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IMPROVING PAVEMENT ASSET MANAGEMENT IN LIBYA: A MARKOV-BASED APPROACH TO MAINTENANCE PLANNING

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Keywords
Pavement condition, Road in Libya, Markov model, asset management, Pavement Deterioration, Maintenance strategies

ABSTRACT
Pavement condition in Libya is one of the most important issues on the national level. The prediction of the current and future condition of the pavement using a reliable asset management model is of a great importance in order to develop a suitable maintenance strategy that combines both, the least cost maintenance procedures and an acceptable serviceability of the road to ensure the comfort of the driver.

This study introduces a model to estimate the condition of Benghazi – soloq road, as a sample for the roads in Libya, in the future and discusses some of the maintenance strategies that represent the main outcome from this model.

Many conditions cause the pavement to deteriorate through its lifetime. When inspection takes place to investigate the condition of the road and it was found degraded, maintenance should start to restore the road to an acceptable condition using different maintenance techniques.

This paper depends on a Markov model that predicts the deterioration of the pavement with time for a certain asset management policy. The model is practiced on pavement with a certain maintenance policy and it investigates the pavement's efficiency for this policy.

Deterioration, inspection, and maintenance of the pavement will be the three main components of the model that will affect the outcome of this model and then the decision taken after analyzing the results.

Problem statement

Pavements undergo progressive deterioration upon exposure to traffic. This gradual process, droved by traffic and weather conditions, advances through various stages until the pavement reaches its worst condition. The challenge lies in developing a new maintenance strategy that provides a cost-effective solution while ensuring the road's serviceability and comfort for drivers.

Aims and Objectives

- Provide a technical evaluation for the road network in Libya (with the Benghazi-Suluq desert road used as the sample) in terms of the pavement condition index (PCI).
- Determine the general condition of the road network (Benghazi-Suluq desert road) in order to build a deterioration and maintenance model that takes into consideration the inspection period and the change of the pavement condition, on a scale from an excellent state to a failed state.
- Determine the reasons for road deterioration in Libya and classify them according to their severity.
- Develop a model for the deterioration and maintenance of pavement using a Markov model, which gives the probability that the pavement will be in a particular state at some future time and at what state maintenance procedures would be most cost-effective.
- Provide recommendations for maintenance based on the outcomes from the models.

Data Collection and Analysis

An extensive data collection effort has been initiated, although some difficulties have been encountered due to limited data availability on the studied road (Benghazi-Suluq desert road). To address this, data from another similar road, with the same conditions and located near the investigated road, has been collected and reflected in our study.

The analysis involves examining the provided data on roads in Libya to determine their condition. From these data, a relationship between the condition of the pavement and its age, starting from the road's operating day to its current state, is established.

Pavement Deterioration and Defects

Pavement deterioration begins immediately after construction due to continuous use and the passage of time. Recognizing the types and causes of deterioration is crucial for selecting the most appropriate and effective maintenance procedures (Atkinson, 1997).

Okigbo (2013) describes these deteriorations or defects as conditions in the pavement that negatively impact its appearance, serviceability, or structural integrity. These defects can affect both humans and vehicles and include issues such as uneven road lanes, inappropriate road shoulders, uneven pavement, traffic light malfunctions, and incorrectly marked road signs (Okigbo, 2013).

These general pavement problems are also prevalent on Libyan roads and highways.

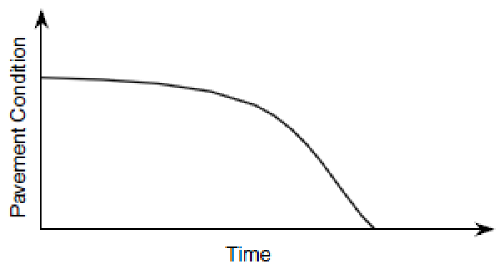
Types of Pavement Deterioration

Brockenbrough (2009) categorizes pavement deterioration into three types:

1. **Structural Deterioration:** This type is caused by continuous traffic loading, which reduces the pavement's ability to bear stresses and shortens its lifespan.
2. **Functional Deterioration:** This type can accelerate structural deterioration, but primarily affects the quality of the ride and road friction.
3. **Environmental Deterioration:** This deterioration results from aging and weathering, influenced by the pavement materials, and later stages may resemble structural or functional deterioration.

Fwa (2006) explains that road pavement deteriorates over time due to various factors such as design deficiencies, environmental conditions, traffic loading, and material aging.

Figure 1 shows a typical relationship between pavement condition and time (Fwa, 2006).



Atkinson (1997) identifies the most common types of deterioration as aging and weathering, potholes, rutting, pushing, deformation, fretting, cracking, polishing, plucking, and embedment.

Pavement Maintenance: Maintenance involves keeping structural components safe and serviceable (Atkinson, 1997). Fwa (2006) defines highway maintenance as actions to keep highway elements safe and usable. Pavement maintenance aims to repair faults and prevent future damage (Lavin, 2003). Lavin identifies two main maintenance categories: preventive and structural maintenance.

Preventive Maintenance: Preventive maintenance, as defined by AASHTO (Fwa, 2006), involves cost-effective treatments to preserve and improve a roadway system without significantly increasing structural capacity. It aims to reduce defects, extend pavement life, keep roads safe, and maintain good condition. NCHRP (2004) lists treatments such as crack sealing, fog seals, slurry seals, scrub seals, microsurfacing, chip seals, thin overlays, and ultrathin friction courses.

<u>Crack Sealing or Filling</u>: Low-cost treatments to delay deterioration, applicable for cracks 3-25 mm wide (Lavin, 2003). Crack sealing involves placing sealing material in working cracks, while crack filling addresses non-working cracks to prevent water infiltration.

Fog Seals: Diluted asphalt emulsion applied without cover aggregate to renew wearing surfaces, close cracks, and stop raveling (Johnson & Snopl, 2000). Best used in warm weather to allow curing.

Chip Seals: Adds a new surface layer, stops raveling, delays oxidation, and reduces water infiltration, increases friction, and seals cracks (Brockenbrough, 2009). Involves spraying bitumen or emulsion followed by a coarse aggregate layer.

Slurry Seals: Mix of fine aggregate and bitumen emulsion with cement, closing hairline cracks, increasing friction, delaying raveling, and reducing oxidation (Johnson & Snopl, 2000; Lavin, 2003).

Microsurfacing: Polymer-modified bitumen emulsion mix with crushed aggregate and mineral filler to prevent raveling, improve skid resistance, and fill small ruts (NCHRP, 2004). Adds stability and stiffness, suitable for thicker applications (Lavin, 2003).

Structural Maintenance Structural maintenance includes activities to repair or improve pavement integrity (Lavin, 2003), such as pothole filling, patching, reconstruction, and overlays. Patching, defined by Atkinson (1997), restores pavement stability and ride quality. Pothole filling provides temporary hazard repair. Overlays involve hot-mix asphalt mixtures to improve friction and skid resistance (Johnson & Snopl, 2000; NCHRP, 2004).
Selecting the right, cost-effective maintenance procedures is crucial for the current condition of roads and highways in Libya, particularly as it is a developing country.

Pavement Management systems

Pavement management systems (PMS) are crucial tools for highway engineers in decision-making processes (Ferreira et al., 2002). Widely used globally since the 1980s, these systems help highway administrations develop maintenance and rehabilitation (M&R) policies for road pavements under their jurisdiction (Ferreira et al., 2002). According to Ferreira et al. (2002), PMS are based on two key components: models for predicting pavement conditions and processes for determining M&R policies. These prediction models can be either probabilistic or deterministic. Deterministic models use regression formulas to show changes in pavement condition over time, while probabilistic models employ Markov chains for the same purpose.

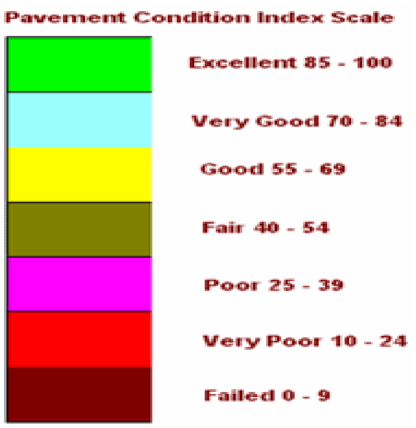


Figure 1 - Pavement Condition Index (PCI) scale (Gulf Engineering House, 2010)

Pavement Deterioration Prediction Using Markov Chains

Butt et al. (1987) developed a model using Markov chains to predict pavement deterioration over time. They divided the pavement's lifespan into six-year segments, creating a transition matrix for each period. Having detailed information about the pavement's condition, including the Pavement Condition Index (PCI), is crucial for predicting future conditions using these matrices. Suman & Sinha (2012) highlight that Markov transition probability matrices effectively represent the changes in pavement condition over its lifespan. These matrices are based on states and transitions (see Figure 3).

Figure 3 - Transition probability matrix (TPM) (Elhadidy, Elbeltagi, & Ammar, 2015)

$$
\text{TPM} = \begin{array}{c} \text{State} \\ 1 \\ 2 \\ . \\ n \end{array}
\begin{array}{c} \begin{array}{cccc} 1 & 2 & . & n \end{array} \\
\begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,n} \\ . & . & p_{i,j} & . \\ p_{n,1} & p_{n,2} & . & p_{n,n} \end{pmatrix} \end{array}
$$

In the transition probability matrix (TPM), the pavement's condition transitions from state 1 (new condition) to state n (failed condition) (Elhadidy et al., 2015).

Butt et al. (1987) note several advantages of the Markov probability decision process:

1. Future actions are determined based on pavement performance, without being overly specific.
2. Current and future maintenance needs can be identified probabilistically.
3. It allows for cost-effective solutions by selecting less conservative maintenance actions that still meet performance standards.

Fundamental experiments

In order to reach a pavement deterioration model and a rational and effective pavement maintenance and rehabilitation model, an assessment for the pavement surface operational condition was carried out previously by in Libya through researches for Engineering Studies. Detailed visual inspection of the existing pavement condition was carried out along the total length of the Benghazi-Suluq road and all the distresses and deficiencies were recorded, then the pavement condition index (PCI) for the mentioned road was determined.

A deep analysis for the conducted data was carried out trying to establish a prediction model for both, deterioration and maintenance using Marcov chain.

Pavement Condition Index (PCI)

Reliable and repeatable procedures are essential for assessing pavement condition, a crucial component of any pavement management system. These procedures should be accessible and straightforward to use in any setting. The Pavement Condition Index (PCI) procedure is one of the most commonly used techniques globally (ACES, 2009).

The PCI serves as a valuable visual survey tool, providing decisions similar to those of experienced highway engineers and is easily repeatable. It offers a reliable method for rating the structural condition of pavement sections and selecting suitable maintenance techniques (Federal Construction

Council, 1985).

A comprehensive field survey was conducted to evaluate the surface conditions of a major desert road. The PCI categorizes pavement conditions into seven ratings, from "Excellent" to "Failed," aiding in the development of maintenance strategies.
The inspection process involves visually assessing existing distresses, identifying their severities and quantities as outlined in the PCI distress guide. Tools used include odometers for measuring distress lengths and areas, straight edges, rulers for measuring rut and depression depths, and the PCI distress guide (ACES, 2009).

Table 1 - Pavement maintenance assignment procedures (ACES, 2009)

PCI condition category	Pavement maintenance procedure
Excellent	Do nothing
Very Good	Single chip seal
Good	Thin overlay
Fair	Thin overlay with fabric
Poor	Thick overlay
Very Poor	Reconstruction
Failed	Reconstruction

After completing the PCI survey, the results are used to calculate the PCI. This calculation considers the impact of each distress on the pavement's condition. Deduct values for each type of distress and severity level are determined using specific deduct value curves for issues such as alligator cracking, lane/shoulder drop-off, longitudinal and transverse cracking, rutting, and potholes.

Experimental procedure

Modeling approach

A successful pavement management system requires a deterioration model to predict the future condition of the pavement and a maintenance model to restore it to an acceptable state. This system also includes planning for inspection and maintenance to monitor and mitigate deterioration effects. In this study, models are developed using the Markov probabilistic approach, representing discrete states and predicting transitions between states over time. Prescott & Andrews (2013) proposed a Markov model for predicting railway track performance and condition changes over time, considering asset management plans and maintenance strategies. This model will serve as a guide for modeling pavement deterioration and maintenance in this research, adapted from railway tracks to pavements.

Pavement Deterioration and Inspection

The general condition of the pavement over several years, from 1997 to 2013, is illustrated in Table 1, which shows the relationship between the PCI and the service years, along with maintenance actions performed during this period.

This relationship can be more clearly understood by plotting PCI values against the pavement's age, as shown in Figure 4.

Figure 4 - A plot of the relation between PCI values and the age of the desert road

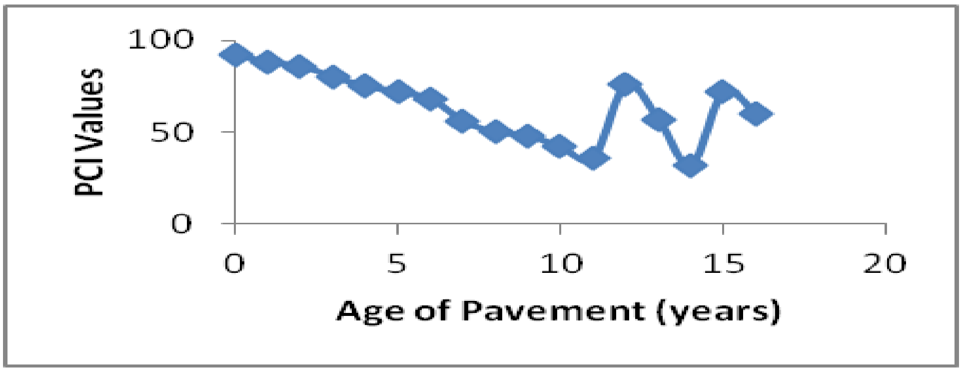


Figure 4 indicates that pavement can either maintain its current condition or degrade to a worse state. This suggests that maintenance was absent until the pavement reached 11 years, at which point maintenance was conducted to restore it to a very good condition.

Figure 5 presents a segment of the Markov model for pavement deterioration and inspection during one duty cycle.

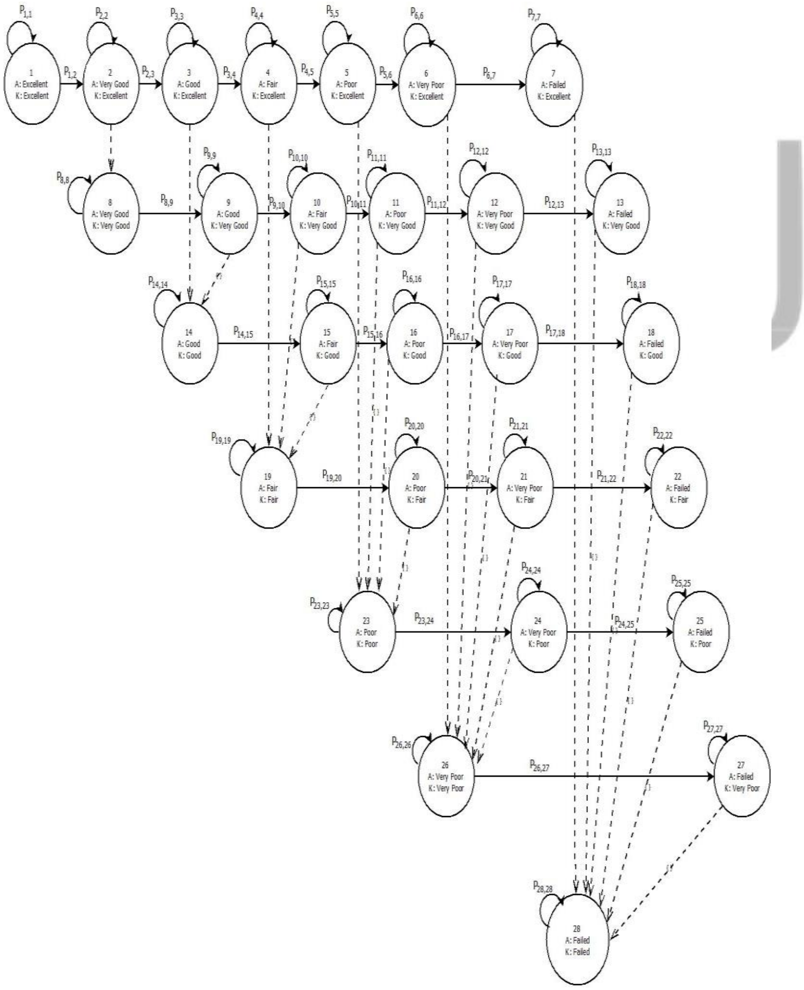


Figure 5 - State transition diagram for a Markov model of the deterioration and inspection during one cycle of the pavement service life

The state transition diagram includes twenty-eight states representing the pavement's condition throughout its life. These conditions are categorized as actual (A) and known (K) conditions. Both conditions are the same when the pavement is in excellent condition (state 1) or when an inspection occurs (dashed lines in Figure 5). This shows that the pavement has degraded since the last inspection (states 8, 14, 19, 23, 26, and 28). For instance, state 5 indicates an actual poor condition (A: Poor) requiring maintenance, though the last inspection rated it as excellent (K: Excellent).
Figure 5 also illustrates probabilistic deterioration transitions between states with a probability of Pi,j representing the likelihood of the pavement transitioning from state i to j within a duty cycle.
The data in Table 2 will be utilized to determine the probabilities for the pavement either staying in or further deteriorating beyond the "Poor" state. Since no data is available for the condition beyond "Poor," maintenance is initiated once this state is reached.

Maintenance actions and their durations for a 7-kilometer road segment, aimed at restoring the pavement to the "Very Good" state.
Table 2 - Duration of each maintenance action for a 7 km road

PCI condition category	Pavement maintenance procedure	Duration of the maintenance (days)
Excellent	Do nothing	-
Very Good	Single chip seal	-
Good	Thin overlay	15
Fair	Thin overlay with fabric	15
Poor	Thick overlay	20
Very Poor	Reconstruction	60
Failed	Reconstruction	60

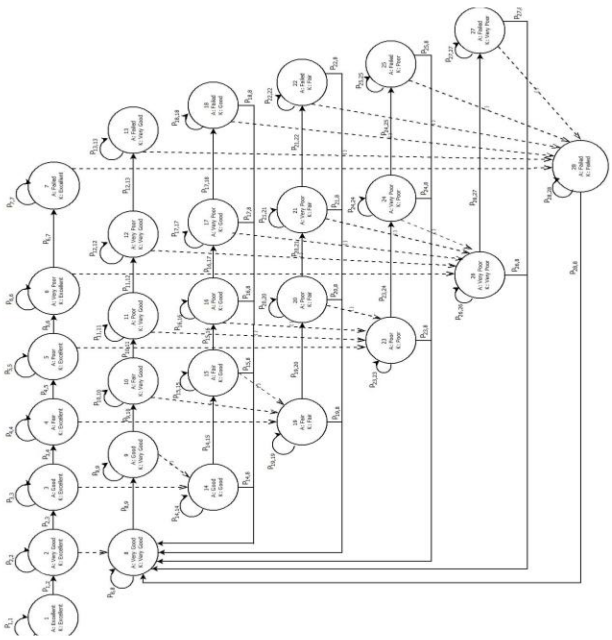


Figure 6 – Deterioration, inspection and maintenance transitions diagram for a Markov model during one cycle of the pavement service life

Probability Formulae

A transition probability matrix (TPM) of order (28 x 28) can be derived from the deterioration, inspection, and maintenance transitions diagram, representing all transition probabilities.

$$\text{TPM} = \begin{bmatrix} P_{1,1} & \cdots & P_{1,28} \\ \vdots & \ddots & \vdots \\ P_{28,1} & \cdots & P_{28,28} \end{bmatrix}$$

In the TPM, pavement conditions change from state 1 to state 28 (Deterioration) and from state 28 to state 1 (Maintenance) with a probability $P_{i,j}$.

The transition probabilities are calculated using the Expected Value principle P=1/E. This expression is derived from the expected value of a geometric random variable.

The initial pavement condition is represented by an initial vector matrix (IP).

$$\text{IP} = (A_1\ A_2 \cdots A_{28})$$

The state vector for any duty cycle t is calculated by multiplying the initial state vector IP by the TPM raised to the power t:

$$P^*(t) = \text{IP}.\ (\text{TPM})^t$$

This method allows predicting the pavement state at any future time. The final matrices are solved using MATLAB

Results and discussion

Based on the analysis of historical data and using the expected value formula (P=1/EP = 1/E), transition probabilities (per day) between each state for both deterioration and maintenance were calculated. Additionally, the probabilities for the pavement to remain in a certain condition without changes were determined. Unlike the usual practice of conducting maintenance only when the pavement reaches the "Poor" state, maintenance was considered at all stages. Furthermore, the maintenance procedures were assumed to restore the pavement to the "Very Good" state rather than the "Excellent" state.

Each TPM must meet the following requirements:

- The sum of probabilities in each row must equal one.
- No negative values are permitted in the matrix.
- Notably, the matrix reveals two key points:
- Pavement cannot improve to a better state without remedial actions.
- $P_{28,28}$ shows that once the pavement reaches its worst condition, further degradation is not possible.

The initial vector matrix (IP) represents the starting condition of the pavement. Initially, the pavement is in the "Excellent" state following rehabilitation, so the IP matrix is:

$$IP = (1\ 0\ \ 0\ \cdots\ \ 0)$$

This indicates a 100% probability of being in the "Excellent" state at time 0. With the transition probability matrix (TPM) established, the future condition of the road can be predicted by multiplying the IP vector by the TPM raised to the power of the future time period.
For example, the pavement condition after 10,950 days (30 years) is calculated as:

$$P * (10{,}950) = IP \cdot (TPM)^{10{,}950}$$

This vector represents the pavement condition after 30 years, without considering inspection times. During inspections, the known state is dominant until the inspection is completed, revealing the actual state. With annual inspections (every 365 days), the vector matrix after 365 days is:

$$P ** (365) = IP \cdot (TPM)^{365}$$

$$P^{**}(365) = (0.7124\ 0\ 0\ \cdots\ 0.0037\ 0\ \cdots 7.37\times10^{-50}\ \cdots\ 3.62\times10^{-9})$$

This matrix shows a 71.24% probability of the pavement remaining in the "Excellent" state, 28.31% in the "Very Good" state, and less than 1% in any other state after the first inspection. This percentage shows that pavement spends a minimal amount of time (less than one day) in undesirable conditions such as the "Poor," "Very Poor," and "Failed" states. These percentages indicate a manageable situation, as the conditions are well-documented and revealed. The majority of the pavement's lifespan is in the "Very Good" or "Good" states. This is predictable because, once the pavement's condition is identified during inspections; maintenance begins promptly, resulting in a relatively short duration for the pavement to remain in its known condition.
This efficient maintenance approach ensures that the pavement stays in acceptable conditions for most of its lifespan, enhancing overall serviceability and comfort for users. Considering the cost of maintenance, approximate maintenance costs based on data from Meneses & Ferreira (2014) and Ferreira et al. (2002):
Table 3 - Some approximate prices of the used maintenance techniques in Libya

PCI Condition Category	Pavement Maintenance Procedure	Cost (LYD/m²)
Excellent	Do nothing	0
Very Good	Single chip seal	1.1
Good	Thin overlay	4.9
Fair	Thin overlay with fabric	11.2
Poor	Thick overlay	13.76
Very Poor	Reconstruction	15.6

Using this data, the analysis revealed significant differences in cost and performance among the evaluated maintenance strategies:

- **Baseline Strategy (Maintaining to "Very Good" after any deterioration):** This proactive approach resulted in the highest proportion of time (99.8%) spent in desirable conditions (Excellent, Very Good, or Good). However, it incurred the highest cost at an assumed LYD 3.16 million for the modeled 7km, 7.5m wide road.
- **Current Practice maintaining from "Poor" to "Very Good":** This reactive strategy, currently employed by authorities, proved to be the second cheapest at an assumed LYD 2.89 million. However, it resulted in a slightly lower proportion of time (99.2%) spent in desirable conditions compared to the baseline.
- **Alternative Strategies maintaining from "Poor" to "Good":** This strategy emerged as the most cost-effective, costing an assumed LYD 2.835 million while maintaining a high proportion (99.4%) of time spent in desirable conditions.
- **Maintaining from "Fair" to "Very Good":** Despite the higher intervention frequency, this strategy proved to be the most expensive at an assumed LYD 3.528 million and surprisingly resulted in a lower proportion (97.7%) of time spent in desirable conditions compared to the other strategies. A summary of the results is presented in Table 1.

Table 4- Comparison of Maintenance Strategies (Assumed Costs in LYD)

Strategy	Cost (Assumed LYD)	Avg. Days in Convenient Conditions	Probability of Staying in Convenient Conditions (%)
Maintaining to "Very Good"	3.1605M	10,928.40	99.8
Maintaining from "Poor" to "Very Good" (Current Practice)	2.8896M	10,866.30	99.2
Maintaining from "Poor" to "Good"	2.835M	10,882.50	99.4
Maintaining from "Fair" to "Very Good"	3.528M	10,696.50	97.7

The results demonstrate the significant impact of maintenance strategy on both cost (in assumed LYD) and pavement serviceability. While the current practice (maintaining from "Poor" to "Very Good") is less expensive than the proactive baseline strategy, it results in more time spent in less desirable conditions. This highlights a trade-off between cost savings and user experience.

The most notable finding is the cost-effectiveness of maintaining from "Poor" to "Good." This strategy offers a compelling balance, achieving near-optimal serviceability (99.4% in desirable conditions) at the lowest assumed cost (LYD 2.835 million). This suggests that restoring the pavement to a "Good" state is sufficient for maximizing long-term performance without incurring the higher costs associated with restoring to "Very Good" after every instance of deterioration.

The counterintuitive result of the "Maintaining from Fair to Very Good" strategy, which is the most expensive and yet results in the lowest proportion of time spent in desirable conditions, warrants further discussion. This outcome likely arises from the increased frequency of interventions. While each intervention restores the pavement to a high condition state, the cumulative time spent undergoing maintenance reduces the overall time spent in convenient conditions. This emphasizes that simply increasing intervention frequency does not necessarily translate to improved long-term performance and can lead to unnecessary expenditures.

The analysis of average probabilities under the current practice revealed that the pavement spends a considerable portion of its lifespan in "Very Good" (37.2%) and "Fair" (37.2%) conditions. This further underscores the need for a more optimized maintenance approach to minimize time spent in less desirable states. The average probabilities and days spent in each condition are shown in Table 2.

Table 5- Average Probabilities and Days in Each Condition

Condition	Probability (%)	Avg. Days in Condition (Lifetime)
Excellent	0.00393	0.43
Very Good	37.21	4074.65
Good	24.81	2716.7
Fair	37.21	4074.5
Poor	0.68	74.5
Very Poor	0.03504	3.8
Failed	0.0029	0.32

Conclusion

- A Markov model for one of the Libyan roads road with a sample of 7 km length) was introduced and implemented to come up with number of maintenance strategies, and a thorough investigation was carried out for each strategy. The pavement's condition was introduced by the PCI measurement through 17 years period and an inspection for pavement was carried out. Also some maintenance techniques were introduced to be used in repairing this road.

- Assumed field data were used to obtain the transition probability matrix that gives the transitions between each state.

- The introduced model has helped in achieving the main objectives behind constructing it, which are:
    1. Knowing the time that the pavement spends in each condition and whether pavement is known to be in these conditions or not.
    2. Perform different maintenance strategies on the pavement and trying to choose the one that combines both, the least cost and the comfort for the drivers and passengers.

- The model was coded and executed by Matlab.

- The model is qualified to treat so many problems with acceptable computing potentials.

- The main problem facing the roads in Libya is the incompatibility between the planned maintenance procedures and the applied ones in reality which comes from the unqualified contractors' work and the absence of control over them.

- The suggested model is appropriate to be applied to several roads in Libya since they have the same conditions and they are run by the same system.

- The project could be extended to include factors that have a relatively considerable effect on the condition of the road and make the deterioration prediction more detailed and accurate. These factors include: the soil condition and its stiffness for the sub grade of the road, the effect of the annual average daily traffic, the drainage effect, etc.

- The main disadvantage of this model is that it has a kind of illogical assumptions of discrete transition periods of times and it uses the current condition of the pavement to give decisions about the future condition.

- The size of the model was relatively large which made the analysis process kind of difficult.

The main challenge faced this study was in the data collection phase where there was not sufficient archived data in the ministry of public works and housing or in any other organization in Libya which made this project depends on some assumptions especially for the maintenance techniques prices

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