ASIAN JOURNAL OF ENGINEERING, SOCIAL AND HEALTH

Volume 5, No. 6 June 2026
p-ISSN 2980-4868 | e-ISSN 2980-4841
https://ajesh.ph/index.php/gp

Uncovering Nonlinear Urban Road Geometric Thresholds Using Mars Traffic Modelling

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Keywords	Abstract
road geometry; Multivariate Adaptive Regression Splines (MARS); traffic performance; knot points; grade-separated u-turn	Urban traffic facilities in densely populated metropolitan areas often experience performance degradation due to the complex interactions between road geometric characteristics and driver behavior. Conventional traffic modeling approaches generally assume linear relationships, which may fail to capture critical threshold effects in heterogeneous traffic environments. This study aims to identify nonlinear relationships between urban road geometry, driver behavior, and traffic performance, as well as to determine critical threshold values that significantly influence operational efficiency at a grade-separated u-turn facility. The research employed a quantitative approach using microsimulation and Multivariate Adaptive Regression Splines (MARS) modeling. A total of 62 simulation scenarios were developed by varying geometric parameters, including turning radius, gradient, and weaving section length, along with behavioral variables such as motorcycle proportion and time headway. Traffic performance was evaluated using average delay and through-traffic indicators, while MARS was applied to detect nonlinear interactions and critical knot points. The results demonstrate that the MARS models achieved high predictive accuracy, with generalized R-squared (GRSq) values of 0.6687 for delay and 0.9231 for through traffic. Critical thresholds were identified at a turning radius of 12 meters, a gradient of 4%, and a weaving section length of 40 meters. Motorcycle proportion and time headway were also found to significantly affect traffic performance. These findings confirm that traffic performance is influenced by nonlinear interactions between geometric design and driver behavior. Therefore, MARS provides an effective analytical framework for identifying design-sensitive thresholds and supporting more adaptive, behavior-oriented urban road planning and traffic management strategies.

INTRODUCTION

Rapid population growth in developing cities, such as the Jakarta greater area, contributes to the urbanization phenomenon (Batubara et al., 2025; Nurrokhman et al., 2026; Pravitasari et al., 2024; Silver, 2024; Suhartini & Jones, 2023). Following this, road facilities along vital corridors are crucial in terms of balancing productivity and efficiency of mobility (Flory & Nyaronga, 2025; Kveladze et al., 2025; Rivadeneira et al., 2024; Zhang et al., 2025). Commuter traffic in suburban areas requires infrastructure capable of accommodating fluctuating vehicle volumes. Delays caused by at-grade crossings often worsen travel times, especially during peak periods. In 2021, the Jakarta Provincial Government operationalized the Tapal Kuda Tanjung Barat Flyover, a facility built as a government solution to address this challenge.The empirical study provided by Rifai et al. (2021) highlights the inefficiency of the facility. The findings show a queue length reaching 400 m and a degree of saturation of 1.61, proving the inaccuracy between the feasibility analysis and actual conditions.

Consequently, researchers are questioning the value gap, hypothetically assuming that extreme designs are the main cause of the problem regarding the constraints (Alruwaili, 2026; Mothilal et al., 2025; Pinheiro, 2025). Facing the issue of limited land and vertical cantilever clearance from the active rail underneath, it becomes a limitation in determining the design. However, the study did not consider the impact of geometric variables on driver response when traffic grows. Geometric parameters such as a sharp curve radius (12 m) and a steep gradient (5.49%) cause driver adjustments to driving behavior, which over time will lead to inefficiencies in individual comfort and the traffic network (Harantová & Bulková, 2025).Static standards-based design approaches often fail to address the need for such performance reductions. The lack of adaptation to local rider behavior is a determining factor due to their psychophysical response to extreme geometry (Eom & Park, 2025). Linear regression models, often used in similar modeling, are based solely on model simplification, thus under-recognizing driver behavior, which is local and disaggregated (Gülhan et al., 2021; Mar'ah A., Ruliana & Septiana, 2024; Pratama et al., 2025). Furthermore, the linear model's inability to capture performance anomalies at extreme points leads to a gap between the design plan and the reality on the ground.In the case of the Tanjung Barat Flyover, significant geometric changes trigger drivers to maneuver aggressively.

This phenomenon creates a non-linear relationship where changes in geometric parameters are projected into disproportionate delay spikes.Given this urgency, a statistical method capable of detecting "thresholds" in the interaction of driver behavior with geometric design is needed. The Multivariate Adaptive Regression Splines (MARS) approach is considered capable of addressing this need. Through its linear fragmentation and critical point features, the model can detect thresholds for changes in traffic performance resulting from the interaction of driver perception with geometric design.The specific issue addressed in this study concerns the nonlinear interaction between road geometric variables and driver behavior at the Tapal Kuda Tanjung Barat Flyover. The facility was developed to respond to delays caused by at-grade crossings, yet its design is constrained by limited land and vertical clearance above the active railway. The manuscript notes that the facility involves critical geometric parameters, including a 12-meter turning radius and a 5.49% gradient, which may influence driver maneuvering behavior and traffic efficiency.

Therefore, the case represents an important context for examining how compact urban road geometry affects delay and through traffic.Previous studies have shown that conventional linear models are often insufficient for explaining complex traffic performance. Gülhan, Özuysal, and Ceylan used the Multivariate Adaptive Regression Splines method to evaluate intersection properties and improve urban traffic performance, demonstrating the usefulness of nonlinear modeling in transportation analysis. Haleem, Gan, and Lu applied MARS to develop crash modification factors in urban freeway interchange influence areas, showing that spline-based models can detect complex relationships in road safety contexts. Chen and colleagues (2017) also used MARS for data-driven fuel consumption estimation, confirming its relevance for transportation systems where multiple interacting variables affect performance outcomes.Other recent studies support the need to integrate geometry, simulation, and behavioral sensitivity in traffic modeling.

Harantová and Bulková examined the impact of geometric modifications and signal plan optimization on urban intersections, emphasizing that infrastructure design changes can significantly affect urban traffic operations. Eom and Park investigated microscopic simulation to evaluate traffic efficiency and safety under different behavioral conditions, indicating that driver behavior must be considered when assessing road performance. These studies suggest that traffic performance is shaped by the interaction between physical design and behavioral response, rather than by geometric standards alone.Despite these contributions, a research gap remains in identifying precise critical thresholds or knot points where geometric and behavioral variables begin to cause significant changes in traffic performance. Many studies focus on average effects, linear relationships, or general model accuracy, but fewer examine how turning radius, gradient, weaving length, motorcycle proportion, and headway interact at specific threshold values in heterogeneous traffic. This gap is important because urban road design decisions often require practical reference values that can guide planners under land constraints.The urgency of this research lies in the need to prevent design-performance mismatches in compact urban road facilities. When geometric design is evaluated only through static standards, the resulting facility may technically satisfy minimum design requirements but still create operational inefficiency in the field. In heterogeneous traffic environments such as Jakarta, drivers frequently adjust speed, spacing, braking, and acceleration based on local traffic density and available maneuvering space. Therefore, identifying nonlinear thresholds can help planners anticipate when a design parameter begins to produce significant delay or capacity reduction.The novelty of this study is its use of Multivariate Adaptive Regression Splines to uncover nonlinear critical thresholds in urban road geometry by combining microsimulation output and behavioral variables. The study does not merely estimate whether geometric variables influence traffic performance but identifies knot points where their effects change direction or intensity. In the manuscript, the model detects critical thresholds such as a 12-meter turning radius, 4% gradient, 40-meter weaving section, and behavioral thresholds related to motorcycle proportion and time headway. This makes the research valuable because it converts complex nonlinear relationships into practical planning references.

This research aims to analyze the nonlinear interaction between geometric variables, driver behavior, and traffic performance at a grade-separated u-turn facility. Specifically, it seeks to identify threshold values of turning radius, gradient, weaving length, motorcycle proportion, and headway that significantly influence delay and through traffic. The study contributes theoretically by expanding the application of MARS in urban traffic performance modeling and contributes practically by providing evidence-based geometric design references for planners working in land-limited urban corridors. The benefit of this research is that it supports more adaptive, behavior-sensitive, and performance-oriented road design for congested metropolitan areas.

METHOD

This research relies heavily on the quality and range of variance of the sample data used. By implementing quantitative study, this study optimizes the valid baseline from secondary data to analyze the sensitivity using MARS to uncover the non-linear interactions between variables. Following this, the basis functions are generated by RStudio to interpret the data into visual knot point analysis. The dataset generated in this research was compiled in stages, with a workflow described in the following paragraphs:

The first step is to select the afternoon rush hour base model which goes through prior two stage validation with RMSE score of 9.67 (<10) for queue length variable and GEH of 4.8 (<5) for average delay. Subsequently, this baseline is deemed to have the highest urgency for improvement and the best representation for each independent variable. Furthermore, the disaggregated driving behaviors must be packaged as accurately as possible to reflect their variation across test scenarios. The determined variables and their sample test ranges For optimize reliability data variance.

Table 1. Variables and Range of Analysis Test Sensitivity

Variable Types	Variables	Unit	Range sample	Interval
Dependent	Average delay	Second / vehicle .	-	-
	Through traffic	Junior high school / hour	-	-
Independent	**Geometric**			
	- Turning radius (R)	Meter	10 – 20	2
	- Gradient / slope (G)	%	3.5* – 6	0.5
	Behavior Driving			
	- Segment length of weaving section (W)	Meter	-	**
	- Time headway (CC_{1})	Second	0.5 – 4.0	***
	- Motorcycle proportion (P_{MC})	%	40 – 100	10

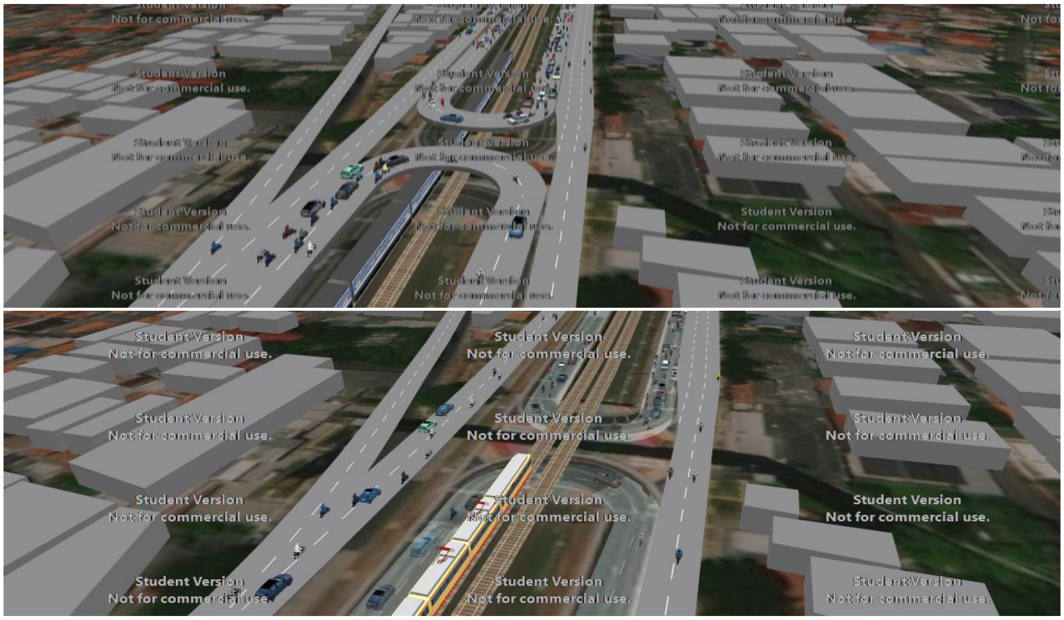
Information:

** Initiated by 2%, but hampered by limited land*

*** Length of weaving section (W) is calculated from land availability and adjustments to ramp gradient at every scenario*

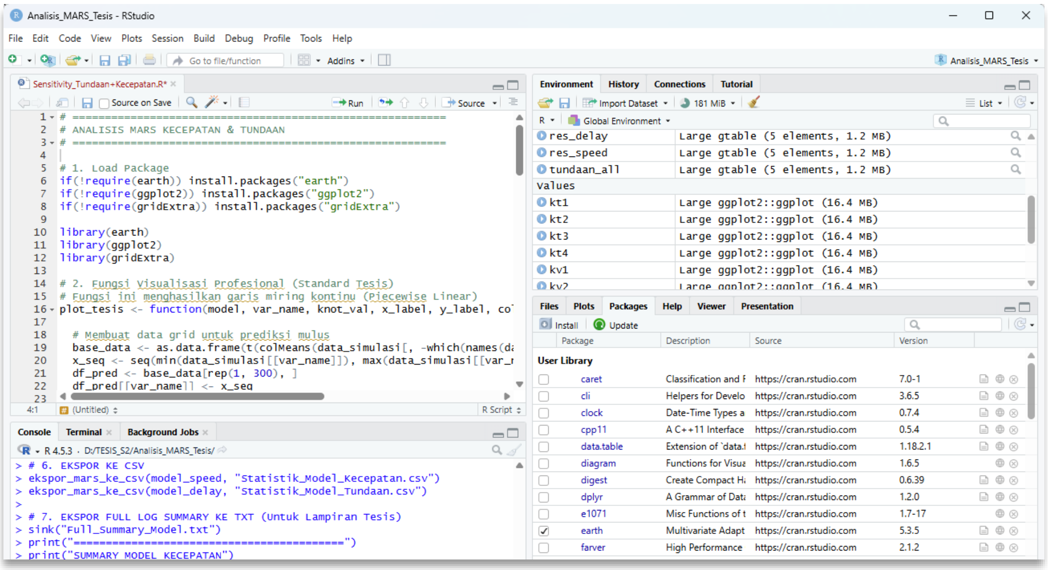
**** Wiedemann-99 preset in PTV VISSIM*

Next, it is determined the quantity and combination of compiled samples as many as 62 random-cross scenarios. This is an aim for optimizing the MARS model in detecting interaction effects between independent variables. According to Friedman, the number of scenarios requirement is considered feasible because this satisfies the non-parametric minimum standard to ensure the coefficient stability of the model. In this study, with four input variables, giving the variable-sample ratio of 15 to 1, which is satisfies the tolerance ranging from 10 – 20 to 1. All sample Then input into the microsimulation model Vissim For tested later the results yeah recapitulated For analysis continued.



Picture 1. Simulation Running Process on Flyover and Underpass Structure

MARS model analysis is performed after the output from the Vissim simulation run has been summarized. This is done by using the RStudio application and its pyearth algorithm for automatic processing. RStudio's output, a summary report for each model and a variable sensitivity graph, can then be used to represent the MARS model.



```r
# ============================================================
# ANALISIS MARS KECEPATAN & TUNDAAN
# ============================================================

# 1. Load Package
if(!require(earth)) install.packages("earth")
if(!require(ggplot2)) install.packages("ggplot2")
if(!require(gridExtra)) install.packages("gridExtra")

library(earth)
library(ggplot2)
library(gridExtra)

# 2. Fungsi Visualisasi Profesional (Standard Tesis)
# Fungsi ini menghasilkan garis miring kontinu (Piecewise Linear)
plot_tesis <- function(model, var_name, knot_val, x_label, y_label, co

  # Membuat data grid untuk prediksi mulus
  base_data <- as.data.frame(t(colMeans(data_simulasi[, -which(names(da
  x_seq <- seq(min(data_simulasi[[var_name]]), max(data_simulasi[[var_r
  df_pred <- base_data[rep(1, 300), ]
  df_pred[[var_name]] <- x_seq
```

```
> # 6. EKSPOR KE CSV
> ekspor_mars_ke_csv(model_speed, "Statistik_Model_Kecepatan.csv")
> ekspor_mars_ke_csv(model_delay, "Statistik_Model_Tundaan.csv")
>
> # 7. EKSPOR FULL LOG SUMMARY KE TXT (Untuk Lampiran Tesis)
> sink("Full_Summary_Model.txt")
> print("========================================")
> print("SUMMARY MODEL KECEPATAN")
```

```
res_delay     Large gtable (5 elements, 1.2 MB)
res_speed     Large gtable (5 elements, 1.2 MB)
tundaan_all   Large gtable (5 elements, 1.2 MB)
Values
kt1           Large ggplot2::ggplot (16.4 MB)
kt2           Large ggplot2::ggplot (16.4 MB)
kt3           Large ggplot2::ggplot (16.4 MB)
kt4           Large ggplot2::ggplot (16.4 MB)
kv1           Large ggplot2::ggplot (16.4 MB)
kv2           Large ggplot2::ggplot (16.4 MB)
```

	Package	Description	Source	Version
	User Library			
☐	caret	Classification and F	https://cran.rstudio.com	7.0-1
☐	cli	Helpers for Develo	https://cran.rstudio.com	3.6.5
☐	clock	Date-Time Types a	https://cran.rstudio.com	0.7.4
☐	cpp11	A C++11 Interface	https://cran.rstudio.com	0.5.4
☐	data.table	Extension of `data.t	https://cran.rstudio.com	1.18.2.1
☐	diagram	Functions for Visua	https://cran.rstudio.com	1.6.5
☐	digest	Create Compact Ha	https://cran.rstudio.com	0.6.39
☐	dplyr	A Grammar of Data	https://cran.rstudio.com	1.2.0
☐	e1071	Misc Functions of t	https://cran.rstudio.com	1.7-17
☑	earth	Multivariate Adapt	https://cran.rstudio.com	5.3.5
☐	farver	High Performance	https://cran.rstudio.com	2.1.2

Picture 2. MARS analysis process with RStudio

RESULTS AND DISCUSSION

Output from MARS method has unique and different characteristics compared to standard linear regression. This can be seen from the working data plot forming split (by knot points) into several flexible segments. This allows identification to influence variables different geometrics on each levels value. The output from running the MARS model can be seen in the summary report for each independent variable, explained in the following table:

Table 2. MARS Model Variable Output Results for Delay (seconds/vehicle)

Notation	Term	Coefficient	Std_Error	t_Statistic	p_Value
a_0	(Intercept)	87.92	2.93	30.01	8.73E-36
Bf1	max(70-pMC)	0.56	0.11	4.98	6.54E-06
Bf2	max(4-Gradient)	-32.62	5.39	-6.05	1.33E-07
Bf3	max(Radius-12)	1.37	0.46	3.01	3.92E-03
Bf4	max(12-Radius)	8.76	1.71	5.12	4.07E-06
Bf5	max(pMC-80)	-1.10	0.18	-6.23	6.78E-08
Bf6	max(CC1-1.5)	9.90	1.49	6.65	1.39E-08
	GRSq	**0.6687**	NA	NA	NA
	RSq	**0.7862**	NA	NA	NA

Source: Analysis Results, 2026

Based on the MARS output, the model for the delay variable shows quite good accuracy with RSq and GRSq values of 0.7862 and 0.6687 , respectively . The table above also identifies that time headway has the most significant influence with a p-value of 1.39x10 -8 , which is far below the threshold (<0.05). On the other hand, the structure type variable is not included in the model due to its too high p-value.

Table 3. MARS Model Variable Output Results for *Through Traffic* (smp /hour)

Notation	Term	Coefficient	Std_Error	t_Statistic	p_Value
a_0	bx(Intercept)	2119.79	65.82	32.21	5.03E-36
Bf1	max(2-CC1)	848.34	48.95	17.33	2.94E-23
Bf2	max(pMC-50)	36.34	7.23	5.03	6.23E-06
Bf3	max(Gradient-4)	127.92	28.64	4.47	4.32E-05
Bf4	max(12-Radius)	-105.14	25.74	-4.08	1.53E-04
Bf5	max(CC1-1.5)	-217.87	38.02	-5.73	5.11E-07
Bf6	max(pMC-60)	-50.40	13.77	-3.66	5.88E-04
Bf7	max(pMC-70)	53.86	15.27	3.53	8.90E-04
Bf8	max(pMC-80)	-33.44	11.10	-3.01	4.01E-03
Bf9	max(40-Weaving)	-17.52	5.41	-3.24	2.09E-03
	GRSq	**0.9231**	NA	NA	NA
	RSq	**0.9618**	NA	NA	NA

Source: Analysis Results, 2026

Based on the MARS output, the model for the through traffic variable shows high accuracy with RSq and GRSq values of 0.9618 and 0.9231, respectively. The small difference between the two parameters, which is 0.04, indicates that the model does not experience overfitting. The table above also identifies that time headway has the most significant influence with a p-value of 2.94x10 -23, which is far below the threshold (< 0.05). On the other hand, the structure type is not included in the model due to its high p-value.

From the summary result as shown in tables 2 and 3, can identified basis function (hinge function) which can then be used to form a mathematical model . The model used as formulation predictive for every variables bound as explained in equality following

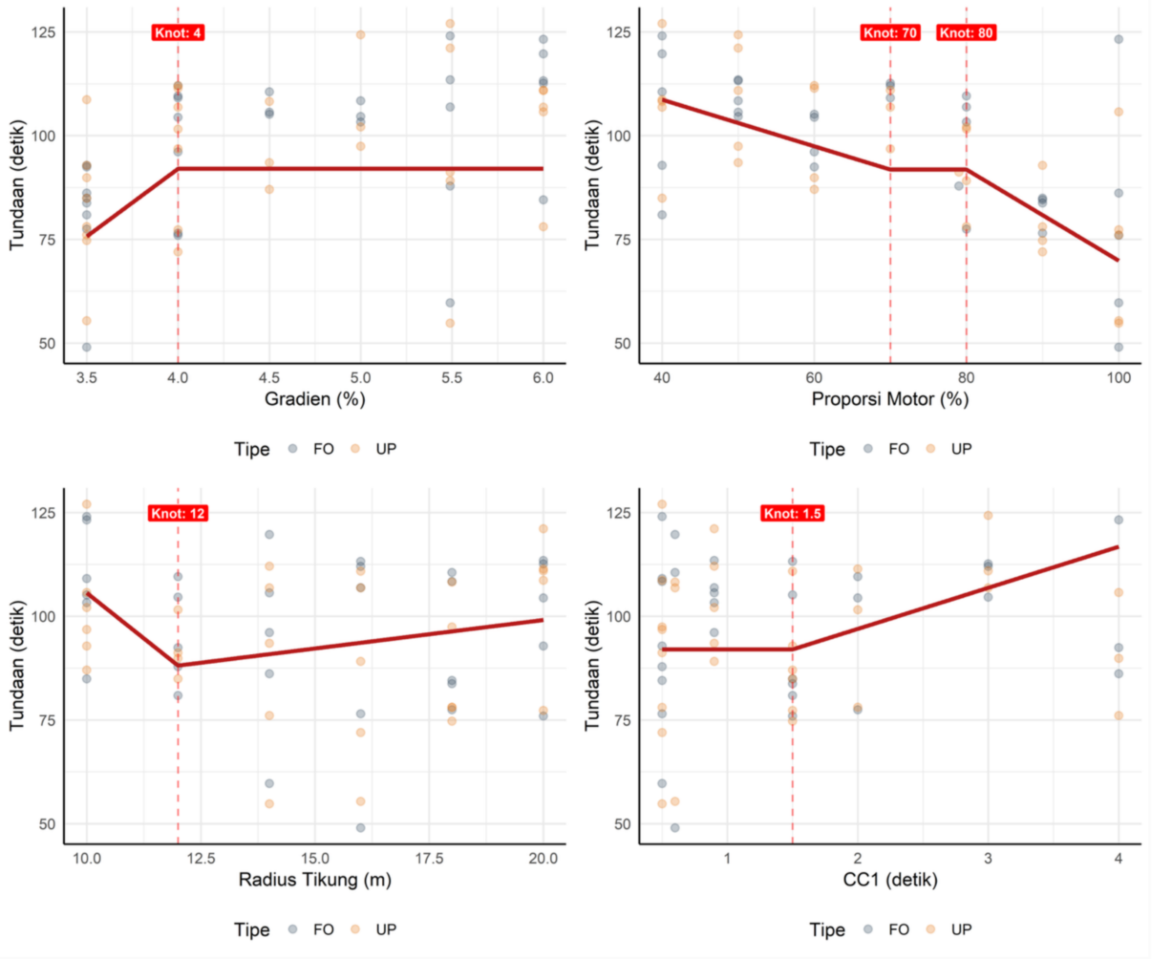
$$"\boldsymbol{Tundaan}" = 87.92 + 0.56(70 - pMC) - 32.62(4 - g) + 1.37(R - 12) + 8.76(12 - R) - 1.10(p - 80) + 9.90(CC1 - 1.5)$$

$$\begin{aligned}"\boldsymbol{Through\,Traffic}" &= 2119.79 + 848.34(2 - CC1) + 36.34(pMC - 50) + 127.92(g - 4) \\ &\quad - 105.14(12 - R) - 217.87(CC1 - 1.5) - 50.40(pMC - 60) \\ &\quad + 53.86(pMC - 70) - 33.44(p - 80) - 17.52(40 - w)\end{aligned}$$

Where :

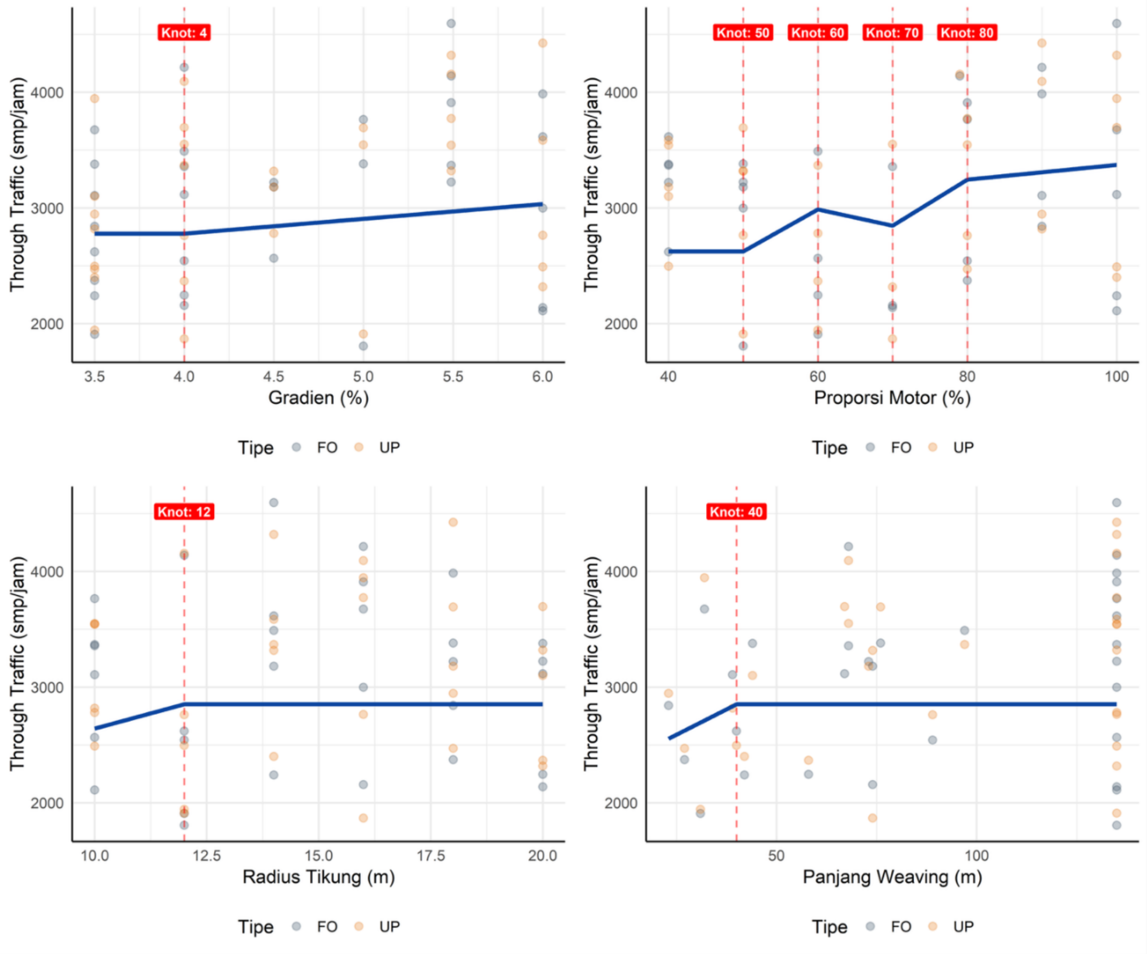
w : Segment length of weaving section pre- ramp-up (meter)
R : Turning radius segment u-turn (meter)
g : U-turn ramp gradient (%)
p_{MC} : Motorcycle proportion in general traffic (%)
Q : Type structure (FO=0; UP=1)
CC_1 : Headway time (seconds)

Other outputs of the MARS model besides from summary result that is sensitivity chart. Through this visual analysis, we can identify critical points (knot points) in each variable, as can be seen in the graph following.



Picture 3. Chart sensitivity and knot point(s) of the Delay model

The graph above shows that every independent variables analyzed on the delay model own point each critical in the form of visual thresholds. On the gradient variable knot point is at 4 %, proportion of motorbikes have 2 points critical at 70 and 80%, turning radius own threshold at 12 meters, and headway time is at 1.5 seconds.



Picture 4. Chart sensitivity and knot point(s) of the *Through Traffic model*

The graph above show that every independent variables analyzed on the *through traffic* model own point each critical in the form of visual thresholds. On the gradient variable knot point is at 4 **%,** proportion of motorbikes have 4 (four) points critical at **40, 50, 60, and 70%,** turning radius own threshold at **12 meters,** and weaving section length is at **40 meters**.

The three outputs of the MARS model algorithm in table 2 and 3 show several key points. In table 2 (delay model), with the difference between RSq and GRSq values being much larger than the *through traffic model*, the model is still considered feasible and representative for modeling disaggregated traffic behavior. Local driver behavior has heterogeneous characteristics due to the intensity of irregular interactions between vehicles (*non-lane-based driving*), so it has a high level of difficulty to model.

The sensitivity graph for the delay model (Figure 3) highlights the gradient variable. At a threshold value of 4%, driver perception changes, at which point drivers begin to lose momentum and perform inefficient maneuvers. Furthermore, the radius variable indicates a change in driving patterns within a 12-meter radius. Forcing the design implementation below this value would result in vehicles having to decelerate with suboptimal U-turn maneuvers.

Meanwhile, in terms of driving behavior, the motorcycle proportion variable indicates that motorcycle dominance can reduce the potential for delays. Meanwhile, the time headway variable is able to provide tolerance for vehicle platooning stability with close distances of 0.5 – 1.5 seconds. Beyond this range, vehicle maneuvers are considered inefficient and cause additional delays. Both of these findings are caused by aggressive driving that occurs at the study location. This situation requires drivers to constantly brake and accelerate, especially in weaving areas and turn areas.

The second sensitivity graph indicates how sensitive the independent variables are to continuous flow performance (Figure 4). This performance indicator has a high sensitivity to turning radius, where a value below 12 meters can significantly reduce continuous flow. In terms of rider behavior, the proportion of motorcycles has a significant impact on flow capacity. Although there are four knot points, it can be concluded that each increase in the proportion of motorcycles can increase continuous flow capacity.

CONCLUSION

This study concludes that the relationship between urban road geometric characteristics and traffic performance is inherently nonlinear, particularly in grade-separated u-turn facilities operating under heterogeneous traffic conditions. By applying the Multivariate Adaptive Regression Splines (MARS) approach, the research successfully identified critical threshold values that significantly influence traffic delay and through traffic performance. The findings indicate that a turning radius of 12 meters, a gradient of 4%, and a weaving section length of 40 meters represent important geometric thresholds beyond which driver behavior and traffic performance change substantially. In addition, behavioral variables such as motorcycle proportion and time headway were found to have a significant impact on traffic operations, demonstrating that traffic performance is determined not only by infrastructure design but also by the interaction between road users and geometric conditions. The high predictive accuracy of the MARS models further confirms the effectiveness of nonlinear modeling techniques in capturing complex traffic dynamics that are often overlooked by conventional linear approaches.

Future research is recommended to expand the scope of analysis by incorporating additional geometric, operational, and environmental variables such as lane width, sight distance, weather conditions, traffic composition, and vehicle speed characteristics. Studies conducted in different urban contexts and road facility types would also enhance the generalizability of the findings and provide broader design recommendations. Furthermore, integrating real-world traffic observations with advanced machine learning techniques, such as Random Forest, XGBoost, or Artificial Neural Networks, may improve predictive capability and allow comparisons among different modeling approaches. Future investigations should also examine long-term traffic performance and safety implications associated with critical geometric thresholds to support the development of more adaptive, behavior-sensitive, and sustainable urban transportation infrastructure.

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