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CONCEPTUAL DESIGN OF A RULE-BASED MODEL FOR PAVEMENT ASSESSMENT

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ABSTRACT

The traditional process of pavement condition assessment has been utilized with the purpose of developing pavement management systems. As a result, current pavement management systems started to become statistical data analysis tools, losing sight of the underlying engineering mechanics that play the major role in defining pavement condition.

Hence, in this paper a rule-based model for pavement assessment has been developed and presented. The developed model is defined as an abstracted state machine with predefined states connected with sequential logical links that define the transition from one pavement state to another. Two domains were defined for the pavement states and the model was built using two types of pavement surface distress, cracks and rutting, in conjunction with roughness data. The pavement data was obtained from the Ministry of Transport in Saudi Arabia, for the highway segment connecting the cities of Jazan and Jeddah.

1 INTRODUCTION

Pavement condition evaluation is traditionally a process by which field surveys and testing are carried out to characterize the condition of an existing pavement structure, from both structural and functional perspectives. The structural condition of a pavement indicates its ability to support current and future traffic loadings, whereas the functional condition refers to its ability to provide a safe, smooth, and quiet riding surface for the traveling public (Hass et al. 1994).

Network-level evaluations are conducted on pavement sections within a network of pavements for which a transportation agency is responsible, with the general purpose being to document current conditions and to identify needed projects for maintenance preservation and rehabilitation. Furthermore, pavement assessment results are used to help prioritize projects and allocate budgets, and to determine needed funds. In addition, the collection of performance data on a pavement network over time provides a valuable tool for tracking pavement performance as well as a mechanism for developing specific performance models that can be used to predict future conditions, both with and without the application of pavement treatments (Mubaraki 2015, Mubaraki 2012).

Visual condition surveys generally include determinations of types of distress, their severity, their extent, and their locations. There are several means for conducting pavement condition surveys, varying according to the agencies involved. Pavement condition data is then compiled into a pavement condition index (PCI) which ranges from zero to 100, where 100 represents excellent pavement condition. The PCI values are based on pavement distress types, with severity and quantity data collected through visual inspection, and calculated using a weighted sum function. Traditionally, to collect the appropriate distress data an inspector is sent to a particular pavement section to visually inspect and record the existing distress types, severities, and quantities. However, considering the size of the pavement network, this procedure is both time-consuming and costly. Results obtained from this process are also qualitative and subjective, varying from one inspector to another depending on his training and experience.

Hence, more modern pavement assessment methods are being carried out using automated systems that collect data on an array of pavement distress types using a mobile vehicle that travels at speeds between 40 – 70 kilometers per hour, which is relatively efficient from time and cost perspectives. The pavement distress types collected depends on the configuration of the data collection vehicle. The most common pavement distress types collected are pavement thickness, longitudinal roughness, rutting, surface cracks, raveling, and potholes. Most of the distress types observed by the vehicles are surface-based, reflecting surface layer conditions, such as surface cracks, rutting, raveling, and potholes. Measurements of pavement depth are carried out using ground-penetrating radar (GPR) technology, which is almost the only subsurface criterion that can be reliably collected using a moving data collection vehicle (Ming et al. 2014). On the other hand, pavement longitudinal roughness data can be attributed to either surface or subsurface pavement layers, and in some cases, it can be attributed to both layers. Hence, pavement roughness is primarily calculated in terms of international pavement roughness index (IRI) which is based on vertical profile data for the pavement that are collected in a relatively very short time and without excessive cost (Mubaraki 2015).

2 RESEARCH SIGNIFICANCE

Implementing a methodology of pavement evaluation for highways and roads requires a well-planned basis, and must be an integral part of the overall pavement management system (PMS). Pavement roughness data, solely, is typically used in a wide range of PMS functionalities at network and project levels, for both rural and urban road pavements. For example, at the network level, roughness data can provide a functional evaluation of the pavement surface which can be incorporated in project selection and programming. The roughness data also helps in construction quality control and in the evaluation of rehabilitation options (Hass et al. 1994).

Application of pavement distress data such as cracking, rutting, and raveling, has been recognized by pavement engineers as an important parameter for quantifying the quality of pavement surface. Similar to roughness, it is important at both the network and project levels of pavement management systems. Traditionally, pavement distress information is used in selecting appropriate treatments. At the network level, the concern is with determining what class of treatment is required, for example, continued routine maintenance or resurfacing. At the project level, the concern is with estimating the extent and the most appropriate method of pavement repair, such as patching or resurfacing a certain area of alligator cracking (Hass et al. 1994).

Given the current automated pavement assessment technology available for a broad range of distress types, analysts and decision makers are usually flooded with a large volume of data to analyze and process. With the massive volume of data, analysts have often seemed to be immersed in numerical and statistical analysis to the point of overlooking the mechanical nature of the problem, at some times omitting such considerations altogether. This utilization of pavement distress data often lacks integral reasoning regarding the causalities associated with each distress type and their relative magnitude. For example, a combination of mild levels of pavement distress types might seem to warrant only minimal routine maintenance, while in fact it indicates a more serious problem that is growing in the subsurface layers of the pavement, for which the warranted maintenance cannot halt its progression (Mubaraki 2013).

Hence, the ultimate goal is to develop a smart PMS that integrates different kinds of pavement distress analysis with good reasoning, to predict unseen problems before their evolution, in order to allow for pre-emptive maintenance in advance. In this paper, a conceptual design for a mechanistic rule-based PMS under development will be presented, and sample data from Saudi Arabia will demonstrate its application. The proposed PMS relies on defining a set of pavement conditions that can be mapped for two surface distress types, cracking and rutting, and pavement roughness. Surface cracks and rutting both reflect structural integrity for the pavement's surface layer, while pavement roughness is basically a serviceability measure that might be used as an indicator for the overall structural integrity of the pavement.

3 RULE-BASED MODELS

The rule-based models have been developed by using a Fuzzy Rule-Based System. Fuzzy inference is a method that interprets the values in the input vector based on user defined rules, and it assigns values to the output vector. The advantage of this approach is knowledge representation in the form of "*If–Then"* rules, the capacity of taking linguistic information from human experts and combining it with numerical information, and the ability of approximating complicated nonlinear functions with simpler models (Fritz et al. 2010). No modeling approach is without disadvantages. For example, rule-based models are not as easy to integrate into generic asset management software; although rule-based models are comparatively easy to calibrate, the process is by no means trivial. Domain knowledge and experience with model effects are still needed. It should also be noted that some of the disadvantages of the regression-based approach can be overcome to some extent by refining the models to include cases of exceptional situations. An example of this approach is when the Highway Development and Management Model (HDM) rut prediction equation is extended to include a "probability of rapid rut development" which is then used to judiciously adjust the predicted rut rate.

In fuzzy logic models, the concepts of membership functions and sets are used to model systems in which there are elements of vagueness. In essence, membership functions require that the modeller identify classes in both the input and output variable. Relationships between the input membership function and the output membership are then expressed by rules. These rules can be based on fundamental and/or empirical knowledge. For example, consider a simple deterioration model aimed at predicting the rut rate on a network segment. We can say:

- when the cracked area is high, the rut increment is very high, and
- when the structural number is low, the rut increment is high.

The fuzzy membership sets in these examples are "high cracking", "low structural number", and "very high" and "high" rut increment. The limits to these sets - that is, what constitutes "high rut rate" or "low structural number" - are determined on the basis of domain knowledge, and not on statistics based on small and possibly biased samples. Using a known or predicted value for (say) cracked area, we can determine the degree of membership to the "high cracking" fuzzy set. Membership functions are typically defined such that they can assume values from zero to one. The degree of membership to the set "high cracking" is then used to in turn determine the degree of membership to the set "very high rut increment". Again, the limits for each of these sets will typically be determined using experience of pavement behavior in general, along with the specifics of the network in question.

In a study conducted by Loukeri and Chassiakos in 2004, deterioration prediction models were developed for asphalt pavements using fuzzy systems. The methodology was implemented considering the characteristics of the road network in Greece and the expertise of local pavement maintenance engineers. The model development considered several parameters, such as pavement distress type (cracking, disintegration, surface distortions, surface defects), traffic loads, environmental conditions, soil type, pavement material properties and design features, construction quality, and, most importantly, pavement age. The implementation led to models that are considered quite realistic by pavement construction and maintenance experts. It appears that these models can be effectively employed in pavement management systems so as to provide the necessary input to optimize maintenance decisions regarding the appropriate rehabilitation type and the timing of application. The development includes the following three phases.

In the first phase, (qualitative) data were collected from expert responses regarding all relevant factors and the way that they affect distress initiation and propagation. Second, a fuzzy rule-based system was developed to represent the expert knowledge using fuzzy rules of the *if – then* type. In the third phase, several sets of random crisp data for the independent and the dependent variables were generated by the fuzzy system.

4 METHODOLOGY

The proposed model is based on the concept of abstracting the pavement system into a state machine that is defined by a set of finite states and a sequential logical network that defines the transition from one state to another (Egon et al. 2003, Ronald et al. 2011). For the current ASM model developed, the states of the pavement are mapped in two domains, cracks and roughness, and rutting and roughness. Due to insufficient historical data for the selected site, the transition network was developed based on logical and expert judgment (Shahin and Kohn 2002).

4.1 Site Selection and Data Acquisition

The methodology consisted of three phases. The first phase was to acquire pavement roughness and distress data for a 200-km stretch of Saudi Highway 5, which connects Jeddah city with Jazan city (Al-Swailmi 2002, Mubaraki 2014). This site was selected specifically because it offers a diverse and broad spectrum of topology and climates. For the current study the focus in pavement data was limited to cracking percentile, rutting percentile, and road surface profiles in terms of International Roughness Index (IRI), which were obtained from the Ministry of Transport (MOT), Pavement Management System (PMS) database.

4.2 Data Analysis

4.2.1 Cracking % vs. IRI

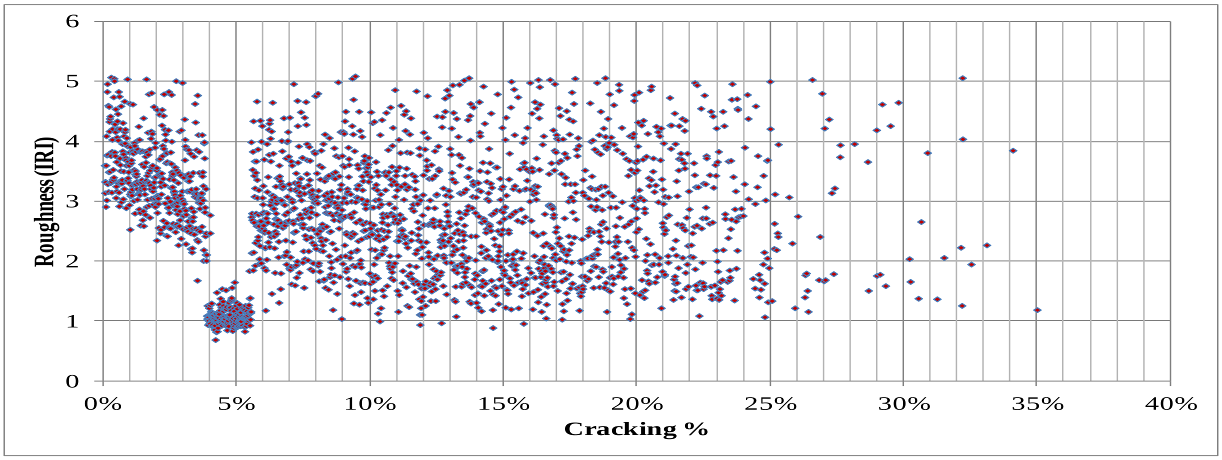

Figure 1: Cracking % vs. Pavement Roughness for the Selected Sample Highway

Figure 1 illustrates the cracking distress % in the sample highway and the corresponding pavement roughness index (IRI) value. The cases featuring 0% cracks have been eliminated from the data set. It was noticed that the IRI never exceeded the value of 5 in most data points, and that is due to the fact that the data-collecting van drivers are instructed to avoid driving on deformed segments of the road. Also, for a cracking distress between 4% and 6%, the IRI values were clustered around 1. This irregularity most probably represents segments of the road with a very good IRI but with longitudinal cracks between the road and its paved shoulders. In order to have better insight into the interaction between pavement surface cracks and roughness, the data has been sliced into 2% segments, and pavement roughness data was further analyzed as shown in Figure 2.

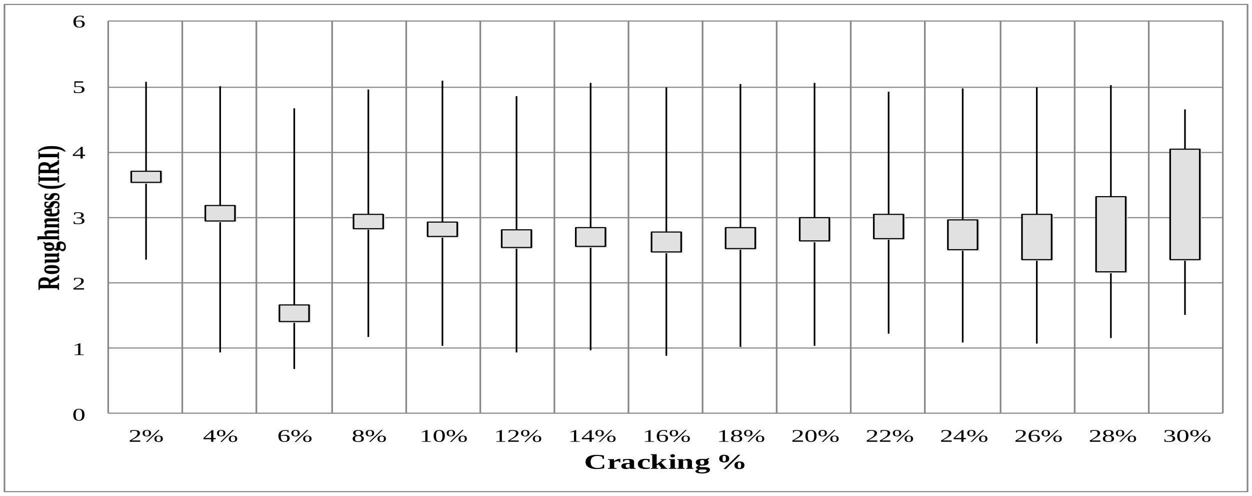

Figure 2: Segmented Cracking Distress % vs. Average Roughness Bounds at 95% Confidence Interval

Figure 2 illustrates the bounds of the average IRI for each segment, with a 95% degree of confidence (the rectangles) and it depicts also the min/max range of IRI values observed for each cracking % segment (the line).

4.2.2 Rutting % vs. IRI

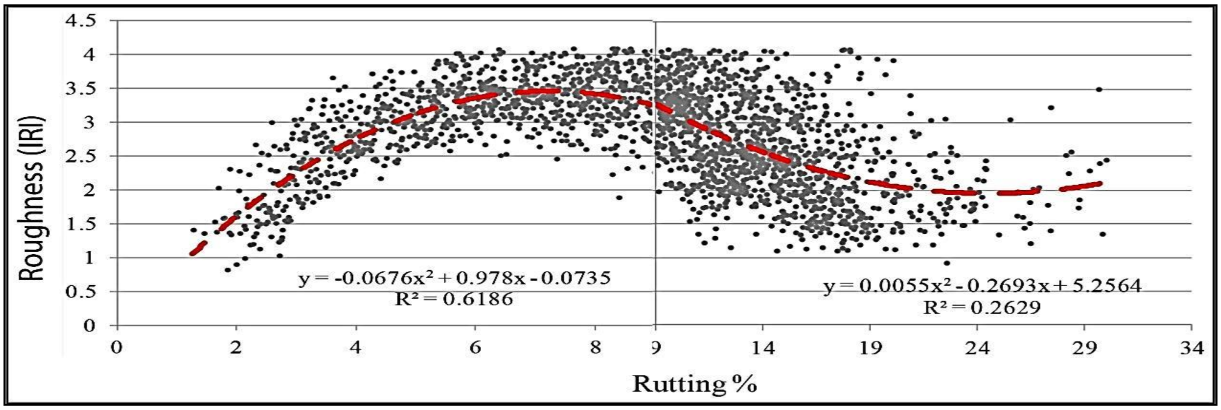

Figure 3: Rutting Distress % vs. Roughness (IRI) Data

Figure 3 illustrates the rutting distress data vs. roughness data. It can be seen that there is a two-scheme pattern for data where the relationship starts to become directly proportional between rutting % and IRI until it reaches 8%, and then it starts reversing course. Hence, as shown in Figure 3, the two trend lines were developed for each segment of the data. It is important to mention that the correlation coefficients for the first and second region were 0.743 and -0.553, respectively.

4.3 Rule-Based Model Development

The aim of this model is to develop an approximate estimation for the current condition of the subsurface structure of the pavement by inference derived from cracking, rutting, and roughness data as presented in Figures 2 and 3. Figure 4 depicts a typical cross-section for a flexible asphalt pavement on the left side;

an abstracted icon for the same profile is shown also on the right side of Figure 4. For simplicity, the pavement cross-section details have been abstracted into only two layers, Surface and Subsurface layers. The condition for each of the layers has been given three color indications, as following:

Green: Implies a good status for the layer

Yellow: Implies an acceptable/weak status, with the potential to become worse if not properly maintained

Red: Implies a structurally damaged status and requires rehabilitation/reconstruction

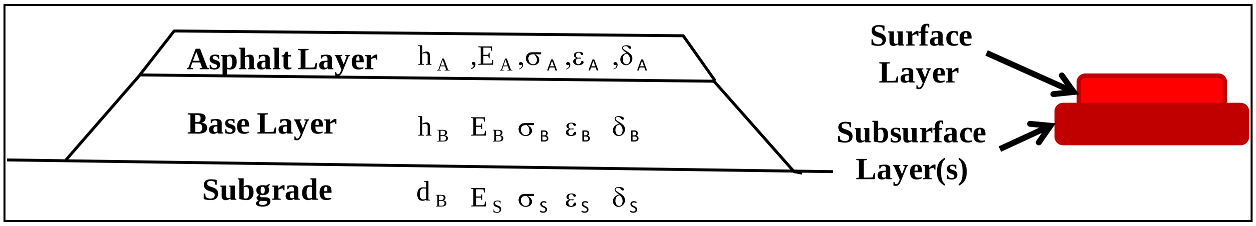

Figure 4: Typical cross-section in a Flexible Pavement Road and the Abstracted Icon for Pavement Structure

4.3.1 PAVEMENT STATES BASED ON CRACKING % AND IRI and Evolution Logic

By exploiting the cracking % and IRI domain obtained from the current data set and depicted in Figure 2, we were able to identify six distinctive pavement states under different combinations of cracking distress % and IRI values. Transitional links that represent the logical evolution from one state to another have been identified as well.

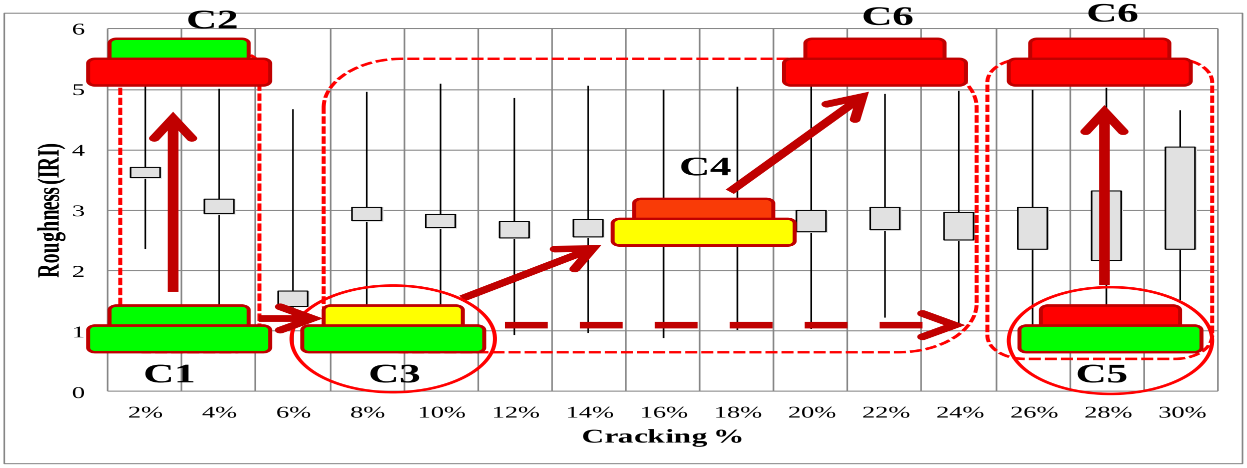

Figure 5: Pavement Structural States and Transitional Links Based only on Cracking % and Roughness

Table 1 includes further detail with regard to the parameters that define each state and describe the corresponding surface, subsurface, and overall pavement condition. Two of the states, C2 and C6, have been identified as terminal states, which implies that serious reconstruction for the subsurface layers is needed in order to recover the serviceability of the road. Hence, in such cases, the pre-terminal states C3 and C5 are of critical importance, and decision makers must take pre-emptive action in order to avoid the terminal states.

State C1 is an exception, which leads to a terminal state (C2), but in this case surface cracks are not the cause of damage. For this specific scenario, the cause of deterioration is not due to the surface layer, but to either poor structural properties of the subsurface layers or poor design/construction of the subsurface layers, and decision makers cannot do anything to prevent the evolution from State C1 to either C2 or C3.

Table 1: Pavement States based on Cracking % and IRI data

State	Cracking%	IRI	Pavement Qualitative State	Surface Condition	Subsurface Condition	Progression / Remarks
C1	< 5%	< 2	Ideal /Good	Good with minimal cracks	Good with minimal deformations	This state will evolve to either C1 or C3.
C2	< 5%	>3	Failed	Good with minimal cracks	Major structural deformation	Terminal State
C3	5-14%	<2	Moderate	Moderate surface cracks with limited depth in surface layer	Good with minimal deformation	Depending on climate and traffic conditions, will evolve to C4 or C5
C4	14-18%	<2	Deteriorating	Significant surface cracks partially penetrating surface layer	Moderate deformation in subsurface layers	Depending on climate condition and surface treatment, will evolve to C6 (Terminal State)
C5	> 18%	< 2	Moderate	Major surface cracks passing surface layer	Good with minimal structural deformation	If not treated will evolve to C6 (Terminal State)
C6	>18%	> 3	Failed	Widespread deep surface cracks	Major structural deformation	Terminal State

4.3.2 Pavement States based on Rutting % and Roughness and Evolution Logic

Similar to the previous section 4.3.1, we will also exploit the rutting % and IRI domain, to define the different qualitative states of a pavement and the corresponding transitional logical links between states. We were able to identify seven distinctive pavement states as depicted in Figure 6, which represent the possible scenarios for pavement conditions under different combinations of IRI and rutting distress levels.

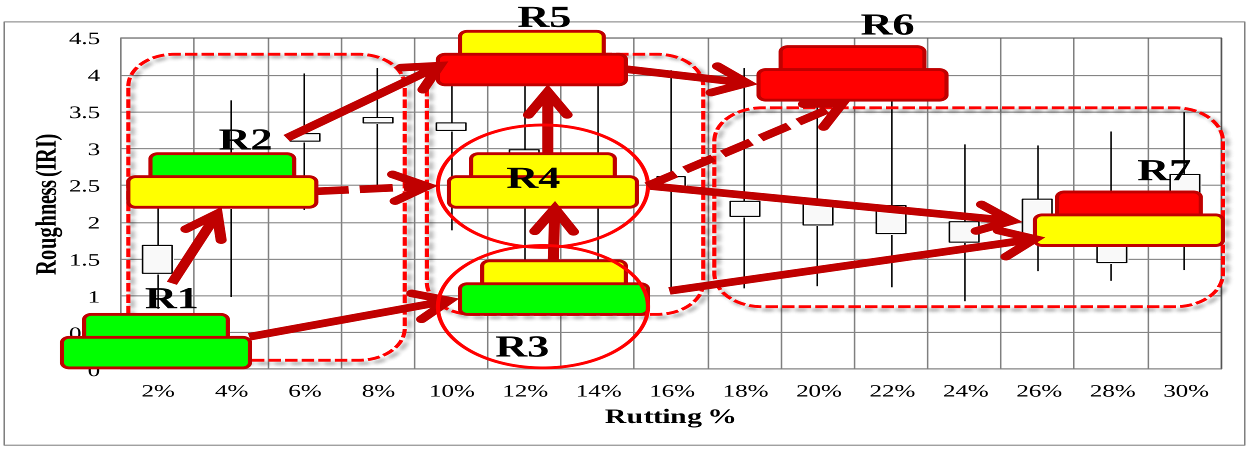

Figure 6: Pavement Structural States based only on Rutting % and Roughness

The seven identified pavement states are defined in Table 2 with the attributes associated with each of them. Three states, R3, R5, and R6, were identified as terminal states, i.e., the states that warrant major rehabilitation/construction work. The transition links between states are a solid or dashed line, where the solid line implies "most probably" and the dashed line implies "less likely". This designation was based partially on the statistical observations, the same as in the previous section, and supplemented with logical reasoning. In order to avoid terminal states, states R3 and R4 can be considered as critical states, where preventive maintenance must be applied in order to avoid costly rehabilitation work in the future. On the contrary, for state R2, any budget allocated for preventive surface maintenance for this case will be simply a waste of money. The reason for this is that state R2 occurs as a result of major deformation in the subsurface, which implies either poor design or poor construction for the pavement layers.

5 DISCUSSION

In the previous section, thirteen pavement states were identified using two surface distress measures, namely cracking % and rutting %, and international roughness index (IRI). Furthermore, the transition links are proposed as depicted in Figures 6 and 7. In this discussion we will try to give some insights and provide the reasoning for the descriptions of the different pavement states and the transitions that link them.

5.1 Cracking % and Roughness Domain

In this domain, six pavement states have been defined.

1: State C1 represents a new pavement where there are no cracks and the roughness index is within the desired level.

2: State C2 is a <u>terminal state</u> that represents a pavement with no surface cracks, but with high roughness. State C2 might be the result of either a weak surface layer or a weak subsurface layer. If the surface layer was weak, most probably the plastic deformation in the pavement will result in longitudinal grooves (rutting); hence, it can be assumed that the subsurface is weak and was the main cause behind this condition. Highway segments in this state will need major reconstruction work.

Table 2: Pavement States based on Rutting % and IRI data

State	Rutting %	IRI	Overall Pavement Condition	Surface Condition	Subsurface Condition	Progression / Remarks
R1	< 8%	< 2	Ideal /Good	Good with minimal rutting%	Good with minimal deformations	This state will evolve either to R2 or R3 depending on mechanical properties of Surface and Subsurface layers
R2	< 8%	< 2	Moderate	Good with minimal rutting%	Moderate subsurface structural deformation	Will evolve to R5 or R4 state (pre-terminal state)
R3	8-18%	< 2	Moderate	Moderate rutting with limited depth in surface layer	Moderate subsurface structural deformation	Depending on climate and traffic conditions, if not treated will evolve to R4 or R7 (pre-terminal state)
R4	8-18%	<2	Deteriorating	Moderate rutting with limited depth in surface layer	Moderate deformation in subsurface layers	Depending on climate condition and surface treatment, will evolve to R5 (pre- terminal state)
R5	8-18%	>3	Failed	Moderate rutting with limited depth in surface layer	Significant deformation in subsurface layers	Terminal State if not treated will evolve to R6 (Terminal state)
R6	>18%	>3	Failed	Deep rutting	Significant deformation in subsurface layers	Terminal State
R7	>18%	>2	Failed	Deep rutting	Moderate subsurface deformation	Terminal State

3: State C3 is a <u>pre-terminal state</u> and represents an older pavement with moderate surface cracks and minimal pavement roughness. This indicates that the subsurface layers are in good condition, but if the cracks in the surface layer are not treated, this state will evolve to C4, where the surface cracks will deepen and allow high moisture content in subsurface layers. This state also has the potential to evolve to C5. This pavement state must receive special attention in order to avoid reaching terminal state C6.

4: State C4 is an evolved state for state C3. If no treatment is applied to the surface layer, this state will evolve to a terminal C6 state, where the surface cracks will cover major areas and excessive damage will occur in the subsurface layer, which will require major rehabilitation work. Treatment and maintenance work for the surface layer in this state most probably will postpone but not prevent evolution to the terminal state C6.

5: State C5 is a pre-terminal state where surface cracks are spread on the surface layer but the subsurface layers are not affected. This scenario is likely due to dry weather and low precipitation, which is the case for the current set of data. This state, if not treated, results in deep cracking in the surface layer; stresses due to axle loads then will not be distributed as sought on the subsurface layers, which will damage those layers and lead to excessive deformation. Hence, at this pavement state special attention must be given to apply the right treatment to the surface layer, in order to preserve the pavement structure.

6: State C6 is a terminal state where deep cracks are spread over major segments of the surface layer and the vertical profile is exhibiting excessive deformation, which deems the highway not usable for safe transportation. This state [will need] calls for major rehabilitation work.

5.2 Rutting % and Roughness Domain

In this domain, seven states have been defined as the following:

1: State R1 represents the base state where the pavement is still new, with almost 0% rutting and a low roughness.

2: State R2 represents an evolution from the pavement state R1. This evolution is most probably due to weak subsurface layers, because most of the deterioration was in the longitudinal profile (roughness) and was limited in the lateral profile (rutting). Most probably, this state will evolve directly to the terminal state R5 or to state R4, then eventually to R5. For this state, no treatment can be applied to the subsurface layers, and any surface treatment will be simply a wasted resource.

3: State R3 represents a pavement structure where the subsurface layers are well designed and constructed, but the surface layer is weaker and exhibits a moderate range of rutting. This is a pre-terminal state that requires immediate treatment, which will most probably be a resurfacing layer; otherwise it will evolve to state R4 and then to terminal state R5.

4: State R4 is basically an evolution from states R3 or R2, where the rutting was extended to the subsurface layers to some extent. If the historic root for the pavement segment was R3, then this state can be considered as pre-terminal and will need resurfacing treatment to avoid full damage to the subsurface layers.

5: State R5 is a terminal state where most of the damage occurred in the subsurface layers. Most probably this state is an eventual result for a poor subsurface layer, and will need major rehabilitation work.

6 / 7: States R6 and R7 are both terminal states where both surface and subsurface layers are damaged and the pavement will require major rehabilitation work.

6 CONCLUSION

In this paper, a system for assessing the integrity of pavement subsurface layers has been developed and presented. This system can be used to identify critical cases that need urgent attention in order to avoid costly rehabilitation work. The proposed rule-based system was based only on a single data set for a route located in Saudi Arabia. It is also important to emphasize that the current transition links for both domains are based on logical and expert judgment. Such transitional links should follow probabilistic values which can be obtained from historical data to incorporate exogenous factors that are not taken into account in the model. The other alternative for developing these links is via numerical modeling and analysis. It is understandable that the portability of this system is limited and each area needs to calibrate a system based on its own pavement data that reflect local weather, traffic, and subgrade conditions.

7 References

Al-Swailmi, S. 2002. Road Networks in Gulf Countries and Maintenance Programs*, First Gulf Conference on Roads*, Proceedings of the Conference: 520-532, Kuwait City.

Egon, B. and Staerk, R. 2003. Abstract State Machines: A Method for High-Level System Design and Analysis, Springer.

Hass, R., Hudson, W. and Zaniewnski, J. 1994. Modern Pavement Management. Krieger Publishing.

Jooste, F., Esterhuysen G., Judd D., and Jordaan G. 2010. Implementation of a Rule-Based Deterioration Model for Dual Carriageway Road Networks, 24th ARRB Conference, Melbourne, Australia.

Loukeri E., and. Chassiakos A. 2004. Development of Pavement Performance Models using Fuzzy Systems, *Proceeding of the Fourth International Conference on Engineering Computational Technology* Stirlingshire, UK, Paper 129.

Ming L. Wang, Jerome Lynch, and Hoon Sohn. 2014. Sensor Technologies for Civil Infrastructures, Volume 2: Applications in Structural Health Monitoring, Woodhead Publishing Series in Electronic and Optical Materials.

Mubaraki, M. 2015. A methodology for project-level maintenance for urban roads, Transport, ICE, 168(3): 239 –255.

Mubaraki, M. 2014. Identification of Pavement Distress Types and Pavement Condition Evaluation Based on Network Level Inspection for Jazan City Road Network, The Journal of Engineering Research (TJER),11(1): 44-54, 2014.

Mubaraki, M. 2013. Proposed integrated road surface management system for small municipalities. Municipal Engineer, ICE, 166(4), 239.2013.

Mubaraki, M. 2012, Maintenance Strategies at Project Level for Low Volume Urban Roads, International Journal of Pavement Research and Technology. 5(4): 225-223

Ronald, E., Raymond, H., Sharon, L., and Keying Ye, 2011. Probability and Statistics for Engineers and Scientists. Prentice Hall.

Shahin, M. and Kohn, S. 2002. Pavement Maintenance Management for Road and Parking Lots, Kluwer Academic Publishers, Massachusetts, U.S.A.