Sustainable Structures and Materials, *Vol. 6, No. 2, (2023) 88-95*
DOI: https://doi.org/10.26392/SSM.2023.06.02.088

Development of Lane Utilization and Speed-Density Model for Multilane Highway: A Case Study in Islamabad Pakistan

Haseeb Ahsan[*1], Bilal Ahmed Zaidi[2], Afaq Khattak[1]

[1]Department of Civil Engineering Islamic International University Islamabad, Pakistan
[2]Department of Civil Engineering University of Engineering and Technology Taxila, Pakistan
*Corresponding author/ E-mail:ahsanhaseeb829@gmail.com

(Received April 18, 2023, Revised May 20, 2023, Accepted June 21, 2023)

ABSTRACT. *Islamabad Expressway is a multilane urban road that provides access between Islamabad the Capital of Pakistan and Rawalpindi. The traffic composition on Islamabad Expressway is varied with a high proportion of cars and other vehicles like buses, trucks, and bikes. Different factors affect lane usage of a road section such as speed of vehicles, rate of traffic flow, and compositionof vehicles. Limited study has been conducted on the assessment of speed-density model and lane utilization patterns for various vehicle classifications on multi-lane highways. In this research endeavor, an eight-hour video data set was recorded from the Islamabad Expressway utilizing a mobile camera during both peak and off-peak hours to encompass a diverse range of traffic scenarios on the road. A model was established to estimate the correlation between speed and density and a corresponding mathematical equation was derived. Four vehicular categories are considered for studying lane utilization behavior. The lane utilization behavior was modeled using the lane utilization factor for all four lanes and structural equations were developed for laneutilization factors for all four lanes using SPSS software. The results of our study will help futureresearchers to check the behavior of speed with density on the Islamabad expressway and compare traffic characteristics with other roads in Islamabad and to check the behavior of lane utilization and lane discipline. The results of our study are also helpful for road development authorities to design the lane following their usage. The study outcomes can contribute to the development of micro-level traffic simulation models.*

Keywords: Lane Utilization Factor, Multi-lane highway, Lane Discipline, Structural Equations, Speed Density Relationship.

1. INTRODUCTION

Lane utilization is defined as the average volume per lane divided by the total volume withina specified interval, providing insight into the distribution of traffic across different lanes. Its value is influenced by vehicular speed and flow rates. Lane utilization is considered crucial dueto its role as a key parameter in enhancing the accuracy of microsimulation models [1]. The experience of previous studies suggests that traffic flow parameters vary according to the total flow rate from one lane to another lane traveling along a multi-lane road section. In prior studies,traffic volume has been employed to characterize the distribution of traffic volume for uncongested traffic scenarios Amin and Banks [2]. The section of the motorway which is far away from the merging or diverging section, vehicles are divided on road section depending upon total traffic flow. This distribution is comparable to lane utilization, capacity, and safety as noted by Brackstone et al [3]. Carter et al. [4] found in their investigation that heavy vehicles, adherence to lane discipline regulations, and the presence of on and off-road ramp all contribute to the heterogeneity of traffic behavior across lanes. They arrived at the conclusion that there is a variation in the q-u curve for each lane and location. Data was gathered and analyzed using the Analysis of Variance (ANOVA) method, specifically along the Queen Elizabeth Way (QUW). The analysis of lane speed distribution revealed that the median lane speed is highest in the center lane, followed by the shoulder lane and then the median lane. This concurs with the May formula. The results of the lane occupancy analysis showed that during peak hour, there was an increase in volume on the shoulder lane and a decrease in volume on the center lane. Chang and Cassidy [5] analyzed Daganzo's Theory [6] using data from freeways, which was obtained from loop detectorsalong the Gardiner Expressway in Toronto, Canada. The sample data was selected in a manner to emulate the transitional state of traffic flow. Upon analyzing individual lanes, the formation of queues was observed in the center lane during semi-congested conditions and attributed to the influence of the phenomenon known as the 'rabbit effect. However, the shoulder-lane experiences a state of uncongested traffic. Theoretical traffic behavior model was used Daganzo [6] instead of analyzing the data collected. Drivers showed two different behaviors according to their analysis. First a driver named Rabbit changes their lane based on their maximum will speed. In the second case, a driver named Slug has less space in the traveling process. Despite not utilizing real-world data and constructing his model for lane utilization behavior, Daganzo's theory [6] continues tobe widely regarded by researchers in the field of traffic flow. Work has been done on traffic flow parameters which varied according to the total flow rate from one lane to another lane traveling along the multi-lane roadway section Lynch et al. [7]. Duret et al. [8] developed a study of lane flow ratio on the three-lane highway of South Lyon in France. They observed continuing changein total flow, with a noticeable decrease in shoulder and center lane and an increase in the median lane. While Ferrari [9] said it also explains lane changes in different ways by drivers of different regions. In Greece, Tsamboulas and Golis [10] developed a study related to lane utilization. The study considered a multivariate model, incorporating traffic flow that was disaggregated byvehicle category and space mean speed, in addition to the total traffic flow. Gunny [11] reported that trends in a lane change in Turkey are different from other well-developed countries. He provided the reason behind this called '*untidy lanes*' which means lane which has no markings that also cause indiscipline by the drivers. Lanes without markings lead indiscipline. Because drivers are not well guided with no lane mark on the road then how they can adjust their vehicle according to traffic rules and regulations. In relevant research Hall and Gunter [12] revealed that lane capacity values are small for shoulder lane and increase from center to median lane. Heidemann [13] developed a model to derive and analyze the division of total traffic volume to individual lanes and the frequency of lane change by vehicles. Hurdle et al. [14] carried this study at two points in Toronto, Canada. Based on their observations, the capacity of the shoulder lane was found to be lower in comparison to the center and median lanes. Jaeyong, et al. [15] conducteda lane-by-lane analysis of traffic flow in Korea. The analysis results of their study suggest that more than one lane can be used as an indicator before congestion is assessed. Furthermore, the outcomes of the study can be applied to the development of advanced navigation systems such as car navigation systems and dynamic message displays, aimed at controlling traffic flow. Knoop et al. [16] utilized lane utilization as a function of traffic density in The Netherlands and observed that the speed limit and presence of on-ramps have a significant impact on lane utilization. Observations from the studies indicate that the majority of research on Lane utilizationhas been conducted in developed countries. A scarcity of studies has been conducted in the context of multilane roads. In regard to the Islamabad Expressway, it is noteworthy that the road accommodates a diverse range of vehicles, resulting in unique traffic conditions distinct from bothdeveloped countries and other roads within Islamabad. Systematic research is necessary to formulate the most optimal model that represents the correlation between speed and density. The objective of this study is to construct equations that depict the lane utilization factor. The present research endeavors to investigate the lane utilization factor, which is considered as the dependent variable. The analysis adopted multivariate techniques and incorporated traffic volume, mean vehicle velocity, and the composition of various vehicle classes as independent variables.

The aimwas to construct a speed-density model for the Islamabad Expressway, with the objective of analyzing lane utilization behavior and lane discipline for different categories of vehicles on the expressway. Comparisons of lane utilization factors between different lanes and vehicle classes were conducted and observed on the roadway.

2. RESEARCH METHODOLOGY

The aim of the present study is to develop speed-density model and lane utilization model for the traffic conditions on the Islamabad expressway. Data collected on a road section help us in developing lane utilization factors. Video graphic data collection and its extraction details are given in subsections below.

2.1 Data Collection and Extraction

First of all, reconnaissance survey was carried out to select suitable site for data collection where different traffic composition can be covered. We selected Islamabad Expressway as data collection site as it consists of different vehicular composition. A foot over bridge was selected tocollect video graphics data as shown in figure 1 left side. The purpose of the study was to developrelation between speed-density and model for lane utilization. The speed had key role as dependentvariable. It was calculated using trap length of 60 m marked as shown in figure 1 right side. Timeto cover this trap length was noted using stopwatch. Speed can be calculated if we have values ofdistance and time. Both peak and off-peak hours were selected for data collection in one directionof flow. Eight hours data was collected in different time intervals from 8 am to 11 am and 4:30 pm to 6:30 pm on different days of week to cover almost all traffic conditions. After the collection of video graphic data, extraction of data was done by dividing video graphics data into small intervals of
1.5 minutes. Further, this interval was divided into 9 intervals of 10 seconds. Density was calculated by counting the number of vehicles passing in 10 s and dividing it by the specified traplength of 60 m as shown in figure 1 left side.

Average of all values was calculated. The lane utilization factor is calculated with the help of formula given below in (Eq. 1).

$$LUF_i = \frac{V_i}{V} \times 100 \qquad (1)$$

Where, V_i Traffic volume for i^{th} lane (veh/hr), V Total volume (veh/hr), LUF_i Lane UtilizationFactor in percentage for i^{th} lane.

Fig-1: (Left) Fixed Camera for video at the foot over bridge, (Right) Trap length measurement

2.2 Descriptive Statistics

The allocation of various vehicle classes across the lanes is represented through pie charts. Then, lane utilization factors relations have been developed with car proportions, average speed, and volume count (for lanes 2, 3, and 4) using SPSS. Lane utilization characteristics for vehicles of distinct categories, including cars, buses, and trucks, are depicted through the use of pie charts. 75.36% of cars and 71.30% of buses and 73.80% of Trucks follow lane discipline. The proportion of cars is higher in Lane 1, the descriptive statistics are showing the proportion of othervehicles. As shown in Fig. 2, the proportion of cars along the lanes decreases in a linear manner, ranging from lane-1 to lane-4. Conversely, the proportion of trucks and buses along the lanes increases in a linear fashion, from lane-1 to lane-4.

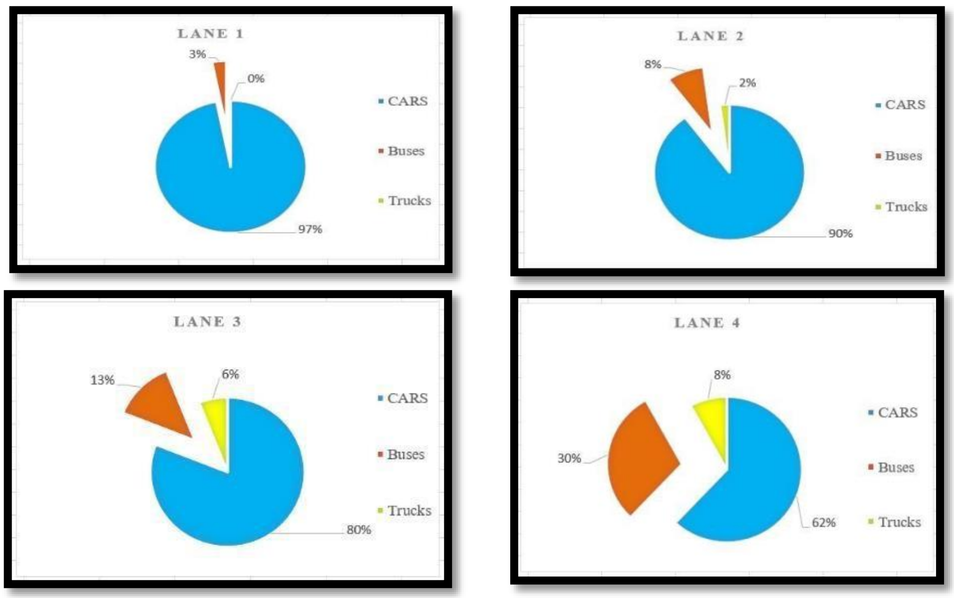

Fig-2: A summary of the descriptive statistics on Lane Utilization for various lanes and different vehicle categories is provided

2.3 Model Development

The primary objective of our current case study is to develop a speed-density model for the Islamabad Expressway and analyze the lane utilization behavior for each lane, taking intoconsideration four distinct vehicle categories. The data collected at time intervals of 1 minute and 1.5 minutes were utilized to calculate traffic density. These time intervals were chosen toencompass the entire spectrum of traffic scenarios. To develop the relationship between speed and density, 30 data points were selected, out of which 6 points were determined to be outliers and removed. The relationship between speed and density is depicted in Fig. 3. An equation was derived to represent the relationship between speed and density, which is given as Eq. 2.

$$\text{Speed} = -1831\ln \text{Density} + 136.11 \qquad (2)$$

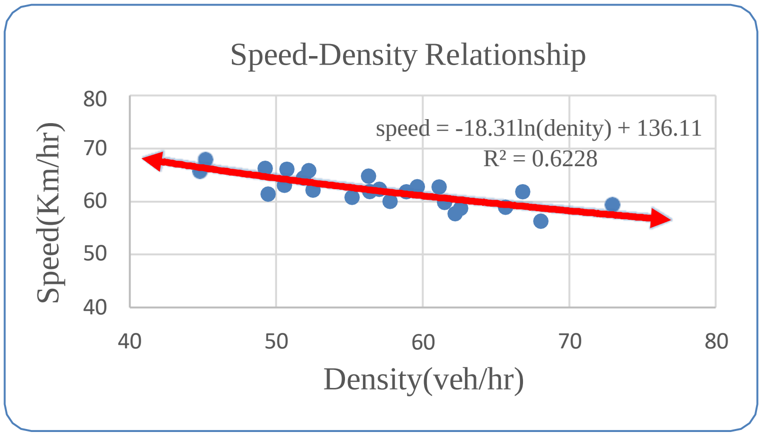

Fig-3: Relationship between speed and density for Islamabad Expressway.

Hourly volume was then divided into different vehicle categories, including cars, buses, and trucks, and extracted from the traffic composition at various time intervals. The proportion of cars and average stream speed were taken as independent variables, and the lane utilization factorwas taken as the dependent variable. Linear regression was applied to all lanes using the data obtained from field extracted results, and the results are presented in Table-1. Similarly, Proportions of cars, buses, and trucks are taken as an independent variable for developing multivariate linear regression models for lanes 2, 3, and 4 and the results obtained.

The unstandardized coefficient shows the change independent variables due to a change of 1 unit in independent variables. The standardized coefficients predict the impact of independent variables on thedependent variables. The higher value of the standardized coefficient has more effect. In the modelsummary, R square tells us how well our model fits our data and the results are given below in (Table-1). Similar to Table-1three more tables were obtained for lanes 1,2, and, and 3.

Table-1: Summary of the model for the Lane Utilization Factor for lane 4

Variables of Model	**Unstandardized Coefficients**		**Standardized Coefficients**			**Model Summary**			
	B	**Std. Error**	**Beta**	**t**	**Sig.**	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
(Constant)	276.824	103.848		2.666	0.014	0.708	0.502	0.47	2.239
Bus	.009	.115	.013	.081	0.936				
Car	-267.249	101.214	-16 .598	-2.640	0.015				
Speed	-258.170	101.524	-14.044	-2.543	0.019				
Truck	-267.589	1102.864	-7.091	-2.601	0.017				

Notes: t - t statistic value; Sig. – Level of Significance

The Structural equations for lanes 1,2,3 and 4 are given below as (Eq. 3,4,5and 6). They can help us in determining the value of the Lane utilization factor for all lanes. Stream speed is showing the average speed in that particular lane and showing the proportion of cars in that lane similar to bus proportion and truck proportion.

$$\left(LUF_{lane1}\right) = (-15.318 + .030Stream_{speed} + 50.378Car_{Prop} + 90.159Bus_{prop}) \quad (3)$$

$$\left(LUF_{lane2}\right) = \left(245.14 - 0.104Stream_{speed} - 207.701Car_{prop} - 225.001Bus_{prop} - 268.224Truck_{prop}\right) \quad (4)$$

$$\left(LUF_{lane3}\right) = (-105.77 + .149Stream_{speed} + 131.194Car_{Prop} + 123.850Bus_{prop} + 126.592Truck_{prop}) \quad (5)$$

$$\left(LUF_{lane4}\right) = (276.82 + .009Stream_{speed} - 267.24Car_{Prop} - 258.17Bus_{prop} - 267.589Truck_{prop}) \quad (6)$$

2.4 Model Validation

Model validation is examining the model structure to see how closely it corresponds to the actual scenario. From the whole data, 30 % of the points were selected for the validation process.Prediction of lane utilization factors was conducted through the substitution of independent variable values into Equations 3, 4, 5, and 6. Subsequently, a statistical comparison was performed between the predicted and observed lane utilization factors, and the Mean Absolute Percentage Deviation (MAPD) was calculated using Equation 7.

$$MAPD = \frac{LUF_{Observed} - LUF_{Predicted}}{LUF_{Observed}} \quad (7)$$

The comparison between the predicted lane utilization factor and observed lane utilization factor is given below in (Fig. 4). MAPD defines the variation between predicted and observed lane utilization factor and its values between 7-11% are acceptable. R square in our case is 0.5811which is showing how close is our predicted lane utilization factors to our observed lane utilization factors.

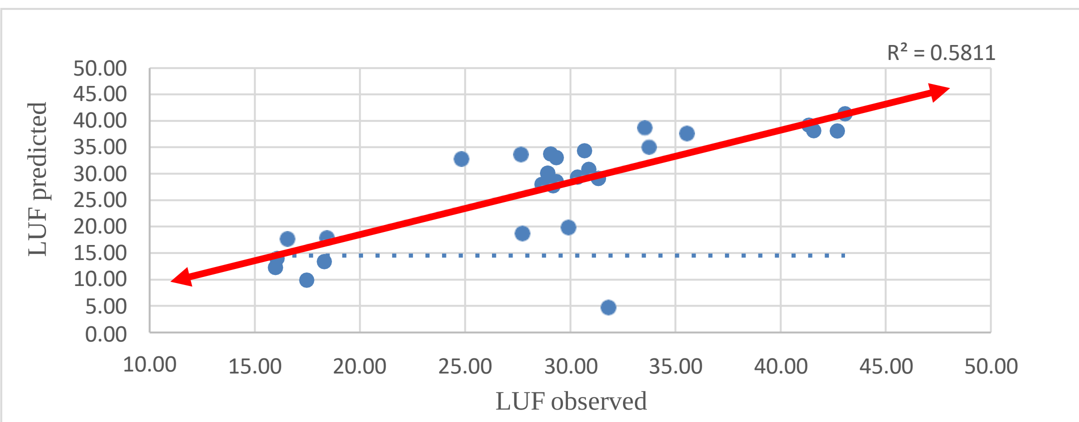

Fig-4: Graph between predicted and observed lane utilization factor

3. RECOMMENDATIONS

Multiple linear regression analysis was utilized to construct lane utilization models for each lane, considering distinct vehicle categories. The investigation was conducted on a basic section free from merging and diverging. Future studies should encompass merging and divergingsections. Alternative analysis techniques such as Partial Least Square Structural Equation Modeling may also be employed for data analysis. It should be noted that the results of this studyare limited to the empirical findings and cannot be generalized to other roadways. Further research could involve applying discrete choice theory and multinomial logit modeling to examine the factors affecting the behavior of drivers for lane selection on multi-lane urban roads.

4. CONCLUSION

The research investigated lane utilization among various vehicle categories on a multi-lane expressway. The analysis was performed using multiple linear regression to develop models for each vehicle category. The results demonstrated a high proportion of cars on the median lane anda high proportion of buses on the shoulder lane, which can be attributed to the regulation mandating heavy vehicles to stay on the shoulder lane. Lane usage percentages for cars, buses, and trucks are 75.36%, 71.30%, and 73.80%, respectively. For lanes 1 to 4, the proportion of lane usage by cars is 97%, 90%, 80%, and 62%, respectively, due to the high speed of cars. The median lane predominantly accommodates high-speed vehicles, whereas the shoulder lane isutilized by low-speed vehicles, such as buses and trucks. A comparison of the observed and predicted lane utilization factors revealed substantial similarity. The average observed and predicted values of the lane utilization factor for lanes 1 to 4 are, respectively, 38.30, 38.19, 29.16,28.60, 14.97, 13.87, 13.62, and 13.20. The research indicates that a substantial number of buses, cars, and trucks failed to comply with their assigned lanes. The results of this study can be utilizedin the road design process, based on the established vehicle utilization patterns, and can functionas a reference for future simulation-based studies.

REFERENCES

[1] Ponnu B, Narula S, Arkatkar SS, Velmurugan S. Lane usage, following behavior, and time-gap models for a multi-lane freeway in India. Transportation letters. 2015 Feb 1;7(1):14-23.

[2] Amin MR, Banks JH. Variation in freeway lane use patterns with volume, time of day, and location. Transportation research record. 2005;1934(1):132-9.

[3] Brackstone M, McDonald M, Wu J. Lane changing on the motorway: Factors affecting its occurrence, and their implications.

[4] Carter M, Rakha H, Aerde MV. Variability of traffic-flow measures across freeway lanes. Canadian journal of civil engineering. 1999 Jun 1;26(3):270-81.

[5] Chung K, Cassidy MJ. Test of theory of driver behavior on homogeneous freeways. Transportation research record. 2004;1883(1):14-20.

[6] Daganzo CF. A behavioral theory of multi-lane traffic flow. Part I: Long homogeneous freeway sections. Transportation Research Part B: Methodological. 2002 Feb 1;36(2):131-58.

[7] Deacon JA, Lynch RL. Determination of Traffic Parameters for the Prediction, Projection, and Computation of EWL's.

[8] Duret A, Ahn S, Buisson C. Lane flow distribution on a three-lane freeway: General features and the effects of traffic controls. Transportation research part C: emerging technologies. 2012 Oct 1;24:157-67.

[9] Ferrari P. The effect of driver behaviour on motorway reliability. Transportation Research Part B: Methodological. 1989 Apr 1;23(2):139-50.

[10] Golias J, Tsamboulas D. Macrolevel estimation of highway lane usage. Journal of transportation engineering. 1995 Jan;121(1):40-9.

[11] Gunay B. A methodology on the automatic recognition of poor lane keeping. Journal of advanced transportation. 2008 Apr;42(2):129-49.

[12] Hall FL, Allen BL, Gunter MA. Empirical analysis of freeway flow-density relationships. Transportation Research Part A: General. 1986 May 1;20(3):197-210.

[13] Heidemann D. Distribution of traffic to the individual lanes on multilane unidirectional roadways. InPROCEEDINGS OF THE SECOND INTERNATIONAL SYMPOSIUM ON HIGHWAY CAPACITY, VOLUME 1 1994.

[14] Hurdle VF, Merlo MI, Robertson D. Study of speed-flow relationships on individual freeway lanes. Transportation Research Record. 1997;1591(1):7-13.

[15] Yoon J, Kim H, Lee EE, Yang I, Jeon W. 국내 다차로 고속도로 자료를 이용한 차로별 교통류 특성 분석. 한국도로학회논문집. 2016 Jun 15;18(3):87-94.

[16] Knoop VL, Duret A, Buisson C, Van Arem B. Lane distribution of traffic near merging zones influence of variable speed limits. In13th International IEEE Conference on Intelligent Transportation Systems 2010 Sep 19 (pp. 485-490). IEEE.