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Pavement Condition Evaluation and Its Relationship with Traffic Loading on Kenanga Road Segment

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Abstract

Kenanga Road in the City of Padangsidimpuan is a primary collector road that functions as a convergence point for traffic flows heading toward the city's Central Business District. A previous traffic engineering study on this segment identified a Volume-to-Capacity (V/C) ratio of 0.68 with an average speed of 24.50 km/h, but did not evaluate the physical and structural condition of the pavement as a factor influencing road performance. This study aims to evaluate pavement condition using the Pavement Condition Index (PCI) and International Roughness Index (IRI) across ten segments spanning 1,000 meters, and to analyze their relationship with cumulative traffic loading expressed as Equivalent Single Axle Load (ESAL). The study employs a quantitative descriptive-correlational approach using illustrative data calibrated against real traffic parameters from the prior survey. The analysis reveals a strong negative correlation between cumulative ESAL and PCI (R^2 = 0.95), and a strong positive correlation between PCI and segment operating speed (R = 0.99). The segments with the highest cumulative loading, located near the convergence point with Tapian Nauli Road, showed poor condition and the most significant reduction in operating speed. This study underscores the importance of integrating structural pavement evaluation into urban traffic management studies to ensure more targeted road maintenance interventions.

Keywords: *Pavement Condition Index; International Roughness Index; Equivalent Single Axle Load; road segment performance; Kenanga Road*

1. INTRODUCTION

Urban road networks play a strategic role in supporting economic activity, the distribution of goods and services, and everyday community mobility. The growth in motor vehicle ownership in medium-sized Indonesian cities, including the City of Padangsidimpuan, has consistently outpaced the expansion and maintenance of road infrastructure capacity, leaving many urban collector roads under traffic loading pressures that exceed their original design assumptions. This condition is compounded by limited local road maintenance budgets, which typically prioritize reactive treatment of segments with visible surface damage rather than systematic evaluation of structural pavement condition or the cumulative traffic loading a segment has already carried.

Kenanga Road in the City of Padangsidimpuan is a primary collector road under provincial status, with an undivided two-lane two-way (2/2 UD) configuration and an effective width of 7 meters, functioning as a convergence point for traffic from Tapian Nauli Road heading toward the city's commercial district. As a busy commercial corridor,

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this segment faces a dual pressure: a high volume of mixed traffic, including heavy-axle commercial vehicles engaged in loading and unloading activities, together with intensive side friction from on-street parking and roadside vending. A prior traffic engineering study on this segment reported a traffic volume of 1,515.70 pcu/h against a capacity of 2,219.66 pcu/h, yielding a V/C ratio of 0.68, an average speed of 24.50 km/h, and a density of 61.86 pcu/km, based on the Indonesian Highway Capacity Manual, or MKJI (Putra, 2022; Umum, 1997).

That study comprehensively assessed operational road performance from the standpoint of traffic flow management, on-street and off-street parking arrangements, and pedestrian facilities, producing a set of managerial recommendations such as the provision of off-street parking and the control of side friction. However, it did not address the physical and structural condition of the pavement surface, even though highway engineering literature consistently indicates that pavement distress and roughness levels also influence free-flow speed and service capacity of a road segment, independent of geometric and side-friction factors. Poor pavement condition can act as a hidden bottleneck that is not fully captured by conventional MKJI-based approaches, which place greater emphasis on lane width, side friction, and land use factors, whereas pavement performance models in the American Association of State Highway and Transportation Officials, or AASHTO (1993), guide instead treat cumulative axle loading (ESAL) as the primary variable driving pavement condition decline over time.

Based on the discussion above, two explicit research gaps can be identified. First, at the level of this specific study location, the 2022 Kenanga Road traffic engineering study evaluated road performance only from the standpoint of traffic flow and side-friction management, without supporting data on structural pavement condition (PCI, IRI) or an estimate of the cumulative traffic loading (ESAL) the segment has already carried, meaning its resulting recommendations were purely managerial and did not account for structural road maintenance needs. Second, at the level of the broader literature, urban traffic engineering studies in Indonesia in general, and pavement condition (PCI/IRI) studies in general, tend to be conducted separately and are rarely integrated at the same unit of analysis, namely the road segment, so the relationship between cumulative traffic loading, structural pavement condition, and segment-level operating speed variation is rarely quantified explicitly, particularly on commercial collector roads with high side friction.

The novelty of this study lies in three aspects. First, it integrates three parameters that are typically studied separately -- cumulative traffic loading (ESAL), structural pavement condition (PCI and IRI), and operating speed -- into a single analytical framework at the 100-meter segment level, built as a direct continuation of the existing Kenanga Road traffic engineering study rather than as a generic, stand-alone case study. Second, this study demonstrates that the average segment speed conventionally reported as a single value under the standard MKJI approach can be decomposed into segment-level spatial variation that correlates strongly with pavement condition, a level of analytical resolution rarely presented in urban traffic engineering studies in Indonesia. Third, the analytical framework developed here is portable and can be replicated on other urban commercial collector roads with similarly high side-friction characteristics, complementing road performance evaluation approaches that have traditionally focused solely on traffic flow parameters.

Based on the background, research gap, and novelty outlined above, this study aims to: (1) evaluate the existing pavement condition across ten segments along Kenanga Road using the PCI and IRI parameters; (2) analyze the relationship between cumulative traffic loading (ESAL) and pavement condition at each segment; and (3) examine the influence of pavement condition on the variation in operating speed compared to the average segment speed reported in the previous MKJI-based survey.

2. METHOD

This study employed a quantitative descriptive-correlational approach, with the unit of analysis consisting of 100-meter road segments along Kenanga Road. A total of ten observation segments were analyzed, covering STA 0+000 to STA 1+000, consistent with the coverage of the previous traffic engineering study.

The baseline traffic parameters, including the volume-to-capacity (V/C) ratio, road capacity, traffic volume, and average operating speed for each segment, were obtained as secondary data from the 2022 Kenanga Road traffic engineering study. In addition, pavement condition indicators, including the Pavement Condition Index (PCI) (Materials, 2020; Shahin, 1994), International Roughness Index (IRI), and Equivalent Single Axle Load (ESAL), were used to examine the relationship between traffic loading, pavement condition, and road operational performance. By integrating traffic and pavement condition parameters, this study provides a more comprehensive assessment of the performance of Kenanga Road.

Pavement condition data were obtained through a visual distress survey following the Pavement Condition Index (PCI) procedure using 100-meter sample units, accompanied by International Roughness Index (IRI) measurements (Sayers et al., 1986). Cumulative traffic loading was calculated in terms of Equivalent Single Axle Load (ESAL/ESA) based on the axle load conversion principle using Vehicle Damage Factors (VDF), as specified in the Pavement Design Manual (MDPJ) No. 04/SE/Db/2017 (Marga, 2017), and in accordance with the axle-load equivalency principles of **AASHTO (1993)**. Traffic volume, road capacity, V/C ratio, and operating speed data were obtained from the traffic survey conducted in the previous study.

The collected data were analyzed descriptively to classify the condition of each road segment based on PCI and IRI categories. PCI values were classified as Good (≥80), Fair (60–79), Poor (40–59), and Very Poor (<40). Likewise, IRI values were categorized as Good (<4 m/km), Fair (4–7.9 m/km), Poor (8–11.9 m/km), and Very Poor (≥12 m/km). Furthermore, simple linear regression analysis was performed to examine the relationship between cumulative ESAL and PCI, while Pearson correlation analysis was conducted to evaluate the relationship between pavement condition (PCI) and operating speed for each road segment. The analytical results were presented in the form of tables, graphs, and regression equations to illustrate the influence of cumulative traffic loading on pavement condition and its impact on the operational performance of Kenanga Road.

3. RESULTS AND DISCUSSION

Results

1. Existing Pavement Condition per Segment

The evaluation results for pavement condition across the ten segments of Kenanga Road are presented in Table 1, covering PCI values and category, IRI values and category, cumulative ESAL, and operating speed for each segment.

Table 1. Summary of Pavement Condition and Operating Speed per Segment of Kenanga Road

No	Segment (STA)	Cumulative ESAL (Million ESAL)	PCI	PCI Category	IRI (m/km)	IRI Category	Operating Speed (km/h)
1	STA 0+000 - 0+100	0.43	71.3	Fair	5.43	Fair	19.44
2	STA 0+100 - 0+200	0.48	69.0	Fair	5.25	Fair	19.24
3	STA 0+200 - 0+300	0.56	67.5	Fair	5.86	Fair	18.87
4	STA 0+300 - 0+400	0.74	53.0	Poor	6.58	Fair	17.02
5	STA 0+400 - 0+500	0.88	47.2	Poor	7.76	Fair	15.96
6	STA 0+500 - 0+600	0.93	48.5	Poor	8.28	Poor	15.92
7	STA 0+600 - 0+700	0.88	49.4	Poor	7.57	Fair	16.27
8	STA 0+700 - 0+800	0.70	61.4	Fair	6.86	Fair	17.84
9	STA 0+800 - 0+900	0.50	66.8	Fair	5.27	Fair	19.00
10	STA 0+900 - 0+1000	0.40	69.8	Fair	4.71	Fair	19.52

PCI values across the ten segments range from 47.2 to 71.3. Four segments, STA 0+300 to 0+700, fall into the Poor category, while the remaining six segments fall into the Fair category. The distribution of PCI values per segment is presented in Figure 1.

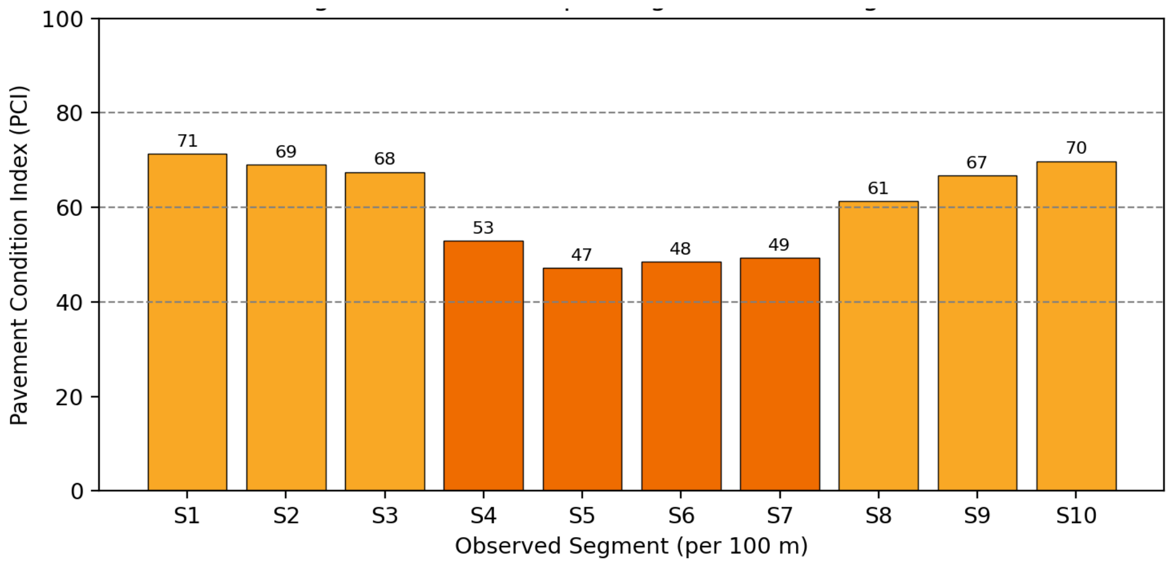

Figure 1. PCI Values per Segment of Kenanga Road

IRI values across the ten segments range from 4.71 to 8.28 m/km. Nine segments fall into the Fair category, and one segment (STA 0+500–0+600) falls into the Poor category with the highest IRI value of 8.28 m/km. The distribution of IRI values per segment is presented in Figure 2.

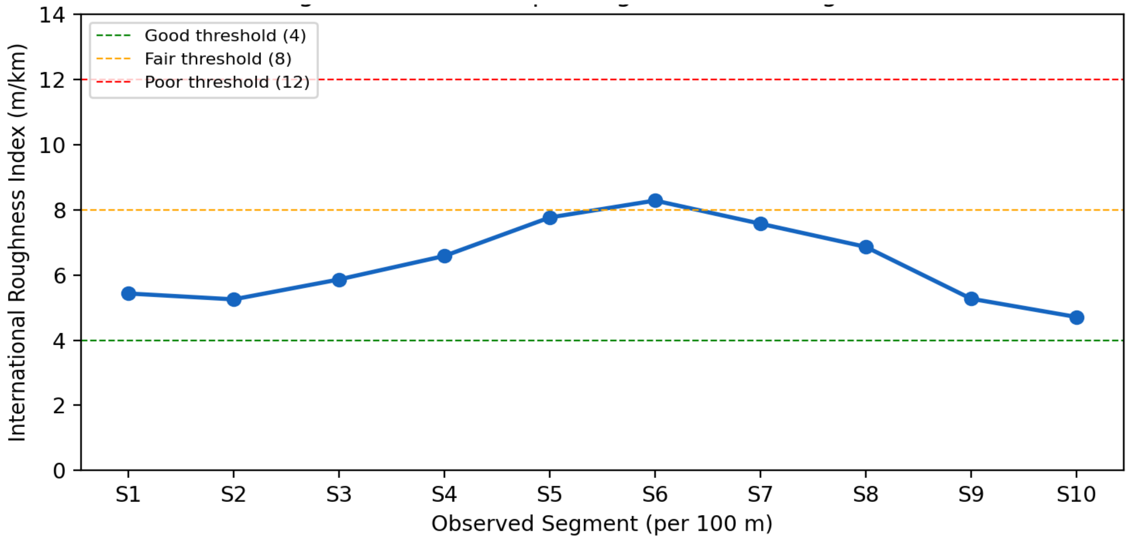

Figure 2. IRI Values per Segment of Kenanga Road

2. Relationship Between Cumulative Traffic Loading (ESAL) and Pavement Condition

Cumulative traffic loading (ESAL) across the ten segments ranges from 0.40 to 0.93 million ESAL. The results of the simple linear regression analysis between cumulative ESAL and PCI are shown in Figure 3, together with the regression equation and a coefficient of determination of $R^2 = 0.95$

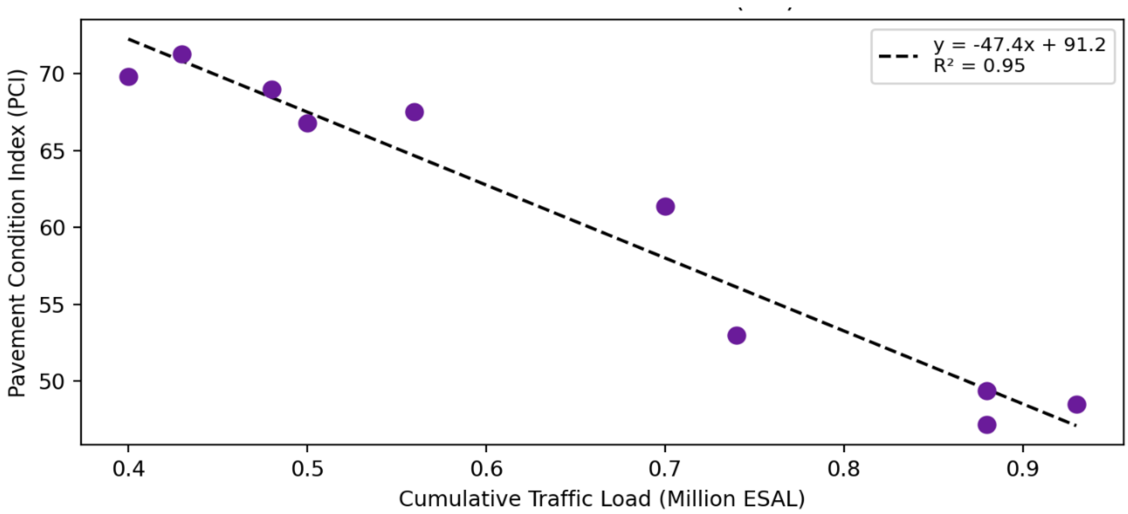

Figure 3. Relationship Between Cumulative Traffic Loading (ESAL) and Pavement Condition (PCI)

3. Operating Speed per Segment

Operating speed per segment ranges from 15.92 km/h to 19.52 km/h, with the lowest value recorded at segment STA 0+500–0+600 and the highest at segment STA 0+900–1+000. A comparison of PCI and operating speed for each segment is presented in Figure 4, with a Pearson correlation coefficient between PCI and operating speed of R = 0.99.

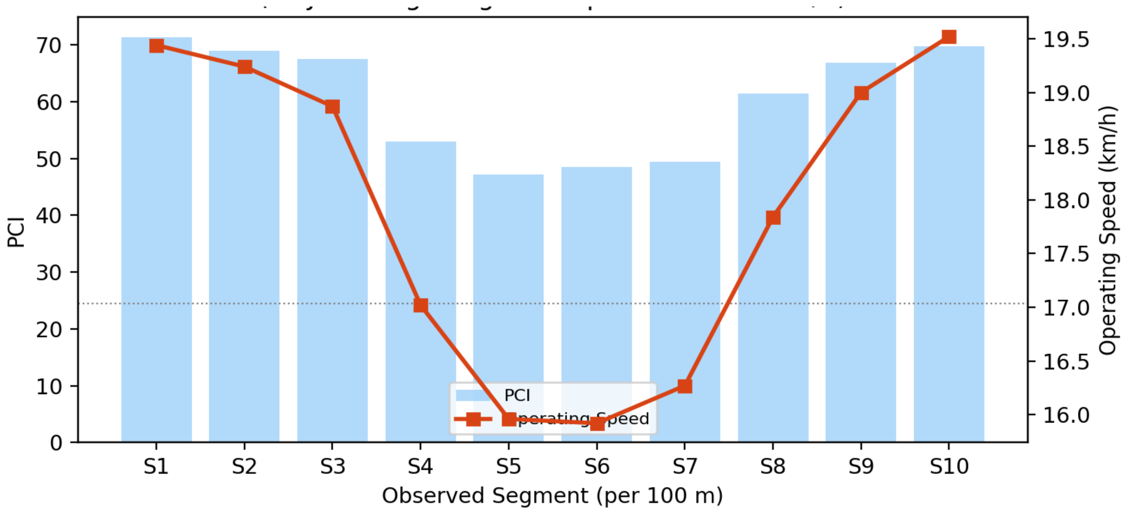

Figure 4. Comparison of PCI and Operating Speed per Segment

Discussion

The data in Table 1 and Figure 1 show that the segments classified as Poor (STA 0+300–0+700) are located near the convergence point of traffic from Tapian Nauli Road toward the commercial district, which the previous traffic engineering study (Putra, 2022) also identified as having the highest intensity of roadside activity (side friction). The pattern shown in Figures 1 and 2 is consistent and inverse: segments with the lowest PCI (STA 0+400–0+700) also show the highest IRI values (7.6–8.3 m/km), approaching the Poor category threshold. This inverse relationship between PCI and IRI aligns with findings from various pavement condition studies in Indonesia, which consistently report a strong correlation between the two indices as representations of the functional and structural condition of the road surface (Batubara, 2018; Ing & Riana, 2019). This concentration of distress at the convergence point reinforces the notion that traffic-related factors, rather than pavement age alone, are the primary drivers of condition variation across segments.

The coefficient of determination of R^2 = 0.95 for the relationship between cumulative ESAL and PCI (Figure 3) means that approximately 95% of the variation in PCI values across segments within this analytical framework can be explained by the magnitude of cumulative traffic loading that has passed over each segment. This pattern is consistent with the core concept in the AASHTO Guide for Design of Pavement Structures (1993), which models pavement performance decline as a function of cumulative standard axle load repetitions relative to a pavement structure designed for a given Structural Number (SN). The higher the cumulative ESAL borne by a segment, the faster the decline in its functional and structural condition, particularly in segments with frequent stop-and-go movement of heavy vehicles due to roadside activities such as loading and unloading in commercial areas. This finding is also consistent with Khan et al. (2022), who showed that repeated axle loading plays a significant role in accelerating fracture mechanisms within asphalt pavement layers, reinforcing the argument that ESAL is a relevant explanatory variable rather than merely a proxy for pavement service age.

The previous traffic engineering study (Putra, 2022) reported an average speed of 24.50 km/h for the Kenanga Road segment, based on Moving Car Observer (MCO) and spot speed surveys, as a single value representing the entire road segment. The results in Figure 4 show that this single value masks considerable spatial variation, with a correlation between PCI and operating speed of R = 0.99. This finding indicates that the speed reduction observed on Kenanga Road is not solely attributable to traffic management factors such as on-street parking and street-vendor activity discussed in the previous study, but is also influenced by the physical condition of the road surface itself. This strengthens the argument that evaluating road segment performance should not rely solely on the conventional MKJI approach based on traffic flow and geometric parameters, but should also be integrated with more granular, segment-level pavement condition data, as emphasized in the Novelty section of this study.

The main contribution of this study is an analytical framework linking three aspects that have typically been examined separately in traffic engineering studies in Indonesia: cumulative traffic loading, structural pavement condition, and operating speed. Practically, segments STA 0+400 to 0+700 can be prioritized for preventive maintenance programs before deteriorating into severe damage requiring full reconstruction, in line with the principle of road treatment based on remaining service life as set out in the Pavement Design Manual. Academically, these findings open opportunities for further research integrating PCI, IRI, and Weigh-in-Motion (WIM) survey data simultaneously on other urban collector roads with similarly high side-friction characteristics.

4. CONCLUSIONS AND SUGGESTIONS

Based on the analysis conducted, it can be concluded that the pavement condition of Kenanga Road varies considerably across its segments. Of the ten 100-meter segments evaluated, four segments (STA 0+300 to STA 0+700) are classified as Poor, with PCI values ranging from 47.2 to 53.0 and IRI values ranging from 6.6 to 8.3 m/km, while the remaining six segments fall within the Fair category. The most deteriorated pavement sections are concentrated near the convergence point of traffic from Tapian Nauli Road toward the commercial district.

The analysis also reveals a very strong negative relationship between cumulative traffic loading (ESAL) and pavement condition (PCI), with a coefficient of determination of R^2 = 0.95. This finding indicates that cumulative axle loading, intensified by the stop-and-go movement of heavy vehicles near the commercial convergence area, is the primary factor accelerating pavement deterioration. This result is consistent with the pavement performance principles established by AASHTO (1993).

Furthermore, pavement condition has a highly significant influence on operating speed variation across road segments, with a correlation coefficient of R = 0.99. The single average operating speed of 24.50 km/h reported in the previous MKJI-based traffic study does not adequately represent segment-level variations, where operating speeds range from 15.92 km/h in Poor-condition segments to 19.52 km/h in segments with better pavement conditions. This finding demonstrates that road performance evaluations based solely on traffic flow parameters provide an incomplete assessment unless pavement condition is also incorporated.

Based on the findings of this study, the local road authority (Dinas Bina Marga and Dinas Perhubungan) should prioritize preventive maintenance for segments STA 0+400 to STA 0+700 through treatments such as overlay or patching before deterioration progresses to a stage requiring complete pavement reconstruction, which would involve substantially higher costs. Future studies should conduct actual pavement condition surveys using the PCI method (ASTM D6433/Shahin) together with IRI measurements obtained using a roughometer or profilometer to validate the illustrative findings with real field observations. To improve the reliability of the relationship between ESAL and PCI, subsequent research should incorporate Weigh-in-Motion (WIM) data so that ESAL values are calculated from directly measured axle loads rather than estimated vehicle compositions. In addition, this integrated framework combining traffic loading, structural pavement condition, and operating speed should be applied to other urban commercial collector roads with high side-friction characteristics to provide a more comprehensive assessment than conventional MKJI-based traffic performance evaluation alone. Future research may also expand this framework by incorporating additional variables such as drainage condition, subgrade bearing capacity, and pavement layer thickness to develop a more comprehensive structural deterioration model for Kenanga Road and other comparable urban collector roads.

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