

Development of a Predictive Model for Road Maintenance Management Based on Correlation of IRI, PCI and Traffic Data

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ABSTRACT

National road infrastructure is a strategic asset requiring effective, data-driven maintenance management systems. This study develops a predictive model for road maintenance management through correlation analysis of International Roughness Index (IRI), Pavement Condition Index (PCI), and traffic parameters on the 155 km Makassar-Parepare corridor. A quantitative descriptive-explanatory approach was applied to 26,818 observation segments spanning 2020-2024 from the BBPJN South Sulawesi Pavement Management System. Multiple regression models were developed with 70:30 validation split, and Earned Value Management (EVM) was implemented on 50 maintenance projects totaling IDR 65.08 billion. Results show a significant negative IRI-PCI correlation ($r = -0.2710$, $p < 0.001$) and weak positive IRI-AADT correlation ($r = +0.1898$, $p < 0.001$). The regression model yielded $R^2 = 0.1110$ for IRI prediction (RMSE = 1.03 m/km) and $R^2 = 0.1053$ for PCI (RMSE = 12.55), with pavement age (AGE) as the strongest predictor. Validation shows the Moderate Scenario 2024 prediction (IRI 5.71 m/km) nearly identical to actual data (5.70 m/km). EVM analysis produced mean CPI of 0.9758 and mean SPI of 0.9435. Integration of predictive models, EVM, and IRMS unit costs yields a data-driven maintenance strategy with 15-20% potential budget savings through timely preventive maintenance.

Keywords: IRI, PCI, predictive model, earned value management, road maintenance management, makassar-parepare corridor.

INTRODUCTION

Road infrastructure plays a crucial role as the lifeblood of a nation's economy and social connectivity. In Indonesia, the total road network spans over 542,000 kilometers [1], a national asset that requires careful, sustainable management and maintenance. The currently dominant reactive maintenance system leads to significant budgetary waste, as road segments are often left to deteriorate into a state of severe damage before any intervention takes place.

The Makassar-Parepare national road corridor stretches approximately 155 kilometers, traversing the city of Makassar, the regencies of Maros and Pangkajene and Islands (Pangkep), Barru Regency, and the city of Parepare. This corridor comprises 19 national road segments that facilitate the movement of people and goods, while serving industrial zones, ports, and economic hubs in the western part of South Sulawesi. The growth in Gross Regional Domestic Product (GRDP) per capita within this corridor—ranging from 27.8% to 45.0% between 2020 and 2024—coupled with a surge in motor vehicle ownership (notably an 80.9% increase in Maros Regency), necessitates a more systematic approach to road maintenance management.

Research into the relationship between the International Roughness Index (IRI) and the Pavement Condition Index (PCI) as indicators of road condition has been conducted extensively. An aggregate R^2 of 0.31 was obtained using a Long-Term Pavement Performance (LTPP) dataset comprising 3,954 records collected over 28 years [2]. Regional characteristics significantly influence the IRI-PCI relationship [3], and a dual-model approach—incorporating distress types, climatic data, and traffic information—has been developed, yielding a validation R^2 of 0.89 [4]. At the local level, studies on the Maros-Makassar road segments [5, 6] have identified correlation characteristics

consistent with Indonesia's tropical conditions. Regarding project control, [7] found that projects with a mature Earned Value Management (EVM) environment can achieve cost savings of up to 25% against the budget baseline, while [8] demonstrated that implementing EVM in road construction projects in developing countries can significantly improve the predictability of project completion. However, the integration of road deterioration predictive models with EVM-based cost-schedule performance analysis remains very limited in the literature, particularly concerning the conditions of national roads in Indonesia.

This research aims to: (1) analyze the statistical correlations between the International Roughness Index (IRI), Pavement Condition Index (PCI), and traffic data, based on 26,818 observation segments from the 2020–2024 period; (2) develop a multiple regression predictive model for forecasting future IRI and PCI values; (3) implement EVM across 50 maintenance projects to measure cost and schedule performance; and (4) formulate an integrated maintenance prioritization strategy, incorporating the unit costs used in the Integrated Road Management System (IRMS) for South Sulawesi.

International Roughness Index (IRI)

The International Roughness Index (IRI) is an international standard for measuring road surface unevenness, developed by the [9]. IRI is defined as the accumulated vertical displacement of a standard vehicle's suspension per unit of distance traveled (m/km). Its fundamental concept involves simulating the dynamic response of a "quarter-car" vehicle model traveling at a speed of 80 km/h over a measured road profile. The IRI has been adopted by over 100 countries for road condition evaluation and can be measured using various methods—ranging from laser profilers to crowdsourced data from connected vehicles [10]. Demonstrated that the use of data from connected vehicles can provide IRI coverage for up to 98% of a road network [11]. The classification of road conditions based on the International Roughness Index (IRI) [12], is presented in Table 1.

Table 1. Classification of Road Conditions Based on IRI [12]

IRI Value (m/km)	Classification	Description
$\leq 4,0$	Good	Surface very even, maximum comfort
4,1 – 8,0	Fair	Surface becoming uneven, reduced comfort
8,1 – 12,0	Minor Damage	Significant unevenness, potentially hazardous
$> 12,0$	Severe Damage	Highly uncomfortable condition, immediate attention required

Pavement Condition Index (PCI)

The Pavement Condition Index (PCI) is a method for assessing road pavement conditions, developed and adopted as the ASTM D6433-23 standard [13]-[14]. The PCI measures the structural and functional condition of pavement on a scale of 0–100, accounting for 19 types of distress in asphalt pavements across three severity levels: low, medium, and high. The PCI provides a comprehensive numerical representation that links the visual condition of the pavement to recommended maintenance actions [15]. Combining the PCI with the International Roughness Index (IRI) offers a more comprehensive overview of road conditions than using either indicator alone [16]-[18].

IRI-PCI Correlation and Deterioration Factors

The relationship between the IRI and the PCI is a subject of intensive research. Theoretically, the IRI describes ride comfort, while the PCI describes the structural condition of the pavement—the two are related but not identical. Utilized the Long-Term Pavement Performance (LTPP) dataset and found an r^2 value of 0.31, with significant variation across different regions [2]. Confirmed that the IRI-PCI relationship differs significantly between arid and tropical climates [3]. Developed a dual-model approach that integrates distress types, climatic data, and traffic, yielding a validation R^2 of 0.89 [4]. In the Indonesian context, studies [16], focusing on the Maros-Makassar-road section—demonstrate a correlation consistent with tropical deterioration characteristics. Confirm

the importance of pavement age and vehicle load as variables in modeling the deterioration of national roads [19], [20].

Earned Value Management (EVM)

Earned Value Management (EVM) is a project management methodology that integrates scope, schedule, and cost into a single performance measurement system. Three fundamental metrics—Planned Value (PV), Earned Value (EV), and Actual Cost (AC)—are used to derive the Cost Performance Index ($CPI = EV/AC$) and the Schedule Performance Index ($SPI = EV/PV$). CPI and SPI values greater than 1.0 indicate cost efficiency and favorable schedule progress. Found that projects with a mature EVM environment can achieve cost savings of up to 25%, while. Demonstrated that implementing EVM in road construction projects within developing countries enhances project predictability. Highlighted the potential for integrating historical project performance data with machine learning models to predict future road maintenance performance [21], [22].

RESEARCH METHODOLOGY

Research Design and Location

This study employs a descriptive-explanatory quantitative approach based on three analytical pillars: (1) a correlational analysis of the International Roughness Index (IRI), Pavement Condition Index (PCI), and traffic parameters; (2) predictive modeling of deterioration using multiple regression; and (3) project performance analysis using the EVM methodology. The entire analysis relies on secondary data from the 2020–2024 period, with no primary data collection. The research is situated along the ± 155 km Makassar–Parepare national road corridor in South Sulawesi Province, encompassing 19 national road segments that traverse the city of Makassar and the regencies of Maros, Pangkep, and Barru, as well as the city of Parepare. The analysis was conducted in 100-meter segments, yielding 5,344–5,380 segments per year, for a total of 26,818 observation segments across the study period.

Research Data and Variables

The research data were derived from 10 datasets: IRI, PCI, and AADT data per segment from the BBPJS South Sulawesi Pavement Management System (PMS) (2020–2024); IRI prediction scenarios from the PMS; Earned Value Management (EVM) project data from BBPJS contract documents; Gross Regional Domestic Product (GRDP) per capita and registered motor vehicle data from the Central Statistics Agency (BPS) of South Sulawesi; budget allocations (RKAKL) from the Directorate General of Highways; maintenance unit costs from the Integrated Road Management System (IRMS); and climate and topographical data for the corridors from the Meteorology, Climatology, and Geophysics Agency (BMKG) Region IV Makassar. The dependent variables in the predictive model are future IRI (IRI_{t+n}) and future PCI (PCI_{t+n}), while the independent variables include current IRI, current PCI, AADT, the percentage of trucks, and pavement age (AGE).

Analysis Technique

The analysis was conducted in sequential steps: (1) descriptive statistics for each variable per year; (2) Pearson correlation analysis at $\alpha = 0.05$ for 26,818 pairs of observations; (3) development of a multiple regression model using a 70:30 data split (training $n = 18,552$; testing $n = 6,266$); (4) model evaluation using R^2 , RMSE, and MAE; (5) Earned Value Management (EVM) analysis by calculating $CPI = EV/AC$, $SPI = EV/PV$, $CV = EV - AC$, and $SV = EV - PV$ for 50 maintenance projects; (6) validation of the official Pavement Management System (PMS) prediction scenarios against actual data; and (7) integration of the predictive model with the South Sulawesi IRMS unit costs (regional coefficient of 1.06). The predictive model equations developed are:

$$IRI_{future} = 5.0365 + 0.3001 \times IRI_{current} - 0.0058 \times PCI_{current} - 0.000003 \times AADT + 0.0021 \times TRUCK_PCT - 0.4682 \times AGE \quad (1)$$

$$PCI_{future} = 70.4096 - 2.2957 \times IRI_{current} + 0.2028 \times PCI_{current} - 0.000016 \times AADT - 0.1418 \times TRUCK_PCT + 11.2459 \times AGE \quad (2)$$

RESULTS AND DISCUSSION

Description of Road Conditions in the Corridor (2020–2024)

Road condition data from 26,818 observed segments show an average International Roughness Index (IRI) value for the corridor of 5.50 m/km, with a standard deviation of 1.23 m/km—a value classified as "Fair" (Sedang) according to Bina Marga (2022) standards. The IRI trend shows an increase from 4.78 m/km (2020) to 5.81 m/km (2022), driven by a post-pandemic surge in AADT—from 8,631 vehicles/day (2020) to 48,298 vehicles/day (2022)—before improving to 5.70 m/km (2024) as a result of periodic preservation programs. The distribution of IRI conditions is presented in Table 2.

Table 2. Distribution of IRI Conditions, 2020–2024 (Measured Data from BBPJN South Sulawesi)

Years	N Segment	Average IRI	Std. Dev.	Good (%)	Fair (%)	RR (%)	RB (%)
2020	5.380	4,78 m/km	1,43	38,8	60,5	0,7	0,0
2021	5.370	5,49 m/km	1,11	9,1	88,7	2,1	0,1
2022	5.380	5,81 m/km	1,00	6,6	90,9	2,5	0,0
2023	5.344	5,72 m/km	1,09	7,8	89,8	2,4	0,0
2024	5.344	5,70 m/km	1,18	13,0	85,1	1,9	0,0

Source: BBPJN South Sulawesi (2020–2024)

The average Pavement Condition Index (PCI) for the corridor is 82.70, indicating a "Very Good" structural condition according to ASTM D6433-23. The highest value was recorded in 2024 (85.58), following an intensive rehabilitation program in 2023, which was supported by a peak RKAKL (Budget Implementation List) allocation of IDR 588.6 billion. The socio-economic context shows significant growth: Gross Regional Domestic Product (GRDP) per capita increased by 27.8% (in Parepare) to 45.0% (in Maros), while motor vehicle ownership also rose—with Maros Regency recording the highest growth at +80.9%, reaching 163,026 units by 2024.

Correlation Analysis Between Variables

A Pearson correlation analysis was conducted on 26,818 pairs of observations at a significance level of $\alpha = 0.05$. The results are presented in Table 3.

Table 3. Pearson Correlation Matrix (n = 26,818 Observations)

Variable Pair	Correlation Coeff. (r)	p-value	Strength and Direction
IRI vs PCI	-0,2710	< 0,001	Weak negative, significant
IRI vs AADT	+0,1898	< 0,001	Weak positive, significant
IRI vs TRUCK_PCT	-0,0187	> 0,05	Not significant
AADT vs TRUCK_PCT	-0,6059	< 0,001	Moderate negative, significant

Source: Analysis results (2024)

The IRI-PCI correlation of $r = -0.2710$ ($p < 0.001$)—classified as weak yet significant—reflects the unique characteristics of road deterioration in the Indonesian tropics. Periodic maintenance programs (RKAKL) selectively improve the International Roughness Index (IRI) through surface treatments without necessarily yielding a proportional improvement in the Pavement Condition

Index (PCI); this occurs when functional interventions enhance ride quality without comprehensively addressing structural damage. These findings are consistent with Hamedi et al. (2020), Radwan et al. (2024), and Evans et al. (2025), who demonstrate that correlations vary based on regional conditions and maintenance patterns.

The positive IRI-AADT correlation ($r = +0.1898$, $p < 0.001$) indicates that higher traffic volumes are associated with increased surface roughness, though this influence is not independent; it is mediated by maintenance quality, pavement age, and environmental conditions. A moderate negative correlation between AADT and the percentage of trucks (TRUCK_PCT) ($r = -0.6059$, $p < 0.001$) suggests that road segments with high total traffic volumes tend to be dominated by passenger vehicles, whereas lower-volume segments exhibit a higher proportion of trucks—a pattern typical of mixed-use corridors that serve both urban centers and interregional logistics routes.

Multiple Regression Predictive Model

A multiple regression model was developed using a data split of 70% for training ($n = 18,552$) and 30% for testing ($n = 6,266$). The model equations are presented in equations (1) and (2). The model coefficients and performance are presented in Table 4.

Table 4. Coefficients and Performance of Multiple Regression Predictive Models

Predictor Variable	Coefficient	Model IRI ($R^2=0.111$)	Model PCI ($R^2=0.105$)
AGE (Strongest Predictor)	-0,4682 (IRI)	Periodic maintenance cycles improve IRI	Periodic preservation improves PCI systematically
IRI_current	+0,3001	Current poor conditions tend to persist	-2.2957: High roughness exacerbates structural deterioration
PCI_current	-0,0058	Good structural condition dampens roughness	+0.2028: Good initial condition is maintained
AADT	-0,000003	Minimal impact, intensive maintenance	-0.000016: Cumulative effect on PCI
TRUCK_PCT	+0,0021	Percentage of trucks increases roughness	-0.1418: Trucks accelerate structural degradation

Source: Analysis results (2024)

The AGE variable emerges as the strongest predictor in both models—with a negative coefficient of -0.4682 for the IRI model and a positive coefficient of +11.2459 for the PCI model. This phenomenon reflects the periodic maintenance mechanism for national corridors: preservation programs scheduled based on pavement age systematically improve pavement condition. This is consistent with the findings who emphasize the significance of the age factor in pavement performance prediction models.

The low R^2 values (0.1110 for IRI and 0.1053 for PCI) should be interpreted within their proper context. In large datasets ($n > 26,000$) characterized by high variability—stemming from the heterogeneity of 19 road segments—low R^2 values are typical in linear pavement performance modeling; for instance, reported an R^2 of 0.31 using the LTPP dataset. The RMSE values—1.03 m/km for IRI predictions and 12.55 for PCI—remain within a satisfactory range for supporting maintenance decision-making at the corridor level. Machine learning methods, such as Random Forest and Hybrid AI-LiDAR, can yield higher R^2 values, suggesting these as promising avenues for future study.

Validation against official Pavement Management System (PMS) scenarios demonstrates satisfactory accuracy: the 2024 "Moderate Scenario" prediction of 5.71 m/km (IRI) is nearly

identical to the actual observed value of 5.70 m/km, confirming that the model effectively captures the deterioration dynamics of the corridor for maintenance planning purposes.

Earned Value Management (EVM) Analysis

An EVM analysis was conducted on 50 corridor maintenance projects spanning the 2022–2024 period, with a total Budget at Completion (BAC) of IDR 65.08 billion. The aggregate results show a Total Planned Value (PV) of IDR 35.92 billion, Total Earned Value (EV) of IDR 34.02 billion, and Total Actual Cost (AC) of IDR 35.69 billion. This yields a Cost Variance (CV) of -IDR 1.66 billion, a Schedule Variance (SV) of -IDR 1.90 billion, a Cost Performance Index (CPI) of 0.9758 (indicating a 2.42% cost overrun), and a Schedule Performance Index (SPI) of 0.9435 (indicating a 5.65% schedule delay). EVM performance by type of work is presented in Table 5.

Table 5. EVM Performance by Type of Work (50 Projects, 2022–2024)

Type of Work	Project N	Total Value	Average CPI	Average SPI	Description
Surface Treatment	8	Rp 5,81 M	1,060	1,045	Best
Patching	10	Rp 6,95 M	1,011	0,979	Good
Overlay AC	22	Rp 38,57 M	0,950	0,925	Fair
Rehabilitasi	10	Rp 15,76 M	0,896	0,873	Weakest
TOTAL	50	Rp 65,08 M	0,9758	0,9435	

Source: EVM analysis results (2022–2024)

Surface Treatment demonstrated the best performance (CPI 1.060, SPI 1.045), indicating that this type of work is not only cost-efficient but also completed ahead of schedule. Conversely, Rehabilitation showed the weakest performance (CPI 0.896, SPI 0.873), with a 10.4% cost overrun and a 12.7% schedule delay. This performance disparity can be attributed to technical complexity: Rehabilitation requires multi-stakeholder coordination, more intensive site preparation, and is more susceptible to weather-related disruptions. Who identified that the complexity of the scope of work is positively correlated with the risk of cost overruns.

Temporal analysis indicates that projects executed during the dry season (July–September) tend to have higher SPI values compared to those carried out during the rainy season. This confirms the importance of scheduling maintenance with consideration for the tropical climate cycle—characterized by an annual rainfall of 2,000–2,500 mm and a rainy season spanning October to March—as per data from the BMKG (Meteorology, Climatology, and Geophysics Agency) Region IV, Makassar.

Integrated Maintenance Strategy

The integration of predictive deterioration models, historical EVM performance analysis, and the South Sulawesi IRMS (Integrated Road Management System) unit costs (with a regional coefficient of 1.06) has resulted in a data-driven maintenance strategy framework, presented in Table 6.

Table 6. Integrated Maintenance Strategy: IRI, South Sulawesi IRMS Unit Costs, and Historical CPI

IRI Condition	Priority	Optimal Treatment	South Sulawesi Price (IDR/m ²)	Historical CPI	Allocation
IRI > 12 m/km (Severely Damaged)	Critical	Flexible Pavement Reconstruction	1.923.900	0,896	Sesuai

IRI Condition	Priority	Optimal Treatment	South Sulawesi Price (IDR/m ²)	Historical CPI	Allocation
IRI 8–12 m/km (Slightly Damaged)	High	Overlay AC / Str. Overlay 80mm	475.940	0,950	40%
IRI 6–8 m/km (Moderately High)	Medium	Surface Treatment / Slurry Seal	86.920	1,060	35%
IRI 4–6 m/km (Moderate)	Low	Routine Maintenance /Condition	4.452 – 8.268	1,011	25%

Source: Integrated analysis results (2024)

A potential budget saving of 15–20% can be achieved through a preventive maintenance mechanism: addressing road segments with an International Roughness Index (IRI) of 6–8 m/km using surface treatment (IDR 86,920/m², Condition Performance Index [CPI] 1.060) before they deteriorate into severe damage requiring full reconstruction (IDR 1,923,900/m², CPI 0.896). The cost ratio between these two interventions is 1:22.1, meaning that the cost of one square meter of reconstruction is equivalent to 22 square meters of preventive treatment—a compelling economic argument for shifting the paradigm from reactive to preventive maintenance.

Allocating the budget at a ratio of 40–35–25% for high, medium, and low-priority segments, respectively, enables the optimization of the maintenance portfolio by accounting for actual conditions, projected deterioration, and historical implementation efficiency. Extreme fluctuations in the annual budget plan (ranging from IDR 116.5 billion to IDR 588.6 billion per year) must be stabilized through multi-year planning based on predictive models to prevent a maintenance backlog that would further degrade the condition of the road corridor. The Directorate General of Highways at the Ministry of Public Works and Housing (2021; 2024a) and Sitanggang et al. (2022) confirm that a GIS-based Pavement Management System (PMS) approach, utilizing real-time IRI and Pavement Condition Index (PCI) data, represents a relevant development direction for Indonesia's national road network.

CONCLUSION

Based on a comprehensive analysis of 26,818 observed segments over the 2020–2024 period along the Makassar–Parepare corridor, it can be concluded that: 1) There is a weak yet statistically significant correlation between IRI and PCI ($r = -0.2710$, $p < 0.001$), as well as a correlation between IRI and the Annual Average Daily Traffic (AADT) ($r = +0.1898$, $p < 0.001$). The weak correlation reflects the deterioration characteristics of tropical roads in Indonesia, which are influenced by periodic maintenance programs (RKAKL), local construction practices, and a humid tropical climate (annual rainfall of 2,000–2,500 mm). 2) The multiple regression model yielded an R^2 of 0.1110 for IRI prediction (RMSE = 1.03 m/km) and an R^2 of 0.1053 for PCI (RMSE = 12.55), with pavement age (AGE) serving as the strongest predictor. Validation indicates that the 2024 "Moderate Scenario" prediction (IRI 5.71 m/km) is nearly identical to the actual data (5.70 m/km). 3) Earned Value Management (EVM) analysis of 50 projects (totaling IDR 65.08 billion, 2022–2024) resulted in an average Cost Performance Index (CPI) of 0.9758 (a 2.42% cost overrun) and an average Schedule Performance Index (SPI) of 0.9435 (a 5.65% delay). "Surface Treatment" projects performed best (CPI 1.060, SPI 1.045), while "Rehabilitation" projects performed the weakest (CPI 0.896, SPI 0.873). 4) Integrating the predictive model, EVM, and the South Sulawesi Integrated Road Management System (IRMS) unit costs (with a regional coefficient of 1.06) facilitates a data-driven maintenance strategy. This includes an optimal allocation of 40%–35%–25% across high, medium, and low-priority categories, as well as the potential for 15–20% cost savings through timely preventive maintenance on road segments with an IRI of 6–8 m/km.

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