DATA INTEGRATION OF PAVEMENT MARKINGS: A CASE IN TRANSPORTATION ASSET MANAGEMENT

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Abstract

Effective transportation asset management requires the implementation of tools such as software, hardware, databases, and data collection systems. Pavement markings make up one component in transportation asset management, which are complex networks that require large databases. Typically these databases are maintained in different areas within an agency and are most often incompatible. Combining new and old tools, this paper addresses the need for better data integration and utilization while incorporating current information technologies.

Specifically, this paper presents integrated transportation asset management system for estimating the current and future condition of pavement markings. The paper describes the data structure, in the form of a physical model, integrating a pavement marking relational data schema with existing information technology systems. Software was found to be useful in developing the data schema. The software produced an XML file that is compatible with a variety of existing database structures such as Oracle, SQL, and MS Access. Additionally, the system included an algorithm which implements the data structure and predictive models to estimate the condition of the asset at any point in time or space on the highway system.

Using either measured data or predicted data the system gives managers an opportunity to decide on the best possible condition state of the asset and perform queries or optimizations. Ultimately, managers can develop cost effective strategies for pavement marking asset management.

Keywords: Data Integration, Pavement Markings, Asset Management, Data Model, Data Schema, Retroreflectivity

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INTRODUCTION

There are many components to asset management which include things like asset inventories, condition assessments, and data integration strategies. In many highway agencies separate data managements systems are often incompatible and data integration among these systems becomes impractical or expensive [Gharaibeh, Darter, and Uzarski, 1999]. Assessing the condition of an asset is labor, equipment, and data intensive and requires the implementation of computing tools. Specifically, the FHWA Office of Asset Management Research and Development Activities highlighted the need for agencies to conduct research on data integration and the various uses of integrated data for asset management [FHWAa, 2007].

Pending FHWA requirements call for assessing the condition of pavement marking retroreflectivity, which means that incorporating computer based automated measurement tools can greatly improve the assessment process. This paper provides a solution to the data integration problem of incorporating various attributes of pavement markings, both measured and predicted, into an existing transportation asset management (TAM) system.

BACKGROUND

Every asset has a set of attributes and each attribute has a condition at any particular time. One or more measures, typically collected with sensors or other technologies, helps assess the condition. Agencies store these measures as a series of values that represent the asset condition in the form of an asset inventory.

Regulations sometimes establish minimum and maximum allowable values of an attributes condition. In the case of pavement markings the primary attribute of interest to the FHWA is the coefficient of retroreflected luminance (R_L) which is recorded in units of milli-candles per meter squared of luminance ($\text{mcd}/\text{m}^2/\text{lx}$). Of course, there are many other attributes of interest that all need to be considered to effectively and holistically manage this asset. The TAM goal is to find the condition of pavement markings, with regard to their R_L value, and display both the current and future condition in an easy to interpret map format. With good map representations transportation decisions makers can better understand the condition of the asset statewide and take appropriate actions such as better prioritization of the pavement marking budget.

Transportation Asset Management (TAM)

In 2006 Cambridge Systematics, Inc. authored Nation Cooperative Highway Research Program (NCHRP) Report 551, Performance Measures and Targets for Transportation Asset Management. The backbone to this asset management approach is a performance-based framework for decision makers that transcend all levels of the organization [Cambridge Systems Inc., 2006].

NCHRP Report 551 makes a key point of highlighting the need for quality information using scientific methods to collect and analyze data about the asset. Collecting inventory data can be time consuming and costly. Furthermore, the quality of data is one of the most important factors for implementing IT systems [Rasdorf et al., 2003]. The validity of the analysis hinges on the quality of the data used to perform the analysis. Estimating the condition of an asset relies heavily on the five parameters highlighted by Rasdorf et al., which are positional accuracy, attribute accuracy, data lineage, completeness, and consistency [2003].

Previous research has found that mobile collection is the most practical, safe, and efficient method of collecting retroreflectivity data [McDiarmid, 2001]. However, in a large transportation system, mobile collection can still only measure a small percentage of the total asset. For example, NC measures approximately ten percent of the roadways at a cost of approximately \$200,000 per year. Statistical methods to estimate the rest of the condition of the asset is a way to generate quality information about the asset while saving nearly \$1.8 million dollars per year in data collection alone.

Estimating the condition state of an asset follows the TAM process which according to the Federal Highway Administration (FHWA) is a cost effective approach to systematically measure, maintain, upgrade and operate a physical asset. The process combines engineering principles with sound business practices and economic theory for the purpose of improving decisions regarding the asset [FHWA, 1999]. Pavement is an example of an important transportation asset and pavement management systems are the tools for collecting and monitoring TAM information.

Definition of the Asset

The first and most crucial step to asset management is to clearly define each of the assets in terms that are clear and measurable. There are six parameters that define the pavement marking asset in a measurable way providing a common understanding throughout the organization. At the same time they provide enough detail for effective asset management. For pavement markings these parameters are defined below using a standard format for NC's transportation assets [Love, 2007].

1. Asset Identification: Pavement marking.
2. Decision Actions: Marking/re-marking. Management is concerned about all the issues associated with marking and remarking pavements. This would include safety, service life, budgeting, and compliance with Federal standards.

3. Condition Indicator: The condition indicator defines the basic LOS increment; here, color-coding is used to define the condition of pavement markings while offering the capability to display the LOS cartographically.
4. Performance Measure: The performance measure for pavement markings is the coefficient of retroreflectivity luminance (R_L), which is measured in $\text{mcd/m}^2/\text{lx}$.
5. Performance Target: The performance target is a percent compliance with any established standard for pavement markings. The performance target is the specific and measurable goal to achieve with this asset.
6. Minimum Standard: The minimum standard for pavement marking retroreflectance is represented by a LOS “red” in Table 1. The standard complies with proposed Federal standards and is clearly measurable.

Level of Service

Translating R_L into level of service (LOS) increments enables agencies to quantify or characterize the condition of the attributes of an asset in a meaningful way for decision makers. LOS is the common definition that provides the foundation to implementing tools that use existing data to predict the condition state of the asset beyond the boundaries of the sample data. That is, we want to appropriately and optimally sample, and then extrapolate what we find to the larger asset population. We do this because many assets are too numerous to individually measure. Additionally, LOS increments allow for a simplified method to assess conformance of an asset's conditions against a set of regulations. Finally, LOS increments can clearly relay information about the condition of an asset to legislators who ultimately control the funding and to the public.

Table 1 shows the five LOS increments that were established for pavement markings in NC [Sitzabee, 2008]. The left columns show the increment values for thermoplastics and the right columns show the increment values for paint-based markings. All values are in $\text{mcd/m}^2/\text{lx}$. The red LOS indicates the minimum standard for retroreflectivity that will be used by NC until the Federal standard is published. This minimum standard is used to define the end of service life condition.

A graduated LOS scale was used where blue indicates the pavement marking at the highest LOS and red indicates pavement markings that no longer meet the minimum requirements for NC pavement marking retroreflectivity. The following statements qualitatively define the LOS increments:

1. LOS Blue (A): This section of pavement marking is operating at the highest level of service with greater than five years of service life remaining. No action is necessary.
2. LOS Green (B): This section of pavement marking is operating sufficiently and is expected to have two to five years of service life remaining. No action is necessary.
3. LOS Yellow (C): This section of pavement marking is nearing the end of its effective service life and likely has one to two years of service life remaining.
4. LOS Amber (D): This section of pavement is within one year of failure and will likely need to be replaced in the next year's restriping schedule.

5. LOS Red (F): This section of pavement marking is below the minimum standard for pavement marking. There is no remaining service life left and this section should be replaced as soon as possible.

Table 1. LOS Increments and NC Minimum Retroreflectivity Standards

LOS	Thermoplastics		Waterborne Paint	
	White	Yellow	White	Yellow
Blue (A)	≥ 275	≥ 210		
Green (B)	200-274	145-209	≥ 250	≥ 215
Yellow (C)	175-199	125-144	150-250	115-215
Amber (D)	150 - 174	100 - 124	100-149	65-114
Red (F)	≤ 149	≤ 99	≤ 99	≤ 65

PAVEMENT MARKING TRANSPORTATION ASSET MANAGEMENT SYSTEM

TAM requires the implementation of tools such as software, hardware, databases, and data collection systems. Combining new and old tools, this paper addresses the need for better data integration and utilization while incorporating current information technologies. The first step of the “generic process,” as presented by the FHWA in 2007, is to inventory the asset and determine its current condition and performance. The second step is to predict the condition and performance of the asset over time. Both steps benefit from and even require the integration of automation, computing, IT, sensors, and controls.

The TAM system shown in Figure 1 illustrates the data integration of pavement marking attributes and predictive models that will provide the best possible prediction of R_L at any given point in time or space. Highlighted by the dashed line are the key components of the system. These components represent the data integration elements of the pavement markings TAM system and are a significant contribution presented in this paper. Each component within the system is further defined below. Additionally, each component in Figure 1 designates the appropriate corresponding table or figure to which it is related.

Pavement Marking Degradation Models (Predictive Models)

Thermoplastic and paint-based pavement markings make up the majority of markings in place throughout the United States [Migletz and Graham, 2002]. Previously, a statistical analysis established degradation rates for both thermoplastic and paint based pavement markings in NC [Sitzabee, 2008].

The use of statistical methods (based on sampling) to estimate the condition of an asset is a key component to providing quality information while minimizing data collection cost [Cambridge Systems Inc., 2006]. The models presented in Table 2 are the result of that previous analysis and are a critical component in the TAM system presented in this paper.

Figure 1. Transportation Asset Management System

As shown in Figure 1, the predictive models feed directly into the algorithm. The models each require the use of three key variables which are time, initial R_L , and AADT. Each is further defined below.

1. Time – is a continuous variable and is the most significant variable affecting degradation of pavement marking retroreflectivity. All pavement-marking studies reviewed included time as the most significant variable affecting retroreflectivity degradation.
2. Initial Retroreflectivity – is a continuous variable measured in $\text{mcd}/\text{m}^2/\text{lx}$. This variable is the initial value of retroreflectance and is measured within the first 30 days of application of the marking.
3. AADT - Annual average daily traffic is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day.

Table 2. Summary of Retroreflectivity Degradation Models

Category	Model
White Edge Thermoplastic	$R_L = 223 + 0.39 * R_{L \text{ Initial}} - 2.09 * \text{Time} - 0.0010 * \text{AADT}$
White Middle Thermoplastic	$R_L = 173 + 0.59 * R_{L \text{ Initial}} - 2.89 * \text{Time} - 0.0026 * \text{AADT}$
Yellow Edge Thermoplastic	$R_L = 193 + 0.40 * R_{L \text{ Initial}} - 1.69 * \text{Time} - 0.0016 * \text{AADT}$
Yellow Middle Thermoplastic	$R_L = 128 + 0.41 * R_{L \text{ Initial}} - 1.99 * \text{Time}$
Paint	$R_L = 55.2 + 0.77 * R_{L \text{ Initial}} - 4.17 * \text{Time}$

Where:

R_L = Retroreflectivity in mcd/m²/lx

$R_{L \text{ Initial}}$ = Initial Retroreflectivity in mcd/m²/lx

Time = Time in months since installation

AADT = Annual Average Daily Traffic in vehicles per day

MMS Data Structure

A data model is a set of constructs for representing objects and processes in a digital form [Longley, Goodchild, Maguire, and Rhind, 2005]. Decisions about the type of data model to use are strongly influenced by types of analysis expected and the level of information available or needed to fully understand the complexity of the system modeled [Longley et al., 2005]. We have chosen to use a relational data model.

There are four major phases to developing a working model of a physical system [Longley et al., 2005]. The first phase consists of developing an understanding of the system and the major components that influence it. Second is the development of a conceptual model, which is a human-oriented (often partially structured) model of selected objects and processes that are thought relevant to the particular problem domain. Third is the development of a logical model, an implementation-oriented representation of reality that is often expressed in the form of diagrams. Finally, the physical model portrays the actual computer implementation using tools such as a relational database or a GIS and often comprises tables stored as files.

Physical Model

Development of the physical model is the final step in developing the data management system before actual implementation. In the physical model all the necessary components are identified as well as the specific tables needed in each component. Furthermore, key relationships between databases and components are also defined.

The data schema was developed in detail using Enterprise Architect software. The purpose of using data modeling software is to design and build the architecture of a database. Enterprise Architect software has the capability to export a data schema into a variety of database formats compatible with Oracle, Microsoft Access, and SQL databases.

The basic output file generated from the pavement marking (PMS) data structure is an extensible markup language (XML) file. XML files are expected to become widely accepted and a new interface standard [Halfawy and Froese, 2007]. The advantage of using an XML file is the ease with which the data structure can be shared among various information systems. Another distinct advantage of software-generated XML files is the ability to predetermine and specify the

type of database system that the XML file will be imported into. Proprietary systems, on the other hand, can often inhibit the ease of integration across an organization [Pradhan, Laefer, and Rasdorf, 2007].

To ensure that the data schema could be implemented an XML file was generated for a Microsoft Access database. Once generated, the data schema was exported as an XML file. The XML file was then successfully imported into a Microsoft Access database. Once imported into Microsoft Access a set of sample data was imported to verify that the table structure was complete and that the correct relationships were in place.

When structuring tables for a database model it is important to normalize the structure. This means that one needs to eliminate redundant data and ensure that data dependencies make sense. Eliminating redundant data can be achieved by establishing the appropriate cardinality in the relationship between tables. Grouping data into functional areas which make sense in the domain of interest is also required. In our case this was achieved by dividing the database tables using a temporal theme. The initial marking table contains all the static characteristics of pavement markings. Each additional table maintains only the attribute values that would change over time.

Figure 2 shows the physical model. The model elements are:

1. The core module which stores the non-spatial data about the road network. This is maintained as tabular data in a relational database.
2. The road-line-work data which stores the spatial model of the road system. It is structured as an ARCGIS personal geo-database (which is similar to a Microsoft Access database) that includes all the topological and geometric relationships of the network.
3. The cost and budget element which is a tabular database that contains the maintenance and repair cost data. These data are maintained in a separate database than that of the roadway data (core module).
4. The maintenance element contains all the maintenance and repair data. This is also known as the Maintenance Management System (MMS). This module contains all the non-spatial maintenance and repair information maintained by the agency. This database also contains all the condition assessment information collected from the maintenance condition assessment program which is a biennial condition assessment based on a random sample process.
5. The pavement marking relational database whose schema is defined in Figure 3. It contains all of the necessary attributes for pavement marking management.

Database Organization of Pavement Marking Attributes

This section presents the organization of some of the pavement marking attributes in a relational database format that follows the structure of the NCDOT core module [Smith, Tran, and Rasdorf, 2001]. This formatting is crucial since it will enable the linkage of pavement marking data with the myriad of data already available throughout the NCDOT.

Figure 2. Physical Relational Database Management System Model

The tables are presented below using a common format [Smith et al., 2001] where the table name is presented along with its primary key and attributes. The primary key is the unique value that identifies each row in the database table. The table name is bold and the primary key is bold and underlined.

Proposed Tables for Pavement Markings

This section presents the tabular structure of the pavement marking database. The tabular structure presented here provides all the necessary information required to implement the data structure for pavement markings whether one is using the MMS front-end software or any other existing software package.

Initial Pavement Marking (**Place ID**, Color, Material Type, Lateral Location, Thickness, Width, Bead Type, Cost, Manufacturer, Product Name, Installation Temperature, Lineage, Application Date, GPS Coordinates)

The initial pavement marking table contains all the attributes that would be defined at the installation of a new pavement marking.

Figure 3. Pavement Marking Database Schema

Place ID – Unique name/label given to the road segment under consideration

Color – White or yellow

Material Type – Paint, thermoplastic, polyurea, epoxy, or other

Lateral Location – Edge or middle

Thickness – Thickness of marking material in mils

Width – Width of marking in inches

Bead Type – Standard, large, or highly reflective elements

Cost – Cost of marking per linear foot

Manufacture – Name of the material manufacture

Product Name – Name of the product used for marking

Installation temperature – Ambient air temperature in degrees Fahrenheit

Length – Length of the pavement marking in miles to the tenth

Application Date – Date of the marking installation

GPS coordinates – Latitude and longitude of the pavement marking initial start point

Initial R_L (Place ID, Initial R_L , Date, Number of Valid Scans, Chainage, Collection Device)

The initial R_L table defines the initial retroreflectivity characteristics associated with a pavement marking. Although the R_L values could be associated with the Initial Pavement Marking table, initial R_L is typically collected 14 – 30 days after the installation of a pavement marking and warrants management in an independent table.

Place ID – Unique name/label given to the road segment under consideration

Initial R_L – Initial retroreflectivity value in $\text{mcd/m}^2/\text{lx}$

Date – Date of the initial R_L data collection

Number of Valid Scans – Records the number of valid R_L values over a tenth mile increment

Chainage – Tenth mile increment for the road segment under consideration. The value always starts at zero from the beginning road segment node and increases in tenth mile increments until the segment run ends.

Collection Device – Laserlux or LTL 2000

Recurring R_L (Place ID, Recurring R_L , Date, Number of Valid Scans, Chainage, Collection Device)

Similar to the Initial R_L table, the recurring R_L table defines the retroreflectivity characteristics associated with the pavement marking on a particular date when measured. The attribute fields remain the same as the initial R_L table with the exception of the recurring R_L field. This table could be specifically labeled for specific dates of interest like quarterly, 6-month, or annual R_L .

Algorithm

Consistent with the need to use GIS to solve practical transportation issues [Venigalla and Casey, 2006] this section provides a procedure, in the form of an algorithmic process, to solve a pavement marking management issue. Specifically, this process will display the predicted condition of the unmeasured pavement marking asset at any point in time. For NC this is approximately 90 percent of the asset (the initial 10% is actually measured). Figure 4 shows a diagram of the algorithm developed for processing pavement marking retroreflectivity data.

The purpose of the algorithm is to identify all the inputs, processes, and outputs necessary to determine retroreflectivity values and to spatially display them for a given road segment. The algorithm could be used to spatially display retroreflectivity values for any DOT, agency, or organization with a similar database structure.

The algorithm identifies the steps necessary to meet the organization's primary asset management goal, which is to determine the percent compliance with governing regulations for any regulated attribute, in this case for pavement marking retroreflectivity. Here the final output displays the performance-based predicted retroreflectivity values in their current or future state. By displaying the condition in the predetermined LOS identified earlier the user can easily see where the pavement markings fall below the minimum requirements. This can be done in the current condition or by adjusting the date of interest to predict the condition state at some future point.

Table 3 presents each process used in the algorithm. Identified for each process are the required inputs and the expected output. Column two shows the procedural steps which correspond to the step numbers identified in the diagram. The time process requires the user to identify a date of interest. This could be set with a default for the current date and would result in displaying the

predicted retroreflectivity values (of the 90% of unmeasured roads) in their current state. However, the date could be easily modified to project the condition state at some point in the future (for all roads).

The algorithm shows the display as an end state but this could be further refined to display all the retroreflectivity values sorted by LOS increment. This makes it easy to create a cartographic image identifying the condition of the asset. One possible result is a map of all retroreflective values that are below the minimum standard. By adjusting the LOS increments to match their own standards, any state agency could implement this algorithm and display current or future condition state for retroreflectivity.

Measured Data

In NC approximately 10 percent of the pavement markings retroreflectivity is still measured on an annual basis (this is done to ensure the desired level of quality control). For roadways with such measured data it would be foolish to use predictive models to estimate the retroreflectivity values. In this case the TAM system bypasses the predictive algorithm and goes directly to a display option. Since this data structure uses a relational database the display can be tabular or can be presented graphically through GIS on an easily understood map.

Of course, measured data identifies the value of a condition attribute at one specific point in time. Additionally, managers have the option to display the condition of the measured data at a specific time side-by-side with the predicted condition at the same time, as shown in Figure 6 of the example below. This will give managers the ability to adjust the prediction appropriately for the current condition. Since a small portion of the asset's condition is still measured, these measured sections can be used to calibrate or even update the predictive models used in the process.

CONDITION DECISION TO PERFORM QUERIES AND DEVELOP STRATEGIES

Recall that the goal of a TAM system is to provide managers with the best possible condition of the asset, either predicted or measured. The process presented here implements computing tools and enables managers to make decisions based on a state-wide condition assessment that was previously unavailable. With the inclusion of the visual inspection process the decision maker now has a clear and holistic view of the asset. Although not the primary focus of this paper this section summarizes the use of visual inspections and the integrated use of a pavement management system as shown outside the dashed line in Figure 1.

Visual Inspections

There are both objective and subjective evaluation systems in use today to measure retroreflectivity of pavement markings. Objective measurements use retroreflectometers (mobile or handheld) while subjective evaluations are typically done through visual inspections by a trained observer. Both approaches are considered viable methods for measuring retroreflectivity in the United States [Migletz and Graham, 2002], the latter because of cost considerations.

Figure 4. Pavement Marking Retroreflectivity Algorithm

Trained observers can typically estimate the condition of the asset and determine whether the asset needs to be replaced or not [Migletz and Graham, 2002] . Incorporating the human factor (inspectors) into the TAM decision loop provides feedback to the process that helps to evaluate the accuracy and viability of the process. Additionally, the system can be used to prioritize the road segments selected for visual inspections. For example, managers might want to visually inspect a section of road that is reporting inconsistent predictions or other roads in areas where the measured values are old and are no longer reliable.

Table 3. Process Input and Output for Pavement Marking Algorithm

Process	Step Number	Input	Output
Join all data	1	<ul style="list-style-type: none">• Core Module• Road line work• Pavement marking data	All data
Select surface material	2	All data	Asphalt PM data
Select category	3	Asphalt PM data	PM data by category
Select AADT	4	Core Module	AADT for segment of interest
Select initial RL	5	Pavement marking data	RL for segment of interest
Select application date	6	Pavement marking data	Application date for segment of interest
*Time process	7	<ul style="list-style-type: none">• Application date for segment of interest• *Date of interest	Time in months
**Calculate RL using predictive model	8	<ul style="list-style-type: none">• PM data by Category• Time• initial RL• AADT	Display RL at date of interest

* Requires user input

** Use appropriate model for category where Paint only requires time and initial RL

Pavement Management System

Recall that Figure 1 shows a link to an existing pavement management system (PMS). This link provides managers with information to optimize the transportation asset management beyond pavement markings. Using the power of a GIS, a user can integrate information from various sources and spatially connect that information to identify aspects of the transportation system that would otherwise be unapparent [Flintsch et al., 2004]. Armed with the best possible estimate, the asset manager can use a GIS to perform queries on the system and explore spatial relationships of the asset. This is particularly useful in optimizing project funds and leveraging existing systems in developing strategies for pavement markings.

Inclusion of the PMS is an additional piece to the overall strategy development. Although external to pavement markings the PMS provides managers with the holistic picture of the roadway and enables managers to make smart decisions regarding pavement markings. For example, on a given road segment a pavement marking manager might decide to use a long-life marking but prior to implementation he queries the projected maintenance activities from the

PMS to see that the road segment is scheduled for resurfacing the very next year. Now the appropriate decision might be to use a shorter life material (cheaper) thus aligning the pavement marking material life with that of the road surface.

LIMITATIONS

There are two key limitations that need to be overcome in order to implement the proposed TAM process. First, agencies need to implement a protocol to record the necessary variables needed to implement predictive models. Second, agencies need to overcome location referencing issues. This section highlights these limitations and presents recommended solutions.

Recording Key Variables

The predictive models require the use of initial R_L , time, and AADT. AADT and time are critical but in most cases are readily available. However, initial R_L values are often not recorded, especially for in-house performed work. In the case of NC this represents approximately 60 percent of the roadway. The authors advocate that recording the initial R_L value and installation date are easy to do. These values can be measured at the time of installation and then recorded in the MMS when the marking crews record other information such as labor hours.

In the case where initial R_L values are not available and a highway agency didn't want to add the expense of collecting and maintaining initial R_L values they could implement two alternative methods for estimating initial R_L . First, the highway agency can use the average R_L value as measured from empirical data for like materials. Second, they could use the required specification value to estimate the initial R_L value.

Location Referencing

Because of the spatial aspect of the transportation system, location referencing is a key component of data integration. Location referencing systems (LRSs) consist of techniques and procedures for accurately collecting, storing, maintaining, and retrieving location information [Flintsch et al., 2004]. Pavement management systems typically use a location referencing method known as linear referencing. This is particularly useful in transportation networks because of its ability to accurately locate most transportation features, including pavement markings, in a one-dimensional form [Flintsch et al., 2004]. The key to GIS and transportation data integration is to establish an LRS identifier which is simply a unique individual identifier specific to a given segment of roadway [Rasdorf, Janisch, and Tilley, 2002].

Another consideration is that the increased use of GIS technologies and automated data collection equipment has increased the use of GPS-based coordinate referencing as a location referencing method [Flintsch et al., 2004]. This is different from a linear referencing system approach in that it identifies a single point in space. Both methods are applicable in transportation applications.

In a nationwide survey of DOT's, 35 percent of agencies surveyed indicated they used a coordinate-based location referencing system [Flintsch et al., 2004]. An additional 13 percent indicated they used a GPS-based state plane coordinate system [Flintsch et al., 2004]. Most

agencies indicated that GPS technology was not the sole LRS used and that linear referencing methods were still used in conjunction with the GPS based LRS [Flintsch et al, 2004]. Location referencing remains the most popular method for linking transportation asset management databases and implementing a single state-wide referencing system is a key component to successfully integrating state transportation agency asset management data [FHWA, 2007].

Unfortunately, the LRS used to identify the location of the pavement marking retroreflectivity data in NC did not follow any of the standard linear referencing formats. The data were collected using a localized LRS that does not conform to either the state or county milepost system. Furthermore, the NCDOT's contract with the data collection contractor did not prescribe that pavement marking retroreflectivity data be collected using a particular location referencing method. The system used by the contractor was a blended system that used route identification with the start and end points of measured sections identified with a mile post, an intersection, or an offset distance. Because of the unique LRS used, the localized referencing system precluded or at least significantly complicated the integration of pavement marking retroreflectivity data with the existing database structure.

Incompatibilities in location referencing posed problems in developing this data model. The LRS component had to be resolved before the physical model could be implemented. Fortunately, NC has the ability to match location using an LRS filter. However, the filter requires the use of one of four supported referencing systems [LRS Integration Guide, 2006]. In this case, 2006 and 2007 pavement marking retroreflectivity data contained longitude and latitude data for each 0.1-mile road segment. This information was used by the filter to locate retroreflectivity data (in a GIS) as a feature. Once the data were implemented as a feature, the data were "snapped" to the existing LRS.

DEMONSTRATION

One of our goals is to provide transportation agencies with a mechanism to confidently assess the condition of pavement markings at a point in space and time without having to physically measure all pavement markings. This section presents an example of the end product from implementing the proposed algorithm (using the proposed data structure and pavement marking degradation models).

Figure 5 is a thematic map developed using the ARCGIS application of our asset management system and displays the actual retroreflectivity data for the northbound yellow edge line along a 12-mile stretch of Interstate 95 in NC. This equates to displaying the measured condition state shown in Figure 1 which follows the measured data path, bypassing the algorithm. The retroreflectivity data were added using latitude and longitude and then the points were "snapped" to a route feature created from the primary roads data file. The values use a graduated scale based on the previously established LOS increments for NC.

Figure 6 shows both the actual and predicted R_L values of the northbound yellow edge line for the portion of the interstate illustrated in Figure 5. Having both the predicted and measured values displayed side-by-side gives the agency a sense of the accuracy of the process.

Figure 5. I-95 Actual R_L Values for Yellow Edge Pavement Markings

In this case the system achieved a high level of accuracy and was deemed a success. Additionally, the predicted line demonstrates the ability of a transportation agency to estimate the condition of the asset without having to physically measure it. If desired, it is possible to separate and display the measured and predicted data.

Maps like those illustrated in Figures 5 and 6 provide managers with an effective tool to highlight the condition of pavement markings as an asset. This is useful to convey the condition of the asset to the public and to legislators when competing for funding for this asset. However, thematic maps are not the end products in GIS, but are a means to store information that is necessary for analysis and decision making. Maps, views, reports, and displays can all be extracted from these thematic layers to meet user needs without changing the underlying thematic maps themselves [Rasdorf et al., 2003].

Asset Management Strategies

Table 4 is an excerpt from the event table generated in the demonstration and represents another way for managers to use the available data to make asset management decisions. The location column identifies location of a specific road segment (N YE represents a northbound yellow edge line). The predicted R_L value represents the condition state at a specified time of interest, which in this case is October 2007. Also provided in Table 4 is the age of the pavement marking when it is expected to reach the minimum standard. This column uses the same predictive model but rearranges the variables to solve for age given R_L equal to the minimum standard value. This enables agencies to determine the year that the marking will need to be replaced, which is the fifth column.

The TAM system allows managers to use updated cost figures, which are constantly changing, by integrating data from external sources, like the PMS. Here the cost per foot column was added to Table 4 to demonstrate the ability to combine the cost basis with the condition state and estimate the total cost for that section of road, which is also shown in Table 4 (last column). Presenting the data in this way allows managers to determine key budget (as well as maintenance) needs. This is a small example of how queries can be used to influence and help develop pavement marking asset management strategies.

Validation of Models

The TAM system relies on the use of integrated data and predictive models. However, it is imperative that good models be used. To validate the predictive models used on our system we conducted a simulation that matched our demonstration example. Recall that the predicted value for the northbound yellow edge was calculated to be $147 \text{ mcd/m}^2/\text{lx}$. This value is determined using the predicted equation which includes the intercept, initial R_L , time, and AADT. The coefficient for each parameter has its own variance.

To further understand the variance associated with a predicted value, a series of simulations was conducted. Summarized in Table 5, the simulations used the same input values for the variables as in the single prediction. The difference for the simulation is in the coefficients for each variable as shown in Table 5. Here, the coefficients were replaced with a random number generator based on a normal distribution using the mean coefficient value and standard error.

Figure 6. I-95 Actual and Predicted (2006) R_L Values for Yellow Edge Pavement Markings

The results after 100 simulations, found the average predicted value was 133 mcd/m²/lx with a standard deviation of 35.9 mcd/m²/lx. The results of the simulation help us to understand the variance in the predicted value and know that the predicted value can easily differ by as much as 36 mcd/m²/lx. This is something that managers would need to account for when making decisions.

Table 4. Predicted RL and Cost Data for I-95 Halifax Example

Location	Predicted R_L (mcd/m ² /lx) Oct 2007	Age (months) R_L at min	Minimum Standard (mcd/m ² /lx)	Replace in FY	Cost per Foot (\$)	Total Cost (\$)
I-95 N YE	119	78	100	2008	0.55	35,500
I-95 N WE	244	112	150	2011	0.55	35,500
I-95 N WS	149	67	150	2007	0.65	41,900

For example, a predicted value of 147 mcd/ m²/lx for a yellow edge line would classify the marking as LOS green (see Table 1). With a range of 145 mcd/ m²/lx to 209 mcd/ m²/lx for yellow thermoplastic markings puts this right on the border of LOS green and yellow. In fact the marking could easily be in the LOS yellow range. Although budget issues and other factors will impact the decision, managers should pay particular attention when markings are within 36 mcd/ m²/lx of failure. If the measured values were not available this would be a case where managers should consider moving this up on the priority list for a visual inspection.

Table 5. Simulator Parameter and Coefficient Estimate Values

Term	Coefficient	Std Error	Variable Input
Intercept	193.3	21.12	-
RL Initial	0.3963	0.0836	243
Time	-1.69	0.260	60
AADT	-0.0016	0.00044	36500

SUMMARY

This paper presents solutions for data integration issues and presents an integrated TAM system for estimating the current and future condition of pavement markings as a transportation asset. This paper describes the data structure, in the form of a physical model, specifically integrating a pavement marking data schema with existing IT systems (MMS). Software was found to be useful in developing a relational data schema. The software produced an XML file that can be easily imported into a variety of existing database structures.

Additionally, the TAM system included an algorithm that utilizes the data structure to establish the condition of the asset. Using predictive models based on a small sample of measured sections (10 percent), the algorithm estimates the condition of the remaining portion of the asset (90 percent), at any location on the highway system. With the inclusion of measured data and an allowance for visual inspections, managers can query and display the condition of the asset and perform strategy development for maintenance, rehabilitation, or replacement of the asset.

FINDINGS

Asset management relies heavily on data collection. While much data is collected manually this simply isn't practical. Automated means are critical to effectively support asset management systems. This means that a variety of sensors and data collection devices need to be incorporated

into asset management systems. The data also needs to be well organized in integrated databases and be carefully geo-referenced.

Implementing information technology to link predictive models with databases and a GIS, this paper presented a clear and effectively way to implement an asset management strategy. Relying heavily on IT, the TAM system provided here gives asset managers a way to estimate pavement marking conditions state-wide without having to physically measure the asset. Ultimately, this process eliminates the need to collect data to establish the condition of an asset. With integrated data and smart computing the TAM system shows a method to manage pavement markings without collecting data on every mile of an asset each year. In NC this equates to a \$1.8 million annual savings.

Our TAM system includes AADT, time, and initial R_L as critical variables. AADT is readily available to most highway agencies. Installation date directly relates to time and is a must have for predictive models. Both installation date and initial R_L need to be collected (or at least estimated) for use of the predictive models. This paper highlights the importance of a highway agency to have good protocols for collecting and maintaining initial R_L data for effective asset management of pavement markings.

RECOMMENDATIONS

In this paper the TAM system was designed for pavement markings but the results from can be generalized to provide a design process for other assets. Furthermore, using the concepts presented herein, system designers can expand the concepts to meet asset management needs for more comprehensive and complex systems.

In many asset management systems there is a need for ongoing data collection. Agencies should implement protocols to analyze data needs. Consideration should be given to the use of automated sensors and smart computing techniques to minimize the amount of data collected and maximize the impact that the data have on managing an asset.

To predict pavement marking condition states requires that initial R_L , AADT, and pavement marking installation data be recorded and maintained in a compatible database similar to the one presented in this paper. Recording these attributes at the time of installation is highly recommended, would have a nominal cost, and would require little change in current practices. In cases where initial R_L is unavailable or impractical to collect, it is recommended that agencies use empirical data or specification values to estimate the initial R_L .

The inability to locate the attributes of an asset remains the number one issue in implementing effective asset management. LRSs rely heavily on IT and good location referencing is still a significant limitation in managing pavement markings in many DOTs. Because of the spatial aspect of transportation systems it is highly recommended that highway agencies select and implement a single LRS. This will enable agencies to use location as a means of integrating pavement marking data into the overall transportation data management.

Finally, it is recommended that highway agencies continue to use a visual inspection process in their management of pavement markings. The visual inspection can be used to verify the condition estimates produced by the model. In fact, the model estimates can be used to prioritize

the visual inspection plan or even prioritize the limited dollars that are available for retroreflective data collection. Thus, a dual check and balance is achieved to ensure the best possible estimate for the condition of the asset at any time or location.

DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, the U.S. Government, NCSU, or the NCDOT.

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