Rigid pavement performance models by means of Markov Chains with half-year step time

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Rigid pavement performance models by means of Markov Chains with half-year step time

Pavement Management Systems employ pavement performance models to plan the most effective allocation of public funds. The most used models are the deterministic and the probabilistic or stochastic ones. Among stochastic models, the Markov Chains are receiving considerable research attention. In this paper, Transition Probability Matrices (TPMs) are presented for Portland Cement Concrete (PCC) pavement road network in the Republic of Moldova with available International Roughness Index (IRI) data collected in spring and in autumn from 2013 to 2015. Although one-year cycle time is usually employed, half-year cycle time was defined to handle a bigger amount of transitions. The aim of this paper is to prove that TPMs for rigid pavements can be developed using IRI values from a short period, with a half-year step time, for a road network where the time since last major rehabilitation varies in each section and where maintenance and rehabilitation activities are carried out simultaneously. In order to consider all these aspects, some assumptions must be made. Roughness seasonal variations can arise in PCC pavements due to the effect of curl and warp. Hence, a threshold of 0,40 m/km was defined as the maximum improvement on a section after half-year step for not being considered as maintenance work or spurious data. When the IRI value improves more than 4 m/km after one step, a Rehabilitation activity is considered. That rehabilitation is not used in the matrix calculation, but the subsequent deterioration contributes. Results demonstrate that rigid road sections can jump two condition states in one transition, instead of only remaining in the same condition state or shifting to the next one. Obtained matrices give an overview of deterioration tendencies of rigid pavements, and they fit better to real data if a large proportion of no rehabilitated or maintained sections are compared to predicted values.

Keywords: transition probability matrices; Portland cement concrete pavements; Markov Chains; pavement management; pavement deterioration; International Roughness Index; probabilistic models; rigid pavements

1. Introduction

Various factors, such as material ageing, traffic loading or environmental effects, make road pavement deteriorate gradually. In order to preserve pavement characteristics like riding comfort, safety and pavement distress at acceptable level, pavement maintenance is compulsory. As total maintenance costs exceed available funds, asset management techniques combining engineering, business, and technological aspects are necessary to best invest limited budgets. Pavement Management Systems (PMS), developed from asset management techniques in the 1960s, are used by highway administrations for managing, planning, budget allocation and pavement maintenance activity programming. (Fwa 2006) The summary of the essential elements that compose a PMS are listed below.

- Data collection for present pavement condition evaluation
- Future pavement condition prediction by means of performance models
- Network-level and project-level maintenance and rehabilitation planning taking into account local conditions and traffic, and material and financial resources.

Present pavement condition is assessed by means of one or more indices directly obtained from the road. There are several pavement condition data classification to evaluate highway condition The Pavement Management Guide (AASHTO 2012) categorized them in the following types:

- Pavement distress measurement
- Surface characteristics, including, on one hand, longitudinal profile and roughness, and on the other hand, surface texture and friction
- Sub-surface characteristics
- Structural evaluation

Nonetheless, there is no consensus about the correct approach to data collection and every road administration usually has its own catalogue (Flintsch and McGhee 2009).

Although surface characteristics are only a small portion of the total pavement structure, they represent an important item since they are directly related to highway users' safety and comfort. As presented in the World Road Congress in 1987, the pavement surface texture, defined as the deviation of the pavement form a true planar surface (AASHTO 1993), can be classified according to the wavelength (λ): microtexture ($\lambda \leq 0,5$ mm), macrotexture ($0,5 < \lambda \leq 50$ mm), megatexture (50mm $< \lambda \leq$ 500 mm) and roughness or unevenness ($\lambda > 50$ mm) (PIARC 1987). Microtexture and macrotexture are mainly related to tyre-pavement friction and consequently to safety (among other properties) and roughness to comfort. Several ways of measuring the longitudinal profile have been developed, resulting in various indices, such as Present Serviceability Rating (PSR) and Present Serviceability Index (PSI). Aiming to avoid the dependence on the longitudinal profile measurement device, the World Bank proposed the International Roughness Index (IRI) from the results of the International Road Roughness Experiment carried out in Brazil in 1982 (Sayers *et al.* 1986). Nowadays, the IRI is the most recognized standard for road roughness measurement because of its stability over time and transferability throughout the world. The algorithm proposed by Sayers (1995) defines the IRI and it represents the accumulated suspension stroke of a vehicle, divided by the distance travelled during the same period. Usually employed units are mm/m or m/km.

IRI data are employed by many road administrations to measure riding quality and to identify where maintenance and rehabilitation activities must be performed (El-Assaly *et al.* 2002, Pantha *et al.* 2010, Souliman *et al.* 2010, Abaza and Mullin 2013, Khattak *et al.* 2014, Gulfan-E-Jannat *et al.* 2016). The Ministry of Transport and Road Infrastructure (MoTRI) of the Republic of Moldova has collected IRI values from main Moldovan highways since 2000 and they are deployed to assess the present road network condition.

Many performance models have been developed for future pavement performance. The deterministic and probabilistic models are the most employed and they are generally referred as the fundamental groups (Huang 1993, Hong and Wang 2003, Amin 2015). Deterministic models are used if historical condition data of an index or indices are available. They establish a relationship between the index (or indices) and one or more variables, after statistical regression analysis. On the contrary, probability based models provide the probabilistic distribution of the expected variable, not a precise value. Although both models forecast the future condition, the stochastic ones can introduce uncertainty in pavement performance, which is said to be probabilistic in nature (Golroo and Tighe 2009, Kobayashi *et al.* 2012, Thomas and Sobanjo 2013). Therefore, some levels of uncertainty must be assumed (Abaza 2016a).

Among probabilistic models, Markov Chains are receiving considerable research attention for infrastructure performance modelling (Roelfstra *et al.* 2004, Sinha and Knight 2004, Baik *et al.* 2006, Zou and Madanat 2011, Marzouk *et al.* 2012, Lethanh and Adey 2013). These models need establishing a series of condition states and time periods. Then, by means of one of more transition probability matrices, it is possible to foresee the probability that a pavement section in a condition state at a given time stage will remain in the same or shift to other state in the next stage. Further discussion is provided in section 2.

This paper aims to develop Transition Probability Matrices (TPM) for Portland Cement Concrete pavements of National roads of the Republic of Moldova. It was demonstrated that is feasible to develop TPMs using IRI data from a short period, with sections with different time since last major rehabilitation and while maintenance and rehabilitation works are performed, as long as some assumptions are made.

Section 2 defines the TPM theory. Moldovan roads and present PMS are described in section 3. Section 4 contains the necessary assumptions to obtain TPMs. Results are discussed in section 5. Finally, conclusions are exposed in section 6.

2. Theory about Transition Probability Matrices

This section provides an overview of Markovian probability matrices. The Markov prediction model is a stochastic process that follows three restrictions (Ortiz-García *et al.* 2006). The process should be discrete in time, should have a countable or finite state space and should satisfy the "Markov property" (Isaacson and Madsen 1976). This property indicates that any future condition state of the process depends only on its present state and not on the past states. (Hillier and Lieberman 1990). Pavement deterioration is said to fulfil the Markov property (Kerali and Snaith 1992).

There are three fundamental elements in a Markov Chain: The state probability vector, the cycle or step time and the transition matrix. The number of condition states (CS) and the number of transitions are concepts also related to the main elements. The state or condition probability vector indicates the pavement percentages or proportions that are included in each CS at any time. The transition matrix represents the probability of each CS to transiting from its current state to the same or to another one in one cycle time. The cycle time is the discrete-time interval taken between two points of time. The fundamental elements are described individually:

(1) The state or condition probability vector is a row vector indicating the condition of the pavement by means of the proportions of pavement sections in each CS.

For example, consider an index ranging from 10 to 0, with 10 being the best value and 0 the worst. This index could be divided into 5 CSs: 10,0-8,0; 7,9-6,0; 5,9-4,0; 3,9-2,0; 1,9-0. Imagine that the current condition index of the road shows that 45 % of sections has an index value in 10,0-8.0 range, 30 % in 7,9-6,0 and 25 % in 5,9-4,0, the present state vector of that road, $A = \{a_1, a_2, ..., a_i, ...a_n\}$, is:

$$A = \{0,45;\ 0,30;\ 0,25;\ 0;\ 0\} \qquad (1)$$

The sum of all a_i should be equal to one and all the elements must be nonnegative.

(2) The step or cycle time is the time interval considered between two stages. Generally data is collected one a year due to seasonal climate change, and consequently, one-year step has been usually selected (Ortiz-García *et al.* 2006).

(3) The transition probability matrix, commonly denoted by *P*, represents the pavement deterioration with time. It is a squared matrix, with *n* rows and *n* columns, where *n* is the number of considered states. In the example presented previously, *n* = 5. Its general form is

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \qquad (2)$$

Each element p_{ij} expresses the probabilities of an element in condition state *i* in stage *t* to change to condition state *j* in stage *t+1* (Eq. 3).

$$p_{ij} = prob\left[X(t+1) = j \,/\, X(t) = i\right] \qquad (3)$$

Therefore, p_{ij} is described as the conditional probability of any considered variable (any index) in state *i* in present stage will be in state *j* after exactly one cycle time. TPM elements of the matrix must meet the following restrictions (Wang *et al.* 1994):

$$0 \leq p_{ij} \leq 1, \text{ for all i and j, and i, j = 0, 1, 2,..., n.} \tag{4}$$

$$\sum_{i}^{n} p_{ij} = 1, \text{ for all i and i = 0, 1, 2, ..., n.} \tag{5}$$

Analyzing more deeply the matrix, elements placed in the main diagonal, p_{ii}, provide the probability of a road section to stay in the same CS after one step. Elements p_{ij} for $i > j$ indicates that the section can evolve to a better state in next cycle. Without maintenance or rehabilitation activities, this concept must be refused in a normal pavement deterioration process. In this paper pavement deterioration is only analyzed. Hence, elements p_{ij} is equal to 0 for each *i* greater that *j*. Moreover, element p_{nn} is equal to 1, by applying Eq. 5. It expresses that a section in their worst condition cannot deteriorate further. Consequently, the general form of *P* representing only pavement deterioration is

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \Lambda & p_{1n} \\ 0 & p_{22} & p_{23} & \Lambda & p_{2n} \\ 0 & 0 & p_{33} & \Lambda & p_{3n} \\ \mathrm{M} & \mathrm{M} & \mathrm{M} & & \mathrm{M} \\ 0 & 0 & 0 & \Lambda & 1 \end{bmatrix} \tag{6}$$

Normally, many authors assume the idea that sections can only remain in the same CS (without maintenance and rehabilitation works) or deteriorate to the next CS, according to reasonable condition state and cycle time (Butt *et al.* 1987, Mayet and

Madanat 2002, Costello *et al.* 2005, Abaza and Murad 2007, Abaza and Murad 2009). Thus, only element $p_{i,i}$ and $p_{i,i+1}$ are present in TPM,

$$P = \begin{bmatrix} p_{11} & p_{12} & 0 & \cdots & 0 \\ 0 & p_{22} & p_{23} & \cdots & 0 \\ 0 & 0 & p_{33} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \quad (7)$$

By means of matrix multiplication of present state vector and the TPM, condition vector of next stage can be calculated, as indicated in Eq. 8 and 9.

$$A_1 = A_0 \times P_1 \quad (8)$$

$$A_2 = A_1 \times P_2 \quad (9)$$

Where A_0, A_1 and A_2 are the state vector of a road at time t = 0, t = 1 and t =2 respectively and P_1 and P_2 are the transition matrices corresponding to transitions form step 0 to 1 and from 1 to 2 respectively. Supposing that the TPMs remain constant over time, the same matrix can be applied to any t to t+1 transition. Processes that fulfil this idea are called homogenous Markov Chains and they show a stationary condition, assuming that the deterioration rate over the analysis period does not change. Hence, state vectors in any future time t, or after t transitions, can be calculated applying Eq. 8 t times (Chapman-Kolmogorov equations):

$$A_t = A_{t-1} \times P = A_{t-2} \times P \times P = A_{t-2} \times P^2 = A_{t-3} \times P^3 = \ldots = A_0 \times P^t \quad (10)$$

Some authors used the homogenous Markov Chains to model pavement deterioration. (Smith 1974, Kulkarni 1984, Carnahan 1988, Kallen 2011) Nevertheless, traffic volumes, environmental factor or subgrade strength could change during pavement life, and, hence, different TPMs should be applied, resulting in a non stationary Markov Chain, which is said to be more realistic (Feighan *et al.* 1988, Li *et al.* 1997, Hong and Wang 2003). However, greater efforts and time are needed to obtain a specific matrix for each transition. Therefore, some transitions in a certain period are calculated by means of the same TPM. Butt *et al.* (1987) concluded that the same TPM could be employed for a period up to 5 years without affecting significantly the performance of the Markovian model.

Among the various methods for the estimation of the probability matrix, two techniques are the most employed: historical deterioration data analysis from a period or experts' knowledge (Tabatabaee and Ziyadi 2013). In the first method, the probability for each transition, p_{ij}, is calculated by means of Eq. 11:

$$p_{ij} = \frac{N_{ij}}{N_i} \tag{11}$$

Where N_{ij} is the number of road sections that shift from state i to state j during one step and N_i is the total number of sections that were in state i before the transition. Butt *el al.* (1987) exposed a methodology that minimized the absolute distance between the real 'Pavement Condition Index – age' data points and the points obtained (as a prediction) by the Markov model over a 30 years data set. Ortiz-García *et al.* (2006) proposed three methods with the aim of minimizing the residuals. The first method need the original data to be available, the second one calculated the TPM from a regression equation generated from the original data and the last one employs the distributions of the original data of each year. Abaza (2016a) introduced a simplified methodology based on a factor, C_i, which can be applied to present TPM to calculate non-stationary matrices associated with staged-periods. Abaza (2016b) also presented a technique that only needs two steps of pavement distress evaluation.

3. Data collection on Moldovan roads.

The Republic of Moldova became independent in 1991 following the disintegration of the Soviet Union. The total area is 33.843,5 km^2 and it is bordered by Romania and Ukraine. The Ministry of Transport and Roads Infrastructure (MoTRI) is the public institution in charge of developing and performing the policy in the area of transport and road infrastructure. Moreover, the State Road Administration (SRA), directly subordinated to the MoTRI, is the corporative road agency responsible for road construction, maintenance, rehabilitation, safety and all decisions concerning the use of funds for roads.

The Republic of Moldova has a road network of 9373 km in 2015, which has practically not changed since its independence. Moldova inherited from the Soviet Union a well-developed road network, with a road density of 314 km per 1000 km^2 and 2,6 km per 1000 persons, and therefore, there was no need for expansion. The immediate post-Soviet years were characterized by an economic collapse and consequently by a significant reduction in road traffic and maintenance expenditures.

3.1. Road Classification

Based on their ownership, Moldovan public roads are divided into:

- National roads, which are public property of the state. There are two groups, according to is importance: Magistral roads (denoted as Mxx), the most important ones, and Republican roads, (Rxx).
- Local roads, which are public property of administrative-territorial units.

For road classifications, Moldova has followed the classification of the Russian Construction Standards (SNiP), which combines function and standard with traffic volumes. The present technical categories for Moldovan road (Ministerul Dezvoltării Regionale şi Contrucţiilor 2015) are shown in Table 1.

In Table 2 Moldovan roads in 2015 are classified by ownership, technical category and surface type. PCC pavements represent the 8,6 % of the national road network, and the proportion in the local road network is regarded as insignificant, with only 0,7 % of the 6034 km of local roads. Only National roads are analyzed in the paper. As observed, some sections are classified in more than one category. Only 2,5 km of rigid pavement are classified in the technical category 3. Hence, no performance prediction model is established for PCC pavement in this category.

Generally, PCC pavement structure in Moldova can be classified as Jointed Plain Concrete Pavements (JPCP), with joint spacing of 4 and 4,5 m, and some cases of 5 m. In longitudinal joints tie bars were employed and in transverse joints dowels. Generally, tie bars are 12 mm in diameter, with a length of 800 mm and they are spaced at intervals of 1,00 m. Dowel bars usually have a diameter of 25 mm and a length of 500 mm. They have a centre-to-centre spacing of 300 mm, and sometimes, greater values are adopted. Slab thickness varies from 15 to 30 cm, as a function of heavy traffic volume. Obtained pavement samples showed that crushed stone or untreated materials were employed for base layers, and in subgrade layers, untreated granular materials. Cement or lime treated subgrade soils were not found.

3.2. Road Condition assessment

Since Moldovan independence in 1991, a constant decline in Moldovan road network condition has been certified. In recent years, attempts to reverse this trend have been carried out. Figure 1 presents the National Road condition evolution from 1992 to 2015, based on IRI data available on SRA.

From 2000 to 2012, the SRA has systematically collected roughness data covering 41 National roads, consisting of average IRI per kilometre by road and year. Nonetheless, there are many gaps in the dataset, with years with no data or poorly represented. An average roughness of 6,1 m/km over the period 2001-2010 shows that the national road network was in a not very adequate condition. IRI values in National roads from 2010 to 2015 reflect an improvement on road condition (Figure 1).

In 2012, the SRA estimated a maintenance strategy, in which all of the roads are targeted to be in maintainable condition in year 2032 (20 years strategy) with no constraints on budget. It gave an indication of the amount and cost of work required to bring the total network of 9373 km to at least satisfactory condition and maintain it in that condition over the stated period. Table 3 presents the 2013 to 2032 network needs split into the categories Rehabilitation, Periodic Maintenance, and Routine Maintenance. Obviously, the available funding for the road network of Moldova for rehabilitation, periodic and routine maintenance works is lower than those figures. Maintenance and rehabilitation budget allocation from 2013 to 2015 is shown in Table 4. This highlight the necessity of developing future prediction models to implement an efficient strategy in the Pavement Management System of the SRA.

Since 2013, the SRA have followed a standardized IRI data collection framework with the aim of developing a complete National Pavement Management System, collection data National roads (Magistral and Republican) twice a year, in spring and in autumn.

4. Development of Transition Probability Matrices for Moldovan Roads

Some assumptions in fundamental aspects were made in order to develop an adequate pavement performance model for Moldovan rigid pavements:

(1) Road type: In this paper, TPMs were obtained for Portland Cement Concrete pavement roads, i.e. rigid pavement roads. They represent 8,6 % of National road network, including Magistral and Republican roads. Only periodically and systematically collected IRI data from 2013 to 2015 were deployed.

(2) Cycle time: Half-year time cycle was adopted. Usually, one-year step time is employed taking into account the annual data collection and seasonal climate change (García-Ortiz et al. 2006). Nonetheless, in this case available data period was short, only from 2013 to 2015, but with 2 data collection per year. Therefore, in order to establish a more significant performance model, the 6 available data sets were employed, giving the possibility of handling 5 transitions.

(3) Technical category: As shown in Table 2, there are not enough road sections in technical category 3 in PCC and National Roads. Only 2,5 km are classified in category 3 and 2,9 in mixed category 3-4. Consequently, no significant length for analysis in this classification was available. An individual TPM for categories 1 (ADT > 8000 vehicles/day), 2 (3500 < ADT ≤ 8000) and 4 (200 ≤ ADT ≤ 750) was developed.

(4) Layer thickness: Moldovan roads are classified in technical categories based on the Average Daily Traffic (ADT). It is impossible to obtain a TPM based on concrete layer thickness as they are not identified by the SRA. They are only distinguished according to the surface layer. It is assumed that, for the same inputs (ADT), similar or equivalent outputs (pavement layers and proportional thickness) were employed. Furthermore, technical categories represent similar or equivalent transverse cross sections because roads are classified according to ADT. Some pavement samples were obtained in representative roads in order to

know the pavement structure and dimensions. Samples showed a correspondence between traffic volume and employed slab thickness. Hence, technical categories are adopted as classification of roads with similar or equivalent slab thickness.

(5) Number of condition states: Whereas some indices have a limited range for their values, like Pavement Condition Index, ranging from 100 to 0, IRI represents the measure of the pavement roughness and it may vary enormously. A value near 0 represents the absolute perfection. In new pavements, IRI values usually vary from 1,5 - 2,0 m/km and damaged ones may have values around 10 m/km. Values over 12,0 m/km represent unpaved roads. Generally, CSs with the same range width are employed. For IRI values, 7 states of 2 m/km were proposed; from state 1 “excellent” (0,0 - 1.9 m/km) to state 7 “failed” with values over 12 m/km (> 12) (Adedimila 2009). Initially, a constant condition state range of 2 m/km was established, starting from 0 m/km. Nevertheless, a minimum number of sections in that CS is necessary to handle so as to obtain significant results. Consequently, a minimum of 10 sections in each CS was imposed to be considered. If the minimum was not achieved, that CS was put together with next one. As a result, CSs indicated in Table 5 were obtained in each technical category. In Table 5, the average value of roughness in each band is indicated. In technical category 1 and 2, the best CS is ‘2. Good’, and, although it could be stated that its average value was 2 m/km, as it ranges from 0 to 4 m/km, there were very few values with an IRI value below 2. The same happened in technical category 4, where for ‘3. Fair’ condition state, the average value is 5 due to the small proportion of sections with a value under 4 m/km.

(6) Analysis period: Generally, real data based performance models are calculated from the first moment, when the road is in service and continues during pavement life (Wang *et al.* 1994, Li *et al.* 1997, Abaza 2016a). As indicated, there have not been any new roads since the independence of Moldova in 1992. Hence, it was impossible to study roads from the initial moment. Consequently, roads at different moments of their service life were analyzed. TPM elements were calculated applying Eq. 11 to sections in each CS. As varying CSs of the total network are introduced, the TPM provides an overview about PCC pavement deterioration.

(7) Maintenance and Rehabilitation (M&R) works: As discussed in section 2, since the paper focuses on the deterioration modelling, no improvements were considered and, hence, elements under the main diagonal are equal to 0, as represented in Eq. 6. In 2013-2015 period, M&R works were carried out. Maintenance (M) works usually employed in Moldova in rigid pavements are joint resealing and joint load transfer restoring. Rehabilitation (R) works in PCC pavements are partial depth patching, full depth parching and slab replacement. In order to distinguish between M and R works, a threshold must be established. Table 6 presents some real cases from Moldovan highways. When a better value was obtained, as in example No. 1 of Table 6, it is undeniable that a R activity was performed (from autumn 2013 to spring 2014). In this case, deterioration from spring 2013 to autumn 2013 contributed to the TPM. Although it is known the precise activity in that road, the improvement from autumn 2013 to spring 2014 was not introduced in the TPM calculation, because it is not the aim of this paper. However, subsequent deterioration, from 2014 onwards, was also considered. This deterioration does not reflect the evolution of a new road, but

of a rehabilitated one. This is the situation of Moldovan roads because no new roads have been constructed since 1992. As stated previously, the performance of roads with varying time since last major rehabilitation was forecasted. An improvement of 4 m/km in IRI value indicates a R work on the road. This is the normal case in Moldova because normally rigid pavements are not rehabilitated until an IRI value of 5,0 or 6,0 m/km is achieved in the section. Following this idea, data of example No. 2 does not come from a new road, but from a renewed one before 2013. And these data were also employed for TPM calculation.

(8) Seasonal variation: In the example No. 3 of Table 6 an improvement is observed between spring 2013 and autumn 2013. This small improvement reflects a seasonal variation and not a maintenance actuation. Roughness seasonal variability of jointed Portland Cement Concrete pavements are attributed to the effect of curl and warp, which is highly correlated to pavement surface temperature (Baus and Hederson 2008). Karamihas *et al.* (1999) showed a recorded average diurnal roughness variation of 0,075 m/km with a maximum daily change in IRI at 0,20 m/km. In another research, Karamihas *et al.* (2001) found that the average change in roughness during the day was 0,20 m/km and for an individual section, it could achieve a maximum of 0,40 m/km. Johnson *et al.* (2010) registered seasonal variations below 0,10 m/km in South Carolina, which was considered fairly small. It was also shown that diurnal impacts of slab curling on the Half-car Roughness Index can be as high as 0,63 m/km with an average value around 0,16 m/km (Chang *et al.* 2010). Winter is said to be the season that increases most IRI values and it is recommended not to collect data in winter, especially in February (Perera and Kohn 2002). Consequently, an improvement of 0,40 m/km (a -0,40 m/m difference between values) was

considered as combination of daily and seasonal variations. A section could improve its IRI value 0,40 m/km without being considered spurious or related to maintenance work. A better CS could be obtained due to seasonal variation (example No. 4 between spring 2013 and autumn 2013). In these circumstances, IRI values were registered as if both data belonged to the same CS (3, fair, $4 < IRI \leq 6$).

(9) Improvements not related to rehabilitation or seasonal variations: In example No. 5 of Table 6, there is an improvement in IRI values from autumn 2013 to spring 2014. As the improvement is between 4,00 and 0,40, in absolute terms, a M operation was supposed to be carried out in that section, but not a R operation. Budget allocated in each roads is registered in the SRA, but it is not recorded the precise M operation performed. Hence, comparison among minor treatments is not possible. Values between these two thresholds (improvements of 0,40 and 4,00) were not considered (in the example No. 5 data from 2014 and 2015). Usually, this type of improvements is connected to activities such as punctual pothole reparation that may continue again in next periods, as shown in example No. 5 between spring 2015 and autumn 2015.

(10) TPM structure: Initially, no assumption was made about the TPM structure. Unlike some authors that state that $p_{i,i}$ and $p_{i,i+1}$ elements must be only present in TPM (Eq. 7), results must show if this consideration is fulfilled in Moldovan roads . In order to take into account that a section can drop by more than one state in one cycle, it was established a minimum of 1 % of total transitions in that CS.

5. Results and discussion

Table 7 presents the roads employed in the TPM calculation. It is indicated their technical category and the length considered. Some roads had no data from 2013 and only IRI values from 2014 and 2015 were used.

The total number of sections in each CS in all stages and the quantity of transitions to each CS are shown in Tables 8 to 10 for categories 1, 2 and 4 respectively. The elements of provisional TPMs are indicated in brackets.

According to the provisionally developed matrices, sections can jump 2 condition states in one cycle time. In category 2 (Table 9), there were 36 road sections that shifted their CS from 2 (good, IRI ≤ 4) to 4 (poor, 6 < IRI ≤ 8) in only one transition. Since it represents more than 1 % of the cases, it must be considered. Likewise, in category 4 (Table 10), 4 sections changing from CS 3 to CS 5 were registered, representing more than 3 %. On the contrary, in category 2 (Table 9) there was only one section that jumped from CS 3 to CS 5, (0,1 %). Therefore, it was not taken into account. The same phenomenon happened in category 1 (Table 8), where one section shifted from 'good' to 'poor' CS in one cycle time. As a result, this a priori concept, which is widely mentioned in the literature about pavement transition probabilities, even in Portland Cement Concrete pavements, cannot be assumed in Moldovan highways, because it occurs in a significant proportion.

Calculated transition matrices and real road data evolution were compared. However, it was only possible to carry it out with sections that were not maintained (M) or rehabilitated (R) during the 2013-2015 period. They are denoted as No Maintenance and Rehabilitated sections, 'No M&R sections', and the difference between consecutive IRI values is always under the seasonal variation threshold (0,40 m/km). IRI value improvements between 0,40 m/km and 4 m/km (in absolute terms) were related to a maintenance operation and those sections was not further considered. If the improvement is over 4 m/km, it means that a reconstruction work was performed. After the rehabilitation, IRI evolution was considered again, but that section could not be taken into account to analyze the IRI evolution in No M&R sections. The following data were compared:

- The average IRI value of No M&R sections from 2013 to 2015, denoted as 'Average IRI of No M&R sections'. The total number of available sections that fulfil that condition was constant during the analyzed period. The range of ± 1 Standard Deviation (SD) of IRI values was also presented. The SD was calculated according to Eq. 12.

$$SD = \sqrt{\frac{\sum_{i}^{n} (x_i - \bar{x})^2}{n}} \quad (12)$$

- The state vector for each stage was defined, according to No M&R sections' IRI values and, after applying Eq. 13, the average IRI value of the sections in that stage was obtained. It is denoted as 'No M&R sections' vector'.

$$IRI_{average} = a_2 \cdot 3 + a_3 \cdot 5 + a_4 \cdot 7 + a_5 \cdot 9 \quad (13)$$

Where a_2, a_3,..., a_5, are the elements of the state vector, as indicated in Eq. 1, and each element represent the percentage of sections in that CS (from 2 to 5). The values 3, 5, 7, 9 represent the average value of IRI in each CS as exposed in Table 5.

- Predicted state vector of next stages was obtained applying Eq. 10 to the condition vector of the first stage and obtained TPM. Again, the average IRI value of the sections in every stage was calculated using Eq. 13. These values are denotes as 'Predicted IRI'

In Figure 2 the comparison between the three described items is shown for technical category 1. As data from 2014 and 2015 were only available for category 1, only 3 transitions are shown, represented in abscises. The predicted IRI value was close to real data and it was between the real data ± 1 Standard Deviation

In Figure 3, the comparison between described items for data available in the 2013-2015 period for category 2 is provided. As observed, predicted IRI values tend to overestimate the values of No M&R pavement sections. This tendency was examined. Table 11 indicates the percentage of No M&R sections from the total in each technical category. There are very few No M&R sections in the 2013-2015 period in category 2. The ride quality road improvement, consequence of the budget allocated in category 2 is shown in Figure 4, representing the CS of all the road sections (191) with data available from 2013 to 2015.

According to Table 11, there are only 3 sections in category 4 that were not maintained or rehabilitated in the analyzed period. Hence, no comparison between real data and predicted values was made.

The election of the threshold of 4 m/km for rehabilitation works was also analyzed. For technical categories 1 and 2, the value for considering rehabilitation activity in a section was changed to 2,00; 3,00 and 5,00 instead of 4,00 m/km. Similar analysis as in Figure 2 and 3 was carried out. In category 1, the number of considered sections, No M&R sections, in each hypothesis remained constant, 217. Small quantity of variations on the number of transition was found and, hence, the obtained TPMs were very similar. Consequently, predicted IRI values were almost identical, as exposed in Table 12.

In technical category 2, when analyzing data available in 2013 to 2015, the number of No M&R sections in each hypothesis remained invariable, 28, and therefore the average IRI of No M&R sections and from condition vector were identical. However, there was bigger difference between the quantity of considered transitions according to established threshold and, therefore, there were some variations in the developed TPMs. Figure 5 shows the predicted IRI values in each hypothesis. Adopting the lowest threshold, 2 m/km; the amount of considered transition cases increased. On the contrary, the highest threshold, the least transitions were considered. Nevertheless, all the models showed a tendency to overestimate the average IRI value of all the No M&R sections. Once again, the reason is that, when analyzing No M&R sections, very few were considered to map No M&R sections performance, 28 from 191, as indicated in Table 11. Nonetheless, all the sections with deterioration (or an improvement lower than 0,40 m/km due to seasonal variation) or after rehabilitation contributed in the TPM calculation. Hence, sections with better and worse deterioration were considered. Usually M&R works are not applied to section with the lowest levels of deterioration but to sections with high degradation. Therefore, taking into account the big amount of sections and the transitions analyzed, obtained TPMs were considered to be able to forecast IRI evolution in Moldovan rigid roads. Moreover, the threshold of 4 m/km was estimated adequate for defining R operations.

Furthermore, transition matrices were calculated if data from the same season were only computed, i.e., if data were collected only once a year, in spring or in autumn. Matrices were obtained following the same process and assumptions explained before, but this time, only spring data or autumn data were deployed. The only different assumption is related to seasonal variations. After one year, seasonal variations cannot be taken into account. Therefore, any improvement in IRI value is considered as a result of a maintenance (improvement between 0 and 4 m/km) or rehabilitation (improvement over 4 m/km). TPMs with one-year cycle time, for spring and autumn values, for each technical category (1, 2 and 4) are shown in Figure 6. Using previously obtained six-month TPMs, matrices resulting after one-year cycle time were also calculated, i.e. after two cycle time of six months, applying Eq. 10 for two cycle times, as indicated in Eq. 14.

$$A_2 = A_0 \cdot P^2 \tag{14}$$

As observed in Figure 6, there are small differences in matrix values. Matrices for technical category 1 are quite similar, and the variability when applying to the same vector is not important. The half-year step matrix provides the lower deterioration rate. In category 2, the six-month TPM is placed between the annual TPM, establishing an similar performance. Finally, for category 4, a bit higher degradation is obtained with half-year matrix.

Although there are some differences in the results, the employment of half-year TPMs is a better option in cases where maintenance and rehabilitation operations are performed simultaneously in the road network, like in Moldova. Firstly, as activities are carried out at anytime, the whole sequence of IRI values must be observed so as to better identify the improvement works and, consequently, better censor data. Secondly, using data from both seasons, more transitions are available, which implies a more accurate and reliable matrix. Lastly, when more sections are not improved during the analysis period, as in technical category 1, a better prediction is obtained and matrices are almost similar. On the contrary, if few sections are not rehabilitated or maintained, as in category 4 (only the 2 %, Table 11), variations are greater. As a conclusion, the comparison of cycle times suggests the adequacy of a six-month step time for Moldovan roads if M&R works are carried out simultaneously.

After eliminating the transition cases that represented less than 1% of the cases, final TPMs for Moldovan PCC pavement roads in categories 1, 2 and 4 are exposed in Table 13 to 15 respectively.

Finally, supposing an ideal state vector in moment 0, with all the section in best CS, the IRI evolution of the 3 road categories was studied (Figure 7). IRI performance of technical category 1 showed a uniformly decreasing rate. Categories 3 and 4, which started in different ideal IRI values (as a result of considering different initial CSs) showed a quickly deterioration and both have an asymptotical tendency to the medium value of the worst state (CS 5) after 5 years since last major rehabilitation.

6. Conclusions

Pavement performance models are crucial elements for the planning of M&R activities in any PMS in order to allocate efficiently public funds. Stochastic models are said to better represent probabilistic nature of pavements. Among them, Markov Chain models are receiving great attention. In this paper, Transition Probability Matrices were developed in order to represent roughness performance of Moldovan Portland Cement Concrete pavements by means of IRI values collected systematically in spring and in autumn from 2013 to 2015. They were obtained in specific circumstances after some assumptions were made:

- A complete road network with different ages. Generally, a road or some roads are analyzed since they are opened to traffic to obtain its (or their) performance model. Since the independence of Moldova, no new highways have been constructed and IRI values started being collected in 2000, but until 2013 they were not systematically collected. Hence, it was impossible to follow road deterioration as complete data were not available. On the contrary, all the sections from 2013 were analyzed, with different age since last major rehabilitation. Thus, a general vision of the performance at different ages was obtained.

- Half-year cycle time. Usually, one-year cycle time is employed in TPMs based on seasonal climate change. As the analyzed period was so short, half-year step time was introduced in order to take into account more condition transitions. As seasonal variations could appear in rigid pavement, as a consequence of surface temperature change, a threshold of 0,40 m/km was established as the maximum improvement that a section could have without being considered related to maintenance operations or spurious data.
- Maintenance and rehabilitation works simultaneously. In 2013-2015 period M&R activities were also performed in PCC pavements in Moldova. Deterioration after rehabilitation was introduced in the calculation in order to obtain the TPM, similarly to those sections that were rehabilitated before 2013. In order to consider a rehabilitation work, an improvement of 4 m/km on IRI value was imposed. The step of that improvement was not employed, but deterioration after it contributed to the analysis. Improvements between the thresholds of 0,40 m/km (seasonal variations) and 4 m/km (rehabilitation works) were supposed to be a result from maintenance or spurious data and they were no longer considered.

Transition Probability Matrices were developed for Moldovan technical categories 1, 2 and 4. There were no enough data available for category 3. Some conclusions were obtained.

On one hand, predicted values were compared to real values of sections with No M&R activities during the analyzed period. If the average IRI value of a large proportion of No M&R sections was employed, the estimated one was near to the real one, within the range of the average value and the average + 1 Standard Deviation. If not, the predicted values tended to overestimate the IRI value. It occurred because there was no need to maintain or rehabilitate less deteriorated sections. Hence, sections no so deteriorated were compared to the general trend of all sections, including sections with better and worse performance. Therefore, obtained matrices provided an adequate overview of PCC pavement deterioration trends in each category.

On the other hand, TPM literature assumes that sections in a condition state can only remain in the same state or evolve to next one. Results in Moldovan roads showed that some sections can have a drop of two condition states in only one step. As the proportion were above 1 %, when more than 10 cases in that condition state were considered, this phenomenon that takes place in Moldovan rigid roads must be reflected in the Transition Probability Matrices.

References

AASHTO, 1993. *Guide for Design of Pavement Structures*. Washington, DC: American Association of State Highway and Transportation Officials.

ASHTO, 2012. *Pavement Management Guide. 2nd Edition.* Washington, DC: American Association of State Highway and Transportation Officials.

Abaza, K.A., 2016a. Simplified staged-homogenous Markov model for flexible pavement performance prediction, *Road Materials and Pavement Design*, 17 (2), 365-381.

Abaza, K.A., 2016b. Back-calculation of transition probabilities for Markovian-based pavement performance prediction models. *International Journal of Pavement Engineering*, 17 (3), 253-264.

Abaza, K.A. and Murad, M.M., 2007. Dynamic probabilistic approach for long-term pavement restoration program with added user cost. *Transportation Research Record: Journal of the Transportation Research Board*, 1990, 48-56.

Abaza, K.A. and Murad, M.M., 2009. Predicting flexible pavement remaining strength and overlay design thickness with stochastic modeling. *Transportation Research Record: Journal of the Transportation Research Board*, 2094, 62-70.

Abaza, O.A. and Mullin, A.P., 2013. Modeling of pavement deterioration in cold regions. *In*: J.E. Zufelt, ed. *10th International Symposium on Cold Regions Development 2013: Planning for Sustainable Cold Regions* , 2-5 June 2013 Anchorage, Alaska, ASCE, 416-427.

Adedimila, A.S., Olutaiwo, A.O., and Kehinde, O., 2009. Markovian probabilistic pavement performance prediction models for a developing country. *Journal of Engineering and Applied Sciences*, 4 (1), 13-26.

Amin, M.S.R., 2015. The pavement performance modeling: Deterministic vs. stochastic approaches. *In*: S. Kadry and A. El Hami, ed, *Numerical methods for reliability and safety assessment*, Switzerland: Springer International, 179-196.

Baik, H.-S., Seok, H.J., and Abraham, D. M., 2006. Estimating transition probabilities in Markov Chain-based deterioration models for management of wastewater systems. *Journal of water resources planning and management*, 132 (1), 15–24.

Baus, R.L. and Henderson, A.T., 2008. *Development of Improved Rideability Specifications for Rigid Pavements and Bridge Decks. Report No. FHWA-SC-08-02*. Columbia, SC: University of South Carolina, Department of Civil and Environmental Engineering.

Butt, A.A., Shanin, M.Y., Feighan, K.J., Carpenter, S.H., 1987. Pavement performance prediction model using the Markov process. *Transportation Research Record: Journal of the Transportation Research Board*, 1123, 12-19

Carnahan, J.V., 1988. Analytical framework for optimizing pavement maintenance. *Journal of Transportation Engineering*, 114 (3), 307-322.

Chang, G., Rasmussen, R., Merritt, D., Garber, S., and Karamihas, S., 2010. *Impact of Temperature Curling and Moisture Warping on Jointed Concrete Pavement Performance, TechBrief, Publication No. FHWA-HIF-10-010*, Washington, DC: Federal Highway Administration.

Costello, S.B., Snaith, M.S., Kerali, H.G.R., Tachtsi, L. V., and Ortiz-García, J. J., 2005. Stochastic model for strategic assessment of road maintenance. *Proceedings of the Institution of Civil Engineers-Transport*, 158 (4), 203-211.

El-Assaly, A., Ariaratnam, S.T., and Hempsey, L., 2002. Development of Deterioration Models for the Primary Highway Network in Alberta, Canada. *In: Annual*

Conference of the Canadian Society for Civil Engineering, 5-8 June 2002 Montréal, QB, Canada, 2451-2460.

Feighan, K.J., Shahin, M.Y., Sinha, K.C., and White, T.D., 1988. Application of dynamic programming and other mathematical techniques to pavement management systems. *Transportation Research Record: Journal of the Transportation Research Board*, 1200, 90-98

Flintsch, G.W. and McGhee, K.K., 2009. *Quality Management of Pavement Condition Data Collection. National Cooperative Highway Research Program Report 401*. Washington, DC: Transportation Research Board.

Fwa, T.F., 2006. *The handbook of Highway Engineering*. Boca Raton, FL: CRC Press.

Gulfam-E-Jannat, Yuan, X.X., and Shehata, M., 2016. Development of regression equations for local calibration of rutting and IRI as predicted by the MEPDG models for flexible pavements using Ontario's long-term PMS data. *International Journal of Pavement Engineering*, 17 (2), 166-175.

Golroo, A. and Tighe, S., 2009. Use of soft computing applications to model pervious concrete pavement condition in cold climates. *Journal of Transportation Engineering*, 135 (11), 791-800.

Hillier, F.S. and Lieberman, G.J., 1990. *Introduction to operations research. 5th Ed.*, New York, NY: MacGraw-Hill.

Hong, H.P., and Wang, S.S., 2003. Stochastic modeling of pavement performance. *International Journal of Pavement Engineering*, 4 (4), 235-243.

Huang, Y.H., 1993. Pavement Analysis and Design. Englewood Cliffs, NJ: Prentice-Hall.

Isaacson, D.L. and Madsen, R.W., 1976. *Markov chains: Theory and applications*. New York, NY: Wiley.

Johnson, A.M., Smith, B.C., Hong Johnson, W., and Gibson, L.W., 2010. *Evaluating the Effect of Slab Curling on IRI for South Carolina Concrete Pavements. Report No. FHWA-SC-10-04*. Columbia, SC: South Carolina Department of Transportation.

Kallen, M.J., 2011. On the use of uniformization to estimate transition probabilities in categorical condition data. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 225 (2), 233-239.

Karamihas, S.M., Perera, R.W., Gillespie, T.D., and Kohn, S.D., 1999. *Guidelines for Longitudinal Pavement Profile Measurement. NCHRP Report 434*. Washington, DC: Transportation Research Board.

Karamihas, S.M., Perera, R.W., Gillespie, T.D., and Kohn, S.D., 2001. Diurnal Changes in Profile of Eleven Jointed PCC Pavements. In: *7th International Conference on Concrete Pavements. The use of concrete in developing long-lasting pavement solutions for the 21st century*. 9-13 September 2001. Orlando, FL: International Society for Concrete Pavements, 69-80.

Kerali, H.R., and Snaith, M.S., 1992. *NETCOM: The TRL visual condition model for road Networks. Contractor Report No. 921*., Crowthorne, UK: Transport Research Laboratory.

Khattak, M.J., Nur, M.A., Bhuyan, M.R.U.K., and Gaspard, K., 2014. International roughness index models for HMA overlay treatment of flexible and composite pavements. *International Journal of Pavement Engineering*, 15 (4), 334-344.

Kobayashi, K., Kaito, K., and Lethanh, N., 2012. A Bayesian estimation method to improve deterioration prediction for infrastructure system with Markov chain model. *International Journal of Architecture, Engineering and Construction*, 1 (1), 1-13.

Kulkarni, R.B., 1984. Dynamic decision model for a pavement management system. *Transportation Research Record: Journal of the Transportation Research Board*, 997, 11-18.

Lethanh, N., and Adey, B.T., 2013. Use of exponential hidden Markov models for modelling pavement deterioration. *International Journal of Pavement Engineering*, 14 (7), 645-654.

Li, N., Haas, R., and Xie, W.C., 1997. Development of a new asphalt pavement performance prediction model. *Canadian Journal of Civil Engineering*, 24 (4), 547-559.

Marzouk, M., Awad, E., and El-Said, M., 2012. An integrated tool for optimizing rehabilitation programs of highways pavement. *The Baltic Journal of Road and Bridge Engineering*, 7 (4), 297-304.

Mayet, J. and Madanat, S., 2002. Incorporation of seismic considerations in bridge management systems. *Computer-Aided Civil and Infrastructure Engineering*, 17 (3), 185-193.

Ministerul Dezvoltării Regionale şi Contrucţiilor, 2015. *Proiectarea drumurilor publice. NCM D.02.01:2015.* Chisinau, Moldova: MDRC

Ortiz-García, J.J., Costello, S.B., and Snaith, M.S., 2006. Derivation of transition probability matrices for pavement deterioration modeling. *Journal of Transportation Engineering*, 132 (2), 141-161.

Pantha, B.R., Yatabe, R., and Bhandary, N.P., 2010. GIS-based highway maintenance prioritization model: an integrated approach for highway maintenance in Nepal mountains. *Journal of Transport Geography*, 18 (3), 426–433.

Perera, R.W. and Kohn, S.D., 2002. *Issues in Pavement Smoothness: A summary Report. NCHRP Web Document 42. Contractor's Final Report.* Washington, DC: Transportation Research Board, National Research Council.

PIARC, 1987. Report of the Committee on Surface Characteristics. *In: Proceedings of the XVIII World Road Congress,* 13-19 September 1987. Brussels, Belgium. Paris, France: World Road Association (PIARC).

Roelfstra, G., Hajdin, R., Adey, B., and Brühwiler, E., 2004. Condition evolution in bridge management systems and corrosion-induced deterioration. *Journal of Bridge Engineering*, 9 (3), 268-277.

Sayers, M.W., 1995. On the calculation of IRI from longitudinal road profile. *Transportation Research Record: Journal of the Transportation Research Board,* 1501, 1-12.

Sayers, M.W., Gillespie, T.D., and Paterson, W.D., 1986. *Guidelines for the conduct and calibration of road roughness measurements. World Bank Technical Paper 46*, Washington, DC: The World Bank

Sinha, S.K. and Knight, M.A., 2004. Intelligent system for condition monitoring of underground pipelines. *Computer-Aided Civil and Infrastructure Engineering,* 19 (1), 42-53.

Smith, W.S., 1974. *A flexible pavement maintenance management system.* Thesis (PhD). University of California.

Souliman, M.I., Mamlouk, M.S., El-Basyouny, M.M., and Zapata, C.E., 2010. Calibration of the AASHTO MEPDG for designing flexible pavements in Arizona conditions. *International Journal of Pavements*, 9, 2-13.

Tabatabaee, N. and Ziyadi, M., 2013. Bayesian approach to updating Markov-based models for predicting pavement performance. *Transportation Research Record: Journal of the Transportation Research Board*, 2366, 34-42.

Thomas, O. and Sobanjo, J., 2012. Comparison of Markov chain and semi-Markov models for crack deterioration on flexible pavements. *Journal of Infrastructure Systems*, 19 (2), 186-195.

Wang, K.C., Zaniewski, J., and Way, G., 1994. Probabilistic behavior of pavements. *Journal of transportation Engineering*, 120 (3), 358-375.

Zou, B. and Madanat, S. (2011). Incorporating Delay Effects into Airport Runway Pavement Management Systems. *Journal of Infrastructure Systems*, 18 (3), 183-193.

Table 1. Technical Categories of Public Roads in Moldova. Source: Ministerul Dezvoltării Regionale şi Contrucţiilor 2015.

Technical category	**Average Daily Traffic (in physical vehicles)**	**Recommended road**	**Width (m)**	**Functional destination**
1-a	over 16000	Highways	15 - 30	Roads with highly intense traffic, designed exclusively for auto-vehicles circulation
1-b	8001–16000	Express roads	15 - 30	Roads with intense traffic
2	3501–8000	Two lane roads	7.5	Roads with medium traffic
3	751–3500	Two lane roads	7	Roads with reduced traffic
4	200-750	Two lane roads	6	Roads with very low traffic
5	under 200	Two lane roads	-	Secondary roads

Table 2. Length of Road Network (km) by denomination, technical category and surface type, in 2015. Source: SRA.

Road ownership	Classification	Categories	Asphalt Concrete	Portland Cement Concrete	Surface Treatment	Gravel	Earth	Total
National roads	By denomination	Magistral (km)	550	249	18	3	0	**820**
		Republican (km)	2136	38	99	246	0	**2519**
	By technical category	1 (km)	49	34.9				**83.9**
		1-2 (km)	16.1					**16.1**
		2 (km)	493.3	232.2		3		**728.5**
		2-3 (km)	54.5					**54.5**
		3 (km)	1497.3	2.5	60.2	63.7		**1623.7**
		3-4 (km)	174.6	2.9	33.8	58.2		**269.5**
		4 (km)	394	14.9	23	121.3		**553.2**
		not specified (km)	7.2			2.8		**10**
	Total length (km)		**2686**	**287**	**117**	**249**	**0**	**3339**
	%		80.4	8.6	3.5	7.5	0.0	
Local roads	Length (km)		**2438**	**42**	**343**	**2717**	**494**	**6034**
	%		40.4	0.7	5.7	45.0	8.2	
Total	Length (km)		**5124**	**329**	**460**	**2966**	**494**	**9373**
	%		54.7	3.5	4.9	31.6	5.3	

Table 3. Hypothetical financial plan for 2013-2032 with unconstrained budget. Source: SRA.

Road Class	**Length (km)**	**Rehabilitation (million €uro)**	**Periodic Maintenance (million €uro)**	**Routine Maintenance (million €uro)**	**Total (million €uro)**
Magistral Roads	820	619	314	70	1003
Republican Roads	2519	1973	805	215	2993
Local Roads	6034	1337	616	512	2465
Total	**9373**	**3929**	**1735**	**797**	**6461**

Table 4. Maintenance and rehabilitation budget in 2013-2015 period in Moldova.

Source: SRA.

Year	Maintenance (million €)	Reconstruction (million €)	Total (million €)
2013	55.68	20.97	76.65
2014	62.00	31.76	93.76
2015	47.19	32.32	79.51

Table 5. Established condition states for each technical category, based on IRI values.

Technical category	**Considered condition states**	**IRI value range**	**Average value of roughness in each band**
1	2. Good	IRI ≤ 4	3
	3. Fair	4 < IRI ≤ 6	5
	4. Poor	IRI > 6	7
2	2. Good	IRI ≤ 4	3
	3. Fair	4 < IRI ≤ 6	5
	4. Poor	6 < IRI ≤ 8	7
	5. Very poor	IRI > 8	9
4	3. Fair	IRI ≤ 6	5
	4. Poor	6 < IRI ≤ 8	7
	5. Very poor	IRI >8	9

Table 6. Examples of IRI values and their consideration in the analysis.

	Spring 2013		Autumn 2013			Spring 2014			Autumn 2014			Spring 2015			Autumn 2015		
Example	**IRI value**	**Con S***	**IRI value**	**Con S***	**T?: (Y/N)***	**IRI value**	**Con S***	**T?: (Y/N)***	**IRI value**	**Con S***	**T?: (Y/N)***	**IRI value**	**Con S***	**T?: (Y/N)***	**IRI value**	**Con S***	**T?: (Y/N)***
1	6.72	3	6.97	3	Y	2.63	2	N	2.72	2	Y	2.79	2	Y	2.85	2	Y
2	1.86	2	1.95	2	Y	2.15	2	Y	2.5	2	Y	2.92	2	Y	3.07	2	Y
3	5.53	3	5.22	3	Y	5.45	3	Y	5.66	3	Y	5.89	3	Y	6.09	4	Y
4	4.11	3	3.79	3	Y	4.05	3	Y	4.23	3	Y	4.45	3	Y	4.65	3	Y
5	5.37	3	5.9	3	Y	5.05	M*	N	5.21	-	N	5.31	-	N	4.02	M*	N

* Con S: Considered state. T?: (Y/N): Transition considered?: (Yes/No). M: Maintenance

Table 7. Road employed in the TPM calculation for rigid pavements in Moldova.

Road denomination	Technical category	Road itinerary	Considere d inital PK	Considered final PK	Considered length (km)	Observations
M3	1	Chişinău-Giurgiuleşti-Romanian border	0	31.7	31.700	2014 & 2015 data only
M14	2	Brest--Chişinău-Tiraspol-Odesa (Ukraine)	724.20	910.60	186.400	2014 & 2015 data only
M21	2	Chişinău-Dubăsari-Poltava (Ukraine)	4.95	24.00	19.050	
R25.1	2	R 25 — access to road M1	0.00	11.70	11.700	2014 & 2015 data only
R12	4	Donduşeni-Drochia-Pelinia-M14	47.90	61.90	14.000	
				TOTAL	**231.15**	

Table 8. Total number of transition in technical category 1 and provisional TPM elements.

Section in each CS	Prior CSs	Sections in each CS after one cycle time		
		j = 2	*j = 3*	*j = 4*
490	*i = 2*	464 *0.947*	25 *0.051*	1 *0.002*
224	*i = 3*	0 0	209 *0.933*	15 *0.067*
20	*i = 4*	0 0	0 0	20 *1.000*

Table 9. Total number of transition in technical category 2 and provisional TPM elements.

Section in each CS	Prior CSs	Sections in each CS after one cycle time			
		j = 2	*j = 3*	*j = 4*	*j = 5*
995	*i = 2*	525 *0.528*	433 *0.435*	36 *0.036*	1 *0.001*
1374	*i = 3*	0 0	1102 *0.802*	257 *0.187*	15 *0.011*
134	*i = 4*	0 0	0 0	117 *0.873*	17 *0.127*
15	*i = 5*	0 0	0 0	0 0	15 *1.000*

Table 10. Total number of transition in technical category 4 and provisional TPM elements.

Section in each CS	Prior CSs	Sections in each CS after one cycle time		
		j = 3	*j = 4*	*j = 5*
114	*i = 3*	87 0.763	23 0.202	4 0.035
45	*i = 4*	0 0	33 0.733	12 0.267
12	*i = 5*	0 0	0 0	12 1.000

Table 11. Sections available and sections with No M&R works in each category.

Technical category	Data available from 2013 to 2015			Data available from 2014 to 2015		
	Section considered	**No M&R sections**	**Percentage of No M&R section of the total**	**Section considered**	**No M&R sections**	**Percentage of No M&R section of the total**
1	-	-	-	317	217	68.45
2	191	28	14.66	1982	365	18.42
4	140	3	2.14	-	-	-
Total	331	31	9.37	2299	582	25.32

Table 12. Average IRI of No M&R sections, IRI value obtained from condition vector of No M&R sections and predicted IRI values according to different hypothesis.

Stage	Average IRI of No M&R section	IRI from condition vector	Hypothesis 1: Seas. Var*: -0.40. R work*: -4.00	Hypothesis 2: Seas. Var*: -0.40. R work*: -2.00	Hypothesis 3: Seas. Var*: -0.40. R work*: -3.00	Hypothesis 4: Seas. Var*: -0.40. R work*: -5.00
Spring 2014	3.579	3.525	3.525	3.525	3.525	3.525
Autumn 2014	3.587	3.590	3.640	3.640	3.640	3.641
Spring 2015	3.701	3.682	3.754	3.753	3.754	3.755
Autumn 2015	3.781	3.756	3.865	3.865	3.866	3.867

* Seas. Var: Seasonal variation threshold. R works: Rehabilitation work threshold.

Table 13. Definitive Transition Probability Matrix for technical category 1.

Prior CSs	Sections in each CS after one cycle time		
	j = 2	*j = 3*	*j = 4*
i = 2	*0.949*	*0.051*	*0.000*
i = 3	0	0.933	0.067
i = 4	0	0	*1.000*

Table 14. Definitive Transition Probability Matrix for technical category 2.

Prior CSs	Sections in each CS after one cycle time			
	j = 2	*j = 3*	*j = 4*	*j = 5*
i = 2	*0.528*	*0.436*	*0.036*	*0.000*
i = 3	0	*0.802*	*0.187*	*0.011*
i = 4	0	0	*0.408*	*0.592*
i = 5	0	0	0	*1.000*

Table 15. Definitive Transition Probability Matrix for technical category 4.

Prior CSs	Sections in each CS after one cycle time		
	j = 3	*j = 4*	*j = 5*
i = 3	0.763	0.202	0.035
i = 4	0	0.733	0.267
i = 5	0	0	1.000

Figure 1. Condition state evolution of Moldovan National roads from 1992 to 2015. Source: SRA.

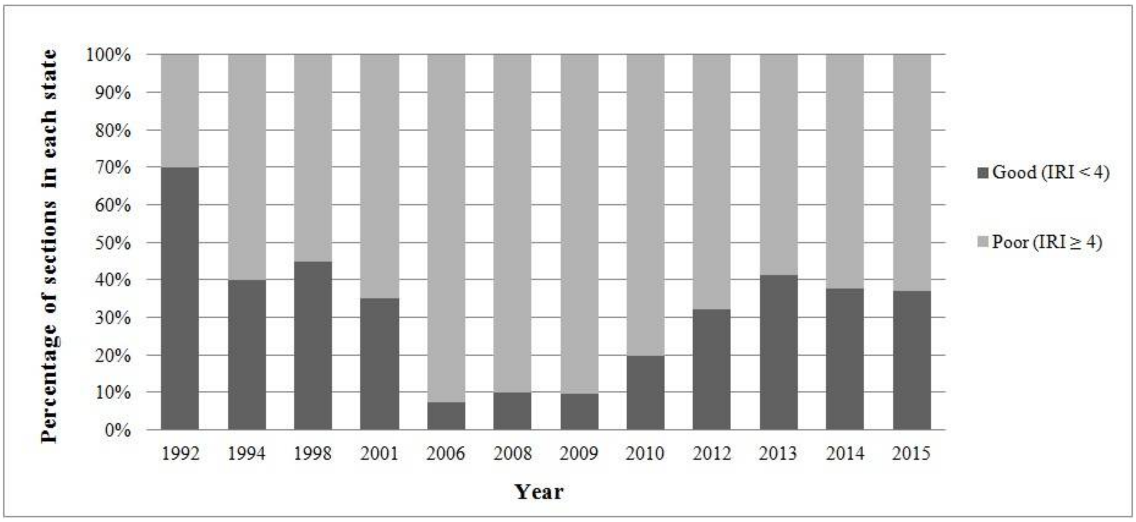

Figure 2. Comparison between ‘Average IRI value of No M&R sections’, ‘No M&R sections’ vector’ and ‘Predicted IRI’ in technical category 1.

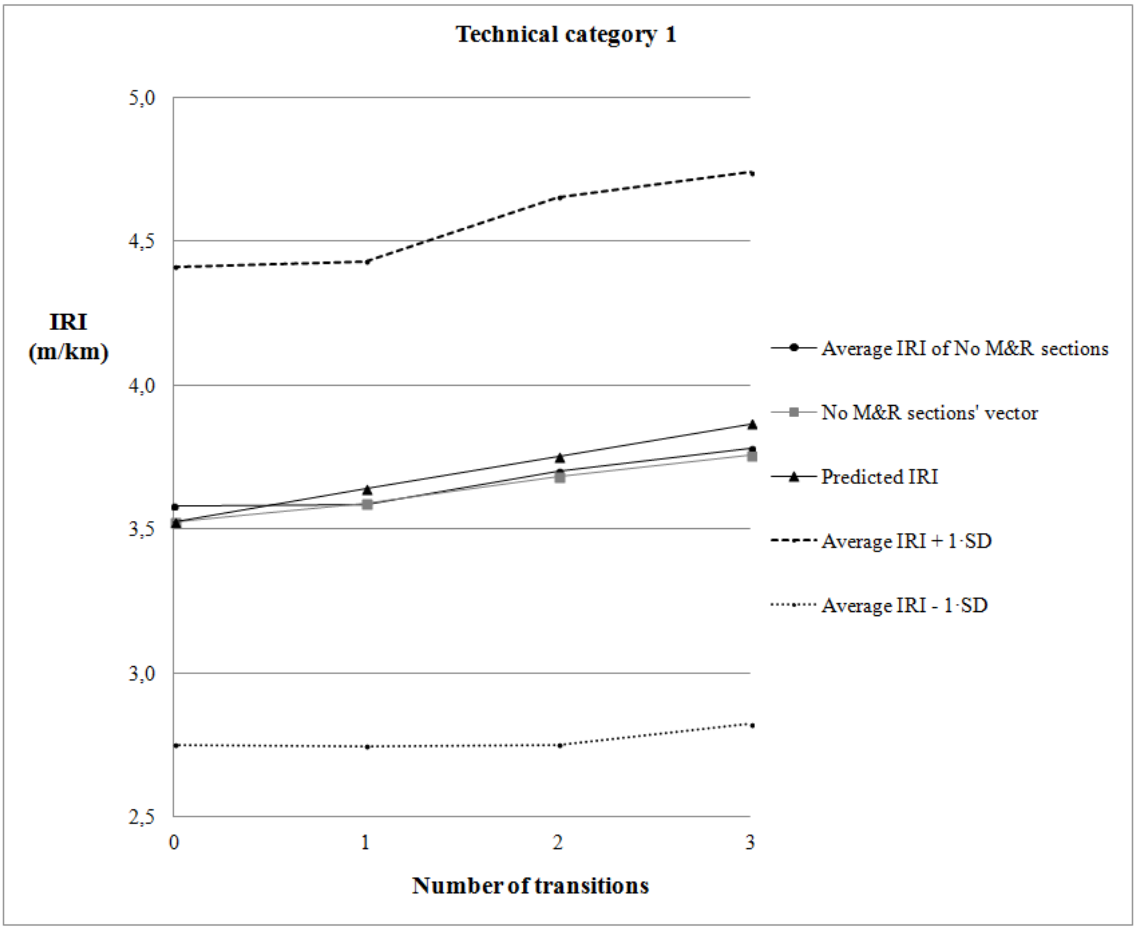

Figure 3. Comparison between ‘Average IRI value of No M&R sections’, ‘No M&R sections’ vector’ and ‘Predicted IRI’ in technical category 2.

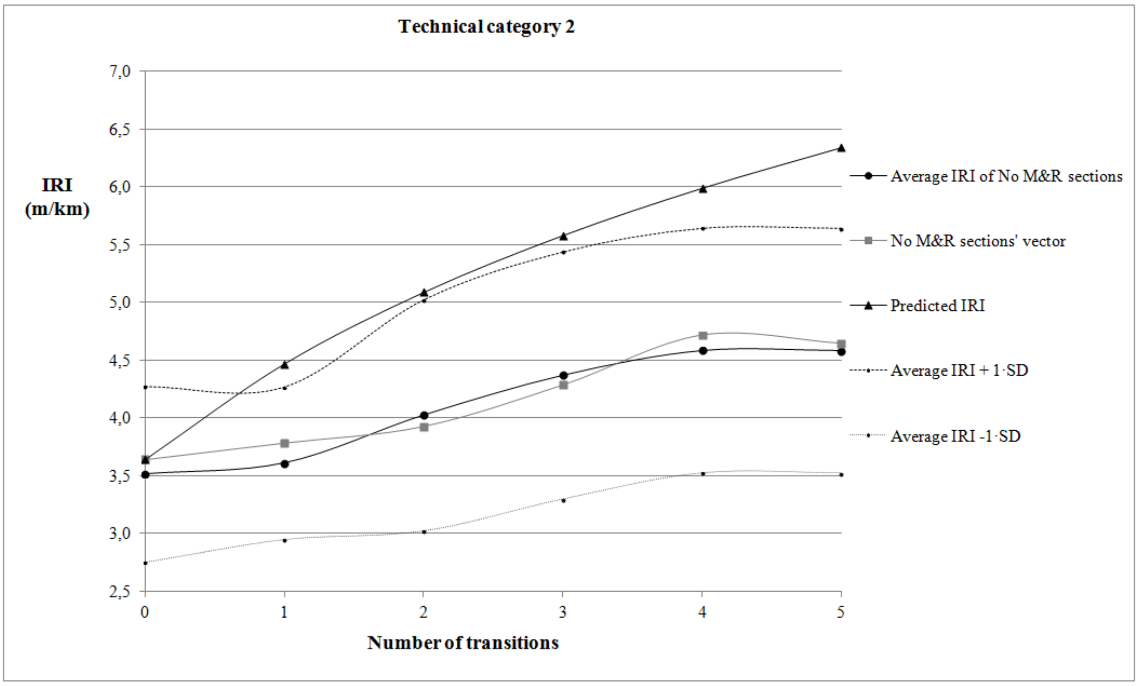

Figure 4. Road state evolution of PPC roads in technical category 2 in Moldova with available data from 2013 to 2015.

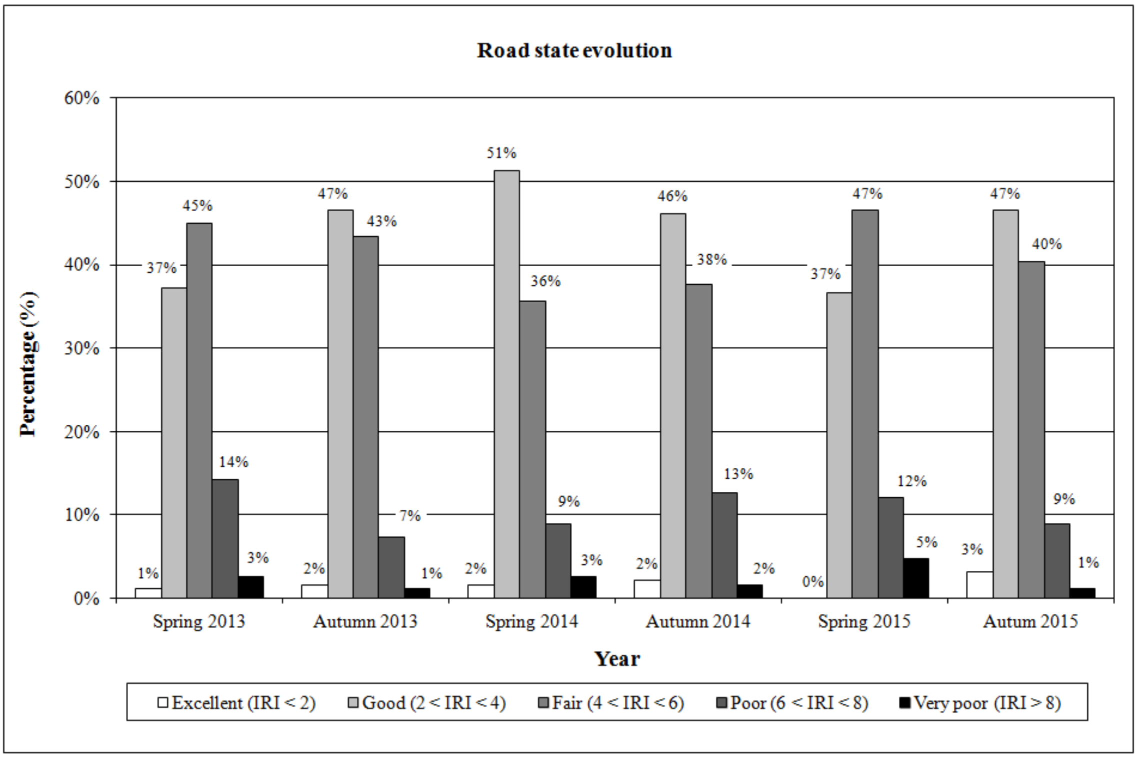

Figure 5. Comparison between ‘Average IRI of No M&R sections’, ‘No M&R sections’ vector’ and ‘Predicted IRI’ according to different rehabilitation thresholds in technical category 2.

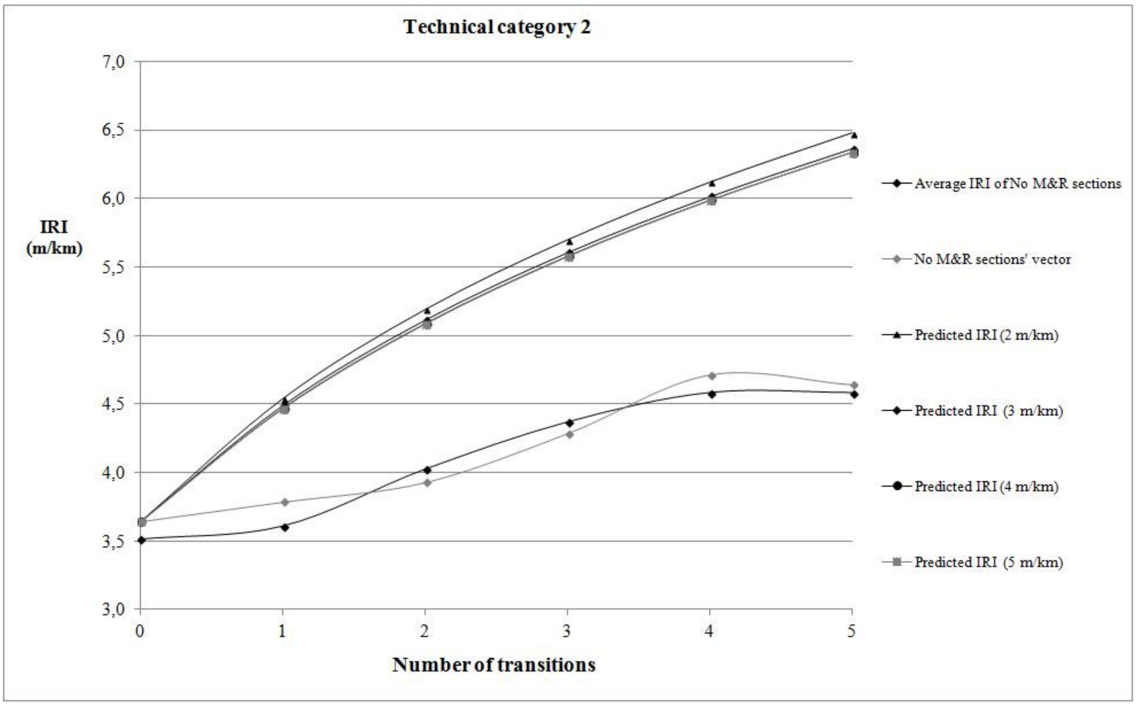

Figure 6. TPMs with a full-year cycle time using only spring data or autumn data and TPMs obtained from TPMs with half-year cycle time applying 2 transitions; for technical categories 1, 2 and 4.

Transition Probability matrix only with data from spring for Tech. Category 1

	$j = 2$	$j = 3$	$j = 4$
$i = 2$	0.835	0.143	0.022
	(76)	*(13)*	*(2)*
$i = 3$	0	0.760	0.240
	0	*(38)*	*(12)*
$i = 4$	0	0	1.000
	0	0	*(5)*

Transition Probability matrix only with data from autumn for Tech. Category 1

	$j = 2$	$j = 3$	$j = 4$
$i = 2$	0.869	0.131	0.000
	(119)	*(18)*	*(0)*
$i = 3$	0	0.889	0.111
	0	*(40)*	*(5)*
$i = 4$	0	0	1.000
	0	0	*(3)*

TPM with 6-months cycle time for a full-year cycle time for Tech. Category 1

	$j = 2$	$j = 3$	$j = 4$
$i = 2$	0.897	0.096	0.070
	(464)	*(25)*	*(1)*
$i = 3$	0	0.870	0.130
	0	*(209)*	*(15)*
$i = 4$	0	0	1.000
	0	0	*(20)*

Transition Probability matrix only with data from spring for Tech. Category 2

	$j = 2$	$j = 3$	$j = 4$	$j = 5$
$i = 2$	0.422	0.527	0.047	0.004
	(197)	*(246)*	*(22)*	*(2)*
$i = 3$	0	0.697	0.278	0.025
	0	*(308)*	*(123)*	*(11)*
$i = 4$	0	0	0.725	0.275
	0	0	*(29)*	*(11)*
$i = 5$	0	0	0	1.000
	0	0	0	*(1)*

Transition Probability matrix only with data from autumn for Tech. Category 2

	$j = 2$	$j = 3$	$j = 4$	$j = 5$
$i = 2$	0.265	0.613	0.107	0.015
	(178)	*(411)*	*(72)*	*(10)*
$i = 3$	0	0.681	0.297	0.022
	0	*(402)*	*(175)*	*(13)*
$i = 4$	0	0	0.921	0.079
	0	0	*(35)*	*(3)*
$i = 5$	0	0	0	1.000
	0	0	0	*(6)*

TPM with 6-months cycle time for a full-year cycle time for Tech. Category 2

	$j = 2$	$j = 3$	$j = 4$	$j = 5$
$i = 2$	0.279	0.579	0.132	0.011
	(525)	*(433)*	*(36)*	*(1)*
$i = 3$	0	0.643	0.313	0.044
	0	*(1102)*	*(257)*	*(15)*
$i = 4$	0	0	0.762	0.238
	0	0	*(117)*	*(17)*
$i = 5$	0	0	0	1.000
	0	0	0	*(15)*

Transition Probability matrix only with data from spring for Tech. Category 4

CSs	$j = 3$	$j = 4$	$j = 5$
$i = 3$	0.650	0.325	0.025
	(26	*(13)*	*(1)*
$i = 4$	0	0.533	0.467
	0	*(8)*	*(7)*
$i = 5$	0	0	1.000
	0	0	*(2)*

Transition Probability matrix only with data from autumn for Tech. Category 4

CSs	$j = 3$	$j = 4$	$j = 5$
$i = 3$	0.753	0.222	0.025
	(61)	*(18)*	*(2)*
$i = 4$	0	0.533	0.467
	0	*(8)*	*(7)*
$i = 5$	0	0	1.000
	0	0	*(2)*

TPM with 6-months cycle time for a full-year cycle time for Tech. Category 4

CSs	$j = 3$	$j = 4$	$j = 5$
$i = 3$	0.582	0.302	0.116
	(87)	*(23)*	*(4)*
$i = 4$	0	0.537	0.403
	0	*(33)*	*(12)*
$i = 5$	0	0	1.000
	0	0	*(12)*

Figure 7. Predicted IRI evolution for each technical category from an ideal state vector with all the section in best condition.