DETERIORATION MODELS IMPLEMENTATION FOR A MANAGEMENT SYSTEM OF TOLL ROADS IN MEXICO

Gloria Beltrán, Universidad Nacional de Colombia - Universidad Nacional Autónoma de México. Email gibeltranc@unal.edu.co

Alexandra Ossa. Instituto de Ingeniería, Universidad Nacional Autónoma de México. Email: aossal@iingen.unam.mx

ABSTRACT

In order to provide decision making elements about maintenance and conservation of pavements, in a toll road network in Mexico, some existing deterioration models are adapted to predict future progression of distresses, commonly used by government agencies as control indices of pavement condition.

In this work, five highways are studied using non-destructive testing data; homogeneous sectors were defined first to behaviour characterization purposes. By adapting existing deterioration models, future progression of rutting, smoothness and skid resistance was predicted for each sector. Key variables affecting deterioration were involved into analysis: climate, traffic, road geometry, pavement structure features and material properties.

This practice, have contributed to a better definition of future maintenance program, taking into account additional criteria to those defined by government agencies. Furthermore, it was possible to identify typical patterns on future condition of pavements for the entire network studied here.

Keywords: Highway management systems, deterioration models, pavement conservation.

INTRODUCTION

The highway management systems require extensive knowledge about current condition and problem definition for existing pavements. Maintenance solutions, costs and priorities in toll ways, are commonly based on surface pavement conditions, available budged, experience, intuition and knowledge of experts. For the specific case of toll ways in Mexico, government agencies demand acceptable levels for certain condition indicators.

Given the large number of factors involved, the variety of alternative solutions, the error costs and the need to make decisions quickly, is clear that additional reliable forecasts about deterioration processes and remaining life should be involved.

This paper proposes the adaptation of deterioration models, which have been successfully used in other cases, to predict future behavior of those indicators used as acceptance criteria and decision making in highway concessions.

It is expected that the adopted models, provide benchmarks for remaining life definition and intervention priorities identification along the road network analysed. Additionally, it is intended to identify feasible solutions, taking into account traditional maintenance practices applied by the highway managers, along with local and international recommendations.

TOLL ROAD NETWORK ANALYZED

The studied network, consist of five roads located in México, with a total length of 441.5 km (1,327 km-lane); the main characteristics of each road are listed in Table I.

Table I - Road network features

Highway #	Lanes	Length (km)	Traffic (10^5) axle-year 2010
1	4	105	2
2	4	117	9
3	2	103	2
4	2	76.5	6
5	2	40	3

For this network, the acceptance criteria of government agencies about rutting, International Roughness Index - IRI and skid resistance are shown in Table II.

Table II – Control parameters - Acceptance criteria

Parameter	**Acceptance value**
Rut depth	≤ 10 mm
IRI	≤ 2.81 m/km
Skid resistance	≥ 0.6

The data base was formed by available information measured via non-destructive testing during year 2010: surface deflections, through High Weight Deflectometer – HWD; thicknesses by means of ground Penetration Radar – GPR; IRI, rutting, skid resistance, surface texture, and distresses, with high performance devices. Parameters derived from these measures, such as Pavement Condition Index – PCI and elastic layer moduli, were also available; additionally, structural number – SN was determined from expressions suggested by Paterson (1987).

$$SNP = 3.2 * Def^{-0.63}$$ For non-treated bases

$$SNP = 2.2 * Def^{-0.63}$$ For cemented bases

All those parameters were useful to homogeneous sectors definition along each highway; to that specific purpose, the cumulative differences method proposed by AASHTO (1993) was applied upon measured surface deflections via HWD. Tables III to VII, show all 71 sectors obtained for the road network with corresponding mean values of rutting, IRI and skid resistance.

Table III – Homogeneous sectors for Highway # 1

SECTOR			Layer thickness (cm)				Rut depth (mm)	IRI (m/km)	Skid resistance
No.	From K	To K	Asph. Conc.	Base	Subbase	Total			
1	10.6	15.6	9.7	18.7	19.5	47.9	5.80	2.26	0.82
2	15.6	21.5	8.6	17.3	24.2	50.1	4.61	1.88	0.91
3	21.5	24.4	8.6	17.3	24.2	50.1	3.74	1.68	0.97
4	24.4	29.5	8.6	17.5	13.2	39.3	3.57	1.48	0.97
5	29.5	35.4	8.8	16.2	30.0	55.0	4.95	1.81	0.95
6	35.4	39.0	8.8	16.2	30.0	55.0	4.13	1.69	0.95
7	39.0	44.5	8.8	25.0	15.0	48.8	3.38	1.72	0.96
8	44.5	50.0	8.4	13.7	12.2	34.3	4.56	1.77	0.90
9	50.0	53.8	9.2	15.9	19.5	44.6	2.04	1.55	0.88
10	53.8	59.0	9.2	15.9	19.5	44.6	4.73	1.95	0.95
11	59.0	64.0	9.1	21.5	12.0	42.6	4.63	1.86	0.94
12	64.0	69.0	9.7	14.0	18.1	41.8	4.48	1.97	0.96
13	69.0	74.0	8.6	15.4	32.2	56.2	5.30	1.94	0.94
14	74.0	80.0	7.7	16.0	26.0	49.7	6.14	1.84	0.94
15	80.0	84.4	8.9	23.6	10.2	42.7	6.51	1.82	0.93
16	84.4	90.0	7.7	14.7	11.4	33.8	4.77	1.95	0.91
17	90.0	95.5	8.7	14.3	15.9	38.9	5.21	1.82	0.93
18	95.5	99.5	8.7	14.3	15.9	38.9	5.19	1.67	0.90
19	99.5	105.0	7.1	30.1	10.1	47.3	4.74	1.75	0.70
20	105.0	110.0	6.9	19.6	18.1	44.6	5.10	1.66	0.65
21	110.0	115.2	8.2	47.4	17.5	73.1	4.19	1.52	0.64

Table IV – Homogeneous sectors for Highway # 2

SECTOR			LAYER THICKNESS (cm)					Rut depth (mm)	IRI (m/km)	Skid resistance
No.	From K	To K	Asph. Concr.	Base	Treated Base	Subbase	Total			
1	115.0	125.5	7.3	12.8		22.5	42.6	7.53	1.81	0.72
2	125.5	129.5	8.4	14.5		23.6	46.5	5.18	1.84	0.75
3	129.5	144.0	10.2	19.9		15.6	45.7	2.92	1.62	0.76
4	144.0	149.0	8.4	21.7		19.2	49.3	2.75	1.33	0.84
5	149.0	155.0	8.5	16.1		17.0	41.6	3.73	1.55	0.80
6	155.0	160.0	7.5	22.2		15.5	45.2	4.27	1.70	0.77
7	160.0	174.0	9.9	16.3		15.0	41.2	4.33	2.15	0.75
8	174.0	181.0	9.8	25.8		13.0	48.6	3.61	1.76	0.73
9	181.0	184.0	7.2	20.9		15.2	43.2	2.04	1.66	0.78
10	184.0	187.5	11.4	11.4		19.0	41.7	2.62	1.98	0.73
11	187.5	188.5	10.5		10.4	19.1	39.9	3.75	2.05	0.68
12	188.5	195.0	10.1	18.5		24.0	52.5	4.05	1.54	0.66
13	195.0	200.0	9.5	20.3		11.6	41.4	3.06	1.35	0.68
14	200.0	212.0	10.1	19.9		16.4	46.4	2.42	1.41	0.65
15	212.0	225.0	8.5	16.6		18.7	43.8	3.40	1.73	0.64
16	225.0	232.0	8.2	20.7		18.9	47.9	4.00	2.24	0.65

Table V – Homogeneous sectors for Highway # 3

SECTOR			LAYER THICKNESS (cm)				Rut depth (mm)	IRI (m/km)	Skid resistance
No.	From K	To K	Asph Concr.	Base	Subbase	Total			
1	0.0	3.5	9.5	21.1	19.4	49.9	4.49	1.88	0.21
2	3.5	12.0	6.8	20.9	15.1	42.8	6.42	2.76	0.64
3	12.0	18.0	7.5	*8.4	18.6	34.5	3.79	1.74	0.34
4	18.0	22.0	6.0	*6.0	22.2	34.3	4.58	1.69	0.42
5	22.0	33.0	8.0	*7.6	18.3	33.9	5.08	1.85	0.36
6	33.0	38.5	8.5	*8.1	19.2	35.8	5.30	2.06	0.41
7	38.5	52.0	15.3	19.1	11.5	45.9	6.54	2.08	0.45
8	52.0	57.5	12.6	18.8	19.3	50.7	5.16	1.70	0.33
9	57.5	64.0	12.7	19.2	11.7	43.6	7.63	2.08	0.41
10	64.0	68.0	14.0	18.8	19.2	52.0	8.87	2.42	0.41
11	68.0	79.0	11.8	21.2	19.5	52.5	8.48	1.97	0.35
12	79.0	87.5	11.9	19.1	17.8	48.7	9.03	2.14	0.30
13	87.5	92.5	7.7	11.2	19.1	38.0	3.72	2.19	0.29
14	92.5	97.5	7.2	10.4	20.8	38.4	12.97	3.47	0.28
15	97.5	103.0	7.9	9.6	20.5	38.0	10.65	2.23	0.32

Shaded values are unacceptable

Table VI – Homogeneous sectors for Highway # 4

SECTOR			LAYER THICKNESS (cm)				Rut depth (mm)	IRI (m/km)	Skid resistance
No.	From K	To K	Asph. Concr.	Base	Subbase	Total			
1	0.0	12.5	8.2	8.6	18.9	35.6	5.16	2.58	0.71
2	12.5	18.0	7.9	10.1	18.1	36.2	6.71	2.86	0.72
3	18.0	27.0	8.0	9.0	20.8	37.8	6.25	2.39	0.73
4	27.0	33.5	8.1	7.8	17.3	33.2	8.68	3.10	0.68
5	33.5	41.5	8.0	7.8	21.4	37.2	5.63	2.67	0.68
6	41.5	56.0	7.9	7.7	25.5	41.0	4.80	2.25	0.70
7	56.0	61.0	7.2	7.9	20.9	36.0	10.43	2.69	0.62
8	61.0	68.5	8.1	7.9	17.7	33.8	9.73	3.44	0.69
9	68.5	76.0	6.9	11.8	25.2	44.0	10.34	3.90	0.45

Shaded values are unacceptable

Table VII – Homogeneous sectors for Highway # 5

SECTOR			LAYER THICKNESS (cm)				Rut depth (mm)	IRI (m/km)	Skid resistance
No.	From K	To K	Asph. Concr.	Base	Subbase	Total			
1	0.0	2.5	10.8	16.2	16.8	43.8	4.99	2.45	0.63
2	2.5	7.0	11.5	11.2	16.2	38.9	4.03	2.61	0.61
3	7.0	9.0	12.3	12.3	21.8	46.3	4.17	2.49	0.62
4	9.0	14.0	10.8	15.5	13.3	39.6	3.80	2.44	0.59
5	14.0	17.0	10.0	16.3	17.8	44.1	3.99	2.86	0.59
6	17.0	24.0	11.5	15.9	15.5	43.0	3.92	2.40	0.61
7	24.0	30.0	13.2	15.7	16.0	44.9	4.20	2.62	0.66
8	30.0	34.0	8.0	22.5	18.6	49.1	4.27	2.34	0.64
9	34.0	36.0	12.0	16.9	17.4	46.3	3.67	2.15	0.66
10	36.0	40.0	11.5	14.3	16.1	41.9	4.86	3.10	0.66

Shaded values are unacceptable

POTENTIAL SOLUTIONS

The definition of intervention alternatives to keep the pavements in a proper state during the analysis period was established considering the current condition of the previously mentioned indicators.

To formulate feasible alternatives, the main intervention activities within the regulations of the Secretariat of Communications and Transportation, SCT, were identified. Furthermore, the maintenance practices traditionally applied by the concessioner, regarding the technological limitations and other restrictions imposed by traffic, were considered. Finally, criteria and recommendations based on the local experience (Orozco, 2005) and international recognized experiences (ARA, Inc. & ERES Consultants Division, 2004; U.S. Army Corps of Engineers, 2001; COMITRAN - Coronado, 2000) were integrated. As a result, the following interventions were defined.

For surface problems: crack sealing with or without caulking (depending on the opening), slurry seal and microsurfacing with or without milling.
For structural problems: overlay with or without milling and reconstructions with partial recovery of the granular course and the asphalt layer, are recommended. The milling needs, depends on the combined effect of different indicators and distresses.

DETERIORATIONG MODELS

In order to define the long-term maintenance program for the studied network, future conditions that roads will exhibit during the life-time of the concession, were predicted. In general, the prediction of the pavement deterioration is a complex work, due to the number of variables involved.

The historical evolution of some indicators of condition recorded on the roads was reviewed to explore the possibility of defining proper deterioration models based on observed behavior of the pavement. However, during the information analyses it was found erratic variations in the behavior patterns of some indicators, uncertainty in the dates of the auscultation tests, some discrepancies between the results interpretation and the absence of complete information for some roads.

Therefore, pre-established and recognized models, to estimate future conditions of pavements from nondestructive tests, were adapted. Different methodologies and models to predict pavement deterioration are described in technical literature for different countries. For the Mexican roads analyzed here, deterioration models proposed by Paterson (1987) were used, which have a further experimental and theoretical foundation; those models constitute the basis for the HDM-4 road administration system (Association Mondiale de la Route - World Bank 2000). By adapting these deterioration models, the remaining life and future behaviour of pavement surface was predicted for each homogeneous sector. Key variables affecting deterioration were involved into analysis: climate, traffic, road geometry, pavement structure features and material properties.

In this study, modeling of control parameters is conducted: rut depth, Smoothness (IRI) and skid resistance; cracking was modeled too, since the progression of rut depth and IRI, depend on the cracking. The following paragraphs describe general characteristics of each model, including some criteria used to analyze the specific road network. Details of mathematical expression for each model can be found at Paterson (1987).

Rut depth

Rut depth in every-year analysis was determined by adding two deformation components: structural and plastic. The former component was modeled considering road traffic, compaction and structural characteristics of the layers underlying the road surface, environmental conditions and the presence of cracks. The latter component, due to the plastic deformation of the asphalt concrete, was modeled through the relationship among variables such as traffic, the speed of heavy vehicles, construction defects and total thickness of bituminous surfacing.

Cracking

The adapted models present separate relationships for predicting thermal and structural cracking. The former type was not detected during testing activities. Hence only structural cracking was simulated.

This model considers that structural crack initiation occurs when 0.5% of the carriageway surface area is cracked. Model equations are defined for different types of pavement base course, and depend mainly on the thickness and type of road surface. The progression of structural cracking predicts the percentage of cracked area, taking into account the road maintenance history, the surface construction quality and cracking initiation time, which is defined as the time when small percentages of wide cracking (opening >3 mm) appears in the surface.

Smoothness

Four components related to structural properties of pavement materials, cracking, rutting and environmental conditions, where taken into account for future prediction of smoothness.

The structural component of smoothness is related to pavement structure deformation due to the shear stresses imposed by traffic loading. Those components related to the cracking and rutting are proportional to the deterioration itself, while the environmental element of the smoothness is related to local changes of moisture and temperature.

Skid resistance

This parameter is directly related to the micro texture of pavement surface. It depends on stone aggregates whose surfaces may vary from rough to polished. The model expresses the time evolution of skid resistance as a function of annual increasing of commercial vehicles volume.

MODELING PROCEDURE

With the deterioration models selected, a detailed review of the required parameters to calculate the evolution of the different distresses was carried out. Decision trees implicit in each model were identified and, the corresponding equations were programmed in Excel, including the potential solutions and their effects in each control indicator.

For the deterioration modeling, initial calibration factors were assumed. It is worth mentioning that those factors should be adjusted based on future testing programs. Even though deterioration is being currently forecasted with a certain degree of uncertainty, it is expected that periodical adjustments or “calibrations” provide to the concessionaire, adequate models for the specific conditions of each road, with high accuracy and confidence levels.

The deterioration modeling results, allow to identify the time in which the condition indicators of the pavement exceed acceptable levels, i.e. the time when intervention is needed. In such cases, the following hypotheses about the impact over control indicators progression are applied:

- Local cracks sealing causes a decreasing in the cracked area up to 0%
- The slurry seal intervention causes a decreasing of the cracked area up to 0% and improves skid resistance of the pavement surface.
- The micro-surfacing procedure causes a decreasing in the cracked area up to 0%; it corrects rutting and increases pavement smoothness and the skid resistance on pavement surface.
- Overlay and leveling procedures improve all control indicators.

The interventions carried out to improve a specific indicator tend to have a beneficial impact on the others as far as there is a relationship among them. For example, the rutting and smoothness evolution depend on the cracking, so a micro surfacing improves both indicators to a certain extent; likewise, most actions carried out to decrease rutting also improve the smoothness. On the other hand, the interventions to correct skid resistance on pavement surface, generally have not significant impact on the progression of smoothness and rutting.

RESULTS

As a result of the deterioration models implementation, along with feasible solutions, performance forecasts for a period of 20 years were obtained for each of the 71 resulting homogeneous sectors for five highways studied here; curves about future behaviour of indices, were constructed. Through a detailed analysis, it was possible to identify the following four typical patterns on future surface road deterioration for the entire road network.

First pattern. All condition indices reflect a remaining life > 3 years.

Second pattern. Represents sectors without remaining life under any of the indices considered, which require immediate intervention.

Third pattern. Corresponds to sectors where rutting or IRI fails acceptance criteria and the suggested solution impacts other indices, although they reflect good condition.

Fourth pattern. Sectors where skid resistance is inadequate, but the solution to improve it does not impact the other indices.

As an example to illustrate the results and analysis derived, figures 1 to 3 show the expected progression of rutting, IRI and skid resistance respectively, for highway # 4. It can be seen that sector 3 corresponds to first pattern; sectors 1, 2, 4, 5, 7, 8, 9 exhibit third pattern and sector 6 represents fourth pattern.

Finally, table VII summarizes the patterns classification for all sectors of the five highways analyzed.

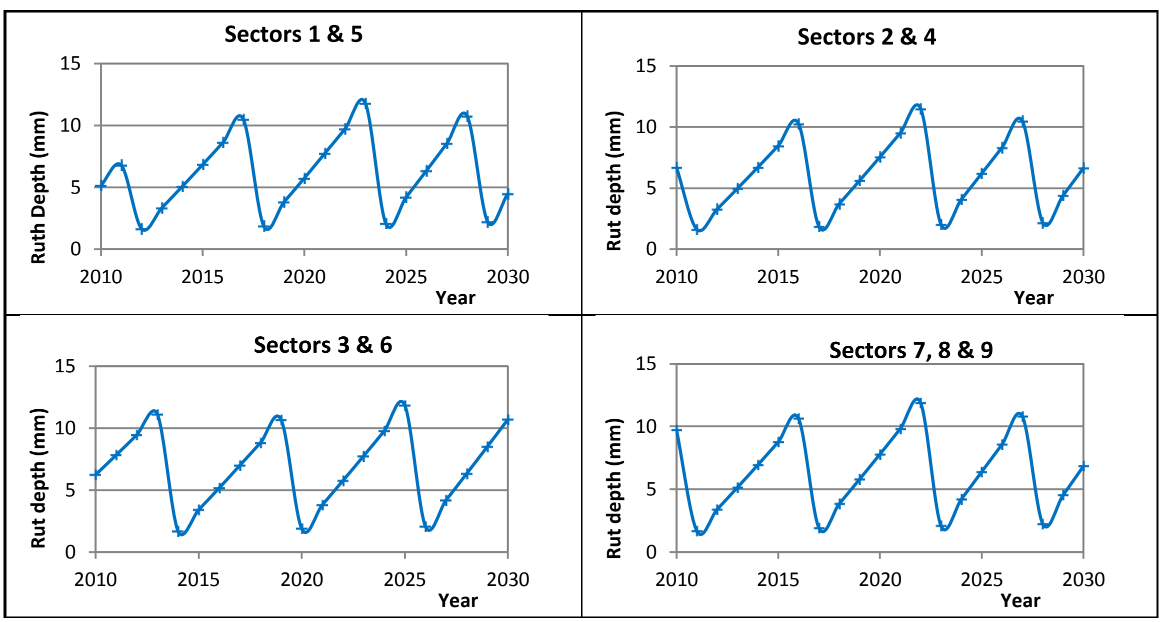

Figure 1 – Rutting progression

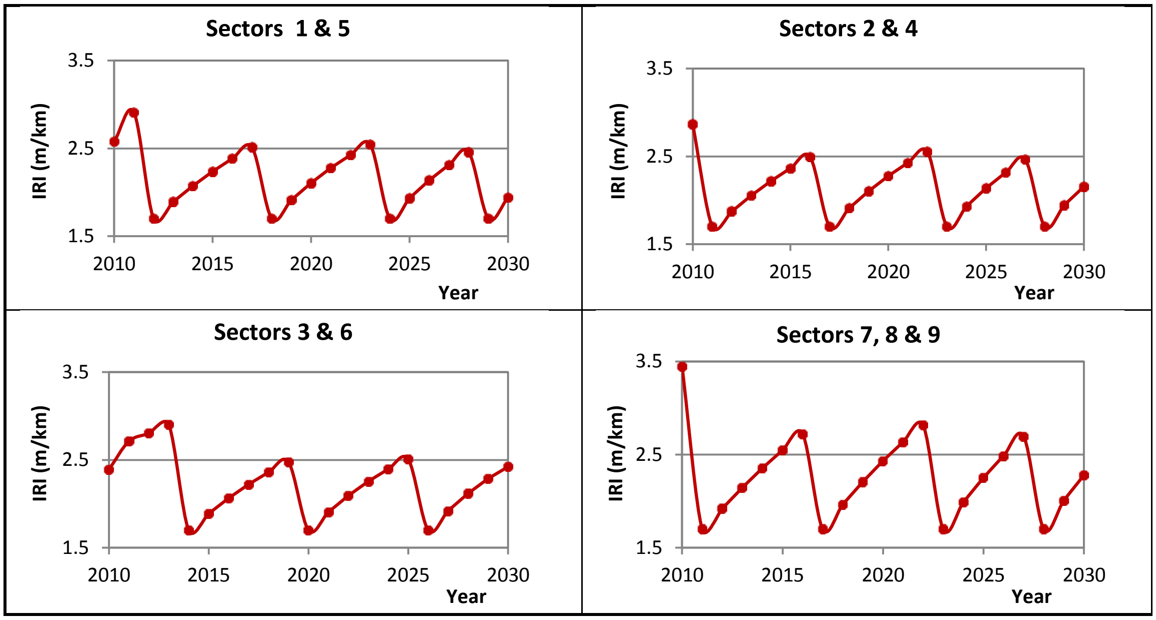

Figure 2 – Smoothness progression - IRI

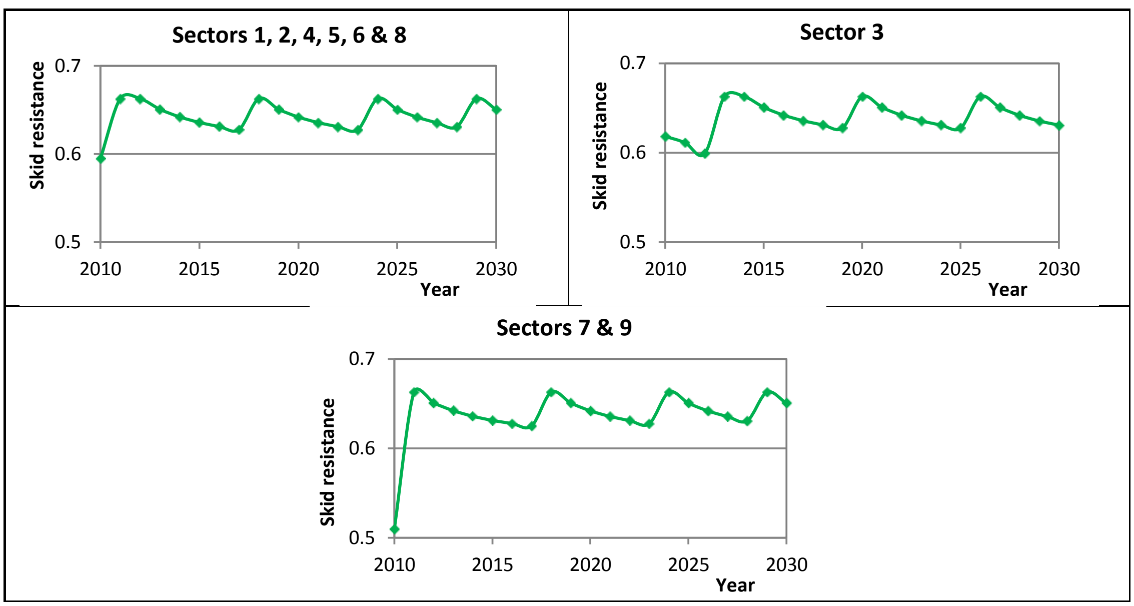

Figure 3 – Skid resistance progression

Table VIII –Behavior pattern expected for each sector along the road network

Highway #	Homogeneous sectors			
	First pattern	**Second pattern**	**Third pattern**	**Fourth pattern**
1	1 to 19			20, 21
2	2 to 10		1	11 to 16
3		2, 10 to 12, 14, 15		1, 3 to 9, 13
4	3	1, 2, 4, 5, 7 to 9		6
5		1 to 3, 5, 7, 10		4, 6, 8, 9

Corresponding highway number sectors are listed in tables III to VII.

All these results help to make decisions about where and when to apply corrective actions to prevent unacceptable levels of pavement condition parameters.

CONCLUSIONS

The deterioration models adapted in this work for managing a highway concessions network in Mexico, has contributed to a better definition of future program of maintenance considering additional criteria to those defined by government agencies. Modelling the particular conditions of highways allowed estimating the remaining life, priorities and opportunities of actions.

Four patterns of expected behavior of control indicators for a period of 20 years, were identified: i) sectors that still have remaining life; ii) sectors where all indices exhibit critical condition and require immediate solution; iii) sectors where IRI or rutting are critical and interventions applied improve other indices; iv) sectors where only the skid resistance is inadequate, but the proposed interventions does not affect the progression of the other indices.

There is some uncertainty in the current deterioration forecasts. It is expected that periodic adjustment or "calibration", provide better accuracy levels and higher confidence. By comparing the predicted behaviour with future performance observed along the highway network, it will be possible to: a) identify the benefit of the applied solutions; b) validate all hypotheses assumed in the analysis; c) adjust all specific calibration constants of each deterioration model; d) develop a database with the historical performance of the toll road network.

RECOMMENDATIONS

It is clear that additional elements should be involved in defining the future maintenance program that allow solutions to structural problems of highways, not evaluated by the control parameters used at present by government agencies.

It is recommended to combine deterioration modeling results with mechanical parameters of pavements obtained periodically from non-destructive deflection tests, carried throughout the concession period. This practice would be useful to obtain bearing capacity of pavement layers, identifying weak materials and therefore partial or full rehabilitation needs. These major interventions improve all indicators considered in this study, being necessary to re-calculate the trends of the models, under these new conditions.

We also recommend periodic auscultation campaigns, in order to compare predicted behavior, with the performance exhibited by the pavement in the future under actual service conditions. These comparisons allow adjusting predictions to the behavior actually observed, identifying structural changes exhibited by the pavement over the time, relationships with repeated load and even with seasonal changes. These campaigns would also reduce the uncertainty associated with the impact of solutions applied, to calibrate models of deterioration and to validate all the assumptions made.

Although typical trends were identified for the entire network, future behavior monitoring and verification must be done in a particular way for each sector along each road.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to ILAP and COCONAL, for the technical support and information provided during this investigation.

REFERENCES

AASHTO (1993). Guide for Design of Pavement Structures. American Association of State Highway and Transportation Officials. Washington, D.C.

ARA, Inc. & ERES Consultants Division (2004). Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report, National Cooperative Highway Research Program-NCHRP, TRB, NRC.

Association Mondiale de la Route – World Bank (2000). Analytical Framework & Model Descriptions. HDM-4 Documentation, vol. four. The Highway Development and Management Series.

ASTM Designation D6433 (2003). Standard practice for roads and parking lots pavement condition index surveys. West Conshohocken, PA.

ASTM Designation D4694 (2003). Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device. West Conshohocken, PA.

Barrantes, R., Loría, L., Sibaja, D., Porras, J. (2008). Desarrollo de herramientas de gestión con base en la determinación de índices para la Red Vial Nacional. Proyecto # UI-PI-04-08. Laboratorio Nacional de Materiales y Modelos Estructurales. San José, Costa Rica: LanammeUCR.

COMITRAN, Coronado J. (2005). Manual Centroamericano de Mantenimiento de Carreteras. Tomo III. Consejo Sectorial de Ministros de Transporte De Centro América, 2000.

Consejo de Directores de Carreteras de Iberia e Iberoamérica (2002). Catálogo de Deterioro de pavimentos flexibles colección de documentos Vol. 11.

Chen, D. y Scullion, T. (2008). Forensic Investigation of Roadway Pavement Failures. Journal of Performance of Constructed Facilities, Vol. 22, No. 1, pp. 35-44, ASCE.

Federal Highway Administration (2003). Distress identification manual for the long-term pavement performance program. Publicación No. FHWA-RD-03-031. US Department of Transportation.

Federal Highway Administration, FHWA (2006). Geotechnical aspects of pavements. Publicación No FHWA NHI-05-037. U.S. Department of Transportation.

Loizos A.; Karlaftis A. y Karlaftis M. (2007). An approach for optimizing pavement design – redesign parameters in PPP projects. Structure and Infrastructure Engineering, Vol 3, No. 3, pp. 257 – 265, Taylor & Francis.

Orozco, R. V. Evaluación de pavimentos flexibles con métodos no destructivos. Tesis de Doctorado en Ingeniería, UNAM. México.

Paterson, W. (1987). Road deterioration and maintenance effects, models for planning and management. The World Bank. Washington, USA.

SCT – Secretaría de Comunicaciones y Transporte. Normas N-CSV-CAR, años 2000 a 2009.

U.S. Army Corps of Engineers, Ladd, M. and Grau, R. (2001). Paver asphalt surfaced airfields Pavement Condition Index – PCI. United Facilities Criteria - UFC-3-270-06. Department of Defense, U.S. Department Research and Development Center, Vicksburg, MS.