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Development of Traffic Flow Model: Case Study of Kathmandu Ring Road

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Abstract:
Macroscopic flow models represent how the behavior of one parameter of traffic flow changes with respect to other. The most important among them is relationship between speed, flow and density. Flow-Speed-Density plays an important relationship in dynamic macroscopic modeling. The relationship among flow, speed and density has been foundation of traffic engineering which is derived from the concept of flow. Eight different speed-density models were calibrated using field survey data considering free flow condition that is Greenshield, Greenberg, Polynomial, Northwestern, Pipes-Munjal, Underwood, Drake with Taylor series and Underwood with Taylor series.
An anticipated traffic flow in an urban road network is creating various problems associated with the speed, delay and congestion. Therefore, any improvement of transport system performance requires the adequate concepts on the principles of flow pattern or the representation of traffic flow phenomena for the particular local conditions.
The study aims at the development of an appropriate traffic flow model with specific parameter from the field measurement of traffic parameters. The study has taken the most important road-section of Kathmandu Ring Road (KRR) for calibrating the traffic flow models in consideration. Furthermore, these models have been validated to define the most suitable one for the specific case of KRR
Traffic flow parameters were extracted from the video-record of the field survey conducted for five days from 8:00 to 11:00 for the calibration of traffic flow models. The calibrated models were tested for the validation with the traffic flow data of another road-section. Data extracted from the video-record were analyzed using the statistical tool i.e. R (version 3.6.1) to calculate the best fit model on this road section.
The study showed that Underwood with Taylor series model proved to be the best fit model with reasonable estimate of free flow speed and density. The model can be used for the estimation of the capacity and service volume of road which helps in traffic operation and management. It helps to predict the future scenario of speed and density relationship.
Key words: *Space mean speed, density, traffic flow model, free space mean speed,*

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I. Introduction

Traffic flow theory is very complex, which requires more than casual observations. Speed tends to decrease when flow increases and vice versa. There are more other variables for describing the traffic flow such as speed, density, volume (flow), headway, spacing, occupancy, clearance and gap. These are important for the elaboration of efficiency of overall traffic system and as well as planning for improvement of highway network. Theoretically, traffic flow theory has been understood as the analogies of fluid flow, some examples of macroscopic model are Greenshields model, Greenberg model, Underwood model, Pipes- Munjal Generalized model, Van Aerde model, Polynomial model, Drake model. Based on these theories, various macroscopic models have been developed for studying steady state of traffic flow. These models consider the response of each individual vehicle in disaggregate manner.

Furthermore, speed-flow-density relationship are useful for highway design and planning process as they provide a quantitative estimate of the change in speed as function of anticipated change in traffic demand. These concepts are useful for explaining the contemporary issue such as congestion in an urban area and developing the pertinent solutions.

Kathmandu, the capital city of Nepal is gradually facing traffic problems manly traffic congestion which affects the reduction in efficiency of transport network. The reduction in overall travel time is major concern for individual urban dweller. Ultimately these issues can be termed as the reduction in Level of Service (LOS) of the road network. The traffic management approaches for improving the LOS are mainly basically related to the speed, traffic volume and the density along the particular section of road. This study has been focused on the development of traffic flow model for the Kathmandu Ring Road (KRR). For this purpose, traffic flow parameters have been measured from the field observations and correlated for the most suitable model calibration. Furthermore, the model has been validated by the use of additional data obtained from the field.

II. Literature Review

Traffic flow models:

Modeling the speed-flow-density relationship began with the linear model developed by Greenshields. A study in Highway (Roess, et al., 2009) has initiated to revise or improve such an oversimplified relationship. These efforts include Greenberg's model (Greenberg, 1959), the Underwood model (Underwood, 1961), Northwestern (Drew, 1968), Pipes- Munjal Generalized model (Pipes, 1967), Del Castillo and Benitez modified Greenshield Model (Jaya- Krishan and Tsai, 1995), Van Aerde model (Van Aerde, 1995). These models are shown in Table 1.

Table 1: Single- Regime Speed- Density Models (Source: Wang et al, 2011)

S. N.	Single- regime Model	Function	Parameters
1	Greenshields Model (1935)	$V = v_f(1 - \frac{k}{k_j})$	v_f, k_j
2	Greenberg Model (1959)	$V = v_m log\frac{k_j}{k}$	v_m, k_j
3	Underwood Model (1961)	$V = v_f \exp(-\frac{k}{k_o})$	v_f, k_j
4	Northwestern Model (1967)	$V = v_f \exp\left(-\frac{1}{2}\left(\frac{k}{k_o}\right)^2\right)$	v_f, k_o
5	Drew Model (1968)	$V = v_f\left[1-\left(\frac{k}{k_j}\right)^{n+\frac{1}{2}}\right]$	v_f, k_j
6	Pipes–Munjal Model (1967)	$V = v_f\left(1-\left(\frac{k}{k_j}\right)^n\right)$	v_f, k_j
7	Newell Model	$V = v_f[1 - exp]\left(-\frac{\lambda}{v_f}\left(\frac{1}{k}-\frac{1}{k_j}\right)\right)$	v_f, k_j, λ
8	Modified Greenshields Model	$V = v_o + (v_f - v_o)\left(1-\frac{k}{k_j}\right)^\alpha$	v_f, k_j, v_o
9	Del Castillo Model (1995)	$V = v_f\left\{1 - exp\left[\frac{c_j}{v_f}\left(1-\frac{k_j}{k}\right)\right]\right\}$	v_f, k_j, c_j
10	Van Aerde Model (1995)	$k = \left(\frac{1}{c_1 + \frac{c_2}{v_f - v} + c_3 v}\right)$	c_1, c_2, c_3, v_f
11	MacNicholas Model (2008)	$V = v_f\left(\frac{k_j^n - k^n}{k_j^n + mk^n}\right)$	v_f, k_j, n, m

Where:

v - Speed, v_0 – initial speed, k - density, v_f - free-flow speed, k_j - jam density

The comparison of these models with the position of empirical data is shown in Figure 1.

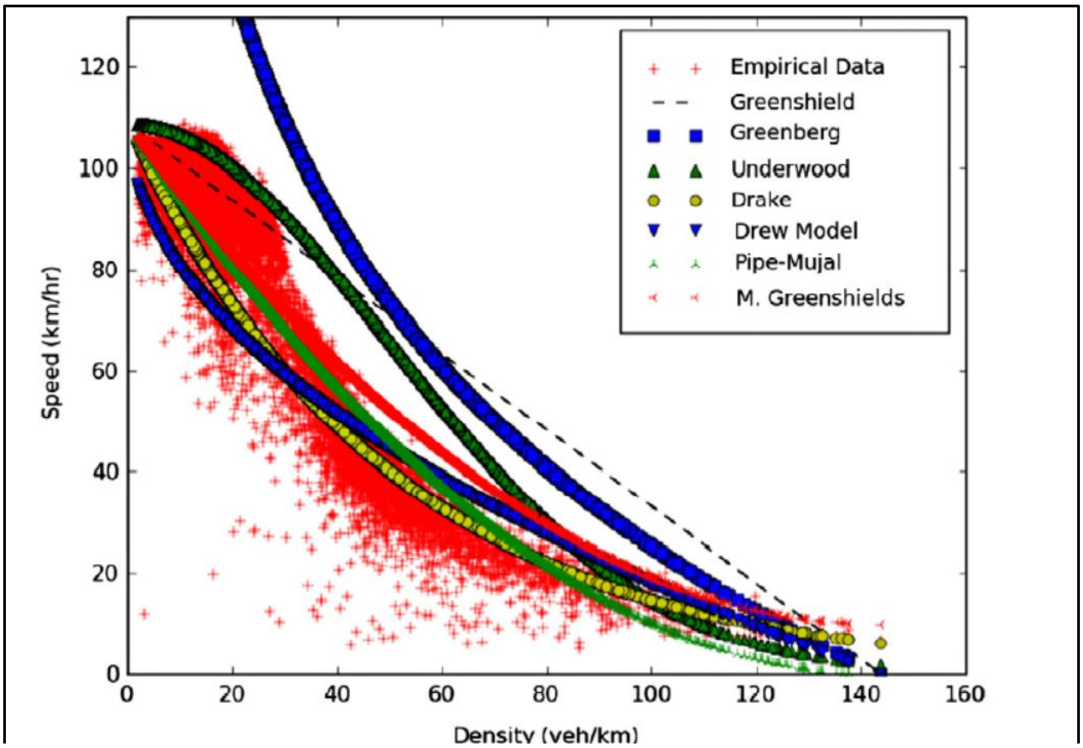

Figure 1: Performance of Single-Regime Models (Source: Wang et al. 2011)

The main concern of the existing speed- flow- density model is their limited capacity to satisfy both criteria at the same time: mathematical elegance and empirical accuracy i.e. attractive mathematical simplicity and sufficient to match empirical observations (Roess, et al., 2009). In 1955, Light hill and Whitham developed a theory that describes the traffic flow on long crowded road using a first- order fluid dynamic model. Four year later, (Greenberg, 1959) developed a logarithmic speed- density model and was later found that this model bridged the gap between macroscopic model and microscopic car following models. The disadvantages of Underwood model (Underwood, 1961) are prediction of infinity jam density and availability of optimum density from empirical observation. Ludovic Leclercq concerned only on urban street rather than on freeway. The Drew model (Drew, 1968), Pipes- Munjal model (Pipes, 1967) and modified Greenshield model (Jaya Krishnan and Tsai, 1995) proposed Greenshield model shortcomings because they are varied form of original assumptions.

The Van Aerde speed- density model was derived from the Van Aerde car-following model (Van Aerde, 1995). But gradient model did not match empirical observation in this study.

Van, (Van Aerde, 1995) successfully applied and calibrated single regime speed flow model for both freeways and arterials in both the micro and macro domains. Van Aerde model is flexible enough to allow speed at capacity to be set in excess of Greenshield value and allow jam density to be specified. This model was able to describe both the congested and un-congested traffic condition through a single continuous relationship.

Shah (Shah, et al., 2011) performed the selection of best suitable traffic model, in Anand-Vidyanagar road. This research selected an efficient and suitable traffic flow model to predict the space mean speed with respect to mean free flow speed. Regression Analysis was used on this research. The correlation factors with Greenberg and Greenshields were found as 0.956 and 0.860 respectively. Therefore, Greenberg model was found more suitable than Greenshields.

Tiwari (Tiwari & Marsani, 2014) proposed a conventional Underwood model on Jadibuti-Suryabinayak section. However, the model cannot be used for predicting speed at high densities. This research addresses the necessity of understanding the relationship between traffic flow parameter (speed- flow- density). Syed Omar and Ch. Mallikarjuna (Syed & Ch., 2016) proposed the implication of the observation of the data corresponding to macroscopic traffic variable in the context of heterogeneous traffic condition.

Passenger Car Unit (PCU):

The PCU may be considered as the measure of the relative space requirement of a vehicle class compared to that of passenger car under a specified set of roadway, traffic and other conditions. The factors affecting PCU values are vehicle characteristics, transverse and longitudinal gaps, traffic stream characteristics, roadway characteristics, regulation and control of traffic, environmental and climatic conditions etc. In the context of Nepal, the PCU values for each type of vehicles are mentioned below:

Table 2: Equivalency Factors (Department of Roads, 2013)

S.N.	Vehicle Type	Equivalency Factor
1	Bicycle, Motorcycle	0.5
2	Car, Auto Rickshaw, SUV, Light Van and Pick up	1
3	Light (Mini) Truck, Tractor, Rickshaw	1.5
4	Truck, Bus, Minibus, Tractor with trailer	3
5	Non-motorized carts	6

Level of Service:
Traffic performance on the highway is expressed in terms of Level of Service (LOS). LOS can be defined as the quality of traffic flow on a roadway as perceived by the road users (CSIR-Central Road Research Institute , 2017). LOS tries to answer how good the present traffic situation on a given facility. It can be defined at six levels from “A” to “F”.

III. Research Methodology

Research Approach:
The study explores the problem using analytical research strategy. The study on the speed-flow-density relationship was based on the mathematical elegance and empirical accuracy. The urban traffic flow related data collected from the field observation enabled the entire modeling process. Primary data were collected from image analysis of video graphic survey. The observation points were plotted, and analysis was done in ***R*** programming to get the required research result.

Study Area:
Balkhu-Sanepa section of Kathmandu Ring Road (KRR) was taken for the study. This road section is located in the institutional and business purposes. The length of section is 150 m and straight in alignment.

Figure 2: Study area (Google Map)

The Balkhu-Sanepa road section is straight enough which is illustrated in Figure 2. Taking larger distance for density measurement might not be realistic which lead to parallax error while extracting speed and density data. Thus 150 meter length was considered for the field measurement.

Figure 3: photograph of study road section

Traffic flow characteristics data were collected as the Primary Data set from the field survey. These data consist of both lateral and longitudinal distribution of vehicle in traffic stream. Field survey was done for primary data collection. The primary data mainly considered for the research are as:
Speed: the speed of the individual type of vehicle was calculated from time elapsed for passing the entry and exit of 150 m length of the study road section.
Flow: Traffic flow is a stochastic process with random variations in vehicle and driver characteristics. Vehicle number was counted using the video records for the unit time.
Density: It is the number of vehicle for the given instant located along the unit length of road as one kilometer. The numbers of vehicles snapped within the 150 m long study road-section were noted and converted the field density for one kilometer.
The field survey was conducted in 15-19 December, 2019. The field data capturing was done from 8:00 to 11:00 AM in morning.
Basic relations among the traffic flow parameters and other calculations were performed as per the (CSIR-Central Road Research Institute , 2017) and Nepal Road Standard 2013 ((Department of Roads, 2013).
The space mean speed was calculated by using the relationships:

$$V_s = \frac{(3.6*n*L)}{\sum t_i}$$

Where,

- V_s = Space mean speed (Kmph)
- n = number of samples taken
- L= length of road section (m)
- $\sum t_i$ = sum of travel time of observed vehicle (sec)

The recorded video was replayed on large screen monitor and 15 minutes classified traffic flow counts were made (Roess, et al., 2009). To ensure accuracy in the count, vehicles of one particular category were counted in one round of play of the video and the video was recounted as many times. Then, the traffic flow count was recorded by making separate column for different vehicles categories in Microsoft excel.

The data analysis was performed by using excel sheet and statistical tool i.e. R (version 3.6.1) to calculate the best fit model for traffic flow along the study road-section. Then, the extracted data was first used in calibration of various model such as Greenshield, Greenberg, Underwood, Polynomial, Drake, Pipes- Munjal, Modified Drake Model and Modified Underwood Model. Based on goodness of fit (R^2 value) and realistic estimate of free flow speed and jam density the most suitable model was recommended on for this study road-section.

The additional field data recorded from 22 to 23 December was used for the validation of the models. Validation in different road section compared to the one where calibration is done helps to check the performance of the model in different scenario. The validation process was used to compare observed and field speed measurement. The details pertaining to the statistical validation through the t-test for different parameters:

speed, flow and density. The estimated t- statistics, p and t- critical values obtained from standard t- distribution table for 5% level- of- significance (95% confidence level) along with their respective degree of freedom.

IV. Results And Discussions

Data from study road-section are used to calibrate the traffic flow models defining the best fitted one. The speed and density were calculated from the data extracted from the video-record of the study road section. The speed and density data are shown in Table 3.

Table 3: Speed and density data calculated from video-record of the study road-section

Day and Date	Time	Average Speed (Kmph)	Average Density (veh/km)
15th December (Sunday)	9:00 - 9:15	52.66	39
	9:15 -9:30	50.04	47
	9:30- 9:45	51.93	42
	9:45-10:00	51.73	39
	10:00-10:15	52.49	41
	10:15- 10:30	53.16	26
	10:30-10:45	53.92	21
	10:45-11:00	54.32	18
16th December (Monday)	7:50-8:05	58.99	11
	8:05-8:20	53.89	21
	8:20-8:35	56.63	14
	8:35-8:50	57.33	13
	8:50-9:05	55.05	24
	9:05-9:20	53.78	31
	9:20-9:35	53.14	27
	9:35-9:50	55.54	18
	9:50-10:05	53.31	26
	10:05-10:20	53.87	38
	10:20-10:35	53.19	26
	10:35-10:50	52.86	40
17th December (Tuesday)	7:50 - 8:05	54.14	25
	8:05 - 8:20	55.91	14
	8:20 - 8:35	55.74	16
	8:35 - 8:50	52.21	40
	8:50 - 9:05	51.51	36
	9:05 - 9:20	52.64	32
	9:20 - 9:35	53.06	31
	9:35 - 9:50	53.22	31
	9:50 - 10: 05	53.86	32
17th December (Tuesday)	10:05 - 10:20	52.72	31
	10:20 - 10:35	53.96	25
	10:35 - 10:50	54.42	24
18thDecember(Wednesday)	8:09- 8:24	55.11	22
	8:24- 8:39	53.98	24
	8:39- 8:54	55.53	24
	8:54-9:09	54.25	21
	9:09-9:24	52.41	32
	9:24-9:39	59.94	8
	9:39-9:54	51.56	38
	9:54-10:09	51.45	39
	10:09 -10:24	53.01	27
	10:24-10:39	50.79	46
	10:39-10:54	51.45	43
19thDecember(Thursday)	7:53 - 8:08	57.63	12
	8:08 - 8:23	54.70	21
	8:23 - 8:38	54.41	24
	8:38 - 8:53	51.89	36
	8:53 - 9:08	52.16	33
	9:08 - 9:23	52.76	36
	9:23 - 9:38	52.97	32
	9:38 - 9:53	52.51	43
	9:53 - 10: 08	51.67	47
	10:08 - 10:23	53.28	35
	10:23 - 10:38	54.02	21
	10:38 - 10:53	53.88	33

Model formulation:

The speed and density data were plotted for the calibration of various models as described in the literature review. The most common model the Greenshields model is shown in Figure 4. The other parameters of Greenshields model are calculated as below:

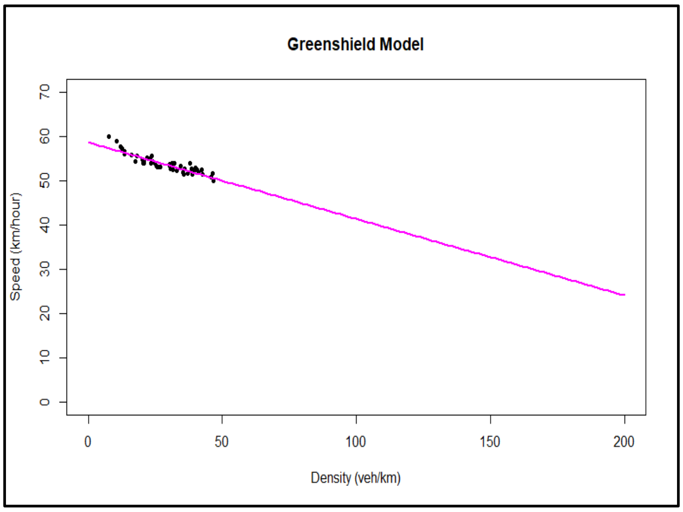

Figure 4: Greenshields Model fit

The Greenshield model was formulated by using R programming as:

$$V = 58.617 - 0.1726K$$

Note: Coefficient of Determination R^2= 0.7908; Degree of Freedom = 53; Residual Standard Error = 0.8874; P Value < 2.2 *10^{-16} ; F- Statistic = 200.4.

$$V = 58.617\left[1 - \frac{K}{339.69}\right]$$

Where,

Free flow speed (v_f) = 58.617 Kmph

Jam density (k_j) = 339.697Veh/Km

Density and speed corresponding to maximum flow can be obtained by $\frac{dq}{dK}$ =0 which yields

Speed corresponding to maximum flow (v_O) = $\frac{v_f}{2}$ = 29.305 Kmph

Density corresponding to maximum flow (K_O) = $\frac{k_j}{2}$ = 169.845 Veh/Km

Basic Parameters of this linear model are free flow speed and jam density which are obtained as 58.61 kmph and 339.69 Veh/km respectively. Velocity corresponding to maximum flow and density corresponding to maximum flow can be obtained by $\frac{dq}{dK}$ = 0. Speed at capacity is obtained as 29.3 kmph and density at capacity is obtained as 169.84 Veh/km.

The coefficient of determination is found to be 79.08% which is strong fit. But Greenshield model is linear and valid only in moderate traffic conditions. In this model, linear relationship between speed and density is supposed but in field such relationship is difficult to obtain. Hence, other models like Greenberg model, Underwood model, Polynomial model, Drake model and so on are introduced.

The calibration results of various traffic model of morning data (8:00 am to 11:00 am) is summarized in

Table 4. It is compared in terms of free flow speed (v_f), jam density (k_j), speed corresponding to maximum flow (v_O), density corresponding to maximum flow (K_O) and R^2 Value.

Similarly, other models have been plotted and basic parameters were calculated for each model. The summary of the calibrated models is shown in

Table 4. Each model are characterized by the free mean speed, density, and coefficient of determination.

Table 4: Calibrated traffic flow models by using the morning data

S.N	Model	Equation	Calibration	v_f Kmph	k_j (Veh/Km)	v_o Kmph	K_o Veh/Km	R^2 Value
1.	Greenshield	$V = v_f(1 - \frac{k}{k_j})$	V = 58.61 (1- $\frac{K}{339.69}$)	58.61	339.69	29.301	169.845	0.7908
2.	Greenberg	$V = v_0 log\frac{k_j}{k}$	V = 4.4375 ln ($\frac{4775455.882}{K}$)	-	4775455.882	4.4375	1756792	0.8733
3.	Polynomial	V=a+b*K+c*K^2	V= 0.0046523*K^2 – 0.4348364*K+61.86	61.86	-	-	-	0.8567
4.	Northwestern	$V = v_f exp(-\frac{1}{2}(\frac{k}{k_0})^2)$	V = 56.26 exp ($\frac{-K^2}{19357.336}$)	56.26	-	34.12	98.38	0.6962
5.	Pipes-Munjal (n=2)	$V = v_f\left(1 - \left(\frac{k}{k_j}\right)^n\right)$	V = 56.23 $(1 - \frac{K^2}{201336.412})$	56.23	141.90	37.485	81.93	0.6821
6.	Underwood	$V = v_f exp(-\frac{k}{k_0})$	V = 58.75 exp ($\frac{-K}{314.812}$)	58.75	-	21.61	314.812	0.7992
7.	Drake with Taylor Series	$V = V_f(1 - \frac{K^2}{2*K_c^2} + \frac{K^4}{8*K_c^4} - \frac{K^6}{48*K_c^6})$	V = 59.38 (1- $\frac{K^2}{3977.23} + \frac{K^4}{5364046.97} - \frac{K^6}{2.126*10^{10}}$)	59.38	79.667	35.875	44.59	0.8642
8.	Underwood with Taylor Series	$V = V_f * e^{-K/Kc}$	V = 66.632 (1- $\frac{K}{61.56} + \frac{K^2}{2192.82} - \frac{K^3}{215219.64}$)	66.632	98.2541	22.211	61.56	0.8904

Polynomial model does not yield the realistic data. Whereas, Greenberg model yields high jam density and low speed at maximum flow despite high R^2 value. Similarly, underwood model and northwestern model does not yield corresponding jam density. Underwood model cannot be used for predicting speed at high densities. Greenberg model is in logarithmic form, Greenshield model is in linear form whereas, Underwood model is in exponential form and so on. As different model are in different form and they are linearized for model calibration, so it cannot be compared residual standard error to each other. If error is less, coefficient of determination should be increased. But, in reality it could not be observed this from above calibration data.

Validation of Calibrated Models:

For validation process, speed-flow-density data were collected from another road section than the study road section. The data were collected during 22-23 December, 2019. The observed speed data were used for the validation of the calibrated models. The field data of speed and density is shown in TABLE 5

.**Table 5:** Speed density data for validation

Day and Date	Time	Average Speed (Kmph)	Average Density, (veh/km)
22nd December (Sunday)	7:56-8:11	53.78	21
	8:11-8:26	55.69	18
	8:26-8:41	52.82	34
	8:41-8:56	52.42	23
	8:56-9:11	52.89	37
	9:11-9:26	51.81	37
	9:26-9:41	50.91	40
	9:41-9:56	52.15	42
	9:56-10:11	52.57	40

Day and Date	Time	Average Speed (Kmph)	Average Density, (veh/km)
	10:11-10:26	51.66	44
	10:26-10:41	53.81	31
	10:41-10:56	53.69	31
23rd December (Monday)	7:50 - 8:05	54.57	23
	8:05 - 8:20	53.64	31
	8:20 - 8:35	54.06	27
	8:35 - 8:50	52.93	34
	8:50 - 9:05	51.45	43
	9:05 - 9:20	51.78	42
	9:20 - 9:35	52.32	35
	9:35 - 9:50	51.68	42
	9:50 - 10: 05	53.74	39
	10:05 - 10:20	54.56	16
	10:20 - 10:35	54.27	19
	10:35 - 10:50	55.23	21

Hence accept null hypothesis i.e. H_0: $\mu_1 = \mu_2$. Therefore, the mean of difference between actual and predicted speed is equal to zero. An alternative hypothesis (Ha): The difference between actual and predicted speed is not equal to zero. i.e. Ha: $\mu1 \neq \mu2$.
Level of Significance (α) = 0.05
Confidence Interval (C.I) = 0.95
From Sample: Sample Mean ($\overline{X}$) =0.4001218 km/hr
Sample standard deviation (S) =0.825682788 km/hr
Number of observations (N) = 20
Then,

$$\text{t- Value (t)} = \frac{\overline{X}-\mu}{\frac{S}{\sqrt{N}}} = 2.1672$$

Again, the critical value of t at level of significance (α) = 0.05 and 19 degree of freedom for two tailed test.

t- Critical = 2.093024

The validation parameters for Grenshield model are shown in calculated in

Table 6: T-test between actual and predicted speed of Greenshield model in Table 6

Description	Variable
Mean	0.4001218
Observation	20
Hypothesized mean difference	0
Degree of freedom	19
t value	2.1672
P (T<= t) two-tail	0.04314
t critical value	2.093024

The validation was performed with the statistical parameters t-statistical value, t-critical value and p-value for each model calibrated in this study.

Table 7: T-test for difference in Observed and Actual Value

Model	t- statistical value	t critical value	P value
Greenshield	0.50762	2.063899	0.6164
Greenberg	0.24167	2.063899	0.8111
Polynomial	0.26557	2.063899	0.7928
Northwestern	0.88556	2.063899	0.3846
Pipes- Munjal	0.92037	2.063899	0.3665
Underwood	0.49138	2.063899	0.6276
Drake With Taylor Series	0.97867	2.063899	0.3375
Underwood with Taylor Series	0.44486	2.063899	0.6604

Here, t- statistical value is greater than t critical value and P value is less than level of significance (i.e. P value <0.05). So, accept alternative hypothesis that is the mean difference between actual and predicted speed is not equal to zero. Hence, Greenshield model can be excluded from best fit model for evening hour data.

V. Conclusion And Recommendations

This study has been conducted for development of macroscopic model for the traffic flow conditions of Kathmandu Ring Road. The various traffic flow models have been considered and calibrated by using the field measurement of traffic flow parameters. The Greenshields, Greenberg, Polynomial, Northwestern, Pipes-Munjal, Underwood, Drake with Taylor series and Underwood with Taylor series models were calibrated. Data has been taken from Bus, Car, Micro bus, Motorcycle and Truck. For validation purpose of the calibrated model, the field data from another road section was used. The factors that affect speed-flow-density relationship on a roadway are design speed, access control, presence of truck, speed limit and so on.

This study was compared to various traffic flow models for finding the best fit model. Greenshield model, Underwood model, Drake model and pipes- Munjal model doesn't get validated. The Underwood Model with Taylor series expansion with R^2 = 0.8904 yield the best fit of data. Underwood Model with Taylor series expansion can be recommended as a macroscopic q-k-v model for free flow condition. An Underwood model with Taylor series expansion yield realistic data than comparison to other models. This model helps in predicting future scenario of speed and density with anticipated change in traffic flow, then will be used for improvement of traffic flow operation.

Based on these results, Underwood model with Taylor series expansion can be recommended for studying traffic flow pattern. This could helps in predicting future scenario of traffic parameters that is speed and density.

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