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Highway Asset Management Framework for Longevity of Infrastructure – A Case Study for China-Pakistan Economic Corridor

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Abstract: Pavement management system (PMS) affords objective information and useful data analysis to make consistent, cost-effective, and defensible decisions related to the pavement preservation at network and project level. Pavement functional and structural evaluations using performance indicators such as international roughness index (IRI), surface distress, rutting, deflection data etc. are the key element of PMS. A departure from exiting stand-alone evaluation practices, this research presents project-level functional and structural evaluation and its integration into a PMS framework for more accurate and realistic forecasting of the pavement needs over the analysis period. A case study of an in-service pavement is presented to demonstrate the applicability of proposed framework. Owing to the non-availability of time-series performance data at present, pavement serviceability and structural capacity data before and after of an in-service pavement rehabilitation was explored for overlay treatments (conventional and crumb rubber- modified (CRM) asphalt mixtures) effectiveness analyses. Results of functional evaluation quantified the extent to which CRM improves the functional performance of the pavement, in terms of the drop in IRI. CRM asphalt mixture exhibited relatively superior functional performance in contrast to conventional asphaltic wearing course by a margin of 8% higher drop in IRI, on average. Non-destructive testing technique for pavement structural evaluation using falling weight deflectometer (FWD) data was employed to assess structural capacity of pavements. A computer-aided program was developed for estimation of structure number effective (SNeff) to be used as an input for overlay design using AASHTO empirical method. Moreover, mechanistic-empirical (M-E) design method was employed using evaluation of layer moduli and overlay design (ELMOD) program for overlay thickness design and pavement remaining service life (RSL). Comparison of pre- and post-rehabilitation deflection data endorsed roadbed soil stiffness and structural adequacy. RSL estimated through traffic data (truck load repetitions) validated the results obtained using empirical and M-E methods. Application of KENPAVE program for evaluation of pavement overlay thickness design was also demonstrated by conducting damage analysis. Integrating structural evaluation with functional evaluation into an overall framework of PMS is envisaged to provide systematic and objective procedures for monitoring and evaluating pavement performance, selecting optimal type of treatment and its thickness design.

Keywords: Pavement Management System, Pavement Structural Evaluation, Remaining Service Life, Maintenance and Rehabilitation Strategies, Short Term Effectiveness Analysis

1. Introduction

Highway asset management (HAM) covers all important facets by integrating financing, planning, engineering, personnel, and information management in the decision-making process. One of the most essential component of

HAM is pavement management system (PMS) which helps the roads managers/ designers to maintain the pavements network in serviceable and efficient condition in most cost-effective manner. Hudson et al. [1] and Finn et al. [2] first introduced the concept of PMS and to determine the direction and specificity of project development and planning, it is exercised at network and project level [3]. Network level PMS is focused to determine and allocate funds for maintaining pavement above specified threshold to keep the pavement in operational condition. Condition forecasting, budget allocation, scheduling inspection and planning work are included at network level using prediction model. At network level most, important prediction model is conducted using "what if analysis", to understand the various budget constraints for maintaining pavement condition [4]. Project level PMS focuses on a specific facility which need to be repaired, its method and timing for repair. Prediction models at this level are developed for selecting specific alternatives for expected climatic and traffic conditions [5]. An important component of most efficient PMS is its capability to predict its remaining service life (RSL) through pavement evaluation. Pavement evaluation is a generic term to determine the pavement ability to serve the users for designed life [4]. There are two types of pavement evaluation i.e. pavement functional evaluation and structural evaluation. Pavement functional evaluation is carried out to check its ride quality through performance indicators e.g. roughness or ride quality, surface distress, rutting, skid resistance. While pavement structural evaluation (PSE) is carried out to check its structural capacity for the traffic loading for designed life and performance indicators are deflection data, layer elastic modulus, subgrade CBR or resilient modulus [6]. In past researches most PMSs focused on pavements functional evaluations, albeit functional evaluation can never be a substitute to structural evaluation, rather both accompaniment each other [7]. Like pavement roughness data, deflection data has also become a vital tool to evaluate the structural integrity and capacity of newly constructed or rehabilitated pavements. Pavement structural capacity reflects its load carrying capacity and normally conducted at the project level to assess whether work is needed to increase pavement strength to accommodate projected traffic loads [6]. One of the simple and reliable method to check the structural capacity of pavement is non-destructive deflection testing (NDT) being advantageous over destructive testing that it cause little or no disruption to the traffic and its less time consuming and results are comparatively more accurate. Using NDT devices such as falling weight deflectometer (FWD) the structural adequacy of pavement is estimated by analysing deflection basin [8]. In FWD total of eight deflection sensors from D_0 to D_7 measured the pavement surface deflections. The first deflection sensor D_0 is located at the centre of the loading plate, while the rest seven sensors were located at varying distances up to 6 feet from the load centre. To analyse the deflection data centre-deflections are normalized and used to evaluate the pavement structure and design for overlay thickness [9]. Using FWD data pavement structural adequacy is determined through back-calculation process. Back-calculation approach is commonly used for pavement evaluation by calculating the layer moduli for complete pavement and for individual layers and making most optimal pavement rehabilitation strategies [10]. Although back-calculation is the most popular method for finding the pavement structural health, still method has four limitations observed over a period. First limitation is that it produces several sets of layer moduli and it's not unique to comply with the deflection basin resulting in errors within the acceptable range [11]. Second limitation is non-accuracy of layers moduli prediction which disturb the assumption of extending the pavement layers to infinity due to transverse & longitudinal cracking due to pavement edges [12]. If pavement layer thickness is less than 75mm, it is difficult to back-calculate the pavement layers moduli, due to the geometry of the loading and measuring system [13]. Fourth limitation is AC layer temperature at the time of testing, as layer stiffness is related to temperature variation. After back-calculation of layer moduli, next important step is to predict RSL of in-service pavements. The RSL is the expected life of existing pavement in number of years during that pavement can carry the estimated traffic in condition above the threshold values both structurally and functionally [14].

In Pakistan, National Highways Authorities (NHA) has established Road Asset Management Division (RAMD) to maintain the road network in most efficacious manner and a regulatory body known as Road Assets Management System (RAMS) Directorate part of RAMD is carrying out such activities which are needed to achieve these objectives [15]. RAMS is using Highway Development and Management tool-4 (HDM-4) provided by World Bank as management tool to maintain its road networks. HDM-4 is computerized database which includes pavement geometric data, condition & traffic data and to some extent structural data of pavement. Database collects the pavement inventory data, pavement friction & condition data and location of pavement distresses, maintenance history of pavement, ride quality data and maintenance cost and traffic data. Compiling all this data an annual maintenance plan is prepared at national level. Annual maintenance plan includes routine maintenance plan, periodic maintenance plan and rehabilitation plan and then distributed to all the regional levels to implement on project level [16].

Although RAMS partially fulfil the requirement of PMS in Pakistan but in backdrop of China-Pakistan economic corridor (CPEC) there is no effective mechanism to monitor the highway network effectively. Although collection of pavement structural data is time and resource consuming and most agencies lack in this aspect. Resultantly most network level decisions for planning rehabilitation strategies are taken on based on pavement functional data which sometimes leads to inaccurate assessment, being muddled pavement structural health evaluation. This research discusses how to incorporate functional and structural evaluation at network level into overall PMS and the steps needed to make this information as part of the decision-making process for pavement maintenance, rehabilitation, or replacement. Regular monitoring of structural capacity of pavement is needed to improve the overall effectiveness of concessionaire decisions about M&R, and to ensure optimal utilization of all available financial resources. It is envisaged that integrating structural evaluation with functional evaluation into overall framework of PMS would provide objective and systematic procedures to maintain the inventory of pavement infrastructure, pavement performance monitoring, selection of optimal type of treatment and thickness design, and its application time.

Highways are most valuable assets of the governments, even marginal savings due to improved practices contribute towards substantial revenues. In backdrop of CPEC huge highways network is appearing in country, for smooth operations of the network, an efficacious PMS is required. At present there is no effective PMS in country and mostly, decisions for pavement preservation are reactive in nature and based on pavement functional evaluation only. Structural evaluation component into PMS through deflection testing, adds value in decision-making and provide a true picture of structural adequacy. Therefore, there is a need to develop a framework for integration of pavement functional and structural evaluation into an overall PMS.

2. Objectives and Scope

The objective of this study was to develop a framework for integrating structural and functional evaluation of highways in overall PMS and to demonstrate the applicability of developed framework, using case study of an in-service pavement. The study was focused to develop a framework for integrating pavement functional and structural evaluation into an overall PMS. The developed framework is applicable to evaluate all M-series, N-series and high volume urban highways in Pakistan. The measures of effectiveness (MOE) for pavement functional evaluation are pavement roughness (International Roughness Indicator (IRI)) and FWD deflection data for pavement structural evaluation. Although developed framework is applicable to carryout, long and short-term effectiveness analysis, but owing to non-availability of time series data at present, only short-term effectiveness analysis is presented, using pre- and post-rehabilitation data.

3. Methodology

Before starting the pavement rehabilitation process, a comprehensive condition survey is the most valuable tool which assist the engineer to identify the type of distress present and lead to identify the probable cause of distress. And only by identifying the accurate cause of distress, most appropriate rehabilitation strategy can be selected. A suggested framework for integrating pavement functional and structural evaluation of highways in overall an overall PMS using NDT is shown in figure 1. The stepwise procedure for developed framework including data collection, establishing pavement effectiveness analysis database, pavement structural and functional evaluation using respective input parameters, decision support tool for functional performance evaluation by determining the threshold value, calculating SNeff through NDT and RSL from traffic data and selection of most optimal strategy for pavement rehabilitation. The step wise procedure of developed framework includes managing pavement collection of pavement evaluation data i.e. inventory, construction/ contract data, functional/ class data, surface type, traffic data, geometrics and previous M&R data.

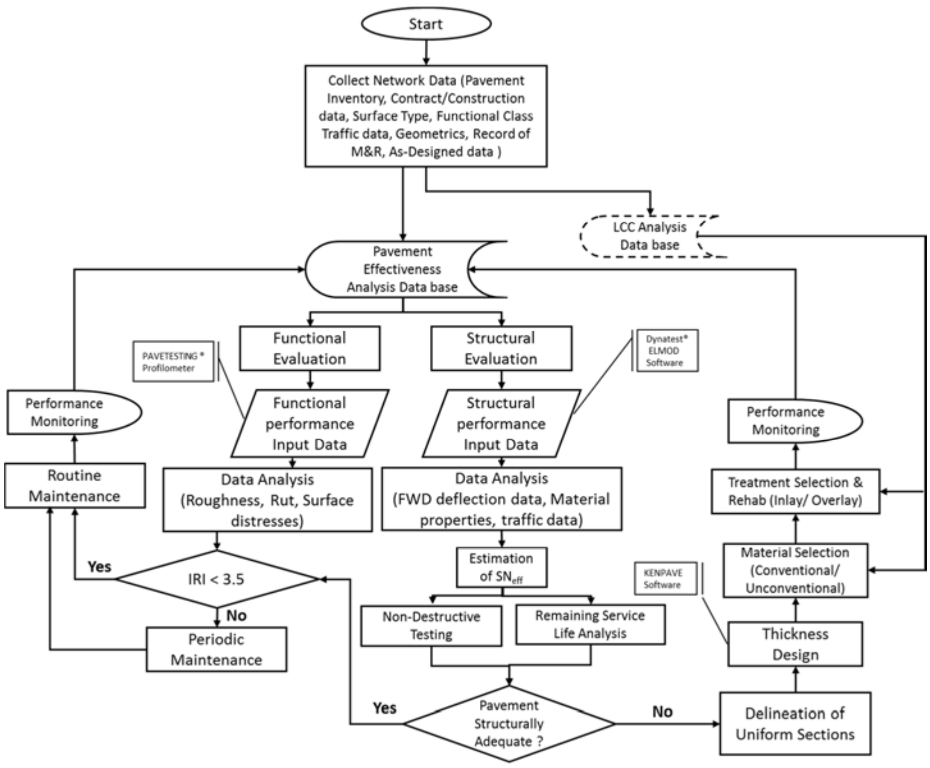


Figure 1. *Framework for integrating pavement structural and functional evaluation into an overall PMS.*

4. Proposed Framework Applicability: A Case Study of in-Service Pavement

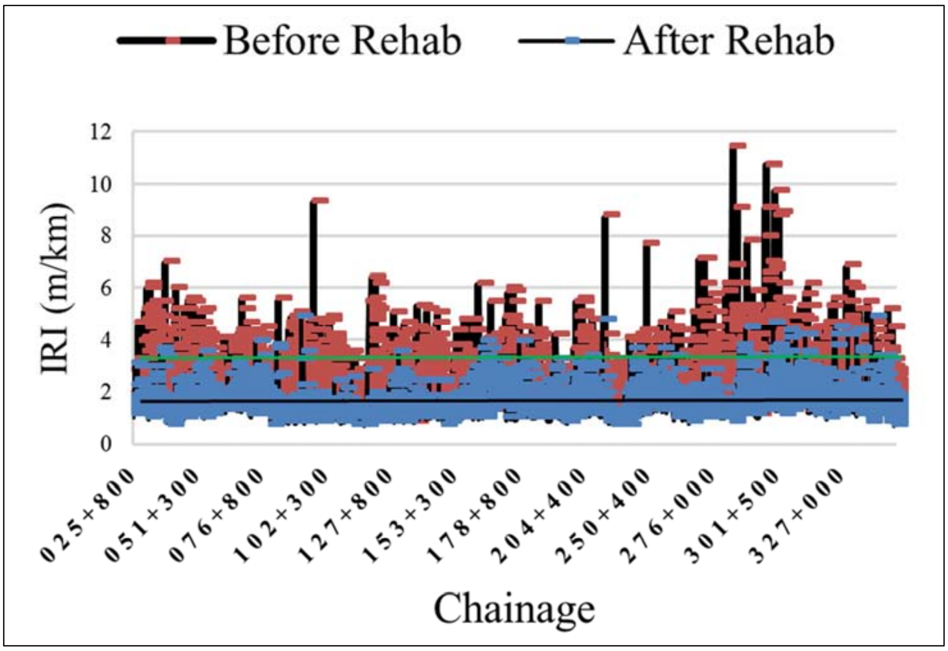
Lahore-Islamabad Motorway (M-2) is a 6-lane (3-lanes in each direction) highway which was first completed and opened to traffic in 1997. The flexible pavement structure was an important element of the transportation infrastructure in Pakistan that was designed for a 10-year service period with anticipated HMA overlay that extends the service life to 20 years and pavement structure was based on design ESALs of about 30 million. Although originally designed for 10 years, the pavement structure has lasted for more than 15 years and has functioned within an acceptable serviceability levels with minor maintenance and preservation actions. Currently, a major rehabilitation has been done on the motorway through various preservation treatments and rehabilitation actions. The cost-effective design of such pavement preservation treatments and rehabilitation actions were based on complete structural and functional evaluation of all lanes of the existing pavement structure to avail the window of opportunity to extend the pavement life by another 10 years or so. After the first major rehabilitation, need was felt to develop a framework by integrating pavement functional and structural evaluation into an overall PMS.

4.1. Pavement Functional Evaluation

For pavement functional evaluation, IRI is the performance indicator used to comment on ride quality, pavement surface conditions and normally measured in terms of m/km or inches/mile. IRI was measured using vehicle carrying a laser mounted device which measure the undulation or roughness in pavement surface. Normally IRI is considered best MOE which represents the user's opinion of ride quality and smoothness of road while traveling. Pavement functional evaluation has been carried out in two stages; in first phase complete data before and after the rehabilitation is analysed to comment on IRI by observing PJ and percentage decrease in IRI after the rehabilitation. In second phase, a representative section-3 (203+000 to 291+900) is analysed, to check the applicability of developed framework.

To carry out the pavement functional evaluation, complete IRI data in south and north bound is analysed to comment on the percentage decrease in IRI values and improvement in pavement functional performance. First the pre-and post-rehabilitation IRI data is plotted to check the decrease in IRI values as shown in figure 2.

IRI data of south and north bound is plotted to check the threshold value which is 3m/km as policy laid down by NHA. To carry out the short-term effectiveness analysis, field performance of CRM asphalt mixture is evaluated, in comparison to conventional asphaltic wearing course (AWC). In M-2 from 00+000 to 142+000, CRM is used in wearing course, whereas from RD 143+000 to 357+000 conventional AWC is used. Improvement in pavement functional performance in terms of IRI can also be reported by comparing the box-and-whisker plot of pre-and post-rehabilitation values using Minitab computer program. Figure 3 shows the sections with CRM and conventional AWC and comparison of both sections in south bound.



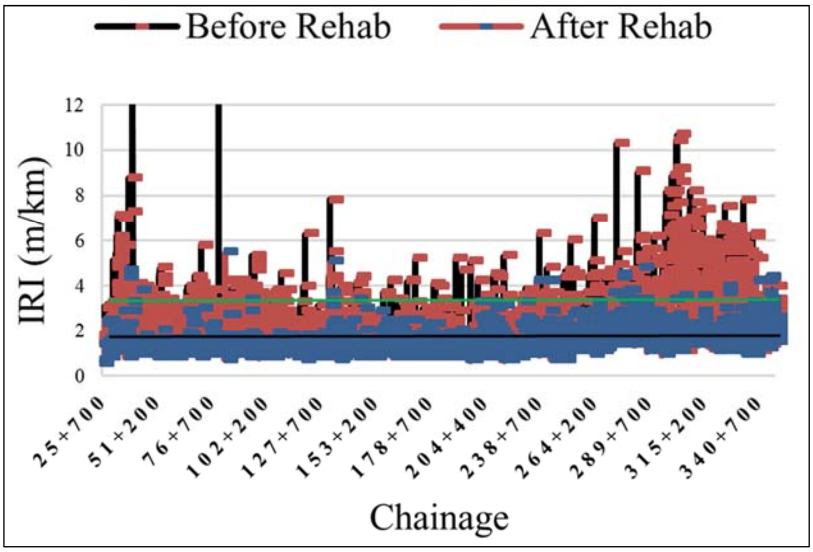


Figure 2. *IRI before and after rehabilitation- SB&NB (truck lane).*

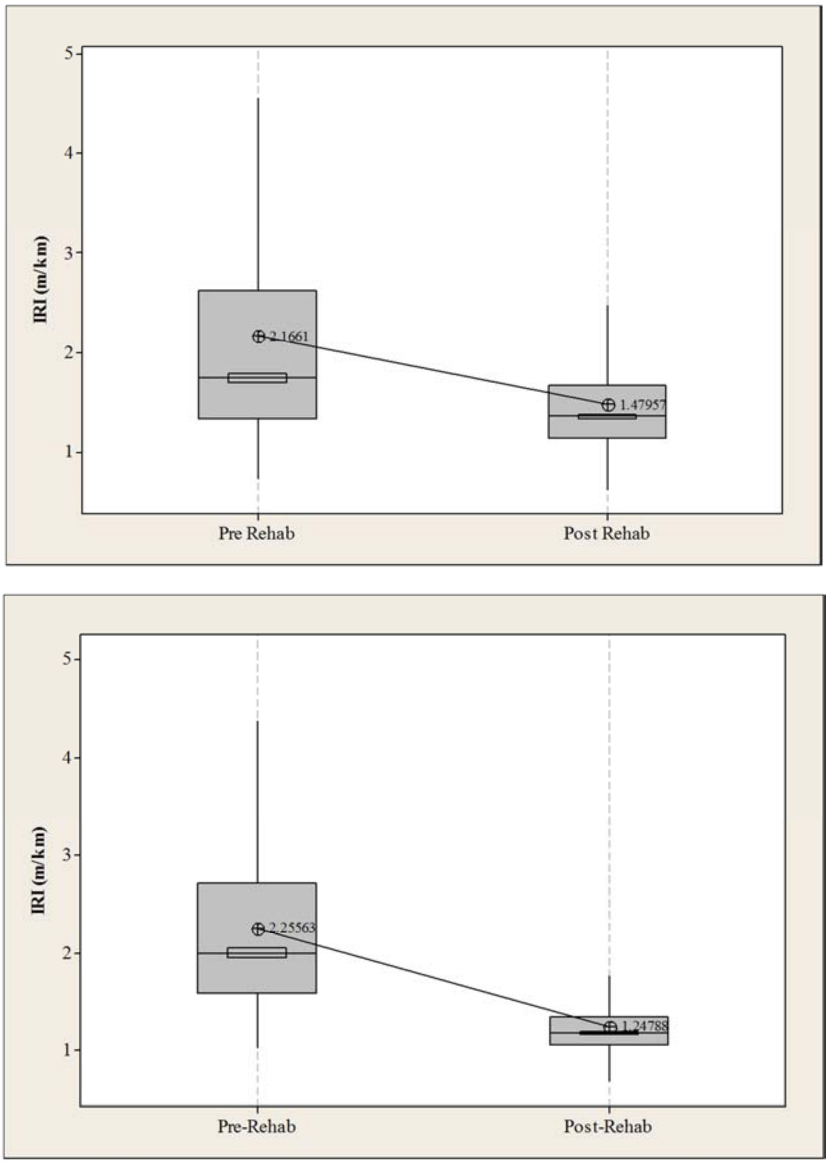


Figure 3. *Comparative box-and-whisker plot of pre- and post-rehab IRI without and with CRM respectively.*

From figure 3, it is evident that in south bound, IRI values dropped from average 2.33m/km to 1.4m/km, in north bound, IRI values dropped from average 2.44m/km to 1.05m/km and ride quality of pavement has improved considerably. Most of the agencies collect IRI data regularly on specific intervals and pavement effectiveness in terms of IRI can be evaluated using PJ which is drop in IRI on application of any treatment. PJ can be defined as any sudden, abrupt or vertical drop in IRI (in case of pavement functional performance) and PJ can be calculated using expression in equation below:

$$PJ = \text{Pre-Rehab IRI} - \text{Post-Rehab IRI} \quad (1)$$

Where

PJ = Performance jump measured in m/km

Here it is pertinent to mention that magnitude of PJ is dependent on pre-rehab IRI, because it is a sudden drop in IRI value after treatment. Generic equation to calculate PJ, as function of pre-rehabilitation can be expressed as

$$PJ = \alpha + \beta * (\text{Pre\_Rehabilitation}) \quad (2)$$

Based on this assumption the functional form of PJ can be computed using regression model and equation is show below and graph in figure 4.

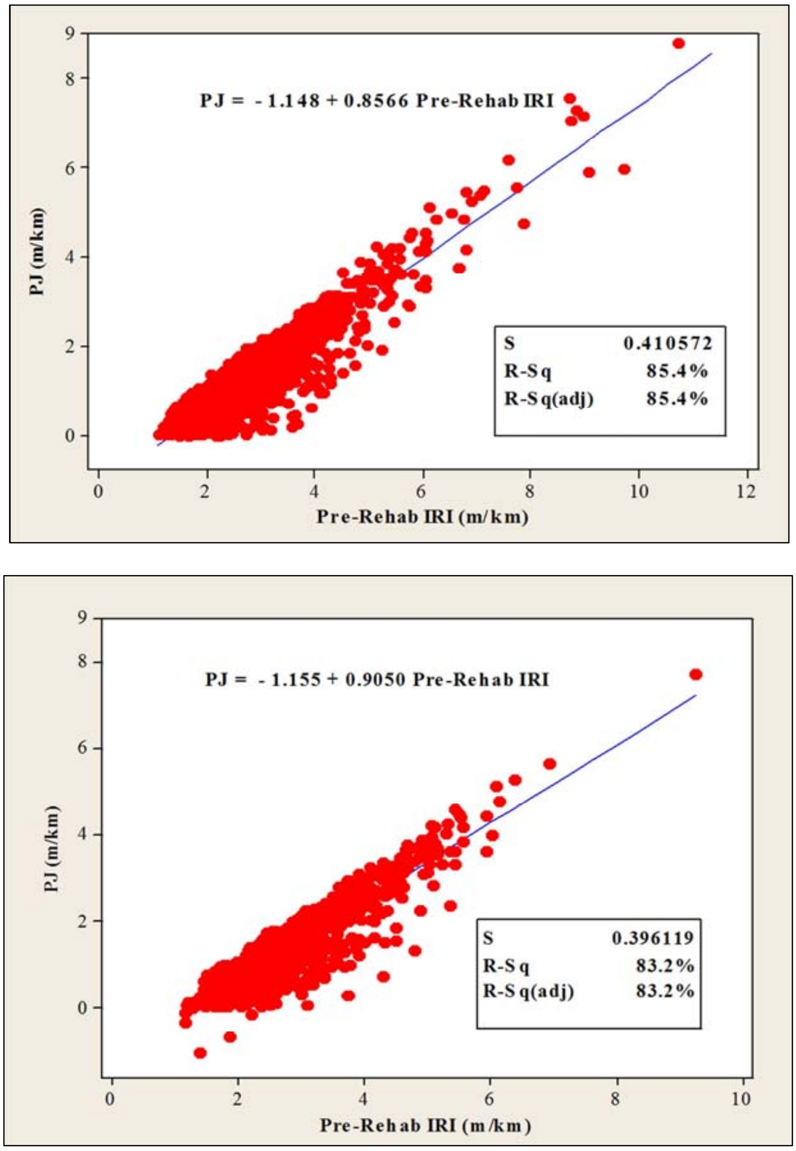


Figure 4. *PJ (drop in IRI) with conventional AWC and CRM-SB.*

$$PJ = -1.148 + 0.8566 (\text{Pre-Rehab IRI}) \quad (3)$$

$$PJ = -1.155 + 0.9050 (\text{Pre-Rehab IRI}) \quad (4)$$

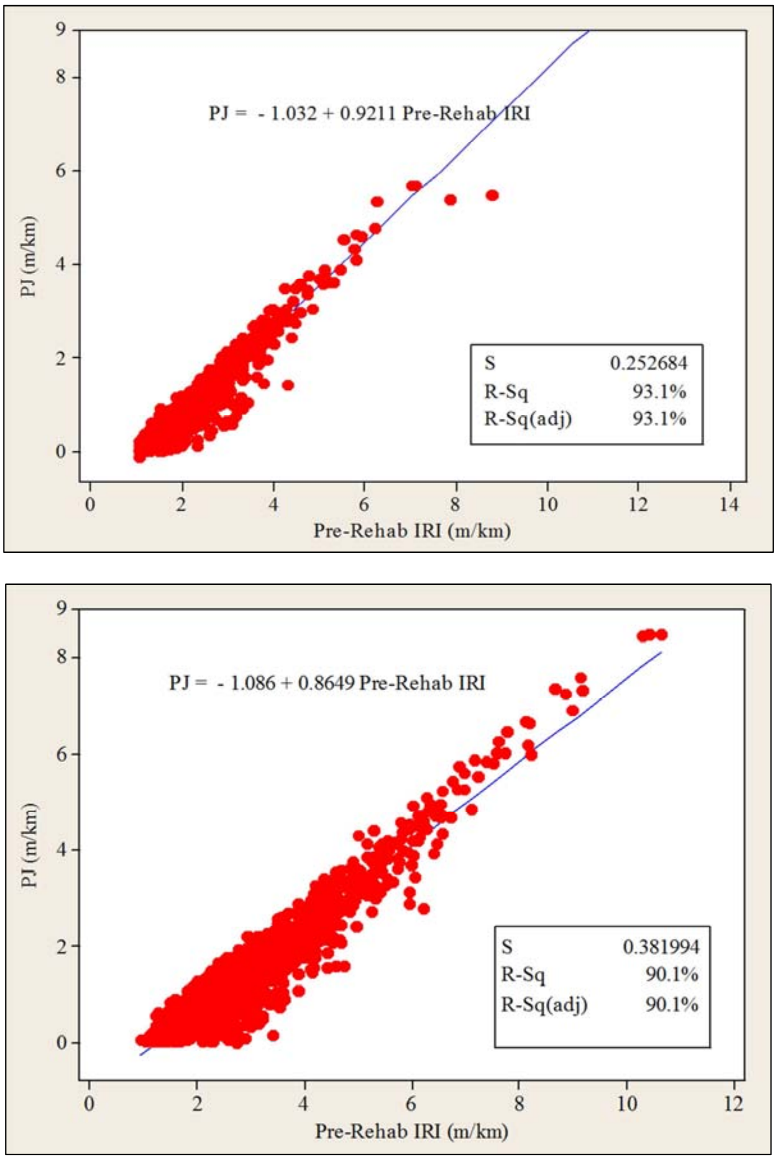


Figure 5. *PJ (drop in IRI) with conventional AWC and CRM-NB.*

$$PJ = -1.032 + 0.9211 \text{ (Pre-Rehab IRI)} \quad (5)$$

$$PJ = -1.086 + 0.8649 \text{ (Pre-Rehab IRI)} \quad (6)$$

CRM asphalt mixture exhibited relatively superior functional performance in contrast to conventional asphaltic wearing course by a margin of 5% and 8% higher drop in IRI, on average, in south and north bound respectively. In other words, the pavement sections constructed with CRM showed overall better short-term effectiveness indices (IRI values) than the corresponding control sections. Results are shown in Table 1.

Table 1. *Comparison of pre-& post-IRI by calculating PJ and drop in IRI.*

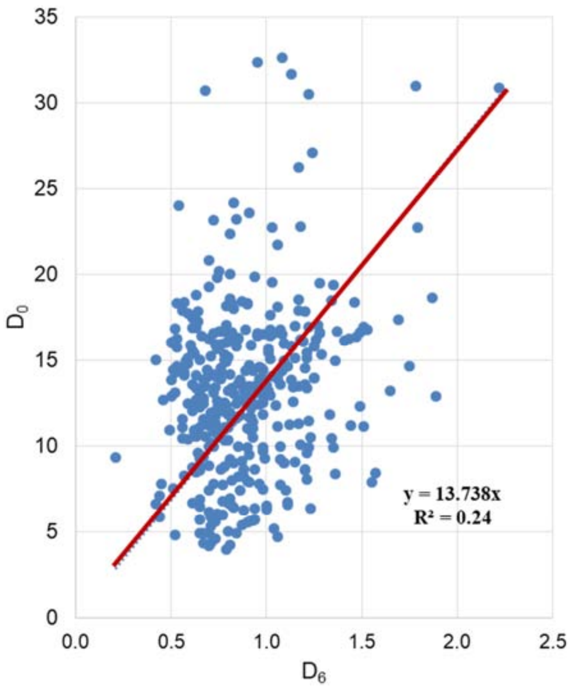
Section	Treatment Type	R^2	Average pre-IRI (m/km)	Average post-IRI (m/km)	Average PJ (in IRI, (m/km)	Percentage Drop in IRI (m/km)
South Bound	Modified (CR 8%)	83.2%	2.23	1.31	0.92	41.25%
	Conventional (CR 0%)	85.4%	2.43	1.49	0.94	38.68%
North Bound	Modified (CR 8%)	93%	2.26	1.24	1.02	45.13%
	Conventional (CR 0%)	91%	2.62	1.54	1.08	41.2%

4.2. Pavement Structural Evaluation

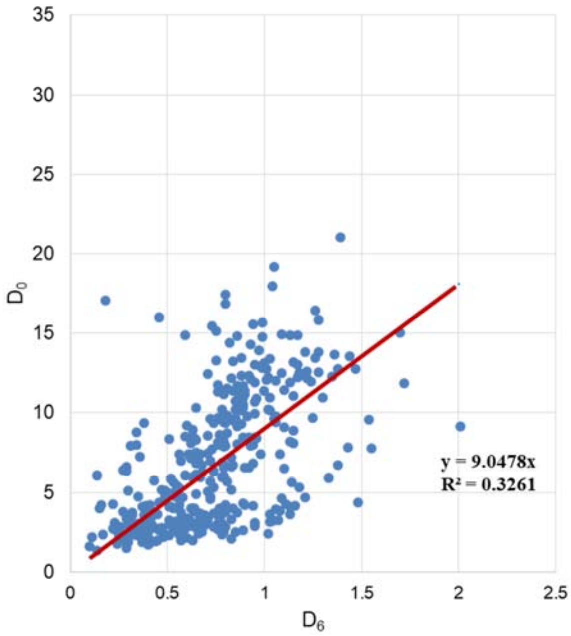
After carrying out analysis of pavement roughness data and identifying the candidate sections for pavement structural evaluation, now FWD data is taken for complete section-3 to comment on pavement structural health and check the pavement RSL by considering traffic counts (truck load repetitions). To carry out pavement structural evaluation, FWD data was collected in following sequence:

FWD deflections data for the outer lane in the south and north bound directions. The FWD data were measured along the outer lanes of each direction at 100 m intervals.

The as constructed layer thicknesses (HMA, base, and sub-base layers) collected from previous studies.

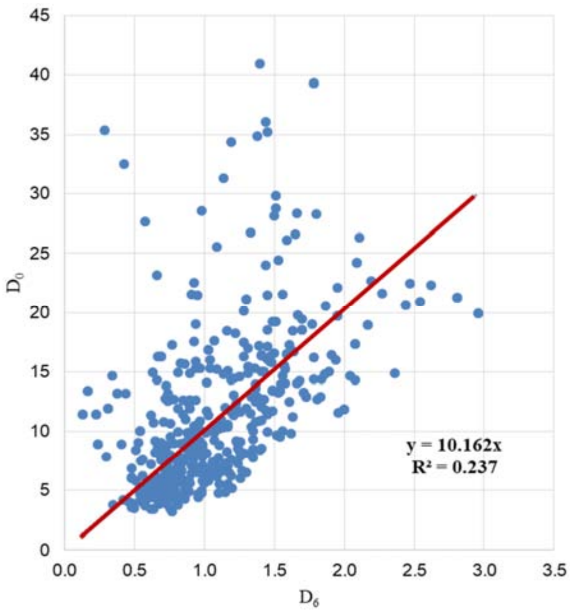


(a) D_0 vs D_6 Pre-rehabilitation

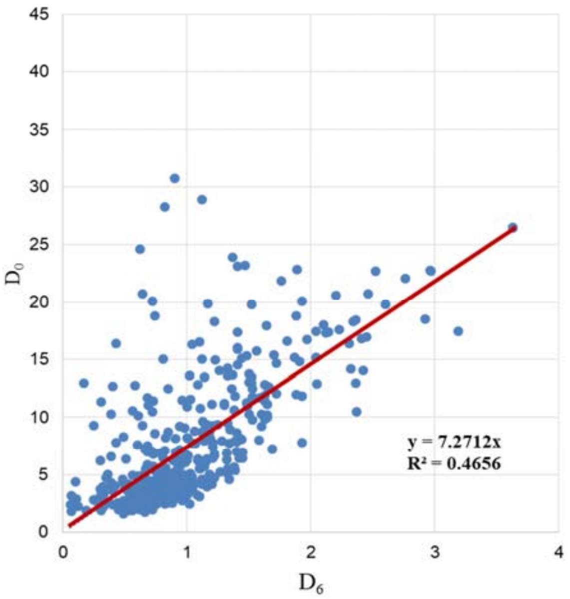


(b) D_0 vs D_6 Post-rehabilitation

Figure 6. *Comparisons between D_0 and D_6 deflections data – South Bound (SB).*



(a) D_0 vs D_6 Pre-rehabilitation



(b) D_0 vs D_6 Post-rehabilitation

Figure 7. *Comparisons between D_0 and D_6 deflections data – North Bound (NB).*

Figures 6 and 7 show comparisons between D_0 and D_6 deflections and the frequency distribution of D_6 to D_0 ratios along the south and north bounds outer lanes of M2, respectively. In general, it can be seen from the figures that the magnitude of D_0 is about thirteen times higher than that of D_6 before the rehab about nine times higher than D_6 after the rehab in south bound. For north bound before rehab D_0 is about ten times than D_6 before the rehab and about seven times after the rehab. Once again, the two observations indicate, in general, relatively stiff roadbed soil.

Figures 8 and 9 show the frequency distribution of D_6 to D_0 ratios along the entire south and north bounds of outer lanes of M2, respectively. In a typical pavement structure about 60 to 80% of centre deflection D_0 is due to road bed soil stiffness or in other terms depend on D_6. Results shown in figure 8 and 9 indicate that in case of M-2, the ratio D_6/D_0 is between 5 to 28 percent of D_0 before the rehab and after the rehab even decreased to 5 to 19 percent. For north bound these values 5 to 35 percent before rehab and after rehab dropped to 4 to 21 percent. This observation also confirms that in general, relatively stiff roadbed soil.

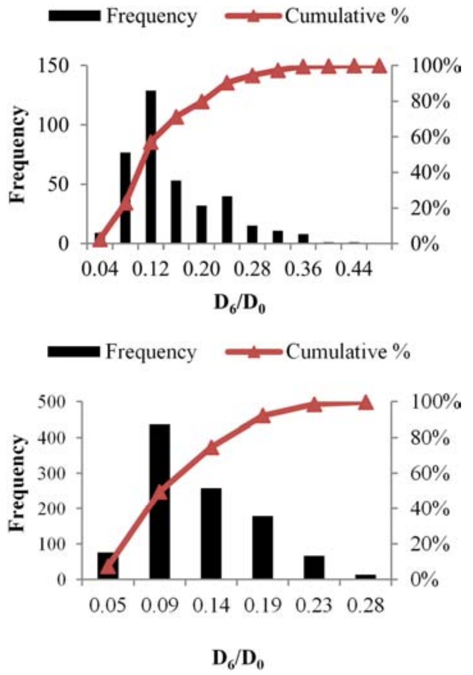


Figure 8. *D_6/D_0 frequency distribution ratio for SB outer lane before and after rehab respectively.*

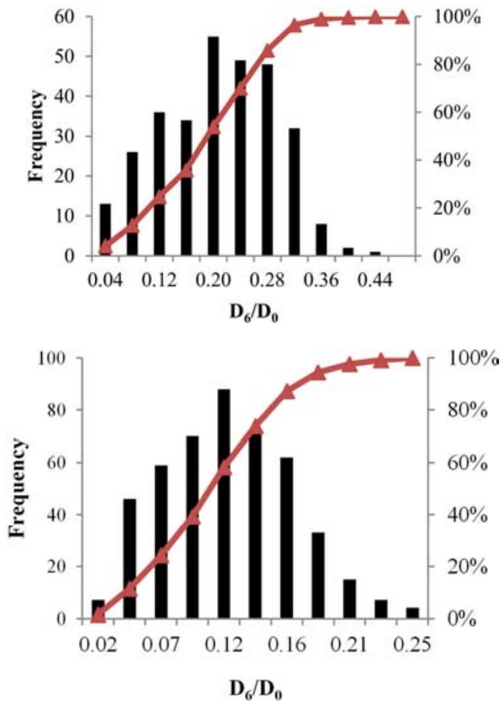


Figure 9. *D_6/D_0 frequency distribution ratio for NB outer lane before and after rehab respectively.*

5. Conclusions and Recommendations

Following conclusions can be drawn based on the result and discussion presented in sections:

5.1. Key Conclusions from Pavement Functional Evaluation

Pre- and post-rehabilitation comparison of IRI shows that in south bound, IRI values dropped from average 2.33m/km to 1.4m/km and in north bound, IRI values dropped from average 2.44m/km to 1.05m/km, which confirms the pavement functional enhancement.

Results of short-term effectiveness analysis quantified the extent to which CRM mixture improves the functional performance of the pavement, in terms of the drop in IRI. CRM mixture exhibited relatively superior functional performance in contrast to conventional AWC, by a margin of 5% and 8% higher drop in IRI, on average, in south and north bound respectively.

5.2. Key Conclusions from Pavement Structural Evaluation

About 90% of D_6/D_0 ratios (that signifies roadbed stiffness) improved to 9% & 12% after rehabilitation, in contrast from 12% & 20% before rehabilitation respectively, which confirms structural adequacy M-2.

Delineation of uniform sections using AASHTO 1993 approach, is useful technique to optimize the pavement thickness.

AASHTO 1993 empirical approach, confirms that pavement was structurally sound, estimated SN_{eff} against SN_f confirmed the structural adequacy.

ELMOD program is ideal for structural evaluation of pavement systems using FWD deflection data, program validates the correctness of empirical method, with average life of 28 years.

Pavement RSL predicted by traffic data divulge 9.81 years, close to actual designed life of M-2 but reliability of this method is questionable.

5.3. Integration of Functional and Structural Evaluation

Serviceability observations (functional evaluation) below the acceptable level are one way to trigger a pavement structural evaluation process, as endorsed by pre-rehabilitation functional evaluation of section-3 of M-2 in north bound, triggered to conduct structural evaluation.

Both functional and structural measures are important and complementary rather than substitutes, they supplement each other, not replace each other, in overall pavement evaluation.

5.4. Recommendations

Based on results, discussion and findings in previous sections, recommendations are listed below: -

Study findings can be shared/ presented to highway agencies, for efficacious management of pavements, especially where concessionaire is undertaking highways projects under BOT regime.

An effective database management system comprising time-series performance (functional and structural) data, traffic data, material data and historical M&R activities be developed for long-term pavement effectiveness analysis.

FWD deflection testing of the newly rehabilitated pavement sections must be adopted as a part of quality control processes and evaluate expected performance.

ELMOD program is useful for pavement engineers/ managers, responsible for the M&R of a highway network, it may be incorporated in pavement management practices.

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