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A new approach to estimating link performance on Indonesian urban roads: deriving the BPR 1964 function

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A new approach to estimating link performance on Indonesian urban roads: deriving the BPR 1964 function

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Abstract. Predictions of traffic volumes on road networks must be precise for transportation planning, and equilibrium trip assignment models based on the Volume Delay Function (VDF) are typically employed. In 1964, the U.S. Bureau of Public Roads (BPR) created a VDF widely used in many countries, including Indonesia. However, using capacity manuals from Western nations in Indonesia did not produce the desired results due to differences in traffic composition and driver behaviour. Using the Indonesian Highway Capacity Manual's macroscopic fundamental diagram, this paper aims to derive a more accurate VDF for Indonesia. This method enables the development of a VDF tailored to the unique traffic conditions in Indonesia. It can enhance the precision of traffic volume forecasts in the region. The BPR function parameters tends to overestimate travel time delay, making the road network model flow misestimated. This is presumably caused by traffic count survey inability to record the build-up of traffic flow in the urban network during peak traffic periods.

1. Introduction

In transportation planning, equilibrium trip assignment models are commonly used to predict traffic volumes on road networks. These models depend on the Volume Delay Function (VDF), which describes the relationship between traffic volume and vehicle delay. The VDF is a crucial component of these models, and its precision substantially impacts the overall precision of traffic forecasts.

In 1964, the U.S. Bureau of Public Roads (BPR) developed a VDF utilised in numerous countries, including Indonesia. The Bureau of Public Roads [1] conducted traffic surveys on multiple road segments and utilised regression analysis to develop the BPR function, which has since become a widely used model. Spiess [2] and Davidson [3], amongst others, have investigated the accuracy of the BPR function. The Webster model [4] accounts for the average phase delay and the additional delay caused by varying vehicle arrival rates.

The BPR function is used to assign traffic in Indonesia and other nations. Using capacity manuals from Western countries in Indonesia did not produce the desired results due to differences in traffic composition and driver behaviour [5]. Observations of travel time delay in various interchange and road networks in Yogyakarta City have consistently reported that the delay function graph and formula described in Indonesian Highway Capacity Manual (IHCM) tend to overestimate the delay time in congested road networks based on western country parameters [6–9]. Several methods have been utilised to calibrate the BPR function parameters. By redesignating the BPR parameter's practical capacity as its steady-state capacity, Steenbrink (1974) adjusted it for Dutch traffic conditions. Suh et al. [10] derived Korea's BPR function parameter using a bilevel programming method based on the Level of Service from the U.S. Highway Capacity Manual, whereas He and Zhao [11] considered all factors that impact road delay. Recently, Huo et al. [12] utilised a deep learning model as a novel method for calibrating the parameters of the BPR function. Irawan et al. [13] created a volume delay function for Indonesia by applying the least squares method to the delay curves from the Indonesian Highway Capacity Manual (IHCM). However, this function requires three distinct parameters of α_1,α_2, and β and for each road type and free flow speed value, making its incorporation into equilibrium traffic assignment models challenging. Nobel and Yagi (2017) use the road and street network of Manila City as a research case and the least squares approach to determine the BPR parameter through trial and error.

The objective of this study is to derive the BPR function and its parameters based on the IHCM macroscopic fundamental diagram for Indonesia's unique traffic composition and behaviour. We employ the generalised method for estimating single and two-regime traffic flow models proposed by Easa and May [14] to derive the VDF from the observed traffic data utilised in the IHCM formulation. Then, The function is then converted into a VDF that depicts traffic influx and fitted with a curve. This method provides the basis for determining the VDF and, eventually, the BPR parameters.

2. Volume Delay Function

2.1. Historical Development of the Volume Delay Function

In traffic engineering, the flow and speed of vehicle movement on a particular road segment are frequently examined [15]. This concept, known as the cost-flow curve, link performance function, volume delay function, and road impedance function, was initially developed for lengthy highway and tunnel segments. It describes the cost incurred due to increased traffic volume, accompanied by a gradual decrease in speed. As the flow approaches the capacity, the speed drop increases, and when the capacity is reached, the maximum flow is achieved. Continually exceeding the capacity will result in instability and a decrease in flow rate [16].

When using one-way trip time functions or cost-flow relationships for route mapping, congestion is considered. Equations or functions are required in a route assignment model to relate road section attributes such as capacity and free flow speed to actual velocity or cost [15]. In addition, he categorizes link capacity functions as either mathematical function methods or theoretical approaches. The mathematical function approach necessitates a simple function replicating observed data, but network or connection properties are typically excluded. Under the queuing theory, the theoretical approach considers signal spacing, settings, and connection factors, resulting in a more complex capacity function. Due to its complexity, it is not easy to implement the theoretical approach into the equilibrium traffic assignment method.

2.2. BPR Function

This research employs a flow-cost curve developed by the Bureau of Public Roads [1]. The function is widely employed. Numerous individuals indicated that the United States BPR function was satisfactory [10]. Branston [15] described how the BPR formula with two parameters replicates the BPR formula with five parameters. Following is a description of the function equation.

$$t = t_f\left[1 + \alpha\left(\frac{q}{C}\right)^{\beta}\right] \tag{1}$$

The variable t represents the travel time in minutes, whereas t_f represents the free flow travel time in minutes. The symbol q represents the traffic volume, which is measured in passenger car units (PCU) per hour. C denotes the route's practical capacity, also expressed in PCU per hour. α and β are parameters that account for various variables influencing the duration of a trip. This equation illustrates the relationship between travel time, traffic volume, and practical capacity. The Bureau of Public Roads [1] suggests α and β values of 0.15 and 4, but does not provide the data used to determine these values.

2.3. Existing Indonesian Delay Function

With a VCR of less than 1, IHCM offered a delay function for urban street networks in the form of a graph that shows the relationship between average speed (v) and Volume Capacity Ratio (VCR). It does not display the speed loss that results from exceeding the capacity. Using western traffic settings, IHCM separately describes the calculation for the interchange delay function based on the car-following theory. This interchange delay function formula is not taken into account in this investigation because macroscopic traffic assignments do not employ it.

Irawan et al. (2010) then used the least squares method to fit a curve to the graph supplied by IHCM to create a volume delay function formula. The equation that results is as follows:

$$t = \alpha_1 \left(\frac{q}{C}\right)^{\beta} + \alpha_2 \left(\frac{q}{C}\right) + t_f \tag{2}$$

The fact that this function requires distinct parameter values for each type of road and free flow speed value has a major negative influence on user equilibrium traffic assignments since different parameter values must be updated for each road included in the model's coverage. Furthermore, because it simply approximates the delay function graph supplied by IHCM, this function is empirical. This study assumed the values of α_1,α_2 and β are respectively 0.19, 0.62 and 8.09 for multilane with free flow speed of 57 km/hour.

3. Indonesian Highway Capacity Manual

3.1. IHCM's Fundamental Macroscopic Diagram

The 1997 Indonesian Highway Capacity Manual (IHCM) contains recommendations for evaluating road and highway capacity and service based on the Highway Capacity Manual (HCM) of the Transportation Research Board. Bang and Carlsson [17] examined Indonesia's traffic volume and flow from the 1990s to 1993. The survey was conducted in several Indonesian cities as samples. The 1997 Indonesian Highway Capacity Manual (IHCM) is the most critical resource for transportation planning in Indonesia.

IHCM describes various traffic flow relationships on urban and interurban roadways. In this study, the urban road traffic flow relationship is utilised. Hence, the relationships are described by the following equations. Figure 1 illustrates the relationship between traffic flow and traffic speed.

$$v = v_f \left[1 - \left(k/k_j\right)^{(L-1)}\right]^{1/(1-M)} \tag{3}$$

$$k_0/k_j = [(1-M)/(L-M)]^{1/(L-1)} \tag{4}$$

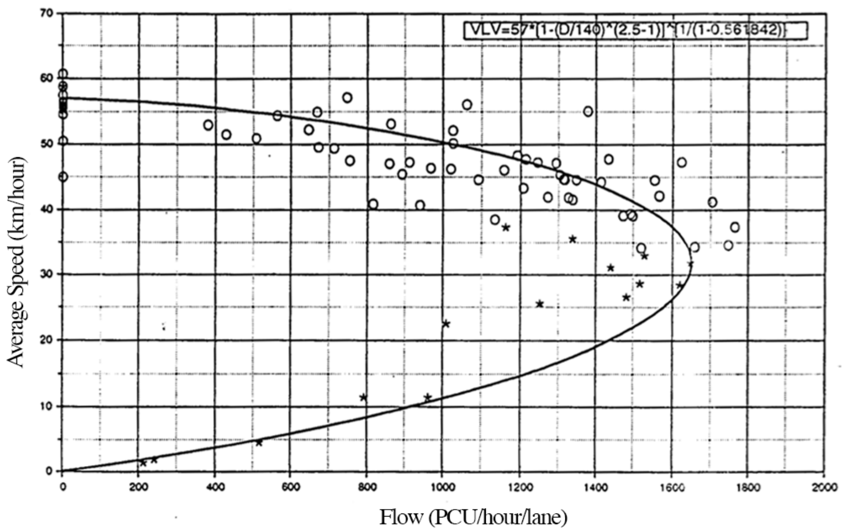

Figure 1. Flow-speed relationship on divided roads [5].

In this equation, the variable v represents the speed of vehicles on a roadway. The free flow speed, denoted by v_f, is the maximum speed can be reached under ideal conditions and without traffic. k indicates the number of vehicles per unit of road length. k_j represents jam density, the maximum possible vehicle density on a highway. L and M are variables that influence the velocity at a given density. In Equation (4), k_0/k_j represents the ratio of optimal link density to jam density, while $[(1-M)/(L-M)]^{1/(L-1)}$ denotes the effect of parameters L and M on this ratio.

The survey data from the unstable flow are highlighted with star points, whereas the circle points represent the measured traffic volume in the stable flow. The IHCM model provides graphical flow-speed relationships but lacks visual representations of speed-density and flow-density correlations and does not clearly state the underlying equations. In addition, the model does not specify the L and M parameters used to generate the fundamental diagram.

3.2. Completing IHCM's Fundamental Diagram

The IHCM traffic model is a variation of the Underwood single regime model developed by May and Keller [18] and Ceder [19] to model the different traffic regimes by deriving the macroscopic equations from the microscopic equations of the car-following theory. The modelling technique utilised the nomograph proposed by Easa and May [14]. In addition, they described two equations for traffic flow (q) as a function of density (k) and speed values (v). The following are the equations.

$$q = v_f\, k \left[1 - \left(k/k_j\right)^{L-1}\right]^{1/(1-M)} \tag{5}$$

$$q = v\, k_j \left[1 - \left(v/v_f\right)^{1-M}\right]^{1/(L-1)} \tag{6}$$

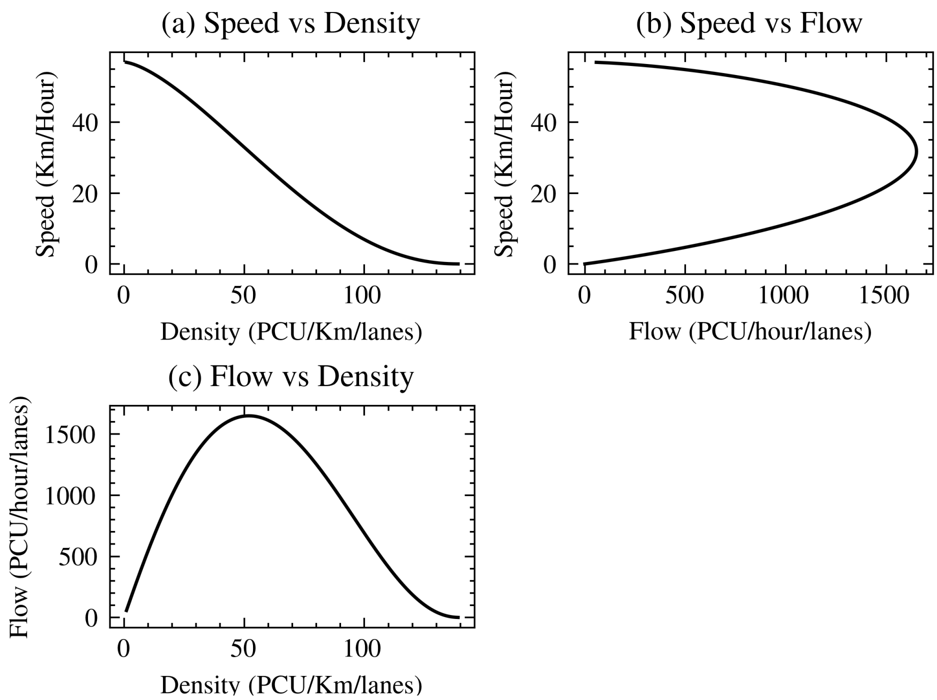

Figure 2. (a) Speed-density relationship (b) Speed-flow relationship (c) Flow-density relationship.

Using Equation (3) and the equation in the upper right corner of Figure 1, the free flow velocity (v_f) along with constants L and M can be determined. The graphs of speed-density and flow-density can then be determined by substituting these values into Equation (3) and Equation (5), respectively. Figure 1 depicts the correct flow-speed relationship equation, which can be derived by substituting Equation (6). Figure 2 shows the speed-density and flow-density graphs. Since IHCM's traffic survey was completed in the 1990s, these diagrams depicting IHCM's fundamental traffic flow are, to the author’s knowledge, published for the first time.

3.3. IHCM's Delay Function

This article describes the relationship between travel time and traffic flow from Equation (3), as depicted in Figure 3. Travel time is defined as the average time it takes road users to cross the road; therefore, it is inversely proportional to the average speed (v).

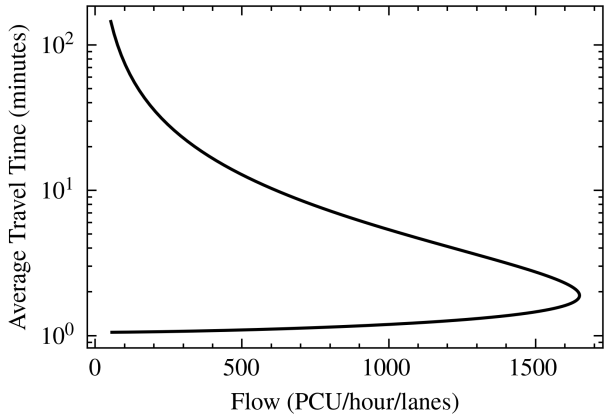

Figure 3. Travel time-flow relationship.

4. IHCM's BPR Parameters

Considering that the BPR equation and IHCM fundamental diagram have different definitions of flow, the IHCM delay function that describes the outflow ability of a road in terms of the delay experienced by vehicles on an urban network must be converted into a delay function caused by the total flow rate entering the street. Then, we select the BPR parameter that most closely matches the curve of the journey time - full flow function- enabling us to predict the BPR parameter for a given set of traffic conditions.

4.1. Total Flow Delay Function

The Network Macroscopic Fundamental Diagram (NMFD) proposed by Geroliminis and Daganzo (2008) introduces urban street network production, performance, and accumulation. Production is the network’s total internal flow, while performance is the network's outflow. Accumulation occurs when production exceeds the maximum discharge that urban street networks can accommodate, also known as capacity. This accumulation reduces the performance of the urban street network, also known as the capacity drop. Figure 2(b) depicts the fundamental steady-state diagram used by IHCM to define performance with speed-flow relationships. However, the BPR function uses production as the variable to calculate the average travel time caused by the urban street network’s accumulation. Hence, to obtain the BPR parameters, the IHCM performance delay function must be transformed into a production delay function.

Skabardonis and Geroliminis [20] created a mathematical model for estimating real-time travel times at signalised intersections. Geroliminis dan Skabardonis [21] incorporate this strategy into NMFD to analyse the impact of queue spillovers on urban street networks. They discovered a strong correlation between spillovers and decreased system output. In addition, they quantified the accumulation of spillovers as the number of vehicles that could be served if the queues from the downstream link did not spill back and impede the arrivals.

By generalising the signalised intersection queue approach of Geroliminis dan Skabardonis [21] to a macroscopic environment, this study proposes that the total flow entering a road is calculated by adding the output flow (q) at a specific density (k) to the total accumulations of spillovers incurred by cars that were not served by the initial outflow. Total spillovers are calculated by integrating the differences between the capacity (C) and the discharge flow from optimal density to the current outflow rate. The following describes the equation. The relationship between IHCM's total flow and average travel time is depicted in Figure 4. Figure 4(a) demonstrates that when full flow exceeded the capacity, travel time increased dramatically due to the shockwave effect caused by the capacity decrease. In contrast, Figure 4(b) depicts the volume delay function from free flow speed to total gridlock.

$$q_t = q(k) + \int_{k}^{k_o} C - q(x)\, dx \tag{7}$$

4.2. BPR Parameters

Using the non-linear least squares method, we derive the BPR parameters by fitting the BPR equation to Figure 4 using the curve fitting technique. We utilised the SciPy library's curve_fit function to fit the BPR equations. The values of α and β are 0.21 and 1.54, respectively. Figure 5 compares the proposed BPR function for Indonesia to the IHCM delay function and other existing VDFs.

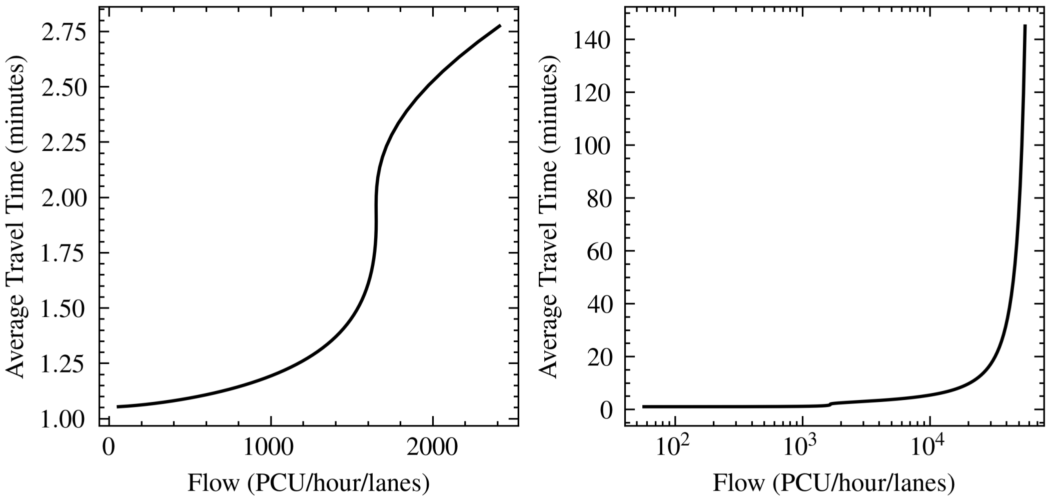

Figure 4. Travel time-total flow relationships for: (a) 0 < density (k) < 70, (b) 0 < density (k) <130.

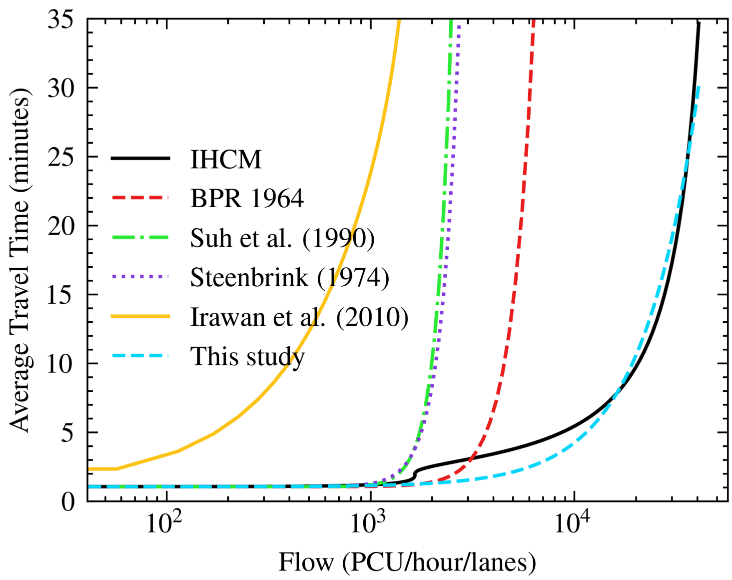

Figure 5. Comparison of various existing VDF and the proposed Indonesian BPR function.

5. Model Application

The road network model is constructed in order to evaluate the precision of the proposed BPR parameter compared to existing BPR parameters and the delay function developed by Irawan et al. [13] for Indonesia. This research employs the urban area of Yogyakarta City, as depicted in Figure 6. The Yogyakarta City Road network model was constructed using the OSMNx library [22] and Open Street Map data. This road network model does not include residential road networks. StraPy library [23] is utilised for user equilibrium traffic assignment. The model consisted of 14 inner origin destinations (ODs) representing each district of Yogyakarta City and 16 outer ODs representing cities and regencies in the surrounding area. The ODs matrices are derived from a 2019 survey conducted by the Transportation and Logistic Research Centre at Universitas Gadjah Mada. In 2019, a primary field survey obtained 68 major road's observed traffic flow.

Traffic assignment results from various volume delay functions are compared to field data using commonly employed metrics, including Mean Absolute Percentage Error (MAPE), Root Mean Squared Error (RMSE), Coefficient of Determination (R^2), and the GEH formula. This study compares the performance of the US BPR, the proposed BPR, the delay functions of Suh et al. [10] and Irawan et al. [13]. The number of iterations is set to 1000 for objective performance comparison. The comparison outcomes are displayed in Table 1.

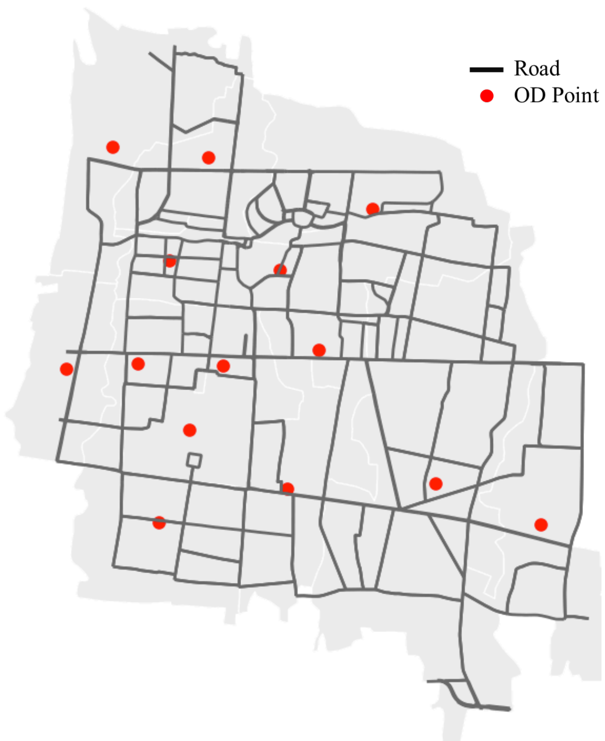

Figure 6. Road network modelled by OSMNx [22].

Table 1. Comparison between various volume delay functions.

	MAPE	RMSE	R^2	GEH
BPR 1964	94.02%	1904	0.6839	29.96
Suh et al. [10]	134.10%	2574	0.6566	38.59
Steenbrink [24]	104.95%	2124	0.6686	32.21
Irawan et al. [13]	69.05%	1536	0.4622	33.28
This study	65.53%	1378	0.7578	22.09

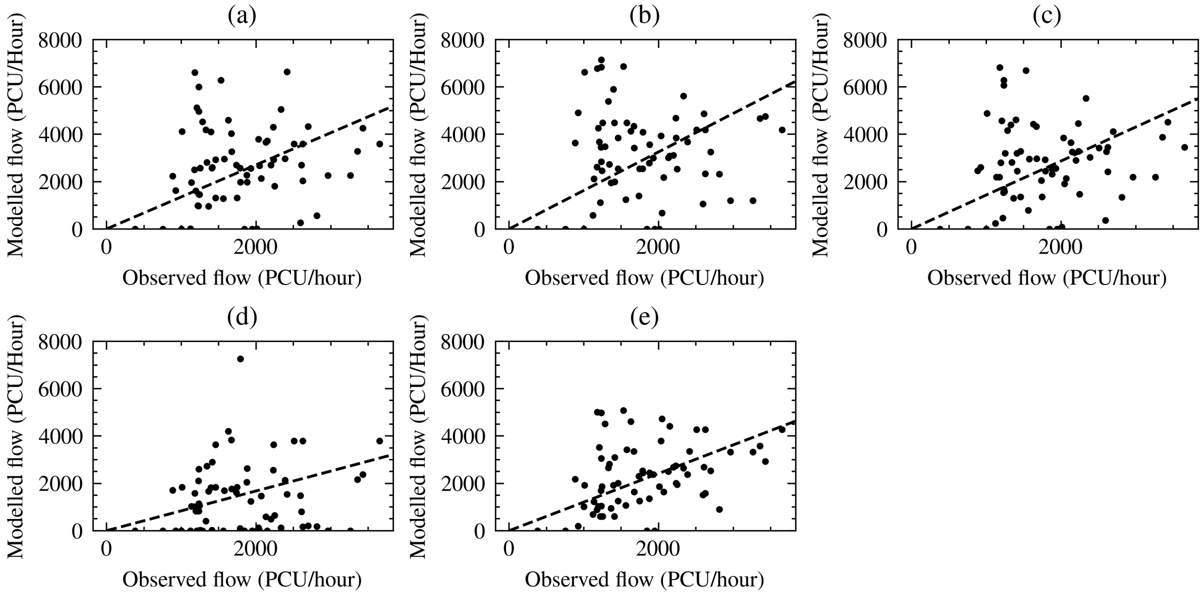

Figure 7. Linear regression between observed flow and modelled flow of (a) Bureau of Public Roads [1], (b) Suh et al. [10], (c) Steenbrink [24], (d) Irawan et al. [13] and (e) This study.

6. Discussion

The BPR function is commonly used in traffic assignment models, particularly in Indonesia's traffic. Table 1 demonstrates that utilizing capacity manuals from Western nations in Indonesia has not always produced representative results due to differences in Indonesia's traffic composition and driver behaviours. As depicted in Figure 6, the BPR function in Western countries such as the United States of America [1] and the Netherlands [24] tends to overestimate travel time delay, resulting in an underestimation or overestimation of road network model flow compared to field data.

Previous attempts to calibrate the BPR function, such as using a bilevel programming method [10], also face this problem because the process only calibrates the BPR function for non-congested conditions, as opposed to calibrating the parameters based on actual production flow, as implied by the BPR formula. Another method proposed by He and Zhao [11] is impractical because it necessitates an exhaustive survey to identify the various factors that influence it. Furthermore, this factor may not be uniform in urban street networks, making large-scale road network traffic assignment inappropriate. By using curve fitting to approximate BPR parameters on a road network model results, Nobel and Yagi (2017) make the BPR parameters model-specific. The characteristics of the BPR could be significantly changed by changes to the road network model. It also has the issue identified by Irawan et al. (2010), which is that the parameters for each type of road and free flow speed value are different.

The implementation of a recently proposed method employing a deep learning model by Huo et al. [12] may require additional development because it lacks theoretical traffic flow fundamentals. It also does not guarantee a global solution and has not been tested against a large-scale road network model's training and test data. In addition, the required travel time data for machine learning is not readily available. Our proposed method provides a more practical approach to deriving the BPR function from international highway manuals.

It is observed that model flow tends to exaggerate observed flow in the field, particularly under congested conditions. It is likely due to the traffic count survey's inability to capture the accumulation of traffic flow in the urban network under congested conditions. Presumably, mean velocity and density are the preferred validations, as they accurately depict the traffic situation. The NMFD discoveries are based on the dynamic relationship between speed and density acquired by fixed detectors [25]. This inaccuracy may also be due to the limited number of iterations and the complexity of street networks in the model, resulting in an incomplete representation of existing road networks.

The method used to transform the traffic flow of the fundamental diagram into the traffic flow used in the link performance function assumes that the accumulation rate is constant and that the relationships in the fundamental diagram are in a steady state. It is not the case in the real world. Variable traffic demand causes repeated changes in accumulation rate under traffic congestion, and fundamental diagram relationships change as urban street network production, accumulation, and performances shift.

Future work could include testing the accuracy of the derived BPR function and its parameters by comparing them to real-world traffic data in various types of macroscopic transportation modelling, such as disaster evacuation modelling or developing a vulnerability index to evaluate road safety [26]. It would be intriguing to investigate the possibility of adapting this method in countries with distinct traffic compositions and behaviours.

7. Conclusion

This study has presented an alternative method for deriving the BPR function and its parameters. Our proposed method utilises the steady-state fundamental diagram, commonly available in country-specific highway capacity manuals worldwide, to provide a practical approach to calibrating the BPR function parameters. This calibration method is the first to bridge the macroscopic fundamental diagram's outflow rate into the inflow rate of the VDF formula based on the concept of production, accumulation and performance of urban street networks found in NMFD. Further testing and potential adaptation for use in other countries with unique traffic characteristics could be valuable areas of future research.

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