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Development of a Flexible Pavement Overlay Thickness Prediction Model Based on Benkelman Beam Deflection and Equivalent Standard Axle on the Malang Section of the Provincial Road

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ABSTRACT

This study aims to develop a regression-based approximation model for flexible pavement overlay thickness on the Malang provincial road section using Benkelman Beam deflection values and cumulative Equivalent Standard Axle (ESA), with a uniform 15-year design life applied only as the traffic-load projection period. This research utilized a quantitative approach with a correlational and predictive design, applying purposive sampling to historical data from the Department of Public Works and Highways across sixteen road segments. Data were analyzed using the standard Benkelman Beam deflection-based overlay design procedure (Pd T-05-2005-B) to determine the required overlay thickness for each segment, followed by Multiple Linear Regression to quantify the empirical relationship between deflection, cumulative ESA, and overlay thickness. The results show that representative deflection is the dominant and statistically significant predictor of overlay thickness (R^2 = 0.983; $p < 0.001$), while cumulative ESA contributes in the hypothesized positive direction. Required overlay thickness across the sixteen analyzed segments ranged from 3.21 cm (Jl. Ir. Soekarno) to 4.54 cm (Wonomulyo-Gubuk Klakah and Jl. Raya Tulungrejo Segmen I); for example, the KM.113+700 - KM.115+405 segment required a 3.87 cm overlay due to a representative deflection of 248.52 mm and cumulative traffic load exceeding 147 million ESA. The regression equation consistently approximated the overlay thickness values obtained from the standard deflection-based calculation across the sixteen analyzed segments. The resulting model should therefore be interpreted as a simplified estimation tool rather than an independently validated predictive model.

INTRODUCTION

Flexible pavement systems are essential infrastructure components that facilitate economic mobility and regional connectivity, particularly in high-traffic corridors such as the Malang section of the East Java provincial road. This corridor reflects broader regional infrastructure and traffic growth trends across East Java Province (Badan Pusat Statistik Provinsi Jawa Timur, 2026). Over time, these pavements undergo structural and functional degradation due to repeated traffic loading, environmental exposure, and material aging. To restore serviceability and structural integrity, applying an asphalt overlay is a primary maintenance strategy (Mallick & El-Korchi, 2022). Determining the optimal overlay thickness is a critical engineering challenge, as under-designing leads to premature pavement failure, while over-designing results in an inefficient allocation of limited maintenance budgets (Fani et al., 2022). Traditional overlay design methods typically rely on evaluating the existing structural condition of the pavement, which is most effectively measured using non-destructive testing equipment to obtain surface deflection values, such as the Benkelman Beam (Bamher, 2020; Wang et al., 2024).

The structural evaluation of existing pavements through deflection testing provides a direct indication of the pavement's current load-bearing capacity. Alongside deflection values, the cumulative traffic load, quantified as the Equivalent Standard Axle (ESA), acts as a primary catalyst for pavement deterioration (Kusnianti & Nasution, 2019). The pavement design life also serves as a fundamental planning parameter, since it determines the projection horizon over which cumulative traffic loading (ESA) is calculated, and therefore indirectly governs the magnitude of structural demand incorporated into the overlay thickness design (Setyawan & Arifin, 2023).

Despite the established relationship between deflection, traffic load, and pavement degradation, previous studies have predominantly relied on generalized empirical nomograms or standard mechanistic-empirical procedures that may not accurately capture localized distress patterns (Azizah, 2021; Irawati & Dewi, 2024). Many existing predictive models often isolate variables, analyzing either traffic loads or deflection independently, without developing a cohesive multivariable predictive framework tailored to specific regional characteristics (Francois et al., 2019; Absyah & Hartatik, 2023). Furthermore, recent research often focuses on toll roads or national highways (Ahmad et al., 2024), leaving a significant gap in predictive maintenance modeling for provincial road networks which experience entirely unique load spectra and maintenance cycles (Wibowo & Mudiyono, 2024). This study introduces novelty by developing an integrated, data-driven prediction model that simultaneously incorporates Benkelman Beam deflection values, ESA, and pavement age, calibrated using empirical data drawn from sixteen distinct road segments across the Malang provincial road network, thereby capturing the structural and traffic heterogeneity that characterizes this section.

By bridging this specific research gap, the present study contributes significantly to the field of pavement engineering and infrastructure asset management. The proposed model offers road authorities a robust, practical tool to accurately forecast overlay requirements, thereby optimizing maintenance scheduling and budget efficiency without the continuous need for extensive destructive testing. The primary objective of this research is to develop a regression-based approximation model for flexible pavement overlay thickness using Benkelman Beam deflection values and cumulative Equivalent Standard Axle (ESA) on the Malang section of the provincial road. A uniform 15-year design life is applied only to determine the cumulative ESA projection period and is not treated as an independent regression predictor. In line with this objective, it is hypothesized that higher deflection values, which signify weaker structural integrity, will necessitate a thicker overlay. It is further hypothesized that an increase in cumulative ESA will positively correlate with an increased required overlay thickness, given a fixed 15-year design life applied uniformly across the analyzed segments. Finally, it is hypothesized that the combined use of representative deflection and cumulative ESA will provide a statistically significant regression-based approximation of the standard overlay thickness calculation under a uniform 15-year design period.

METHOD

Research Design

This study employed a quantitative research approach utilizing a correlational and predictive modeling design. The primary objective of this method was to empirically establish a mathematical relationship between structural and operational pavement parameters to develop a reliable overlay thickness prediction model.

Population and Sample

The population of this study comprised the entire flexible pavement network along the provincial roads in the Malang section, East Java, Indonesia. The research sample consisted of sixteen (16) distinct flexible pavement road segments distributed across this network, encompassing both primary provincial arterials (e.g., KM.113+700 - KM.115+405 and KM.116+000 - KM.118+450) and inter-district connector roads (e.g., Karang Ploso, Jl. Ir. Soekarno, Jl. Dr. M. Hatta, Talok-Druju-Sendang Biru, and the Mangliawan-Tumpang-Wonomulyo corridor), each possessing a complete historical dataset suitable for deflection-based overlay analysis.

Sampling Technique

A purposive sampling technique was utilized to select the road segments. The inclusion criteria for the sample selection required that the segments possess complete and continuous historical datasets, specifically containing recent deflection test results, accurate Average Daily Traffic (LHR) records, and documented pavement age and maintenance history.

Data Collection Types and Techniques

The study utilized secondary quantitative data obtained from field measurement reports and historical traffic databases. The primary analytical variables consisted of representative surface deflection and cumulative ESA. A uniform 15-year design life was applied to all segments only as the projection period for calculating cumulative traffic loading and was not included as an independently varying predictor in the regression analysis. The primary variables collected included:

1. **Structural and Traffic Parameters:** Surface deflection values obtained via the Benkelman Beam method (in mm), Average Daily Traffic (LHR) data used to compute the cumulative Equivalent Standard Axle (ESA) load (Wulansari et al., 2023), and the pavement design life (umur rencana), which was set uniformly at 15 years for all analyzed segments in accordance with the regional highway authority's standard planning period.
2. **Output Parameter:** The required flexible pavement overlay thickness (in cm), calculated for each segment based on the parameters above.

Data Processing and Analysis Techniques

Data processing commenced with data cleaning, outlier removal, and the normalization of variables. The Average Daily Traffic (LHR) data was converted into cumulative Equivalent Standard Axle (ESA) loads using standard Vehicle Damage Factors (VDF). Light vehicles (Golongan 1–4) were excluded from the cumulative ESA calculation, as their Vehicle Damage Factor is negligible compared to that of buses and trucks (Golongan 5A–7C); only medium and heavy vehicle classes were used to compute the design traffic load. Furthermore, the representative deflection values (D_{rep}) for each segment were calculated based on the mean deflection and standard deviation to account for structural uniformity.

For data analysis, the required overlay thickness was determined using the standard Benkelman Beam deflection-based design procedure referring to Pd T-05-2005-B / Manual Desain Perkerasan Jalan (MDPJ) (Direktorat Jenderal Bina Marga, 2024). For each homogeneous road segment, the representative deflection (Dwakil) was calculated as Dwakil = dR + 2S, where dR is the mean corrected deflection and S is the standard deviation, to account for structural variation within the segment, as reflected in the deflection uniformity factor FK = (S/dR) × 100%. The allowable post-overlay deflection (Dstlh ov) was calculated as Dstlh ov = 17.004 × CESA^-0.2307, based on the cumulative Equivalent Standard Axle (CESA) load projected over the design life. The required overlay thickness (Ho) was then derived using Ho = {Ln(1.0364) + Ln(Dwakil) − Ln(Dstlh ov)} / 0.0597. This procedure was applied consistently across the 16 analyzed road segments to obtain a comparable overlay thickness estimate for each segment based on its structural deflection and traffic load characteristics.

RESULTS

In this section, the analytical process and outcomes of the predictive modeling for the flexible pavement overlay thickness on the Malang provincial road section are presented. The analysis was conducted following the sequential data processing steps outlined in the methodology, transitioning from descriptive traffic evaluation to the formulation of the multiple linear regression model.

Traffic Load and Equivalent Standard Axle (ESA) Calculation

The preliminary stage of data analysis involved evaluating the operational conditions of the selected road segments. The Average Daily Traffic (LHR) data was systematically converted to quantify the cumulative structural damage induced by vehicular loads over the pavement's lifespan (Wulansari et al., 2023). The conversion into Equivalent Standard Axle (ESA) values utilized standard Vehicle Damage Factors (VDF) tailored to regional axle configurations (Direktorat Jenderal Bina Marga, 2020). Based on the actual traffic data extraction from the KM.113+700 - KM.115+405 segment, the distribution of commercial vehicle traffic and its corresponding cumulative ESA contribution over the 15-year design life is summarized in Table 1.

Table 1. Distribution of Traffic Volume and ESA Contribution

Vehicle Class	LHR Base Year 2020 (Vehicles/Day)	Average VDF	Cumulative ESA (15 Years)
Light Vehicles (Gol 1-4)	15,350	-	-
Small Buses (Gol 5A)	58,850	0.3	102,955,851
Large Buses (Gol 5B)	6,750	1	39,362,900
Light 2-Axle Trucks (Gol 6A)	1,650	0.55	5,292,123

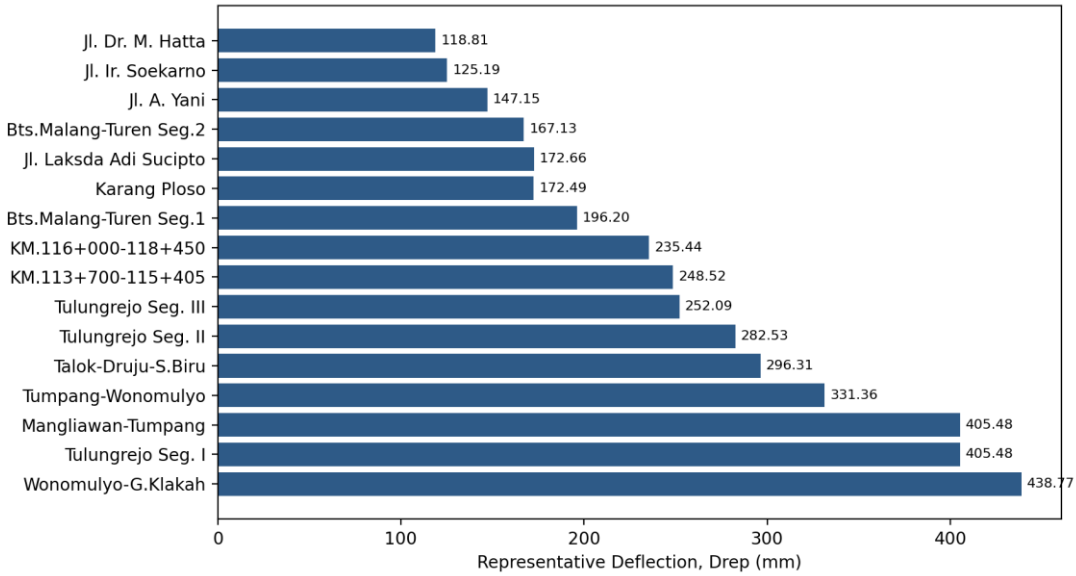
Note: The LHR data reflects the baseline traffic volume recorded in 2020. The ESA values represent the projected cumulative traffic load over a 15-year design life, spanning from 2020 to 2035, for the KM.113+700 - M.115+405 segment of the Malang provincial road.

While Table 1 illustrates the traffic composition for the KM.113+700 - KM.115+405 segment as a representative example, the vehicle class distribution was not uniform across all sixteen segments. Corridors such as the Jl. Raya Tulungrejo segments, Karang Ploso, Jl. Dr. M. Hatta, and Tumpang-Wonomulyo exhibited a markedly higher contribution from light 2-axle trucks (Golongan 6A), exceeding 51 million cumulative ESA — roughly ten times higher than in segments such as KM.113+700 - KM.115+405 or Jl. Ir. Soekarno, where small buses (Golongan 5A) remained the dominant loading factor. This variation indicates that the Malang provincial road network accommodates distinct traffic profiles, ranging from public-transport-dominated corridors to freight/logistics-dominated corridors, which contributes to the variability of cumulative ESA observed across the sample even among segments with comparable traffic volumes.

Benkelman Beam Deflection Analysis

To assess the existing structural integrity of the pavement, structural deflection testing was conducted. The raw deflection data was statistically processed to determine the representative deflection (D_{rep}) for each homogeneous segment. The representative deflection accounts for structural variations and is a critical input for calculating the required overlay thickness. Based on the extracted data from the Malang provincial road, specifically the Kota Batu - Bts. Kab. Kediri section, the recorded deflection values were 248.52 mm for the KM.113+700 - KM.115+405 segment and 235.44 mm for the KM.116+000 - KM.118+450 segment. The distribution of the structural condition based on these deflection values is illustrated in Figure 1.

Figure 1. Representative Deflection (Drep) Across the 16 Analyzed Segments



The structural evaluation revealed that representative deflection values varied considerably across the sixteen analyzed segments, ranging from 118.81 mm (Jl. Dr. M. Hatta) to 438.77 mm (Wonomulyo-Gubuk Klakah), as summarized in Table 2. Segments exhibiting higher D_{rep} values — such as Wonomulyo-Gubuk Klakah, Jl. Raya Tulungrejo Segmen I, and Mangliawan-Tumpang — indicate comparatively weaker subgrade or pavement layers and consistently required thicker overlays (4.4-4.5 cm), whereas segments with lower D_{rep}, such as Jl. Dr. M. Hatta and Jl. Ir. Soekarno, required overlays as thin as 3.2 cm. This range confirms that the deflection-based design procedure produces a proportionally consistent overlay recommendation across the full sample rather than an isolated case.

Table 2. Recapitulation of Representative Deflection, Cumulative ESA, and Required Overlay Thickness for All 16 Analyzed Segments

No	Road Segment	D_{rep} (mm)	Cumulative ESA (15 yrs)	FK (%)	Required Overlay Ho cm)
1	Jl. Dr. M. Hatta	118.81	188,905,471	28.31	3.25
2	Jl. Ir. Soekarno	125.19	140,802,550	28.54	3.21
3	Jl. A. Yani	147.15	130,044,815	27.86	3.31
4	Bts. Kota Malang-Turen, Segmen 2	167.13	138,921,878	28.57	3.43
5	Karang Ploso	172.49	187,564,216	28.59	3.53
6	Jl. Laksda Adi Sucipto	172.66	138,786,878	29.89	3.48
7	Bts. Kota Malang-Turen, Segmen 1	196.2	147,610,873	28.66	3.6
8	KM.116+000 - KM.118+450	235.44	138,921,878	28.82	3.8
9	KM.113+700 - KM.115+405	248.52	147,610,873	28.36	3.87
10	Jl. Raya Tulungrejo, Segmen III	252.09	194,493,545	27.51	3.94
11	Jl. Raya Tulungrejo, Segmen II	282.53	140,802,550	26.22	4
12	Talok-Druju-Sendang Biru	296.31	195,557,801	22.86	4.08
13	Tumpang-Wonomulyo	331.36	188,905,471	19.82	4.17
14	Mangliawan-Tumpang	405.48	194,493,545	20.41	4.37
15	Jl. Raya Tulungrejo, Segmen I	405.48	188,905,471	20.41	4.54
16	Wonomulyo-Gubuk Klakah	438.77	140,802,550	17.54	4.54

Note: All Ho values were computed under a uniform 15-year design life applied to every segment, in accordance with the regional highway authority's standard planning period. Segments 14 and 15 share identical field deflection statistics (verified against source records) but differ in required overlay thickness due to differing cumulative ESA

Calculation of the Overlay Thickness Using the Deflection-Based Design Procedure

The core objective of this study was to establish a mathematical relationship integrating Benkelman Beam deflection (X_1), cumulative ESA (X_2), and pavement age (X_3) to predict the required overlay thickness (Y). Since pavement age was applied as a uniform, fixed 15-year design parameter across all sixteen segments — consistent with the regional highway authority's standard planning period, as described in the Method section — it was retained in the model as a controlled input governing the ESA projection horizon rather than as an independently varying regressor.

Multiple Linear Regression (MLR) analysis was therefore performed on the two structurally varying inputs, deflection (X_1) and cumulative ESA (X_2), to derive the empirical coefficients based on the 16-segment dataset summarized in Table 2. The resulting predictive model is presented in Equation 1.

Because the design life was identical for all sixteen observations, it had zero statistical variance and therefore could not be estimated as an independent regression coefficient.

$Y = \beta_0+\beta_1X_1+\beta_2X_2$ .... (1)

Description:

Y = Predicted Overlay Thickness (cm)

X_1 = Representative Deflection (D_{rep}) (mm)

X_2 = Cumulative Equivalent Standard Axle (ESA)

X_3 = Pavement Age (years)

β_0 = Regression Constant

β_1, β_2 = Regression coefficients for representative deflection and cumulative ESA, respectively

Fitting the model to the 16-segment dataset yielded the following empirical equation:

$Ho = 2.626 + 0.00417(X_1) + 0.00093(X_2)$ …… (2)

Where X_2 is expressed in millions of cumulative ESA for numerical convenience (e.g., an ESA value of 147,610,873 corresponds to $X_2 = 147.61$). The model explains 98.3% of the variance in required overlay thickness ($R^2 = 0.983$; adjusted $R^2 = 0.980$) and is highly statistically significant overall ($F(2,13) = 371.27$, $p < 0.001$). Examined individually, representative deflection (X_1) was a highly significant predictor ($t = 25.17$, $p < 0.001$), confirming that structural condition is the dominant driver of overlay thickness within this sample. Cumulative ESA (X_2) showed the hypothesized positive relationship with overlay thickness but did not reach conventional statistical significance in this multivariable specification ($t = 1.44$, $p = 0.174$), likely reflecting the smaller independent variation in traffic load compared to deflection across the sample — several corridors share closely comparable ESA totals despite being physically distinct segments (Table 2). The resulting overlay thickness values ranged from 3.21 cm (Jl. Ir. Soekarno) to 4.54 cm (Wonomulyo-Gubuk Klakah and Jl. Raya Tulungrejo Segmen I) across the 16 analyzed segments, consistent with the combined influence of structural deflection and cumulative traffic load.

It should be noted that the overlay thickness used as the dependent variable was obtained from the standard deflection-based design equation using representative deflection and cumulative ESA as its principal inputs. Consequently, the high coefficient of determination reflects the ability of the linear regression equation to approximate the underlying standard calculation within the observed data range. It should not be interpreted as independent predictive validation. External validation using observed overlay performance, independently designed overlay thickness, or a separate road-segment dataset is required before the model is used as a stand-alone prediction tool.

DISCUSSION

The regression model developed in this study demonstrates that overlay thickness values generated through the standard deflection-based design procedure can be approximated with a high degree of numerical agreement within the sixteen analyzed segments ($R^2 = 0.983$). This result represents goodness of fit to the calculated dataset rather than independent predictive accuracy. The findings partially confirm the hypotheses formulated in the introduction: representative deflection emerged as a highly significant and dominant predictor of overlay thickness, while cumulative ESA contributed in the hypothesized positive direction, though its individual effect was comparatively modest once deflection was accounted for. This nuanced result suggests that, within this dataset, structural condition (deflection) is the primary determinant of overlay requirements, with traffic load acting as a reinforcing rather than independently decisive factor.

Firstly, the analysis of the structural condition utilizing the representative deflection (D_{rep}) highlights a direct and statistically significant correlation between high deflection values and the need for structural reinforcement ($t = 25.17$, $p < 0.001$). This relationship holds consistently across the full sample: segments such as Wonomulyo-Gubuk Klakah ($D_{rep} = 438.77$ mm) and Jl. Raya Tulungrejo Segmen I ($D_{rep} = 405.48$ mm) required the thickest overlays in the dataset (4.54 cm), while segments such as Jl. Ir. Soekarno ($D_{rep} = 125.19$ mm) required as little as 3.21 cm. As observed in the KM.113+700 - KM.115+405 segment specifically, a D_{rep} value of 248.52 mm necessitated a 3.87 cm asphalt overlay to meet the 15-year design life.

Secondly, the traffic load analysis underscores the unique operational stress experienced by the Malang provincial road section. The extraction of vehicle distribution data revealed a massive accumulation of ESA, heavily driven by commercial transit, particularly small buses (Gol 5A) contributing over 102 million ESA. Unlike national toll roads with strict weigh-in-motion (WIM) enforcement, provincial roads frequently accommodate a diverse and dynamically varying mix of local transit and heavy logistics. The aggressive accumulation of ESA acts as the primary catalyst for structural fatigue. The predictive model captures this dynamic directionally, supporting the hypothesis that higher cumulative traffic loads are associated with thicker required overlays; however, the individual statistical contribution of

ESA in the fitted model was more modest than that of deflection ($p = 0.174$), suggesting that within this 16-segment sample, traffic load variation was comparatively narrow relative to deflection variation — several corridors carrying markedly different vehicle compositions nonetheless produced similar cumulative ESA totals. Future studies incorporating a larger and more traffic-diverse sample may help clarify the independent statistical contribution of ESA to overlay thickness.

Furthermore, because the 15-year design life was applied uniformly as a fixed planning parameter rather than as a variable input, it was not tested as an independent statistical predictor in the regression model; instead, it served to standardize the cumulative ESA projection horizon, ensuring that the resulting overlay thicknesses across all sixteen segments remain directly comparable to one another. Future research incorporating segments with genuinely varying pavement ages (rather than a uniform design life) would be needed to empirically test pavement age as a third predictive variable, as originally hypothesized.

From a practical and administrative perspective, this study bridges the gap identified in previous research, which often relied on generalized empirical nomograms that failed to account for localized distress patterns. The resulting regression equation may provide the regional highway authority with a simplified preliminary estimation tool for screening and maintenance planning. However, it should not replace the standard overlay design procedure or the required field deflection assessment. Engineers may use the equation for an initial approximation, followed by verification using the applicable pavement design method and current field data.This capability greatly enhances the efficiency of maintenance scheduling, ensuring that limited infrastructure budgets are allocated optimally without compromising the structural integrity and serviceability of the Malang provincial road network.

CONCLUSION

The main findings demonstrate that the fitted Multiple Linear Regression equation, using representative Benkelman Beam deflection and cumulative Equivalent Standard Axle (ESA), provides a close numerical approximation of overlay thickness values calculated through the standard deflection-based design procedure across the sixteen analyzed road segments ($R^2 = 0.983$). The uniform 15-year design life was used only as the ESA projection period and was not tested as an independent predictor.The empirical analysis confirms that structural degradation is primarily driven by surface deflection, indicating diminished load-bearing capacity, with cumulative commercial vehicle traffic (ESA) reinforcing this relationship in the hypothesized direction, though its independent statistical contribution was more modest within this sample. By quantitatively linking deflection and traffic load data across a diverse set of provincial road corridors, this integrated, data-driven model proves more comprehensive than traditional, generalized empirical nomograms that rely on isolated variables or single-segment case examples.

Based on these findings, it is recommended that regional policymakers and civil engineering practitioners use this regression equation only as a preliminary supporting tool for maintenance screening and budgeting. Final overlay design decisions should continue to rely on the applicable standard design procedure, current deflection measurements, traffic-load assessment, and continued periodic field verification. Implementing this model can help road authorities forecast overlay needs, optimize long-term maintenance scheduling, and allocate limited infrastructure budgets more efficiently. For future researchers, it is recommended to incorporate road segments with genuinely varying pavement ages to formally test age as a third predictive variable, and to expand the spatial and geographical scope of this study by including datasets from other provincial road networks with different climatic conditions and subgrade characteristics, thereby broadening the model's generalizability and clarifying the independent statistical role of traffic load. Furthermore, future studies could explore the application of advanced machine learning algorithms to complement this regression-based model, thereby continuously refining prediction accuracy and adapting to real-time traffic load fluctuations.

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