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Impact of Traffic Growth on Remaining Life of Rigid Pavement in Horizontal Curves

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Abstract. This study investigates the impact of traffic growth on the remaining design life of rigid pavement on horizontal curve. Increasing traffic volumes and frequent congestion on curved segments may accelerate pavement deterioration; however, limited studies that quantified traffic growth influences the remaining service life of rigid pavements. This research analyzes traffic survey data, subgrade CBR values, and axle load distribution collected from three horizontal curves along STA 34+000–35+625. Traffic enumeration using CCTV for seven days and analyzed using MDP 2024 method to estimate the reduction in pavement design life and potential structural damage. The results indicate a traffic growth rate of 6.53%, which reduced the remaining design life by 2.86 years (2023) and 6.22 years (2024). Fatigue cracking reached 2.22% while erosion damage reached 47.80%. These findings highlight the importance of integrating traffic growth considerations into rigid pavement design and maintenance planning to improve long-term pavement performance.

Keywords: Road Pavement Design Manual 2024 (MDP 2024), Traffic Load Analysis, Fatigue Cracks, Erosion Damage, Pavement Performance, Design Life Prediction.

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1. Introduction

National roads constitute an essential component of the land transportation network system, functioning to connect economic activity centers between regions [1,2]. As arterial and collector roads within the primary road network, national roads play a strategic role in supporting the mobility of goods and people while promoting regional economic growth [3,4]. Along with increasing economic activities and regional development, traffic volumes on national roads have also increased significantly over time. This increase in traffic volume may impose excessive loads on pavement structures, particularly on road segments with specific geometric conditions such as curves or horizontal curves [5,6].

Rigid pavement is widely applied on road segments with high traffic volumes because it provides strong structural capacity, high resistance to heavy traffic loads, and relatively lower maintenance requirements compared with flexible pavement [7,8,27]. However, the performance of rigid pavement is influenced by several factors, including traffic growth, vehicle axle loads, subgrade conditions, and traffic characteristics at specific locations [9,10].

Over the past few decades, numerous international studies have developed pavement deterioration modeling approaches to predict pavement performance and service life. Several studies indicate that increasing traffic volume and heavy vehicle loads are the primary factors accelerating the reduction of pavement design life and increasing the potential for structural damage such as fatigue cracking and erosion damage [11,12]. Studies by Gkyrtis *et al.* demonstrate that traffic growth significantly contributes to the acceleration of pavement structural damage through increased axle load repetitions [13]. Other studies also emphasize that pavement damage analysis based on traffic loading and vehicle axle loads is essential for more accurate estimation of pavement service life and for supporting sustainable road maintenance planning [14,15,26]. These approaches highlight that integrating actual traffic data with pavement performance models is crucial in evaluating pavement structural performance.

Nevertheless, most studies investigating the influence of traffic growth on pavement performance have been conducted in developed countries or rely on international design approaches. In Indonesia, studies analyzing the reduction of pavement design life due to traffic growth using the latest Road Pavement Design Manual (MDP 2024) remain relatively limited. Furthermore, traffic conditions on road segments with curved geometry often exhibit unique characteristics, such as vehicle deceleration, queuing, and static loads caused by stopped vehicles, which may increase stress on pavement structures. However, the influence of these conditions on the reduction of rigid pavement design life has not been widely investigated empirically [16].

The Bandar Baru road section on the Medan–Berastagi route is one of the national road segments that plays an important role in supporting economic mobility and tourism activities in North Sumatra. This road section contains several horizontal curve segments that have undergone road widening to accommodate increasing traffic volumes. Despite the widening, traffic congestion still frequently occurs, particularly at certain curved segments [17,18]. These conditions cause vehicles, including heavy vehicles, to stop or move at low speeds, potentially increasing the load applied to the pavement structure [19].

Based on these conditions, a more comprehensive analysis is required to examine the effect of traffic growth on the reduction of rigid pavement design life on road segments with curved geometric characteristics. Therefore, this study aims to analyze the influence of traffic growth on the reduction of rigid pavement design life and the potential structural damage in the form of fatigue cracking and erosion damage on the Bandar Baru road section STA 34+000–35+625 using MDP 2024 method. The results of this study are expected to contribute to improving the understanding of rigid pavement performance under increasing traffic conditions and provide insights for more effective and sustainable pavement design and maintenance planning.

2. Methods

2.1 Research Design

This study employed a quantitative approach using a technical analysis method to evaluate the performance of rigid pavement based on actual traffic data and subgrade conditions [20,21]. The analysis was conducted to assess the effect of traffic growth on the reduction of pavement design life and the potential structural damage in the form of fatigue cracking and erosion damage along the Bandar Baru road section from STA 34+000 to STA 35+625. The calculations were performed in accordance with the MDP 2024, which represents the latest standard for pavement design and evaluation in Indonesia.

2.2 Research Location

The study was conducted on the Bandar Baru road section located in Sibolangit District, Deli Serdang Regency, North Sumatra. This road segment is part of the national road network connecting Medan City and Karo Regency. The research focuses on three horizontal curve segments that have undergone road widening, namely:

- Curve 1: STA 34+000 – STA 34+200
- Curve 2: STA 35+000 – STA 35+200
- Curve 3: STA 35+450 – STA 35+625

These three segments were selected because they experience high traffic density and frequent congestion, which may potentially affect pavement performance.

2.3 Data Collection Techniques

The primary data used in this study include Average Daily Traffic (ADT) data obtained through a semi-manual traffic enumeration survey using CCTV cameras installed at the research location. The recording was conducted for seven consecutive days over a 24-hour period with an observation interval of 15 minutes. The recorded vehicle data were then classified according to vehicle types based on the classification system specified in the MDP 2024. In addition, subgrade condition data (CBR) were collected using the Dynamic Cone Penetrometer (DCP) test at several points around the study area. The obtained CBR values were used to determine the subgrade bearing capacity that influences rigid pavement performance. Lastly, road geometric data, including road type, number of lanes, lane width, and curve conditions, were obtained through direct field measurements.

The secondary data used in this study include the Road Pavement Design Manual (MDP) 2024, pavement design life planning data, and parameters related to traffic distribution and vehicle axle configuration.

2.4 Traffic Data Validation

To improve data reliability, the traffic survey results obtained from the CCTV-based enumeration method were compared with official traffic data from the relevant authorities, such as the Average Daily Traffic (ADT) data provided by the road management agency. The validation process was conducted by comparing the average traffic volume and vehicle composition between the two data sources. If significant differences were identified, adjustments were made by applying correction factors so that the data used in the analysis could more accurately represent actual traffic conditions.

2.5 Analysis Model

The analysis was conducted using a calculation approach based on the MDP 2024. This method was selected because it is the most recent guideline used for pavement design in Indonesia and includes updated calculation parameters related to vehicle axle loads, traffic distribution factors, and pavement damage analysis.

The stages of analysis in this study include:

1. Conversion of ADT to AADT: The ADT data obtained from the survey were converted into AADT using a correction coefficient based on the survey period.

$$AADT \;=\; \frac{ADT\ (7\ day)}{P} \quad (1)$$

Where: coefficient P = coefficient obtained based on the week and month the survey was conducted.

2. Traffic Growth Calculation: The traffic growth rate was calculated by comparing the traffic data from the survey year with the planned year.

$$i \;=\; \left[\left(\sqrt[n]{\frac{LHRTn}{LHRT0}}\right) - 1\right] \times 100\% \quad (2)$$

Where: $AADT_n$ = AADT survey 2024, $AADT_0$= ADT of the planned year, n = difference in years.

3. Calculation of the Number of Commercial Vehicle Axles (JSKN): The JSKN value was calculated based on the distribution of vehicle types consist of directional distribution (DD) and lane distribution (DL).

$$\text{JSKN} \;=\; (\Sigma LHRT \times JSKN_H) \times 365\ \times DD \times DL \times R \quad (3)$$

Chimney: $JSKN_H$= Total Axles of Each Type of Vehicle, DD = Direction distribution factor, DL = Lane Distribution Factor

4. Analysis of Design Life Reduction: The reduction in pavement design life was calculated by comparing the actual traffic load repetitions with the planned load repetitions within the pavement design life.

$$RL \;=\; 100\left[1 - \left(\frac{E.g}{N1.5}\right)\right] \quad (4)$$

$$\text{Remaining Plan Life} = \frac{RL}{100} \times\ UR \quad (5)$$

Reduction in Plan Life = UR−Remaining Plan Life (6)

Where: Np = JSKN value in the planning year, $N_{1,5}$= JSKN value at the end of the plan period, UR = Plan period, RL = Percentage of remaining plan period.

5. Pavement Damage Analysis: The damage analysis was conducted to determine the potential for fatigue cracking and erosion damage based on vehicle axle load parameters, concrete slab thickness, and subgrade conditions.

$$Se \;=\; a + \frac{b}{D} + C\ .ln\ ln\ (If) + \frac{d}{D^2} + e.[ln(Ef)]^2 + f.\frac{ln(If)}{D} + \frac{g}{D^3} + h.[ln\ ln\ (If)\ ]^3 + i.\frac{[ln(Ef)]^2}{D} + j.\frac{ln(Ef)}{D^2} \quad (7)$$

$$F_3 \;=\; a + \frac{b}{D} + C\ .ln\ ln\ (If) + \frac{d}{D^2} + e.[ln(Ef)]^2 + f.\frac{ln(If)}{D} + \frac{g}{D^3} + h.[ln\ ln\ (If)\ ]^3 + i.\frac{[ln(Ef)]^2}{D} + j.\frac{ln(Ef)}{D^2} \quad (8)$$

Where: Coefficients a, b, c, d, e, f, g, h, i, j are coefficients for equivalent stress prediction, Ef = Effective CBR of Subgrade, D = Thickness of Concrete Slab.

In calculating there are provisions for each, such as for calculating fatigue cracks (*fatigue*) or Nf, first find the Sr value, if the Sr value has been obtained then the provisions apply. An example of calculating the number of repetition loads (Nf) and (Ne) can be seen below:

1. Calculation of the number of load repetitions for fatigue cracks (*fatigue*) (Nf) on the STRT axis group.

a. Calculate the Sr value using the equation for an axle load of 10 kN

$$Sr \;=\; \frac{Se}{0{,}944\ fcf}\left(\frac{PLsf}{4{,}45\ F_1}\right)^{0{,}94} \quad (9)$$

Sr = 0,0390

Terms and conditions apply:

- When Sr > 0.55, then use $Nf \;=\; \left(\frac{0{,}9719 - Sr}{0{,}0828}\right)$
- When 0.45 ≤ Sr ≤ 0.55, Then use $Nf \;=\; \left(\frac{4{,}258}{Sr - 0{,}4325}\right)^{3{,}268}$

- When the value of Sr < 0.45, the value of Nf is Infinite (TT).

In the calculation above, the value of Sr = 0.0390 < 0.45 is obtained, so the Nf value is Infinite (TT).

2. Calculation of the number of load repetitions allowed for erosion (Ne) on the STRT axis group.

a. Calculating Ne for a load of 10 kN

$$(F_2Yes) = 14{,}524 - 6{,}777\left[Max\left(0\ or\left(\frac{PLsf}{4{,}45F_4}\right)^2.\frac{10^{F_3}}{41{,}35} - 9{,}0\right)\right]^{0{,}103} \quad (10)$$

$$= \left(\frac{10^{14{,}524}}{0{,}94}\right) = 3{,}56 \times 10^{14} \quad (11)$$

2.6 Research Assumption

Several assumptions used in this study include:

1. Traffic growth is assumed to be constant throughout the analysis period.
2. The directional distribution factor (DD) and lane distribution factor (DL) follow the provisions specified in the MDP 2024.
3. The subgrade CBR values obtained from testing are assumed to represent the soil conditions of the studied road segments.
4. The thickness of the concrete slab is assumed to be uniform across all research segments.

2.7 Limitations

This study has several limitations, including:

1. The traffic analysis is based on survey data collected over a specific period, which may not fully represent annual traffic variations.
2. The pavement damage analysis focuses only on fatigue cracking and erosion damage, without considering other types of pavement distress.
3. Environmental factors such as temperature variations, rainfall, and drainage conditions were not analyzed in depth in this study.

2.8 Research Flowchart

To clarify the stages of the study, the research process can be described as follows:

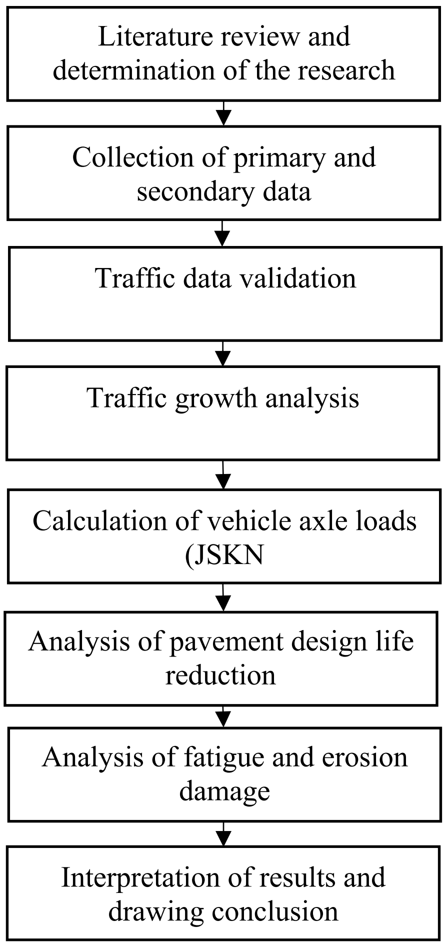

Figure 1. Research Flowchart

3. Results and Discussion

3.1 Traffic Data Survey Results

Table 1. Average Daily Traffic (ADT) in 2024

Goal. Send	Vehicle Type	ADT 2024 (Vehicles/day)	AADT 2024	< AADT	> AADT
1	Motorcycles, and 3 Wheels	6458	6484	5570	7757
2	Sedan, Jeep, Taxi	8889	8924	7667	10676
3	Public transport, minibus	807	810	696	969
4	Pick-up, Mobil Box	2710	2721	2338	3255
5a	Small Bus	626	628	540	752
5b	Big Bus	60	60	52	72
6a	2 Axle Truck (4 Wheels)	283	284	244	340
6b	2 Axle Truck (6 Wheels)	2313	2323	1995	2779
7a	3 Axle Truck	580	583	501	697
7b	Trailer Truck	0	0	0	0
7c1	4 Axle Truck	21	21	18	25
7c2a	5 Axle Truck (Trailer) (1.22-22)	3	3	3	4

Goal. Send	Vehicle Type	ADT 2024 (Vehicles/day)	AADT 2024	< AADT	> AADT
7c2b	5 Axle Truck (Trailer) (1.2-222)	9	9	7	10
7c3	6 Axle Truck	7	7	6	9
8	Non-Motorized	4	4	3	5
	Total	22770	22861	19640	27350

Table 1 shows the traffic survey results indicate that the studied road section experiences relatively high traffic activity dominated by motorcycles and passenger vehicles, followed by a significant presence of commercial vehicles such as pick-up trucks and medium trucks. In contrast, heavy multi-axle and trailer trucks contribute only a small proportion of the total traffic flow. Overall, the traffic composition reflects a mixed traffic pattern consisting of both passenger and freight transport, which may influence the magnitude and distribution of loads acting on the pavement structure.

3.2 Calculating Traffic Growth

$$i \quad = \left[\left(\sqrt[n]{\frac{LHRTn}{LHRT0}}\right) - 1\right] \times 100\% \qquad (2)$$

Where: $LHRT_n$ = LHRT survey 2024, $LHRT_0$= LHRT of the planned year, n = difference in years. With $LHRT_n$= 22861kend/day and $LHRT_0$= 20144 vehicles/day, then the growth rate obtained is 6.53% with a difference between the plan year and the survey year of 2 years.

3.3 Total Number of Commercial Vehicle Axles (JSKN)

Before calculating the JSKN value, the JSKNH value must first be calculated.

Table 2. Actual 2022 Daily Traffic Axis Total Value

Vehicle Type	Group	AADT	$JSKN_H$	(AADT × $JSKN_H$)
Big Bus	5b	48	2	95
2 Axle Truck (4 Wheels)	6a	2093	2	4186
2 Axle Truck (6 Wheels)	6b	945	2	1890
3 Axle Truck	7a	540	2	1081
Trailer truck	7b	0	4	
4 Axle Truck	7c1	53	3	158
5 Axle Truck (Trailer) (1.22-22)	7c2a	30	3	0
5 Axle Truck (Trailer) (1.2-222)	7c2b	0	3	89
6 Axle Truck	7c3	0	3	0
Total				7499

After obtaining the JSKNH value, the JSKN value can then be calculated as follows:

$$\text{JSKN} = (\Sigma LHRT \times JSKN_H) \times 365 \times DD \times DL \times R \qquad (3)$$

Chimney: $JSKN_H$= Total Axles of Each Type of Vehicle, DD = Direction distribution factor, DL = Lane Distribution Factor. Based on the previous calculation, DD = 0.5 and DL = 0.8 are obtained. So from the equation above, the JSKN value for 2024 is obtained as1.71E+08 JSKN.

3.4 Calculating the Plan Life Decrease Value

$$RL = 100 \left[1 - \left(\frac{E.g}{N1.5}\right)\right] \quad (4)$$

$$\text{Remaining Plan Life} = \frac{RL}{100} \times UR \quad (5)$$

Reduction in Plan Life = UR−Remaining Plan Life (6)

Where: Np = JSKN value in the planning year, $N_{1,5}$= JSKN value at the end of the plan period, UR = Plan period, RL = Percentage of remaining plan period.

From the calculation results of the planned road life of 40 years, there is a reduction in each year, where it should be in 2023 with a reduction in age of 1 year from the planned age starting operation, namely in 2022, the remaining planned life is 39 years, but with traffic growth of 6.53%, the remaining planned life is only 37.14 years with a cumulative reduction in age of 2.86 years. For 2024, the actual remaining life is 33.78 years, there has been a reduction in age of 6.22 years, where in the 2nd year after operation, the planned reduction assumption should be 2 years.

3.5 Fatigue Crack and Erosion Damage Data Analysis

Table 4. Total Damage to Fatigue and Erosion That Occurred

Commercial Vehicle Axle Group	Fatigue Crack (*Fatigue*) (%)	Erosion Damage (%)
STRT	0,00	0,00
CTRL	2,22	10,18
STdRG	0,00	36,84
STrRG	0,00	0,78
Total	2,22	47,80

Table 4 shows the analysis of structural damage indicates that the total fatigue cracking reached 2.22%, while the total erosion damage reached 47.80%. Fatigue damage was only observed in the CTRL axle group, contributing 2.22%, whereas the other axle groups showed no fatigue damage. In contrast, erosion damage was more significant and distributed across several axle groups, with the highest contribution from the STdRG axle group (36.84%), followed by the CTRL group (10.18%) and STrRG group (0.78%), while the STRT group showed no erosion damage. These results indicate that although fatigue damage remains relatively low, erosion damage represents the dominant form of structural deterioration in the pavement, primarily influenced by the distribution and repetition of commercial vehicle axle loads.

3.6 Discussion

The findings of this study demonstrate that traffic growth significantly influences the reduction of rigid pavement design life on the Bandar Baru road section. Based on the 2024 traffic survey, the traffic growth rate reached 6.53%, which resulted in a substantial decrease in the remaining service life of the pavement. The analysis indicates that the design life reduction reached 2.86 years in 2023 and increased to 6.22 years in 2024, suggesting that increasing traffic demand accelerates pavement deterioration. This trend confirms that pavement performance is highly sensitive to traffic loading conditions, particularly in road segments with high traffic intensity.

The reduction in pavement service life is primarily associated with the increase in cumulative axle loads caused by traffic growth. In pavement engineering, the cumulative repetition of axle loads is one of the most critical factors affecting structural deterioration. The calculation of the cumulative number of commercial vehicle axles (JSKN) in this study shows a considerable increase in traffic loading, indicating that the pavement structure is subjected to progressively higher stress levels over time. Similar findings have been reported in recent pavement performance studies, which highlight that heavy vehicle traffic and axle load repetitions are key contributors to pavement damage progression [22,23].

The structural damage analysis further indicates that fatigue cracking reached 2.22%, while erosion damage reached 47.80%. Although the fatigue damage remains relatively low, the erosion damage value is comparatively higher, indicating the potential weakening of the subgrade support beneath the concrete slab. In rigid pavement systems, erosion typically occurs due to repeated traffic loading that causes pumping of subgrade materials and loss of support under the slab. Previous studies have shown that erosion-related damage can significantly reduce pavement performance if traffic loading continues to increase without adequate structural reinforcement [24].

Another important factor contributing to the observed pavement deterioration is the geometric condition of the road segment, particularly the presence of horizontal curves. Traffic behavior in curved road segments tends to differ from straight sections because vehicles frequently decelerate, accelerate, or even stop due to congestion. These conditions may generate higher dynamic loads and stress concentrations on the pavement surface. Studies in pavement deterioration modeling have demonstrated that traffic operations involving braking and acceleration can increase the magnitude of pavement stresses and accelerate structural damage [25]. Therefore, the relatively high erosion value observed in this study may also be associated with the traffic behavior commonly occurring in congested curved road sections.

Despite the observed reduction in design life and the occurrence of structural damage, the results indicate that the pavement structure remains capable of supporting the current traffic load. According to the criteria specified in MDP 2024, pavement design is considered adequate as long as the cumulative damage due to fatigue and erosion does not exceed 100%. The results of this study show that the total damage value remains below this threshold, indicating that the existing concrete slab thickness is still structurally sufficient to carry the current traffic load.

When compared with another pavement performance studies, the results of this research reveal similar trends regarding the influence of traffic growth on pavement deterioration. Several studies have reported that rapid traffic growth can significantly shorten pavement service life if not properly considered in pavement design and maintenance planning [25]. However, unlike many previous studies that primarily focus on highway networks with uniform traffic flow conditions, this study highlights the importance of considering localized traffic characteristics, such as congestion and traffic behavior at horizontal curves, which may intensify pavement stress levels.

From an engineering perspective, the findings of this study emphasize the importance of integrating traffic growth projections into pavement design and performance evaluation. Accurate estimation of traffic loads, including heavy vehicle axle loads, is essential for predicting pavement deterioration and optimizing maintenance strategies. Furthermore, continuous monitoring of traffic conditions and pavement performance is necessary to ensure that pavement structures remain capable of supporting future traffic demands.

Overall, this study confirms that traffic growth is a critical factor influencing the reduction of pavement design life and the development of structural damage in rigid pavements. The integration of traffic growth analysis with pavement structural evaluation using the MDP 2024 framework provides valuable insights for improving pavement design strategies and supporting more sustainable road infrastructure management.

4. Conclusion

This study examined the influence of traffic growth on the reduction of rigid pavement design life on the Bandar Baru road section using the Road Pavement Design Manual (MDP) 2024 approach. The findings indicate that increasing traffic volume contributes to a measurable reduction in pavement service life due to the accumulation of commercial vehicle axle loads. Traffic growth of 6.53% was found to accelerate the deterioration process, particularly through the development of erosion damage and fatigue cracking within the pavement structure. Although the calculated damage values remain below the critical threshold defined in the MDP 2024 criteria, the results demonstrate that continuous traffic growth can gradually reduce pavement structural performance if not considered in pavement design and maintenance planning. These findings highlight the importance of incorporating accurate traffic growth projections and axle load analysis in rigid pavement design to ensure long-term pavement performance.

From an engineering perspective, the study emphasizes the need for periodic monitoring of traffic conditions and pavement performance, particularly on road segments with complex geometric characteristics such as horizontal curves where traffic congestion frequently occurs. Future research is recommended to integrate broader traffic datasets, long-term monitoring of pavement deterioration, and comparative evaluation using alternative pavement design methods to improve the reliability of pavement performance prediction and support more sustainable road infrastructure management.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT for language editing, grammar correction, and layout refinement. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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