EMPIRICAL STUDIES ON TRAFFIC FLOW IN ADVERSE WEATHER CONDITONS

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Abstract- Transportation engineers should have coordination with meteorological department and try to study the effect of weather conditions on traffic flow. For better functioning of traffic operations engineers can use this knowledge. The aim of present work is to quantify the impact of rainfall, temperature, visibility and wind speed on traffic flow. Traffic and weather data were collected from Highway Traffic Management System installed at Jaipur Plaza in India on NH8 which connects Delhi to Mumbai. The length of the data is two years. In this research weather parameters have been categorized on the basis of daily variation and investigated their impact on traffic flow. Rain more than 10 mm/hr, visibility less than 1 km and temperature (less than 10^oc and more than 40^oc) showed traffic volume reductions of 14%-18%, 5%-10% and 2%-5% respectively. Further weather adjustment factor was computed as the ratio of the traffic volume under existing weather condition relative to the base key parameter. Finally models for weather adjustment factor for traffic flow have been developed corresponding to variation in rainfall, temperature and visibility. These findings indicate that the impact of rain is more significant than currently reported in the Highway Capacity Manual and therefore indicate the need to carefully examine freeway operation strategies during adverse weather events.

Index Terms- Weather, traffic flow, weather adjustment factor, capacity, visibility, model

1. INTRODUCTION

1.1 Background

Transportation activities are affected in many ways when severe weather conditions are existing in nature and also there is significant after effects of these weather events. Due to high winds usually thunder, rain or snow, cyclone or influx of water, traffic operations will be blocked and sometimes has to be removed from place of danger which will give heavy financial loss. Due to daily changes in weather events mobility of roads is affected and travelers feel unsafe. Due to low visibility there can be accidents. If there is high intensity rainfall, traffic jam will take place which will create delay, increase in travel time, more fuel consumption. FHWA (2006) reported that the occurrence of adverse weather increased overall travel time nearly 7 to 36 percent.

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For improvement in transportation system researchers should have approach to relevant data sets. By using these weather and traffic data sets they can develop model which will give the relation between traffic flows to specific weather events. These models will be useful in finding out present impact on transportation system and also for making long term plan. If such type of information is available with transportation managers, they can strengthen their system in three ways. Firstly by giving proper advice during weather events, secondly by controlling the effect of weather on traffic and thirdly by developing fruitful policy for future. This will also be helpful to regulate traffic flow and roadway capacity during weather events by modifying signal timings/plans and speed limits, closing roads and constructing circuitous routes.

1.2. Research Needs and Approach.

- The preceding literature review shows that there is an initial base of research regarding the impacts of precipitation (both rain and snow) and other weather events on macroscopic traffic flow parameters and system performance. However, the results of these studies in terms of weather impacts on speed, capacity and volumes are variable and often apply to certain traffic states, on particular type of facilities, and in specific locations. There is a need to improve and/ or expand our understanding of how these common weather events impact driving behavior and traffic flow under varying demands, on heterogeneous facilities and in different locations.

- It is necessary to relate measures of weather's relative intensity (e.g. mm of rain or snow fall per hour) to traffic flow, as there has been limited research on the issue.
- Much of the research work pertaining to weather impact is obtained from studies outside India. Hence research should be conducted to expand the limited guidance about the impacts of weather on traffic flow on urban and non urban roads in India.

1.3 Objective of the work

The overall goal of the present study is to understand the impact of weather conditions on traffic flow. In the light of above background the following are the specific objectives of the present work.
1) To quantify the impact of rainfall, temperature, visibility and wind speed on traffic flow.
2) Development of weather Adjustment Factor for traffic volume for each weather parameter.
3) To develop model which will correlate the traffic volume under existing weather condition to the normal condition due to changes in rainfall, temperature and visibility.

The purpose of present study is to inquire and determine the impact of adverse weather conditions on traffic flow characteristics in terms of percent changes so that traffic managers will be conversant with all these information which will be helpful to improve mobility and safety on the road networks.

2. PREVIOUS STUDIES

To address this issue Highway Capacity Manual 2000 gives information that adverse weather can significantly reduce capacity and speed. The manual categorized rain and snow as light and heavy but does not mention the intensity ranges which is the drawback of this study. For light rain manual recommends that there is percentage reduction of 0% in capacity and 2%-14% in speed respectively. For heavy rain it is stated that there is 14-15% reduction in capacities and 5-17 % reduction in speeds. Ibrahim and Hall (1994) have done significant work in this area and are also included in the highway capacity manual although duration of data was short.

Agarwal, M. (2005) in his paper describes the impact of rain, snow and pavement surface conditions on freeway traffic flow for the metro freeway region around the twin cities. The duration of the data was four years. He has classified the weather data by their intensities and has found out their effects on speed and capacity. Rain (more than 6.25 mm/hr), snow more than 12.5 mm/hr and low visibility (less than 0.5 km) showed capacity reductions of 10-17%, 19-27% and 12% and speed reductions of 4-7%, 11-15% and 10-12% respectively. Alhassan Hashim (2011) et al in their study examines the effect of rainfall on a highway straight section operating under free flow conditions and to evaluate the effect of changes in rainfall intensity on capacity of the section. Data for this study was collected from a two-way interurban arterial in Johr Bahru state of Malaysia. There is capacity loss of 8.14%, 50.3% and 31.09% for the rainfall intensity ranges of less than 2.5 mm/hr, 2.5-10 mm/hr and 10-50 mm/hr respectively. More work is required in this area to build confidence into these findings. Summary of rain effects on capacity, speed and traffic volume from different sources are given in tables 1, 2, 3, 4.

Table1. Impact on Volumes (Hanbali and Kuemmel, 1992)

Snowfall	Weekdays (Range of volume reduction)	Weekends (Range of volume reduction)
< 25 mm	7-17%	19-31%
25-75 mm	11-25%	30-41%
75-150 mm	18-34%	39-47%

Table 2. Summary of rain effects on capacity

Capacity Reduction	Capacity Reduction	Capacity Reduction	Capacity Reduction	Capacity Reduction
Researcher	Ibrahim and Hall	Brilon and Ponzlet	Smith	Prevedouros and Chang
Location	Toronto, Ontario	Germany	Hampton Roads, Virginia	Honolulu, Hawali
Year	1994	1995	2004	2004
Light	[no	12-47%	4-10%	8.3%

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Rain	value]			
Heavy Rain	14-15%	12-47%	25-30%	8.3%

Table 3. Summary of rain effects on speed

Speed Reduction	Speed Reduction	Speed Reduction	Speed Reduction
Researcher	Ibrahim and Hall	Kyte	Smith
Location	Toronto, Ontario	Idaho	Hampton Roads, Virginia
Year	1994	2001	2004
Light Rain	1.9-12.9 Km/h	9.5 Km/h	3-5%
Heavy Rain	4.8-16.1 Km/h	9.5 Km/h	3-5%

Table 4. Freeway Traffic Flow Reductions due to Weather (FHWA Report 2008)

Weather Conditions	Average Speed	Free Flow Speed	Volume	Capacity
Light Rain/Snow	3%-13%	2%-13%	5%-10%	4%-11%
Heavy Rain	3%-16%	6%-16%	14%	10%-30%
Heavy Snow	5%-40%	5%-64%	30%-44%	12%-27%
Low Visibility	10%-12%			12%

3. METHODOLOGY

The study area is National Highway 8 (Delhi- Jaipur) section managed by the National Highway Authority of India. The site selected for the study is located at Jaipur and is shown in figure 1. The study used a larger data of two years (from June 2009- August2011) of traffic and weather information. The location of Jaipur on NH-8 is given in figure 1

Fig. 1. Location map of NH-8 showing Jaipur

3.1 Data Collection

Traffic and weather data were collected from highway traffic management system installed at Jaipur plaza (Tikaria Village) on NH-8 which is passing through Delhi-Jaipur-Kishangarth- Ajmer- Mumbai. In the traffic data, classified traffic volume count per day was available. In the weather data average, minimum and maximum values of visibility in Km, temperature in ^{0}c and wind speed in m/s were available on daily basis.

Jaipur to Kishangarth Expressway is used on an average by 19000 vehicles a day. Most of them are heavy vehicles with 40% being multiaxle. However, there are no restrictions on who can use it. This project is part of the Delhi-Mumbai corridor of Golden quadrilateral on National Highway 8 which runs for 1428 Km between the capital and India's biggest city and port. The express way is also India's largest build-operate-transfer (BOT) highway project to date and is Constructed with a state of the art highway traffic management and toll system with two main plazas. It is described as not just a road, but a highway to progress and prosperity.

Connecting the heart of Rajasthan to the marble capital of the state – Kishangarh, the GVK Jaipur-Kishangarh Expressway Limited (GVK JKEL) project is located on the National Highway 8 (NH-8) between Jaipur and Kishangarh. It was the largest six lane BOT road project implemented by NHAI in INDIA. L&T was one of the contractor and developer of this project. He has installed and commissioned Toll and HTMS for the entire stretch. The construction was completed before the scheduled date and it started working in April 2005.

The highway traffic management system (HTMS) comprises state-of-the-art technology including an automatic traffic counter/classified system, emergency communication system at every 2 km, variable message signs (VMS) at six locations to guide and warn motorists about traffic and weather meteorological system and CCTV surveillance system at six locations. The HTMS is operated from a building overlooking the Jaipur Toll plaza, as is the toll control room which checks that the correct fee is being paid for the vehicle type. It provides information on weather and traffic flow and helps to reduce traffic congestion, environmental degradation and checks for potential accidents. Traffic counter and classifier are used to measure tolled traffic for audit purpose located on elevated roads at 2 locations.

Table 5. Project overview- HTMS system: HTMS comprises of 5 sub systems

Sub system name	Purpose	Location	Qty
Traffic counter and classifier	To measure tolled traffic for audit purpose	On elevated roads at 2 locations	3
Weather stations	To capture weather information for informing driving conditions for road users	At 3 locations spread over stretch	3
Transmission system	Provided at complete stretch of road, For connecting field equipment like CCTV,MET,ATCC,VMS to HTMS control room	Backbone cable laid through crash barrier of elevated sections	1 Set
CCTV	To view traffic at critical junctions at grade level (viewed from elevated road) as well as to view traffic on elevated sections	On poles at elevated roads to view elevated traffic.	11
Emergency call box	To provide facility for calling control room in case of emergency	At every 2 Km interval on elevated as well as road bellow	18 pairs

VMS	To display emergency messages, instructions to road users	On poles, elevated road, below road	13

Roadside logger suitable for 4 lane automatic vehicle classifier and counter are fitted on the road. Weather sensors are located within the range of 1 Km to traffic counter. In the weather data temperature, visibility and wind velocity were collected.

Rainfall data was collected from Indian Meteorological Department Jaipur for two years. IMD has set up stations for rainfall data collection at many places like Sanganer, Jaipur Tehsil etc. It has installed automatic rain gauge station at Sangamner near Airport which is collecting hourly rainfall data. Other sites are having daily data for Monsoon season (June, July, August, and September). Indian Meteorological Department (IMD) used to develop a high resolution daily rainfall data to meet the requirement of research community. Rain gauge stations are located within 5 km from road.

3.2 Data Set Construction

After collecting the weather and traffic data separately the two data sets were merged to form a data set that contained visibility, rainfall, traffic flow, temperature and wind speed respectively. Since the traffic data was available on daily basis, rainfall data has been categorized based on total rainfall per day which is mentioned below.

Type of rain	Daily rainfall (mm)
No Rain	0
Light Rain	0-20
Medium rain	20-40
Heavy Rain	>40

Visibility and wind speed data have been classified on the basis of daily variation. Visibility data will be grouped depending on minimum to maximum variation in a day as < 0.2 km, 0.2-2 km, 2-4 km and 4-6 km respectively. Wind velocity will be classified as 0-4 m/s, 4-6 m/s, 6-10 m/s and >10 m/s respectively. Range of temperature data classification will be < 5^0c, 5-10^0c, 10-20^0c, 20-35^0c and 35-45^0c respectively depending on minimum to maximum value of temperature in 24 hours.

In order to achieve sufficient observations to conduct statistical analysis the data corresponding to each weather type were grouped in a manner to provide as many as replications as possible. For each whether category there was sufficient data to cover all traffic states. Consequently, a seven day period was considered for initial grouping which was selected to ensure sufficient data coverage for the full range of traffic conditions. In the event that a seven day grouping did not provide sufficient data, additional days were included until sufficient data coverage was achieved. Rainfall data was available at three locations in Jaipur but for analysis purpose the data at the location which is nearer to Jaipur plaza has been considered.

3.2.1 Data set construction of traffic volume

There were many days available for no rain, light rain, medium rain and heavy rain conditions. For estimating traffic volume for all categories average value of all the days has been taken which is given in table (6) in the third column. Finally percentage reduction has been calculated with respect to no rain condition which is given in bracket in column (3), because adverse weather can reduce demand on the transportation system.

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3.2.2 Estimation of freeway capacities

For calculating the capacity of the road the method described by smith et al (12) was referred. The paper recommends that mean of the highest 5% of the observed flow rates by a detector would represent the freeway capacity which confirms that the maximum number of vehicles will clear through the road section at least 95% of the time. Additionally this approach fits with primary objective of this research to determine the percentage of changes in freeway capacities due to rain.

3.3 Data Analysis and Model Development

After integrating weather and traffic data comparison will be done for different categories of rain and various ranges of temperature, wind speed and visibility respectively. The base case was considered to be the no rainfall condition with a visibility greater than or equal to 6 km. Percentage reductions in traffic volume for the change in weather conditions has been summarized in the result.

To complete this step of the methodology, a statistical test was used to determine if the percentage changes in capacity based on rainfall intensity were significant. Scheffe's test was used for this purpose because sample sizes from each population were not equal. The test was conducted at the 0.05 significance level

Weather adjustment factor was computed as the ratio of the traffic volume under existing weather condition relative to the base key parameter. Thus weather adjustment factor corresponding to variation of rainfall, temperature, visibility and wind speed will be developed. Having computed weather adjustment factor for traffic volume, a regression analysis was utilized to build a model that predicts the weather adjustment factor (WAF) for a given rainfall, visibility level and temperature respectively.

4 RESULTS AND DISCUSSION

4.1 The research reported in chapter quantifies the impact of adverse weather on traffic stream behavior by finding out percentage reductions in traffic volume and capacity for different weather conditions. Results of the research are summarized in table 6.

Table 6. Percentage reductions in traffic volume due to varying weather type and intensities.

Weather Variable	Range	Traffic volume (Vehicles/day) Percentage reductions	Capacity (Vehicles /day) Percentage reductions
Rain	0 0-20 mm 20-40 mm >40 mm	20733 (0) 19108(7.8) 18413(11.2) 17389 (16.2)	23976 (0) 21531 (10.2) 19686 (17.9) 18451 (23)
Temperature	20-35 0c 10-20 0c 5-10 0c <5 0c 35-45oc	20927 (0) 20844 (0.40) 19917 (4.8) N.A 20129(3.8)	22074 (0) 21683 (1.8) 21036 (4.7) N.A 21861 (1)
Visibility	4-6 km 2-4 km 0.2-2 km <0.2km	20771 (0) 20619 (0.7) 19150 (7.8) N.A	22070 (0) 22000 (0.3) 21000 (4.8) N.A
Wind Speed	0-4 m/s 4-6 m/s 6-10 m/s >10 m/s	20694 (0) 20503 (0.92) 20150 (2.5%) N.A	22396 (0) 22390 (0.03) 22371 (0.1) N.A

Since so many days are available for no rainfall, light rainfall, medium rainfall and heavy rainfall respectively, hence average of all the days has been found out. The column 3 represents average value of traffic volume of all the days of different categories of rain, range of temperature, visibility and wind speed. The base case considered was no rain (0 mm), temp 20-35 ^{0}c, visibility 4-6 Km and wind speed 0-4 m/s. Percentage reductions are given in bracket in the above table (6)

Rain: The site showed statistically significant traffic volume reductions of 5-9%, 10-14% and 14-18% and capacity reductions of 8-12%, 15-20%, and 22-25% in case of light rain, medium rain and heavy rain respectively. The results of the Scheffe's test indicate that the capacity reduction at each rainfall intensity level is statistically significant.

Temperature: For finding out the percentage reduction in traffic volume due to range of temperature base case considered was average value of traffic volume for the range of temperature 20-35 ^{o}c. For the range 5-10 ^{o}c and 35-45 ^{o}c, the value of percentage reductions in traffic volume were 2-5% and 2-4% and capacity reductions were 1-2% and 3-6% respectively.

Visibility: The data for visibility is categorized depending on minimum to maximum value in 24 hours. Due to low visibility (0.2-2 km) percentage reduction in traffic volume and capacity were in the range of 5-10% and 4-6% respectively.

Wind speed: Percentage reduction in traffic volume for the wind speed (6-10m/s) was in the range of 2-3%. However no statistically significant differences in capacities among different ranges of wind speed were found.

4.2 The research reported in this section quantifies the impact of adverse weather on traffic stream behavior by developing weather adjustment factors for traffic volume which is key traffic stream parameter Having computed weather adjustment factors for traffic volume a regression analysis was utilized to develop a model that predicts the weather adjustment factor (WAF) for a given precipitation type (rain), temperature and visibility level for traffic volume. The general model that was considered was of the form:

Weather Adjustment Factor for traffic volume as a function of rainfall intensity

$$WAF= C_1+C_2 R+ C_3 R^2 \quad (1)$$

Weather Adjustment Factor for traffic volume as a function of visibility

$$WAF= C_1+C_2 V + C_3 V^2 \quad (2)$$

Weather Adjustment Factor for traffic volume as a function of temperature

$$WAF= C_1+C_2T+C_3T^2 \quad (3)$$

Weather Adjustment Factor for traffic volume as a function of rainfall and visibility

$$WAF = C_1+C_2R + C_3 R^2 + C_4 V+ C_5V^2 + C_6 Vi \quad (4)$$

Where WAF = weather adjustment factor, R is the rainfall in mm, V is the visibility, T is the temperature, C_1, C_2, C_3, C_4, C_5 and C_6 are calibrated model coefficients, Vi is the interaction term between visibility and rainfall intensity. In all models the interaction term was found to be insignificant and is not discussed for further analysis.

A regression analysis was performed using the Minitab software. First step in the analysis is determining the coefficients. Second step is checking the model significance by using Anova test. The null hypothesis (Ho) was that all model parameters were zero (i.e., C_2 = ---- = Cn = 0), n is the number of model parameters, while the alternative hypothesis (H1) was that the model parameters were not zero (Cj) for at least one j. Since the P-value in the ANOVA test result is < 0.05, it was concluded that at least some of the model parameters (C_2 ----------C_n) were not equal to zero. An example of ANOVA test result for regression between WAF (traffic volume) and rainfall is given in table 7.

Table 7. ANOVA Test Result for WAF (traffic volume) as a function of rainfall

Source of variation	Degree of Freedom	Sum of Square	Mean Square	F	P
Regression	1	.02139	.02139	27.86	.00
Residual Error	21	.01613	.00076		
Total	22	.03753			

Third step in the regression analysis is checking the significance of individual coefficient in the model. For this the value of P has been calculated for each coefficient. A P value less than 0.05 presented against each coefficient means null hypothesis could not be accepted, implying that independent variable was significant and could be included in the model. The various models that were developed for traffic volume are summarized below in table 8.

Table 8. Regression Analysis Summary Results for equations between Weather Adjustment Factor for traffic volume and weather parameters.

Weather parameter	Coefficient value (p-value) C1	Coefficient value (p-value) C2	Coefficient value (p-value) C3	Coefficient value (p-value) C4	Coefficient value (p-value) C5	Coefficient value (p-value) C6	P value anova test	R2 Adj	Normality test: AD	Normality test: p-value
Rain (R)	0.942 (0.00)	0.00147 (0.000)	No value	No value	No value	No value	0.00	0.55	0.439	0.261
Visibility (V)	0.715 (0.00)	0.037 (0.00)	No value	No value	No value	No value	0.00	0.68	0.289	0.565
Temperature (T)	0.6677 (0.00)	0.022 (0.00)	-0.00044 (0.00)	No value	No value	No value	0.001	0.66	0.19	0.874
Rain and Visibility (R&V)	0.837 (0.000	-0.0016 (0.013)	No value	0.0244 (0.10)	No value	No value	0.008	0.37	0.134	0.974

In the regression analysis it is assumed that the residuals should be normally distributed and hence this test is performed on the residuals. For this purpose the value of P is taken as 0.05. If in the normality test the calculated value of P is more than 0.05, the data will be normally distributed. Fig.2 presents a normal probability plot for the residuals calculated for the model developed between WAF for traffic volume and rainfall. The plot also shows the Anderson Darling goodness –of- fit test results. The Anderson- Darling statistic is a measure of how far the points fall from the fitted normal line. The statistic is a weighted squared distance from the plotted points to the fitted line with larger weights in the tails of distribution. A smaller Anderson- Darling statistic indicates that the distribution fits the data better. The Anderson- Darling test's P- value >0.05 indicates that there was no evidence that the residuals were not normally distributed. As summarized above in table 8 all data sets provided no evidence that they were not normally distributed.

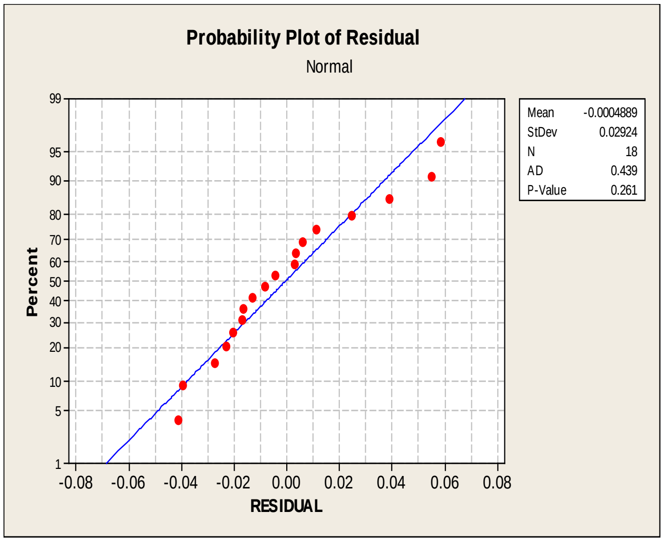

Fig. 2. Residual Normality Test for Rain

For illustration purposes by presenting various models graphically , it has been found that the traffic flow is sensitive to rainfall and traffic volume decreases as the visibility level decreases. The graph of WAF versus temperature shows that maximum value of WAF is at 25^{o}c and it decreases when temperature changes from 25^{o}c to 0^{o}c which indicates that traffic volume deceases when temperature goes on lower side. Similarly traffic volume also decreases when temperature goes on higher side i.e. more than 30^{o}c and is shown in figure 3. The variation of WAF with rainfall and visibility is illustrated by a three dimensional contour plot in fig. 4. When the value of rainfall is 55-66 mm and visibility is 0 to 0.4 km, the table in the figure 4 gives the value of WAF < 0.75 which indicates that traffic volume will be less for higher range of rainfall and lower range of visibility. Exactly opposite is the case when WAF > 0.95.

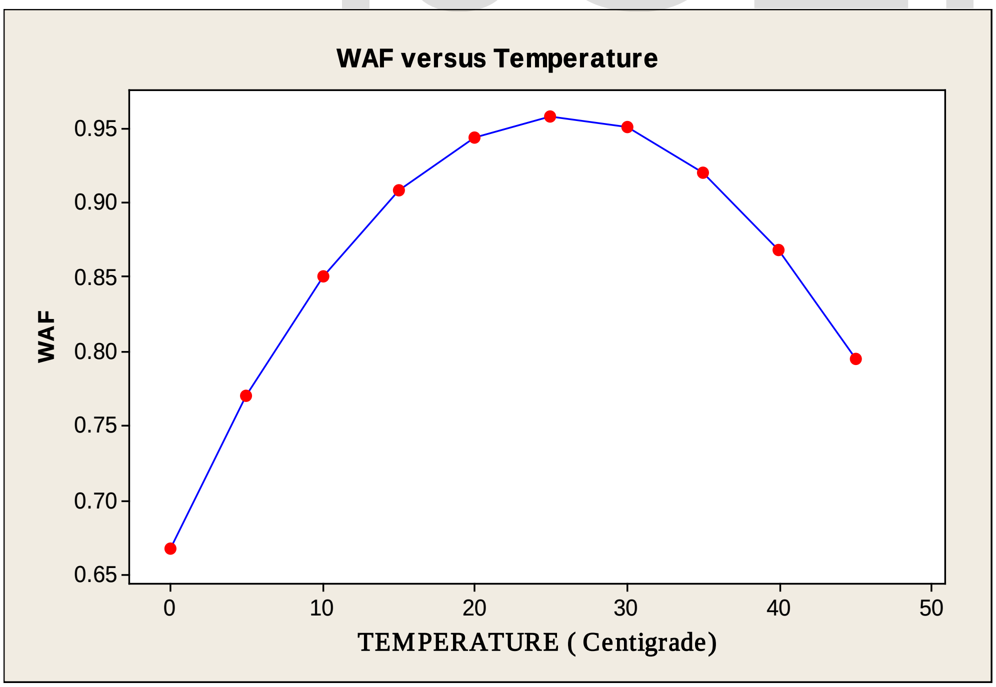

Fig. 3. Variation of Weather Adjustment Factor with Temperature

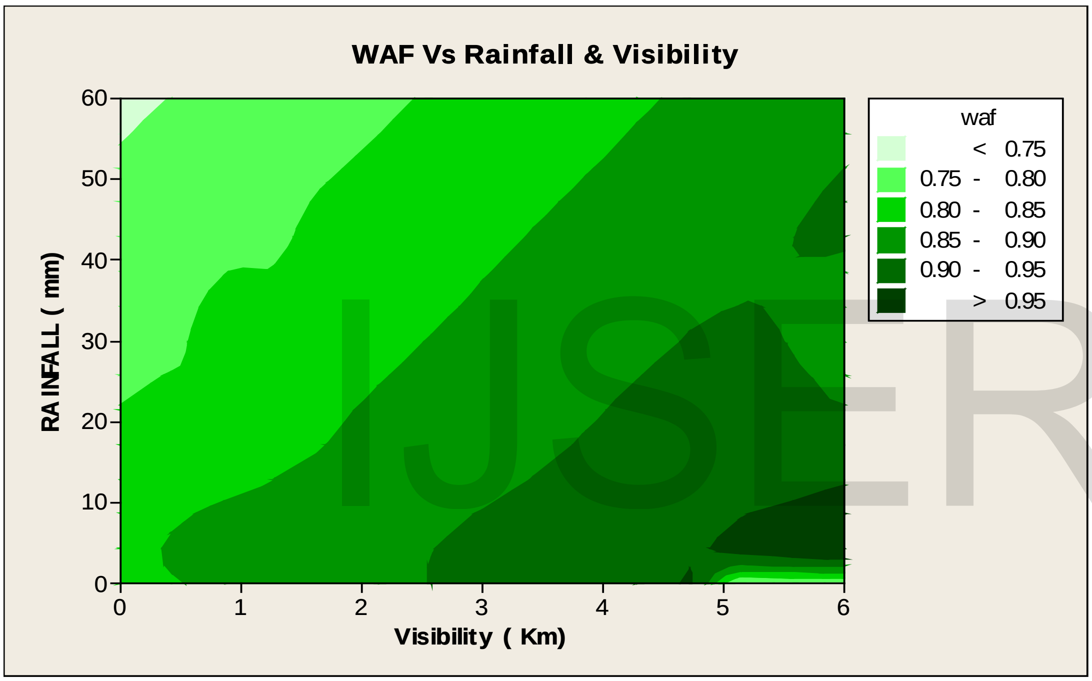

Fig. 4. Variation of Weather Adjustment Factor with rainfall and visibility

5 CONCLUSIONS

The research result reported in the previous section quantified the impact of adverse weather (rainfall, temperature, visibility, wind speed) on traffic flow. The analysis was conducted using weather data and loop detector data obtained from Jaipur Toll Plaza. The study demonstrated the following.

This research found that for light rain (0-20 mm) there is percentage reduction of 5-9% in traffic volume and 9-11% in capacity respectively. The change in capacity is significantly higher as compared to Highway capacity manual 2000.

The impact of heavy rain on capacity was found to be as percentage reductions of 21-26% which is greater as compared to Highway capacity manual.

Cold temperature having minimum to maximum temperature per day (5-10°c) and hot temperature (35-40°c) showed 2-5% and 2-4% percentage reductions in traffic volume respectively.

Lower visibility having daily variation from 0.2-2 Km caused traffic volume reductions of 5-10% and capacity reductions of 4-6% which is lower as compared to Agarwal's study at Minnesota U.S.A.

Winds in the range of 5-10 m/s in Opposite Directions of travel did not cause a significant decrease in traffic volume.

Finally in the study models for traffic flow have been developed. Weather Adjustment Factor for traffic volume varies as a function of daily rainfall, visibility level and temperature. By multiplying WAF to traffic flow at normal condition we can get traffic flow at existing weather conditions. Overall the results of analysis show how weather types and their intensities impact traffic flow. This research provides additional guidance regarding quantitative estimates of traffic flow due to varying temperature, rainfall and low visibility conditions. Quite clearly weather matters need to be taken into account when evaluating system operation and capacity in urban and non urban areas with significant number of days with adverse weather.

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