Impacts of Different Rainfall Intensities on Key Traffic Flow Parameters at North Luzon Expressway Using Underwood's Exponential Model

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Abstract: The study was conducted to establish a relationship about the effects of different rainfall intensities on key traffic stream parameters. Traffic data were gathered using loop detectors in NLEX for a period of seven months. Rainfall data were obtained from the nearest automatic weather station. Traffic data were segregated into different rainfall conditions: clear (0 mm rainfall/hr.), light (0.1-2.5 mm rainfall/hr.), moderate (2.6-7.5 mm rainfall/hr.), and heavy (above 7.5 mm rainfall/hr.). Regression analysis were done for speed-density and flow-density relationships using the exponential model by Underwood. The reduction in average speeds are about 5.34% under light rain conditions, 6.3% under moderate rain conditions, and 7.4% under heavy rain conditions. The average volume decreased by 2.92%, 10.62%, and 12.39% while the capacities reduced by 3.67%, 7.6%, and 17.44% under light, medium, and heavy rain conditions, respectively. Free flow speed and speed at capacity also decreased by 6.9-11.05% and 12.89-16.65%, respectively.

Keywords: Traffic flow, Rainfall, NLEx, Underwood's exponential model

1. INTRODUCTION

1.1 Background

Over the past decades, many studies have examined the impacts of adverse weather conditions on road traffic. It has been found that adverse weather in the form of rain or snow has significant detrimental effects on traffic speed, road capacity, and maximum flow. Weather, in particular rain, affects driver behavior and traffic operations, and the need to account for the effects of weather conditions in real-time traffic forecasting, traffic monitoring, and management in the framework of intelligent transportation systems has been acknowledged in recent years.

The freeway capacity is defined in the Highway Capacity Manual 2000 as the "maximum flow rate that can be expected to be achieved repetitively at a single freeway location and at all locations with similar roadway, traffic and control conditions without breakdown". From the definition, it is clear that the important concepts of capacity rely on prevailing conditions. Any change in the prevailing condition would result in a change in the road capacity.

The capacity of freeway segment is dependent on the speed of the traffic stream and the density. Under bad weather conditions, drivers moderate their speed and increase the headway between vehicles; hence weather impacts the capacity of a freeway segment. Actions like these could reduce road capacities and corresponding traffic intensities. The principal problems of rainfall for road traffic are: poor visibility conditions, decreased adhesion coefficient between the road surface and vehicle, and increased aquaplaning. These problems would worsen traffic stream condition and operation.

1.2 Problem Statement

Despite documented impacts of adverse weather on transportation, the linkages between inclement weather conditions and traffic flow in existing analysis tools and some highway manuals remain unknown.

As the transportation profession continues to seek to operate transportation facilities at the highest possible level of efficiency, it is necessary to account the impact of weather (Smith, et.al, 2003).

This paper addresses the effect of adverse weather on expressway operations, a topic that is of interest for several reasons. Most of the data and analyses presented in standard reference works such as the Highway Capacity Manual 1985 (HCM) deal solely with correcting for other departures from ideal conditions. No corrections are provided for weather effects, in part perhaps because little is known in detail. One of the factors that must be adapted in adaptive control of expressways is weather. Intuitively, rain decreases key traffic flow parameters and the topic of this paper is not simply whether that intuition is correct, but that quantities can be put on those intuitive expectations.

1.3 Rationale

Transportation agencies are seeking to integrate weather data into the traffic operations in order to improve system efficiency. In order to do so, it is essential that transportation professionals have a solid understanding of the impact of various weather conditions on traffic flow. A clear insight into how weather conditions influence traffic is also essential for policymakers. This is underlined by policy issues that are often related to adverse weather events such as increased fuel consumption, economic losses due to traffic delays, and higher traffic counts.

The assessment of weather impacts on traffic intensity is also of significant value to travel-demand modelers. It could also be of use to the future researches and even in revisiting past ones since adverse weather conditions cause important changes in travel decisions such as mode changes, changes in departure time, and diversions to alternate routes as prevalent behavioral adaptations. Much of the studies in transportation engineering in the Philippines that considers the effects of weather particularly rain focuses on the behavior of pedestrians and their mode and route choice. Notwithstanding the amount of rainfall on Philippine roadways, studies of this nature have been very limited at all.

1.4 Objectives

The purpose of this research effort is to investigate the impact of rainfall, at varying levels of intensity, on capacity and other key traffic flow parameters such as average volume, mean speed, free-flow speed, critical density and speed at capacity. In particular, this research expands on the limited guidance currently presented to freeway operations in capacity manuals and intends to make provisions in the making of the Philippine highway capacity manual.

1.5 Conceptual Framework

Greenshields postulated a linear relationship between speed and traffic density. The linear speed–density relation converts into a parabolic relation between speed and traffic flow. It shows a maximal traffic flow with the related optimal traffic density.

As traffic density increases, a road gets congested and the speed of the traffic decreases. Since Greenshields' model, various models have been proposed to analyze the speed–density relationship. Much effort has been devoted to improving the simplified relationship specified by Greenshields. These classical studies, including those of Greenberg (1959), Underwood (1961), Gazis et al. (1961) and Drake *et al*. (1967), are limited to particular expressways and sections thereof. Moreover, the time period covered is also limited and all models assumes normal and clear condition.

Traffic flow parameters can be of stochastic nature because of variations in individual driver behavior, vehicle characteristic and changing road and weather conditions. In an event of rainfall, drivers moderate their speed and increase the headway between vehicles.

The impact of these disturbances to the traffic stream is such that the sight distances of the highway are reduced, speed of vehicles is decreased, headway is increased, and relative travel time is lost. Actions like these could have changes in traffic flow and can reduce road capacities and corresponding traffic intensities. Shown in the figure is the conceptual framework diagram of the study which shows that the occurrence of rainfall can have a change in traffic flow parameters. The computation of such parameters will also depend on the traffic flow model used.

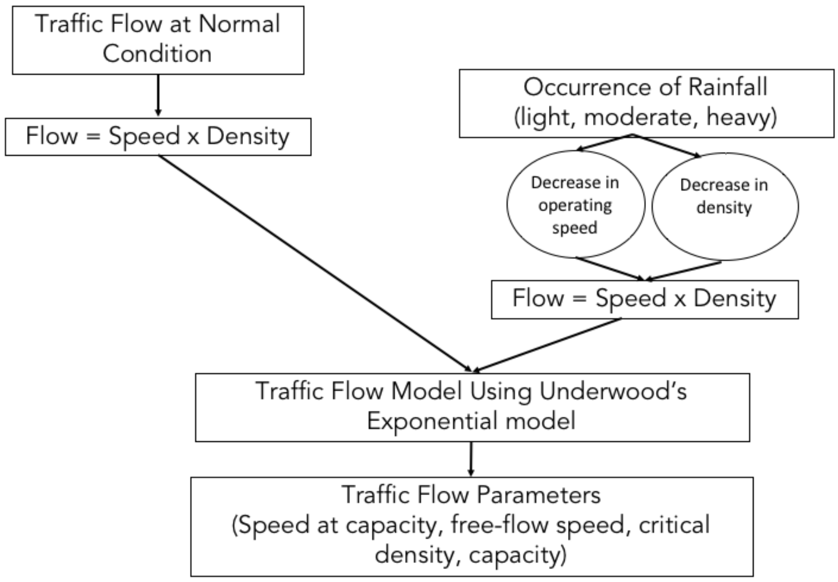

Figure 1. Conceptual Framework

2. REVIEW OF RELATED LITERATURE

2.1 Traffic Flow Theory and Analysis

The beginnings of traffic flow descriptions on a highway are derived from the observations by Greenshields, firstly shown to the public during the Proc., 13 Annual Meeting of the Highway Research Board in Dec. 1933. He carried out tests to measure traffic flow, traffic density and speed using photographic measurement methods for the first time. Greenshields postulated a linear relationship between speed and traffic density.

As traffic density increases, a road gets congested and the speed of the traffic decreases. Since Greenshields' seminal paper, various models have been proposed to analyze the speed–density relationship. Much effort has been devoted to improving the simplified relationship specified by Greenshields. These classical studies, including those of Greenberg (1959), Underwood (1961), Gazis et al. (1961) and Drake *et al*. (1967), are limited to particular expressways and sections thereof. Moreover, the time period covered is also limited and all models assumes normal and clear condition. The commonly used speed-flow-density relationships do not explicitly take into consideration the effect of weather.

2.2 Current considerations of precipitation to traffic flow

Chapter 22 of the Highway Capacity Manual 2000, “Freeway Facilities”, addresses the impact of rain on freeway capacity and operating speeds. The manual first references the researches of Lamm, Choueiri, and Mailaender, who concluded that operating speeds are not affected by wet pavement until visibility is also impacted, and therefore light rain does not impact operating speeds, while heavy rain does. The manual goes on to cite the research of Ibrahim and Hall to provide quantitative information on the impact of light and heavy rain on operating speeds and maximum observed flow rates. For light rain, the manual states that one can expect a 1.9 km/hour reduction in operating speeds during free flow conditions, and a 6.4 to 12.8 km/hour reduction in operating speeds at a flow rate of 2400 vehicles/hour. Furthermore, the manual states that there is no reduction in capacity during light rain. For heavy rain, it is stated that there is a 4.8 to 6.4 km/hour reduction in operating speeds during free flow conditions and a 12.8 to 16 km/hour reduction in operating speeds at a flow rate of 2400 vehicles/hour. Finally, it is stated that there is a 14-15% reduction in capacity during heavy rain.

Although the conventional guidelines for the assessment of traffic flow quality around the world including the HCM has traditionally treated capacity of highway facilities as a constant value, it must be understood that there is no generally valid single capacity value. Even under ideal conditions, a constant value of capacity is not attainable in practice. Other studies also showed that capacities vary under non- ideal conditions as well. Capacity is of stochastic nature because of variations in individual driver behavior, vehicle characteristic and changing road and weather conditions.

2.3 Effects of Different Weather Condition to Traffic Flow

Over the past few decades, many studies have investigated traffic speed-flow-density relationships on freeways under rainy conditions (Agarwal et al. 2006; Billot et al. 2009; Camacho et al. 2010; Rakha et al. 2008). Unrau and Andrey (2006) investigated driver response to rainfall on urban expressways.

Since the early 1950’s, it has been recognized that weather conditions affect driver behavior and traffic flow. Weather phenomena exert significant impacts on traffic flow related parameters, such as free flow speed and capacity (e.g. Kockelman, 1998; Smith et al., 2004; Hranac et al., 2006; Rakha et al., 2007). In addition, adverse weather often affects trip maker decisions related to the selection of travel mode, route, timing, destination, or even the occurrence of the trip. Thus, weather affects both the supply and demand sides of transportation. Studies confirm that adverse weather results in reduced service capacity, diminished reliability of travel, and greater risk of accident involvement.

2.3.1 Impact of Rainfall Intensity to Capacity

According to Rao and Rao, capacity is one of the most important elements of road space supply. When capacity is compromised, motorists will experience increase in travel time. They overtake less, drive slower and increase their following distance.

Adverse weather conditions can significantly reduce the operating speed and capacity in a given road segment. Compared to fair conditions, the HCM 2000 reports a 30% reduction of capacity due to snowfall and 15% due to rain or fog (HCM, 2000). Lamm et al., (1990) reported that speeds were not influenced by the presence of wet pavement until visibility was affected. Accordingly, light rain did not appear to have noticeable impacts on traffic flow compared to heavy rain that resulted in 10% to 15% reduction in capacity. Similar to heavy rain, heavy snow was reported to have a potentially large impact on the operating speed (Ibrahim and Hall, 1994). A 30% drop in capacity was attributed to heavy snow compared to a 10% reduction in the case of light snow. The main explanatory reason behind such drop is the search for a greater lateral clearance and longer headways since the lane markings are obscured by snow accumulation.

2.3.2 Impact of Rainfall Intensity to Traffic Volume and Demand

Adverse weather may also reduce demand for trips when drivers cancel or postpone their activities. However, an increase in demand of vehicle trips may also be observed as travelers switch from transit or non-motorized modes to private vehicle use. Furthermore, adverse weather can also shift the peak-hour demand if the drivers choose to leave earlier or later due to unsafe driving conditions (Mahmassani et al., 2009).

Hanabali and Kuemmel (1992) quantified the reduction in traffic volumes during snowstorms in rural areas of Illinois, Minnesota, New York, and Wisconsin using automatic vehicle detectors data collected during the first three months of 1991. These data included annual average daily traffic and 24-hour counts. Comparing hourly traffic volumes during every snowstorm to the normal hourly traffic volume, a correlation between volume reduction and snowfall was found. The study concluded that the volume reduction was less pronounced during peak-hours and during weekdays. This may be attributed to the non-discretionary type of trips (home to work and work to home trips).

2.3.3 Impact of Rainfall Intensity to Traffic Speed

A study sponsored by Federal Highway Administration (FHWA) confirmed a decrease in speeds during inclement weather (FHWA, 2006). In the HCM 2000, the reported weather impact on speed is based on Ibrahim and Hall's (1994) study. Conducting a regression analysis on the clear weather data, a quadratic model was found to best fit the flow-occupancy relationship; and a simple linear model suited the speed-flow relationship. Moreover, comparing different relationships under different weather conditions, the differences in slope and intercept of the speed-flow function during the rainy conditions were more significant that those between clear and rainy weather. Finally, light snow resulted in a minor drop in free-flow speeds (0.96 km/h), contrary to heavy snow that led to a 37.0 to 41.8 km/h drop. Another related study by Smith et. al. in 2004 concluded that although operating speed reductions were not as dramatic as was the case with capacity reductions, statistically significant reductions from 3 to 5 % in operating speed were observed under rainfall conditions compared to no rain at all.

2.4 Research Considerations

A key area of concern in the Highway Capacity Manual 2000 is it does not define the rainfall intensity ranges associated with the categories heavy and light rain. Given the significant difference in the impact of rain based on its intensity, expressway operators are forced to attempt to classify a rainfall event without a strong basis to support this classification.

Given that the information provided in the Highway Capacity Manual 2000 is based on the work of Ibrahim and Hall, their research was examined in more detail. The data used in their study were collected by the Queen Elizabeth Way Mississauga freeway traffic management system. Dummy variable multiple regression analysis techniques were used to test for significant differences. The authors did address the issue of defining light versus heavy rain. However, the rainfall intensity threshold between the categories of heavy and light rain is not provided in the paper. The researchers also used limited traffic data in their study which is limited to the hours of 10:00 am – 4:00 pm in order to avoid the impact of darkness. Six days' worth of clear data were utilized, and only two days' worth of rainy data were used. Finally, in their conclusion, the researchers stated that regional factors could play a significant role in the results, based on an area's "driver's familiarity with driving in the rain and snow."

Clearly, the Ibrahim and Hall study is a very significant piece of work in that it provides quantitative information concerning the impact of rain on operating speeds and capacity (and therefore, is included in the Highway Capacity Manual 2000). However, an analysis of the work points to the following areas warrants further research.

- Measures of rainfall intensity beyond the categories of light and heavy must be considered and the use of a standardized nomenclature for categorizing different rainfall intensities is needed.
- There is a need to investigate the impact of rainfall using a larger set of data and use a shorter interval data for traffic counts to minimize the potential impacts of the inherent variability of traffic data.
- Research in a different region in order to investigate potential regional impacts must be done since effects can vary from one area to another.

The need to localize the effects of rainfall intensity to traffic flow in a Philippine setting is needed since results from different studies vary widely. Even though most researchers report reductions in traffic flow and speed during rainfall, the estimated reductions cannot be generalized in a uniform manual since there is no generally valid single capacity value. Traffic flow parameters can be of stochastic nature because of variations in individual driver behavior, vehicle characteristic and changing road and weather conditions. There is a need to also clearly define the rainfall category utilized, speed-flow relationship used, different quantitative estimation methods and the consideration of static passenger car equivalent values.

3. METHODOLOGY

3.1 __Site Selection__

The North Luzon Expressway was selected as the site for study in this paper because in order to quantify the effects of a certain prevailing condition to traffic flow, the road section must be free flowing and must have continuous "uninterrupted" flow. There are no external interruptions to traffic flow such as a signalized or stop-controlled intersection in NLEX. Entrance to and exit from the facility occur only at ramps. Furthermore, precipitation can also impact the transportation system due to the collection of water in the carriageway and these events can be prevented because of the good geometric design and drainage system in NLEX. The road section is a 4 to 8-lane limited-access toll expressway that connects Metro Manila to the provinces of the Central Luzon region. It is a component of Expressway 1 (E1) of the Philippine expressway network and Radial Road 8 (R-8) of Metro Manila's arterial road network. Shown in the figure 2 is the NLEX road network (in red marking) showing the connection between Metro Manila and Central Luzon.

Figure 2. Map of Luzon Island Showing the NLEX Road Network

In selecting the ideal area for data gathering, ocular surveys were conducted in order to determine the specific location of the survey area and to verify the availability of a technical shelter that houses the loop detector set that gathers traffic data. Several information were considered in the selection of the location. First were the geometric features of the roadway section which include a level terrain and straight alignment. Opposite direction of the traffic flow must be divided by a median and no weaving sections must be present. The lane must also have a standard width. Most importantly, the location must be as near as possible to the Automatic Weather System (AWS) that gathers the rainfall data in order to represent the actual weather condition on site.

With all the above considerations, the area near Balintawak toll plaza was selected. It is located in between the Balintawak toll plaza and the Smart Connect Interchange and it is specifically located at Km. 11+150 north bound with technical specification of TS2 Balintawak. Shown in Figure 4 is the location of the technical shelter (in blue housing).

The area is located within 1 km of the nearest AWS.

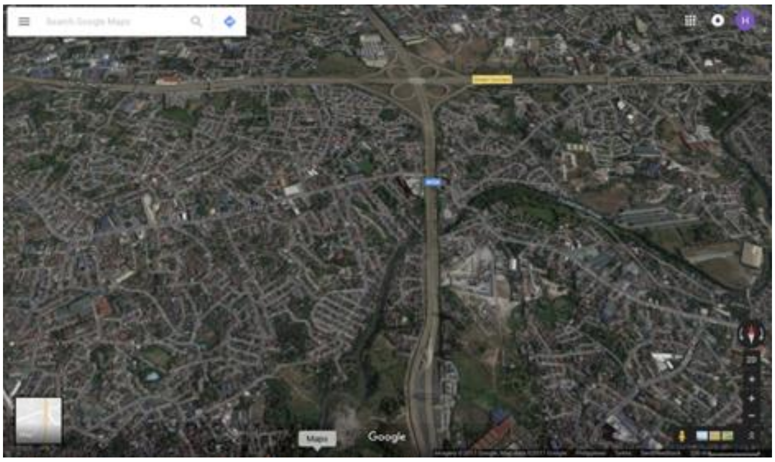

Figure 3. Location of the Technical Shelter

Figure 4. Site Location

The selected road section has four traffic lanes in the north and south bound direction. The lane near the center or median in between the opposite direction is called the overtaking lane. Lanes are numbered from 1 to 4 with lane 1 as the outermost lane as shown in Figure 4. All types of passenger vehicles can utilize lane 4 only for overtaking and must return to lane 3 again for normal cruise, likewise, passing or overtaking along the emergency lane is also disallowed. Toll Plaza have a dedicated lane for trucks and buses usually at the rightmost portion of each barriers.

Two types of data (traffic and rainfall intensity data) were collected and matched into a common database for empirical analysis of rainfall effects.

3.1.1 Traffic Data Collection

Traffic data (i.e., time mean speed and vehicular traffic flow) were collected using loop detectors at the area. These loop detectors provide the average journey time estimates used in the NLigtas mobile app of NLEX with an updated interval every six minutes. These vehicle detectors can detect the number of passing vehicles and the vehicle running speed as well as the length of vehicle by each lane. The information can be identified on the monitoring displays of the traffic control center. The data were collected at intervals of 6 minutes for each lane from June to December 2016.

While what was collected in the data gathering were time mean speed, the space mean speed is needed for the analysis of traffic flow.

Time mean speed, u_t, is the simple average of spot speeds. The space mean speed, u_s, also averages the spot speed, but spatial weightage is given instead of a temporal one. The relationship between the two averages can be described as follows:

$$u_t = u_s + (\sigma^2 / u_s)$$

Hence, time mean speed is equal to space mean speed plus the variance of the spot speed divided by the space mean speed. Time mean speed will always be greater than space mean speed since variance cannot be negative. If all the speed of the vehicles is the same, the spot speed, time mean speed, and space mean speed will also be the same. In this case, the variance will be equal to zero.

Since available data in the loop detectors were in terms of time mean speed, it was assumed that it is equal to space mean speed. The assumption can be acceptable since data were gathered in only one segment that has a straight alignment. In this manner, the standard deviation will be very minimal.

Vehicle classification are identified using Optical Vehicle Separators (OVS). The equipment includes vehicle height sensor, axis detection sensor, vehicle intrusion detection sensor, and leaving vehicle detection sensor. The vehicle type is automatically classified based on the detection result of vehicle height sensor and axis detection sensor.

As the traffic density data were not available from the NLEX traffic detector dataset, the traffic density (k) is derived.

3.1.2 Rainfall Data Collection

The rainfall intensity is the rainfall precipitation in a certain period of time. Rainfall data were collected using an Automatic Weather System (AWS). An AWS is a stand-alone device that measures rainfall and collects other weather information and transmits them in real time to the PAGASA head office in Science Garden, Quezon city. The device collects and disseminates weather data inside a weather-proof enclosure. The area of study is less than 1 kilometer from the AWS. This ensures that weather information represents actual conditions at the site. The rainfall data were collected every 15 minutes. The period in which rainfall intensity data were collected is same as that in which traffic data were extracted from the NLEX loop detectors, i.e., from June to December 2016. Shown in the figure 5 are the location of AWS's in Metro Manila.

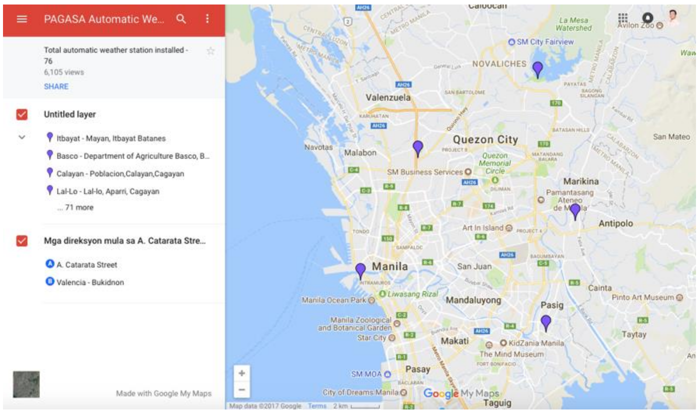

Figure 5. Locations of Automatic Weather System in Metro Manila

Shown in table 1 is the standard nomenclature used by PAGASA in classifying different rainfall events to light, moderate, and heavy rains. Clear conditions signify zero mm of rainfall recorded in the AWS, 0.1-2.5 mm of rainfall is considered light. Moderate rains have measurement of 2.6-7.5 mm of rain while those greater than 7.5 mm are considered heavy rain. Using the weather data, the loop detector data were grouped into different categories i.e. clear, light, moderate, and heavy. Data were grouped based on the intensity of the precipitation.

Table 1. Rainfall Intensity Classification Nomenclature

Rainfall Classification	**Precipitation in mm of Rain**
Clear	0
Light	0.1 – 2.5
Moderate	2.6 – 7.5
Heavy	Greater than 7.5

Source: PAGASA

3.2 Filtering of Invalid Data

The differences between the aggregation intervals of traffic data and rainfall intensity data were noted. The traffic data time interval is 6 minutes; however, the rainfall intensity data were recorded every 15 minutes. According to the study by Andrey and Yagar in 1991, traffic flow and collision risks returns to normal immediately after rain stops. In this study, the precipitation data were paired to their corresponding traffic data using the time the data were gathered.

Raw data were filtered to ensure data validity. Traffic data observed during traffic accidents were removed to prevent the bottlenecks caused by traffic accidents affecting the traffic speed-flow-density relationship. For simplicity, it was assumed that traffic accidents can be cleared, and their impacts can be slightly reduced within one hour after the occurrence of traffic accidents. Thus, traffic speed and flow data within one hour of traffic accidents were removed. According to a study by Salonen and Puttonen in 1982, darkness reduces operating speeds by 5 km/hr. To remove these effects, only daytime data were used in this study. Since different months of the year have different times of sunrise and sunset, only traffic and weather data from 6 AM to 5 PM were used. For empirical analysis, the rainfall intensity data corresponding to invalid space mean speed and traffic flow datasets such as zero speed and flow were eliminated from the common database. Conversely, if the rainfall intensity data were missing during the study period, the corresponding traffic datasets were also removed for analysis.

Shown in Figure 6 is the flowchart for the data filtering done.

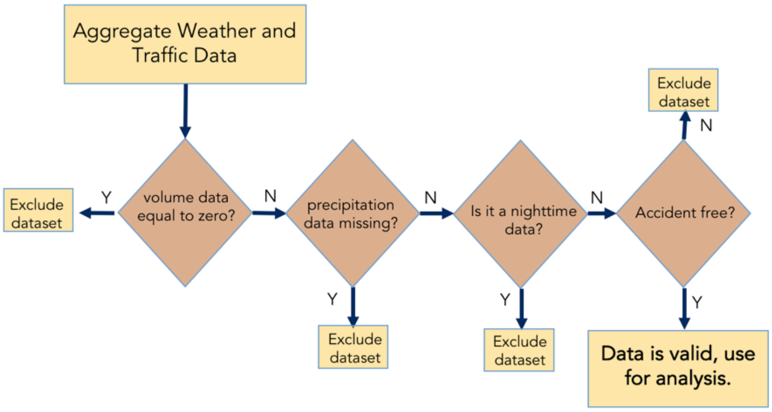

Figure 6. Filtering of Invalid Data Flowchart

3.3 Statistical tests

T-statistics was used to test if the mean parameter values are statistically different. In addition, analysis of variance (ANOVA) tests were conducted to identify any potential statistical differences for various parameters. Consequently, tests for normality and heterogeneity were conducted to the data.

After the statistical test, 2 lanes with relatively significant and ideal values were selected for initial traffic flow models' calibration

4. RESULTS

4.1 Comparison of Average Speed and Volume Data for All Four Lanes

Shown in Figure 7 is the comparison of the average speed and volume for lanes 1 to 4. It can be seen that lane 3 has the highest average speed and volume count at 73 km/hr. and 113 vehicles every 6 minutes, respectively. Lane 4 has an average speed of 70 and an average volume of 90. It is very evident that counts from lanes 1 and 2 are relatively lower most notably with volume with just 57 for lane 1 and 19 for lane 2. The data shows that around 77% of the vehicle classification in NLEX is composed of passenger cars. The remaining 23 % is composed of trucks and buses.

Overstaying on the innermost lane is prohibited for all types of vehicles. Trucks and buses are strictly prohibited from using lane 4 anytime. Lanes 1 and 2 is allotted for trucks and buses, however, passenger buses can utilize lane 3 to overtake but must return to lane 1 or 2 again after doing so. Trucks are absolutely not allowed to utilize lane 3. Slow moving class 1 vehicles are likewise advised to use the trucks and buses lane. For this reason, the initial model calibration was done for lanes 3 and 4 only.

The unit of capacity will be in terms of passenger car units per hour (pcu/hr.). No conversion will be made since the pcu factor for passenger cars is 1. The pcu factor for buses is equal to 2. Since buses are allowed in lane 3 for overtaking purposes, there will be a slight under- estimation of the capacity.

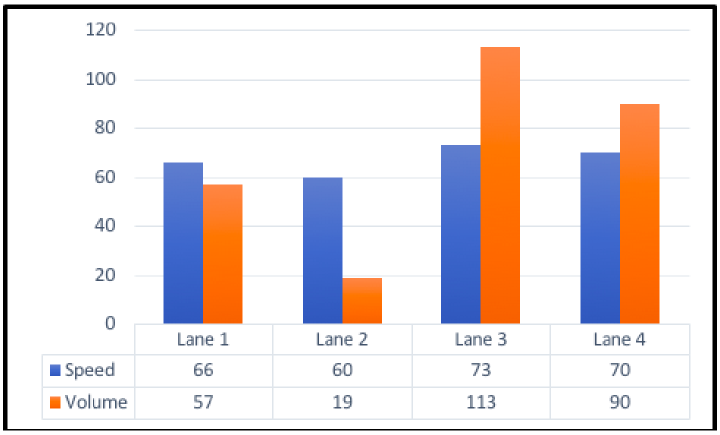

Figure 7. Average Speed and Volume Data for Lanes 1 to 4

4.2 Effects of Rainfall Intensity to Speed-at-Capacity and Jam Density

Figures 8-11 illustrate the observed and calibrated traffic speed-density- relationship for different categories of rainfall intensity together with their corresponding key traffic stream parameters. It is noted that free-flow speed and speed at capacity decreased with rainfall intensity. For example, the speed at capacity is reduced from 43.12 km/hr. under dry conditions to 37.56 km/hr. under light rain conditions to 37.3 km/hr. under moderate rain conditions and further decreased to 35.94 km/hr. under heavy rain conditions. It is also shown in the figures that critical traffic jam densities which are the measure of number of vehicles that the highway section can carry are not significantly affected by rainfall intensity. This means that the maximum number of vehicles accommodated by an urban road is more or less constant whether it is rainy or dry.

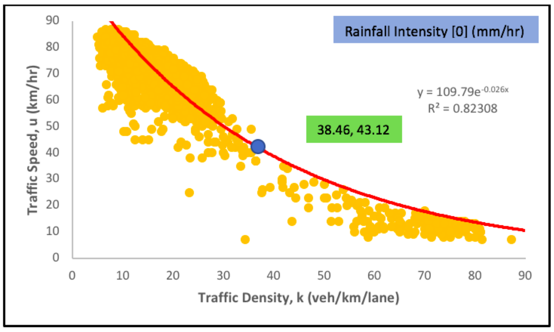

Figure 8. Modeled u-k Relationship (Clear Rain Condition)

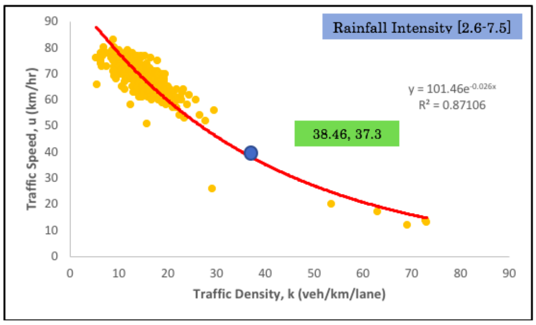

Figure 10. Modeled u-k Relationship (Moderate Rain Condition)

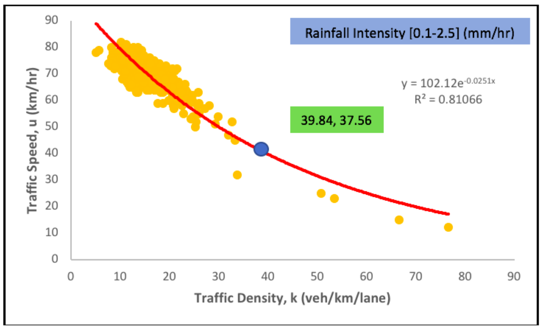

Figure 9. Modeled u-k Relationship (Light Rain Condition)

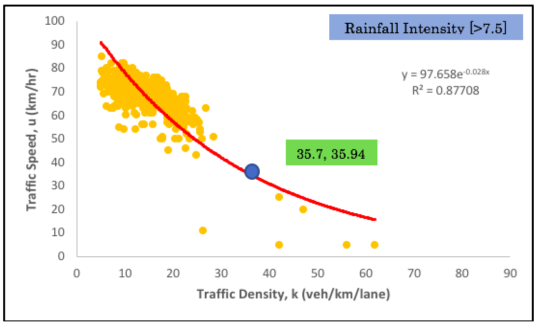

Figure 11. Modeled u-k Relationship (Heavy Rain Condition)

4.6 ***Effects of Rainfall Intensity on Capacity***

Figures 12-15 present the observed and calibrated traffic flow-density relationships for different categories of rainfall intensity, together with their corresponding key traffic stream parameters. This distribution was derived from the u-k diagram using the relationship q=uk. The sample size, n, for each category is also shown. The results demonstrate that the capacity reduction increases with rainfall intensity. For instance, the capacity is reduced significantly from 1554veh/hr./lane under dry conditions to 1497 veh/hr./lane under light rain conditions. The capacity further decreased to 1436 veh/hr./lane under moderate rain conditions and finally to 1283 veh/hr./lane during heavy rain conditions. The capacity reduction rate from dry to heavy rain conditions is (1554− 1283)/1554*100%= 17.44 %.

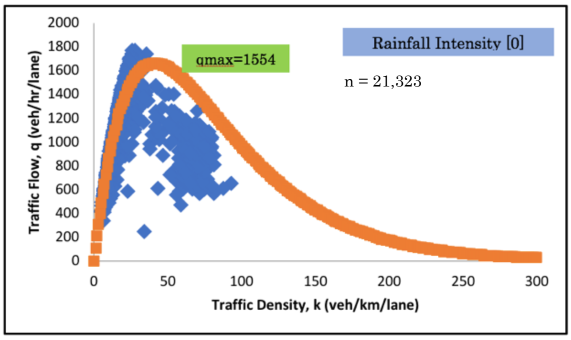

Figure 12. Modeled q-k Relationship (Clear Rain Condition)

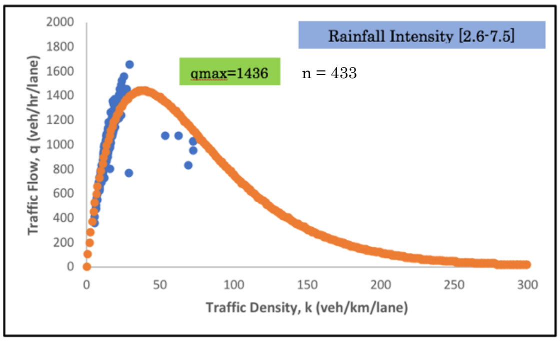

Figure 14. Modeled q-k Relationship (Moderate Rain Condition)

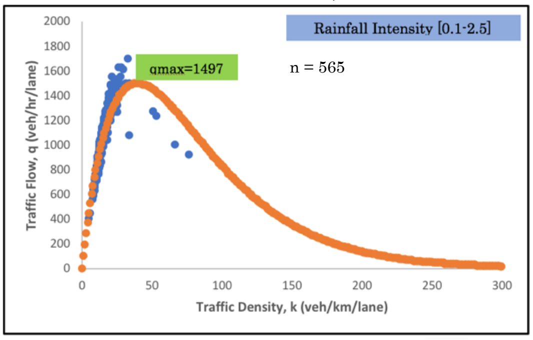

Figure 13. Modeled q-k Relationship (Light Rain Condition)

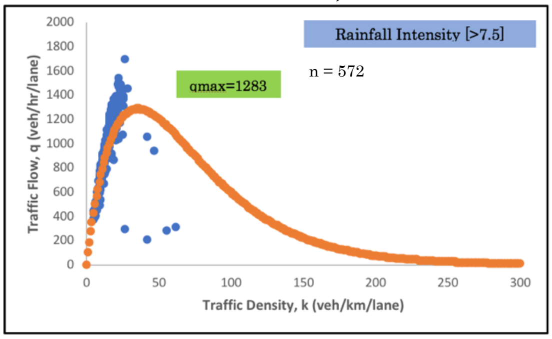

Figure 15. Modeled q-k Relationship (Heavy Rain Condition)

The effect of rainfall intensity on traffic flow is summarized in Table 2. The average volumes and mean speeds for daylight traffic for all cases shows a decreasing trend under rainfall condition compared to those under dry condition.

Average volume is reduced from 1130 veh/hr./lane under dry conditions to 1100 veh/hr./lane under light rain conditions. The average volume further decreased to 1010 veh/hr./lane under moderate rain conditions and finally to 990 veh/hr./lane during heavy rain conditions. The average volume reduction rate from dry to heavy rain conditions is (1130−990)/1130*100%=12.39.

Also, speed decreases as the rain intensity increases. For mean speed, the range of reduction is 5.3-7.4% in all cases suggesting that drivers were constrained by rainfall condition. Interestingly, free-flow speed dropped by 6.9-11.05% because of rainfall, thus suggesting that at reduced traffic flow, even if it is one vehicle on the roadway, maximum free-flow speed is not reached. It depicted a free-flow situation where drivers cannot choose speeds due to poor weather condition.

Table 2. Key Traffic Flow Parameters Under Different Rainfall Intensity

	Clear	Light	Moderate	Heavy
Average Speed (km/hr.)	73	69.1	68.4	67.6
Average Volume (veh/hr.)	1130	1100	1010	990
Free flow speed (km/hr.)	109.79	102.12	101.46	97.658
Critical density (veh/km)	38.46	39.84	38.46	35.7
Speed at Capacity (km/hr.)	43.12	37.56	37.3	35.94
Capacity (pcu/hr.)	1554	1497	1436	1283

Figures 16 and 17 shows the superimposed observed and modeled u-k and q-k relationship. It can be seen that free-flow speed is decreasing with increasing rainfall intensity while there is no significant change in jam density. It is also evident that the capacity is decreasing as shown in the lowering of the peak of the curve of the flow-density relationship.

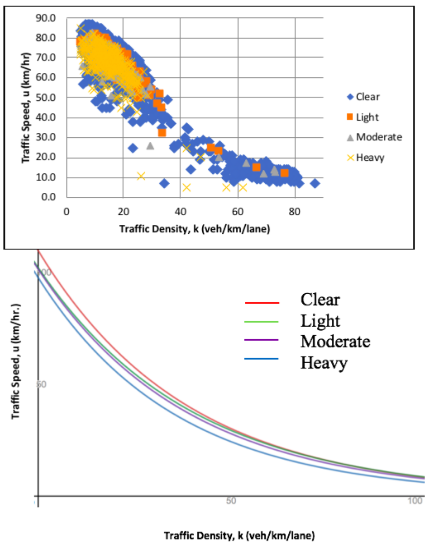

Figure 16. Superimposed observed and modeled u-k relationship

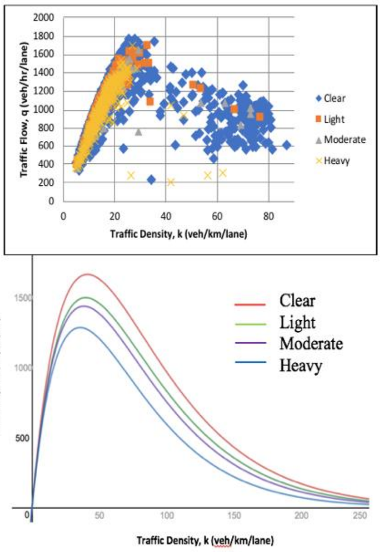

Figure 17. Superimposed observed and modeled q-k relationship

Shown in the tables 3 and 4 are the Analysis of Variance (ANOVA) for speed and volume. ANOVA for speed shows that the p-value is essentially zero which is less than the value of alpha of 0.05. Furthermore, the F-value of 207.61 is way more than the critical F-value of 2.605. This shows that the difference of the speeds within and between groups is significant at 95% level of confidence.

In the ANOVA for volume, p-value is also zero and is less than the alpha of 0.05. The F-value is equal to 139.27 which is greater than the critical F-value of 2.605. It can be concluded that the difference of volume or flow within and between groups is also significant at a level of confidence of 95%.

Table 3. Analysis of Variance of Speed

SUMMARY

Groups	*Count*	*Sum*	*Variance*
Clear	21323	1556391	50.84965493
Light	565	39022	47.99038474
Moderate	433	29601	72.24554144
Heavy	572	38676	70.82203961

ANOVA

Source of Variation	*SS*	*df*	*F*	*P-value*	*F crit*
Between Groups	32188.19427	3	207.607	7.200E-133	2.605
Within Groups	1182932.378	22889			
Total	1215120.572	22892			

Table 4. Analysis of Variance of Volume

SUMMARY

Groups	*Count*	*Sum*	*Variance*
Clear	21323	2412683	406.1628627
Light	565	62044	400.0108391
Moderate	433	43585	353.012531
Heavy	572	56875	621.3946426

ANOVA

Source of Variation	*SS*	*df*	*F*	*P-value*	*F crit*
Between Groups	171471.5093	3	139.27	1.9737E-89	2.605
Within Groups	9393128.425	22889			

5. CONCLUSION

5.1 Study Summary

Different rainfall intensities have a direct effect on traffic flow. The study was conducted to model and establish a relationship about the effects of rainfall intensities on key traffic stream parameters: average volume, average speed, free flow speed, capacity, critical density, and speed at capacity. Speed and volume data were gathered using loop detectors near Balintawak toll plaza in NLEX for a period of seven months from June to December 2016. Traffic data were collected at an interval of 6 minutes. Rainfall data were obtained from the nearest automatic weather station provided by PAGASA. Traffic data were segregated unto different rainfall conditions: clear (0 mm rainfall/hr.), light (0.1-2.5 mm rainfall/hr.), moderate (2.6-7.5 mm rainfall/hr.), and heavy (above 7.5 mm rainfall/hr.). Regression analysis were done for speed-density and flow-density relationships using Underwood's exponential model. Key traffic flows were computed under different rainfall conditions and results were compared.

5.2 Research Findings

The results show that rainfall has a clear effect on key traffic stream parameters as summarized in Table 5. It showed a significant decrease under different rainfall conditions. The reduction in average speeds are about 5.34% under light rain conditions, 6.3% under moderate rain conditions, and 7.4% under heavy rain conditions. The average volume decreased by 2.92%, 10.62%, and 12.39% while the respective capacities or maximum flows reduced by 3.67%, 7.6%, and 17.44% under light, medium, and heavy rain conditions. Free flow speed and speed at capacity also decreased by 6.9-11.05% and 12.89-16.65%, respectively. Lastly, the critical density has no significant change. The change in critical density showed no consistent pattern compared to other traffic flow parameter. Furthermore, the values for critical density during clear and moderate rain are the same. The findings of this research can be used in the consideration of rainfall intensity effects to traffic flow in the making of a Philippine highway capacity manual.

Table 5. Summary of Results

	Clear	**Light**	**Moderate**	**Heavy**
Average Speed (km/hr)	-	5.34%	6.3%	7.4%
Average Volume (veh/hr)	-	2.92%	10.62%	12.39%
Free flow speed (km/hr)	-	6.9%	7.6%	11.05%
Critical density (veh/km)	-	-3.59%	0%	7.18%
Speed at Capacity (veh/hr)	-	12.89%	13.5%	16.65%
Capacity (pcu/hr)	-	3.67%	7.6%	17.44%

5.3 Recommendation for Future Work

The effects of weather on traffic flow in this study were solely based on rainfall intensity. However, there is also a need to demonstrate the effects of other environmental factors such as wind speed, visibility, road surface condition, and other environmental indicators. Furthermore, human factor focused on individual reactions to driving conditions is a major concern. Driver behavior that includes acceleration, deceleration, car-following, lane changing behavior, and gap acceptance can also be considered.

There is also a need to consider a more complicated traffic flow model to clearly describe the relationship in speed-density and flow-density. Models that would result in a value of R^2 closer to 1.0 would better describe the said relationship.

Similar studies should also be carried out on different location and other road types so as to investigate road type and regional differences.

There is a need to take steps to improve traffic flow and operation during rainfall condition with the aim of minimizing delays and crashes due to reduced key traffic flow parameters. Some known traffic management strategies such as use of emergency lanes, temporary use of shoulders, deployment of variable message sign, etc. can be studied for suitability and effectivity.

REFERENCES

1. Agarwal, M., Maze, T. H., and Souleytette, R. (2006). “The weather and its impact on urban freeway traffic operations.” Proc., 85th Transportation Research Board Annual Meeting, Transportation Research Board, Washington, DC.
2. B. L. Smith, K. G. Byrne, R. B. Copperman, S. M. Hennessy, and N. J. Goodall. 2004. An Investigation into the Impact of Rainfall of Freeway Traffic Flow. Paper presented at the 83rd annual meeting of the Transportation Research Board, Washington D.C.
3. FHWA (1977).*Empirical Studies on Traffic Flow in Inclement Weather*, Final Report, Federal Highway Administration, Publication No.FHWA-HOP-07-073, Washington, D.C.
4. Hanbali, R. M., and D. A. Kuemmel, 1993: Traffic volume reductions due to winter storm conditions. Transp. Res. Rec., 1387, 159–164.
5. Highway Capacity Manual 1985, Transportation Research Board, Washington, D.C., 1985.
6. Highway Capacity Manual 2000, Transportation Research Board, Washington, D.C., 2000.
7. Ibrahim, Amal T. and Hall, F. L. Effect of Adverse Weather Conditions on Speed-Flow-Occupancy Relationships. In Transportation Research Record 1457, Transportation Research Board, National Research Council, Washington DC, 1994, pp. 184-191.
8. Jones, E. R. and Goolsby. M. E. (1970). The Environmental Influence of Rain on Freeway Capacity. Highway Research Record 321. National Research Council. Washington. D. C.
9. Kockelman, K. M. Changes in Flow-Density Relationship Due to Environmental, Vehicle, and Driver Characteristics. Transportation Research Record 1644, Transportation Research Board, National Research Council, Washington DC, 1998, pp. 47-56.
10. Lamm, R., Choueiri, E.M., and Mailaender T. Comparison of Operating Speeds on Dry and Wet Pavements of Two-Lane Rural Highways. In Transportation Research Record 1280, Transportation Research Board, National Research Council, Washington DC, 1990, pp 199-207.
11. Mahmassani, H. S., Dong. J., Kim, J., Chen, R. B., and Park, B. (2009). Incorporating Weather Impacts in Traffic Estimation and Prediction Systems. Final Report. Publication No. FHWA-JPO-09-065. EDL 14497. US Department of Transportation.
12. Padget, E. D., Knapp, K., and Thomas, G. B. (2001). Investigation of Winter-Weather Speed Variability in Sport Utility Vehicles. Pickup Trucks. and Passenger Cars. Transportation Research Record 1779.
13. Sigua, Ricardo G., Fundamentals of Traffic Engineering, Quezon City: The University of the Philippines Press, c2008
14. Unrau, D., and Andrey, J. (2006). “Driver response to rainfall on urban expressways.” Transp. Res. Rec., 1980, 24–30.