600 meters (e.g., link 22 and link 28) and the highest powered radio shown in Table 5 only has a range of 1600 m. For this reason, in this example there is a need for a cellular modem in more than one guardrail in the guardrail sensor network which increases the overall guardrail sensor network cost. In this case, one can eliminate the next largest link identified in Table 3 to create two independent guardrail sensor networks. In the provided example, link 28 of length 1656.59 m that connects guardrails 25 and 23 would be eliminated. This would result in two autonomous guardrail sensor networks: the first network contains 26 guardrails (1-19 and 23-29) and the second network contains guardrails (20-22 and 30). Table 6 shows the required communications link type and associated installation cost for each communication link. Note that there is no installation cost for radio links.

Table 6: Required communication media for each guardrail link

Link	From Guardrail	To Guardrail	Communication Type	Installation Cost
1	1	4	High Power	N/A
2	4	3	Hardwire	\$39.94
3	3	5	Hardwire	\$41.46
4	5	6	Hardwire	\$8.34
5	6	8	Medium Power	N/A
6	8	24	Hardwire	\$14.15
7	24	7	Hardwire	\$34.67
8	7	9	Medium Power	N/A
9	9	11	Medium Power	N/A
10	11	10	Low Power	N/A
11	10	13	High Power	N/A
12	13	12	Low Power	N/A
13	12	16	Medium Power	N/A
14	16	15	Hardwire	\$14.80
15	15	14	Hardwire	\$6.70
16	14	17	Medium Power	N/A
17	17	18	High Power	N/A
18	18	19	Low Power	N/A
19	19	22	Link Eliminated	N/A
20	22	21	Hardwire	\$25.60
21	21	20	Low Power	N/A
22	20	30	High Power	N/A
23	30	28	High Power	N/A
24	28	29	Hardwire	\$11.31
25	29	26	High Power	N/A
26	26	27	Medium Power	N/A
27	27	25	High Power	N/A
28	25	23	Link Eliminated	N/A
29	23	2	Hardwire	\$36.22
30	2	1	Medium Power	N/A
			TOTAL INSTALLATION	\$233.19

Since each guardrail communicates with two other guardrails (except for those located at the terminal end of a chain of guardrails), we must assure that the strength of the radio at each guardrail matches the links that it touches. When two different strength radio links touch the same node, you must use the maximum of the two strengths when sizing the guardrail’s radio. For example, consider guardrail 11 which is connected to guardrail 9 through link 9 (medium power) and also to guardrail 10 through link 10 (low power). In this case, we must use the medium power radio at guardrail 11 to satisfy the performance requirements. Also, note that the cellular modem can be placed at any of the individual guardrails in the guardrail sensor network since there purpose is to assure a communications path back to the ODOT Control Node. In this case, we place the cellular modem on guardrails 20 and 24 because they do not have a radio which can create interference. Using these facts, Table 7 shows the the required communications media and associated cost for each guardrail assuming a 30 year lifespan with the values of each communications type evaluated at present worth assuming an 2.3% interest rate.

Table 7: Total estimated cost per guardrail over 30 year lifecycle

Guardrail	Communication Media	Communication Cost	Total Cost for Sensing	Total Cost
1	High Power Radio	\$52.00	\$68.3	\$550.33
2	Hardwire + Medium Power	\$45.00	\$66.8	\$541.79
3	Hardwire	\$0.00	\$69.1	\$391.66
4	Hardwire + High Power Radio	\$52.00	\$96.1	\$578.15
5	Hardwire	\$0.00	\$57.7	\$380.25
6	Hardwire + Medium Power	\$45.00	\$57.3	\$532.33
7	Hardwire + Medium Power	\$45.00	\$95.7	\$570.69

8	Hardwire + Medium Power	\$45.00	\$63.4	\$538.46
9	Medium Power Radio	\$45.00	\$320.	\$795.18
10	High Power Radio	\$52.00	\$117.	\$599.97
11	Medium Power Radio	\$45.00	\$142.	\$617.74
12	Medium Power Radio	\$45.00	\$65.7	\$540.69
13	High Power Radio	\$52.00	\$70.0	\$551.99
14	Hardwire + Medium Power	\$45.00	\$92.7	\$567.72
15	Hardwire	\$0.00	\$90.6	\$413.18
16	Hardwire + Medium Power	\$45.00	\$64.1	\$539.19
17	High Power Radio	\$52.00	\$119.	\$601.78
18	High Power Radio	\$52.00	\$60.1	\$542.12
19	Low Power Radio	\$40.00	\$66.5	\$536.52
20	Hardwire + Cellular Modem	\$211.00	\$60.4	\$701.39
21	Hardwire + Low Power Radio	\$40.00	\$67.4	\$537.48
22	Hardwire	\$0.00	\$91.6	\$414.11
23	Hardwire	\$0.00	\$93.2	\$415.78
24	Hardwire + Cellular Modem	\$211.00	\$69.5	\$710.58
25	High Power Radio	\$52.00	\$143.	\$625.21
26	High Power Radio	\$52.00	\$570.	\$1,052.24
27	High Power Radio	\$52.00	\$694.	\$1,176.88
28	Hardwire + High Power Radio	\$52.00	\$64.7	\$546.78
29	Hardwire + High Power Radio	\$52.00	\$63.4	\$545.48
30	High Power Radio	\$52.00	\$61.4	\$543.40
Total Cost				\$17,659.0

Conclusions

In this paper we have introduced a generalized asset management-based methodology for the integration and deployment of new sensors into an existing ITS. The methodology employs a three phase approach that incorporates data modeling, spatial analysis using Geographic Information Systems (GIS), and cost optimization to provide enhanced decision support when integrating new sensing capabilities into an existing ITS.

The value of the proposed methodology was illustrated through an example integration of a guardrail sensor network in high collision segment of roadways in a metropolitan area of Montgomery, Ohio. The results demonstrate that the methodology provides an effective means for planning new sensor deployments by providing a structured approach to modeling the existing ITS, identifying optimal sensor placement, and analyzing cost and performance tradeoffs to yield the optimal solution for a given set of requirements.

The approach, started with Phase I, modeling the existing ITS network within the Ohio Department of Transportation (ODOT). Through the use of two models, DIV-2 and SV-1, necessary insight was gained to understand the interfaces required to integrate guardrail sensors into the ODOT ITS. The second phase consists of a spatial analysis of vehicle accidents in 2010 with a geographic information systems (GIS) model to determine the best locations to place the guardrail sensors within Montgomery County, Ohio. Using a density analysis, Phase II produced two areas of interest with high vehicle accident rates outside of traffic camera locations. One location is on a longitudinal portion of a major road, I-70, and consists of 26 guardrails and the other in a more rural setting along Ohio 40 consisting of 4 guardrails. The third phase used total cost of ownership and optimization techniques to select the hardware that satisfies the performance requirements at a minimum cost. The estimated cost of sensing for each guardrail was modeled over a 30 year period resulting in a sum cost for a 30 guardrail sensor network of \$17,659.07 and with the addition of the hardwire installation cost of \$233.19 results in a total cost of ownership of \$17,892.26.

This approach accounts for proper AM in the sense that a usable process was built using three models to determine how to integrate a new technology into an already robust existing ITS network. This process aids in the decision making process and provides data that can be used in transportation budget considerations. With multiple systems in use on the road today, organizations such as ODOT must implement new technology on the basis that it's not only feasible or practical, but that it can be done so responsibly, that there is sound reasoning behind where it could best be implemented, and lastly that there is funding for it (requires the total cost of ownership be known). The data modeling, GIS spatial analysis, and cost optimization provide those tools that DOTs need to incorporate a guardrail sensor network in their respective ITS networks and prove that it is cost effective.

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Figure Captions List

Figure 1. ODOT SV-1 Systems/Services Interface Description.

Figure 2. ODOT DIV-2 “Logical Data Model”.

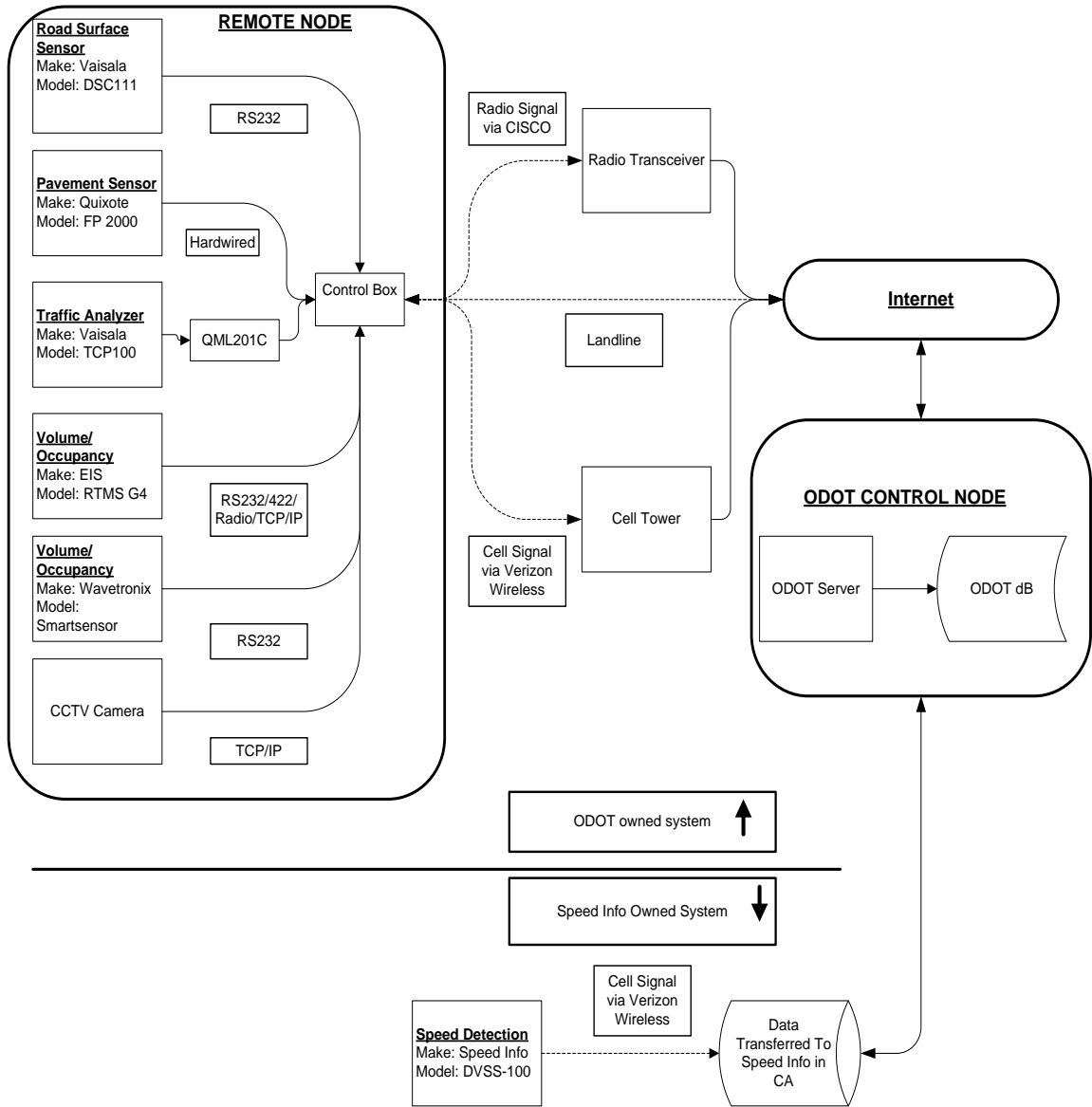


Figure 1: ODOT SV-1 Systems/Services Interface Description.

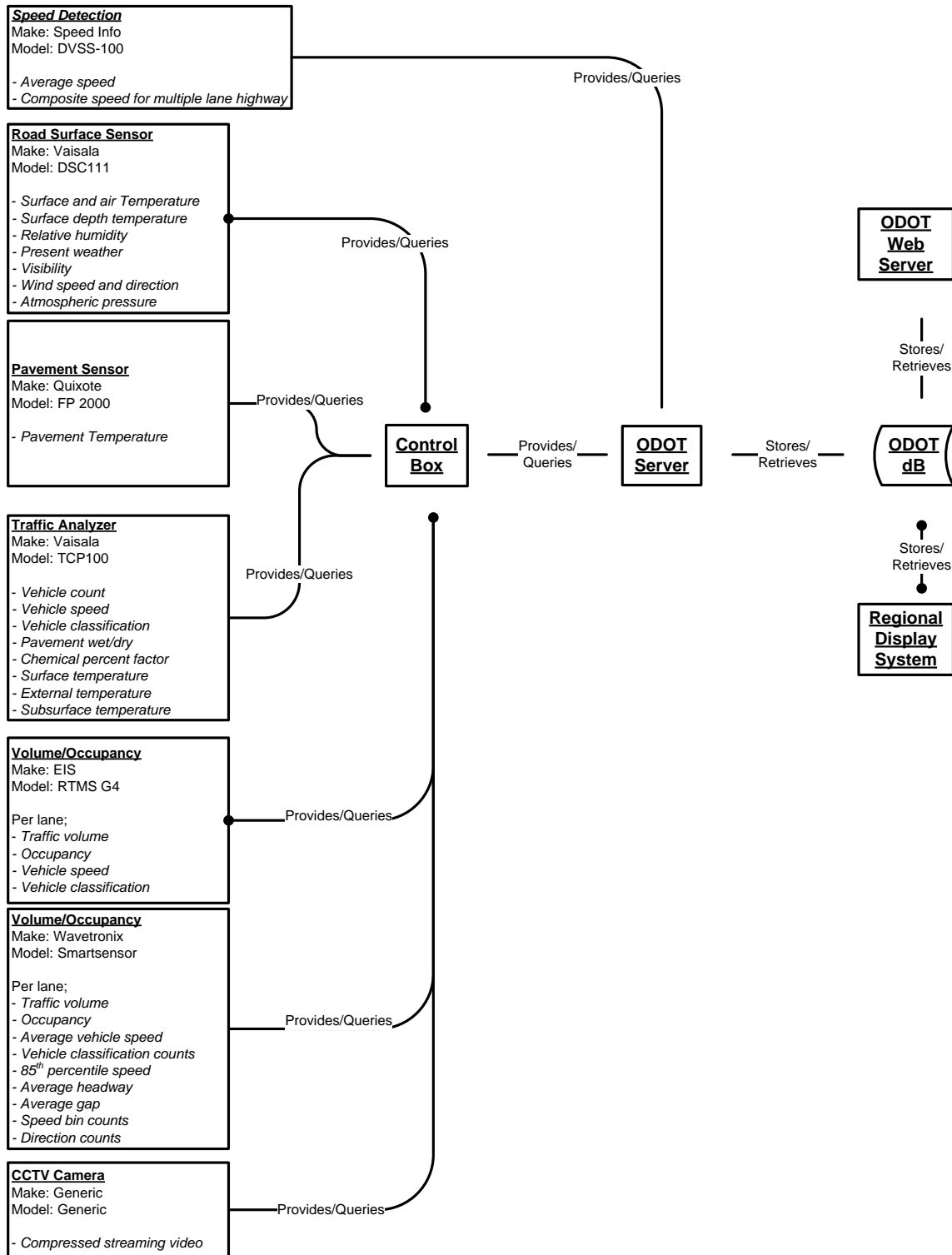


Figure 2: ODOT DIV-2 “Logical Data Model.”

IV. Scholarly Article

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Computing Applications and Modeling for Real Time Impact Detection of Sensors on Guardrails

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Ph.D.

Abstract

The Interstate Highway System neared completion in the early 1990s after 40 years of construction. Completing this milestone gave way to a shift from new construction to the maintenance, management, and reconstruction of the nations existing infrastructure. Making this shift is critical as those highways are now suffering from increased usage, environmental issues, and age. Departments' of Transportation need to maintain, and where possible, improve the existing transportation system using intelligent transportation system technologies. Executing new technologies relies heavily upon computing. This paper presents a case study for incorporating impact-activated sensors placed on guardrails. The purpose of this paper is to demonstrate the usefulness of computing in solving real world civil engineering problems using the guardrail sensor case study as an example. The case study will focus on data modeling. The data models are built from a systems engineering approach, which portrays what is necessary and emphasizes the conceptual, logical and physical views. Building the data models

demonstrates asset management principles taking a systematic approach and incorporating engineering principles.

Keywords

Computer models, Transportation management, Analysis, Infrastructure, Intelligent Transportation Systems.

Introduction

The United States Interstate Highway System neared completion in the early 1990s after 40 years of construction. Completing this milestone gave way to a shift from new construction to the maintenance, management, and reconstruction of the nation's roadways. Making this shift is necessary as those highways that were constructed are now suffering from increased usage, environmental issues, and age (FHWA, 1999). Departments of Transportation (DOTs) need to maintain and where possible, improve the existing roadways in order to support the increased use and constant decay of the system. Now more than ever the United State Department of Transportation (U.S. DOT), with the support of the Transportation Research Board (TRB), need the means to make the maintenance and improvements possible. The U.S. DOT and TRB held a conference to discuss these very issues bringing together decision makers, infrastructure owners, and researchers (Schofer et al., 2010). The participants outlined current challenges as well as opportunities facing ground transportation and developed a guide for future research. The conference focused on four areas and provided recommendations for each (Schofer et al., 2010). The four areas are:

1. Inventory and condition assessment methods

2. Innovative and environmentally friendly materials and methods for preservation, restoration, and reconstruction
3. Strategies for rapid repair and restoration
4. Methods for modeling deterioration processes and estimating life-cycle cost

The U.S. DOT and TRB recognize a need to improve on highway infrastructure and these focus areas encourage the development and modeling of new technologies to improve on existing Intelligent Transportation Systems (ITS) infrastructure. Those technologies require the use of computers and this paper presents a solution to implementing guardrail sensors into an ITS through data modeling and integration.

For example, DOTs rely heavily on computers to manage the vast quantity of data needed to assess the condition state and inventory of a system (Sitzabee et al. 2009). Additionally, information across highway agencies is often incompatible due to separate data management systems. Under the inventory and conditions state recommendations was a request to develop new and enhanced sensing and data collection techniques (Schofer, 2010). This paper proposes the data modeling structure to implement sensors on guardrails into a Transportation Asset Management (TAM) System using the Ohio DOT as a specific case. The improved data integration is accomplished using a systems engineering approach to database modeling and considers software, hardware, databases, and data collection systems.

Given the need to improve on existing roadways in order to account for increased use and stress due to age and the resulting conference held by U.S. DOT and TRB's to address this need, the authors present this case study to explore the practicality of placing

impact activated sensors on guardrails. Incorporating sensors on guardrails for the purpose of real-time impact detection is not a one dimensional problem. It involves taking a close look at the compatibility with the existing Intelligent Transportation System (ITS), the location for the placement of the sensors, and the cost of implementing such a system. The guardrail sensor study examines all three levels, but focuses heavily on the question of integration compatibility specifically with the Ohio Department of Transportation's (ODOT) ITS network. The question of integration compatibility with the ODOT ITS is addressed with data modeling. The purpose of this paper is to demonstrate the usefulness of computing in solving real world civil engineering problems using the guardrail sensor case study as an example. Additionally, this paper demonstrates the usefulness of applying impact activated sensors to guardrails for the purposes of improved maintenance as the sensors notify DOT's of impact and therefore damage to infrastructure assets. The effectiveness of these sensors for the enhanced 9-1-1 system is also shown as the sensors can drastically improve emergency response times to accidents.

Background

Transportation Asset Management (TAM) is the foundation to managing our nation's vast transportation system. TAM involves business practices that emphasize management techniques to focus and maximize limited resources. The goals and policies of a TAM program are to meet a required level of service in terms of operations, maintenance, and safety in the most cost effective manner while operating within budget constraints (Cambridge Systematics, 2002). Managing a large transportation system is

both complex and data intensive which requires extensive computing and robust computer databases.

Database modeling is a critical step in identifying the components, relationships, and data required to manage large infrastructure systems like our nation's roadways. Baugh Jr. et al. present an approach to modeling a simple component of ITS systems in addition to their logical coordination by using finite state verification tools (Baugh Jr. et al., 2000). Baugh et al. use product and process data modeling finite state models for project planning and management. These support repetitive cycles, communication and so on. Information models in this same category attempt to represent products and processes in a computer readable form that is also clear. With this in mind Baugh Jr. et al. apply finite state verification to traffic signal controls. Specifically, the researchers took a close look at two of the three aspects of traffic signal controls, which are roadway signal controls, Traffic Management Center (TMC) signal control, and TMC regional traffic control. The roadway signal controls manage traffic signals at major intersections in more urban areas. The TMC signal controls allow personnel in the TMC to monitor as well as manage the traffic flow at signalized intersections. The TMC regional traffic control allows for analyzing, controlling, and managing area traffic flow (Baugh Jr. et al., 2000). With computer modeling, and computing in general, Baugh et al. provide a basis for designing a fully actuated traffic signal as well as an approach to modeling and finite state verification which is a template for others. This approach provides yet another TAM decision making tool to assist in the effort to improve current roads.

Sitzabee et al., used database modeling as a key step in data integration of pavement marking attributes for North Carolina's TAM system (Sitzabee, 2009). The essence of the North Carolina work was the melding of empirically derived predictive models into a GIS based TAM system, which they did through extensive data modeling (Sitzabee, 2009). The first of the data models presents the data integration of the predictive model and measured data. The second of the models illustrates the physical database management model. The physical model design portrays the computer implementation with tools such as a relational database and is comprised of the database tables (Sitzabee et al., 2009; Longley et al., 2005). Additionally, the proposed pavement marking database incorporates modeling with the recommended tables demonstrating how the data are stored. The purpose of this discussion is to illustrate how computing allows for the development of a pavement marking TAM and how those lessons can be furthered through alternative tools for computer and system modeling.

Another example of the effectiveness of computing in civil engineering comes in the way of high-quantity, low cost assets and addressing information technology (IT) issues when developing AM systems for these assets. Rasdorf et al. (2009), discuss that original applications of IT to AM focused primarily on low quantity and high cost assets; however, this approach needs to be applied to the higher quantity, lower cost elements of transportation networks. The high quantity, low cost assets are just as necessary to transportation systems as those more expensive low quantity assets (Rasdorf et al., 2009). Given the need for such assets it is also recognized that there is an emphasis placed on the importance of IT in managing them properly. The IT aspect allows for data to be

processed, stored, and used in TAM systems. In the case of high quantity assets the amount of data being processed can be significant. IT implementation issues exist in areas such as asset identification, asset location, data availability, data fragmentation, and unsuccessful data collection (Rasdorf et al., 2009). The assets that are high quantity, low cost are still necessary. In most cases the assets are critical to the safety and mobility of the public on current highway infrastructure (Rasdorf et al., 2009). Asset management of these components needs improvement and can be accomplished with improved technology and computing. Bridging the gap between these assets and a complete functional TAM system free of IT issues is an improved computing approach.

These three papers represent the strengths that computing brings to the field of civil engineering and how it can be used effectively to solve emerging infrastructure challenges. Again, construction on the Interstate Highway System is near complete and today's roads are suffering from stress and age and need to be improved upon if they continue to be utilized. Proper TAM will allow for these roads to continue to function for years into the future, but in order to implement TAM, technology is necessary. Technology enables TAM in two key areas. The first area is the collection, storage and analysis of data and the second is the communication of results to decision makers inside and outside of the FHWA (FHWA, 1999). This information supports the conclusion that effective TAM requires extensive data management. The sufficient data needs to be utilized and to collect that data, computers and automated data collection tools are necessary.

This case study demonstrates how computing can be used to improve infrastructure management across civil engineering. The case study is an in-depth look at placement of sensors on guardrails for the purposes of real-time impact detection. More specifically the case study examined how to determine the cost effectiveness of implementing a new asset such as guardrail sensors on today's transportation infrastructure. The importance of improving on guardrails was concluded from a study by J.D. Michie and Maurice E. Bronstad (1994). The two researchers determined that six percent of guardrail impacts result in injury or fatality and ninety percent of the total vehicle impacts are unreported entirely (Michie and Bronstad, 1994). Not much is known about this ninety percent, but most likely some of these result in injuries as well. Furthermore, Michie and Bronstad's study shows that of the six percent of accidents resulting in injuries or fatalities, many involve guardrails that are out of date, incorrectly constructed, inadequately maintained, or involve accidents that are outside the design range of modern guardrail systems (Michie and Bronstad, 1994). This information indicates the placement of sensors on guardrails should be a high priority; therefore, this case study takes a three phase approach in determining the cost effectiveness of sensor implementation. The first phase involves data modeling of an existing ITS network from several views. The second phase employs a geographic information system (GIS) to determine optimum placement of the sensor in a given location. The third phase utilizes a cost model to demonstrate how to determine cost effectiveness of implementing the system. All three phases of the case study demonstrate the effectiveness of computing; however, this paper will focus specifically on the first phase of this case study, data modeling.

Methodology

Phase I data modeling is an integral part of the process in determining how a new asset will integrate into an existing ITS network. "A data model is a set of constructs for representing objects and processes in digital form" (Longley et al., 2005). In this particular case the network being modeled is the ODOT. Two modeling forms are apparent. Longley et al.'s four step approach using mainly GIS applications or the systems engineering, data model approach. Longley's four steps are as follows:

1. *Reality* - This modeling level requires understanding and defining the real world phenomena such as buildings, bridges, roads and so on. At this level, only a basic understanding of how the sensors operate and where they are located is required (Longley et al., 2011).
2. *Conceptual Model* - This modeling level consists of a partially structured model of selected objects and processes making up a broad overview of the existing network (Longley et al., 2011). At this level, an understanding of all the sensors, their connections to each other, their reach back capability and finally the storage of the data they produce is required.
3. *Logical Model* - This level of modeling defines the ontologies of the entire ODOT ITS network and the sensors implementation, but it's important to understand this level of modeling is not to scale. It's the computer based view of the network and so

the specific databases, the specific information going to and coming from those databases are included within this portion of the model (Longley et al., 2011).

4. *Physical Model* - This level of modeling contains the greatest detail and is specific enough to implement. It entails the working details of the processes within the databases that make up the ODOT ITS network. That is to say actual databases are modeled with exactly how the various sensors tie into them (Longley et al., 2011).

The second approach to modeling is the systems engineering based approach and the one that has been adopted for the case study. It proposes eight views of which the last three are presented that met the requirements for the study. While the two approaches have similarities, the systems engineering approach better fits what is needed to effectively model the ODOT network for the purposes of the guardrail sensors. This approach has been prescribed to serve as the overarching, comprehensive framework and conceptual model as it enables the development of architectures to facilitate managers at all levels to make decisions through information sharing across organizations (Wennegren, 2009). The DoD utilizes these views as it is necessary in entering the Net-Centric Operations and Warfare (NCOW) and the need to understand and portray complex relationships is critical during this time (DODAF, 2004). It has been adapted to this case study as it best represents the considerations that needed to be made in order to better understand the type and quantity of data and ensure they are taken into account (DODAF, 2011). The eight DoD systems engineering views are presented as follows:

1. *Project View (PV)* – Describes the relationships between operational and capability requirements and the various projects being implemented. It also details dependencies between capability management and the acquisition process. Examples of this view include the portfolio relationships and project timelines (DODAF, 2011).
2. *Capability View (CV)* – Articulates the capability requirement, delivery timing, and deployed capability needed. Examples of CV models include the phasing, dependencies and services mapping (DODAF, 2011).
3. *Services View (SvcV)* – Articulates the performers, activities, services and their exchanges providing for or supporting any AM function. Examples of this view include the services matrix, operational activity to services traceability matrix and resource flow matrix (DODAF, 2011).
4. *Standards View (StdV)* – Articulates applicable policies, standards, guidance, constraints, and forecasts. Examples of this view include the standards profile and forecast (DODAF, 2011).

5. *All View (AV)* – This view covers the overarching aspects of the systems architecture context that relate to all models. Examples of AV models would be the overview/summary information and integrated dictionary (DODAF, 2011).

6. *Systems View (SV)* - Describes the legacy systems/independent systems, composition, interconnectivity, and context providing for or supporting system functions. Examples of this include the interface description and systems matrix. The SV-1 (systems interface description) will be used to identify systems, system items, and the interconnections between them (DODAF, 2011).

7. *Data View (DIV)* - Describes the data relationships and alignment structures in the architecture content. Examples of this view include the logical data model and physical data model. The DIV-2 (logical data model) will be used to document data requirements and structural business process rules (DODAF, 2011).

8. *Operational View (OV)* - Describes the operational scenarios, processes, activities and requirements. Examples of this view include the relationships chart, resource flow diagram and the event trace description. The OV-6C (event trace description) will be used to describe operational activity and trace actions within the ODOT ITS network (DODAF, 2011).

The last view, while not one of the eight views prescribed by the DoD, represents another critical component of the systems engineering approach and is effective in describing requirements for the integration of a new sensor into an existing ITS. The last view is as follows:

Entity Relationship Diagram (ERD) - Describes relationships between entities in a database and used as a way to visualize a relational database.

Longley et al. (2011) describe the modeling at four levels, only three of those levels really describes what is necessary in implementing a guardrail sensor network. "The physical model portrays the actual implementation in a GIS and often comprises tables stored as files or databases"(Longley et al., 2011). This physical model is critical to the modeling, but one model does not suffice for these purposes. Additionally, Longley et al. suggest a reality based model and this too is insufficient. The systems engineering approach, utilized by the DoD, more accurately portrays what is necessary for implementation and puts more emphasis on the conceptual, logical and physical views with four other levels. These levels describe not only what an entire ITS system looks like from a broad overview with the SV-1, but also takes into account how the data flows with the DIV-2, exactly how data are queried with the OV-6C, and provide a visualization of a relational database with the addition of the ERD.

Other considerations must also be accounted for, such as how existing sensors are clustered together in particular regional areas. This leads to a better understanding of where existing infrastructure is available. Another consideration would be the type of

communication available, i.e. - serial or Ethernet. Knowing this determines the type of sensor necessary. Does it send inexpensive binary data or does it need to be more capable, sending multiple pieces of data at a time?

Several assumptions and limitations within this methodology have been identified. A primary limitation is that the product of utilizing the methodology is a set of models, which are only a representation of what has actually been implemented. No model is perfect and can't possibly account for every single detail present in reality. For example, the specific construction of the ITS network database is a representation of what is understood to exist and may differ in aspects of its structure. Modeling the network also does not describe the timeline over which the network was constructed. More specifically, there may be apparent flaws in the construction of the network or components that could be implemented more effectively; however, these were more than likely unavoidable given the time span in which it was constructed and the technology available at the time it was constructed.

Our methodology demonstrates a useable template that any persons in the ITS industry concerned with AM can use. AM by definition "is a systematic process of maintaining, upgrading, and operating physical assets cost effectively...AM provides a framework for handling both short- and long-range planning" (FHWA, 1999). Responsibly implementing new technology, and that technology's integration into the existing ITS infrastructure, means considering AM principles. Data modeling demonstrates this. Sitzabee et al. (2009) considered AM when proposing a pavement marking TAM. The TAM process "is a cost effective approach to systematically

measure, maintain...physical asset" (Sitzabee et al., 1999). Taking a cost effective approach, the pavement marking TAM estimates pavement marking condition without having personnel physically measuring it and thereby saves tax payers large sums of money.

Taking these considerations into account, the results were developed with the systems engineering approach in mind. The following section demonstrates three of the eight views described above in systems engineering, in addition to the Entity Relationship Diagram.

Results

All the models have been constructed with the guardrail sensor already having been integrated. This is possible since the data models revealed that the sensors communicate primarily serial data, which is low cost and very common in terms of the technology needed for a guardrail sensor.

Figure 1 shows the SV-1 diagram, which is a systems view of the existing ODOT IT system. Shown here are the legacy systems, composition, and interconnectivity. This figure displays the primary sensors which are all tied to a central control box by land lines. The control box then communicates by wireless cell or radio out to the cell and radio towers. Not all the sensors are present at each location, but rather they are clustered together in convenient packages that ODOT deemed appropriate. The clusters vary and there are a number of configurations that comprise the different sensor combinations across the state. For example, one cluster would include the eight different sensors shown on Figure 1, which are the speed detection, road surface sensor, pavement

sensor, traffic analyzer, volume and occupancy sensors, etc. Other clusters may only include combinations of these sensors.

Figure 1: SV-1 or systems view of the network.

The systems view is also broken down by ODOT owned systems and ODOT contracted systems. This provides another explanation for the Speed Info sensor being broken out of the main group and placed below the other seven sensors. It is also the reason Speed Info speed detection systems are not clustered with any other sensor. The Speed Info system is a standalone vehicle speed sensor that sends its information to the Speed Info headquarters in California wirelessly and demonstrates how the system can easily integrate outsourced data collection and maintenance. The reasoning for sending the data to California prior to being sent to ODOT is due to Speed Info being a proprietary system used by ODOT. The data is processed and immediately sent back to ODOT. The organization of Figure 1 reflects several large sections that include Remote Node, the ODOT Control Node and the internet. The Remote Node represents the sensor group ODOT owns and has control over and the ODOT Control Node represents the final location of the information. The Remote Node sensors and Speed Info sensors communicate the data to the Control Node.

The flow of data moves from the sensors to the control box, whereupon RS232 data converts from serial to Ethernet with a DigiPort converter box. The appropriate means of communication, landline, wireless cellular signal, or radio signal are responsible for sending data. The cellular and radio signals communicate with the

nearest tower where they then travel via hard line through the internet and then the ODOT server and finally the ODOT database.

Figure 2 is the logical model displaying the data flow view of the ODOT ITS network. The flow of information is just as important in this view as the measurements and information being collected by individual sensors. The flow of data describes how data collection occurs and how it is stored in the database. The provides/queries statement on each sensor connection expresses this flow. Additionally, this provides/queries statement represents the database querying the sensors and the sensors in turn providing the data. This demonstrates that the sensors are asked for information rather than just sending data continuously to the database, which would lead to more data being sent than needed. Again, the researchers emphasize that the main sensors communicate solely with the control box and then the control box communicates with the ODOT server. The Speed Info sensor is a separate system and communicates directly with the ODOT server. Once at the ODOT server, data funnels into the individual database tables automatically for each sensor. The tables collect all the information listed on the sensor in addition to the time and location (of the sensor) of the data.

Figure 2: Data flow view (DIV-2).

Figure 3 explains the specific layout of tables within the database. This figure is an entity relationship diagram explaining the relationships of the data from each sensor within the database. The notation below each sensor table symbolizes 0 (circle), 1 (single line), or many (v-shape) pieces of data and the equals sign (two lines) means 1 and only 1 piece of data. These symbols explain that the sensor tables specifically will store and

send multiple pieces of information or none at all. The tables at the bottom only store one type of attribute such as the location or sensor make and model. Figures 1, 2, and 3 explain the network from the broad systems overview down to the actual database and the location of the data and how the database stores them. The next step is to understand how the data are collected in terms of push and pull scenarios.

Figure 3: Entity Relationship Diagram (ERD).

Figure 4 adds to the DIV-2 data flow view and illustrates how the collection of information take place. Effectively, the ODOT server queries the control box to provide certain data at certain time intervals. At the appropriate time, the control box asks each sensor for its respective data and those sensors provide that data back to the control box. The control box will send all the data to the ODOT server. As you can see, the Speed Info speed detection system sends its information directly to the ODOT server. Once the server collects the data needed at that time interval, the data are then sent to the database and then onto ODOT employees within the regional control center for their use.

Keep in mind that for maintenance applications this data pull approach is effective and eliminates the over collection of redundant data, a key TAM concept. However, if the enhanced 9-1-1 system is considered, a data push approach would need to occur to alert that system of an event in real time.

Figure 4: Operational view (OV-6C) displaying operational activity.

Conclusions

This information garnered from the systems engineering perspective explains that the sensors, which researchers notionally built, can be completed with very cost effective

components. Figure 1, shows that the sensors send RS232, which is binary or serial data. Figure 2, demonstrates that the sensor will both provide data and be queried, which will be a requirement in the protocol. Both of these tell us that the sensor will have similar relationships within the database as the other sensors, which Figure 3 further reinforces. Figure 4 explains in further detail the provides/queries relationship between the Remote Node and Control Node.

Addressing the issue of integrating guardrail sensors into an existing ITS network effectively demonstrates the usefulness of computer data modeling in solving real world civil engineering related problems. Building the data models also demonstrates AM principles by taking a systematic approach and incorporating engineering principles.

Key Findings

The Federal Highway Administration (FHWA) defines AM as a systematic process and one that incorporates engineering principles and provides tools to facilitate an organized approach to decision-making (FHWA, 1999). AM requires extensive data management and to collect that data computers are necessary. Through the implementation of data modeling, this case study proves that guardrail sensors can be easily integrated into an existing ITS network. The importance of computing in the application of the sensor integration process is demonstrated through data modeling of the ITS network. While only a case study, this method can serve as a template for others to use while incorporating AM into their research.

Those who implement this method must consider the cost effectiveness, from the appropriate data model views (GIS/systems engineering), the architecture of the existing

infrastructure to support a new technology, and data communication format (serial/Ethernet). The data modeling in itself is cost effective requiring only computer software. Determining whether to utilize the GIS or systems engineering approach while building the data models depends on the developers' requirements. An understanding of the architecture of existing infrastructure is needed to evaluate the cost effective approach by providing lower cost locations to begin the integration of the sensor. Determining if the data communicated within the existing network is serial or over Ethernet helps in understanding requirements of a sensor that is to be introduced into the network.

The four views in this method of data modeling for the guardrail sensor case study provide critical insight into the requirements. SV-1 shows that the sensors send RS232 serial data. DIV-2 demonstrates that the sensor will provide data and be queried and the SV-1, DIV 2 and ERD illustrate that the sensor has similar relationships within the database as the other sensors. OV-6C explains further the relationship between the Remote Node and Control Node. Each view provided information necessary in order to implement a new technology into an existing ITS network. This case study demonstrates the effectiveness of computing while integrating sensors into existing networks as well as the importance of AM in doing so.

We recognize limitations for the methodology; however, we also recognize several additional limitations for the case study as well. The first is that the basis of the data modeling is only on the ODOT ITS network. ITS networks across the US vary and as such these models require tailoring in order to fit into other applications. Secondly, many of the elements of the ITS network for Montgomery County, Ohio were developed

through discussions with ODOT employees after gathering specifications on each sensor within the network. Regardless of these limitations this method can be applied anywhere nationwide and serve as an AM tool and demonstrates the effectiveness of computing and considerations that need to be made while incorporating sensors into existing networks.

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Figure Captions List

Figure 1. SV-1 or systems view of the network.

Figure 2. Data flow view (DIV-2).

Figure 3. Entity Relationship Diagram (ERD).

Figure 4. Operational view (OV-6C) displaying operational activity.

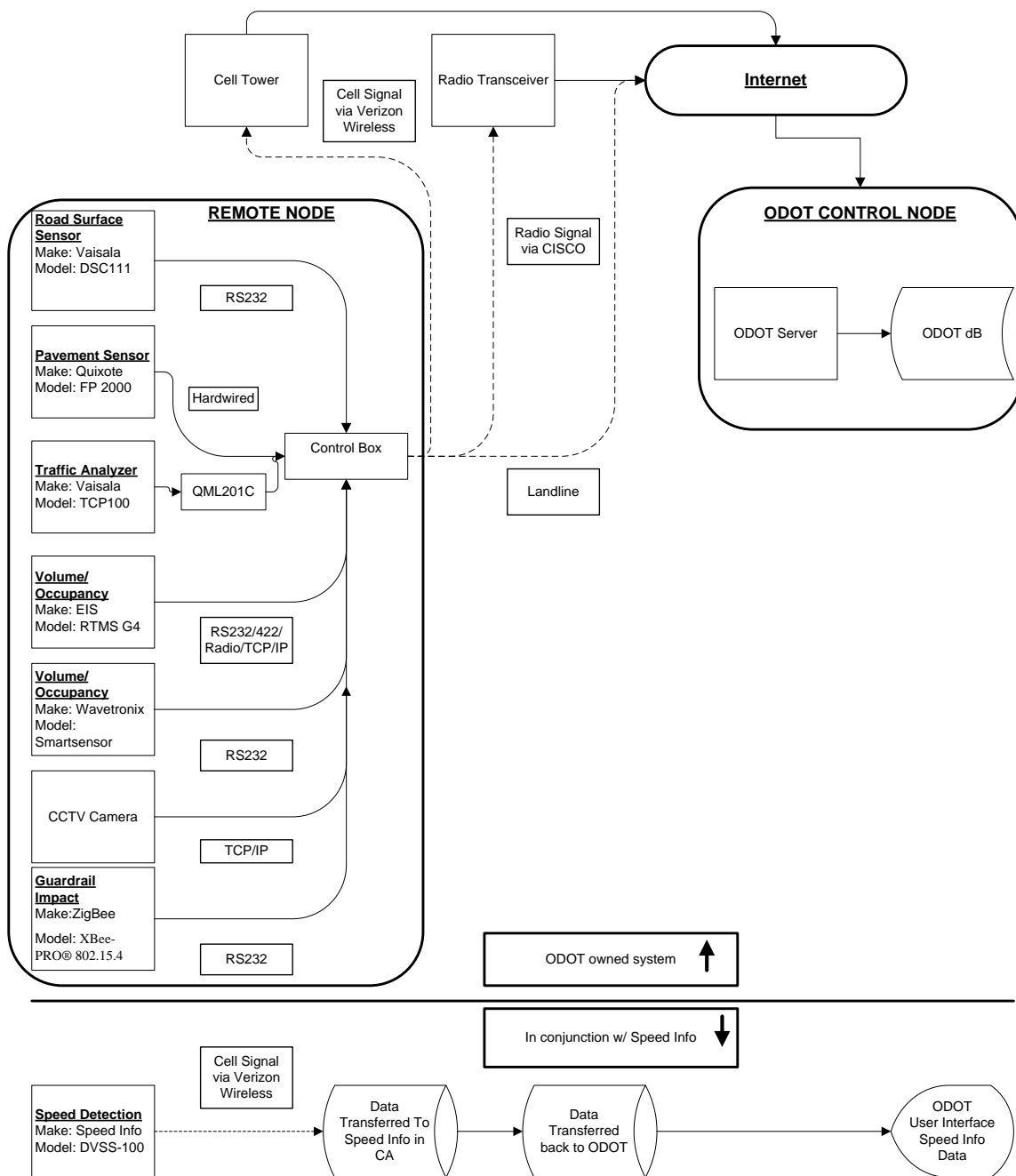


Figure 1: SV-1 or systems view of the network.

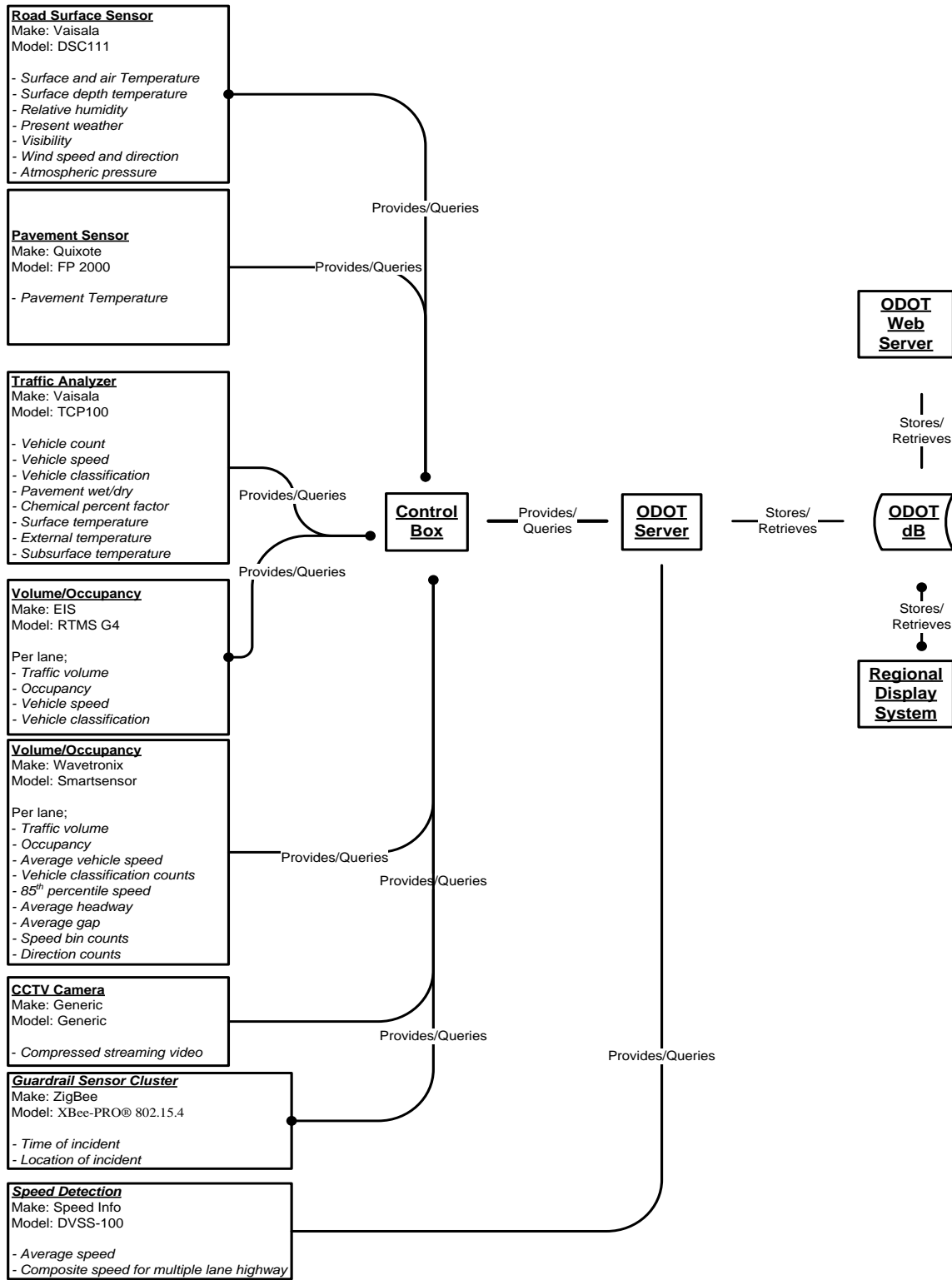


Figure 2: Data flow view (DIV-2).

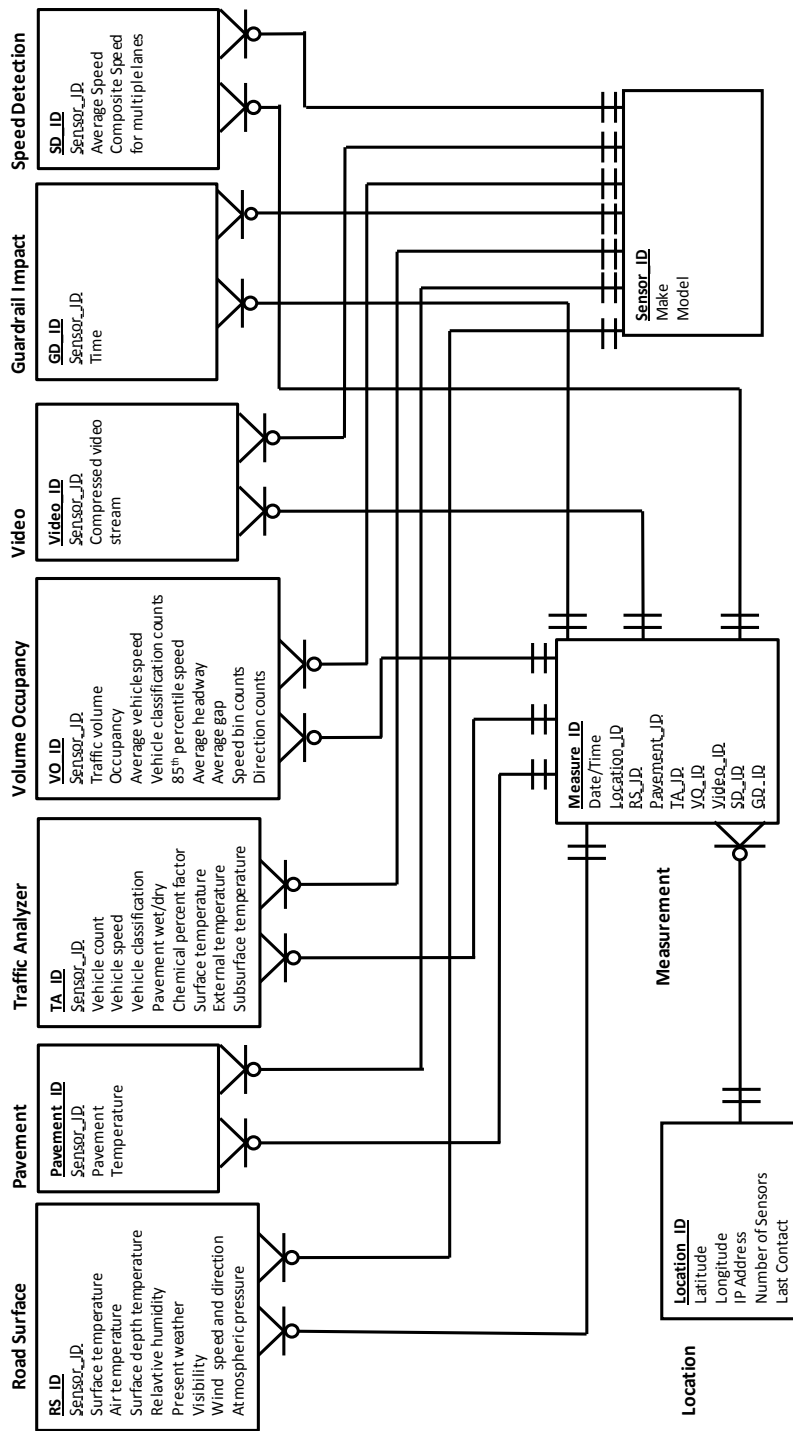


Figure 3: Entity Relationship Diagram (ERD).

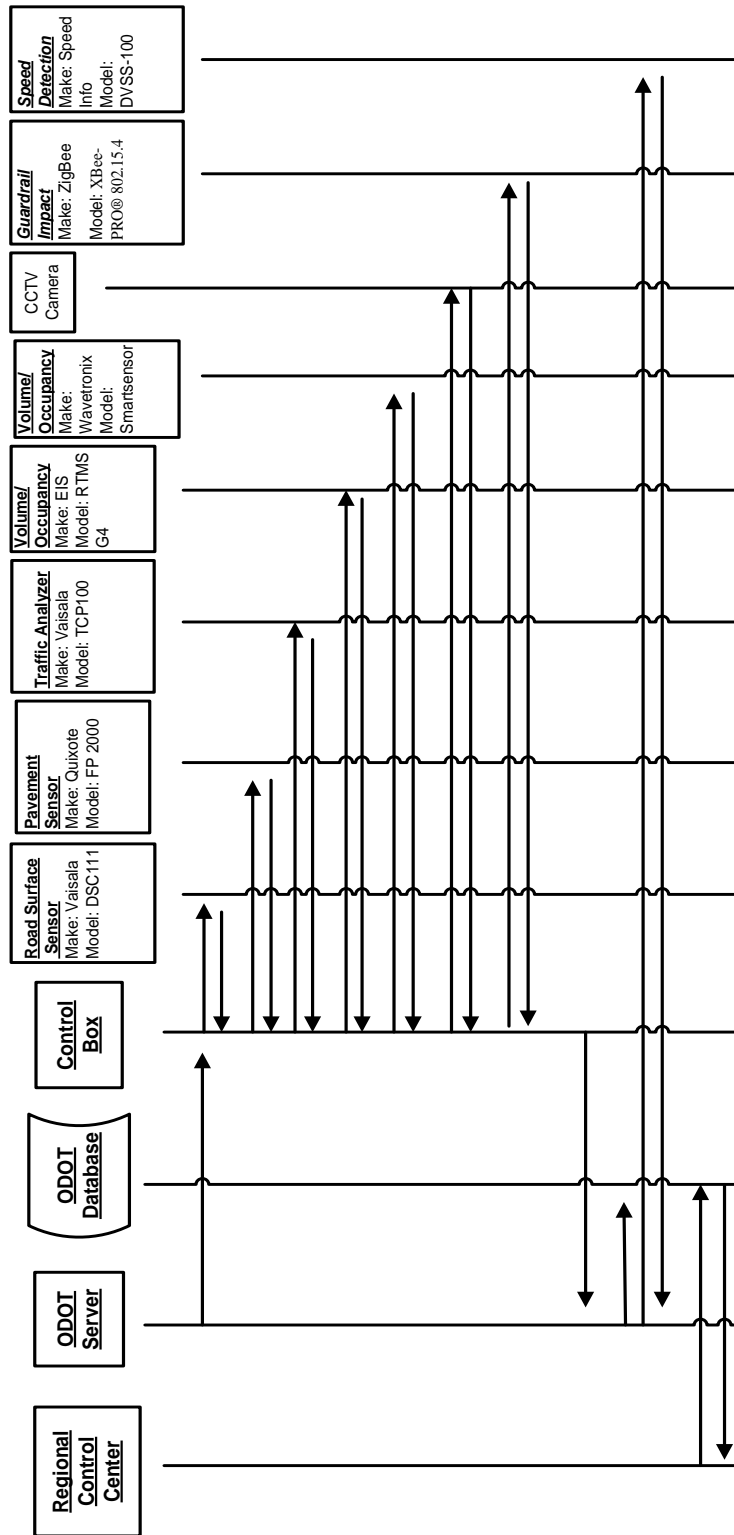


Figure 4: Operational view (OV-6C) displaying operational activity.

V. Conclusions

This thesis explores asset management's (AM) connection with intelligent transportation systems (ITS), a three phase methodology for sensor integration into existing ITS networks, and the usefulness of computing in solving real world civil engineering (CE) related problems. This thesis adds to the knowledge base of ITS and integrating a new sensor with existing networks. Additionally, each topic is explored with an emphasis on AM. The implementation of a guardrail sensor is utilized as a case study throughout each topic in order to demonstrate the importance of AM, the integration of a new sensor and data modeling.

The thesis follows the scholarly article format with three papers representing three main thrusts of the research. The first paper explains AM's connection with ITS through the safety and maintenance standpoint of current guardrail assets. The second paper utilizes a three phase approach providing a methodology integrating new sensors into existing ITS networks. Finally, the third paper demonstrates the usefulness of computer data modeling.

AM's Connection with ITS

The US Federal Government is actively developing ITS networks and seeking out new technologies. The key players, i.e.- FHWA, TRB and organizations like them, are advancing a rapidly growing industry. New engineers in the transportation industry need training and those currently in the industry may need retraining. The emerging and changing systems of transportation infrastructure are far different then they were 30 years

ago. Enabling technologies such as the internet, have made information readily available with far more information than ever before, which can be easily accessed (Sussman, 2005). Additionally, AM policies and guidance need to be updated continually. Policies and goals, planning and programming, program delivery, information and analysis together comprise the framework for AM today and into the future. ITS rely heavily on data and AM principles (FHWA, 1999). The incorporation of sensors on guardrails into the existing ITS systems close the data gap and in the 90% of unreported guardrail collisions. Advances in ITS can improve emergency response times to the estimated 6% of injuries and fatalities. Guardrail sensors also improve maintenance and preservation capabilities of communities across the country (Michie and Bronstad, 1994). Proper management, maintenance, and advancing of roads is necessary in order to provide a faster, easier, and safer means of travel (Wootton, 1995).

Three Phase Methodology for Sensor Integration

To accomplish the advancement of the nation's highway infrastructure a three phase methodology is proposed as a template for others to use in their own research. The three phases involve data modeling, performing a spatial analysis with GIS, and life cycle and cost optimization. The purpose of the first phase is to develop models to describe and document all of the elements of the existing ITS network which are necessary to understand when integrating a new sensor. Modeling allows for the understanding of what the existing system consists of including sensors, collection boxes, reach back systems and databases. In modeling, the existing system, and the requirements for a new

component(s) become clear. Understanding all the system components allows the person doing the modeling to understand the direction of flow of data, how much data are created and the type of data used. It also allows for an understanding of the organization of the data within the database(s).

The second phase exploits spatial analysis using a geographic information systems (GIS) model to determine the best locations to place the sensors. GIS provides people with the information about where events have occurred (Longley et al., 2011). Knowing where events occur allows for better decisions to be made in regards to the location selection for new transportation infrastructure assets. Additionally, data about these events can also be embedded giving users a sense of scale and in turn a deeper understanding of the events (Longley et al., 2011).

The third phase uses cost optimization techniques to identify the minimum cost solution that satisfies the sensor network requirements. Information from the first two phases provides the insight necessary to determine the total cost of ownership. It's critical to understand that in order to have real-time sensing a reach back network must be in place. Taking the information from the first two phases into consideration a model sensor system should be built including the sensor and any reach-back equipment necessary. The model can be physical or notional, but by detailing the components of the system using the information garnered from the first two phases a more realistic cost can be developed for the sensor system. Life cycle cost analysis (LCCA) provides DOTs a responsible decision making tool and allows for proper asset management. Effective asset management means the management of highway assets and integration of new

assets requires economic responsibility and sound investment strategies (FHWA, 1999). In estimating life cycle costs, DOTs and the FHWA can forecast budget requirements and determine the feasibility of a new asset more accurately. LCCA is widely accepted as a useful project evaluation tool and estimates the users cost over the life of a project or system (FHWA, 1999).

This three phase approach accounts for proper AM in the sense that a usable process is presented using three models to determine how to integrate a new technology into an already robust existing ITS network. This process aids in the decision making process and provides data that can be used in transportation budget considerations. With multiple systems in use on the road today, organizations such as ODOT may implement new technology on the basis that it's not only feasible or practical, but that it can be done so objectively, that there is sound reasoning behind where it could best be implemented, and lastly that it is cost-effective (requires the total cost of ownership be known). The data modeling, GIS spatial analysis, and cost optimization provide those tools DOTs need to incorporate a guardrail sensor network in their respective ITS networks.

Usefulness of Computing in Solving Real World CE Problems

AM by definition is a systematic process and one that incorporates engineering principles and provides tools to facilitate an organized approach to decision-making (FHWA, 1999). AM requires extensive data management and to collect that data computers are necessary. This case study proves through the use of data modeling guardrail sensors can be integrated into an existing ITS network. Through an effective

database architecture that uses sensors for remote data collection the use of computing to solve real world civil engineering infrastructure related problems is demonstrated. This case study presents a method and can serve as a template for others to use while incorporating AM into their research. The four views used in this method of data modeling for the guardrail sensor case study provide critical insight into what is required. SV-1 shows that the sensors send RS232 serial data. DIV-2 demonstrates that the sensor provides data and can be queried and the SV-1, DIV 2 and ERD illustrate that the sensor has similar relationships within the database as the other sensors. OV-6C explains further the relationship between the Remote Node and Control Node. Each of the views provide information necessary in order to implement a new technology into an existing ITS network.

The link between AM and ITS, the three phase methodology for incorporating new assets into an existing ITS network, and the usefulness of computing in solving real world civil engineering infrastructure related problems all incorporate AM principles and demonstrate its importance. Additionally, the three phase methodology provides future researchers with the tools necessary and a template to implement new sensing technology in existing ITS networks. Data models are also demonstrated as key to the understanding of the integration of the new sensing technology. The efforts to improve the overall efficiency of transportation systems and infrastructure using modern computing and communication and data processing technologies define ITS (Tarko and Roupail, 1997). The deterioration of roads due to age and use in addition to the construction of new roads

being complete demonstrates the importance of ITS (Wootton and Garcia-Ortiz, 1995).

In order to execute AM and improve ITS systems, the three papers discussed in this thesis should be considered.

Key Findings

The research in AM, ITS and the process of integrating a sensor into existing networks resulted in three papers that cover these topics in detail. Contained within those papers the importance of AM principles with ITS is explained, a methodology is proposed outlining the integration process and the use of computing during the integration is demonstrated. The following represent the key points from these topics:

- Remote sensing is practical for guardrail impacts and serves to improve both maintenance and safety of all those on the road.
- Integrating sensors into an existing ITS network should be done after the architecture has been modeled, a GIS approach to a placement strategy developed and life-cycle cost analyzed.
- Systems engineering methods can successfully aid in creating ITS architecture and assist in determining necessary considerations for sensor integration.

Future Research

Schofer et al. noted that the Transportation Research Board and U.S. DOT Research and Innovative Technology Administration both recognize the need for improved ITS networks on US highways. The two agencies collaborated on a conference

to discuss improvements to these systems (Schofer et al, 2010). Two conference outcomes included continued development of infrastructure condition and performance sensors as well as methods for rapid testing of new materials and designs (Schofer, 2010). These two cannot both be researched in the context of this thesis; however, future research could provide more breadth on these subjects.

Recommended areas for future research include expanding on the guardrail sensor case study. Development of a placement strategy of individual sensors on guardrails could be expanded upon to determine where exactly they should be placed and at what sensitivity level they should operate to detect vibrations due to impact. Additional topics to be further developed include the analysis of the variability in sensor implementation techniques across various DOTs within the US. The techniques these DOTs utilize may prove useful to research and determining the accuracy of their measurements and whether or not proper AM principles are enforced. Also, applications for emergency response and enhanced 9-1-1 were not researched heavily and these could be greatly expanded upon. Additionally, only 10% of the accident data is utilized for Montgomery County. Finding an area with more data and determining a way to better incorporate that into a sensor placement methodology should be considered. Lastly, GIS spatial analysis was utilized, but only in terms of analyzing vehicle accident density. Additional, spatial analysis techniques would provide more robust data.

Lastly, presented in the Appendix are documents that were useful in the research of this thesis. Appendix A contains the expanded literature review with information on past research in the AM and ITS fields. Finally, Appendix B contains the original

methodology explaining the original three phase approach to integrating a new sensor into an existing ITS network.

Appendix A – Expanded Literature Review

This section will discuss the resources utilized researching the issue of applying sensors to guardrails. The issue has been broken down into several components, which include a background of intelligent transportation systems, guardrail and safety background, current research and data utilized, and the methodology. The methodology is a critical aspect of the thesis; however, the background and details leading to the methodology provide a better understanding of the issue and how it can be resolved. The other components of the thesis demonstrate how useful the sensors will be in regard to maintenance and emergency services notification.

Intelligent Transportation Systems (ITS) background

The definition and brief history of ITS start with Andrzej P. Tarko and Nagui M. Roupail (1997) who state that, ITS has been defined as the efforts to improve the overall efficiency of transportation systems and infrastructure using modern computing, communication and data processing technologies. The history portion of ITS comes from another source; however, the majority of experts agree on the summarization. Transportations roots begin with the Egyptian Pharaohs, Chinese Dynasties and Roman Legions; however, ITS began more recently in the early to mid 1970s from a need to maintain and improve the current transportation infrastructure. The federal government at that time was concluding building the interstate highway system and knew it was time to begin maintenance programs to reduce the effects of stress and aging. The stress referred to here is the stress that's constantly increasing with the increasing traffic and variety of vehicles on the roads (Wootton, 1995).

The real importance of ITS has never faded; however, recently a conference report was published that reinvigorated the need for constant development of ITS. The U.S. DOT Research and Innovative Technology Administration combined with the Transportation Research Board brought together infrastructure owners and decision makers in the industry to determine the direction of future research in order to maintain and improve today's roads. Conference participants identified four research areas, including inventory and condition assessment methods, environmentally friendly materials and methods for the preservation of the infrastructure, rapid repair strategies and lastly, methods to model the deterioration. These four areas were further broken down into six research themes that help provide a greater understanding of what's required to advance existing transportation infrastructure. This conference stands as a testament that the U.S. needs smarter, more capable and longer lasting transportation infrastructure (Schofer and others, 2010).

Guardrail and safety background

The above topics cover the background of ITS, its importance and the fact that improving upon it is a real requirement to be met. What hasn't been covered yet is why there's a need to address ITS from the standpoint of guardrails. This discussion comes from an article by Jarvis D. Michie and Maurice E. Bronstad that provides relevant information supporting the need to continue the use of guardrails on the roads. It addresses the issue of guardrails, which have been labeled by some researchers as roadside hazards. The article uses real, accurate data to argue that guardrails are a necessary barrier between vehicles on the road and any highway infrastructure or

obstructions behind the guardrails. The article simultaneously dismisses the reports that guardrails cause more injuries than they prevent. Michie and Bronstad state that in their opinion, the misperception of guardrail performance is based on incomplete and misleading accident data. They also state that the conclusions that guardrails are a hazard are invalid. Current data indicate that 50 to 60% of guardrail accidents result in injuries or fatalities.

The guardrail, by necessity, is located within the highway clear zones and closer to traffic than hazards or other objects in order to shield people from the hazards or objects, but as a result is exposed to a greater frequency of impacts. Deficiencies in the data generally presented on guardrails could be due to the fact that only the most severe impacts are reported; in addition, police officers untrained on guardrail technology may not be reporting the incident correctly.

The article further describes the estimated number of guardrail accidents, both fatal and non-fatal. The authors look at the type of accident in comparison to the performance of the barrier, for example an obsolete barrier compared to an ideal barrier. They also discuss the longitudinal impacts compared to the terminal impacts on guardrails and how the terminals are overrepresented comprising 40% of guardrails accidents resulting in fatalities or injuries. Longitudinal barriers have been given poor performance ratings, based on improperly reported accident data. The success rate of longitudinal barriers is actually upwards of 94%. The authors discovered during investigation into the reporting of accidents that 90% of guardrail impacts are unreported. Six percent of all guardrail impacts result in fatality or injury; however, there is no

evidence of what becomes of drivers or passengers involved in the unreported 90% of accidents. Additionally, Michie and Bronstad contend that maintenance on guardrails has not been completed as it should have been causing certain guardrails to fail during impact with vehicles; however, the original data does not make a distinction between the two and this skews the results. A high number of guardrail impacts are unreported and may result in injuries or fatalities; in addition, maintenance on guardrails has been neglected and is causing further damage to vehicles as well as injury to the passengers. These two factors as well as the data stated above provide the justification for investigating combining guardrails with ITS (Michie and Bronstad, 1994).

The design criteria of the guardrails are described in detail in the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (2009). The manual provides uniform guidelines for crash testing both permanent and temporary highway safety features and the recommendations for evaluation criteria to assess test results. Specific information can be garnered about the longitudinal barriers in regards to design parameters for six categories of barriers and four primary vehicle types. The six categories comprise the test levels that the individual barriers are suited for and the vehicles that the guardrails are designed for. The vehicles range from a 2,420 lb passenger car to a 5,000 lb pickup truck all the way up to a 79,300 lb tractor trailer.

Knowing how the guardrails are tested and what they are designed for, for example the types of impacts and vehicles, leaves one question unanswered. What, of all the guardrail types available, is the best starting point when deciding to place sensors on

guardrails on major highways? Tabiei states the w-beam guardrail is the most widely used guardrail in the country to serve as a roadside barrier and any test conducted should be done with the w-beam guardrail in mind (Tabiei, 2000).

Once a specific guardrail is identified, more details can be garnered from the Standard Handbook for Civil Engineers. Aside from the many topics on civil engineering that are discussed within this text, details on longitudinal barriers are given to include types and amounts of deflection in each barrier type. Although very little of the handbook is utilized, the barrier section has been key in gaining a understanding of existing highway infrastructure (Ricketts, 2004).

Within the topic of guardrails are the components of design, maintenance, and safety. A great deal of research has been conducted under the topic of design. Several articles are useful in assessing improvements to the design of both w-beam guardrails and concrete jersey barriers. W. Lynn Beason and others discuss the advantages of changing the slope on a standard jersey barrier (common modular concrete barrier) from two separate angles, which grow consecutively steeper, into one single angle or slope and increasing the overall height several inches. These two changes should result in a safer, more effective barrier, based on the results of the full-scale crash tests (Beason and others, 1991). Glauz and others discuss the advantages of altering a standard steel w-beam guardrail into a taller thrie-beam guardrail. Instead of two jutting ridges along the vertical axis of the guardrail, three ridges are used. This change came about as a result of the taller, wider, and generally larger vehicles that are on the road today. Full scale crash tests were conducted and the authors determined that it is an effective design (Gluaz and

others, 1991). Nathaniel R. Seckinger and others discuss the difference made by embedding the guardrail posts in pavement mow strips. The study involved the standard w-beam guardrail, but looked specifically at the effects of the pavement mow strips on different guardrail post types, for example wood and steel. The results concluded that steel posts resisted impacts the most and yielded the least amount of deflection from both full-scale crash tests and computer modeling (Seckinger and others, 2005).

The next focus of the literature review is the safety aspect and more specifically the 9-1-1 emergency calling system. Julia Layton discusses the beginnings of the calling system and the workings of different 9-1-1 emergency call systems. The 9-1-1 system began in 1957 when the National Association of Fire Chiefs wanted to start a nationwide phone number for people to use to report fires. Over the decade that followed, other organizations became involved and everyone agreed to use one number for all emergencies. The number 9-1-1 was chosen as it is short, easy to remember and was not yet an assigned area code anywhere in the United States (U.S.). In 1968 a town in Alabama, known as Haleyville, set up the first 9-1-1 system in the country. During that year a second 9-1-1 emergency call system was started in Nome, Alaska (Layton, 2011). From then on, 9-1-1 was the standard phone number to use across the country as well as countries outside the U.S., for the purposes of reporting emergencies (NENA, 2010). The standard for notifying the authorities of emergencies had been set; however, the specific functioning of the system has been changing in recent years.

The 9-1-1 emergency system is really two systems, the basic and the enhanced version. The basic version is being slowly phased out and by 2006 only seven percent of

the 9-1-1 service across the U.S. was using this. It works by having the phone company recognizing a number after someone calls and routing the call to a dedicated 911 switch that sends the call to the designated Public Safety Answering Point (PSAP) for that area. The PSAP dispatcher answers the 9-1-1 call. The PSAP derives what the emergency is from the caller, where the emergency has occurred, and then obtains the contact information from the person calling since the system does not generate the location or contact information electronically.

The enhanced 9-1-1 call system works in a similar fashion with a few more components. The components include an automatic number identifier at the phone company that sends the number to the dispatch when someone calls; automatic location identifier that sends the persons address on record from the phone company also to the dispatcher; additionally, a master street address guide has been added to the enhanced version of 911 in order for the 911 network to know which area dispatch to send the call. The calling process is similar to the basic system. When a call is placed it goes to the phone company's 9-1-1 switch, which then routes the call to the master street address guide, that returns the call to the switch and then to the designated PSAP with the caller's number and location (Layton, 2011).

This enhanced process would be the most useful in terms of incidents occurring with guardrail collisions; however, both the basic and enhanced 911 systems are designed for land lines, not wireless networks. A wireless network would have to be utilized with a guardrail sensor given the exorbitant lengths of phone cable that would need to be installed to every guardrail in a given PSAP area. In terms of information sent, however,

the guardrail system would mimic the information that the enhanced system transmits, for example location of the incident.

The 9-1-1 emergency call system has had two phases of modification to its system to accommodate wireless users, which brings the possibility of wireless sensors on guardrails tied into the 9-1-1 emergency call system even closer to reality. The first phase allows for the PSAP to see the caller's number and location of the nearest cell tower to the caller. This first phase of modification allows for the location of the individual who places the call to be narrowed down to a radius 6 to 30 miles. This creates too large an area to efficiently locate someone during an emergency without additional information. If a collision does occur with a guardrail, there is no way to narrow the exact location of the emergency with only a 6 to 30 mile signal radius. That's where phase II comes in. Phase II enables the PSAP to locate the emergency to within 50 to 300 meters. As of 2006, 65% of the PSAPs had implemented this system, making it easy to install wireless sensors on the guardrail (Layton, 2011). Because, 86 million people were already subscribers to wireless phone service by 1999, Phase II implementation was critical (NENA, 2010).

From this point, the research moves into the sensors category. Research of a guardrail sensor preceded the data collection. Lawrence A. Klein's discusses many aspects of the systems currently in use in today's infrastructure, including sensor functions, arterial systems, network systems, and intersection controls. There is also information about pre-timed control and actuated control. One of the most relevant sections of his book covers freeway incident detection. Incident detection aids in creating

faster roads. The incident detection allows for accidents to be reported miles up the road, before a vehicle reaches the scene of an accident, and allows drivers to be rerouted, in turn maintaining traffic speed and avoiding large scale traffic jams. A system such as this could be further enhanced with the use of guardrail sensors. The technology could provide those on the road instant alerts about traffic conditions ahead of them and work in conjunction with other incident detection technologies.

Current research and data utilized

Weiyun Jiao and others applied wireless sensors to guardrails for the purposes of impact detection, within the vicinity of traffic cameras. They found that vibratory properties of the guardrail, demonstrated during an accident, perform sufficiently enough to aid in identifying the occurrence of an accident. Real-time vibration data were recorded by nodes with accelerator sensors on the guardrail using an ad hoc or specific network. The collision between the vehicle and guardrail was identified in terms of the vibration threshold and the camera was then triggered to take continuous photos of the incident and send the photos to some control center. This idea was tested on the northern Fifth Ring in Beijing, China. The system was comprised of several of the vibration sensors with three axis accelerometers, a ZigBee short distance communicator to talk to the camera, the motionless camera, and another ZigBee wireless transmitter to send the data to the remote control center. The system was not tested with actual vehicle collisions, but rather impact hammers with a measurement range of 50 to 100 KN in order to simulate the impact of vehicles on the guardrails (Jiao and others, 2008).

Both the safety and maintenance portions of this thesis require a working knowledge of where these guardrails are being impacted and on what roads. Crash data provide this information from several sources. The first such source is the Ohio.gov public internet site, which allows access to a public database containing information on crash statistics. Data inquiries can be performed for either the state of Ohio as a whole or by a specific county. The database allows access to information on crash statistics from the annual Traffic Crash Facts books for any specific date or longer time period over the past five years. The sections contained on the database include general statistics, crash, death and injury, driver, unit (vehicle type, number of passengers), alcohol, and finally city or village statistics. Reports can then be accessed under the main category of crash statistics for a variety of sub-categories including crashes by light condition, weather condition, and location by crash severity. It is the location of crashes that applies to this thesis and given the ability to search by county, Montgomery county is used as the focus of this study as it's in the vicinity of Wright Patterson AFB and it encompasses a number of heavily trafficked state roads. Beyond using the online search engine for the database, bulk data can be extracted from the database over any date period specified, not to exceed a year. In the case of this thesis, crash statistics were downloaded from the database for the entire year of 2010 for Montgomery county (Ohio.gov, 2011).

Methodology

Additional resources in understanding the existing Ohio network and completing the three phase methodology include personal interviews conducted in May of 2011 with two employees of the Ohio Department of Transportation's Traffic Engineering Office.

The senior ITS engineer works within the operations center for the ODOT ITS network making him an appropriate resource for firsthand knowledge of the system. Specific sensor models and manufacturers as well as sensor distributions were derived from these interviews. An understanding of the flow of information and data from each sensor to the ODOT main office was provided (Saylor and Comer, 2011). How the information on the network blueprint would be explained conceptually and visually has come from DoD Architectural Framework lectures, which provides the structure for organizing systems such as the ODOT ITS network (Grimaila, 2011).

One of the last topics to be reviewed is that of geographic information systems (GIS). The GIS book by Paul Longley and others is of importance in this thesis and has formed the basis for both phase I and II of the methodology. Essentially, the topics covered include basic information on GIS and how it can be used to provide a way to find solutions to complex problems. The text covers various topics including GIS anatomy, various applications of GIS, representing geography and spatial data analysis. Spatial data analysis was used in phase II of the methodology to locate the most significant areas of traffic accidents across Montgomery County. Additionally, the overview of data modeling proved useful as did the information on entering data points such as traffic accident locations (Longley, 2011).

An additional source for data modeling is information provided by Dr. Michael Grimaila at the Air Force Institute of Technology (AFIT) entitled DoDAFv2.0, Systems Architecture. The lecture describes systems architecture in detail covering the levels of

modeling that were used in this thesis. Each level and a brief description are discussed below.

Conceptual: This modeling level consisted of a partially structured model of selected objects and processes making up a broad overview of the existing network. It's the systems view of the existing network and includes connections as well as all the systems involved (Grimaila, 2011). This level was depicted with a graphical representation of a large area (Ohio) with digital figures to represent a radio tower, sensor, and ODOT headquarters.

Logical: This level of modeling consisted of a more specific layout of the ODOT ITS network and the sensors data requirements and business processes. It's important to understand this level of modeling is not to scale (Grimaila, 2011). This level was depicted with the data view.

Physical: This level of modeling contains the greatest detail. It entails the working details of the processes within the databases that make up the ODOT ITS network. That is to say actual databases are modeled with exactly how the various sensors tie into them (Grimaila, 2011). This level was depicted with the systems view of the database.

The third phase of the methodology involves optimization in the selection of the shortest path between the endpoints of 30 pre-defined guardrails within Montgomery County. The optimization comes in the form of the Traveling Salesman Problem (TSP). Cliff T. Ragsdale provides a definition for the TSP, which states that it's "one of the most

famous problems in the field of management science (Ragsdale, 2007:385). It can be described as a salesperson who wants to find the least costly (shortest) route for visiting clients in a certain number of cities and visit each city only once before returning home. By converting the endpoints of the guardrails into a TSP the solution determines the shortest path between them all, which is the least expensive order in which they need to be connected.

Arash Behzad and Mohammad Modarres provide information on the third phase of the methodology and converting the guardrail endpoints from a General Traveling Salesman Problem matrix into the Traveling Salesman Problem matrix in their article. The General Traveling Salesman Problem (GTSP) was introduced by Henry-Labordere in 1969. The GTSP is an extension of a TSP that has a degree of complexity in comparison to a TSP that makes it difficult to find an optimal or near optimal solution. In comparison, there are many very efficient methods for solving a TSP. For that reason it is wise to convert the GTSP into a TSP and ensure that the number of nodes is equal. A TSP typically has more nodes, sometimes two to three times the number of nodes of a GTSP. Behzad and Modarres propose a new method to convert the GTSP into a TSP with the same number of nodes and obtaining an optimal solution of GTSP (Behzad and Modarres, 2002). The specific method will be demonstrated in Chapter 4.

Further research was necessary for the purposes of gaining a better understanding of the physical sensor network and its pricing. To better understand the cost of the sensor network it's necessary to have an understanding of the components that will be used. Cirronet, Inc. provides key information in a white paper on ZigBee radio's and why they

are the better choice for wireless networking. Zigbee has several options available for both short and long range wireless applications to include a 1mW and 100mW power radios. The 100mW radio uses the same component as the 1mW radio with the exception of a power amplifier being added for approximately \$10. The article makes recommendations for which of the two powers of radio are best for a given situation and explains a concept known as multipath fading. Multipath fading occurs with obstacles between the transmitting radio and its intended receiver. The obstacles all deflect the signal simultaneously and what occurs is an effect where several copies of this signal arrive at the receiving end at different times and out of phase. This effect reduces signal strength and adds to path loss. Multipath fading can be avoided with the 100mW radio transmitter in longer range scenarios and situations where there may be infrastructure or natural objects along the intended path of the transmission such as on guardrails along major roads. The 1mW radio is better suited to indoor or very short range applications within 100' indoors or 300' outdoors maximum. The 100mW radio has an indoor range of 300' and an outdoor line of sight range of 4000'. The advantage of both of these systems is their low power characteristics. Both can be put in a sleep mode making them ideally suited to battery powered devices such as the guardrail sensor. The sleep mode allows it to only consume power while it's transmitting and then go back to sleep consuming only very minimal power. A 100mW radio may consume 150mA while transmitting and 3uA while asleep easily extending its battery life to months versus hours depending on the protocol for transmission and reception of signals (Cirronet, 2005).

Understanding which radio to build into a sensor provides a better understanding of what a sensor network would cost to build.

The long term cost of such a network requires more analysis than just assigning an initial build cost of four different communication types.

Appendix B – Preliminary Methodology

The methodology for this thesis will consist of a three phase modeling approach. The first phase will be modeling the existing ITS network within the Ohio Department of Transportation (ODOT) via the software package Microsoft Visio. The second phase will consist of a spatial analysis with a GIS model to determine the best locations to place the guardrail sensors and the third phase will be a cost optimization model to determine the optimum balance between cost of the guardrail sensor system and its performance. For the purposes of this thesis the performance is defined as the strength of radio transmission with a ZigBee type radio module. The following is a more detailed discussion of each of these phases of the methodology.

Phase I – Data Model

This portion of the methodology answers the question of how a guardrail sensor will tie into the existing ODOT network. The data model provides a detailed visual aid and in depth understanding of how the ITS network is structured and operates in Ohio. It also incorporates the existing sensors in Ohio's ITS network currently and demonstrates how the new guardrail sensor be incorporated into such a network. Existing sensors refer to the video traffic cameras, road temperature sensors, traffic speed sensors, dynamic message boards, and any other sensor that might be on interstates or other major highways today in Ohio delivering real time information to ODOT's central office in Columbus, Ohio. In doing so, it's necessary to view the model from one of two approaches each with four levels of modeling. The first approach is the geographical

information systems (GIS) and the second is systems engineering. The GIS approach levels include reality, which requires only a basic understanding of how the various sensors operate within the existing network down to the fourth level. The fourth level in the GIS approach is a detailed description of the actual data that's being sent from the sensors to the individual databases contained within ODOT's main office. These levels of data modeling differ slightly from the systems engineering approach. The GIS approach is identified below with general descriptions and accounts of how they apply to the ODOT sensor network situation (Longley, 2011).

Reality: This modeling level is comprised of real world phenomena such as buildings, bridges, roads and so on. At this level, only a basic understanding of how the sensors operate and where they are located is required. For example, the guardrail sensors will be placed on w-beam guardrails along the interstates in locations that coincide with traffic cameras and tied into the network that feeds information and data into the ODOT database.

Conceptual: This modeling level consists of a partially structured model of selected objects and processes making up a broad overview of the existing network. For example, the current network for Ohio Department of Transportation (ODOT) really consists of sensors (video feeds, speed sensor,

dynamic message boards, etc.) that are hardwired to a local control box. This local control box provides both power and communication via Verizon wireless modem or CISCO radio antenna. From there, a signal from the control box is transmitted to a local area network or cell tower and then transmitted over either fiber optic or leased phone lines back to ODOT HQ. The information and data from the sensors are stored in one of a multitude of databases at ODOT and then sent to the respective departments (traffic engineering, road maintenance) for the purposes of analyzing relevant details.

Logical: This level of modeling consists of a more specific layout of the entire ODOT ITS network and the sensors implementation, but it's important to understand this level of modeling is not to scale. It's the computer based view of the network and so the specific databases, the specific information going to and coming from those databases are included within this portion of the model.

Physical: This level of modeling contains the greatest detail. It entails the working details of the processes within the databases that make up the ODOT ITS network. That is to say actual databases are modeled with exactly how the various sensors tie into them. For example, the guardrail sensors will transmit RS232 serial data via hard line to the control box with the time and location of impact.

The systems engineering approach is similar, but suggests 8 viewpoints. For the purposes of this thesis 4 of the 8 will be utilized, which are described below and within the scope of this thesis (Grimaila, 2011).

Operational View: Describes the operational scenarios, processes, activities and requirements. The OV-6C will be used to describe operational activity and trace actions within the ODOT ITS network.

Data View: Describes the data relationships and alignment structures in the architecture content. The DIV-2 will be used to document data requirements and structural business process rules.

Entity Relationship Diagram: Describes relationships between entities in a database and used as a way to visualize a relational database (cornell, XX).

Systems View: Describes the legacy systems/independent systems, composition, interconnectivity, and context providing for or supporting DoD functions. The SV-1 will used to identify systems, system items and the interconnections between them.

Again, this a four part network modeling approach that will primarily be a visual representation of the actual systems in place today with the new guardrail sensor integrated into them in a practical, useable manor. Chapter IV (Results) will provide both the ‘as-is’ data models in addition to the ‘to-be’ models describing the ODOT ITS network currently and than what it would look like with the addition of the guardrail

sensor. This data modeling approach will demonstrate how a new guardrail sensor would tie into the existing ODOT ITS network.

Phase II – Locating Optimum Sensor Location via GIS

The second of three phases involves GIS spatial analysis in order to determine the optimum locations of sensor placement throughout a given area. For the purposes of this thesis, only Montgomery County, Ohio will be used as a model to determine the optimum locations. Within Montgomery County, only the major state owned roads are modeled. The major state owned roads include interstates I-675, I-70 and I-75 as well as state routes US 35 and US 40. Narrowing it to those roads specifically, a map will then be built of these major roadways across Montgomery County. After that, locations that also have with video feeds visible on the web (from Buckeye Traffic site) will be cross referenced with the locations with the highest incident rate (vehicle crashes) to identify where the sensors should be placed. The traffic camera locations are being used in order to minimize false positives. To expand on the issue of false positives, the ODOT traffic camera database maintains video files for a period of five days, after which they are recorded over. If something were to happen in those areas with cameras and a guardrail sensor notified DOT or 911 of an impact at that point, the video file could be accessed within five days to verify there was, in fact, a vehicle incident (Saylor, 2011). Beyond eliminating false positives, several radii around the traffic cameras will be included such as $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of a mile. The maximum radius of $\frac{3}{4}$ of a mile demonstrates the effective range of a video camera, and all three radii allow the user to determine at what distances the camera ranges overlap, and therefore may help in minimizing the need for sensors.

For example, if two cameras are a half a mile away from each other, they both fall within their half mile radii and half way between them is only a quarter of a mile. The quarter mile distance is to record an incident on the traffic camera, and it allows one sensor to be placed between them in turn limiting the amount of wire connecting the sensor to the traffic camera control box, if in fact a wired system is chosen (Saylor, 2011).

The crash statistics will be garnered from the Ohio.Gov Department of Public Safety site for crash statistics. The database allows the user to search for several types of statistics on vehicle crashes, the most important of which are the death and injury statistics, general statistics and crash statistics. The user can then narrow the search further by selecting one of 17 different categories, such as crashes by month, crashes by location, and so on. The most intriguing is that of the crashes by location (general roadway locations such as intersection, off ramp and so on) the highest incident rates are at four-way intersections and areas referred to as “not an intersection,” which infers longitudinal portions of the roadway. The statistics can be further narrowed by geographic area, which include state or county. Data can also be downloaded for a given area and given time of year. This database will provide the basis for the project to determine which location to focus on. Again, the purpose of using GIS is to determine the optimum location of the guardrail sensors in relation to the existing traffic cameras.

Phase III – Cost Optimization Model

The third and final phase of the methodology for this research consists of a cost optimization model to determine the optimum cost to performance mix. This takes into account all the data garnered thus far and allows the primary conclusions to be drawn

about the total cost of ownership. This phase has been broken into two components to allow for better determining of cost and formulating a useable model that can be used by anyone interested with another set of data. The initial portion of this phase was developing a model that determines the best order of connecting guardrails. In order to determine the optimum order in which to connect each guardrail an optimization model was used in Concorde. “Concorde is a computer code for the symmetric traveling salesman problem (TSP) and some related network optimization problems. The code is written in the ANSI C programming language and it is available for academic research use. Concorde's TSP solver has been used to obtain the optimal solutions to the full set of 110 TSPLIB instances, the largest having 85,900 cities.” (Concorde, 2011) The premise is that the guardrails need to be connected to each other in groups and each group will transmit back to the control box either wirelessly or by wire. The Concorde program being developed here determines the best way to connect the guardrails within each of the groups and is robust enough to develop a solution.

Initially, the optimization model was to take into account the distances that each guardrail endpoint was from every other guardrail endpoint; however, there was no differentiation between what sides of the road (North or South) the guardrails are on. The list of endpoints was a mix from each side of the road, 30 guardrails each with two ends which equates to 60 guardrail endpoints. The optimization was to occur in a matrix of manually entered values for each of the 60 endpoints so the dimensions were 60 x 60. The 60 x 60 matrix contained 3600 values, which is why a robust solver such as Concorde was necessary. These values were then manipulated from the General

Traveling Salesman Problem (GTSP) format into the Traveling Salesman Problem format (TSP). The GTSP format determined the shortest route connecting each guardrail once forming 29 connections between 30 guardrails. The TSP format found the shortest path to all points, which would create 59 connections and require each guardrail be visited twice. The TSP is typically much more time intensive to solve for this reason; however, the TSP is more common and therefore more solutions have been developed. This is the reasoning behind the GTSP being converted into a TSP format for the ease of solving it. What would occur in this solution was a more easily solvable GTSP and it allowed for each guardrail to be connected only once to every other guardrail forming only 29 connections between all 30 guardrails (Behzad and Modarres, 2002:1). The premise is that each guardrail only needs to transmit to any other guardrail from one location or endpoint within its structure rather than from multiple locations or endpoints.

Within each guardrail the information from the detection of an incident is transmitted to the guardrail end containing the transmitter, which is then sent out through the connections at the other guardrail ends, than onto the central transmission location for that group of guardrails and immediately after, it's sent to the control box for the traffic camera or directly to ODOT from the central transmission location.

The list of 29 guardrail connections is output from the model with the list of distances between each connection and that information is then used for the second component of this phase of the methodology. This second portion of the research is used to determine the lowest cost communication type that has a sufficient range for each particular guardrail connection and is assigned manually. The second component does

not require optimization and determines which of the four communication types will be assigned to each of the 29 connections. The four communication types include permanently (hardwire) powered radio, and low power wireless radio, medium power wireless radio and high power wireless radio. Low, medium and high power radio types all use a battery power source, presumably lithium. Determination on the size and type of battery source will also occur during this phase. Each communication type has a total cost and an effective range. The output from this is the quantity of each communication type that will be used and the total cost for all 29 connections. Again, the reason for this phase of the methodology is to determine the optimum blend of performance considering the cost of the individual guardrail sensors and the power source utilized over a predetermined period of time.

The cost portion of this phase is developed for each communication type separately based on the range of each sensor type, its power source, and its life span. Experimentation was not conducted during this research so a sensor was never actually built, but rather a hypothetical model for each communication type was developed to better understand an initial and annual maintenance cost. The costs for each communication type were all built by specifying a radio transceiver, an accelerometer, a microcontroller and a power supply that fit each type. The life spans of each sensor were evaluated over a 30 year period and the total cost of each, over the 30 year period, were then converted into a present worth. The discount rate for determining the present worth of each option from the OMB A-94 is 2.3% for a 30 year period, which is the real interest

rate as opposed to the nominal interest rate. Using this discount rate, all four costs for the lifetime of each communication type can be evenly evaluated for a 30 year period.

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Vita

Captain Matthew Dana Sturtevant graduated from Maranacook Community School, Readfield Maine, in 1998. He completed his undergraduate studies at St. Lawrence University and Clarkson University, where he earned separate degrees in Physics and Mechanical Engineering respectively after graduating in the Fall of 2003. His first duty station was Ellsworth AFB, Rapid City South Dakota, where as a member of the 28th Civil Engineering Squadron he served as the Chief of Maintenance Engineering and Readiness Flight Chief. In 2007, he moved to Great Falls Montana, where he joined the 819th RED HORSE Squadron and as Project Engineer, Chief of Engineering and finally, Engineering Flight Chief, he led numerous projects both at home and abroad. On two separate deployments, the first in 2007 and the second in 2009, he served as Site Officer in Charge, commanding over 70 individuals and leading millions of dollars in construction in support of Operations Iraqi Freedom and Enduring Freedom. In the fall of 2010, Captain Sturtevant moved to Dayton Ohio where he began his graduate studies in Engineering and Management at the Air Force Institute of Technology.

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