Development of Roughness Prediction Model for Sri Lankan Expressways

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ABSTRACT

Expressways play a pivotal role in industrial and export development in Sri Lanka by providing access to the production sector in addition to the passenger transport in between transport hubs. A reliable pavement performance prediction model is essential for pavement management systems to optimize the cost of maintenance and rehabilitation planning. In this study, pavement roughness prediction of expressways in the long-term performance was conducted using International Roughness Index (IRI) which is used as a global parameter to measure the ride comfort of road users and the unevenness of pavement. Firstly, initial IRI values for Sri Lankan expressways were established by using current data and found that, it varies between 0.90 to 1.45 m/km. Secondly, IRI prediction model developed with cumulative traffic volume, considering outer lane IRI as the dependent variable due to higher deterioration rate compared to inner lane. Moreover, it was found that, there is a good relationship between IRI with cumulative traffic with R-squared of 0.60. Further, it can be concluded that, the outcomes of this study can be effectively used for Sri Lankan context in long term performance evaluation and expressway maintenance planning.

KEYWORDS: *International Roughness Index, Expressways, Pavement Deterioration, Cumulative traffic*

1 INTRODUCTION

Road's assets develop as a consequence of facilitating trade by improving access to education, business, health, and other community services. An efficient road transport would lead to higher incomes and economic well-being (Perera et al., 2019). As a result, enhancing road quality increases personal and community mobility, and drives economic growth. Maintaining roads at a higher quality level generates socio-economic benefits, such as reducing transport costs by minimizing vehicle damage and travel time, making trips to farms or markets easier, and increasing visits to commercial centers, among other benefits (Kothari et al., 2022). As the World Bank notes, road infrastructure is one of the most important public assets in any country (The World Bank, 2017). Proper monitoring and maintenance

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schemes can ensure the preservation of road strength, quality, and safety, regardless of whether the road is paved or unpaved. Reliable road condition monitoring is crucial in achieving a better-quality road network within a region or country.

Pavement condition is an important aspect of road maintenance decision making. The need of quick identification of pavement condition deterioration is highly important to road agencies. If a road agency is unable to make timely repairs to pavement that is in the early stages of deterioration, the condition of the pavement will rapidly get worsen, resulting significant increments in maintenance cost due to the need of more costly rehabilitation methods or requiring reconstruction of the affected road segments (Pasindu et al., 2020). The use of pavement condition data to support maintenance and resurfacing strategies and to justify budget needs, becomes more critical as more data-driven approaches are being used by the road agencies. Both manual data collection techniques and automated data collection techniques (used techniques are line and area scanners, ground-penetrating radar, acoustic sensors, optical imagery, LIDAR, etc.) are used for this purpose (Denis, 2014).

In Sri Lanka, there are more than 300 km of expressways in different environments and terrain conditions (Road Development Authority, 2017). Predicting pavement performance of such roads are challenging due to lack of data availability and complexity of contributing factors on deterioration. An accurate pavement performance prediction model with the capability of assessing local deterioration patterns with heterogeneous traffic composition would be a handful tool in road asset management systems. Various researchers proposed different performance prediction models for expressways, but due to lack of adoptability of such models to Sri Lankan context, those are no longer accepted. Moreover, there are no real field investigations conducted in Sri Lanka to predict the performance.

To cater that problem, this study is focused on developing pavement performance prediction model to adopt in maintenance decision making. The objective of this research is to identify the factors related to pavement deterioration and to use the collected data from expressways to forecast the roughness progression with the relevant explainer variables traffic volume.

1.1 Roughness as a Pavement Condition Evaluation Metric

Road pavements are designed and maintained to ensure its primary objectives are achieved during its life cycle, i.e. a) to have adequate structural capacity to withstand the vehicular loading on the pavement which is referred as the structural performance and b) to ensure the rider comfort and satisfactory skid resistance are available which represents the functional performance of the pavement. Pavement roughness can be measured by using various indices such as Ride Number (RN), International Roughness Index (IRI), Half-car Roughness Index (HRI), Mays Ride Meter (MRM), Quarter-car Index (QI), and Present Serviceability Index (PSI) (Múčka, 2017). Among those, International Roughness Index (IRI) is globally accepted as a suitable parameter to measure the pavement roughness as an indication of cumulative vertical displacement recorded due to the irregularities on the pavement over a measured distance and normally represented in m/km or mm/km (Múčka, 2017). Roughness also refers to the longitudinal profile of a pavement as shown in Figure 1.

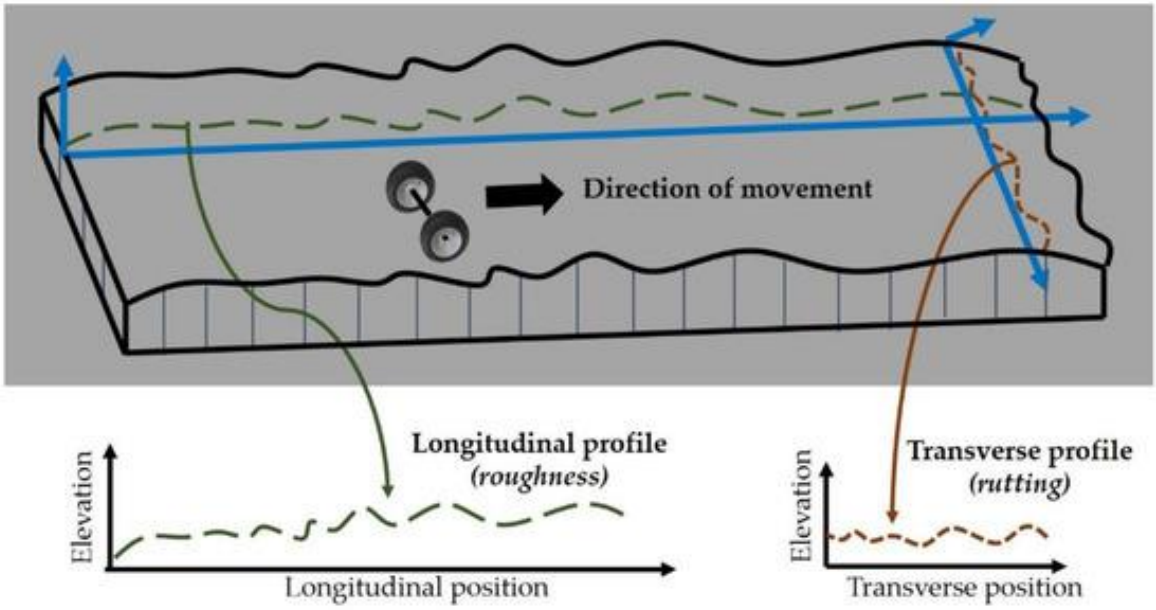

Figure 1. Pavement Roughness Derivation from a Longitudinal Profile *(Gkyrtis et al., 2021)*

The acceptable roughness values can also be established based on the operational speed of the road, as the resulting vibration induced by the pavement roughness would be affected to an extent by the speed of the vehicle (Yu et al., 2006). This is an important consideration for road agencies as the definition of the maintenance thresholds can be varied depending on the type/hierarchy of the roadway within the network. For example, to initiate rehabilitation works, an expressway which would have higher operational speeds (90-100 km/h) would have a lower maximum acceptable IRI value (e.g. 3-4) compared to the IRI threshold (8-10) of a low volume rural road which would have lower operating speeds (30-40 km/h). Table 1 illustrates the IRI thresholds for different roadways concerning operating speed.

Table 1. IRI Thresholds for different operating speeds *(Yu et al., 2006)*

Ride Quality Level	**IRI Thresholds at Different Speeds (m/km)**					
	20	**40**	**60**	**80**	**100**	**120**
Very Good	< 5.72	< 2.86	< 1.90	< 1.43	< 1.14	< 0.95
Good	5.72 – 8.99	2.86 – 4.49	1.90 – 2.99	1.43 – 2.24	1.14 – 1.79	0.95 – 1.49
Fair	9.00 – 11.39	4.50 – 5.69	3.00 – 3.79	2.25 – 2.84	1.80 – 2.27	1.50 – 1.89
Mediocre	11.4 – 16.16	5.70 – 8.08	3.80 – 5.40	2.85 – 4.05	2.28 – 3.24	1.90 – 2.70
Poor	> 16.16	> 8.08	> 5.40	> 4.05	> 3.24	> 2.70

The relationship for equivalent IRI values corresponding to different speeds is given as in Equation 1 (Múčka, 2017).

$$IRI(v_2) = \left(\frac{v_1}{v_2}\right)^{0.5} IRI(v_1) \quad (1)$$

Where, this choice of IRI values should meet the condition of the same quarter-car model suspension relative velocity response for two different velocities. For example, for two road speed limits, v_1 = 50 km/h (local roads) and v_2 = 110 km/h (highways), IRI (110)/IRI (50) = 0.67 should hold.

1.2 State-of-Practice: Application of IRI Progression Modelling in Expressways

Expressways are known to be an important integral part of a road network in a country since it is operated with higher speeds generally between states/provinces with a comfortable riding quality. Therefore, it is important to use a metric having good precision and repeatability, to monitor expressways. The roughness measurement devices are also categorized based on their accuracy and the data collection frequency. The ASTM standard E 950 (ASTM, 2003) defines roughness into four categories from Class I to Class IV based on the precision level, sampling interval, bias etc. Since Class I & II measurements measure the actual road profile with high precision, those are adopted to measure IRI in expressways.

Typically, a Network survey vehicle is equipped with a digital Laser Profiler (DLP) which has the capability of estimating various data types in higher accuracy and precise levels. Most of the equipment can collect data for 3.6 m width at once and it reduces survey time and costs due to the ability to collect data at expressway operational speeds (usually up to 100 km/h). These laser measurements produce outputs such as roughness, rutting, longitudinal profile, faulting, transverse profile, raveling and macro texture (ARRB, 2000). Table 2 illustrates the overview of the pavement condition metrics which can be measured by laser profilers.

Table 2. Overview of Pavement Condition Metrics Measured in Laser Profilers

Pavement condition metrics assessed	**Attributes measured for each metric**	**Laser Profiler Type(s) / Road agency**
Roughness	Longitudinal profile	ROMDAS Laser Profiler (ROMDAS Data Collection Ltd, 2011) ARAN System (Sršen, 2002) PaveProf V2.0 (PaveTesting® Ltd, 2011) LCMS-2 (Pavemetrics, n.d.) Laser Profiler NTUA (Loizos & Plati, 2008) Haweye-2000 (ARRB, 2000)
	Profilograph Index (PI), Ride Quality Index (RQI), Half Car Ride Index (HRI), Ride Number (RN)	PaveProf V2.0 (PaveTesting® Ltd, 2011)
Rutting	Rut type, Width (single or double), depth, cross section area and percentage of deformation	ARAN System (Sršen, 2002) PaveProf V2.0 (PaveTesting® Ltd, 2011) LCMS-2 (Pavemetrics)
Faulting	Elevation difference	Haweye-2000 (ARRB, 2000)

Moreover, various studies worldwide have implemented IRI based measurements in their expressways and superhighways as presented in Table 3. From that it can be observed that initial IRI threshold is in between 1.6 – 3 m/km while maintenance threshold is in the range of 2.7 – 4.3 m/km for expressways.

Table 3. IRI Thresholds for Expressways and Superhighways in Worldwide

Country	**Road Type**	**IRI Limit Specification (m/km)**	
		New Roads	**Maintenance Intervention**
Australia	Freeways	1.60	3.50
	Main roads (100 km/h)	1.90	3.50
Russia	Speed > 50 km/h	1.90	4.30
Czech Republic	National highways	1.26	2.76
Missouri, USA	Highways and first-class roads	2.20	4.20
Norway	Highway	2.00	3.50
New Zealand	Highway	-	3.82
Philippine	National primary roads	3.00	-

The performance prediction models can be classified into two categories as deterministic and probabilistic models (Lytton, 1987). The deterministic models are either empirical or empirical-mechanistic (M-E) models consisting of primary response, structural performance, functional performance, and damage models (George et al., Models for Predicting Pavement Deterioration, 1987). The probabilistic models include Markov chain (MC), Bayesian regression, and survivor curves (Lytton, 1987) (Carnahan et al., 1987).

Empirical models are developed by implying the regression analysis which generates the relationship between parameters such as pavement age, cumulative traffic load, climate condition, pavement aging effect, etc. The roughness deterioration rate differs with the climate condition, traffic density has developed for empirical modelling as shown in Table 4.

Table 4. Empirical IRI Deterioration Models for Expressways

Reference	Factors Used	Key Findings
(George, MDOT Pavement Management System, 2000)	AC overlay thickness, (TOPTHK), CESAL, Pavement age	Regression equation: $IRI = (3.095 + Age^{0.3571} (1+CESAL^{0.3054}))\ TOPTHK^{-0.3235}$ Pavement age is the most significant predictor of deterioration. Power models found to be the best representation.
(ARA, I. E. D. , 2004)	Pavement age, fatigue cracking $(FC)_T$, transverse cracks $(TC_s)_H$, Patches $(P)_H$, Freezing Index (FI)	Model: Bituminous treated base $IRI=IRI_0+0.0099947(age)+0.0005183(FI)+0.00235(FC)_T+18.36\{1/(TC_s)_H\}+0.9694(P)_H$
(Albuquerque & Núñez, 2011)	Modified Structural Number (S), ESAL (N), Climate (C)	$IRI_{(HMA)} = -173.4 + e^{(5.177 + 0.001 * C - 0.002 * S + 0.005 * N)}$ To reach IRI intervention IRI of 3.5m/km this model would take 9 years.
(Paterson, 1987)	Structural Number (SNC), ESAL, pavement age, Wearing course type	Regression Model: $IRI=[IRI_0+725(1+SNC)^{-4.99}\times ESAL] \times e^{0.0153AGE}$

2 DATA COLLECTION

In this study, the entire expressway network in Sri Lanka is selected as the study area which consist of 312 kms in length (Figure 2), and Table 5 shows a summary of details of expressway network. IRI data is collected from Planning division, Road Development Authority, Sri Lanka and IRI data consist in 100 m sections from year 2017 to 2021, measured by Hawkeye 2000 laser profiler (ARRB, 2000) which is a Class-I roughness measuring equipment as per ASTM Standard (ASTM, 2003). For the analysis, raw IRI data were segmented to 1 km sections. Moreover, Traffic data is collected from the Statistics Reports published by National Transport Commission, Sri Lanka (National Transport Commision, 2023).

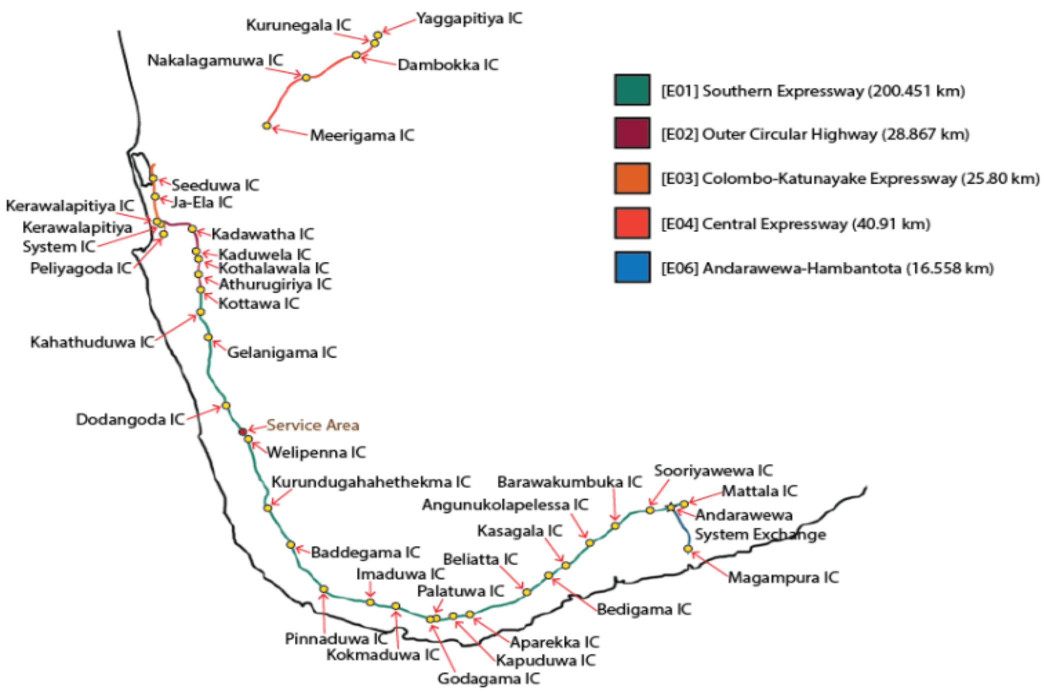

Figure 2. Expressway Network in Sri Lanka *(Road Development Authority, 2017)*

Table 5: Expressway Network in Sri Lanka *(Road Development Authority, 2017)*

Expressway	Segment	Length (km)	Year of Opening
E01 Southern Expressway	Kottawa To Galle	100.0	2011
E01 Southern Expressway	Galle To Matara	36.0	2014
E01 Southern Expressway	Matara To Mattala	64.0	2020
E02 Outer Circular Expressway	Kottawa To Kaduwela	11.0	2014
E02 Outer Circular Expressway	Kaduwela To Kadawatha	8.7	2019
E02 Outer Circular Expressway	Kadawatha To Kerawalapitiya	8.6	2019
E03 Colombo to Katunayake	Colombo To Katunayake	25.6	2013
E04 Central Expressway	Kurunegala To Meerigama	41.2	2021
E06 Magampura Expressway	Andarawewa To Hamabantota	15.1	2019

3 ANALYSIS & RESULTS

3.1 Initial IRI of Expressways in Sri Lanka

Firstly, the data analysis was conducted to find initial IRI of expressways in Sri Lanka. Initial IRI is defined as the IRI value of a pavement within first six months after the construction or a rehabilitation/overlay operation. All expressways in Sri Lanka are multilane roads and it is essential to decide the lane which shows a greater variation in IRI, for the study. Thus, a comparative analysis is conducted on IRI deterioration for inner lane and outer lane separately. Figure 3 shows the deterioration pattern on Southern Expressway (EA01) from Kottawa (0+000) to Galle (100+000).

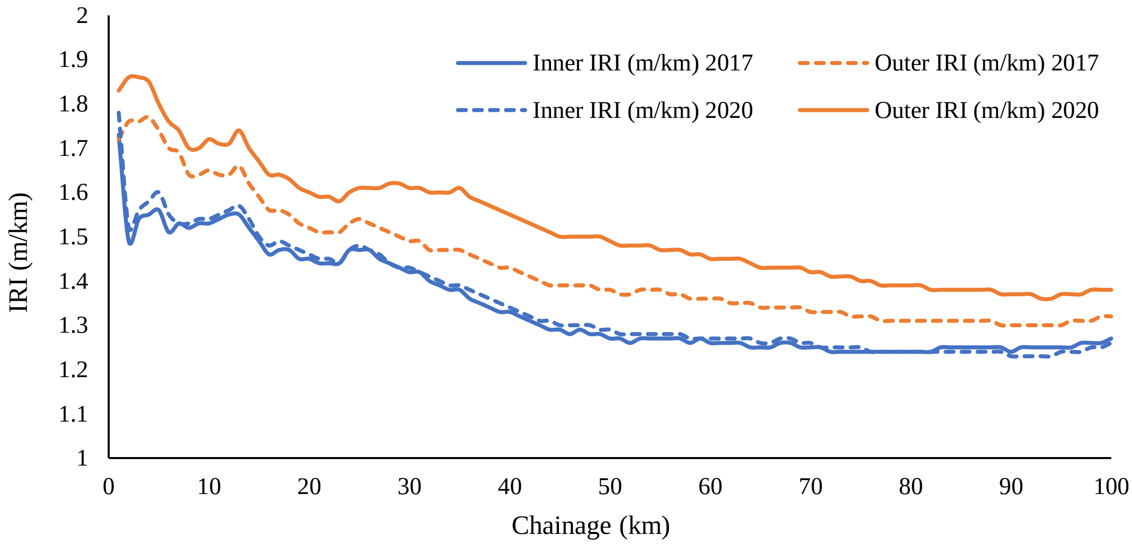

Figure 3: IRI deterioration of inner and outer lanes on Southern Expressway in Sri Lanka

From the results, it can be clearly observed that IRI deterioration on outer lane is higher than the IRI deterioration in inner lane. Further, a statistical analysis is conducted to validate the hypothesis by comparing the two populations of IRI differences in inner and outer lane and the summary of results shown in Table 6. Furthermore, Figure 4 shows the normal distribution curves of inner and outer lane separately. From the results it can be concluded that IRI deterioration difference of outer lane is higher than the inner lane.

In Sri Lanka, lane discipline is not well-maintained by road users in most of the Class A and B roads due to the driver behavioral factors and heterogeneous traffic composition. However, compared with Class A and B roads, lane discipline is observed to be more adopted in expressways since the inner lane is used only for overtaking maneuver while the outer lane is used for travelling. Hence outer lane is used by most slow-moving vehicles such as heavy vehicles and higher traffic volume can be observed. Contra verse, since the inner lane is used only for overtaking maneuver, lesser traffic volume can be observed. Therefore, these results show that the outer lane is more critical in deterioration modelling in expressways. Hence for the IRI deterioration modelling, IRI of outer lane is used as the pavement condition evaluation metric in this study.

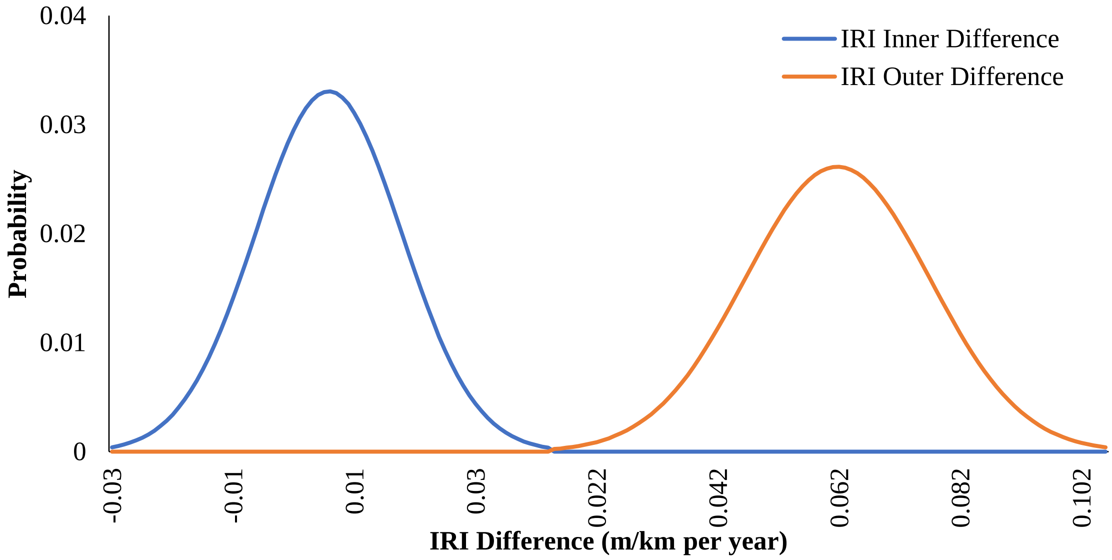

Figure 4. IRI difference for inner and outer lanes of E01 (Kottawa to Galle section) from 2017 to 2020

Table 6. Summary of Statistical Analysis between Inner and Outer Lane effect to IRI Progression

Statistical parameter	Inner lane IRI difference (m/km per year)	Outer lane IRI difference (m/km per year)
Mean	0.006	0.062
Observations	100	100
Hypothesized mean difference	0.05	
Z-statistics	3.12	
Z-critical one tail	1.64	

Considering the Sri Lankan context, three expressways' initial IRI data was available to evaluate the initial IRI as presented in Table 7. From that, it can be observed, initial IRI varies from 0.90 – 1.45 m/km. Moreover, the box-whiskers plot presented in Figure 5 shows the variation of initial IRI among the selected expressway segments.

Table 7. Initial IRI values of Sri Lankan Expressways

Expressway	Description	Chainage From (km)	Chainage To (km)	Opening year	Average Initial IRI (m/km)	Standard deviation (m/km)
E01 Southern Expressway	Matara to Mattala	136.0	200	2020	1.11	0.09
E02 Outer Circular Expressway	Kadawatha to Kerawalapitiya	19.7	28.3	2019	1.08	0.07
E04 Central Expressway	Kurunegala to Meerigama	37.1	78.3	2021	1.19	0.14

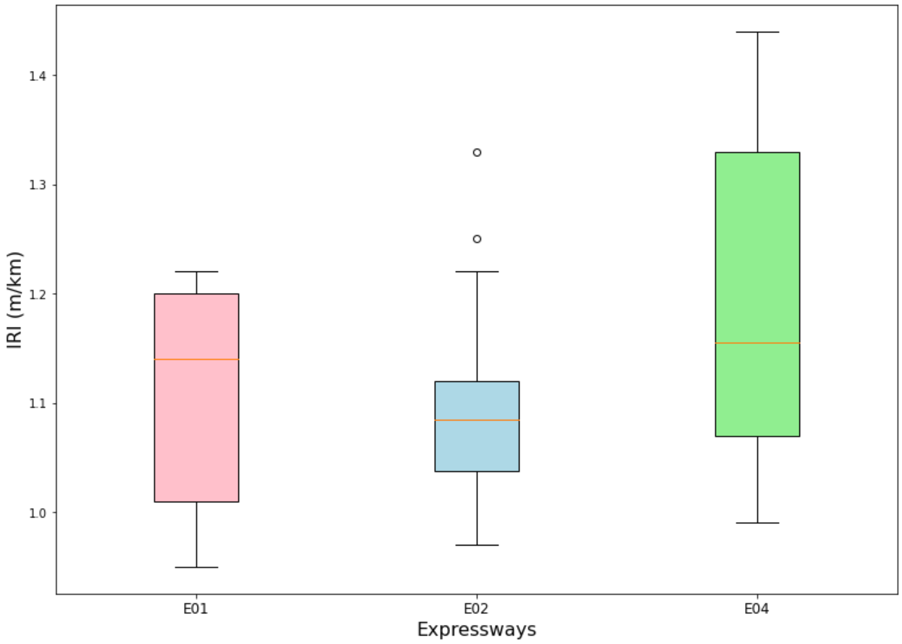

Figure 5. Boxplot of Initial IRI for Sri Lankan Expressways

3.2 IRI progression curve for Sri Lankan Expressways

Secondly, IRI progression is evaluated with the cumulative traffic volume on expressways from the latest rehabilitation. The annual traffic volume data was segmented for interchanges and evaluated by using simple linear regression analysis. IRI value on outer lane is used as the dependent variable and cumulative traffic volume used as the independent variable. Cumulative traffic value is presented in millions of vehicles. The results shown that, there is a good relationship between IRI with cumulative traffic with R-squared value of 0.60. Equation 2 illustrates the relationship while Figure 6 shows the graphical representation. Moreover, Table 8 presents the summary of the regression analysis.

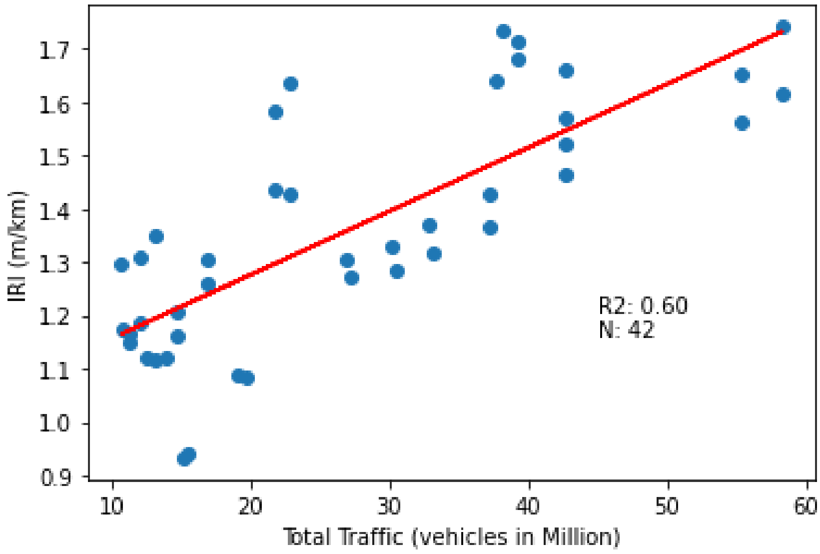

Figure 6:IRI vs Cumulative Traffic in expressways in Sri Lanka

$$IRI(i) = 1.04 + (0.02 \times Cum\_Traffic) \qquad [R^2=0.60, N=42] \qquad (2)$$

Where, IRI(i) is the IRI value of the expressway section in m/km, Cum_Traffic is the total number of vehicles traveled on the expressway from the construction or latest rehabilitation in unit of million vehicles.

Table 8: The statistical summary of IRI vs Cumulative Traffic model

Statistic			**Value**		
R-squared			0.60		
No. Observations			42		
F-Statistics			60.66		
Probability (F-statistics)			0.00		
Model parameters (method-least square)					
	Coefficient	Standard error	T-statistics	P > |t|	95% CI
Constant	1.037	0.047	21.917	0.000	[0.942, 1.133]
Cum_Traffic	0.012	0.002	7.788	0.000	[0.009, 0.015]

Further, a analysis is conducted to develop a non-linear relationship between IRI with cumulative traffic. However, it was found that there was no significant improvement in non-linear analysis in terms of model fitting. Figure 7 presents the variation of R-squared with the degree of non-linear polynomial functions. From that, it can be concluded that the linear model is a better interpreter for the IRI progression with cumulative traffic in expressways.

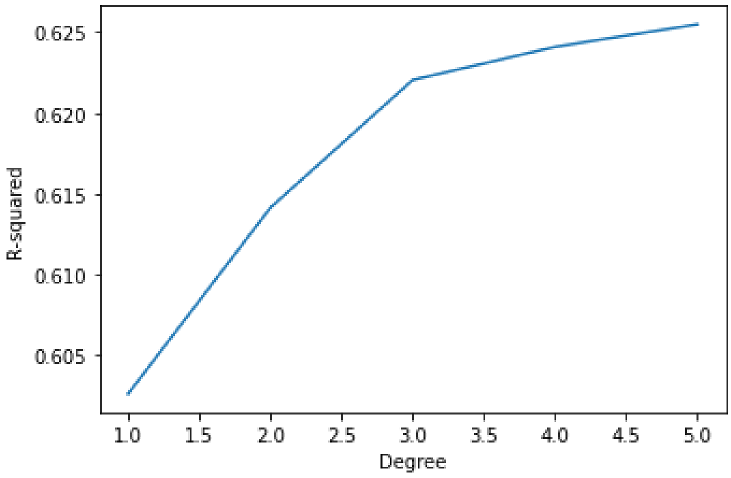

Figure 7: Variation of R-squared with Degree of Polynomial functions

4 CONLUSION

In this study, Sri Lankan expressway network is selected as the study area to develop a roughness prediction model for expressways. IRI is selected as the roughness measurement metric while cumulative traffic data used to develop the prediction model. Firstly, the initial IRI range was established by considering IRI value within the first six months after a rehabilitation activity. It was found that initial IRI vary between 0.90 to 1.45 m/km which agrees with the practice worldwide. Secondly, IRI prediction model developed with cumulative traffic volume prevailing on expressways. For this analysis, outer lane IRI is considered as the dependent variable since it was shown that IRI deterioration in outer lane is relatively higher than that in inner lane due to heavy vehicle and higher traffic volumes. It was found that there is a good relationship between IRI with cumulative traffic while the model shows R-squared of 0.60. Further, it was elaborated that the linear model is effective in interpretation since higher order polynomial functions doesn't produce significant improvement in the prediction model. Finally, the findings of the study would promote the use of pavement roughness as the objective quantitative approaches to predict pavement performance of local expressway conditions which would enable to adopt pavement maintenance management systems for their maintenance planning and ensure the roads are maintained in a more efficient manner.

5 ACKNOWLEDGEMENTS

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