Building a Sustainability Index for Highway Infrastructures: Case Study of Flexible Pavements

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Abstract: - The road network system consists of highway infrastructures which need to be maintained periodically in order to increase the life span of the system and to provide riding comfort to the travelling public. Deterioration of pavements gives rise to the need for periodic or routine maintenance and rehabilitation. Factors that cause pavements to deteriorate are accumulated traffic axle loads, environmental conditions, climate, etc. Deterioration creates conditions that undermine the performances of pavements. A literature review indicates that analytical methods have been developed to design different components of pavement performances due to pavement conditions and sustainability. Some of these existing models were mostly based on definitions, operation, structural and functional research oriented analysis; and they have contributed substantially to the society. However, the integration or correlations of sustainability indices with pavement condition indices were not fully explored. In order to fully understand and develop a model, the triple sustainability dimensions (environmental, economic and social) which plays a major role in planning for both construction and maintenance of these infrastructures is considered and introduced into the model using a multi-linear regression analysis (MLRA). The following possible four characteristics of pavement performance indices for flexible pavements are considered (as independent variables) and analyzed for each section of pavement under consideration: (1) roughness, (2) surface distress, (3) skid resistance index, and (4) structural deflection. A 2 link numerical example using hypothetical data is performed to illustrate the developed approach.

Key-Words: Flexible Pavements; Sustainability Index; Pavement Condition indices; Multi-Linear Regression Analysis (MLRA) Model; Pavement Performance Evaluation;

1 Introduction

1.1 Background and Motivation

This paper explores the problem of building a sustainability index for highway infrastructures using flexible pavements as a case study. For the
past couple of decades, there have been global concerns on climate changes; energy usage, environmental impacts, financial limitation as they affect highway transportation infrastructures both in developed and developing countries. Engineers and policy makers have been looking into different ways to planning, designing, constructing, operating, and maintaining pavements in order to sustain highway infrastructures. Pavement infrastructures are known to be very vital and important in transporting people and goods from one point to another; which makes it one of the fundamental components of any transportation system both in the United States of America and the world in general.

Although many researchers have written on pavements in different perspectives such as pavement evaluations, maintenance, pavement management systems, to name a few; very few research works have been carried out on pavement serviceability and sustainability. The aim of this paper is to characterize some major transportation sustainability indicators and correlate them to pavement Performance/evaluation indices. The paper addresses the problem of sustainability in the context of pavement performance (pavement conditions) in a multi-linear regression analysis framework. The facility is divided into sections and each section is analyzed and correlated in order to obtain a strongly correlated index. The motivation behind this paper therefore is to develop a comprehensive model that determines the relationship between pavement conditions (indices) and sustainability indices (environmental sustainability, economic sustainability, and social sustainability) known as the universally accepted “triple bottom line” or (“Three Pillars”) sustainability (see figure 1 [6]).

1.2 Problem Statement

Prior to maintaining any highway infrastructure such as pavements and bridges, the preferred mode of maintenance is selected based on the need and availability of funds for the project. The next deciding issue is whether to maintain or fix the problem of the highway infrastructure or do-nothing. The planning and maintenance strategies depend largely on the type of highway infrastructure to be maintained or rehabilitated. Another important issue to be considered is the environmental and social impacts – such as: types of material used (not within the scope of this paper), environmental pollution, and traffic congestions.

![Fig. 1: Modified “Three Pillars” of Sustainability Model [6]](image)

In the past two decades transportation industry has shown increasing interest in the concept of sustainability due to the phenomena of climate change, accidents, resource depletion, increased degradation of quality of the life of pavements and bridges; and inequity of access. This paper intends to develop a statistical multi-linear regression analysis model (MLRA) that would support pavement managers/engineers to make rational decisions to enhance pavement performance and sustain the infrastructure. The goal here is to provide a mathematical tool that would enable agencies meet the basic needs and improve the quality of life of pavements; while the natural resources they depend on are maintained and enhanced for their benefits and the future generations without compromising safety, health and efficiency.

2 Literature Review

2.1 Introduction

The literature review discusses past related research works pertaining to pavement conditions, transportation sustainability, maintenance strategies, and pavement maintenance optimization models. It also provides detailed perception on past researches that relate to pavement conditions and sustainability models. The purpose of literature review is to establish the originality of this paper in order to obtain useful background information concerning the research topic. Although there have been a lot of research works on pavement facility maintenance optimization and pavement sustainability, very few researches have been done on maintenance optimization in the context of pavement (condition) performance indices and sustainability indices; i.e.,
determining how sustainability indices depend on pavement conditions. The literature search provides several reports as reference materials on this research work. These reports, relevant to the research topic were reviewed to determine how pavement conditions correlate with the “three-pillar” sustainability dimensions (environmental, social, and economic); such as environmental pollutions, congestion, and travel time, noise, water pollution, to mention a few. Also, how rapid axle loads on pavements can quickly reduce the life span of a pavement (pavement distresses); which ultimately affects the user’s comfort when pavements become distressed. Pavement conditions directly influence the cost of operating the vehicles such as fuel consumption, accidents – termed as “user and social costs”. Accident is outside the scope of this research. The organization of this section consists of definition and history of sustainability, pavement condition overview and evaluation, brief description of pavement management system (PMS) is introduced in order to establish the importance of PMS in pavement management; as well as existing past models that relate to the topic of this paper.

2.2 Definition and History of Sustainability

The word “sustainability” is often used especially in terms of public policy. In this paper, the definition is directed towards transportation infrastructures, such as pavement management. Sustainability is defined as the process to continuously maintain and meet the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, WCED 1987 [6]). According to FHWA, sustainability in transportation perspective is defined “as providing exceptional mobility and access in a manner that meets development needs without compromising the quality of life of future generations. A sustainable transportation system should be safe, affordable, and renewable, operate at a fair level, emits emissions at reduced level, healthy to the society, and the use of new and non-renewable resources” [13].

The development of sustainability started about twenty years ago between 1972 and 1992 during various international conferences. The first meeting was held during one of the UN conferences on Human Environment in Stockholm in 1972. Sustainability on a world scale was the major issue of discussion, which generated a momentum that created series of recommendations. Highway infrastructure deteriorates over time primarily due to traffic demand (axle loads), environmental conditions, and other factors. Transportation infrastructure system in the U.S.A. needs to be maintained periodically in order to increase the life span of the facility. Pavement is one of the most valuable components in transportation infrastructure system, and it is therefore very important to keep these facilities in good condition by carrying out periodical maintenance. In order to effectively meet this obligation, an efficient pavement management system (PMS) is considered. PMS is a tool that provides a technical-economic approach to assessing problems associated with pavement conditions. Various components of a road network system are analyzed and quantified in order to achieve total or partial optimization of pavement performance over certain period of time. A brief detail of the PMS is provided under the section of general overview.

2.3 Pavement Performance Evaluation

This section discusses the concept of serviceability and its importance. As earlier stated in the abstract, there are four major characteristics of evaluating pavement conditions: roughness i.e. the comfort of rideability, pavement distress i.e. surface condition, pavement deflection i.e. structural failure, and skid resistance, i.e. safety. Each of these characteristics is imbedded in the triple bottom-line factors of sustainability, examined and explained briefly.

Pavement roughness is the irregularities of the pavement surface which makes the smoothness of the surface to be either comfortable or uncomfortable to the rider. Present serviceability rating (PSR) and present serviceability index (PSI) were first introduced in the AASHTO Road Test to qualitatively and quantitatively rate the quality of rideability of pavements. The PSR is a grade number in a pavement section to rate the ability of the section to serve the designed traffic loads. Its rating scale is from 0-5; where 0 signifies very poor and the number 5 signifies “very good” as illustrated in figure 2. The PSI is a surrogate of PSR which is based on physical measurements and not based on panel ratings. Another closely related performance indicator is Pavement Condition Index (PCI) which was developed by U.S. Army Corp of Engineers to rate pavement condition. The PCI can be obtained through pavement serviceability evaluation panels (group of evaluators) which provide information concerning pavement conditions. PSI rates and evaluates the condition of a road network on annual
basis; it provides numerical rating of a road segment within the network or project system. Its numerical rating is between 0-100; where 0 is the worst condition and 100 is the best condition as illustrated in figure 2 below. The PCI is normally conducted annually in order to evaluate changes that occur in a road network system. It is a subjective method of evaluation based on inspection and observation. The PCI is an informative tool that tells the current condition of the road network and its deterioration over time. Some uses and benefits of PCI include identifying the need for immediate maintenance and rehabilitation (M & R) of roads; developing a road network preventive maintenance strategies and budgets; and for evaluating pavement materials and designs (see fig 2 [17]).

![Figure 2: Benefits of M & R as a function of pavement condition (PCI) [17].](image)

In order to develop an effective PCI, the road network should be divided into manageable segments or sections; sections with relatively uniform pavement structures, design and traffic volumes will have similar performance characteristics. For instance, a road network in urban settings should be kept in manageable length (shorter lengths for roads with severe deteriorated conditions) due to high volume of traffic activities. Whilst in the case of rural settings, the road network can be kept in manageable longer lengths due to lighter volume of traffic. In this research proposal, the roadway under consideration is arterial roadway that intersects between two state roadways.

The road section under consideration will be identified (using existing database from Maryland SHA) based on the following basic history:
- Road class (highway or freeway and arterial);
- Length, width, and geometry;
- Type and volume of traffic (trucks, auto, ADT and AADT);
- Initial construction date;
- Maintenance history, and
- Current PCI conditions based on past PCI conditions.

The condition of a pavement provides information through the PMS, when the pavement has some defects, such as surface defects: ravelling, flushing; surface deformation: rippling & shoving, wheel track rutting, distortion; cracking: longitudinal, centreline, pavement edge, and transverse defeats.

Pavement condition states are used to measure pavement performance in terms of discrete condition levels as stated above. These condition states help to provide information as to how the pavement would perform under each category in order to develop pavement serviceability indices such as International Roughness Index (IRI), Present Serviceability Index (PSI), Pavement Serviceability Rating (PSR), Structural Index (SI), Functional Index (FI), Rideability Index (RI), etc. Pavement serviceability (PS) was initiated by American Association of State Highway Official (AASHO) Road Test. In the proposed research paper, some of the relevant pavement indices (IRI and PSR, SRI (skid resistance index), SDI (surface distress index), and DI (deflection index) that relate to the paper objectives will be defined, analyzed, and introduced into the proposed model.

### 2.4 Pavement Serviceability

This section discusses the following definitions and their correlations of present serviceability, individual present serviceability rating, present serviceability rating (PSR), present serviceability index (PSI), and the performance index (PI). These terms are defined to correlate the subjective rating of pavement performance with objective measurements. Pavement serviceability is defined as the ability of the pavement to carry the accumulated traffic axle loads it is designed to serve under the existing pavement condition. There are two major methods for determining pavement serviceability; the Present Serviceability Index (PSI) and the International Roughness Index (IRI). These two methods are discussed and analyzed in this research. Also discussed are the relationship between PSI and IRI and their analysis based on existing models.

Present Serviceability Index (PSI) is the ability for a particular pavement section to serve the traffic (with}
different traffic mix, high volume of traffic, and high speed) under pavement current condition. PSI method was developed by AASHO Road Test according to Carey and Irick, 1960 [7]. The PSI is mostly based on both pavement distress condition and roughness, such as patching, cracking and rutting (in flexible pavements).

PS is the ability of a road section to serve vehicular traffic due to axle loads imposed on that particular section of the road under its current condition. PSR is defined as the rating of a pavement under its current conditions as illustrated in figure 3.

![Fig 3: Individual Present Serviceability Rating](image)

The PSI is a combination of mathematical formulation that is obtained from measuring pavement sections used to predict the PSR. AASHO Road Test originally developed the mathematical equations for PSI (the equations below were not used in determining the PSI in the numerical example) for both flexible and rigid pavements respectively (Jayawickrama et al, 1998 [29]).

\[
PSI = 5.03 - 1.9 \log (1+SV) - 0.01\sqrt{C+P} - 1.38RD^2 \tag{1}
\]

\[
PSI = 5.41 - 1.80 \log (1+SV) - 0.09\sqrt{C+P} \tag{2}
\]

Where:

- **SV** = Slope variance (rad²),
- **P** = bitumen patching in ft²/1000ft²
- **RD** = average rut depth in inches,
- **C+P** = the relative extent of cracking and patching in the wheel-path (ft²/1000ft²)

2.4.1 Correlations between PSR and IRI

There have been several correlations between PSR and IRI. According to literature reviews, the two most important correlations were reported by Paterson, 1986 [31]; and Al-Omari and Darter, 1992 [1], an Illinois funded study. Expressed mathematically in equations (3) and (4), respectively:

\[
PSR = 5.0e^{-0.18IRD} \tag{3}
\]

\[
PSR = 5.0e^{-0.26IRD} \tag{4}
\]

where,

- **PSR** = present serviceability rating
- **IRI** = international roughness index

The higher the value of PSR, the smoother the riding pavement surface. The PSR is a subjective ride based on individual observation of pavement conditions; while the IRI is based on the average rectified slope (ARS) – a filtered ratio of a standard vehicle's accumulated suspension motion (measured in millimetres, inches, etc.) divided by the distance travelled by the vehicle (5) [24]. For the purpose of this research, existing IRI shall be extracted from MDSHA database to determine the PSR. Table 1 below illustrates FHWA IRI thresholds.

<table>
<thead>
<tr>
<th>Condition Category</th>
<th>IRI Threshold (in/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>&lt;95</td>
</tr>
<tr>
<td>Fair</td>
<td>95 ≤ IRI ≤ 170</td>
</tr>
<tr>
<td>Poor</td>
<td>&gt;170</td>
</tr>
</tbody>
</table>

\[
IRI = ARS*1000 \tag{5}
\]

2.5 Skid Resistance (SR)

Skid resistance is a vital part or component of pavement performance evaluation. According to Highway Research Board, National Academy of Sciences, Washington D. C., [22], skid resistance is the force that develops when the tires are prevented from rotating on pavement surfaces. SR can cause skid related incidents or accidents if inadequately designed. It is the responsibility of the agency to provide road users reasonably safe pavement surface
for good ride quality depending on the materials and construction quality, such as microtexture (small-scale texture of pavement aggregate that is in contact between the rubber tires and the pavement surface) and macrotexture (the large-scale texture of the pavement aggregate that controls the escape of water from the rubber tires which may cause loss of SR if the speed is increased) (Corley-Lay, 1998) [8]. SR of a pavement increases in the first 2-3 years of the initial construction and decreases over the remaining years of the pavement due to wear of the pavement surface either by traffic or loose aggregate. Seasonal variation does affect SR – such as higher in the fall and winter and lower in the spring and summer seasons (Awoke G. S., 2011[2]). SR on dry pavements is higher than that of wet pavements, as illustrated in table below (Jayawickrama et al, 1996 [22]).

There are different techniques of measuring SR; the most common in US are the surface texture measurement, the locked wheel tester, and the spin up tester. Details of the various techniques are not within the scope of this research and so will not be discussed in this paper. The measurement of SR can be quantified using either skid number or friction factor; expressed mathematically:

**Friction factor**: \( f = \frac{F}{L} \) .................. (6)

**Skid number**: \( SN = 100f \) .................... (7)

where,

\( F \) = frictional resistance to motion in plane of interface

\( L \) = load perpendicular to interface

Table 2: Skid Resistance Threshold and treatment actions

<table>
<thead>
<tr>
<th>Skid Number</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>If SN &lt; 30</td>
<td>Take measurements to correct</td>
</tr>
<tr>
<td>If SN ≥ 30</td>
<td>Acceptable for low volume roadways</td>
</tr>
<tr>
<td>If SN 31 - 34</td>
<td>Frequent monitoring of pavements</td>
</tr>
<tr>
<td>If SN ≥ 35</td>
<td>Acceptable for high volume and heavily traveled roadways.</td>
</tr>
</tbody>
</table>

This section of the research discusses the effect of pavement deflection on the road network system. Structural deflection is one of the four components for evaluating and measuring pavement performance. It also plays an important role in evaluating pavement structures because the size and shape of pavement deflection is a function of factors that cause pavements to deteriorate. Such factors include, but not limited to the following: axle loads due to traffic volumes, temperature, and moisture due to expansion and contraction of the pavements; and pavement structural section. There are various methods and techniques for measuring pavement structural deflection; such as backcalculation, impact load deflection (Falling Weight Deflectometer - FWD), the static deflection, and steady state deflection. Detailed description of these techniques is not within the scope of this research. Figure 3 illustrates how deflection is measured in flexible pavements when a force is applied. For instance, when a truck drives along a pavement section on a roadway, the set of tires are the weights (i.e. empty) applied to the pavement surface and the load is transferred to the subgrade; which causes the pavement structure to deflect. This deflection is known as deflection basin as illustrated in the figures 4. But in the case of static or stationary load, the applied force is applied repeatedly using cyclic load and the deflection basin is measured in a number of locations as either single or multiple quick impacts.
2.7 Surface Distress

This category of pavement evaluation is the collection of pavement condition data. It is the presence of different types of distresses due to either construction defects, traffic loads, environmental or climate interaction; such as cracks and surface distortions. Data can be collected manually or auto collection processes. Data collected are through manual process are recorded on special forms as severity and extent. This paper considers three most common types of flexible pavements distress: patching, cracking, and rutting. These distresses are identified using distress identification manual developed for the Strategic Highway Research Program (SHRP) – [36].

2.8 Effects of Pavement Conditions

This section of the research discusses the impacts pavement conditions have on three sustainability dimension (environmental, social and economic). Each of these will be discussed separately (in the final work) based on the condition of the pavement in order to achieve the stated set goals and objectives of the research work.

There are several effects caused by pavement conditions, such as vehicle speed, safety, delay or congestion, increased travel time, environmental pollutions, social impacts and economic impacts, but to mention a few. All these effects are caused by the roughness of the pavement surfaces and they all correlate. This paper categorizes these effects into two cost components (user costs and agency costs). These costs are analyzed using LCCA model.

Roughness is the irregularities that occur on Pavement surfaces due to age, environmental effects, climate and traffic usage. These irregularities cause discomfort, delay, and safety issues to the users and more expensive for the agency to maintain or rehabilitate. The World Bank classified roughness as one of the main factors in the analysis and trade-offs involving road quality vs. user cost [32]. Roughness is quantified using IRI and PSR; with IRI being the most important index to determine performance.

2.9 Past Models

In this section we discuss different past models as they relate to the proposed dissertation research objectives. Models provide insights to different areas of pavement management systems, such as predicting future condition of pavements, estimation and timing of maintenance, it helps provide feedback to the design process, and life-cycle cost analysis (Haas, et al, 1994) [19]. The purpose of developing models is to preserve the pavement conditions, strengthen the pavement structures, and extension of life span service of the pavement.

According to Darter (1980) [9], there are four basic measures for developing reliable pavement models. These measures include database from existing pavements, adequate functionality of the model, models that meet the statistical criteria for prediction error, and measures that include all parameters that have relevant effects on pavement performance. There are several existing models used for assessing and predicting pavement conditions; some of which include: Markov processes, regression, neural networks, fuzzy logic, expert systems, etc. These techniques are used for creating index for pavement condition evaluation and future prediction of pavement conditions.

2.10 Review of Relevant Statistical Methods

Literature review indicates that there are several statistical methods for pavement performance. In
order to successfully understand the data and develop the model, the following logic shall be considered in the proposed model: data collection, determination of sample size “n”, regression analysis, analysis of variance, mean square of error (MS\_E), confidence level, F-tests & t-tests, etc. The following logic can be expressed mathematically:

1. Sample size (n) =

\[ n = \frac{X^2 \cdot N \cdot P \cdot (1 - P)}{(ME^2 \cdot (N - 1)) + (X^2 \cdot P \cdot (1 - P))} \]  

(8)

where,

n = sample size

\( X^2 \) = Chi-square for the specified confidence level

N = Population size

P = Population proportion

ME = desired margin of error

2. Confidence Intervals (CI) =

\[ CI = \text{Mean} \pm \left( Z \cdot \frac{\sigma}{\sqrt{n}} \right) \]  

(9)

Where,

CI = confidence interval

z = standard normal variates

\( \sigma \) = assumed standard deviation

n = sample size

3. Standard Error (S\_e) =

\[ S_e = \sqrt{\frac{MS_E}{n}} \]  

(10)

Where,

MS\_E = mean square error

n = sample size

The z-score is a good method for checking the validity of data used and this method will be introduced in the proposed model using the following formula:

4. \[ Z_i = \frac{X_i - \bar{X}}{S} \]  

(11)

where,

\( X_i \) = value of data i

\( \bar{X} \) = sample mean

S = sample standard deviation

3. Methodology

3.1 Introduction

Established literature reviews have shown that analytical methods have been developed to design different components of pavement performances due to pavement conditions and sustainability, such as, definitions of sustainability, pavement performance optimization, pavement condition indices, to name a few. Some of these models were mostly based on definitions, operation, structural and functional research oriented analysis; and they have contributed substantially to the society. However, the integration or correlations of sustainability indices with pavement condition indices were not practically fully explored. The purpose of this paper therefore is to establish relationships between sustainability indices and pavement performance indices. In order to implement this task, a multi-linear regression analysis (MLRA) model is considered, analyzed, quantified, weighed, and correlated, using the selected indicators. MLRA is considered for the proposed model because of the multiple variables involved in the research paper.

The following four categories for pavement performance evaluation considered in the analysis are:

1. Serviceability:
   - IRI
   - PSI
   - PSR
2. Skid resistance – safety
3. Structural capacity (deflection) index,
4. Surface distress index:
   - Patching,
   - Cracking,
3.2 Method of Data Collection

This paper consists of using existing IRI and ADT/AADT data from Maryland State Highway Administration (MSHA) as well as data obtained from conducting field investigations and measurements for pavement conditions. The data collected are in the following categories: Serviceability (IRI, & PSI), Structural capacity (SCI), Surface distress (PCI), and Safety or skid resistant index (SRI). The collected data is analyzed to obtain the importance and significance of the relationship between pavement evaluation indices and selected triple dimension sustainability indices, such as environmental impact (carbon monoxide, Nitrogen oxide, water runoff, and noise), social impact (fuel consumption, congestion), and economic impact (vehicle operation costs, user costs and agency costs). These indicators will be analyzed and weighed individually.

3.3 Methodology Approach

For the purpose of this paper, the methodology approach is in two components – pavement index analysis, and sustainability index analysis. Each component is analyzed using hypothetical data and developed into a model that would provide a standard template plan that is used to generate the needed level of investment that can sustain the highway infrastructures for a long-term horizon. The paper involves two variables – pavement performance index (PPI) as the independent variables and sustainability index as the dependent variables. The sustainability index (SI) is a function of pavement performance indices (PPI) (12). Only the first three independent variables will be analysed in this paper due to time constrain. We chose to use hypothetical data for this paper due to time constrain and they are consistent with normal real world range.

The data are assumed in this paper and collected using manual survey (i.e. five-man panel survey to rate the pavement sections). The pavement condition survey is conducted on a scale of 0 – 1 for SI; and the MLRA is used to model the relationships between the major selected independent variables (IRI, PSR and PSI), using the basic (AASHTO, 2001) MLRA equation (15):

\[ SI = f(\text{IRI, PSI, PSR, SDI, SRI, CI, RI, PI}) \ldots \text{(12)} \]

Assuming:

\[ SI = y \] (dependent variable)

expressed as a function,

\[ Y = f(X) \ldots \text{(13)} \]

therefore,

\[ Y = f(x_1, x_2, x_3, \ldots, x_n) \ldots \text{(14)} \]

\[ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \ldots + \beta_{p-1} x_{p-1} + e \ldots \text{(15)} \]

where,

\[ Y = \text{dependent variable}, \]
\[ x_{1,2,\ldots,p-1} = \text{independent variables} \]
\[ \beta_0 = \text{regression constant (linear regression intercept)} \]
\[ \beta_{1,2,\ldots,p-1} = \text{variable constants (slope for linear regression)} \]
\[ e = \text{random error} \]

Three objectives to consider when developing the MLRA model:

- Estimate the unknown parameters (\( \beta \)),
- hypothesized the proposed linear model, and
- Check if the model is good for predicting the dependent variable \( Y \).

3.4 Model Accuracy

Once the developed model is checked for fitness, it is important to determine if the designed model is good for predicting the dependent variable. In order to perform this, a hypothesis test is carried out on all the regression (\( \beta \) - parameters) constants (excluding \( \beta_0 \)), using the following equation (16); using F-test based on the null (\( H_0 \)) and alternative (\( H_a \)) hypothesis:

\[ H_0: \beta_1 = \beta_2 = \ldots \beta_k = 0 \ldots \text{(16)} \]

\[ H_a: \text{one of the parameters should differ from zero} \]

therefore,

\[ F = \text{model mean square/error mean square}, \]
\[ F = \left( \frac{R^2}{1 - R^2} \right) \left[ n - (k + 1) \right] \frac{1}{k} \] ........................ (17)

Rejection region \( F > F_a \)

where,

\( n \) = number of observations,
\( k \) = number of parameters in the model (except \( \beta_0 \)),
\( R^2 \) = multiple coefficient of determination, and
\( a \) = significance level

### 3.5 Numerical Example

For the purpose of illustration, this paper analyzes a simple hypothetical two lane roadway pavement sections with 2 links \( n = 2 \) (L1, and L2) in a residential community setting with hypothetical input data (see figures 7 & 8). Please note that it is strictly a hypothetical example, just to demonstrate a simple application of our metrology; analysis of realistic data remains to be done in the future.

The roadway connects two hypothetical State maintained roadways used by drivers as cut through to their destinations. Link 1 has a roadway configuration of two-lane roadway with hypothetical data (see figure 7). The volume of traffic on this link is assumed to be low with AADT of less than 10,000 veh/day/lane. Link 2 has roadway characteristics of four lanes (2 lanes each direction) with a 4 ft. concrete median. It is assumed that link 2 has traffic volume of greater 10,000 veh/day/lane. Each lane is 12 ft. wide without shoulders for both links. The proposed analysis is performed in Microsoft Excel. The input data used for this model are listed in Tables 3 & 4, respectively; \( y \) = dependent variable, \( x_1 \), \( x_2 \), and \( x_3 \) = independent variables. The paper assumes parameters \( k = 3 \) (\( x_1 \), \( x_2 \), and \( x_3 \)) to represent IRI, PSR, and PSI, respectively.

where,

IRI (\( x_1 \)) = International roughness Index,
PSR(\( x_2 \)) = Present Serviceability Rating, and
PSI(\( x_3 \)) = Present Serviceability Index.

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**Figure 7:** A simple 2-Lane Roadway with double yellow centre line

**Figure 8:** A sample Roadway of Four lanes with a concrete 4 Feet median.

**Table 3:** Parameters for multi-linear regression model (Link 1).

<table>
<thead>
<tr>
<th>Data Point</th>
<th>( x_0 )</th>
<th>( x_1 ) (IRI)</th>
<th>( x_2 ) (PSI)</th>
<th>( x_3 ) (PSR)</th>
<th>( y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>10</td>
<td>4.9</td>
<td>4.799</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>20</td>
<td>4.6</td>
<td>4.606</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>30</td>
<td>4.2</td>
<td>4.421</td>
<td>0.90</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>40</td>
<td>4.2</td>
<td>4.244</td>
<td>0.85</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>50</td>
<td>4.1</td>
<td>4.073</td>
<td>0.80</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>60</td>
<td>3.9</td>
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**Graphs for Link 1**

**Fig 8a:** Multi-Linear Regression Analysis of SI vs. IRI
Fig 8b: Regression analysis of SI vs. PSI

Fig 8c: Regression analysis of SI vs. PSR

LINK 2:

Table 4: Parameters for multi-Linear regression model (Link 2).

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Graphs for Link 2

Fig 9a: Multi-Linear Regression Analysis of SI vs. IRI

Fig 9b: Multi-Linear Regression Analysis of SI vs. PSI

Fig 9c: Multi-Linear Regression Analysis of SI vs. PSR
4 Results and Discussion

While the hypothetical data used for the numerical example, for the most part exhibit characteristics of real-world pavements, the very high values of IRI appearing in the dataset may not seem realistic. IRI is usually measured in meters/km or millimetre/meter, a higher value usually represents a deteriorating pavement.

The numerical example (using Microsoft excel) shows the graphs of coefficient of determination $R^2$ for the different independent variables for both links 1 & 2 respectively. $R^2$ for link 1 shows perfect fit compared to link 2 $R^2$. This indicates that the regression line perfectly fits the line of data and strongly correlated in link 1 (see figures 8a – 8c).

In link 2, $R^2$ is also strongly correlated because the regression line does perfectly fit the line of data (see figures 9a-9c).

Analyzing the graphs for the different variables, it shows that the independent variables are strongly correlated in link 1; with the independent variable $x_1$ (IRI) $R^2 = 0.99$, $x_2$ (PSI) $R^2 = 0.9957$, and $x_3$ (PSR) $R^2 = 0.9852$. It is observed that and can be concluded from above analysis that the variables in link 1 are highly correlated; which means there is a strong linear relationship between sustainability index and pavement performance indices. While in link 2, the independent variables $x_1$ (IRI) $R^2 = 0.9801$, $x_2$ (PSI) $R^2 =0.9885$, and $x_3$ (PSR) $R^2 =0.9535$. This makes the model to be a useful one when applied to real data.

4.1 Future Work
An extensive work is to be carried out in the future to further analyze more data regarding the “Three Pillar sustainability dimensions (environmental. Social, and economic values) in order to determine the relationships between sustainability indices and pavement performance indices. In conclusion, it is observed that the coefficients of determination $R^2$ are very good fits between the proposed model and data for both links as demonstrated in the graphs above, at least for the hypothetical example presented above.

References:


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