



Quantifying Impact of Rainfall on Road Traffic: A Case Study of Highway 4024 in Phuket

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Abstract

Phuket frequently experiences road flooding due to heavy rainfall and inadequate drainage systems. Preceding studies show that urban rainfall and flooding can disrupt traffic flow. This study aims to quantify the impact of rainfall on the traffic performance of Highway 4024 in Vichit Subdistrict, Phuket, Thailand. This research evaluates how weather conditions influence traffic volume, average speed, and traffic operating conditions, as reflected by the level of service (LOS). Traffic data were manually collected at 15-minute intervals on 17th June 2025 for the rainy day and 24th June 2025 for the dry day. Data collection was carried out during the late afternoon hours. The Passenger Car Unit (PCU) was used to standardize mixed traffic flow, and LOS analysis was applied to evaluate road performance. The results revealed that the average traffic speed decreased from 15.39 km/h under dry conditions to 13.91 km/h under rainy conditions, representing a 9.64% decrease. The average traffic volume was slightly higher during the rainy survey, at 1,572.95 PCU/h compared with 1,356.65 PCU/h under dry conditions, although this difference should be interpreted with caution because the observation windows were not identical. LOS analysis indicated that all observed traffic states fell under LOS F in both weather conditions, showing that Highway 4024 was operating under highly congested conditions and traffic efficiency was further reduced during the rainy survey. These findings suggest that rainfall can impair urban traffic performance and should be considered in transport planning and traffic management for climate-sensitive urban areas.

Keywords: climate resilience, level of service, passenger car unit, traffic congestion, urban transportation

1. Introduction

Phuket contributes approximately 1% to Thailand's GDP. The province, located in the southern part of the country, frequently experiences rainfall which occasionally leads to road flooding. These events cause significant disruption to traffic flow. Phuket's transportation system faces three interconnected challenges: traffic congestion, rainfall and associated flooding, and emissions. The increase in the number of vehicles leads to severe congestion, particularly during rainfall or flooding events [1,2].

Several studies have linked urban rainfall and flooding to transportation disruption. Choo et al. [3] quantified how rainfall depth and water surface levels reduce vehicle speeds, leading to severe congestion. Similarly, He et al. [4] assessed rainfall and flood impacts on accessibility and economic productivity in Kinshasa, highlighting the vulnerability of urban transport systems to flood hazards. These findings justify the need for integrated studies

on urban roads in a monsoon area like Phuket to measure how vehicle movement changes under varying water surface conditions.

Measurement of vehicle movement requires proper comprehension of traffic characteristics. Traffic composition in Southeast Asian cities, including Phuket, is highly heterogeneous and dominated by motorcycles and small vehicles. This complexity necessitates the use of Passenger Car Equivalents (PCE) or Passenger Car Unit (PCU) to standardize traffic flow analysis. PCE values can vary with lane geometry [5] and may require consideration of delays at signalized intersections [6]. In Thailand, Satthamnuwong et al. [7] derived locally calibrated PCE values for four-lane highways, highlighting the importance of region-specific calibration in traffic flow analysis.

Accurate vehicle counting and classification are essential to determine real-world traffic flow. Pratama et al. [8] presented an automated image-processing approach for vehicle counting and classification that complements manual observation techniques in data-scarce regions. Such methodologies provide robust datasets for evaluating congestion levels and the influence of external factors such as rainfall and flooding.

There is limited research quantifying the impact of rainfall on traffic flow, and to the authors' knowledge, there is none for Phuket. A systematic vehicle-counting study under varying weather conditions (i.e., with and without rainfall or flood) is therefore necessary to assess how rainfall intensity and water accumulation affect traffic flow and provide empirical evidence for resilient transport infrastructure planning. Accordingly, this study aims to analyze vehicle flow on Highway 4024 in Phuket, focusing on the impact of rainfall on traffic movement.

2. Materials and methods

As shown in Figure 1, this study begins with the study design phase, involving the selection of Road 4024 and the classification of vehicles into three categories. It then proceeds to the data collection phase, where manual vehicle counts and field observations are conducted at 15-minute intervals under different weather conditions. Finally, the data collected are analyzed to assess traffic flow rate in terms of PCU and consequently assess congestion level using Level of Service (LOS).

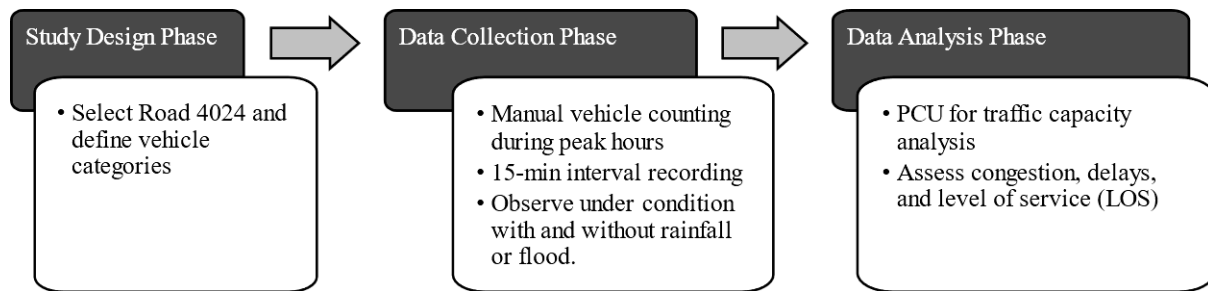


Figure 1 Methodology of the study

2.1 Study Design Phase

Major highways in Phuket such as Phuket Old Town, Highway 402, Highway 4021 and Highway 4024 were examined. However, this study focuses on Road 4024 in Phuket, a route frequently affected by rainfall and flooding, to analyze the relationship between vehicle flow and weather conditions, specifically dry and wet conditions.

2.2 Data Collection Phase

Vehicles were categorized into three groups: (1) motorcycles, bicycles, and tuk-tuks, (2) private cars and four-wheel vehicles, and (3) trucks and buses. Manual vehicle counts were conducted during peak hours at 15-minute intervals under different weather conditions. Table 1 presents the data collection sheet used for manual traffic counting at the actual survey site. The data collectors were expected to count the number of vehicles according to the predetermined categories and record the presence of rainfall or flood, if any. The vehicle count took place during rush hour in Phuket province, and a four-wheeler vehicle equipped with a GPS data recorder was driven along the observation route simultaneously to collect the speed profile. The GPS device recorded the latitude and longitude at one-second interval, from which vehicle speed was later calculated.

Table 1 Data collection sheet

Date:	Time:			
Road Number:	Bicycle, Motorcycle, Tuk Tuk	Four-Wheel Vehicle	Buses and Trucks	Weather conditions
Time (Every 15 minutes)				Rain No Rain Flood No Flood

**Figure 2** Recorded data of the survey route on Highway 4024.

The observation took place on a four-lane section of Road 4024 at coordinates 7°51'50.43"N 98°20'49.30"E, as shown in Figure 2. The GPS data recorder was driven along the surveyed route, beginning at 7°52'03.01"N 98°21'19.50"E and returning at 7°51'30.45"N 98°20'29.46"E, covering a total length of 1.9 kilometers.

2.3 Data Analysis Phase

2.3.1 Classification of PCU

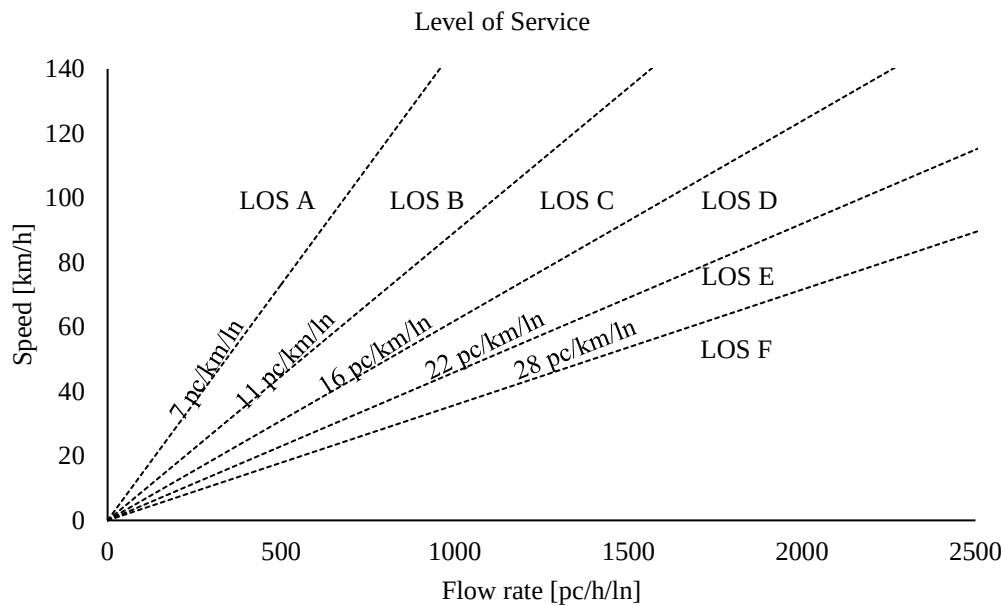
Based on Hsu et al. [5], the PCU can be calculated using a speed ratio method. However, to obtain measurement data for each vehicle type, equipment would need to be installed on individual vehicle types with the owner's permission. This research adopts the PCU classification for all vehicle types provided by the Thailand Department of Highway [9]. The detailed PCU values are presented in Table 2.

2.3.2 Level of Service (LOS)

Congestion can be measured using various parameters: speed, travel time, delay, LOS and congestion indices [10]. Each approach has different measurement methods. LOS can be estimated using the volume to capacity (V/C) ratio to show congestion levels. In this case, it does not account for interrupted flow conditions. According to Teodorovic and Janić [11], the LOS that considers interrupted flow, which is more common in Highway 4024, can be interpreted using Figure 3 plots of speed (km/h) and vehicle flow rate (vehicle per hour per lane, v/h/ln). The corresponding traffic flow characteristics can be interpreted using Table 3 based on the location of the data point in Figure 3.

Table 2 Passenger car units of all vehicle types

Vehicle Types	PCU Unit
Passenger car, less than 7 persons	1
Passenger car, more than 7 persons	1
Light Bus	1.5
Medium Bus	1.5
Heavy Bus	2.1
Light Truck (4 wheels)	1
Medium Truck (6 wheels)	2.1
Heavy Truck (10 wheels)	2.5
Full Trailer	2.5
Semi-Trailer	2.5
Motorcycles	0.333

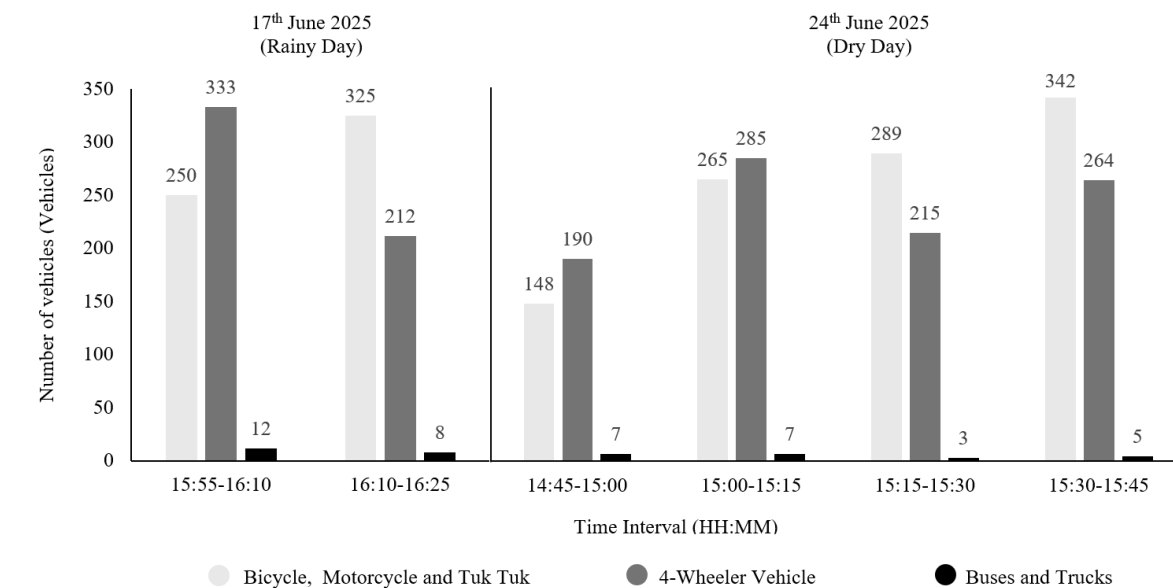
**Figure 3** Level of service for basic freeway segments**Table 3** The rating scale A-F for the level of service (LOS)

LOS	Traffic Flow Description
A	Vehicle moves freely with minimal interaction.
B	Traffic flow is stable with slight restrictions on maneuverability.
C	Traffic remains steady, though maneuverability becomes limited.
D	Traffic conditions are approaching to unstable flow.
E	Traffic flow unstable. Vehicles in the flow are narrowly spaced.
F	Traffic flow has broken down.

3. Results and discussion

This study examined the influence of rainfall on traffic performance along Highway 4024, located in Vichit Subdistrict, Mueang Phuket District, Phuket Province, Thailand. The road functions as a key corridor linking residential areas to the city's economic center. To evaluate the effects of weather conditions on mobility, traffic data were collected during afternoon hours (15:30–17:30) on two different days 17th June 2025 under light rain conditions and 24th June 2025 under non-rainy conditions [12,13], with the objective of quantifying changes in traffic volume, average speed, and traffic operating conditions, as reflected by the LOS.

The vehicle composition analysis showed that traffic on Highway 4024 was dominated by motorcycles and four-wheel vehicles under both rainy and dry conditions, while buses and trucks accounted for only a small proportion of the total traffic stream, as shown in Figure 4. This pattern suggests that the operating condition of the corridor was governed primarily by light vehicles and motorcycles rather than by heavy vehicles. The broadly similar composition observed in both survey conditions also indicates that the more meaningful weather-related difference in this study was not a major shift in vehicle mix, but a deterioration in traffic performance.



Source: Field survey conducted on Highway 4024, Vichit Subdistrict, Mueang Phuket District, Phuket Province, Thailand (2025)

Figure 4 Traffic Volume by Vehicle Type under Rainy and Dry Conditions on Highway 4024.

Building on the vehicle composition results, the comparison of equivalent traffic load and mean operating speed revealed a decline in traffic performance under rainfall. As presented in

Figure 5, the average traffic volume was 1,573 PCU/h under rainy conditions and 1,357 PCU/h under dry conditions, while the average speed decreased from 15.39 km/h to 13.91 km/h, representing a 9.64% reduction. In PCU terms, four-wheel vehicles contributed the largest share of the total traffic load in both conditions, indicating that private vehicles were the main contributors to corridor saturation. Although this pattern is consistent with reduced operating efficiency under rainfall, the lower speed cannot be attributed solely to rainfall. The higher equivalent traffic volume observed during the rainy survey period may be partly due to differences in the observation windows between survey days. This would also be expected to reduce speed under normal traffic-flow conditions. A future study with similar time windows could clarify the mechanism of speed reduction during rainfall.

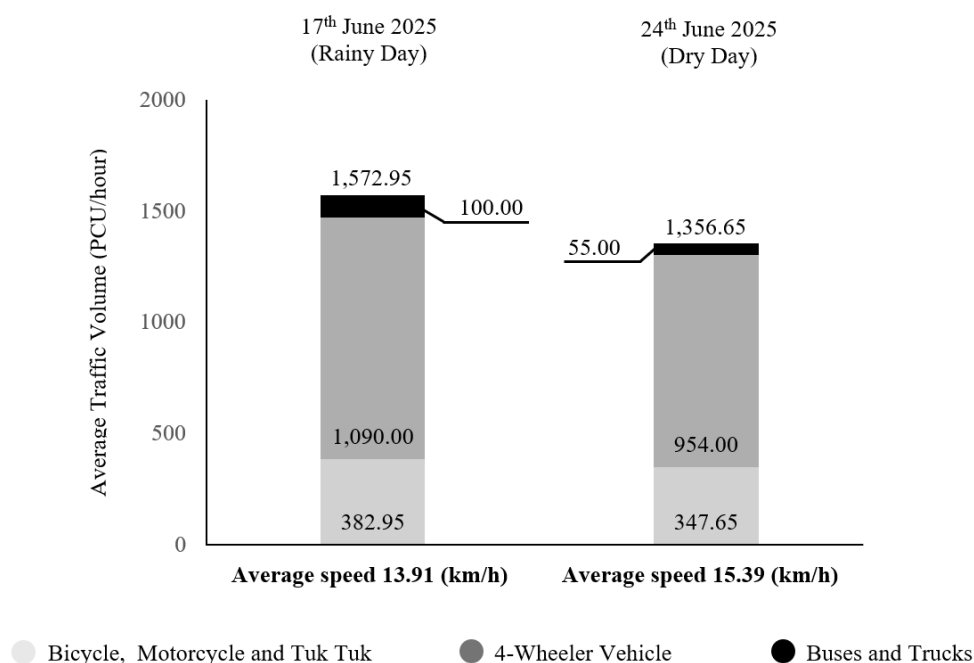


Figure 5 Comparison of Average Traffic Volume and Average Speed under Rainy and Dry Conditions on Highway 4024

This interpretation is consistent with previous research showing that rainfall generally degrades urban traffic performance, especially through reductions in speed and increases in travel time. In Greater London even light rain was associated with higher travel times and the magnitude of impact increased with rainfall intensity [14]. Similarly, rainfall in a city-scale study in China was found to increase congestion, with the effects becoming more pronounced during peak periods [15]. Previous empirical evidence also indicates that rainfall can reduce traffic performance through lower speeds and disrupted traffic operations [16]. Quantitatively, the speed reduction observed here is comparable in magnitude to that reported for other urban road networks. In Haizhu District, Guangzhou, China, rainfall reduced the network-wide average speed by approximately 5% over the full day and by about 11% during the evening peak, with comparable reductions in traffic flow [17]. The 9.64% speed reduction measured on Highway 4024 lies between these values and is close to the evening-peak figure.

The observed relationship between equivalent traffic volume and average speed suggests that rainfall was associated with a deterioration in traffic operating conditions on Highway 4024. While the traffic load remained substantial under both survey conditions, the lower average speed indicates reduced flow efficiency during the rainy period. This result suggests that even without flooding, rainfall can still impair corridor performance and should therefore be considered in the LOS-based assessment of traffic conditions. A reduction in operating speed need not be interpreted solely as a deterioration in performance. It may partly reflect more cautious driving behavior, whereas maintaining higher speeds on wet pavement would raise road-safety concerns. The effect of rainfall on this corridor can therefore be viewed as a trade-off between operational efficiency and road safety rather than just as a decline in performance.

The assessment confirmed that all observed traffic states on Highway 4024 fell within LOS F, as illustrated in Figure 6 and summarized in Table 4. This result indicates that traffic flow on the study corridor was highly congested and unstable during the observation period, with very low operating speeds. Notably, LOS F was observed under both rainy and dry conditions, suggesting that the corridor was already operating close to or beyond its effective capacity. Rainfall therefore did not appear to create congestion as a new condition but rather intensified the deterioration of traffic performance on an already saturated roadway.

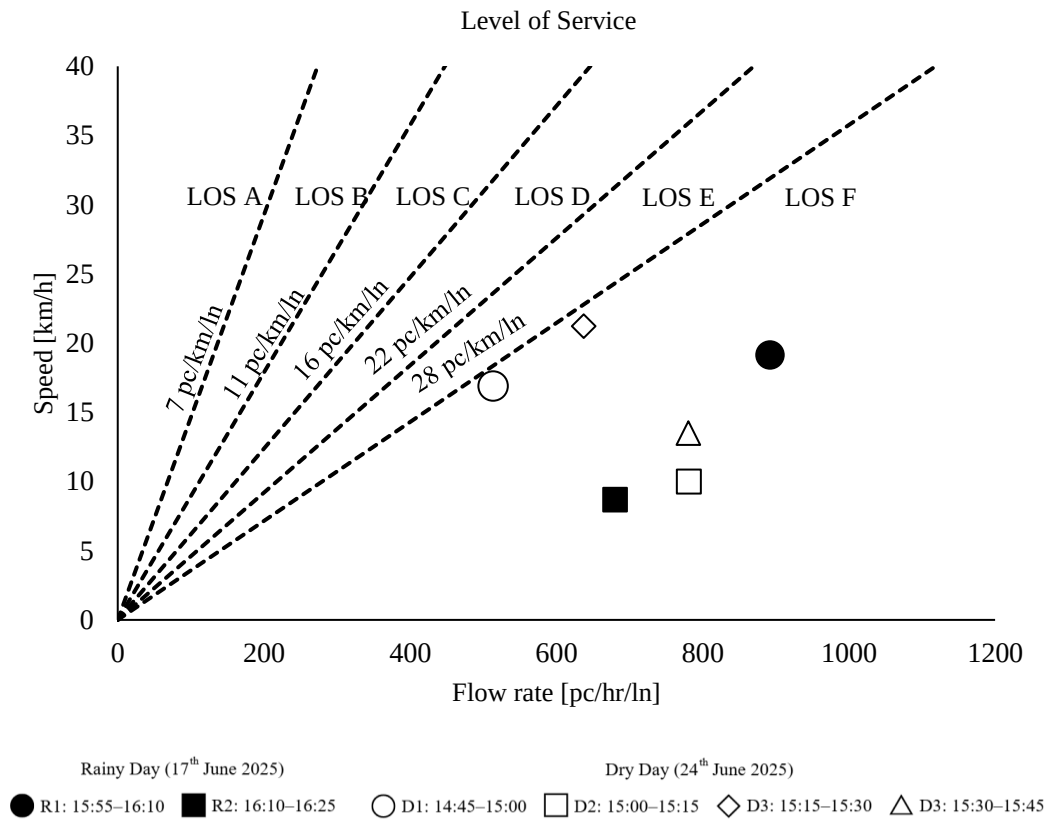


Figure 6 Level of Service Classification on Highway 4024 under Rainy and Dry Conditions (2-lane road). Each point represents a 15-minute interval; dashed lines indicate LOS A–F boundaries based on HCM (2016) [11].

Table 4 LOS classification of Highway 4024 based on flow rate and speed observations under different weather conditions.

Date & Weather Condition	Data Point	Time Interval (15 min)	Flow Rate (v/h/ln)	Average Speed (km/h)	LOS Class
17 th June 2025 Rainy	R1	15:55-16:10	892.50	19.13	F
	R2	16:10-16:25	680.45	8.68	F
	D1	14:45-15:00	513.57	16.89	F
24 th June 2025 Dry	D2	15:00-15:15	781.49	9.97	F
	D3	15:15-15:30	637.47	21.22	F
	D4	15:30-15:45	780.77	13.48	F

This study has several limitations that should be acknowledged. First, the comparability of the results may be affected by the fact that the observation windows were not fully identical between the rainy and dry days. Second, the number of observation intervals was relatively limited, particularly under the rainy condition, for which only two intervals were available. A larger number of observation periods or repeated surveys across multiple days would help improve the reliability and robustness of the findings. Therefore, the results should be interpreted as a preliminary empirical assessment of rainfall effects on traffic performance along Highway 4024 rather than as a comprehensive representation of all traffic responses under varying weather conditions.

Given that Highway 4024 operated under LOS F under both survey conditions, operational recommendations are proposed. Because Phuket is spatially constrained, geometric road expansion may not be a practical response. Instead, targeted demand management measures, such as truck-restricted periods and support for car sharing or carpooling, may be more feasible. This is consistent with Thai transport policy work in Bangkok, which identifies demand management measures as a means to reduce congestion and promote modal shift [18]. Recent review evidence indicates that congestion is not consistently reduced by road expansion alone, but demand-management measures have also shown effectiveness in some contexts when carefully designed and combined with supporting policies [19]. Beyond demand management, the finding that rainfall further degraded performance on an already saturated corridor points to a set of specific measures. First, because Highway 4024 frequently experiences road flooding and standing water during rainfall, improving roadway drainage and maintaining pavement conditions would limit the loss of usable capacity. Second, given the safety implications of variable speed on wet pavement, rain-responsive warning systems and speed limits recommended by the Federal Highway Administration for wet-weather operations, could help manage efficiency-safety trade offs [20]. Third, educational campaigns promoting safe driving behavior during rainfall would complement these engineering and control measures. A multi-criteria assessment of measures for managing road traffic under heavy rainfall similarly found that development of a safe driving culture and public training together with drainage systems that capture, store, and treat excess runoff were the most important and cost-effective options [21]. Prioritizing low-cost, high-impact measures of this kind would be particularly appropriate for spatially constrained conditions typical in Phuket.

4. Conclusion

This study investigated the impacts of rainfall on traffic performance of Highway 4024 in Vichit Subdistrict, Phuket, using traffic flow rate, average speed, and LOS as indicators. Lower traffic speeds and persistent congestion were observed during rainfall, even without flooding, although the speed reduction could not be attributed to rainfall alone because traffic volume also differed between the survey periods. Although traffic flow typically decreases during rain, a higher flow rate was observed due to differences in data collection periods. LOS results indicated unstable traffic conditions, with LOS F indicating that traffic demand already exceeds the capacity of the road. Rainfall further worsened performance by reducing visibility and increasing delays.

The study identifies integrated solutions for climate-resilient land transport planning and traffic management in Phuket where the rainfall can play a critical role in determining the traffic conditions. A follow-up study with repeated surveys across multiple days that include flooding conditions would improve the results and expand recommendations to enhance climate resilience of Phuket's land transport system.

5. Acknowledgement

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6. Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used ChatGPT (<https://chat.openai.com/>) to assist with grammar checking, wording adjustments, and sentence restructuring. After using this tool, the authors critically

reviewed and edited the content as needed and take full responsibility for the content of the publication. The intellectual content, analysis, and conclusions of this paper were developed by the author(s).

7. Author Contributions

Khemika Juajamsai: Data curation, Formal analysis, Methodology, Project administration, Software, Visualization, Writing – original draft; Khemrath Vithean: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing; Tawan Champeecharoensuk: Data curation, Investigation; Poonnapat Tanapatpisan: Data curation, Formal analysis, Software; Nuwong Chollacoop: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing; Wijitbusaba Marome: Conceptualization, Funding acquisition, Resources, Supervision, Validation; Kampanart Silva: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

8. Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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