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Estimating Passenger Car Equivalents (PCE) for Heterogeneous Traffic at Signalized Intersections Using the Time Headway Method

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ABSTRACT

This study evaluates the operational performance of the Simpang Patung Kirab intersection in Kupang City by calibrating local Passenger Car Equivalency (PCE) values using the time headway method. The use of static PCE values from the 2023 PKJI guidelines is often not representative of heterogeneous traffic dominated by motorcycles. Vehicle trajectory data during the afternoon peak hour were extracted from UAV aerial recordings using the YOLO and ByteTrack algorithms, focusing on the time headway of leader-follower interactions between vehicles. Statistical tests confirmed that queue-release behavior is dynamic and heterogeneous. Interactions between heavy vehicles in front of light vehicles resulted in the greatest delay with a headway of 2.398 seconds, while interactions between motorcycles produced the shortest headway of 0.535 seconds. The calibrated PCE values varied across each intersection arm, with motorcycle PCEs ranging from 0.18 to 0.46, indicating significant deviations from standard guidelines. The application of these local PCE values yields more accurate performance estimates, specifically revealing a condition of severe oversaturation on the West arm with a degree of saturation of 1.915. It is concluded that the time headway method effectively represents the operational characteristics of mixed traffic flows and prevents bias in intersection capacity estimates.

Keywords: *passenger car equivalent; time headway; heterogeneous traffic; signalized intersection; degree of saturation*

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Abstract & Indexing

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INTRODUCTION

The growth in vehicle volume in urban areas, when not matched by road infrastructure development, often leads to traffic congestion, particularly at critical points such as signalized intersections. The operational efficiency of an intersection depends heavily on the accuracy of capacity and saturation level determinations, which are fundamentally influenced by the Passenger Car Equivalency (PCE) value. Theoretically, PCE is a vital conversion factor that equates various types of heterogeneous vehicles to a single standard unit (passenger car unit/PCU). In Indonesia, guidelines such as the Indonesian Road Capacity Guidelines (PKJI 2023) have established standard PCE values for various vehicle types. However, various recent traffic engineering studies confirm that the use of these static values often results in significant deviations from actual on-site conditions.

Standard manual intersection performance estimates often underestimate or overestimate the actual impact of a vehicle category under local operational conditions and driver behavior. Previous research has shown that PCE values can differ substantially from those of conventional models, particularly for highly heterogeneous fleet compositions (Sugiarto et al., 2021; Patel & Dhamaniya, 2021). The static specifications listed in the capacity manual have proven to be less sensitive to the actual dynamic friction characteristics of vehicles, driver interactions, and local geometric conditions (Giuffrè et al., 2019). Therefore, a more dynamic formulation is essential to produce equivalent conversions that vary depending on fluctuations in specific traffic conditions (Li et al., 2019; Al-Obaedi, 2016).

One of the main factors distorting the accuracy of the standard PCE value is the predominance of motorcycles in traffic composition. The maneuverability, flexibility, and physical dimensions of motorcycles create a highly dynamic and complex queue-discharge mechanism during the green phase (Patel & Dhamaniya, 2021; Mondal & Gupta, 2021). Motorcycles are not entirely bound by strict lane discipline; they are capable of "seeping" and "filtering," moving through gaps between vehicles, and occupying space in parallel within a queue. Various empirical studies show that the average PCE value for motorcycles at signalized intersections ranges from 0.21 to 0.24, a value that is heavily influenced by vehicle position and interactions within the queue (Mondal & Gupta, 2019; Mondal & Gupta, 2020). Conventional estimation methods have difficulty capturing this phenomenon with precision.

To address the limitations of static methods, the time headway method has emerged as an empirical approach capable of capturing the actual temporal space occupied by a vehicle as it crosses the stop line. Unlike uniform manual approaches, the time headway method calculates vehicle equivalence based on micro-level queue release behavior (Sugiarto et al., 2021). Headway measurements can detect the actual level of saturation under mixed-traffic conditions, where the headway decreases as the initial queue dissipates and stabilizes at a certain vehicle position. Fluctuations in the local PCE value based on this time interval are directly proportional to the estimated total flow (vehicles per hour), which can ultimately prevent errors in traffic signal cycle time design and yield a much more representative saturation level (Asaithambi et al., 2017; Srikanth & Mehar, 2017; Jithender & Sushmitha, 2024; Fan & Lu, 2026).

The need for local PCE calibration is particularly relevant to the context of the Simpang Patung Kirab intersection in Kupang City. As an intersection located in a commercial area, it serves local traffic, trips to the commercial center, and the evening commute, with high and highly heterogeneous traffic volumes during the afternoon peak hours. It is assumed that using uniform values from the 2023 PKJI is not yet fully capable of representing the actual traffic conditions at this intersection, given the high proportion of motorcycles and the presence of heavy vehicles that affect queue clearance efficiency. Unlike previous

PCE time headway studies in Kupang (Bolla et al., 2020; Pedo et al., 2026) that primarily relied on conventional observational methods, this research introduces a novel approach by integrating UAV aerial recordings with YOLO and ByteTrack machine learning algorithms for automated vehicle trajectory extraction. This methodological advancement enables a more precise, micro-level analysis of specific leader-follower interaction dynamics within mixed queues. Therefore, this study aims to evaluate headway times based on leader-follower vehicle interactions, derive and calibrate specific PCE values using the headway method, and analyze their impact on estimates of capacity, delay, and degree of saturation at the Patung Kirab Intersection compared to estimates using the PKJI 2023 standards. This study is expected to provide empirical evidence regarding the importance of adjusting traffic parameters to local operational conditions at signalized intersections in Indonesia.

METHODS OF RESEARCH

1) Data Collection Techniques

Recording of traffic conditions and queue movements on-site was conducted from the air using an Unmanned Aerial Vehicle (UAV), specifically a DJI Mavic Air 2 drone. Recording was performed at 4K resolution at 30 fps to ensure clear identification of vehicle types. Data extraction from the aerial video recordings was processed using the Python programming language within the Visual Studio Code environment. The Ultralytics YOLO object detection algorithm and the ByteTrack tracking algorithm were applied to automatically detect the trajectory of each vehicle and record a timestamp exactly when the vehicle crossed the stop line. These trajectory data were grouped into three main categories: Motorcycles (MC), Light Vehicles (LV), and Heavy Vehicles (HV).

2) Time Headway Analysis Based on Leader-Follower Interaction

The characteristics of queue release were evaluated through microscopic observation of time headway, measured based on the interaction between pairs of vehicles in a mixed queue. Time headway was calculated based on the difference in departure times when the front bumper of the following vehicle crossed the same reference stop line as the vehicle in front of it. The equation used is shown in Equation 1.

$$\boldsymbol{h_i = t_n - t_{n-1}} \quad (1)$$

In equation 1, h_i is the headway time for the nth vehicle (seconds), t_n is the time (in seconds) when the n^{th} vehicle (follower) crosses the stop line, and $t_{(n-1)}$ represents the longitudinal time when the $n\text{-}1^{st}$ vehicle (leader) crossed the same stop line (seconds). This study focuses on seven variations of leader-follower interaction combinations, including: HV-LV, LV-HV, HV-HV, LV-LV, LV-MC, MC-LV, and MC-MC.

3) Passenger Car Equivalence Calibration

Empirical PCE values were derived using the headway ratio approach. The average headway time for interactions between light vehicles (LV-LV) was established as the base headway. PCE values for each vehicle classification were derived by comparing the average headway of that vehicle class to the average headway of light vehicles. The calibration equation applied is shown in Equation 2.

$$\boldsymbol{PCE_i = \frac{\bar{h}_i}{\bar{h}_{LV-LV}}} \quad (2)$$

In equation 2, PCE_i is the calibrated Passenger Car Equivalence value for vehicle type i, $\bar{h}_i$ is the average headway time of vehicle type i when responding to the movement of the vehicle ahead (in seconds), and $\bar{h}_{LV\text{-}LV}$ is the average reference headway time of a light vehicle following another light vehicle (in seconds). This value is calibrated specifically and separately for each intersection arm (North, South, East, and West).

4) Statistical Validation of Heterogeneous Models

To ensure that the differences in headway times between vehicle pairs were not merely random variations, a statistical test was conducted with a significance level of 5% ($p < 0.05$). Three types of statistical tests were applied:

a) Kolmogorov–Smirnov (K-S) Test: Used to reject the null hypothesis, confirming that the headway data follow a specific independent distribution rather than a uniform distribution.
b) Anderson–Darling (A-D) Test: Applied because it is more sensitive to the extreme ends of the distribution, which demonstrates that extreme deviations such as very tight headways between motorcycles are a genuine characteristic of the data.
c) Chi-Square Test (x^2) Used to demonstrate that each group of leader-follower pairs has a significant effect on queue release time.

5) Evaluation of the Degree of Saturation and Delay

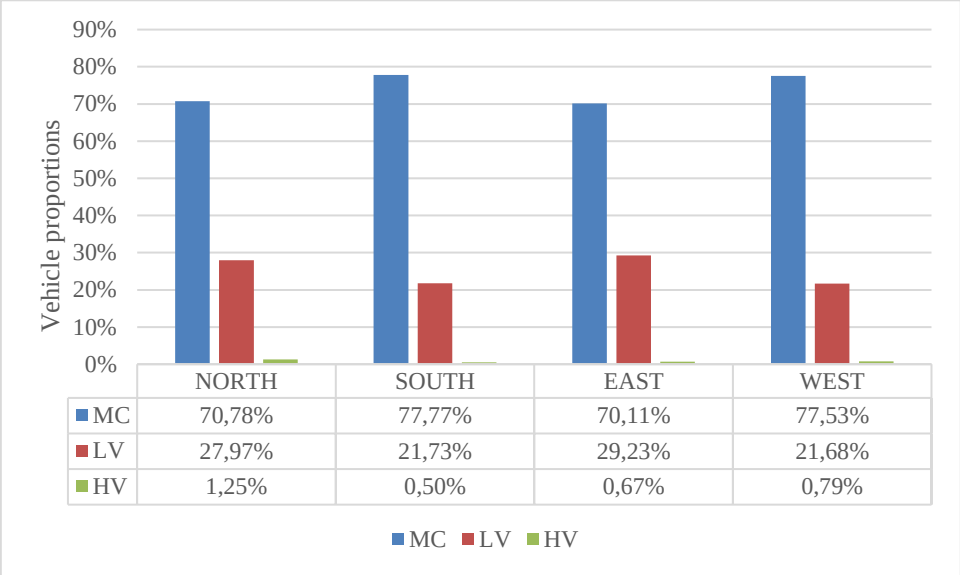
The PCE values obtained from local calibration were then substituted into the intersection capacity analysis. The evaluation focused on calculating capacity (C), arrival volume (Q), degree of saturation (DS = Q/C), and estimating delay times on each intersection arm. The performance results based on the PCE using the time headway method were then compared with the results of the analysis based on the PCE values from the PKJI 2023 static specifications to identify the degree of deviation of the standard guidelines from actual conditions.

RESULTS AND DISCUSSION

Result

1) Operational conditions at intersections and traffic composition

Figure 1 shows the proportion of vehicles during the afternoon rush hour at the Patung Kirab Intersection in Kupang City. The traffic composition shows a predominance of light vehicles and motorcycles, while heavy vehicles account for a smaller proportion. This pattern is consistent with the intersection's location in a commercial area, where it serves commuters heading home from work, travelers heading to the commercial center, and local traffic in the afternoon.



	NORTH	SOUTH	EAST	WEST
MC	70,78%	77,77%	70,11%	77,53%
LV	27,97%	21,73%	29,23%	21,68%
HV	1,25%	0,50%	0,67%	0,79%

Figure 1. Vehicle Breakdown During Rush Hour
Source: Analysis Results (2026)

The proportion of vehicles during rush hour shows that traffic flow is not only high in volume but also heterogeneous in composition. The dominance of motorcycles is a key factor because they exhibit different movement characteristics than light vehicles. Motorcycles can maneuver through gaps between vehicles, form queues that are not strictly lane-based, and have more frequent departure intervals at the start of and during the green phase. In contrast, heavy vehicles require more space and time to maneuver, which can slow down the release of the queue, especially when they are at the front or followed by light vehicles.

The findings in Figure 1 support the research hypothesis that the use of uniform PCE values from the guidelines may not fully reflect actual traffic conditions at signalized intersections in Kupang City (Bolla et al., 2020; Pedo et al., 2026). In a heterogeneous traffic flow, a vehicle's contribution to capacity is determined not only by its type but also by its interaction with the vehicles in front of and behind it. Therefore, the time headway method is relevant for estimating vehicle equivalence based on the queue release behavior observed in the field (Safinatun Naja et al., 2025; Purnamasari et al., 2025). Theoretically, the PCE is a conversion factor that transforms heterogeneous vehicles into passenger-car units. The accuracy of the PCE value is important because it affects the volume in smp/hour, intersection capacity, and the degree of saturation. Studies of signalized intersections with heterogeneous traffic also show that PCE values may differ from guideline values due to variations in vehicle composition, geometry, and driver behavior (Sulistyono et al., 2018) (Sumarsono et al., 2017).

2) Characteristics of Headway Time Based on Leader-Follower Interaction

Table 1 presents the distribution and average headway times based on pairs of lead and trailing vehicles. These results show that headway times vary depending on the combination of vehicle types. In other words, the traffic flow at the Patung Kirab Intersection is not uniform.

Table 1. Distribution and Average Headway Time per Leader-Follower Pair

Leader - Follower	Average Headway (seconds)	Standard Deviation	Proportions of Combinations
HV - LV	2.398	0.255	13.77%
LV - HV	1.999	0.406	13.47%
HV - HV	1.389	0.198	14.15%
LV - LV	1.315	0.676	12.80%
LV - MC	1.228	0.661	10.85%
MC - LV	0.835	0.643	17.51%
MC - MC	0.535	0.405	17.44%

Source: Analysis Results (2026)

Distribution and Average Headway Time per Leader-Follower Pair shows the highest headway in the combination of a heavy vehicle in front and a light vehicle behind, namely 2.398 seconds. This finding implies that light vehicles tend to require more time to begin moving when following a heavy vehicle. This condition may occur because the dimensions of the heavy vehicle obstruct the driver's view from behind, the heavy vehicle accelerates more slowly, and the light vehicle must adjust its speed to match the heavy vehicle's acceleration (Ye & Zhang, 2009; Modupe & Ben-Edigbe, 2023).The combination of a light vehicle in front and a heavy vehicle behind also resulted in a relatively large headway of 1.999 seconds. This result indicates that heavy vehicles still have acceleration limitations even when the vehicle in front of them is a light vehicle. These two patterns confirm that the presence of heavy vehicles reduces the efficiency of queue release, whether they are leading or following vehicles (Ramayanti et al., 2022). Conversely, the combination of motorcycles with other motorcycles resulted in the lowest headway time, at 0.535 seconds. This value indicates that motorcycles can pass the stop line closely and quickly during the green phase. The combination of motorcycles in front of light vehicles also resulted in a low headway of 0.835 seconds. This pattern suggests that the presence of motorcycles in the queue does not always increase congestion. Under certain conditions, motorcycles can actually increase the number of vehicles that clear the intersection during the green phase due to their acceleration capabilities and flexibility in positioning within the queue.

However, this interpretation must be approached with caution. A very low headway for motorcycles does not automatically mean that motorcycles have no impact on capacity. Motorcycles still occupy conflict space at intersections and can affect traffic flow regularity, especially when moving among light vehicles or forming lateral queues (Safinatun Naja et al., 2025). Therefore, the contribution of motorcycles to traffic flow is more accurately represented by the observed PCE values rather than by a single value that does not account for local conditions. The incidence proportions in Table 1 reinforce these findings. The MC-LV and MC-MC pairs were the most frequently occurring combinations, at 17.51% and 17.44%, respectively. The dominance of these two pairs indicates that the nature of intersection operations during the afternoon peak hour is heavily influenced by motorcycle traffic patterns. In contrast, the LV-MC pair has the smallest proportion, at 10.85%, but remains significant as it indicates the interaction between light vehicles and motorcycles in mixed queues.

The standard deviation values in Table 1 also indicate the level of stability in queue release. The HV-LV combination has a low standard deviation of 0.255 seconds, meaning that the headway for this pair

tends to be consistent, although relatively long. Meanwhile, the LV-LV, LV-MC, and MC-LV combinations exhibit greater variation. This variation suggests that the departure behavior of vehicles in these pairs is influenced by the vehicles' lateral position, drivers' responses to signal changes, and opportunities for vehicle maneuvering within the queue. These findings are consistent with time headway theory, which states that a vehicle's equivalence value can be derived from comparing the headway of a specific vehicle to that of a light vehicle used as a reference (Guerrero et al., 2025; Li et al., 2019). This method links PCE to service time at stops. The greater a vehicle's headway relative to a light vehicle, the higher its equivalence value. Conversely, vehicles with shorter headways will result in a lower PCE (Hasyim et al., 2024; Lee, 2015; Al-Obaedi, 2016) .

3) Calibration of Passenger Car Equivalent (PCE) Values

Table 2 presents the PCE values obtained from the time-headway method calibration for each arm of the Simpang Patung Kirab intersection. These values indicate that the PCEs for motorcycles and heavy vehicles are not uniform across the intersection's arms. These differences demonstrate that local operational conditions affect vehicle equivalence.

Table 2. Calibration Results for Corrected PCE Values

Approach	Base Headway (LV-LV) (seconds)	Passenger Car Equivalent of MC	Passenger Car Equivalent of HV
North	1.16	0.46	1.26
South	1.20	0.42	1.21
East	1.48	0.19	1.06
West	1.46	0.18	1.13

Source: Analysis Results (2026)

The results of the calibration of corrected PCE values per branch show that the motorcycle's PCE ranges from 0.18 to 0.46. The highest value was found in the northern arm at 0.46, followed by the southern arm at 0.42. Meanwhile, the eastern and western arms yielded significantly lower motorcycle PCE values, namely 0.19 and 0.18. The high motorcycle's PCE on the north and south approach lanes indicates that motorcycles on both of these lanes utilize relatively more space and travel time compared to conditions on the east and west approach lanes. This may be influenced by queue density, turning patterns, conflicts with other vehicles, the effective width of the approach lanes, and space constraints when motorcycles maneuver. In heavy traffic conditions, motorcycles are not always able to move freely. Motorcycles can be blocked by light or heavy vehicles, causing their contribution to traffic volume to approach that of light vehicles.

Conversely, the very low PCE for motorcycles on the east and west lanes indicates the ability of motorcycles to travel closer together and pass the stop line quickly. These values indicate that a single motorcycle on the east and west arms requires significantly less travel time than a single light vehicle. Thus, applying a uniformly high motorcycle PCE value to both arms could potentially result in an equivalent current estimate that is higher than the actual conditions. The PCE values for heavy vehicles range from 1.06 to 1.26. The north leg yields the highest heavy-vehicle PCE value, at 1.26, while the east leg shows the lowest value, at 1.06. All of these values are greater than one, meaning that heavy vehicles require more space and a longer service time than light vehicles. These results are consistent with the physical

characteristics of heavy vehicles, which have larger dimensions, lower acceleration capabilities, and greater maneuvering space requirements.

Nevertheless, the PCE range for heavy vehicles is not as wide as that for motorcycles. This indicates that the impact of heavy vehicles on queue clearance is relatively consistent across all arms, whereas the impact of motorcycles is more sensitive to local traffic geometry and behavior. These findings are important for analyzing intersections in Kupang City, which is characterized by mixed traffic flow and a predominance of motorcycles. The base headway values for light vehicles relative to other light vehicles in Table 2 range from 1.16 to 1.48 seconds. The north and south approaches have lower base headways than the east and west approaches. This indicates that light vehicles on the north and south approaches exhibit a tighter queue release pattern. These differences may reflect variations in effective width, queue position, turning patterns, and the level of interference at each approach.

By comparison, the PCE value for motorcycles derived from time headway on the north leg 0.46 is close to the value of 0.40 commonly used for the opposing approach in the 2023 PKJI. However, the values on the east and west legs, 0.19 and 0.18, respectively are significantly lower. On the other hand, the PCE values for heavy vehicles resulting from calibration range from 1.06 to 1.26 and generally approach the value of 1.30 used in the 2023 PKJI. The 2023 PKJI uses different PCE values depending on the approach type, with an PCE of 1.00 for light vehicles, 1.30 for heavy vehicles, and 0.15 for motorcycles for the protected approach or 0.40 for the exposed approach. This comparison supports the hypothesis that the 2023 PKJI PCE values may not necessarily be uniformly applicable to all approaches at the Simpang Patung Kirab intersection. Guideline values remain important as a standard reference, but field calibration results provide a more specific representation of actual traffic flow behavior. Therefore, the time headway method can be used as an empirical approach to improve the accuracy of equivalent volume analysis and intersection performance.

4) Statistical Validation of Headway Model

Table 3 presents the results of statistical tests on the heterogeneous headway model. All tests rejected the null hypothesis at a 5% significance level. These results demonstrate that the headway data cannot be treated as a single homogeneous group.

Table 3: Statistical Validation of the Heterogeneous Headway Model

Types of Statistical Tests	Test Statistics	p-value / Critical Value	Validation Conclusion (p < 0.05)
Kolmogorov–Smirnov (K-S)	0.135	p=0,0035	H0 is rejected; the data follow a specific, independent distribution
Anderson–Darling (A-D)	4.1975	Critical Level: 0.7700	H0 is rejected; extreme outliers are significantly present in the recorded data
Chi-Square ($\chi 2$)	31.2837	p=0,0001	H0 is rejected; each group of leader-follower pairs is significantly different

Source: Analysis Results (2026)

Statistical validation of the Heterogeneous Headway Model shows a Kolmogorov-Smirnov statistic of 0.135 with a p-value of 0.0035. Since the p-value is less than 0.05, the null hypothesis is rejected. This means that the observed headway time distribution does not follow the homogeneous distribution assumed in the simple model. The data exhibit a specific pattern influenced by the type of leader-follower pair. The

results of the Anderson-Darling test also support this conclusion. The statistical value of 4.1975 far exceeds the critical threshold of 0.7700. The Anderson-Darling test is more sensitive to differences in the extreme parts of the distribution. Therefore, these results indicate that extreme headway variations such as very low headways in the MC-MC pairs and high headways in the HV-LV pairs are genuine characteristics of the data, not merely random variations. The chi-square test yielded a value of 31.2837 with a p-value of 0.0001. These results indicate a significant difference among the leader-follower pair groups. Thus, heavy vehicles, light vehicles, and motorcycles cannot be assumed to have the same effect on queue clearance time.

Substantively, the results in Table 3 validate the use of a time-headway based PCE model. If all vehicles were considered homogeneous or if the PCE value were considered constant for all approaches, the variations in queue release behavior identified in the data would be ignored (Mondal & Gupta, 2019) (Patel & Dhamaniya, 2021) . In fact, Tables 1 and 2 show that vehicle type and vehicle position in the queue significantly affect service time. Thus, the results of the statistical tests support the research hypothesis that the time headway approach is capable of capturing the heterogeneity of traffic flow at signal intersections. This approach is more suitable for the Patung Kirab Intersection because it serves mixed traffic in a commercial area with a high afternoon travel peak.

Discussion

Table 4 shows the estimated capacity, degree of saturation, and delay on each approach to the Simpang Patung Kirab intersection. The analysis results indicate that the intersection's performance varies across the different approaches. Traffic volume is concentrated on the southern, eastern, and, in particular, western approaches to the intersection.

Table 4. Estimates of Capacity (C) and Degree of Saturation (DS) by Approach

Approach	Volume (Q)	Capacity (C)	Degree of Saturation (DS=Q/C)	Delay
North	486.63	819.00	0.594	46.09
South	1348.48	375.82	0.928	50.33
East	1891.14	1453.84	1.064	155.31
West	1719.59	1776.80	0.968	77.08

Source: Analysis Results (2026)

Shows that the northern approach has a degree of saturation of 0.594. This value indicates that the northern approach is still in a relatively more manageable condition compared to other approaches. Although a delay of 46.09 seconds was recorded, the approach's capacity is still greater than the incoming traffic flow. This situation indicates that the northern approach has not yet experienced a direct excess of demand over capacity, but it is still affected by queues and signal phase coordination at the intersection as a whole.

The south approach has a degree of saturation of 0.928. This value indicates conditions approaching saturation. Incoming traffic has utilized nearly all available capacity, so even a slight increase in volume or an operational disruption could cause traffic queues to grow rapidly. A delay of 50.33 seconds indicates that road users on the south approach have experienced significant delays during the evening rush hour. The eastbound approach has a degree of saturation of 1.064. A value above one indicates that traffic demand

has exceeded capacity. This means that the queue cannot be fully cleared within a single signal cycle and may carry over into the next cycle. A delay of 155.31 seconds illustrates the direct consequence of this oversaturated condition. The eastbound approach becomes a critical point because even a relatively small increase in volume can disproportionately increase queue length and delay.

The western approach shows highly critical conditions, with traffic volume reaching 1,719.94 PCU/hour against a capacity of 1,776.80 PCU/hour, resulting in a degree of saturation of 0.968 and a delay of 77.08 seconds. These values indicate a near-saturated condition operating at Level of Service (LoS) F. The available capacity is barely sufficient to handle the flow of traffic during the afternoon peak hour. With a DS approaching 1.0, there is a high probability of cycle failure, meaning the initial queue cannot be fully cleared within a single green phase and carries over as a residual queue. The significant delay of 77.08 seconds confirms that operational issues on the western approach can lead to unstable queues, unreliable travel times, and potential disruptions to road segments upstream of the intersection (Kullaya et al., 2026; Hang et al., 2020).

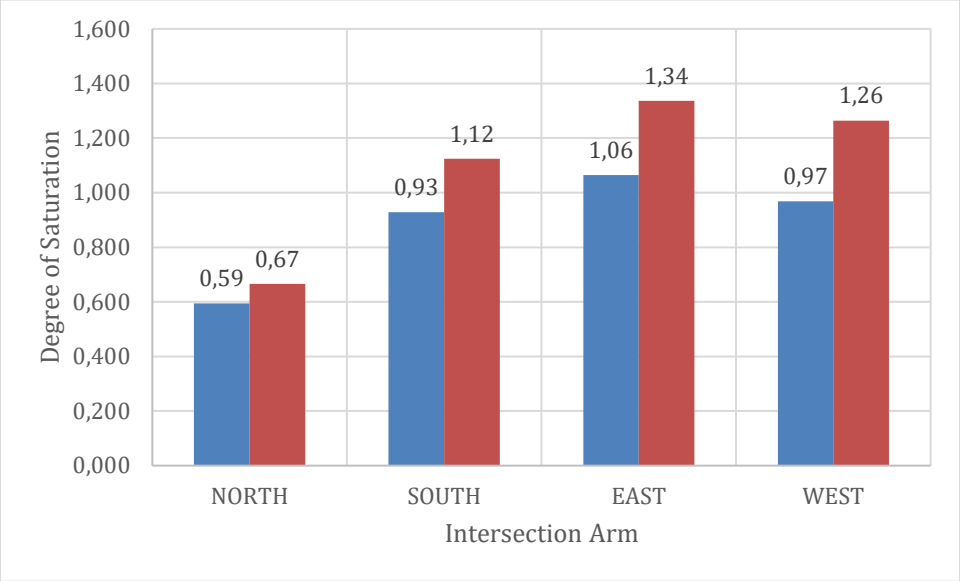


Figure 2. Comparison of DS Values Based on Headway and PKJI 2023
Source: Analysis Results (2026)

Figure 2 compares the degree of saturation values calculated using time-headway-based PCE with those based on the 2023 PKJI. Figure 2 shows that the choice of PCE values can significantly alter the results of intersection performance evaluations. This difference is particularly noticeable on approaches dominated by motorcycles. When a locally calibrated motorcycle PCE is lower than the 2023 PKJI values, it results in a lower volume in PCU/hour. Consequently, the degree of saturation decreases compared to the results based on the 2023 PKJI PCE. However, this decrease does not necessarily mean the intersection is operating optimally. For example, the western approach shows a decreased degree of saturation of 0.968. While no longer well above one, this value indicates a critically near-saturated condition. This means that even though vehicle conversion rates have been adjusted to reflect the actual behavior of motorcycles, the capacity of that approach is barely sufficient to handle peak-hour traffic. Conversely, on approaches where the calibrated motorcycle PCE is close to or higher than the guideline values, such as the north and south approaches, the differences in DS results tend to be smaller or may yield higher traffic volume estimates.

This situation indicates that the use of a standard PCE without calibration has the potential to cause two types of errors. First, the analysis may overestimate traffic volume on approaches where motorcycles are highly efficient at clearing queues (Özgün & Öğüt, 2026; Wadu et al., 2026; Anggoro et al., 2018). Second, the analysis may underestimate traffic volume on approaches where motorcycle interactions are more constrained (Meilinda et al., 2025; Kariyana et al., 2022) .

The findings in Figure 2 support the results detailed in Tables 1 through 4. PCE values are not universal because they are inherently influenced by vehicle interactions, traffic composition, approach conditions, and driver behavior. Previous research has also found significant differences between observed PCE values and guideline values at signalized intersections with heterogeneous traffic (Sugiarto et al., 2024; Nassiri et al., 2017). These differences directly affect estimates of saturation flow, capacity, and the degree of saturation. Overall, the study's findings support the hypothesis that PCE estimates calculated using the time headway method yield values that differ from the static parameters of the 2023 PKJI and that these differences significantly affect intersection saturation levels. The time headway method provides values that are more responsive to local operational conditions, particularly regarding the prevalence of motorcycles and dynamic vehicle interactions within queues (Irwandi et al., 2025; Mondal & Gupta, 2019; Roy & Saha, 2018).

CONCLUSION

This study concludes that evaluating intersection performance using the time headway method has proven effective in representing the dynamic, heterogeneous operational characteristics of traffic at the Patung Kirab Intersection compared to the use of conventional static parameters. The positional interactions between vehicle types (leader-follower) significantly affect the efficiency of queue clearance; the maneuverability of motorcycles tends to accelerate clearance (lowest headway of 0.535 seconds), while the presence of heavy vehicles poses the greatest obstacle to traffic flow (highest headway of 2.398 seconds). The Passenger Car Equivalency (PCE) values resulting from local calibration show a noticeable deviation from the 2023 PKJI standard and are found to fluctuate across each intersection approach. Specifically, the calibrated PCE for motorcycles ranged widely from 0.18 to 0.46, while heavy vehicles ranged from 1.06 to 1.26. The application of these location-specific PCE values yields a more representative assessment of intersection performance, directly revealing critical, near-saturated conditions and delays that might otherwise have been miscalculated if relying solely on standard guidelines. Therefore, this empirical approach is essential for redesigning traffic signal systems and managing intersection capacity in areas with mixed-traffic characteristics. Specifically, addressing the critically congested state on the West approach (degree of saturation = 0.968; delay = 77.08 sec/PCU) requires immediate practical interventions; it is recommended that traffic authorities prioritize geometric capacity expansions, such as lane widening, or implement heavy vehicle access restrictions during afternoon peak hours, as heavy vehicle interactions were empirically shown to cause the most significant delays in queue clearance.

AUTHOR CONTRIBUTIONS

Amy Wadu contributed to the conceptualization of the study, research methodology design, field data collection via UAV aerial recordings, data extraction, statistical analysis, and preparation of the initial

manuscript. Obed Nenobais contributed to data processing, validation of the headway parameters, and substantive interpretation of the intersection performance results. Ludofikus Dumin contributed to the critical review, editing, and refinement of the manuscript. All authors participated in the discussion of the research findings, reviewed and approved the final version of the manuscript, and are responsible for the integrity and accuracy of the work.

CONFLICT OF INTEREST

The authors declare that there are no financial or non-financial conflicts of interest that could have influenced the conduct of the research, data analysis, preparation, or publication of this article.

ARTIFICIAL INTELLIGENCE (AI) USE STATEMENT

In preparing this article, the authors used artificial intelligence tools strictly as writing assistants to improve language structure, grammar, and readability. These tools were not used to generate, manipulate, or alter any primary research data, including the vehicle trajectory extraction or time headway analysis. After using these services, the authors closely reviewed and edited the generated output. The authors take full responsibility for the originality, accuracy, and overall content of this publication.

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