DISCRETE EVENT SIMULATION MODEL FOR PAVEMENT MAINTENANCE POLICY ANALYSIS

Berk Uslu
Research Assistant, Virginia Tech
117 Patton Hall
Blacksburg, VA 24061
Telephone: 540-905-8525
berkuslu@vt.edu

Jesus M. de la Garza
Professor, Virginia Tech
117A Patton Hall
Blacksburg, VA 24061
Telephone: 540-231-5789
chema@vt.edu

Submitted for Presentation and Publication at the 6th Annual Inter-university Symposium on Infrastructure Management (AISIM)

DATE – May 15th, 2010
3,807 words + 4 figures = 4,807 words
ABSTRACT
A pavement investment and management process has a dynamic structure with cause and effect. Better investment decisions for maintenance will increase the condition of the flexible pavement and will end up with better level of service. Therefore, better investments decisions on pavement maintenance will increase the economic growth and global competition for the area. However, improper allocation of money and resources would end up with further deteriorations of the facilities. So asset management encourages highway maintenance managers to spend their scarce budget for the maintenance that is really needed. A well-developed pavement management simulation model will allow highway maintenance managers to consider the impact of choosing one maintenance policy alternative versus another through what-if analysis and having informed decisions.

Discrete event simulation (DES) is an alternative method of analysis that offers numerous benefits in pavement management. Unlike the models currently in use, a decision support model created by utilizing the DES technique would allow fractionalizing the pavement in smaller proportions and simulating the policies on these smaller segments. Thus, the user would see how their decisions would affect these specific segments in the highway network over a period of time. Furthermore, DES technique would better model the multiple resource requirements and dynamic complexity of pavement maintenance processes.

The purpose for this research is to create a decision support tool utilizing discrete event simulation technique where the highway maintenance manager can foresee the outcomes of their what-if scenarios on the specific segments and whole of the highway network evaluated. This simulation engine is created with the discrete event simulation language called STROBOSCOPE. The model consists of two parts which works like a lock and key mechanism. The first part of the model is the data feeding mechanism where information from any network is loaded and the generic engine which can evaluate any road network data fed. The purpose of segregating these two components of the model is to allow the user to evaluate any network regardless of length, number of segments or the location. This paper introduces the DES tool created and discusses the methodology used to create this tool.

1. INTRODUCTION
Transportation infrastructure is a vital part is ensuring the functioning of the civilized society. Transportation is a social leveraging strategy called Scope Enlargement. The movement of goods allows the society to balance the surpluses and shortages of a number of areas, so that all can progress to a higher level of development than would have been possible without it (1). Deterioration of the flexible pavements would cause the level of service for that specific highway to drop and that would cause both more operating costs and economic decline. Poor pavement conditions cost U.S. motorists $67 billion a year in repairs and operating costs – $333 per motorist. Americans spend 4.2 billion hours a year stuck in traffic, at a cost of $78.2 billion a year to the economy (2).

The most important cause of these high user costs and lost time is the fact that the U.S. transportation systems are seriously underfunded. Especially after the last economic down turn, U.S. Department of Transportation would get even more cuts on the budgets for maintenance [3]. Maintenance of highways cannot get enough funding to keep whole of the road in a sufficient condition. Since it is a proven fact that it is less expensive to maintain pavements already in good condition than it is to rehabilitate or reconstruct the pavements in poor condition, keeping the pavement in a good condition should be the main objective in order to achieve lower operation costs and higher level of safety [4]. Although the transportation agencies know this fact, in a report card by the American Society of Civil Engineers (ASCE), US roads are receiving a near
failing grade of “D-” which is showing a worsening trend since the previous grade in 2005 was D and in 2001 the grade was D+. ASCE also estimated that $930 billion is needed over a five year period of time to bring the transportation infrastructure to a good condition (5).

A pavement investment and management process has a dynamic structure with cause and effect. Better investment decisions for maintenance will increase the condition of the flexible pavement and will end up with better level of service; therefore, better investments decisions on pavement maintenance will increase the economic growth and global competition for the area (6). However, improper allocation of money and resources would end up with further deteriorations of the facilities. So asset management encourages highway maintenance managers to spend their scarce budget for the maintenance that is really needed. A well-developed decision support model will allow highway maintenance managers to consider the impact of choosing one maintenance policy alternative versus another through what-if analysis. Thus, simulation programs are crucial tools that are acting as decision support tools for maintenance managers to investigate the future outcomes of different scenarios.

2. **BACKGROUND**

2.1 **Pavement Maintenance Policy Analysis**

Efficient and optimal investments in highway management are needed to improve highway conditions and prove better transportation services providing a positive effect on society and environment. However, the highway maintenance managers need to evaluate a vast array of possibilities and need to make critical decisions. Decision support systems are used to simulate the outcomes of the possible scenarios and helps maintenance managers to better optimize the maintenance schedule. Maintenance managers benefit greatly by using simulation-based tools to test what-if scenarios. An effective simulation model can improve the process of highway maintenance by:

1. Simulating pavement conditions over long period of time.
2. Evaluating if current maintenance policies would be sufficient enough to reach prescribed target levels.
3. Choosing the best policy by comparing different what-if scenarios.
4. Showing where, when and why resources are needed (7).

The prior work on maintenance policy simulations relies on the research done by Allan Chasey in 1995. The work proposed by Chasey was the first step in the development of a framework for combining the impact of maintenance and construction on infrastructure systems. In his research, he brought up the importance of deferred maintenance and proposed mathematical models to simulate the impact of deferred maintenance. He used the Comprehensive Level of Service that joins both maintenance and construction measures into a single measure and used in order to set up his mathematical equations (8).

Research done by Wonkyu Kim on I-81 highway corridor in Virginia was a test for Chasey's preliminary model where several budget allocation scenarios were performed using the simulation model Highway Management System (HMS) (6). HMS is created by the continuous simulation language DYNAMO as well. Then in 1998, Kyeil Kim expended this prior model to simulate the policies in not only highway system, but primary, secondary, and urban roads too (9).

Meanwhile in 1999, Jamal Nasir extended Chasey's model to simulate and evaluate the maintenance policies western region of the Swedish National Road Administration (SNRA). The
simulation software used in that model was PowerSim. PowerSim was again a continuous simulation language that was used to by the companies in Norway to simulate, develop and explore future scenarios (10).

In 2000, Bjornsson and de la Garza introduced the model created by Nasir in US (11). Then, de la Garza and Krueger and created another decision support tool (7). Mathematical equations were embedded in Mat Lab simulation environment and allow maintenance managers to do what-if analysis to evaluate the proposed maintenance scenarios.

Another research branched on this line of simulation tools is the network level optimization model that was established by Sercan Akyildiz. That model uses Linear Programming algorithm and is subject to performance goals and budget constraints and evaluates the pavement condition state in term of lane miles. The tool was developed in Microsoft Excel and calculates the optimal amount of investment for each treatment type in a given period (12).

The relation between the prior works on pavement maintenance policy evaluation tools is better summarized in Figure 1 which represents the overall progress of research done on pavement management decision supporting tools.

2.2 Discrete Event Simulation
Discrete Event Simulation (DES) is a simulation technique where simulation is done in terms of events, in which the highest-priority (least time) event is removed from an event queue and executed. One of the most characteristic features of DES is that its dynamics are event-driven as opposed to time-driven dynamics in Continuous Simulation. The behavior of a discrete-event system is governed by events rather than by ticks of a clock. An event corresponds to the start or the end of an activity. For a production system possible events are: the completion of a part on a machine, a machine breakdown, or a buffer becoming empty. Events occur at discrete time instants. Intervals between events are not necessarily identical; they can be deterministic or stochastic. Typical examples of usage of DES can be found in flexible manufacturing systems, telecommunication networks, parallel processing systems, traffic control systems and logistic systems. The general nature of DES works man-made systems that contain a finite number of resources that are shared by several users all of which contribute to the achievement of some common goal (13).

DES is an alternative method of analysis that offers numerous benefits in pavement management. Unlike the models currently in use, a decision support model created by utilizing the DES technique would allow fractionalizing the pavement in smaller proportions and simulating the policies on these smaller segments. Thus, the user would see how their decisions would affect these specific segments in the highway network over a period of time. Furthermore, DES technique would better model the multiple resource requirements and dynamic complexity of pavement maintenance processes. Because of these characteristics of DES technique, a decision support system created by it would be best fitting to do what-if analysis on project level.

The programming language that is used to set up the pavement management policy analysis model is STROBOSCOPE. STROBOSCOPE is the acronym for STate and ResOurce Based Simulation of COnstruction ProcEsses which is a discrete event based simulation software which is used to pre-plan and simulate the construction processes regardless of complexity (14). The programming language in Stroboscope defines a network of interconnected modeling elements which allows defining the elements in unique behavior and controlling the simulation.

3. THE MODEL
The motivation for this research is to create a what-if analysis tool utilizing Discrete Event Simulation technique for pavement management policy analysis. The simulation model
constructed with discrete event simulation principles would better fragmentize pavement in segments and would allow better investigation and better future forecasts vs. the current simulations constructed following the continuous simulation. To better describe, the current models would allow maintenance managers to investigate a flow of water, but discrete event simulation model will allow them to investigate segments as smaller ice cubes. Moreover, this tool would also have a user interface which allows manual adjustments for simulation variables. The users would manually adjust the budget to spend on different treatments and see how the scenarios created would affect the network. This tool can be used do what-if scenarios, to train new pavement managers and to show different entities on where, when and how much money needs to be invested.

Figure 2 represents the concept of the decision support system. The model consists of two major elements which are the generic simulation engine and the user interface. The data will be segregated from the model and can be manipulated by a user interface which would result in a more user friendly decision support system.

This two parts of the model works like a lock and key mechanism. The first part of the model is the data feeding mechanism where information from any network is loaded and the generic engine which can evaluate any network data fed. The purpose of segregating these two components of the model is to allow the user to evaluate any network regardless of length, number of segments or the location. For the purpose of verification of the model, network data from Salem district of Virginia Department of Transportation (VDOT), was acquired and used in the model.

The working principle of the model is that the user can manipulate the data that is set as matrices as in text form and do what if analysis of the projected scenario. The nature of the model would allow the user fragmentize the network as desired and would give an advantage to investigate the effect of scenarios tested in smaller sections of the network.

3.1 Mechanism of the Model
The decision support tool is created in STROBOSCOPE simulation language and Figure 3 is the graphical representation of this code. The whole stroboscope code can be provided if requested. This section discusses the smaller elements of the simulation and how it works as a whole in greater detail.

Creating Data Matrices
The first step while creating the computational model was to create the data matrices that will later be used in the model. There are four major matrices that are defined. These four matrices are; segment data, budget data, unit price data and procedures data. The segment data consists of the segment numbers, combined condition indices (CCI), lane widths and number of lanes for specific segments that will be evaluated in the model.

The network data that is used in the research is the network data for the Salem District. The specific network data is just used to verify the model. As the creation of the computational model progress, this data matrix will be segregated from the model as well as the other data matrices. Other data matrix defined is the budget data matrix which consists of the annual maintenance budget. This matrix simply represents how much money will be spending at the maintenance activities each year for the specific scenario.

Third data matrix is the procedure data which notes the percentage of the budget that will be spend for each maintenance activity. This matrix is created so that the percent budget planned to be spanned for the 9 different maintenance activities can be changed annually.
Fourth and last data matrix is the maintenance unit cost matrix. This matrix introduces the unit price for each operation that can be used for the maintenance activities. The average unit prices for the procedures that makes up the 9 maintenance activities was acquired by averaging their values from the 2010 VDOT bid tabs. The unit cost per lane mile of the 9 maintenance activities would then be calculated from these unit prices and would be saved to be used in further calculations of the simulation.

All these data matrices are planned to be segregated from the model and will be entered at a user interface that will be created later on the research. This would create the lock of the lock and key mechanism discussed earlier. An add-on for Stroboscope will be created in C++ which allows the model to read data from plain text files. The reason of this segregation is to allow the user to operate the model without interfering with the Stroboscope code. The user can test different scenarios by simply changing the data saved as text file.

Creating Segments
The second aspect of the model that was created was the algorithm that creates the segments listed in the segment data and associates data related to these specific segments. Figure 2 is graphical representation of this algorithm. As the segments are created at the SegmentsToBring node, the computer assigns segment numbers, lengths, CCI’s for each specific segment. Also, the age is calculated according to CCI for each segment as well to be used for further calculations. The formulas that are used to calculate the age of a specific segment are found by applying regression analysis for the deterioration rates used at the research previously done (12).

Table 1 represents the values used in the age calculation of the model. It is stated in the CCI condition ranges and the deterioration rates are taken from Akyildiz’s thesis. Simple regression analysis is applied and the formulas to calculate the age of the pavement are found that way. However, since the deterioration rate for a very poor pavement is not defined, the same formula to calculate the age of a poor pavement is used to calculate the age of a very poor pavement.

Budget Allocation
The model creates the annual budget and allocates it for the 9 different maintenance activities simultaneously while creating the segments. This algorithm uses the procedure data matrix to allocate the annual budget that is listed at the budget data matrix. For example, if the budget allocation for Ordinary Maintenance 4 is 10%, then 10% of the annual budget created would move to the OM4 node which represents the budget for Ordinary Maintenance 4. Figure 3 is the graphical representation of this algorithm. The nodes “OneYear” and “Seqs” are the time controlling element of the model. These nodes assure that the simulation loop starts each year.

Selecting Segments for Maintenance
After the segments are created and the annual budget is allocated, the model moves the created segments to the Candidates node. As the segments enter this node, the costs of applying each of the nine treatments are calculated for each segment. This calculation is repeated every year as the segments enter the Candidates node in each cycle. These calculated values are then used for selecting the segments that would be suitable for applying the treatments. Figure 3 is the graphical representation of this phase of the simulation. The nodes on the middle are the maintenance activities. These activities start from top to bottom. The first one to start is the reconstruction activity which is represented by RC node. This node starts by drawing the amount of money allocated for reconstruction each year of the simulation. After the budget is drawn, it cursers the Candidates node for eligible segments to draw. In order for a segment to be drawn by
the reconstruction activity, the segment needs to be in very poor condition and the cost to apply reconstruction for the censored segment should be less than the budget remaining. The segments are listed in the Candidates node in decreasing order of their age so the activity cursors the segments with the worst condition first.

If a segment is selected, the activity updates its age accordingly and sends the segment to Hold node to stay there for a year. Also, it subtracts the cost of applying the treatment for the segments from the annual allocated budget for that activity. This part of the model simply represents the flow chart which stands for the generic simulation engine in Figure 1. The concept is from a previous research (7). As the figure suggests, there are 5 different stages of pavement conditions and 9 different maintenance activities which would rehabilitate the pavements. For example, if the pavement condition is Very Poor, when we apply reconstruction to that specific segment, the condition of the pavement would improve to Excellent.

_Deteriorating the Non-Selected Segments_

The remaining segments that are not selected by the maintenance activity nodes are moved to the deteriorate node. This node adds one year to the age of the segment which represents year of deterioration. Then, all the segments move to the Hold node to meet with the segments that are treated that year and wait for a year to move to the Candidates node again.

4. **CONCLUSION**

Discrete event simulations programs are extremely helpful in decision support for asset managers. The simulation program created as a result of this research will be used to simulate the dynamics of infrastructure deterioration and maintenance. It will be useful in developing optimal maintenance, repair, and rehabilitation policies and will be able to assist highway maintenance managers in determining both short term and long-term budget requirements for a variety of maintenance strategies. Since it is capable of providing fact based, reproducible evidence to justify the selection of different scenarios, a user can track maintenance budget allocations in relation to the overall condition of the highway.

**ACKNOWLEDGEMENTS**

The research reported in this paper was conducted at Center for Highway Asset Management Programs (CHAMPS) and funded by the Virginia Department of Transportation (VDOT). Any opinions, findings or conclusions are those of the authors and do not necessarily reflect the views of VDOT.

**REFERENCES**


List of Figures

Figure 1 Prior Work
Figure 2 Conceptual Model
Figure 3 Graphical Representation of the Model
Table 1 Age Calculations
FIGURE 1 Prior Work
FIGURE 2 Conceptual Model
FIGURE 3 Graphical Representation of the Model
**TABLE 1 Age Calculations**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Corresponding CCI</th>
<th>Life in That Condition</th>
<th>Age Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>100-90</td>
<td>3</td>
<td>Age=-0.2727*CCl+27.273</td>
</tr>
<tr>
<td>Good</td>
<td>89-70</td>
<td>5</td>
<td>Age=-0.25*CCl+25.25</td>
</tr>
<tr>
<td>Fair</td>
<td>69-60</td>
<td>3</td>
<td>Age=-0.3*CCl+28.7</td>
</tr>
<tr>
<td>Poor</td>
<td>59-50</td>
<td>4</td>
<td>Age=-0.4*CCl+34.6</td>
</tr>
<tr>
<td>Very Poor</td>
<td>49-0</td>
<td>Indefinite</td>
<td>Used the above formula</td>
</tr>
</tbody>
</table>