Investigating the Effects of Weather on Traffic Volume and Speed at the Intra-Urban Expressways

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Abstract

This study analyzes the relationship between vehicle speed and traffic volume on Malaysia's urban expressways under varying weather conditions, particularly focusing on the effects of adverse weather on driving behavior and traffic dynamics. Using advanced radar technology, specifically the SpeedLane™ Pro Counter Classifier, traffic data was collected on the Intra-Urban Expressway in Klang Valley. The data, which includes real-time and historical information on speed, volume, and weather conditions, was compared between dry and rainy days. The analysis revealed that during morning peak hours (7:00-9:00 AM), traffic volumes remain high despite rainfall, particularly in southbound lanes, where speeds exceeded 70 km/h. However, as rainfall intensifies, particularly in the afternoon and evening, traffic speeds in both southbound and northbound lanes decrease significantly, with the most severe reductions observed in southbound lanes during heavy evening rain (20 mm), where speeds dropped to as low as 17.1 km/h. It recommends further research to assess the broader impact of adverse weather on road safety. Further research is recommended to explore broader road safety implications, supported by advanced traffic monitoring technologies for improved traffic management under varying weather conditions.

1. Introduction

Malaysia's rapid growth over the past two decades has significantly impacted road transportation, with road networks becoming the primary mode of transport. Due to the high rate of private vehicle ownership, the use of public transportation in Malaysia has been limited, leading to traffic congestion, accidents, a lack of parking spaces, and increased air pollution. Malaysians prefer their own vehicles over public transportation because of the perceived advantages in speed and mobility. In recent years, Malaysia's transportation landscape has seen significant changes. By 2023, the number of registered vehicles exceeded the country's population, with over 36.3 million vehicles for a population of 32.4 million. Private vehicles, particularly cars and motorcycles, dominate the road, while public transport usage remains a key focus for future development. The government has introduced initiatives to encourage public transport use and shift towards sustainable transportation,

including investments in electric vehicles (EVs) and the expansion of rail networks in urban areas like the Klang Valley (Malaysian Green Technology and Climate Change Corporation, 2024).

Adverse weather conditions, such as rain, storms, high winds, severe heat, and fog, pose safety risks to drivers by reducing road friction, limiting visibility, and negatively affecting driving abilities (Romanowska & Budzyński, 2022). These conditions also significantly impact traffic flow characteristics, with varying degrees of speed reduction. Inclement weather can cause drivers to become stranded, slow down traffic, and impair visibility, making accurate assessments of road capacity and speed limitations essential for effective highway management (Smith, 2015).

Urban expressways in Malaysia are vital for delivering goods and services and ensuring people's mobility. The Klang Valley Expressway, one of the country's busiest routes, faces increasing traffic congestion issues due to urbanization and economic activity. Malaysians drive frequently, and adverse weather conditions can significantly affect driving behaviour, travel demand, and traffic flow characteristics (Chen et al., 2019). While research on the effects of severe weather on Malaysian urban expressways is limited, studies from other countries such as China (Qiu & Nixon, 2008) have shown that bad weather impacts traffic flow parameters and poses a safety threat. The studies highlight that bad weather reduces vehicle speeds, increases travel time, and elevates accident risks, underscoring the importance of traffic management during adverse conditions.

This paper analyses the relationship between vehicle speed and traffic volume on Malaysia's urban expressways under various weather conditions. Further research is needed to evaluate the impact of weather conditions on road users' safety and vehicle speed during adverse weather.

2. Literature Review

2.1 Traffic Volume Characteristics

Several studies have focused on quantifying the impact of rainfall on traffic volume. One notable observation is that heavy rainfall tends to reduce traffic volumes, particularly during peak hours (Suwanno et al., 2021). The reduction in traffic volume can be attributed to a combination of factors, including drivers' reluctance to travel in adverse weather, increased travel times, and potential road closures or restrictions due to flooding or poor visibility.

Traffic volume in Malaysia is not uniformly affected by rainfall; instead, it varies based on the intensity and duration of the rain. Light rain may have a negligible effect on traffic volumes, as drivers are generally accustomed to frequent rain showers and may not alter their travel behavior significantly. However, during heavy rainfall, traffic volume tends to decrease more noticeably, as drivers become more cautious and reduce their travel speed, leading to longer travel times and potentially fewer vehicles on the road at any given time (The Star, 2024).

The 7th Edition US Highway Capacity Manual (US HCM) (Transportation Research Board, 2022) provides methodologies to analyze the impact of weather conditions on traffic volume and flow. While the US HCM doesn't directly quantify the relationship between specific weather conditions and traffic volume, it outlines factors such as reduced visibility, slippery roads, and reduced driver comfort that can influence traffic flow. The US HCM also provides capacity adjustment factors (CAFs) and speed adjustment factors (SAFs) to account for the impact of weather on roadway capacity and speeds. To accurately assess the impact of weather on traffic volume in a specific location, it's recommended to use the US HCM's methodologies in conjunction with local data and expert judgment.

2.2 Speed

Speed can be defined as the rate at which distance is covered per unit of time. It's a fundamental concept in transportation engineering, influencing road design, traffic flow, and safety regulations. According to the National Cooperative Highway Research Program (NCHRP), speed typically refers to the average speed of a group of vehicles on a specific road section. Speed is a crucial parameter in transportation engineering in various calculations and analyses (Fitzpatrick et al., 2003). It is measured in distance units per time, such as meters per second (m/s) or kilometers per hour (km/h). The formula for calculating speed is:

$$\text{Speed (s-unit km/h)} = \text{Distance (d-unit km)} / \text{Time (t-unit hour)} \qquad (1)$$

Vehicles move at varying speeds depending on road conditions, driver behaviour, and vehicle characteristics. Yang (2007) noted that the term "speed" can be used in different contexts, such as design requirements, level of service measurements, or effective control components. The TRB in the US HCM 7th Edition highlights the wide range of speeds observed in traffic streams. Therefore, using a representative value when analyzing traffic flow is essential.

2.3 Weather Conditions in Malaysia

Malaysia is located in an equatorial region, characterized by a tropical climate with consistently high temperatures, elevated humidity levels, and frequent rainfall. The climate in Malaysia can be generally divided into two monsoon seasons: the northeast monsoon, which occurs from December to March, and the southwest monsoon, lasting from June to September. Two inter-monsoonal transitional periods exist in April and October. The northeast monsoon season typically brings the heaviest rainstorms to the east coast of Peninsular Malaysia, while the southwest monsoon in June and July is associated with the driest weather (Lim & Abu Samah, 2004). The country's average annual temperature remains fairly constant at around 27°C, with yearly variations of less than 2°C. Malaysia's average monthly relative humidity ranges from 10% to 90%. As in the case of temperature, the daily relative humidity changes are greater than the annual changes. The average daily minimum can be as low as 42% during the dry months and as high as 70% during the wet months. The country's average annual rainfall is notably high, averaging around 2650 mm, with regional variations ranging from 1800 mm to over 3500 mm each year. This rainfall pattern is affected by both the Southwest and Northeast monsoons, with the Northeast monsoon typically bringing more precipitation (Malaysian Meteorological Department, 2024). Despite the substantial rainfall on Malaysian roads, research on its impact on traffic flow has been quite limited.

2.4 Impact of Weather on Traffic Volume and Speed

The impact of rainfall on traffic volume and speed has been a subject of significant interest in transportation research. Understanding how adverse weather conditions, particularly rainfall, affect road performance is crucial for developing effective traffic management strategies, improving road safety, and enhancing overall transportation efficiency. This review explores the findings of various studies investigating the relationship between rainfall, traffic volume, and speed.

Weather is generally considered an external factor that can influence traffic flow. Numerous studies have specifically examined the impact of rainfall on traffic speed and flow. For instance, Tanner (1952) found that traffic flow decreases with increased precipitation intensity. Regarding speed, Lamm et al. (1990) reported that wet pavement negatively affects speed, particularly when visibility is compromised. As a result, mild precipitation has little impact on traffic flow compared to severe precipitation, which can reduce road capacity by approximately 10% to 15%.

Similarly, Zhang et al. (2019) indicated that severe rainfall reduces visibility and surface friction, thereby affecting traffic speed and road capacity. Other studies have also found that precipitation can reduce traffic speed and capacity regardless of intensity. The impact of weather conditions on traffic flow correlations and characteristics in expressway areas can vary depending on the nature of the roadway, as found by Rakha et al. (2007).

The widely used speed-flow-density correlations do not explicitly account for the impact of weather. Ibrahim and Hall (1994) tested the significance of variations in traffic operating conditions under different weather scenarios using a dummy variable multiple regression analysis approach. Their study found that light rain can cause speed reductions of around 3% to 5%, while heavy rain results in speed decreases of 14% to 15%.

Chung et al. (2006) found that in Tokyo, Japan, free flow speed declined by 4.5% during light rain and by 8.2% during heavy rain. Xiong et al. (2022) analyzed the effects of rainfall on traffic congestion in three Chinese cities: Beijing, Tianjin, and Shijiazhuang. Their findings showed that the average Traffic Time Index (TTI) increased with varying rainfall intensities by 3.3%, 6.6%, and 10.8% in these cities, respectively. The study highlighted that rainfall had the greatest impact during peak hours, with traffic congestion rising as rainfall intensity increased. Akin et al. (2011) reported that rain reduced average vehicular speeds by 8% to 12% and capacity by 7% to 8%. Additionally, wet surface conditions reduced average speeds by 6% to 7%, while light snow significantly decreased traffic volume due to reduced demand.

Hassan et al. (2014) provided empirical evidence showing decreased speed and increased headways under rainy conditions. Their results indicated a 4.2% speed drop from dry to wet weather, with headways of up to 0.5 seconds decreasing by 5%, while headways increased for longer durations. The effect of rainfall on speed and headways is challenging to observe under free-flow conditions due to minimal vehicle-to-vehicle interactions. Unless an incident occurs during rainfall, it is unlikely to cause bottlenecks in traffic flow.

The study found by Mashros et al. (2014) that the rainfall, regardless of its intensity, significantly affects traffic flow and speed on highways, with observed reductions in capacity ranging from 2% to 32% and decreases in mean speed, free-flow speed, and speed at capacity ranging from 1% to 17%. However, the average traffic volume remained unaffected by rainfall conditions. This highlights the critical impact of weather on road performance, emphasizing the need for effective traffic management strategies during adverse weather conditions.

Based on the research by Mukhlas et al. (2016), the analysis indicates that mean speed, flow, and density decrease under various rainfall conditions. Generally, the impact of good weather and different rainfall

conditions on Greenshield's fundamental traffic flow relationships shows weak correlations, except for the relationship between flow and density. The key points in the fundamental diagram derived from the flow-density relationships suggest that critical density, maximum flow, critical speed, jam density, and free-flow speed all decrease as rainfall intensity increases. It can be concluded that the traffic flow characteristics of the two-lane rural highway in Terengganu are significantly affected by rainfall conditions. Hassan et al. (2017) found that the headway pattern during nighttime adhered to the gamma distribution model. Their analysis revealed that the mean vehicle headway increases with rainfall intensity.

Yao et al. (2020) reported that their results identify three peak travel periods: 8:00–10:00, 14:00–16:00, and 18:00–20:00. They observed a reduction in road speeds following rainfall, with a decrease of 6.20% on weekdays and 2.37% on weekends. Additionally, traffic congestion areas expanded by 23.53% on weekdays and 20.65% on weekends. The study also found that rainfall has a more pronounced impact on traffic conditions during weekdays compared to weekends in Shenzhen.

Vidas et al. (2022) found that varying rainfall intensities influence functional relationships and differences in capacity and speed across traffic lanes. Depending on the rain category and specific traffic lanes, reductions in free-flow speed ranged from 4.5% to 11.58%, while lane capacity reductions varied between 2.46% and 12.97%. This study underscores the importance of considering the impact of rainfall at the traffic lane level, which can serve as valuable input data for developing effective traffic management measures to mitigate negative effects.

Although many researchers have observed traffic flow and speed reductions during rainfall, the estimated speed reductions show significant variation. This discrepancy may be due to differences in the rainfall categories used, reliance on inaccurate speed-flow relationships, questionable quantitative estimation methods, or the use of static passenger car equivalent values.

3. Methodology

This paper proposes the use of advanced radar technology to acquire traffic data. Previous research has shown that most traffic data collection techniques have relied on video capture methods and computer software for data extraction. However, radar technology has significantly increased usage over the past 15 years. Radar is a detection method that uses electromagnetic frequencies to estimate an object's radial velocity, direction or angle, and distance from a specific location. As radar technology has evolved, it has proven to be a reliable and precise tool for traffic analysis. Syed Abbas et al. (2022) and Rahman et al. (2024) conducted research utilizing advanced radar technology on Malaysian urban expressways. The findings from this research significantly contribute to the advancement of traffic data collection and analysis methodologies, particularly for intra-urban expressways. By evaluating the correlation between vehicle speed, traffic volume, and traffic density, the study identifies areas prone to congestion and highlights where speed management measures may be necessary.

Tables The data for this study was collected from one of the multi-lane intra-urban expressway in Klang Valley. This location was chosen due to its high traffic density and exposure to varying weather conditions, making it an ideal site for analyzing the impact of adverse weather on traffic flow. The traffic data was gathered between November 7, 2022, Monday and 11th of November 2022, Friday, covering weekdays to account for different traffic patterns. The collection occurred over 24 hours daily, with a total of 12 hours of observation spread across peak and non-peak periods, ensuring a comprehensive assessment of traffic behaviors.

The data collected includes traffic volume (vehicles/hour) and average speed (km/hour) using advanced radar technology. Weather data, including temperature (°C) and precipitation (mm), was sourced from the Malaysian Meteorological Department (MET) database for the nearest meteorological station. This station was located within 10 km from the traffic observation points, ensuring weather data's relevance to the traffic sites. This proximity allows for a reliable correlation between traffic flow and real-time weather conditions.

The use of MET data ensured that weather variables were recorded under the same conditions as the traffic data, thus providing a consistent and accurate comparison between weather impacts and traffic flow characteristics.

The SpeedLane™ Pro radar device is designed to accurately identify each vehicle's lane, speed, and class. It can also calculate lane volume, occupancy, distance or space, average speed (Time Mean Speed-TMS), 85th percentile speed, and headway parameters. Additionally, the SpeedLane™ Pro is used for monitoring multi-lane traffic flow. It is a real dual-beam, high-definition, non-intrusive traffic sensor or collector. This advanced dual frequency modulated continuous wave (FMCW) radar-based device is specifically designed to measure and collect both temporary and permanent traffic data, without requiring a license. The radar provides mechanisms for retrieving both real-time and historical data. Furthermore, the SpeedLane™ Pro is considered a side-firing data solution, with its radar beam covering one or more lanes of traffic at a 90° angle to the urban expressway (2024).

Weather forecasting is a critical method for collecting data on temperature and precipitation across various locations. The Malaysian Meteorological Department (METMalaysia) utilizes the Automated Weather System (AWS) to measure weather conditions in Malaysia. The primary AWS system covers 43 stations, while the auxiliary system includes 221 stations. Differences between these systems involve sensors, observation areas,

methods, and sensor layouts. Weather forecasting plays a vital role in protecting lives and property from natural disasters. Secondary weather data will be obtained from forecast websites such as METMalaysia.

METMalaysia has categorised the rainfall intensity in unit of mm/day as: i) slight rain when the intensity is below 10 mm/day; ii) moderate rain when the intensity is between 10 mm/day and 60 mm/day; iii) heavy rain when the intensity is between 60 mm/day and 150 mm/day; and iv) extreme when the intensity is more than 150 mm/day (METMalaysia, 2024) In conjunction with the rainfall intensity category in a unit of mm/day, MET Malaysia also defines it in unit of mm/hour: i) slight rain as intensity below 2 mm/hr; ii) moderate rain as the intensity between 2 mm/hr and 10 mm/hr; iii) heavy rain as the intensity between 10 mm/hr and 50 mm/hr; and iv) violent as intensity more than 50 mm/hr (2007).

Fig. 1 shows the methodology flowchart for this research. The research process involves identifying relevant parameters, collecting both primary and secondary data, and monitoring data in real-time. The collected data is then analyzed using Microsoft Excel to evaluate the average speed of vehicles on the intra-urban expressway and to identify relationships between speed, volume, and temperature. Visualizing and interpreting the data can gain valuable insights into traffic patterns and vehicle speed factors. Fig. 2 depicts the device and provides an example of its installation at a specific location on the intra-urban expressway.
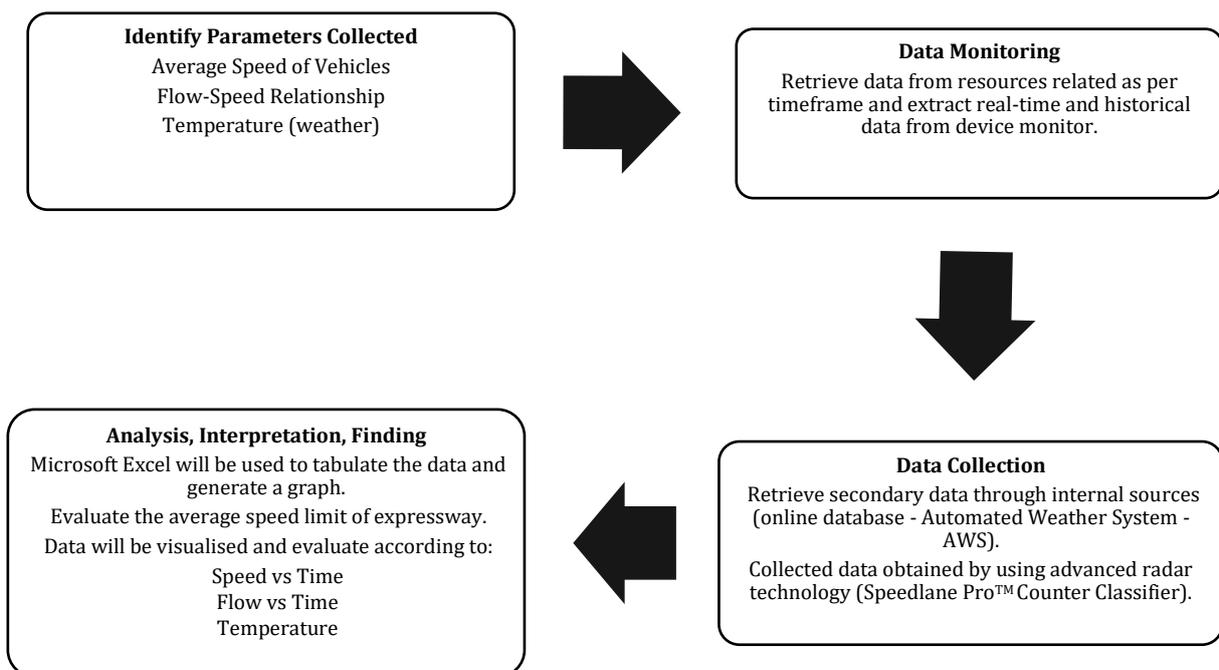
Identify Parameters Collected
Average Speed of Vehicles
Flow-Speed Relationship
Temperature (weather)

Data Monitoring
Retrieve data from resources related as per timeframe and extract real-time and historical data from device monitor.

Data Collection
Retrieve secondary data through internal sources (online database - Automated Weather System - AWS).
Collected data obtained by using advanced radar technology (Speedlane Pro™ Counter Classifier).

Analysis, Interpretation, Finding
Microsoft Excel will be used to tabulate the data and generate a graph.
Evaluate the average speed limit of expressway.
Data will be visualised and evaluate according to:
Speed vs Time
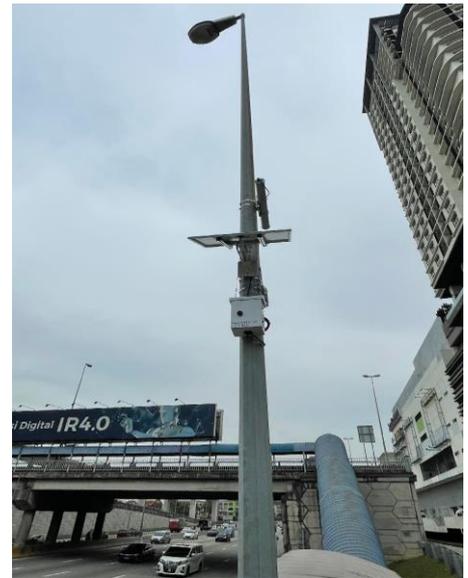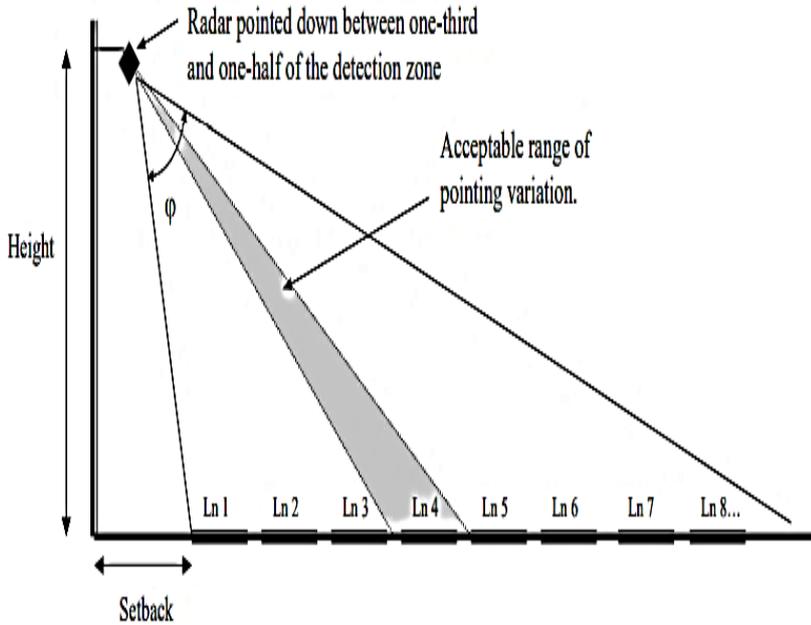Flow vs Time
Temperature

Fig. 1 Methodology Flow Chart

Fig. 2 Setup the Height and Setback Installation of the Speedlane ProTM Counter Classifier device & the device located near the intra-urban expressway (Houston Radar, 2024)

4. Results and Discussion

4.1 Traffic Volume, Speed and Weather Conditions

Table 1 below shows the volume in veh/hr unit values for each lane heading towards the South Bound (SB) and North Bound (NB) directions.

Table 1 Traffic Volume Data for 60 minutes Interval South Bound and North Bound Directions

Time (Hour)	L1 SB Volume (veh/hr)	L2 SB Volume (veh/hr)	L3 SB Volume (veh/hr)	L4 NB Volume (veh/hr)	L5 NB Volume (veh/hr)	L6 NB Volume (veh/hr)
7:00 - 8:00	1064	1369	1832	1641	1632	2414
8:00 - 9:00	1056	1369	1636	2065	1896	2977
9:00 - 10:00	967	1216	1407	1970	1761	2714
10:00 - 11:00	966	1219	1276	1814	1517	2571
11:00 - 12:00	901	1254	1392	1964	1695	2550
12:00 - 13:00	911	1281	1474	1862	1608	2984
13:00 - 14:00	952	1294	1587	1651	1495	2502
14:00 - 15:00	877	1270	1463	1689	1415	2606
15:00 - 16:00	930	1249	1367	1682	1372	2476
16:00 - 17:00	973	1307	1543	1913	1582	2081
17:00 - 18:00	1050	1127	1256	1569	1435	2101
18:00 - 19:00	949	884	1105	1368	1279	2167
19:00 - 20:00	1055	959	976	1649	1341	2496

Table 1 summarize the southbound (SB) lanes L1, L2, and L3 experience varying traffic volumes throughout the day, with peak hours in the morning and dips in the evening. L3 consistently handles the highest volume, followed by L2. Northbound (NB) lanes L4, L5, and L6 also have peak traffic in the morning, with L6 consistently handling the highest volumes.

Table 2 below shows the speed in km/hr unit values for each lane heading towards both the South Bound (SB) and North Bound (NB) directions.

Table 2 Speed Data for 60 minutes Interval South Bound and North Bound Directions

Time (Hour)	L1 SB Speed (km/h)	L2 SB Speed (km/h)	L3 SB Speed (km/h)	L4 NB Speed (km/h)	L5 NB Speed (km/h)	L6 NB Speed (km/h)
7:00 - 8:00	73.1	73.6	88.1	36.5	35.3	38.2
8:00 - 9:00	73.7	73.2	87.8	57.5	49.2	37.0
9:00 - 10:00	71.1	72.3	88.8	56.5	47.8	36.8
10:00 - 11:00	70.3	70.4	86.9	45.0	41.6	38.2
11:00 - 12:00	68.9	69.6	84.3	59.7	48.8	38.7
12:00 - 13:00	65.8	65.8	77.1	51.8	44.5	36.7
13:00 - 14:00	64.9	64.8	75.6	46.1	41.6	37.8
14:00 - 15:00	60.7	60.4	69.9	40.6	37.1	36.1
15:00 - 16:00	58.4	58.8	69.2	44.1	40.3	39.3
16:00 - 17:00	63.9	64.0	73.7	53.5	45.2	38.8
17:00 - 18:00	46.4	36.9	35.3	36.3	34.6	36.1
18:00 - 19:00	20.3	17.1	22.1	32.6	32.7	36.8
19:00 - 20:00	39.9	30.3	30.9	43.7	39.5	37.7

Table 2 summarize the southbound (SB) lanes L1, L2, and L3 experience varying speeds throughout the day, with peak speeds in the morning and significant drops in the evening. L3 consistently maintains higher speeds than L1 and L2. Northbound (NB) lanes L4, L5, and L6 also have peak speeds in the morning, with L4 and L5 experiencing significant drops in the afternoon due to rain. L6 maintains relatively stable speeds throughout the day.

The weather data or the rainfall intensity can be obtained from any weather forecast site or through an application that provides information from meteorological experts (METMalaysia, 2024). Since this study focuses on the relationship between volume-speed and weather conditions, as well as the impact of weather on vehicle speed and traffic volume, the weather data presented in Table 3 will be evaluated.

Table 3 Weather Data for 60 Minutes Interval METMalaysia's Automated Weather System (AWS) Station Near (approximately 10km) to Urban Expressway

Time (Hour)	Temperature (0C)	Intensity (mm/hr)	Rainfall Category
7:00 - 8:00	25.9	17.3	Heavy Rain
8:00 - 9:00	29.9	10.0	Moderate Rain
9:00 - 10:00	32.1	0.1	Cloudy
10:00 - 11:00	34.1	0.1	Cloudy
11:00 - 12:00	33.8	0.1	Cloudy
12:00 - 13:00	29.4	6.4	Moderate Rain
13:00 - 14:00	31.0	5.0	Moderate Rain
14:00 - 15:00	26.6	17.6	Heavy Rain
15:00 - 16:00	26.4	15.5	Heavy Rain
16:00 - 17:00	27.4	10.0	Moderate Rain
17:00 - 18:00	26.4	14.2	Heavy Rain
18:00 - 19:00	26.1	13.3	Heavy Rain
19:00 - 20:00	25.9	20.0	Heavy Rain

The temperature begins at 25.9°C in the early morning, reaching a peak of 34.1°C from 10:00 AM-11:00 AM. The temperature gradually decreases throughout the day, falling to 25.9°C by 7:00 PM-8:00 PM. The day starts with significant rainfall (17.3 mm/hr) from 7:00 AM-8:00 AM, which continues with varying intensity throughout the day. Cloudy conditions are observed mid-morning, but rain resumes in the afternoon and persists into the evening, with the heaviest rainfall (20 mm/hr) occurring from 7:00 PM-8:00 PM.

4.2 Relationship Between Traffic Flow and Speed Due to Weather Conditions

This study examines the relationship between traffic flow and speed with weather conditions, particularly focusing on how adverse weather, such as rain, impacts vehicle speed and traffic flow. To accurately assess traffic flow under various weather conditions, especially during adverse weather, it is insufficient to rely on traffic speed alone; traffic volume data is also essential. It is generally assumed that as traffic volume increases, vehicle speed decreases, leading to a reduction in traffic flow and potentially resulting in congestion. However, even if traffic volume decreases in adverse weather, vehicle speed may still decrease due to reduced visibility and skid resistance. Fig. 3 illustrates the relationship between traffic flow and speed for the southbound and northbound directions of the urban expressway.
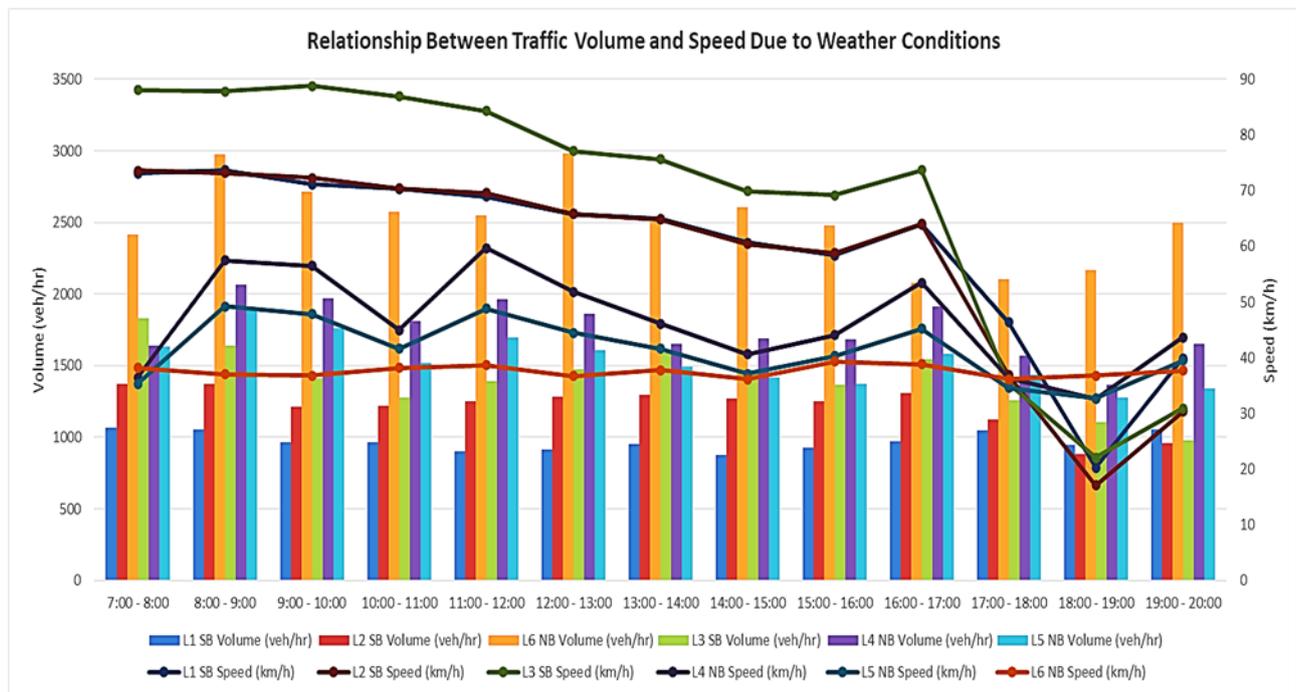

Fig. 3 Relationship Between Traffic Volume And Speed For The Southbound And Northbound Directions of The Urban Expressway

The graph illustrates the relationship between traffic volume and speed for southbound and northbound directions on an urban expressway. Traffic volumes are high in both SB and NB lanes during the morning rush hour (7:00-9:00 AM). Despite the heavy rain, traffic speeds remain relatively high, particularly in the SB lanes, which exceed 70 km/h. Rain is a significant factor in reducing traffic speeds, particularly in the afternoon and evening. As rainfall increases, speeds in both SB and NB lanes drop dramatically, with the most significant decreases observed in the SB lanes. The heavy rain in the evening (20 mm) correlates with the lowest speeds of the day, particularly in the SB lanes, where speeds fall to as low as 17.1 km/h. Traffic volumes decrease slightly in the afternoon but remain relatively high in the NB lanes, especially in L6 NB, where volumes peak at 2984 vehicles per hour from 12:00-1:00 PM. Despite this, speeds drop significantly as rain persists, indicating increased congestion. The evening rush hour sees further reductions in speed, likely due to the combination of continued rainfall and high traffic volumes.

In general, there is an inverse relationship between traffic volume and speed. As traffic volume increases, speed tends to decrease. This is particularly evident during peak hours. Each lane exhibits unique patterns of traffic volume and speed. For example, L6 NB consistently has higher volumes and lower speeds compared to other lanes. The morning rush hour (7:00-9:00 AM) and evening peak (5:00-7:00 PM) are clearly visible in the traffic volume data. The graph shows a potential impact of weather conditions on traffic speed. There appears to be a noticeable decrease in speed during certain time intervals, possibly due to rain or other adverse weather. There are differences in traffic patterns between southbound and northbound directions. For instance, southbound lanes generally have higher traffic volumes during the morning peak, while northbound lanes may have higher volumes during the evening peak. This figure also effectively demonstrates how traffic volume and speed vary throughout the day under different weather conditions, highlighting the relationship between increased traffic volume and reduced speed, particularly during peak hours.

5. Conclusions

This study successfully achieved its objectives, which were (i) to analyze the relationship between traffic volume and vehicle speed during dry and rainy weather conditions and (ii) to evaluate the impact of weather on vehicle speed and traffic volume on expressways.

This paper utilized advanced radar technology, specifically the SpeedLane™ Pro Counter Classifier, which efficiently provided data and quickly monitored all traffic flow characteristics without requiring manual calculations. This technology reduces the safety risks associated with on-site data collection and allows for remote data access through apps or the radar's website. Additionally, weather condition data from METMalaysia's Automated Weather System (AWS) stations demonstrated the ease and effectiveness of modern technology.

The study was conducted in both southbound and northbound directions of the intra-urban expressway in Klang Valley. The main objectives were achieved, confirming the correlation between traffic flow and vehicle speed under different weather conditions. The results also identified the impact of weather on traffic flow and vehicle speed, which were analyzed in detail in previous sections. These findings could assist relevant authorities in developing appropriate mitigation strategies for managing traffic congestion, particularly during the rainy season, which poses increased risks to road users.

The parameters used in this study included traffic volume (vehicles/hour), average speed (km/hour), temperature (°C), and precipitation (mm). The analysis indicated a trend of decreasing vehicle speeds during rainy periods; however, traffic volume showed minimal variation, particularly during evening peak hours when commuters are returning home. Additionally, the findings suggested that the southbound direction generally experienced higher speed values than the northbound direction, which appeared more susceptible to congestion. Understanding these traffic flow dynamics, particularly under adverse weather conditions, can aid road and traffic experts in developing more effective mitigation strategies.

6. Recommendation

Based on the findings of this study, several recommendations can be made to enhance traffic management and safety on urban expressways, particularly during adverse weather conditions:

1. It is recommended that authorities expand the use of advanced radar technologies, such as the SpeedLane™ Pro Counter Classifier, across other major expressways. These systems provide real-time data on traffic flow and vehicle speed, which can be used to monitor and manage traffic more effectively, especially during peak hours and adverse weather conditions.
2. Authorities should consider implementing weather-responsive traffic management strategies. This could include variable speed limits that automatically adjust during adverse weather conditions, such as rain, to ensure safer driving speeds. Additionally, real-time weather updates could be integrated into traffic management systems to provide timely alerts and recommendations to drivers.
3. Increasing public awareness about the impact of weather on driving conditions is crucial. Educational campaigns should be conducted to inform drivers about the importance of reducing speed during rainy conditions and other adverse weather. These campaigns could be disseminated through various channels, including social media, radio, and highway message boards.
4. Although the findings indicate that traffic volume does not experience a notable reduction during rainy periods, it is crucial to ensure that expressway infrastructure, such as drainage systems, can efficiently manage heavy rainfall. Regular maintenance and system upgrades are recommended to mitigate potential hazards like water accumulation on roads, which can lead to dangerous driving conditions and increase the likelihood of accidents.
5. Considering the study's findings that traffic congestion is more prevalent in the northbound direction during peak hours, it is recommended that traffic flow management strategies be tailored specifically for these periods. This could include optimizing traffic light timings, implementing reversible lanes, or providing real-time traffic updates to drivers to help them choose alternative routes.
6. Finally, it is recommended that further research be conducted to explore additional factors that might influence traffic flow and vehicle speed, such as the impact of different types of precipitation (e.g., heavy rain vs. drizzle), the influence of visibility conditions, and the effects of road surface conditions. Such research could provide more comprehensive insights and lead to the development of even more effective traffic management strategies.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Syed Khairi Syed Abbas; data collection: Nur Izzah Farzana Kamarulzaman and Adi Yazid Rosli; analysis and interpretation of results: Syed Khairi Syed Abbas and Nur Izzah Farzana Kamarulzaman; draft manuscript preparation: Syed Khairi Syed Abbas, Jezan Md Diah and Muhammad Akram Adnan. All authors reviewed the results and approved the final version of the manuscript.

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