And., Intl.,J., Appl Sci., Eng., Tech, Vol 06, No 03, November 2026
e-ISSN: 2797-0442

Regime-Dependent Performance of Fundamental Traffic-Flow Models across Motorcycle-Proportion Conditions in Urban Mixed Traffic

Sanju Yedo Oksa, Elsa Eka Putri*, Yosritzal
Department of Civil Engineering, Faculty of Engineering, Universitas Andalas, Padang, Indonesia
*Corresponding author, e-mail: elsaeka@eng.unand.ac.id

Abstract—Motorcycle-dominated urban traffic exhibits heterogeneous characteristics that may influence the suitability of fundamental traffic-flow models under different traffic-composition conditions. This study evaluates the performance of the Greenshields, Greenberg, and Underwood models across different motorcycle-proportion regimes on divided urban road type 4/2T in Padang, Indonesia. Field observations were conducted on Jalan Prof. Dr. Hamka and Jalan Adinegoro, with traffic data collected during a 12-hour observation period and aggregated into hourly observations. The observed data were classified into three motorcycle-proportion regimes: Regime A (59% ≤ %SM < 65%), Regime B (65% ≤ %SM < 70%), and Regime C (%SM ≥ 70%). Speed-density relationships were fitted separately for each regime, and model performance was evaluated using the coefficient of determination (R^2) as the primary criterion and root mean square error (RMSE) as a complementary measure. The results show that Underwood achieved the highest R^2 in Regimes A and B, with values of 0.9100 and 0.8657, respectively, while Greenberg achieved the highest R^2 in Regime C at 0.9449. Greenberg also produced the lowest RMSE in Regime C at 6.55 km/h. These findings indicate that the relative suitability of classical fundamental traffic-flow models varies across motorcycle-proportion regimes, supporting a composition-sensitive approach to model selection in motorcycle-dominated urban mixed traffic.

Keywords: Motorcycle proportion; mixed traffic; fundamental traffic-flow model; speed-density relationship; model performance.

This article *is licensed under the CC-BY-SA license.*

1. Introduction

Urban traffic streams in many developing countries are characterized by heterogeneous vehicle compositions, in which motorcycles coexist with passenger cars and other vehicle types. Such mixed-traffic conditions differ from relatively homogeneous traffic because vehicles with different physical dimensions, operating speeds, maneuverability, and driving behaviors interact within the same traffic stream. Motorcycle-dominated traffic is particularly relevant in many Asian urban environments, where motorcycle operating characteristics and interactions with other vehicles can influence aggregate traffic performance [1], [2], [3]. Motorcycle riders may also exhibit distinctive maneuvering behavior in mixed traffic, such as lane filtering, which further reflects the heterogeneous nature of motorcycle-dominated traffic streams [3]. Consequently, traffic-flow relationships developed primarily from homogeneous traffic assumptions may not represent heterogeneous urban traffic conditions equally well across different traffic compositions.

A fundamental representation of traffic flow describes the interrelationship among traffic volume, speed, and density. The speed-density relationship is commonly used as the basic formulation from which the corresponding volume-density and volume-speed relationships can be derived through the fundamental relationship between flow, density, and speed [4]. Several classical models have been developed to represent this relationship, including the Greenshields, Greenberg, and Underwood

Received: September 30, 2026, Revised: November 4, 2026, Accepted: November 9, 2026
https://doi.org/10.25077/aijaset.v6i3.380

models. These models differ in their mathematical formulations and assumptions regarding the relationship between speed and density, resulting in different representations of traffic-flow characteristics [4], [5]. Previous research has also demonstrated that alternative traffic-flow models can produce different levels of agreement with empirical traffic data, highlighting the importance of quantitative model comparison when selecting an appropriate fundamental relationship [6]. Therefore, the suitability of a fundamental traffic-flow model may depend on the characteristics of the traffic stream being represented.

Among the factors contributing to traffic heterogeneity, vehicle composition is particularly important because changes in the proportion of specific vehicle types can alter the aggregate characteristics of the traffic stream. In motorcycle-dominated traffic, variations in motorcycle proportion may influence speed, volume, density, and the interaction patterns among vehicles. Empirical research in Padang, Indonesia, has demonstrated that motorcycle proportion is associated with variations in traffic-flow parameters on multi-lane urban roads, including differences in speed and density characteristics [7]. More recent research has further examined speed-volume-density relationships under different motorcycle-volume percentages, highlighting the variation of traffic-flow relationships under different motorcycle compositions [8]. Previous research has also investigated mixed-traffic characteristics using different motorcycle-composition classes and the Greenshields, Underwood, and Greenberg models, reporting differences in the estimated traffic-flow characteristics across motorcycle-proportion classes [9]. Studies examining the effect of vehicle type on mixed-traffic performance have likewise demonstrated that variations in vehicle composition can be associated with differences in traffic-flow performance [10].

The relevance of motorcycle-dominated traffic in Padang is also reflected in the city's registered vehicle fleet. Data reported by Katadata/Databoks indicate that Padang recorded 672,854 registered motorcycles out of 869,994 registered motor vehicles in 2025, representing approximately 77.3% of the total registered fleet [11]. Although this figure does not directly represent the motorcycle proportion observed on individual road sections, it provides quantitative context for examining motorcycle-dominated urban traffic in Padang.

The sensitivity of fundamental traffic relationships to traffic composition has also been reported in broader mixed-traffic studies. Research on heterogeneous traffic has shown that changes in vehicle composition can affect the form and parameters of empirical fundamental diagrams, making the representation of mixed traffic more dependent on the prevailing composition and operating conditions [12], [13], [14]. Recent research has further explored fundamental diagrams for heterogeneous and non-lane-based mixed traffic, emphasizing the challenges of representing empirical traffic relationships under heterogeneous operating conditions [14]. These findings reinforce the importance of considering traffic composition when evaluating the applicability of traffic-flow models. In addition, the conversion of heterogeneous traffic volumes into passenger car units requires consideration of vehicle-specific behavior, particularly for motorcycle-dominated conditions [15], [16]. Thus, both traffic composition and the representation of vehicle interactions are relevant when analyzing fundamental traffic-flow relationships in mixed traffic.

Related empirical studies have also examined motorcycle-specific operating characteristics and traffic conditions in urban road environments. Studies have investigated the distribution of motorcycle positions in relation to traffic-flow variables, while other research has examined vehicle speed under different platoon characteristics [17], [18]. Research on motorcycle-lane implementation has further considered traffic performance and riding experience, including studies conducted in Padang and other Indonesian urban road environments [19], [20]. In addition, traffic-speed management research has examined speed characteristics on undivided urban roads [21]. These studies provide additional empirical context for understanding the variation of traffic characteristics and motorcycle-related operating behavior in mixed-traffic environments.

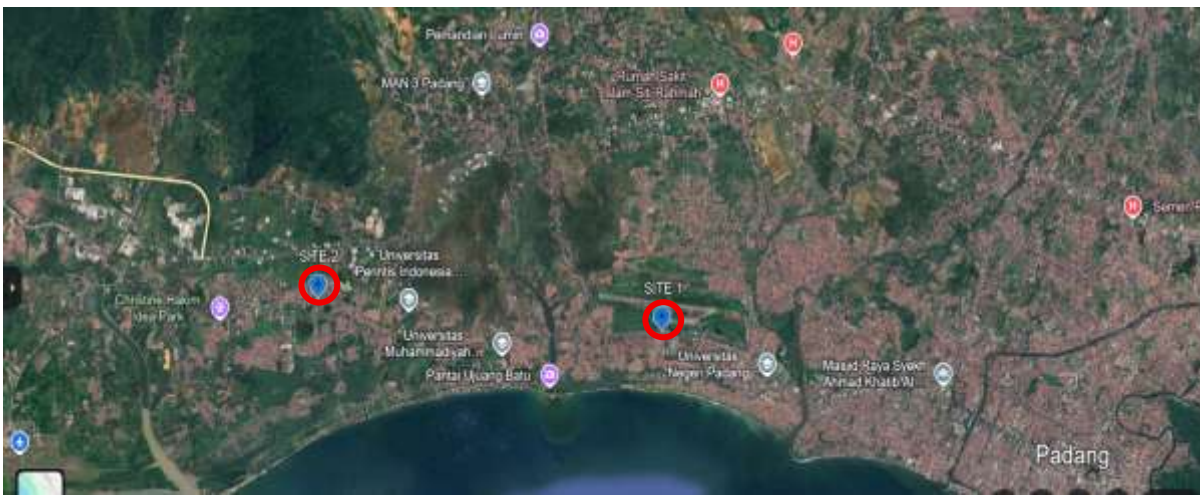
Although previous studies have examined motorcycle-related traffic characteristics and the application of fundamental traffic-flow models to mixed traffic, further empirical evidence is needed to establish whether the relative performance of classical models varies across motorcycle-proportion regimes on divided urban roads. Previous research has investigated motorcycle-composition classes and fundamental traffic-flow models [9], while studies conducted in Padang have documented variations in traffic-flow characteristics associated with motorcycle proportion [7]. However, the comparative performance of alternative classical models across explicitly defined motorcycle-proportion regimes remains an important issue for further empirical investigation. Comparing these models under different observed traffic-composition conditions using consistent goodness-of-fit criteria may help clarify their relative suitability for motorcycle-dominated urban mixed traffic.

To address this gap, this study evaluates the Greenshields, Greenberg, and Underwood models using field observations from two divided urban road sections classified as type 4/2T in Padang, Indonesia. The observations are grouped into three empirically defined motorcycle-proportion regimes, and model performance is compared using the coefficient of determination (R^2) and root mean square error (RMSE). The study contributes empirical evidence on regime-dependent model performance and examines the relevance of motorcycle proportion as a consideration in selecting fundamental traffic-flow models for urban mixed traffic.

2. Method

2.1 Study Area and Observation Period

The study was conducted on two divided urban road sections in Padang City, Indonesia: Jalan Prof. Dr. Hamka and Jalan Adinegoro. Both sections are classified as urban road type 4/2T and carry mixed traffic dominated by motorcycles. The two sites were selected to provide field observations under varying motorcycle-proportion conditions, which are central to the study's objective of comparing the performance of classical fundamental traffic-flow models across different traffic-composition regimes. Traffic observations were conducted in one direction at each site. The analysis focuses on the observed traffic conditions at these two locations and does not assume that they represent all urban roads in Padang. The geographic coordinates of the two study sites are as follows: Site 1 is located at 0°52′41.19″ S, 100°20′53.91″ E, while Site 2 is located at 0°49′26.31″ S, 100°19′35.19″ E. The locations of both sites are shown in Figure 1.



(a)

AIJASET - Vol. 06, No. 03, November 2026. 371-386
https://doi.org/10.25077/aijaset.v6i3.380



(b)



(c)

Figure 1. Study locations and traffic observation segments in Padang City, Indonesia: (a) map showing the two study sites, (b) Jalan Prof. Dr. Hamka, and (c) Jalan Adinegoro.

2.2 Traffic Data Collection

The field observations were conducted on two divided urban road sections, Jalan Prof. Dr. Hamka and Jalan Adinegoro, in Padang, Indonesia, during a 12-hour weekday observation period from 06:00 to 18:00 WIB. Traffic volume was recorded at 15-minute intervals, while vehicle travel time was measured along a fixed 20-m observation segment at both study sites to maintain consistency in travel-time measurement and comparability of the resulting space mean speed estimates. Vehicle observations were classified by type, and motorcycle counts were used to determine the motorcycle proportion for each observation period. The collected data were aggregated into hourly observations for comparative analysis across three motorcycle-proportion regimes. The resulting dataset comprised 24 observations: 11 in Regime A, 7 in Regime B, and 6 in Regime C.

The scope of the data collection imposes several limitations. The observations represent weekday traffic conditions during the surveyed period and therefore do not capture potential variations associated with weekends or other observation periods. In addition, the analysis primarily considers traffic speed, density, and motorcycle proportion; other factors, including road geometry, environmental conditions, and driver behavior, were not explicitly incorporated as explanatory variables in the model comparison. The relatively small and uneven number of observations across the three regimes also limits the generalizability of the findings. Accordingly, the results are interpreted as empirical comparisons within the two study locations rather than as universally applicable relationships. Further research should incorporate longer observation periods, weekend traffic data, additional explanatory variables, and observations from a wider range of road sections to evaluate the robustness of the findings.

2.3 Traffic Variables and Data Processing

2.3.1 Volume

Traffic volume was obtained from classified vehicle counts and converted into passenger car units per hour (pcu/h) using the passenger car equivalency (PCE) values specified in the 2023 Indonesian Highway Capacity Manual (PKJI 2023) for urban road type 4/2T [15]. The PCE values were selected according to the observed traffic volume per lane for each observation interval. For traffic volumes below 1,050 veh/h per lane, the PCE values were 1.0 for passenger cars, 0.4 for motorcycles, and 1.3 for heavy vehicles, whereas for volumes above 1,050 veh/h per lane, the corresponding values were 1.0, 0.25, and 1.2, respectively. The converted hourly volume was subsequently used to calculate traffic density and develop the fundamental traffic-flow relationships.

2.3.2 Space Mean Speed

Space Mean Speed was calculated from the travel times of observed vehicles along the 20-m observation segment. The space mean speed was calculated as the ratio between the total distance traveled by the observed vehicles and the total travel time, thereby representing the average speed over a fixed road segment.

2.3.3 Density

Traffic density was derived from the fundamental flow relationship between traffic volume and Space Mean Speed, expressed as: $D = \frac{V}{S}$ where D is traffic density (pcu/km), V is traffic volume (pcu/h), and S is Space Mean Speed (km/h).

2.4 Motorcycle-Proportion Regimes

To examine the variation in fundamental traffic-flow relationships under different motorcycle proportions, the hourly observations were classified according to the observed motorcycle proportion (%SM). Motorcycle proportion was selected as the classification variable because motorcycles constituted the dominant vehicle type in the observed traffic streams.

Three motorcycle-proportion regimes were defined based on the observed distribution of motorcycle proportion during the survey period. Regime A includes observations with a motorcycle proportion of 59% to less than 65%, Regime B includes observations from 65% to less than 70%, and Regime C includes observations with a motorcycle proportion of 70% or higher. These intervals were established empirically from the observed field-data distribution and are used as analytical groupings for comparing fundamental traffic-flow model performance; they are not intended as universal thresholds for classifying motorcycle-dominated traffic. The definition and distribution of observations within each motorcycle-proportion regime are summarized in Table 1.

Table 1. Definition and distribution of motorcycle-proportion regimes

Regime	Motorcycle proportion (%SM)	Number of observations
A	59% ≤ %SM < 65%	11
B	65% ≤ %SM < 70%	7
C	%SM ≥ 70%	6
Total	-	**24**

The distribution of observations across the two study sites and the three motorcycle-proportion regimes is presented in Table 2.

Table 2. Distribution of observations by study site and motorcycle-proportion regime

Study site	Regime A	Regime B	Regime C	Total
Prof. Dr. Hamka	6	4	2	12
Adinegoro	5	3	4	12
Total	**11**	**7**	**6**	**24**

Each motorcycle-proportion regime was represented at both study sites, although the number of observations differed between sites. This distribution reduces the possibility that the observed differences in model performance are attributable solely to one study site, although site-specific effects cannot be completely excluded.

2.5 Fundamental Traffic-Flow Models

The three classical fundamental traffic-flow models were fitted separately to the observed speed-density data for each motorcycle-proportion regime. Model parameters were estimated through regression analysis using the observed Space Mean Speed and corresponding traffic density. The fitted speed-density relationships were subsequently used to derive the corresponding volume-density and volume-speed relationships for each regime.

2.5.1 Greenshields Model

The Greenshields model assumes a linear relationship between traffic speed and density. In this study, the speed-density relationship was formulated as:

$$S = S_f \left(1 - \frac{D}{D_j}\right) \quad (1)$$

where S is traffic speed (km/h), S_f is free-flow speed (km/h), D is traffic density (pcu/km), and D_j is jam density (pcu/km). The model parameters were estimated from the observed speed-density data for each motorcycle-proportion regime. The resulting relationship was subsequently used to derive the corresponding volume-density and volume-speed relationships.

2.5.2 Greenberg Model

The Greenberg model represents the speed-density relationship using a logarithmic function. The model was formulated as:

$$S = S_m \ln\left(\frac{D_j}{D}\right) \quad (2)$$

where S is traffic speed (km/h), S_m is the speed at maximum flow (km/h), D is traffic density (pcu/km), and D_j is jam density (pcu/km). The model parameters were estimated separately for each motorcycle-proportion regime and were subsequently used to derive the corresponding volume-density and volume-speed relationships.

2.5.3 Underwood Model

The Underwood model assumes an exponential relationship between traffic speed and density. The speed-density relationship was expressed as:

$$S = S_f e^{-D/D_m} \quad (3)$$

where S is traffic speed (km/h), S_f is free-flow speed (km/h), D is traffic density (pcu/km), and D_m is density at maximum flow (pcu/km). The model was fitted separately to the observations in each motorcycle-proportion regime, and the resulting parameters were used to derive the corresponding volume-density and volume-speed relationships. The mathematical formulations and corresponding speed-density equations of the three evaluated models are summarized in Table 3.

Table 3. Mathematical formulations of the evaluated fundamental traffic-flow models.

Model	Relationship form	Speed-density formulation
Greenshields	Linear	$S = S_f(1 - D/D_j)$
Greenberg	Logarithmic	$S = S_m \ln(D_j/D)$
Underwood	Exponential	$S = S_f e^{-D/D_m}$

2.6 Model Evaluation and Selection

The performance of the three fundamental traffic-flow models was evaluated against the observed speed-density relationships within each motorcycle-proportion regime. Model performance was assessed using the coefficient of determination (R^2) and root mean square error (RMSE), which represent complementary measures of model fit and in-sample estimation error, respectively.

2.6.1 Coefficient of Determination (R^2)

The coefficient of determination (R^2) was used as the primary criterion to assess the goodness of fit of each fundamental traffic-flow model to the observed speed-density relationship. For each regime, R^2 was calculated from the correspondence between the observed Space Mean Speed and the speed estimated by each fitted model at the observed density values. A higher R^2 indicates a stronger correspondence between the model estimates and the observed speed data. The R^2 values were calculated separately for each model within each motorcycle-proportion regime.

2.6.2 Root Mean Square Error (RMSE)

RMSE was used as a complementary measure to quantify the magnitude of the differences between observed and model-estimated Space Mean Speeds at the observed density values. A lower RMSE indicates a smaller in-sample estimation error and closer correspondence between the model estimates and the observed speed-density relationship. RMSE was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}} \quad (4)$$

where Y_i denotes the observed Space Mean Speed, $\hat{Y}_i$ denotes the model-estimated Space Mean Speed at the corresponding observed density, and $n$denotes the number of observations.

2.6.3 Model Selection Rule

Model selection was conducted separately for each motorcycle-proportion regime. The coefficient of determination (R^2) was used as the primary criterion for identifying the model that provided the best goodness of fit to the observed speed-density relationship, while RMSE was used as a complementary measure of in-sample estimation error. Accordingly, the model with the highest R^2 within each regime was identified as the best-performing model, and its RMSE value was subsequently considered to assess the magnitude of the associated estimation error.

Because the analysis was based on a limited number of hourly observations within each empirically defined regime, model performance was evaluated using the observations used for model fitting. Therefore, the R^2 and RMSE values reported in this study represent in-sample goodness-of-fit and estimation error rather than independent predictive validation.

3. Results and Discussion

This section presents the observed traffic characteristics and the fundamental traffic-flow relationships obtained from the field data across the three empirically defined motorcycle-proportion regimes. The analysis first examines the observed traffic conditions, followed by the speed-density (S-D), volume-density (V-D), and volume-speed (V-S) relationships derived from the fitted fundamental traffic-flow models. The comparative performance of the models is subsequently evaluated using the coefficient of determination (R^2) and root mean square error (RMSE).

3.1 Traffic Characteristics across Motorcycle-Proportion Regimes

The observed traffic characteristics varied across the three motorcycle-proportion regimes. Table 4 summarizes the mean Space Mean Speed, traffic volume, and traffic density of the observations classified within each regime. Regimes A and B showed relatively similar traffic characteristics, whereas Regime C exhibited a lower mean speed and higher mean volume and density.

AIJASET - Vol. 06, No. 03, November 2026. 371-386
https://doi.org/10.25077/aijaset.v6i3.380

Table 4. Mean traffic characteristics of observations within each motorcycle-proportion regime

Regime	Motorcycle proportion (%SM)	Space Mean Speed (km/h)	Traffic volume (pcu/h)	Traffic density (pcu/km)
A	59% ≤ %SM < 65%	42.70	1,163.01	27.88
B	65% ≤ %SM < 70%	42.65	1,198.60	30.20
C	%SM ≥ 70%	32.74	1,679.03	66.84

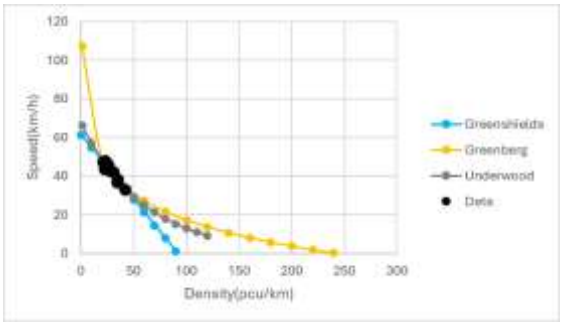
Regimes A and B showed relatively similar mean Space Mean Speeds of 42.70 and 42.65 km/h and mean traffic densities of 27.88 and 30.20 pcu/km, respectively. Their mean traffic volumes were also relatively close, at 1,163.01 and 1,198.60 pcu/h. In contrast, Regime C exhibited a substantially lower mean Space Mean Speed of 32.74 km/h and higher mean traffic volume and density of 1,679.03 pcu/h and 66.84 pcu/km, respectively. These differences provide the empirical traffic-condition context for comparing the fundamental traffic-flow models across the three motorcycle-proportion regimes.

3.2 Fundamental Traffic-Flow Relationships across Motorcycle-Proportion Regimes

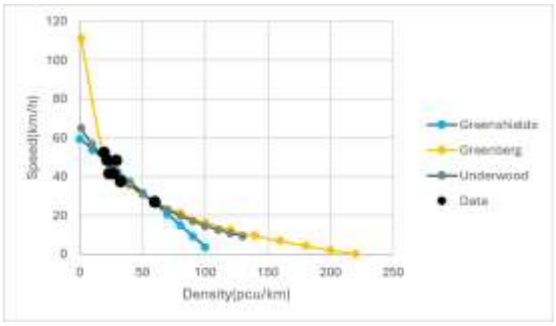
The fundamental traffic-flow relationships were examined separately for Regimes A, B, and C using the fitted Greenshields, Greenberg, and Underwood models. The speed-density (S-D) relationship was used as the primary model formulation, while the corresponding volume-density (V-D) and volume-speed (V-S) relationships were derived mathematically from the fitted S-D equations. The resulting relationships provide three complementary representations of the observed traffic-flow conditions within each motorcycle-proportion regime.

3.2.1 Speed-Density Relationship (S-D)

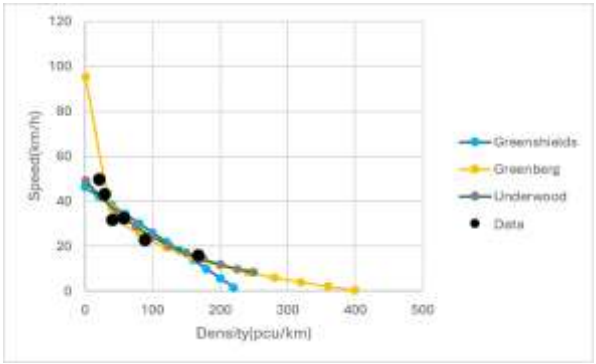
Across all regimes, the observed data generally showed a decreasing speed trend as traffic density increased. However, the relative fit of the three model forms differed among the regimes, with Underwood providing the highest R^2 in Regimes A and B and Greenberg providing the highest R^2 in Regime C. The observed and fitted speed-density relationships for the three motorcycle-proportion regimes are presented in Figure 2.



(a) Regime A



(b) Regime B

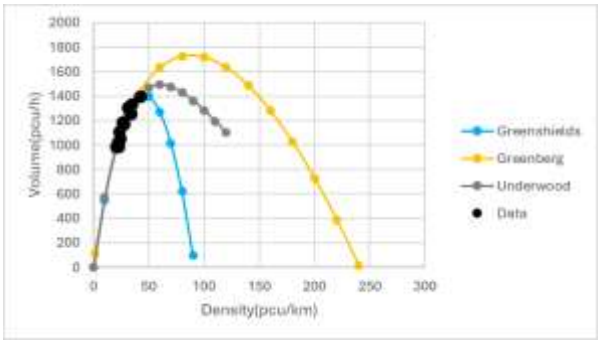


(c) Regime C

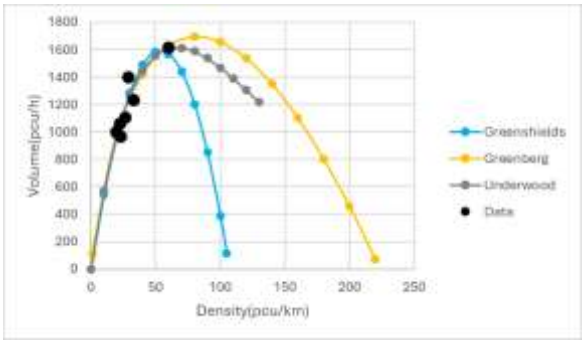
Figure 2. Observed and fitted speed-density relationships across motorcycle-proportion regimes

3.2.2 Volume-Density Relationship (V-D)

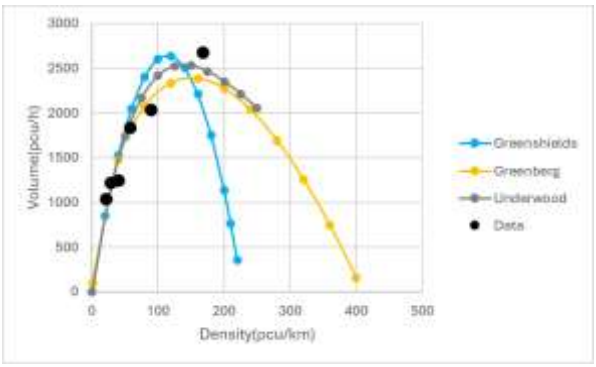
The volume-density relationships were derived from the fitted S-D equations. The resulting curves describe the variation of traffic volume with density and allow the density corresponding to maximum flow (Dopt) to be identified for each model. Figure 3 presents the observed and fitted V-D relationships across the three motorcycle-proportion regimes.



(a) Regime A



(b) Regime B



(c) Regime C

Figure 3. Observed and fitted volume-density relationships across motorcycle-proportion regimes

Figure 3 shows that the estimated optimum density (Dopt) varied across the three model formulations and motorcycle-proportion regimes. In Regime A, Dopt ranged from 45.81 to 88.57 pcu/km, while the corresponding ranges were 53.49-82.21 pcu/km in Regime B and 113.93-150.84 pcu/km in Regime C. Greenberg produced the highest Dopt estimate in each regime, whereas Greenshields produced the lowest. This pattern indicates that the estimated density associated with maximum flow is sensitive to the mathematical form of the selected model. The higher Dopt estimates in Regime C are consistent with the higher mean traffic density observed in that regime; however, they should be interpreted as model-derived estimates rather than independently observed critical densities. The differences cannot be attributed to motorcycle proportion alone because the analysis covers two study sites and does not isolate other potential influences on traffic-flow characteristics.

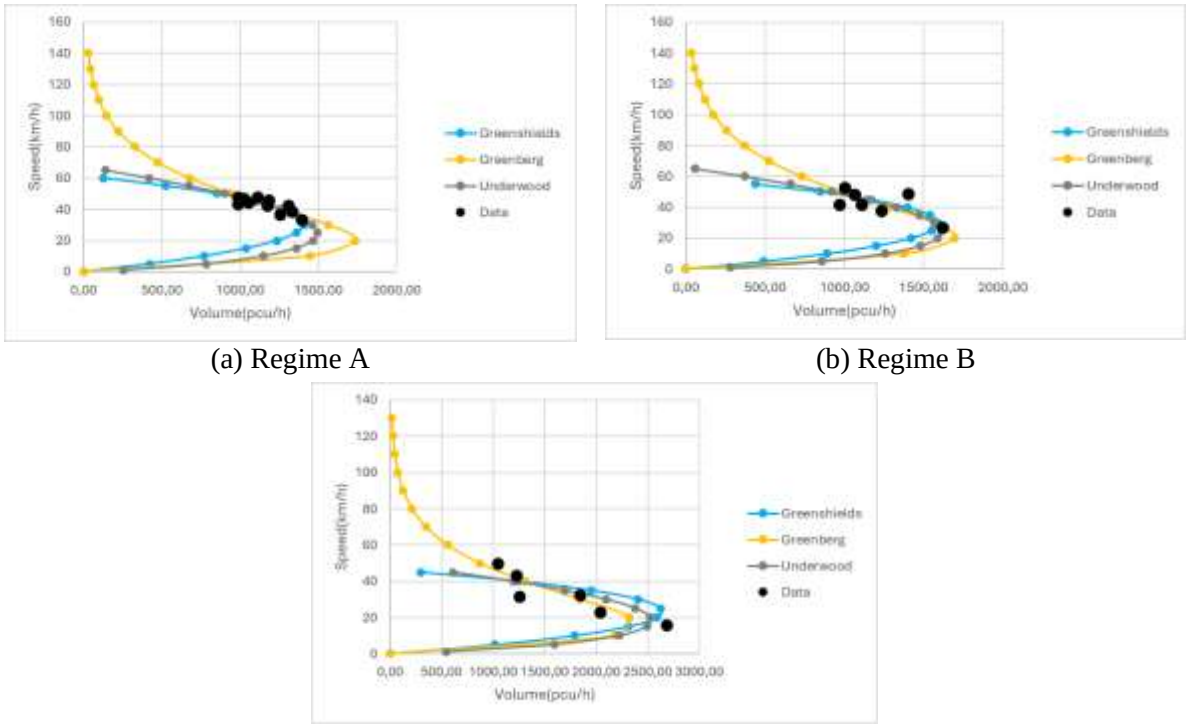
Previous studies have examined the relationship between motorcycle proportion and traffic-flow characteristics on urban roads [13]. Other research has compared the Greenshields, Greenberg, and Underwood models across different motorcycle-proportion classes [14]. These studies provide relevant context for examining traffic-flow relationships under varying traffic compositions. However, differences in road characteristics, traffic observations, and analytical methods should be considered when comparing their findings with those of the present study.

Overall, the estimated density associated with maximum flow varied across the models and motorcycle-proportion regimes. These estimates represent model-derived characteristics and do not establish that motorcycle proportion alone caused the observed differences.

AIJASET - Vol. 06, No. 03, November 2026. 371-386
https://doi.org/10.25077/aijaset.v6i3.380

3.2.3 Volume-Speed Relationship (V-S)

The volume-speed relationships were subsequently derived from the fitted S-D equations. These relationships describe the variation of traffic volume with speed and allow the speed corresponding to maximum flow (Sopt) to be identified for each model. Figure 4 presents the observed and fitted V-S relationships across the three motorcycle-proportion regimes.



(a) Regime A (b) Regime B

(c) Regime C

Figure 4. Observed and fitted volume-speed relationships across motorcycle-proportion regimes

Figure 4 shows that the estimated optimum speed (Sopt), defined as the model-estimated speed associated with maximum traffic flow, varied across the three motorcycle-proportion regimes. In Regime A, Sopt ranged from 19.59 to 30.69 km/h, while Regime B ranged from 20.61 to 29.71 km/h. In Regime C, the estimated values were lower, ranging from 15.84 to 23.16 km/h. This pattern indicates that the fitted models associate maximum flow with lower speeds in Regime C than in Regimes A and B. The pattern is consistent with the lower mean observed speed in Regime C; however, Sopt is a model-derived estimate and should not be interpreted as the observed average operating speed or as direct evidence that motorcycle proportion alone caused the differences.

These differences reflect the distinct mathematical formulations of the three models and their resulting volume-speed relationships. Previous studies have examined the relationship between motorcycle proportion and traffic-flow parameters on urban roads [13], while other research has compared fundamental traffic-flow models across motorcycle-proportion classes [14]. These studies provide relevant context for examining traffic-flow characteristics under different traffic compositions, although their numerical results are not directly comparable with those of the present study.

Overall, Sopt represents the model-estimated speed associated with maximum flow rather than the observed average operating speed. The results indicate differences across motorcycle-proportion regimes but do not establish that motorcycle proportion alone caused these differences.

3.2.4 Fitted Fundamental Traffic-Flow Equations

The fitted equations provide a mathematical representation of the fundamental traffic-flow relationships for each motorcycle-proportion regime. The speed-density (S-D) equations were obtained

by fitting the Greenshields, Greenberg, and Underwood models to the observed traffic data within each regime. The corresponding volume-density (V-D) and volume-speed (V-S) equations were subsequently derived from the fitted S-D relationships using the fundamental relationship among traffic volume, speed, and density, expressed as (V = S \times D). The resulting equations are presented in Table 5.

Table 5. Fitted equations of the fundamental traffic-flow relationships

Regime	Model	Equation
	Greenshields	
	S - D	$S = 61.38 - 0.6699D$
	V - D	$V = 61.38D - 0.6699D^2$
	V - S	$V = 91.63S - 1.493S^2$
	Greenberg	
	S - D	$S = 107.4 - 19.585\ln(D)$
A	V - D	$V = 107.4D - 19.585D\ln(D)$
	V - S	$V = S\exp\left(\frac{107.4 - S}{19.585}\right)$
	Underwood	
	S - D	$S = 67.37e^{-0.0166D}$
	V - D	$V = 67.37De^{-0.0166D}$
	V - S	$V = -60.24S\ln(S/67.37)$
	Greenshields	
	S - D	$S = 59.429 - 0.5555D$
	V - D	$V = 59.429D - 0.5555D^2$
	V - S	$V = 106.98S - 1.800S^2$
	Greenberg	
	S - D	$S = 111.49 - 20.611\ln(D)$
B	V - D	$V = 111.49D - 20.611D\ln(D)$
	V - S	$V = S\exp\left(\frac{111.49 - S}{20.611}\right)$
	Underwood	
	S - D	$S = 65.86e^{-0.015D}$
	V - D	$V = 65.86De^{-0.015D}$
	V - S	$V = -66.67S\ln(S/65.86)$
	Greenshields	
	S - D	$S = 46.325 - 0.2033D$
	V - D	$V = 46.325D - 0.2033D^2$
	V - S	$V = 227.87S - 4.919S^2$
	Greenberg	
	S - D	$S = 95.273 - 15.836\ln(D)$
C	V - D	$V = 95.273D - 15.836D\ln(D)$
	V - S	$V = S\exp\left(\frac{95.273 - S}{15.836}\right)$
	Underwood	
	S - D	$S = 49.61e^{-0.0072D}$
	V - D	$V = 49.61De^{-0.0072D}$
	V - S	$V = -138.89S\ln(S/49.61)$

The mathematical consistency of the equations was examined using the fundamental relationship (V = S \times D). For each motorcycle-proportion regime, the V-D and V-S equations were derived algebraically from the corresponding fitted S-D equations. The goodness-of-fit of the fitted S-D models was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE), as described in Section 2.6. These measures quantify the agreement between model-estimated and observed

speeds for the data used in model fitting. However, because the evaluation was based on the same observations used for fitting, the reported R^2 and RMSE values represent in-sample goodness-of-fit and estimation error rather than independent predictive validation. Therefore, although the equations were checked for mathematical consistency and their fitted S-D relationships were evaluated against the observed data, independent validation using a separate dataset remains necessary to assess their predictive performance and generalizability under other traffic conditions.

3.2.5 Overall Pattern of Fundamental Relationships

Overall, the fitted fundamental traffic-flow relationships showed different characteristics across the motorcycle-proportion regimes. The S-D relationships indicated that Underwood provided the highest R^2 in Regimes A and B, whereas Greenberg provided the highest R^2 in Regime C. The derived V-D relationships produced different estimates of density at maximum flow, while the V-S relationships showed lower optimum speeds in Regime C than in Regimes A and B. These results indicate that both the fitted model form and the resulting optimum traffic-flow conditions varied across the observed motorcycle-proportion regimes.

3.3 Comparative Performance of Fundamental Traffic-Flow Models

The performance of the Greenshields, Greenberg, and Underwood models was evaluated across the three motorcycle-proportion regimes using the coefficient of determination (R^2) as the primary selection criterion and root mean square error (RMSE) as a complementary measure of estimation error. The comparison was conducted to identify differences in model fit under the observed traffic conditions. Table 6 presents the evaluation results for the three models across the three regimes.

Table 6. Performance of fundamental traffic-flow models across motorcycle-proportion regimes

Regime	Model	R^2	RMSE (km/h)
A	Greenshields	0.9027	4.68
A	Greenberg	0.8849	5.09
A	**Underwood**	**0.9100**	4.84
B	Greenshields	0.8016	9.28
B	Greenberg	0.8229	8.77
B	**Underwood**	**0.8657**	8.95
C	Greenshields	0.7966	12.59
C	**Greenberg**	**0.9449**	**6.55**
C	Underwood	0.9093	10.13

The results presented in Table 6 show that the relative performance of the Greenshields, Greenberg, and Underwood models varied across the three motorcycle-proportion regimes. In Regime A, the Underwood model achieved the highest coefficient of determination (R^2 = 0.9100), followed by Greenshields (R^2 = 0.9027) and Greenberg (R^2 = 0.8849). However, Greenshields produced the lowest root mean square error (RMSE) of 4.68 km/h, compared with 4.84 km/h for Underwood and 5.09 km/h for Greenberg. In Regime B, Underwood again achieved the highest R^2 (0.8657), while Greenberg yielded the lowest RMSE (8.77 km/h), followed by Underwood (8.95 km/h) and Greenshields (9.28 km/h). In Regime C, Greenberg outperformed the other models in terms of both R^2 and RMSE, achieving an R^2 of 0.9449 and an RMSE of 6.55 km/h. These results indicate that the relative ranking of the models depended on the observed motorcycle-proportion regime and the evaluation criterion.

Based on R^2 as the primary model-selection criterion, Underwood was selected as the best-fitting model for Regimes A and B, whereas Greenberg was selected for Regime C. The differences in model performance can be understood in relation to their mathematical formulations. The Greenshields model assumes a linear relationship between speed and density, while Greenberg and Underwood represent this relationship using logarithmic and exponential functions, respectively. Because these formulations produce different curve shapes, their agreement with observed traffic data may vary according to the

distribution and characteristics of the observations. Nevertheless, the lower RMSE obtained by Greenshields in Regime A and Greenberg in Regime B indicates that the model with the highest R^2 did not always produce the lowest estimation error. This distinction highlights the importance of interpreting both evaluation measures when discussing model performance.

The results also relate to the empirical model-comparison approach reported by Romanowska and Jamroz [6], who evaluated traffic-flow models using real traffic data and a quantitative assessment framework. Their study supports the importance of assessing model performance against empirical observations rather than assuming that one mathematical formulation is universally superior. However, their analysis concerned expressway traffic in Poland, whereas the present study examined motorcycle-dominated mixed traffic on urban roads in Padang, Indonesia. Therefore, the findings should be compared in terms of their methodological approach rather than assuming that the same model will perform best under both traffic conditions.

Overall, the findings demonstrate that no single model achieved the highest R^2 across all three motorcycle-proportion regimes examined in this study. The observed differences provide an empirical basis for comparing classical fundamental traffic-flow models under different traffic-composition conditions. However, the results do not establish that motorcycle proportion alone caused the differences in model performance. Other characteristics of the observed traffic conditions and the limited number of observations within each regime may also have contributed to the results. Furthermore, because R^2 and RMSE were calculated using the observations employed to fit the models, the results indicate in-sample model fit rather than independent predictive validity. Additional observations and independent validation are therefore needed to assess the generalizability of the findings.

3.4 Discussion

The results demonstrate that the relative performance of the Greenshields, Greenberg, and Underwood models varied across the observed motorcycle-proportion regimes. Underwood achieved the highest R^2 in Regimes A and B, with values of 0.9100 and 0.8657, respectively, whereas Greenberg achieved the highest R^2 in Regime C at 0.9449 and also produced the lowest RMSE of 6.55 km/h. This variation suggests that no single model provided the best representation of the observed speed-density relationships across all three regimes. Similar concerns regarding model suitability under different traffic conditions have been discussed in comparative evaluations of fundamental traffic-flow models [5], [6]. In motorcycle-dominated traffic, vehicle composition is particularly relevant because interactions among vehicle types can influence aggregate traffic characteristics [1], [2], [7], [8].

The differences in model performance can be interpreted in relation to the mathematical structures of the three models and the traffic conditions represented by the observations. The Underwood model assumes an exponential decrease in speed as density increases, whereas the Greenberg model represents speed as a logarithmic function of density. The Greenshields model, in contrast, assumes a linear speed-density relationship [4], [5], [6]. In Regimes A and B, where the mean space mean speeds were 42.70 and 42.65 km/h and the mean densities were 27.88 and 30.20 pcu/km, respectively, the exponential Underwood formulation provided the highest R^2. In Regime C, the mean density increased to 66.84 pcu/km and the mean space mean speed decreased to 32.74 km/h, while the logarithmic Greenberg formulation achieved the highest R^2. These findings indicate that the functional form that best represents the observed data may differ under different traffic conditions. However, because the analysis was based on aggregate observations, the results do not establish that the higher motorcycle proportion directly caused the change in model performance.

Traffic heterogeneity provides a plausible context for interpreting these differences. Motorcycles differ from larger vehicles in physical dimensions, maneuverability, and operating behavior, and their interactions with other vehicles may affect the aggregate characteristics of mixed traffic [1], [2], [3]. Previous studies have examined the influence of motorcycle proportion on traffic-flow parameters and have reported variations in traffic performance under different vehicle-composition conditions [7], [8], [9], [10]. Research on heterogeneous traffic has also highlighted the challenges of representing mixed

traffic using a single generalized relationship [12], [13], [14]. Nevertheless, the present study did not directly measure individual vehicle interactions, lateral positioning, lane-changing behavior, or other microscopic mechanisms. Therefore, these mechanisms provide possible explanations for the observed patterns rather than verified causal findings of this study.

The interpretation of the results must also account for the limited number and uneven distribution of observations. The analysis included 24 hourly observations: 11 in Regime A, seven in Regime B, and six in Regime C. Although both study sites were represented in every regime, the distribution across sites differed. Jalan Prof. Dr. Hamka contributed six, four, and two observations to Regimes A, B, and C, respectively, while Jalan Adinegoro contributed five, three, and four observations. Consequently, the estimated model parameters and performance measures may be sensitive to the limited observations available within each regime, particularly Regime C. Differences in road environment and operating conditions may also contribute to the observed results. The present findings should therefore be interpreted as empirical comparisons within the sampled locations and observation periods rather than as evidence of an isolated motorcycle-proportion effect.

Future studies should address these limitations by collecting more observations across a wider range of motorcycle proportions, traffic demand levels, time periods, and road locations. A more balanced sampling design across motorcycle-proportion regimes and study sites would improve the comparability of the estimated relationships. Where the available sample permits, site-specific effects and other relevant explanatory variables could also be examined explicitly. Independent validation using observations not employed in model fitting would further establish whether the selected models can predict traffic conditions beyond the calibration data. These steps would strengthen the reliability and transferability of the estimated fundamental traffic-flow relationships.

From a practical perspective, the results suggest that traffic engineers should avoid assuming that one classical fundamental traffic-flow model will provide the best representation under all motorcycle-proportion conditions. The Underwood model may be a useful candidate for conditions similar to those represented by Regimes A and B, whereas Greenberg may be a more suitable candidate for conditions resembling Regime C. These selections should be treated as context-specific recommendations because the study did not establish universal motorcycle-proportion thresholds or independently validate the predictive performance of the equations. For traffic planning and operational analysis, the findings support evaluating alternative model formulations against local observations before using their estimates in capacity assessment, traffic-flow analysis, or scenario evaluation. Further research incorporating additional road characteristics and independent validation would be needed before the equations could be recommended for broader operational application.

4. Conclusion

This study evaluated the performance of three classical fundamental traffic-flow models, namely Greenshields, Greenberg, and Underwood, across three motorcycle-proportion regimes on divided urban roads (type 4/2T) in Padang, Indonesia. The results showed that the relative performance of the models varied across the observed traffic-composition regimes. Based on the coefficient of determination (R^2) as the primary model-selection criterion, the Underwood model provided the best fit in Regimes A and B, with R^2 values of 0.9100 and 0.8657, respectively. In Regime C, the Greenberg model achieved the highest R^2 of 0.9449 and the lowest RMSE of 6.55 km/h. These findings demonstrate that the relative suitability of classical fundamental traffic-flow models was not consistent across the observed motorcycle-proportion conditions.

The main contribution of this study is its empirical comparison of classical fundamental traffic-flow models across explicitly defined motorcycle-proportion regimes in motorcycle-dominated urban traffic in Indonesia. The findings support the use of traffic composition as a relevant empirical consideration when selecting a model to represent speed-density relationships. From a practical perspective, the Underwood model may be considered for traffic conditions resembling those observed

in Regimes A and B, whereas the Greenberg model may be considered for conditions resembling Regime C. These results can inform the preliminary selection of models for local traffic-flow analysis and road capacity assessment. However, the model recommendations should be evaluated against local observations before being applied to operational planning, as the present study does not establish universal motorcycle-proportion thresholds or independently validate predictive performance beyond the calibration data.

Future research should expand the analysis to a larger number of road sites and observation periods, with more balanced samples across motorcycle-proportion regimes and traffic conditions. Integrating motorcycle-proportion analysis with passenger car unit (PCU) conversion methods would also help assess how vehicle-equivalency assumptions influence estimated traffic-flow relationships. In addition, independent validation and comparisons with non-classical or data-driven models could establish whether the observed differences in model performance remain consistent across other urban traffic environments. These extensions would strengthen the generalizability of the findings and support more reliable model selection for traffic analysis and planning in motorcycle-dominated cities.

References

[1] C. C. Minh, K. Sano, and S. Matsumoto, "The Speed, Flow and Headway Analyses of Motorcycle Traffic," *Journal of the Eastern Asia Society for Transportation Studies*, vol. 6, pp. 1496–1508, Jan. 2005, doi: 10.11175/EASTS.6.1496.

[2] A. Pandey, M. Sharma, and S. Biswas, "Concept of heterogeneity index for urban mixed traffic," *International Journal of Transportation Science and Technology*, vol. 12, no. 2, pp. 354–372, Jun. 2023, doi: 10.1016/J.IJTST.2022.02.008.

[3] T. Promraksa, T. Satiennam, W. Satiennam, and N. Kronprasert, "Lane-Filtering Behavior of Motorcycle Riders at Signalized Urban Intersections," *J. Adv. Transp.*, vol. 2022, 2022, doi: 10.1155/2022/5662117.

[4] V. L. Knoop, *Traffic Flow Theory: An introduction with exercises*, Third Edition. TUDelft: Delft University of Technology, 2020. doi: https://doi.org/10.5074/t.2021.002.

[5] Z. Lu and Q. Meng, "Analysis of Traffic Speed-Density Regression Models-A Case Study of Two Roadway Traffic Flows in China," in *Proceedings of the Eastern Asia Society for Transportation Studies (EASTS)*, Eastern Asia Society for Transportation Studies, 2013.

[6] A. Romanowska and K. Jamroz, "Comparison of traffic flow models with real traffic data based on a quantitative assessment," *Applied Sciences*, vol. 11, no. 21, p. 9914, 2021.

[7] T. Kurniati and R. Fajriati, "The effect of motorcycle proportion on traffic flow parameters at multi-lane urban road," *MATEC Web of Conferences*, vol. 276, p. 03016, 2019, doi: 10.1051/matecconf/201927603016.

[8] T. Kurniati, Purnawan, Yosritzal, E. E. Putri, and A. Alfaroji, "The study of speed-volume-density relationships with various motorcycles volume percentages," *AIP Conf. Proc.*, vol. 2891, no. 1, May 2024, doi: 10.1063/5.0201360.

[9] R. Sadili, "Analisis Karakteristik Arus Lalu Lintas Campuran dengan Variasi Komposisi Kendaraan Sepeda Motor pada Jalan di Daerah Perkotaan," *Jurusan Teknik Sipil, Universitas Indonesia*, 2011.

[10] T. Sudibyo, Erizal, and M. Fauzan, "The vehicle type effect to the mixed traffic flow performance (case of study: Soleh Iskandar road, Bogor, Indonesia)," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Jan. 2021. doi: 10.1088/1755-1315/622/1/012018.

[11] I. Fadhlurrahman, "Jumlah Kendaraan Bermotor di Kota Padang (27 April 2025)," Katadata / Databoks. Accessed: Oct. 04, 2025. [Online]. Available: https://databoks.katadata.co.id/transportasi-logistik/statistik/49d8de6eaad5d8e/jumlah-kendaraan-bermotor-di-kota-padanghari-ini

[12] N. Maiti and B. R. Chilukuri, "Empirical Investigation of Fundamental Diagrams in Mixed Traffic," *IEEE Access*, vol. 11, pp. 13293–13308, 2023, doi: 10.1109/ACCESS.2023.3242971.

[13] A. K. Das and B. R. Chilukuri, "Fundamental diagram parameters in mixed traffic conditions: measurement methods and models," *Transportation Letters*, vol. 18, no. 3, pp. 523–544, Mar. 2026, doi: 10.1080/19427867.2025.2576260.
[14] N. Maiti, J. A. Laval, and B. R. Chilukuri, "Universality of area occupancy-based fundamental diagrams in mixed traffic," *Physica A: Statistical Mechanics and its Applications*, vol. 640, p. 129692, 2024.
[15] Directorate General of Highways, Ministry of Public Works and Housing, and Republic of Indonesia, "Pedoman Kapasitas Jalan Indonesia, No. 09/P/BM/2023," Jakarta, 2023.
[16] I. Kariyana, "Determination of PCE Based on Motorcycle Behavior at Signalized Intersections in Denpasar, Bali," *civil engineering and architecture*, vol. 10, no. 3, pp. 996–1011, 2022.
[17] T. Kurniati, Purnawan, Yosritzal, E. E. Putri, and A. N. Fajri, "The study of motorcycle positions distributions on-road lanes with traffic flow variables," *AIP Conf. Proc.*, vol. 2599, no. 1, Jun. 2023, doi: 10.1063/5.0116817/2896507.
[18] S. Ramayanti, B. M. Adji, yosritzal yosritzal, and H. Gunawan, "Vehicles Speed in Platoon, Case Study Padang - Bukittinggi Road," *Jurnal Rekayasa Sipil (JRS-Unand)*, vol. 17, no. 1, pp. 97–107, Mar. 2021, doi: 10.25077/JRS.17.1.97-107.2021.
[19] T. Kurniati, E. Afyendo, and E. E. Putri, "Study of potential implementations for motorcycle lanes in Padang city," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 933, no. 1, p. 012033, Sep. 2020, doi: 10.1088/1757-899X/933/1/012033.
[20] T. Kurniati, Purnawan, Yosritzal, and E. E. Putri, "Evaluation of the implementation of the motorcycle lane based on the riding experience," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 771, no. 1, p. 012060, Mar. 2020, doi: 10.1088/1757-899X/771/1/012060.
[21] T. Kurniati, E. E. Putri, and W. A. Setiawan, "Manajemen Kecepatan Lalu Lintas Pada Jalan Tak Terbagi," *Siklus : Jurnal Teknik Sipil*, vol. 10, no. 1, pp. 32–42, Apr. 2024, doi: 10.31849/SIKLUS.V10I1.19547.