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Analysis of Vehicle Platoon Speed Recovery Time Due to Vehicles Stopping at the Stop Line of a Signalized Intersection (APILL)

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Abstract: Transportation is an essential component in supporting mobility and socio-economic activities. The increase in the number of vehicles has led to various traffic problems, such as congestion, delays, and the risk of accidents. The signalized intersection (APILL) located at Jl. Sudirman, Jl. Sam Ratulangi, Jl. Haji Hayun, and Jl. Cik Ditiro has different geometric and functional characteristics because each approach is under different authorities and classifications within the road network system. This study aims to identify the existing performance of the intersection at Jl. Sam Ratulangi – Jl. Cik Ditiro – Jl. Sudirman – Jl. Haji Hayun, analyze the deceleration time required for vehicles to stop at the stop line at the signalized intersection, analyze the recovery time required for vehicles within a platoon to move from a stationary condition to reach normal speed, and examine the relationship between recovery time and traffic flow at the signalized intersection. Data collection in this study was carried out through traffic surveys and observations of vehicle stopping and movement times at the stop line. The data analysis was conducted using the Indonesian Highway Capacity Guidelines (PKJI) method. Based on the analysis of the signalized intersection performance at the Jl. Sudirman – Jl. Sam Ratulangi – Jl. Cik Ditiro – Jl. Haji Hayun intersection, the results indicate high values during peak hours, with the degree of saturation (DS) for all intersection approaches exceeding 0.85. Motorcycles have an average deceleration time of 8.56 seconds, while passenger cars have an average of 8.79 seconds and heavy vehicles 9.12 seconds. Motorcycles exhibit the fastest recovery time at 7.57 seconds, followed by passenger cars at 9.27 seconds and heavy vehicles at 9.5 seconds. The analysis shows a linear and positive relationship between vehicle volume and speed recovery time for all vehicle types. The higher the traffic volume, the longer the time required for vehicles to return to their normal speed after stopping at the stop line. During the afternoon period, with a total traffic volume of 2,178 vehicles and a degree of saturation of 0.64, the analysis results indicate that vehicle volume is the dominant factor influencing vehicle speed recovery time.

***Keywords**: Signalized Intersection, APILL, Geometric Characteristics, Platoon, PKJI, Degree of Saturation, Recovery Time, Stopping Time, Stop Line.*

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I. INTRODUCTION

Transportation is a crucial aspect of modern life, playing a significant role in supporting economic, social, and cultural activities within society. The increasing population has led to a rapid rise in motor vehicle ownership.

The signalized intersection (APILL) at Jalan Sudirman, Jalan Sam Ratulangi, Jalan Haji Hayun, and Jalan Cik Ditiro represents an intersection with unique geometric and functional characteristics, as each approach falls under different authorities and road network classifications. The northern and southern approaches are part of the national road network system, functioning as primary corridors for interregional mobility, while the eastern and western approaches are classified as urban roads that serve local traffic movements. These differences in road status influence governance, handling priorities, and traffic characteristics on each approach, thereby creating distinct challenges in intersection planning and management.

The signalized intersection at Jalan Sam Ratulangi, Jalan Haji Hayun, and Jalan Cik Ditiro plays an important role in regulating traffic flow; however, it frequently becomes a congestion point due to the complex dynamics of vehicle movements. One of the main factors affecting the efficiency of a signalized intersection is vehicle behavior when stopping

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and starting again, as well as when decelerating to a stop at the stop line.

In this context, the phenomenon of platooning—a group of vehicles moving together as a unit—becomes an important aspect to consider. Slow speed recovery within a platoon can reduce traffic efficiency, increase travel time, and elevate the risk of congestion at intersections. Therefore, understanding the pattern of vehicle speed recovery within a platoon after stopping at the stop line is essential to improving the efficiency of signalized intersections.

By understanding the time required for vehicles to decelerate to a stop and to return to normal speed, as well as the relationship between recovery time and traffic flow, this study is expected to contribute to improving traffic efficiency and safety at signalized intersections in Palu City. Accordingly, this research specifically focuses on "Analysis of Vehicle Platoon Speed Recovery Time Due to Vehicles Stopping at the Stop Line at Signalized Intersections", in order to gain a deeper understanding of how speed recovery patterns influence the performance of signalized intersections in Palu City.

II. LITERATURE REVIEW

➢ *Traffic in the Transportation System*

Traffic possesses distinct characteristics and advantages; therefore, it must be developed and utilized optimally to ensure high mobility and accessibility across all regions. In addition, the traffic system should be capable of integrating and harmonizing various modes of transportation to support the effective movement of people and goods. Recognizing the strategic role of transportation in supporting national development and economic growth, traffic must be organized within an integrated transportation system. Such an integrated system is expected to provide transportation services that correspond to the needs of society. The management of traffic should adhere to the principles of orderliness, safety, security, speed, regularity, and smooth flow.

Conceptually, traffic can be understood as a system consisting of various interrelated components that interact and influence one another. One important component of the traffic system is headway, defined as the time interval between two consecutive vehicles passing a specific point on a roadway segment. The concept of headway is commonly used as an indicator in the analysis of traffic capacity and performance. Furthermore, the traffic system encompasses transportation infrastructure and facilities of various modes, including road networks, road equipment, supporting road facilities, public and private transport, as well as different types of vehicles involved in the transportation process. This transportation process refers to the activity of moving people and/or goods from one location to another within a certain distance.

Transportation is a crucial element within the social, economic, and physical systems of a region. In general, transportation can be defined as the process of moving people and goods from one place to another using specific modes of transport. This process involves three main components: transportation facilities (vehicles), transportation infrastructure (roads, railways, ports, and airports), and operational systems that include traffic management and control (Nasution, 2004).

From a regional planning perspective, transportation is not merely viewed as a physical activity but also as part of a network system that plays a role in shaping spatial patterns and supporting regional economic growth (Tarigan, 2005). The primary function of transportation is to support population mobility and the distribution of goods. In addition, transportation contributes to enhancing interregional connectivity, strengthening national integration, and promoting the effectiveness of regional development (Kadir, 2004). An effective transportation system can improve logistical efficiency, accelerate economic growth, and enhance the overall quality of life.4

➢ *Signalized Intersections (APILL)*

According to the Indonesian Highway Capacity Guidelines (PKJI, 2023), traffic signal control devices (Alat Pemberi Isyarat Lalu Lintas – APILL) function as a traffic control system designed to minimize potential conflicts among traffic streams. As a result, interactions that may lead to conflicts—both direct and indirect—can be significantly reduced. Therefore, APILL plays a crucial role in improving both efficiency and safety at road intersections.

APILL is essential in maintaining the operational capacity of intersections, particularly during peak hours, and in reducing accident rates caused by conflicting vehicle movements from opposing directions. To ensure traffic safety, the APILL system does not rely solely on green and red signals but must also incorporate a yellow signal and an all-red phase. The yellow signal serves as a warning to road users that the green phase is about to end, allowing drivers to prepare to stop. Meanwhile, the all-red phase provides a safe clearance interval, enabling the last vehicles from the previous phase to completely exit the conflict area before the first vehicles from the subsequent phase enter the intersection.

The performance of a signalized intersection refers to an evaluation of how effectively an APILL-controlled intersection manages vehicle movements to reduce conflicts and enhance traffic safety and efficiency. According to PKJI (2023), intersection performance assessment aims to estimate capacity and traffic performance in relation to geometric design, signal phasing arrangements, traffic flow, and the surrounding roadside environment. The estimation of capacity and performance values allows for adjustments in planning to achieve the desired traffic performance.

The all-red time is required to clear the conflict area at the end of each signal phase. This interval provides sufficient time for the last departing vehicle to pass the stop line at the end of the yellow signal and fully leave the conflict point. The clearance distance consists of the departure travel distance (LKBR) plus the length of the departing vehicle (PKBR), before the arrival of the first vehicle from another approach (KDT) in the next phase. This incoming vehicle travels from the stop line at the beginning of the green signal to the same

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conflict point, covering the approach travel distance (LKDT). Therefore, the all-red time is a function of vehicle speed and travel distance—both for departing and approaching vehicles from their respective stop lines to the conflict point—as well as the length of the departing vehicle (PKBR).

➢ *Traffic Platoon*

Traffic platoon is an important phenomenon in the study of traffic flow dynamics. In general, a traffic platoon is defined as a group of vehicles moving together in a coordinated manner, tending to maintain relatively uniform spacing and speed. Platoons typically form when vehicles within a traffic stream—either at signalized intersections (APILL) or along specific road segments—depart from a կանգ stop line sequentially, thereby creating a single operational unit that can be analyzed collectively (Roess et al., 2010). The formation of platoons is influenced not only by infrastructure conditions but also by vehicle interactions and traffic signal control strategies (Gartner et al., 2001).

A traffic platoon may also be described as a set of vehicles traveling in close succession, with relatively small inter-vehicle spacing and time gaps, resulting from traffic control measures, upstream disturbances, or roadway capacity limitations. Platoons are commonly observed on urban roadways and at approaches to signalized intersections, where they are formed due to the red phase that causes vehicles to stop and subsequently move together when the signal turns green.

Within traffic flow theory, platoon formation is closely associated with the concept of car-following behavior, which describes how drivers respond to the movement of the vehicle ahead. Each vehicle in a platoon adjusts its speed, acceleration, and safe following distance based on the behavior of the leading vehicle. The lead vehicle has greater freedom in determining its speed, while following vehicles are more constrained by the movement patterns of preceding vehicles. As a result, speed characteristics within a platoon are not entirely uniform, particularly during the initial acceleration phase after stopping at the stop line.

At signalized intersections, platoons are formed periodically in accordance with signal cycles. During the red phase, vehicles accumulate and form a queue. When the green phase begins, vehicles are discharged sequentially, generating a movement wave (shockwave) that propagates along the approach. This discharge process introduces variations in driver reaction time and acceleration, which in turn affect the speed recovery of vehicles within the platoon. The longer the queue, the greater the likelihood of variations in speed profiles among vehicles in the platoon.

The main characteristics of a traffic platoon include platoon size (number of vehicles), platoon length, headway distribution, and speed variation among vehicles. Factors influencing platoon formation and behavior include traffic volume, signal timing settings, roadway geometric conditions, and driver behavior. In the context of this study, understanding traffic platoon dynamics is essential for analyzing how vehicles stopped at the stop line affect the speed recovery of subsequent vehicles.

The formation of platoons is a common phenomenon in urban transportation systems, particularly within signalized road networks. The presence of platoons affects various aspects of traffic performance, including capacity, delay, queue length, and signal system efficiency. Platoon formation is influenced by multiple interrelated factors, including technical, geometric, and behavioral aspects.

Space Mean Speed (SMS) is one of the key parameters in traffic flow theory used to represent the average speed of vehicles over a given road segment within a specific time period. Unlike Time Mean Speed (TMS), which is calculated based on observations at a single point, Space Mean Speed is derived from the travel time of vehicles over a defined road segment. Therefore, it is considered more representative of actual traffic operating conditions. Mathematically, Space Mean Speed is defined as the length of a road segment divided by the average travel time of all vehicles traversing that segment. Since it is based on the harmonic mean, the value of Space Mean Speed tends to be lower than that of Time Mean Speed, especially when there is significant variation in vehicle speeds.

At signalized intersections, Space Mean Speed is particularly suitable for analyzing the speed recovery process of vehicle platoons after stopping at the stop line. When vehicles begin to move during the green phase, variations in acceleration among vehicles lead to speed fluctuations along the approach segment. The use of Space Mean Speed enables researchers to capture the overall actual speed of the platoon, rather than relying solely on point-based observations.

III. RESEARCH METHOD

➢ *Type of Research*

This study adopts a quantitative approach to analyze traffic flow characteristics, particularly focusing on the dynamics of traffic platoons at signalized intersections. The research is classified as an empirical and analytical study, as it is based on field observations and the application of traffic flow theory to evaluate real-world conditions. Furthermore, this research can be categorized as a descriptive and explanatory study. It is descriptive in nature because it aims to systematically describe traffic conditions, including vehicle movement patterns, platoon characteristics, and speed variations. At the same time, it is explanatory, as it seeks to examine the relationships between variables such as signal timing, queue formation, and the speed recovery of vehicles within a platoon.

➢ *Research Location*

The study was conducted in the City of Palu, specifically at the intersection of Sam Ratulangi Street and Cik Ditiro Street, which is a signalized intersection (APILL). The analysis of intersection performance was carried out on all approaches of the signalized intersection. However, the analysis of the vehicle speed recovery phenomenon within a traffic platoon was limited to a single approach, namely the

Sam Ratulangi Street approach (northbound direction). This approach was selected to represent the characteristics of platoon movement and to provide a more focused analysis of speed recovery behavior following vehicle توقف at the stop line.

Fig 1 Research Location

➢ *Data Collection Techniques*

Primary data in this study were obtained directly through field observations, measurements, and video recordings conducted at the study location. The collected primary data include intersection geometric characteristics, such as the number of approaches, the number and width of lanes for each approach, and the approach width at the intersection. In addition, data on intersection characteristics were gathered, including the number of signal phases, signal phase arrangements, signal cycle time, approach type, and roadway gradient, all of which were identified through direct field observation. The study also considered side friction factors, such as on-street parking activities and vehicles entering and exiting adjacent areas, as these conditions influence vehicle behavior within a traffic platoon. Furthermore, traffic volume data were obtained through the calculation of Annual Average Daily Traffic (AADT) for all intersection approaches. Data on vehicle stopping and starting times at the stop line were extracted from video recordings, capturing the process from initial deceleration to a complete stop, the initiation of movement from a stationary position, and the time required for vehicles to recover to normal speed within a platoon.

Secondary data were obtained from relevant technical agencies and supporting literature to enhance conceptual understanding and provide contextual background for the study. These data include land use maps, vehicle population data, and location maps of the study area.

Following data collection, all data and information obtained during the research process—both primary and secondary—were integrated and processed systematically to ensure data completeness and accuracy. The data processing stage began with data checking and screening, in which all data obtained from field observations and video recordings were carefully reviewed to verify their completeness, consistency, and validity. Subsequently, the traffic video recordings were transcribed into structured observation tables.

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This transcription process included recording the time required for vehicles to decelerate from their initial speed until coming to a complete stop at the stop line, as well as the time required for vehicles to start moving from the stop line and recover to their normal speed.

- *Data Analysis Technique*

The analysis and discussion in this study are conducted to address the research questions and achieve the stated research objectives. The analysis focuses on evaluating the performance of the signalized intersection at Sam Ratulangi Street and Cik Ditiro Street, based on the Indonesian Highway Capacity Guidelines (PKJI, 2023).

The intersection performance analysis includes several key parameters. First, intersection capacity is evaluated to determine the maximum traffic flow that can be accommodated by the signalized intersection. Capacity is defined as a function of the saturation flow rate and the effective green time within a signal cycle. Second, the degree of saturation (DS) is calculated as the ratio of traffic volume to intersection capacity. A DS value approaching the critical threshold (greater than 0.85) indicates that the intersection is operating under near-saturated conditions.

Furthermore, queue length is analyzed to estimate the average number of vehicles accumulated at the beginning of the green phase, considering the effective entry width and the average space occupied by a passenger car equivalent. The stopped vehicle ratio is also evaluated to determine the proportion of vehicles that must come to a complete stop within the traffic stream, reflecting the level of interruption experienced by vehicles at the intersection.

In addition, delay is assessed as a key performance indicator, representing the additional travel time experienced by vehicles due to traffic control and geometric conditions at the intersection. Total delay is composed of traffic delay and geometric delay components. These parameters collectively provide a comprehensive assessment of intersection performance under existing traffic conditions.

IV. RESULTS

The signalized intersection (APILL) of Jl. Sudirman – Jl. Haji Hayun – Jl. Sam Ratulangi – Jl. Cik Ditiro in Palu City represents a critical node in the urban traffic network. This location was selected due to its distinctive characteristics: two approaches (Jl. Sam Ratulangi and Jl. Sudirman) are part of the national road network with a primary arterial function, while Jl. Cik Ditiro and Jl. Haji Hayun are classified as urban roads with collector functions. This disparity in road hierarchy positions the intersection not only as a connector for local traffic movements but also as a major corridor for inter-regional mobility.

Geometrically, the intersection consists of four approaches with varying widths. The northern and southern approaches have a width of approximately 13 meters, providing relatively higher capacity, whereas the eastern and western approaches are narrower, at around 7 meters. These geometric conditions significantly influence traffic flow performance, particularly during morning and afternoon peak hours. In addition, side frictions—including on-street parking activities, pedestrian movements, and left-turn-on-red maneuvers—further contribute to the complexity of traffic operations at the intersection.

Field observations indicate that the intersection frequently experiences traffic congestion, especially during peak periods. Although the intersection is controlled by a four-phase traffic signal system, where each approach is served alternately, operational issues persist. The four-phase signal setting is intended to minimize conflict points, particularly for right-turn movements. However, empirical observations reveal that during peak hours, long queues and substantial delays still occur, especially on approaches with high traffic volumes.

The analysis of traffic volume and composition at the intersection indicates that traffic flow across all approaches is predominantly characterized by through movements, with motorcycles forming the majority of vehicle types. This pattern is consistently observed during both morning and afternoon periods, reflecting typical urban traffic conditions with high vehicle density and mobility. The dominance of motorcycles suggests a high level of maneuverability within the traffic stream; however, it also increases the likelihood of operational conflicts, particularly at signalized intersections with mixed traffic compositions.

At the northern approach (Jl. Sam Ratulangi), through movements represent the largest proportion of traffic flow, with peak volumes occurring during the morning (07:00–08:00) and afternoon (16:15–16:30) periods. Motorcycles dominate these flows, followed by passenger cars, while heavy vehicles are negligible. Right-turn movements, although lower than through movements, show a similar temporal pattern and contribute significantly during peak hours. In contrast, left-turn movements consistently record the lowest volumes, indicating a relatively minor contribution to overall intersection demand.

The southern approach (Jl. Sudirman) exhibits the highest traffic intensity among all approaches, particularly during the morning peak (07:31–07:45). Through movements dominate the traffic stream and constitute the primary demand on intersection capacity, supported by moderate right-turn flows and minimal left-turn movements. During the afternoon period, traffic intensity remains high, with motorcycles accounting for the majority of vehicles. This condition highlights the critical role of the southern approach as a major traffic corridor, requiring efficient signal timing to accommodate high demand and reduce delays.

At the eastern approach (Jl. Cik Ditiro), traffic flow is strongly dominated by through movements, with very limited contribution from heavy vehicles. Right-turn movements show moderate volumes, while left-turn movements remain insignificant throughout both observation periods. This indicates that the eastern approach primarily functions as a through corridor, with relatively low complexity in turning

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movements but still requiring effective control to manage peak-hour demand.

Meanwhile, the western approach (Jl. Haji Hayun) demonstrates more fluctuating traffic patterns compared to other approaches, although motorcycles remain the dominant vehicle type. Through movements continue to represent the primary flow, while right-turn movements increase during peak periods and may contribute to potential traffic conflicts. Left-turn movements remain relatively low and stable, suggesting a limited impact on overall capacity. The variability of traffic flow on this approach indicates a higher sensitivity to signal timing and operational conditions.

Tabel 1 Road Condition Classification

Approach	Traffic Flow (pcu/h)	Capacity (pcu/h)	Degree of Saturation (DS)	Delay (pcu/s)	Queue Length (m)
Sam Ratulangi	619	769	0,80	41.156,70	65,71
Sudirman	554	866	0,64	33.610,20	55,77
Cik Ditiro	435	357	1,22	95.276,67	159,52
H. Hayyun	329	371	0,89	27.358,08	59,53

Based on the performance analysis of the signalized intersection (APILL), significant variations in the level of service are observed across all approaches. The northern approach (Jl. Sam Ratulangi) records a traffic flow of 619 pcu/h with a capacity of 769 pcu/h, resulting in a degree of saturation (DS) of 0.80. This value indicates near-saturated conditions, with an average delay of 41,156.70 pcu/s and a queue length of 65.71 m. Although traffic flow remains relatively stable, these conditions suggest that proper traffic management is required to prevent further deterioration of performance.

The southern approach (Jl. Sudirman) demonstrates better operational conditions compared to other approaches, with a traffic flow of 554 pcu/h and a capacity of 866 pcu/h, resulting in a DS value of 0.64. This lower degree of saturation reflects a more stable flow condition, supported by a delay of 33,610.20 pcu/s and a queue length of 55.77 m. Overall, this approach operates within an acceptable level of service, although continuous monitoring is still necessary to maintain its performance under increasing traffic demand.

In contrast, the eastern approach (Jl. Cik Ditiro) exhibits the most critical condition, with a traffic flow of 435 pcu/h exceeding its capacity of 357 pcu/h, resulting in a DS value of 1.22. A DS value greater than 1 indicates oversaturated conditions, where traffic demand surpasses the available capacity. Consequently, this approach experiences extremely high delays, reaching 95,276.67 pcu/s, and a queue length of 159.52 m. These findings clearly identify the eastern approach as the most problematic segment of the intersection and a priority for operational improvements.

Meanwhile, the western approach (Jl. H. Hayun) shows a traffic flow of 329 pcu/h with a capacity of 371 pcu/h, resulting in a DS value of 0.89. This condition indicates that the approach is operating close to saturation. The recorded delay of 27,358.08 pcu/s and queue length of 59.53 m suggest that traffic performance is still manageable but requires optimization. Without appropriate intervention, this approach has the potential to transition into oversaturated conditions similar to those observed at the eastern approach.

➢ *Vehicle Deceleration Time Analysis*

Deceleration time refers to the duration required for a vehicle to reduce its speed until coming to a complete stop at an intersection when the traffic signal turns red. At signalized intersections (APILL), this phenomenon is influenced not only by vehicle characteristics but also by traffic volume and the position of vehicles within a platoon.

Motorcycles (MC) generally exhibit shorter deceleration times due to their smaller size and higher maneuverability compared to passenger cars and heavy vehicles. However, based on field observations, the deceleration time of motorcycles is found to be longer than that of passenger cars during the morning period. The average deceleration time for motorcycles in the morning is approximately 9.02 seconds. This occurs because motorcyclists tend to utilize narrow gaps between vehicles; when traffic flow slows down, they do not immediately stop but instead adjust their speed while searching for safe gaps, resulting in a longer deceleration process. In addition, morning traffic is dominated by motorcycles, which creates relatively more flexible movement conditions. In contrast, during the afternoon period, motorcycles exhibit the shortest deceleration time among all vehicle types, with an average of 8.56 seconds. This shorter duration is attributed to denser traffic conditions dominated by passenger cars, where vehicle movement becomes more constrained and deceleration tends to follow the leading vehicle.

Passenger cars (PC) demonstrate shorter deceleration times in the morning period, with an average of 8.76 seconds. This is primarily due to the dominance of motorcycles in the traffic stream, which provides greater maneuvering space for passenger cars, allowing smoother and more efficient speed reduction without significant interference from heavy vehicles. In the afternoon period, the average deceleration time for passenger cars increases slightly to 8.79 seconds. This increase is associated with higher traffic volumes and the presence of heavy vehicles, particularly when passenger cars are positioned behind them, which affects the deceleration process and results in longer platoon formations.

Heavy vehicles (HV), on the other hand, require longer deceleration times compared to other vehicle groups due to their larger mass, limited acceleration and deceleration

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capabilities, and greater space requirements for braking. Based on field survey results, the average deceleration time for heavy vehicles is approximately 10 seconds. This duration remains relatively high even during the morning period when traffic volumes are lower. In the afternoon, increased traffic volumes further contribute to longer deceleration times, with an average of 9.12 seconds. These findings indicate that heavy vehicles significantly influence traffic flow dynamics, particularly in high-density conditions.

- *Vehicle Deceleration Time Analysis*

The influence of traffic volume on deceleration time is consistent with platoon theory, which explains that vehicles move in groups and interact with one another. The graphical and empirical data indicate that deceleration time is directly proportional to traffic volume. As traffic volume increases, the required deceleration time also becomes longer. The following figures illustrate the relationship between traffic volume and deceleration time during the morning and afternoon periods for each vehicle category.

Based on the analysis of passenger cars (PC), the relationship between traffic volume and deceleration time is found to be strong and linear. In the morning period, the regression coefficient of 0.2841 indicates that each additional vehicle in the traffic stream is associated with an increase in deceleration time of approximately 0.28 seconds. The coefficient of determination ($R^2 = 0.5448$) suggests a moderate positive correlation between the two variables, confirming that traffic volume has a noticeable influence on deceleration time. In the afternoon period, the relationship becomes stronger, with a coefficient of 0.3043, implying that each additional vehicle increases deceleration time by approximately 0.30 seconds. The R^2 value of 0.9392 indicates a very strong correlation, suggesting that traffic volume is a dominant factor influencing deceleration time during peak congestion.

For heavy vehicles (HV), the relationship between traffic volume and deceleration time also demonstrates a strong positive correlation. In the morning period, the coefficient of 0.8324 indicates that each additional heavy vehicle contributes to an increase in deceleration time of approximately 0.83 seconds. The R^2 value of 0.8514 confirms a strong correlation, indicating consistent behavior of heavy vehicles under varying traffic volumes. In the afternoon period, the coefficient decreases to 0.3427, meaning that each additional heavy vehicle increases deceleration time by approximately 0.34 seconds. However, the R^2 value of 0.9338 indicates a very strong correlation, suggesting that despite the lower coefficient, traffic volume remains a key influencing factor.

Similarly, the motorcycle (MC) group shows a positive and linear relationship between traffic volume and deceleration time. In the morning period, the coefficient of 0.2902 indicates that each additional motorcycle increases deceleration time by approximately 0.29 seconds, with an R^2 value of 0.5699, indicating a moderate to strong correlation. In the afternoon period, the coefficient slightly increases to 0.2977, meaning that each additional motorcycle contributes to an increase of approximately 0.30 seconds in deceleration time. The R^2 value of 0.9515 indicates a very strong correlation, demonstrating that motorcycle behavior becomes more constrained under higher traffic density conditions. This suggests that during the afternoon peak, motorcycle movements are more influenced by overall traffic conditions, resulting in increased dependence of deceleration time on traffic volume.

- *Vehicle Speed Recovery Time Analysis*

Vehicle speed recovery time refers to the duration required for a vehicle to start moving again after stopping at the stop line when the traffic signal changes from red to green. This indicator is important as it reflects how quickly traffic flow can resume after being interrupted. The faster vehicles recover and accelerate, the more efficient the intersection performance.

The survey results indicate significant differences in recovery time among vehicle types. During the morning period, heavy vehicles (HV) exhibit the longest recovery time, averaging 9 seconds, which increases to 9.5 seconds in the afternoon. This can be attributed to the physical characteristics of heavy vehicles, including larger dimensions, greater mass, and lower acceleration capabilities. These vehicles require more time to initiate movement from a stationary position, particularly when positioned at the front of a platoon. Additionally, heavy vehicles tend to create backward delay effects, as following vehicles must wait longer to begin moving.

Passenger cars (PC) record an average recovery time of 7.79 seconds in the morning and 9.27 seconds in the afternoon. Although passenger cars generally have better acceleration performance than heavy vehicles, the relatively high recovery times indicate the influence of traffic density and platoon length. Vehicles positioned in the middle or rear of a queue tend to experience delayed responses to the green signal due to limited maneuvering space and dependence on preceding vehicles. This finding suggests that traffic discharge at signalized intersections is not solely determined by vehicle acceleration capabilities but is also influenced by the relative position within the platoon.

The survey data further show that recovery times are generally shorter in the morning than in the afternoon. The average traffic volume during the morning period is 1,762 vehicles, increasing to 2,178 vehicles in the afternoon. This difference in volume is a key factor explaining the longer recovery times observed in the afternoon. The relationship between these findings and platoon theory is highly relevant. In addition to traffic volume, vehicle composition also plays a significant role.

In the afternoon, a higher proportion of heavy vehicles contributes to slower traffic discharge due to their limited acceleration and larger space requirements. Passenger cars positioned behind heavy vehicles experience additional delays, resulting in increased recovery times. Although motorcycles remain relatively faster, their flexibility is reduced under dense traffic conditions in the afternoon, as the available gaps between vehicles become more limited.

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Platoon theory states that vehicles within a group (platoon) influence each other in terms of speed and reaction time. Vehicles at the front of the platoon respond more quickly to the green signal, while those at the rear experience delays due to the sequential nature of movement. In this context, heavy vehicles positioned at the front can slow down the discharge of the entire platoon, whereas motorcycles located at the edges or between queues may accelerate the discharge process due to their ability to maneuver more freely and operate less constrained by platoon movement patterns.

➢ *Analysis of Vehicle Recovery Speed*

Vehicle speed after stopping at a signalized intersection (APILL) is an important indicator for evaluating the efficiency of traffic discharge. This speed reflects how quickly vehicles can return to normal movement once the signal turns green. The influencing factors are not limited to vehicle type, but also include traffic volume and the length of the platoon formed. The analysis of vehicle recovery speed is calculated using the Space Mean Speed (SMS) method. SMS represents the average speed based on the travel time of individual vehicles over the same road segment. In this study, the segment length used is 56 meters for all vehicle types.

Based on survey results and analysis, the average speeds of the three vehicle groups show significant differences between the morning and afternoon periods. One of the main influencing factors is the high traffic volume on the road segment, which affects the movement characteristics of all vehicle types.

During the morning period, the average speed of passenger cars (PC) is 35.89 km/h, decreasing to 29.86 km/h in the afternoon. Heavy vehicles (HV) have an average speed of 30.14 km/h in the morning, which decreases to 23.79 km/h in the afternoon. Meanwhile, motorcycles (MC) record the highest average speeds, reaching 42.61 km/h in the morning and decreasing to 37.74 km/h in the afternoon.

In general, a consistent pattern can be observed in accordance with the principles of SMS and platoon theory, where average speed decreases as traffic volume increases. However, a different trend is found for motorcycles during the morning period, where their average speed is not significantly affected by traffic volume. This occurs because the total traffic volume in the morning is relatively lower and dominated by motorcycles, allowing them to move more freely and achieve higher recovery speeds.

A comparison between vehicle types highlights distinct recovery characteristics. Motorcycles exhibit the highest speeds in both periods, reflecting their superior acceleration and maneuverability, allowing them to utilize gaps between vehicles. Passenger cars occupy an intermediate position, influenced by their position in the queue and surrounding traffic conditions. Heavy vehicles show the lowest speeds due to limited acceleration and larger space requirements. When the proportion of heavy vehicles increases in the afternoon, their obstructive effect on platoon movement becomes more pronounced.

Platoon position further amplifies these differences. Vehicles at the front of the platoon respond immediately to the green signal and have greater opportunities to reach higher speeds. In contrast, vehicles at the rear experience cumulative reaction delays. If a heavy vehicle occupies the leading position, it can significantly reduce the overall platoon speed. This phenomenon aligns with platoon theory, which states that vehicles within a group influence one another. The longer the platoon due to higher traffic volume, the greater the delay experienced by trailing vehicles, leading to a reduction in average discharge speed.

➢ *Analysis of the Relationship Between Traffic Volume and Vehicle Recovery Time*

The relationship between traffic volume and vehicle recovery time is a key indicator in evaluating the performance of signalized intersections (APILL). According to platoon theory, vehicles tend to move in groups, implying that the recovery process is not experienced individually but propagates throughout the entire platoon. Consequently, higher traffic volumes, which lead to longer platoons, are associated with greater delays in vehicle recovery.

Based on the analysis results, the relationship between traffic volume and recovery time for passenger cars exhibits a positive linear trend in both the morning and afternoon periods. During the morning period, a coefficient of 0.2858 indicates that each additional vehicle corresponds to an increase in recovery time of approximately 0.29 seconds, with a coefficient of determination (R^2) of 0.93, reflecting a strong correlation. In the afternoon period, the coefficient increases to 0.3219 with the same R^2 value of 0.93, indicating an even stronger relationship. These findings suggest that increased traffic volume, particularly during the afternoon peak, contributes to longer recovery times due to higher density and extended platoon lengths.

For heavy vehicles, a similar positive relationship is observed, where higher traffic volumes result in longer recovery times. In the morning period, the coefficient of 0.699 indicates that each additional heavy vehicle increases recovery time by approximately 0.70 seconds, with an R^2 value of 0.92, demonstrating a strong correlation. In the afternoon period, the coefficient decreases to 0.3575 while maintaining the same R^2 value of 0.92. This suggests that although traffic volume significantly influences recovery time, other factors such as the physical characteristics of heavy vehicles—including lower acceleration, larger dimensions, and greater space requirements—also play a crucial role in delaying traffic discharge.

In contrast, motorcycles exhibit a more variable relationship. During the morning period, the coefficient of 0.2116 with an R^2 value of 0.68 indicates a moderately strong correlation. This suggests that while traffic volume affects recovery time, other factors such as maneuverability, rider behavior, and the ability to utilize gaps between vehicles also contribute significantly.

To provide a comprehensive understanding, the relationship between total traffic volume and average recovery

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time was also analyzed. In the morning period, a coefficient of 0.1882 with an R^2 value of 0.77 indicates a positive linear relationship with a fairly strong correlation. In the afternoon period, the relationship becomes stronger, with a coefficient of 0.2619 and an R^2 value of 0.92. These results confirm that under higher traffic density conditions, traffic volume becomes the dominant factor influencing vehicle recovery time.

Overall, during the morning period, traffic flow is relatively smoother, characterized by the dominance of motorcycles and passenger cars, and a relatively low proportion of heavy vehicles. This condition results in shorter platoons and more efficient vehicle recovery. Conversely, during the afternoon period, traffic volume increases significantly, leading to longer platoons and slower recovery, particularly for vehicles positioned at the rear of the queue. Although the average recovery time by vehicle type remains relatively similar, higher traffic density results in greater delays.

In conclusion, there is a direct and positive relationship between traffic volume and vehicle recovery time. As traffic volume increases, the time required for vehicles to return to normal speed also increases. This parameter serves as an important indicator for assessing the efficiency of traffic discharge at signalized intersections, where faster recovery times reflect better overall intersection performance.

V. CONCLUSION

Based on the findings and discussions presented in this study, the following conclusions can be drawn:

- The performance analysis of the signalized intersection (APILL) using the PKJI 2023 method indicates that the intersection of Jl. Sudirman – Jl. Sam Ratulangi – Jl. Cik Ditiro – Jl. Haji Hayun operates under a high degree of saturation during peak hours. This condition is primarily influenced by differences in road classification, where Jl. Sudirman and Jl. Sam Ratulangi function as national roads, while Jl. Cik Ditiro and Jl. Haji Hayun are categorized as urban roads. According to PKJI 2023, a degree of saturation (Dj) approaching or exceeding 0.85 signifies the need for operational intervention. The results show that all approaches exceed this threshold, as reflected by considerable queue lengths and average delays, indicating suboptimal intersection performance.
- The analysis of the relationship between traffic volume and deceleration time across different vehicle types reveals that temporal variations exist between morning and afternoon periods. The average deceleration time is recorded at 9.02 seconds in the morning and 8.56 seconds in the afternoon. However, when considering vehicle composition, the morning period tends to exhibit relatively shorter deceleration times (8.76 seconds) due to the dominance of motorcycles, which allow greater maneuverability. In contrast, the afternoon period shows slightly higher values (8.79 seconds), influenced by increased traffic density and a higher proportion of heavy vehicles.
- The analysis of vehicle speed recovery time demonstrates variations among vehicle categories and time periods. Motorcycles require 5.86 seconds to recover speed in the morning, increasing to 7.57 seconds in the afternoon. Passenger cars exhibit recovery times of 7.79 seconds and 9.27 seconds for the morning and afternoon periods, respectively. Meanwhile, heavy vehicles require 9.00 seconds in the morning and 9.50 seconds in the afternoon. These findings indicate that both traffic conditions and vehicle characteristics significantly affect recovery performance.
- The relationship between traffic flow and vehicle speed recovery time shows a positive linear correlation for all vehicle types. Higher traffic volumes are associated with longer recovery times after stopping at the stop line. During the afternoon period, with a total traffic volume of 2,178 vehicles and a degree of saturation of 0.64, the regression analysis yields a coefficient of 0.2619 with an R^2 value of 0.92. This result confirms that traffic volume is a dominant factor influencing the average speed recovery time at the intersection.

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