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Lane-Based Modeling of Traffic Characteristics on Urban Multi-Lane Highway in Mosul City

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ABSTRACT

This research models the relationship between traffic characteristics and lane position on a six-lane divided highway. Both macroscopic and microscopic models were developed to analyse speed-density, speed-flow, and flow-density relationships for each lane, using linear and nonlinear approaches. Additionally, microscopic models were created to investigate speed-spacing, speed-headway, and headway-spacing relationships. Data was gathered using video recordings and radar speed guns, and traditional methods were applied to calculate density and spacing distance, which are typically challenging to measure in the field. Microsoft Excel and SPSS ver.26 software were utilized for analysis. The coefficient of determination (R-square) and the chi-square test were employed to assess the goodness of fit for the models. The results indicated no significant differences between the predicted and observed data, demonstrating critical traffic characteristics and providing insights into vehicular and driver behavior. These models can be utilized to identify various parameters of traffic characteristics in future studies on the examined highway.

1. Introduction

Multilane highways, characterized by having at least two lanes in each direction for traffic flow, are increasingly common due to urbanization and rising travel demands. These highways often lack complete control over access, meaning they might have intersections with traffic lights or even driveways. To accurately assess their performance, especially considering the mix of vehicles using them, traffic data needs to be collected for each lane. This is because density, a key metric for service level on multilane highways, is most representative when analyzed on a per-lane basis.(Chatterjee et al., 2016)

Building on the concept of traffic density, speed-flow-density model has emerged as a widely utilized analytical framework in traffic flow analysis due to its accuracy and simplicity. This model captures the linear relationship between traffic flow (the number of vehicles passing a point per unit time), and speed (average

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speed of vehicles), and nonlinear model with the density (number of vehicles per unit length of road) in a clear graphical form.(AASHTO, 2018) It is essential to assess whether this model is appropriate for a particular study area, such as a six-lane divided highway, and to comprehend the relationship between space parameter and time headway, which reflect vehicular traffic behavior.(Tsuboi & Yoshikawa, 2020)

Several recent studies have also demonstrated that some significant traffic flow phenomena are related to mesoscopic headway distributions. In traffic engineering, vehicle headway distribution models are extensively employed due to their ability to encapsulate the inherent uncertainty in drivers' car-following behaviors. These models offer a precise description of the stochastic characteristics of traffic flows, making them invaluable tools for both theoretical analysis and practical applications.(Li & Chen, 2017) Additionally, understanding vehicle headway distribution is crucial for the development of intelligent transportation systems and accurate vehicle simulations.(Yin et al., 2009)

A study conducted in India aimed to define Level of Service (LOS) criteria for multilane highways on a per-lane basis, factoring in traffic density and lane-specific traffic distribution. The analysis was based on data from two distinct locations on four-lane and six-lane highways. The findings revealed that serviceability differed not only between various road sections but also across individual lanes under heterogeneous traffic conditions.(Chatterjee et al., 2016

Speed–flow–density curves were formulated for two traffic regimes to assess the impact of heavy vehicles (HVs) by considering the platoon dynamics observed on Indian highways. A critical time headway threshold of 3 seconds was established to differentiate between vehicles that are platoon followers and those that are not. The study illustrates that traffic interactions within platoons significantly influence traffic operational quality (level of service) and efficiency. The findings suggest that the platoon regime results in decreased speed at capacity, density at capacity, and overall traffic capacity (Singh & Santhakumar, 2022). In this paper, these curves will be developed to model and analyze the impact of lane position on the speed-flow-density relationships on multilane highway.

In China, a study investigated the best-fitted distribution model for specific headway types under lane management on a multi-lane highway, considering car-truck interactions. The study collected traffic data, including traffic flow rates, percentages of trucks, speeds, and headways. Statistical tests revealed that traffic flow rates, the percentage of trucks, and lane position significantly influence vehicle headways.(Kong & Guo, 2016)

A survey study carried out in China investigates headway distributions, revealing that the dispersion of points on density-flow plots and the shape of traffic flow breakdown curves is implicitly influenced by vehicular headway distributions. The study emphasizes that headway distribution models bridge the gap between macroscopic and microscopic traffic models, integrating the advantages of both approaches.(Li & Chen, 2017)

In a study, empirical headway and spacing distributions were analyzed as outcomes of stochastic car-following behaviors and as reflections of drivers' unconscious and imprecise perceptions of space and time intervals. Headway, or time headway, refers to the time interval, in seconds, between two consecutive vehicles as they pass a specific point on the roadway, using the same reference point on each vehicle. Spacing, or space gap, refers to the distance, in feet, between two successive vehicles in a traffic lane, also measured from the same reference point on each vehicle.(Chen et al., 2010)

A research study in Sri Lanka aimed to address the variation in capacity values due to differences in road characteristics and traffic streams by developing indigenous capacity models. This involved creating a speed-flow model tailored for urban four-lane roads. Headway data were also collected from the surveyed sections to explore its relationship with capacity. The findings indicated that the traffic stream had difficulty maintaining capacity flow for extended periods, particularly at lower speeds.(Jayaratne et al., 2018)

A study conducted in Iraq simulated the characteristics of urban multilane highways to estimate road capacity based on headway time, emphasizing the importance of road user behavior in microsystem traffic analysis. The study also integrated lane position to develop a capacity headway model that captures driver behavior in lane usage. Through regression analysis, the results demonstrated that lane position significantly affects drivers' lane selection decisions and has a notable impact on capacity values, especially in the right lane position.(Qasim et al., 2020)

A study utilized the microscopic traffic simulation model VISSIM to generate traffic flow data and extract essential parameters. The study further analyzed lane change behavior using homogeneous vehicle traffic on four-lane, six-lane, and eight-lane divided highway sections through VISSIM simulation. It was observed that the number of lane changes increases with the number of lanes. However, the per-lane capacity of the roadway tends to decrease as the number of lanes increases. While adding a lane offers more opportunities for vehicles to change lanes, it simultaneously reduces the traffic stream speed under non-lane discipline, leading to a decrease in per-lane capacity.(Srikanth et al., 2020)

Another study used empirical analysis to measure the effects of different percentages of multi-class commercial vehicles (CVs) on capacity, speed on the highway, dynamic passenger car unit (DPCU), and level of service (LoS). Data on speed and flow were gathered from Indian highway segments. According to the study, a larger percentage of multi-class CVs has a major effect on capacity, LoS, DPCU, and highway speed. More specifically, when the mixing rate of multi-class CVs rises, the speed of each individual vehicle drops. Because there was less access control during encounters with multi-class CVs, the study found that there was a considerable fall in traffic environment speed and flow, which resulted in a reduction in highway capacity.(Singh & Santhakumar, 2022)

The Greenshields Linear Model is used to determine the lane-based (ML and KL) and RW capacity. An Indian study established the macroscopic fundamental relationship diagrams among speed, flow, and density under various highway lanes, such as Median Lane (ML) and Kerb Lane (KL), as well as the entire roadway (RW). The analysis's findings demonstrated a clear variation in the vehicles' DPCU values and speeds for each lane and RW. The results of this investigation underscored the significance of considering lane-based attributes instead of comprehensive RW attributes.(Singh & Santhakumar, 2021)

In this paper, the study aims to incorporate lane position into modeling actual headway data observed through field surveys (which can also be calculated as the inverse of traffic flow) alongside actual space data observed through field surveys (which can also be calculated as the inverse of traffic density). Additionally, the study demonstrates the fitting of the speed-flow-density model on a specific multilane highway in Mosul city.

2. Methodology

Establishing correlations between important traffic variables in order to precisely assess traffic conditions and forecast the results of traffic operations is a basic goal of traffic flow theory. These factors consist of flow rate, density of traffic, and speed. The first research examining these connections dates back to 1933 (Greenshields et al., 1933). Also, time headway and spacing between successive vehicles is an important cause it describes vehicular traffic behavior.

2.1. The study area

The research study area consists of a two-mile section of an urban multi-lane highway, featuring three lanes in each direction. As illustrated in Fig. 1, this highway is a major thoroughfare connecting Mosul city with Dohuk city. It passes by several key facilities, including a private hospital, a university entrance, schools, restaurants, and various commercial offices. The highway has a service road on each direction, with two lanes, to facilitate the accessibility to all facilities.

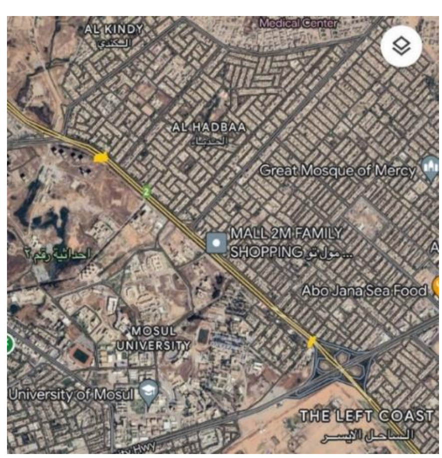


Fig. 1 The multi-lane highway as a study area (google map).

2.2. Data collection

2.2.1. Traffic volume data

Video footage from stationary cameras positioned atop power poles in each highway median will be used to gather statistics on traffic volume, as shown in Fig. 2. It records the traffic flow in each direction, to calculate the number of cars every 15 minutes of twelve hours each day, from 7 a.m to 7 p.m of the day, including the peak and off-peak hour. (Yadav et al., 2014) The traffic volume will be calculated for each lane (median, center, and right lane).

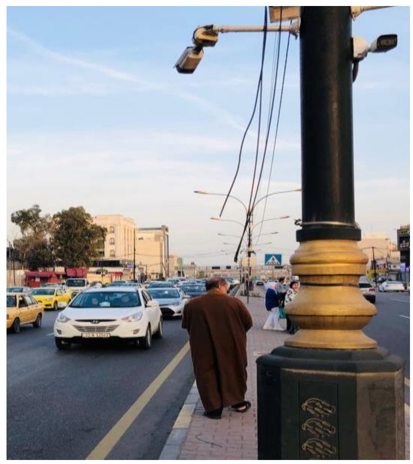


Fig. 2 The cameras on the median of the road for traffic data collection.

2.2.2. Traffic speed data

A speed radar gun, is used for measuring speed data, it can measure the speed of a vehicle by pressing the specific button on the device. The main specifications of this device are (Bushnell, 2015):

- Measures speed from 10 to 200 miles per hour (at a distance of 1500 feet)
- Accuracy: +/- 1 mile per hour
- Dimensions: 8.4 x 6 x 4.3 inches (width x height x depth)
- Weight: 19 ounces

As shown in Fig. 3, using this gun, 100 individual car speed measurements are obtained for each segment in each direction. A statistical table is then utilized to calculate the time mean speed (TMS), space mean speed (SMS), mode speed, median speed, and P85.

Fig. 3 The radar speed gun.

2.2.3. Traffic density

Density is the traffic parameter that is hardest to measure in the field. If the flow and speed of a traffic stream are known, density can be computed with ease using the fundamental flow-density-speed equation. Flow and speed can also be estimated using stationary observer methods. As shown in the eq. (1).

$$\boldsymbol{D = v/s} \quad (1)$$

where D is the density (in vehicle per kilometer per lane), v is the traffic volume (in vehicle per hour), and s is the speed (in kilometer per hour).

2.2.4. Time headway and spacing data

In this research, the average time headway between consecutive through vehicles was measured on a per-lane basis in the road section, during the same hours as the traffic volume data collection. The most common method for collecting time headway data involves measuring the time interval between two vehicles crossing a given point. For this study, time headway was measured using video records of the selected section. A narrow black tape was placed on the screen to serve as a reference point that vehicles would cross. The video recorded the exact time each vehicle passed this reference point in each lane. The time headway for each lane was then calculated by determining the time difference between successive vehicles passing the reference point. (Qasim et al., 2020)

The spacing distance will be calculated by multiplying the speed (m/s) by the time headway (s) at the time of measurement, as direct field measurement is challenging.

2.3. Calibration and validation methods

Regression models are useful tools that are regularly used in a variety of scenarios to predict a dependent variable from a set of variables. This study will employ both linear and nonlinear regression models using Microsoft Excel and SPSS ver.26 software to examine the relationships between speed, flow, density, headway, and spacing distance for each lane (left, center, and right) on the highway segment. Without subsequent performance analysis, the application of modeling techniques can yield poorly fitting results that inaccurately predict outcomes on new data. To validate the models, data will be collected from another highway segment and compared with the developed models' predictions. Calibration, which measures how close the predicted probabilities are to the observed rates for given configurations of the independent variables, will be assessed using the Hosmer and Lemeshow chi-squared test. This test provides a reliable measure of calibration through a statistical test. Additionally, R-squared values will be used to evaluate the models' performance. (Giancristofaro & Salmaso, 2003)

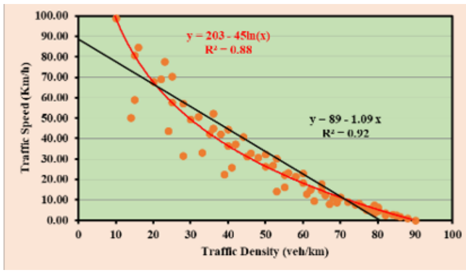
3. Results and discussion

3.1. Results of regression models

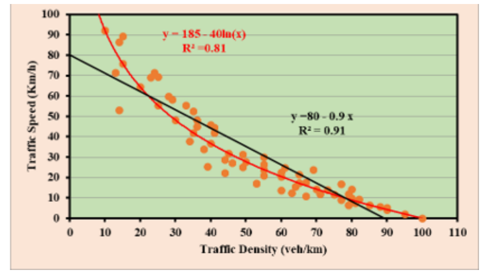
3.1.1. Speed-Flow-Density model

In this research, both linear and nonlinear models were developed to predict the relationships between traffic characteristics (speed, flow, and density) for each lane of the multi-lane highway in the study area, as shown in Fig. 4. The line representing the relationship corresponds to the optimal correlation between space mean speeds and traffic density. As the speed of vehicles decreases, density increases until the vehicles come to a stop at approximately 90-100 vehicles per kilometer.

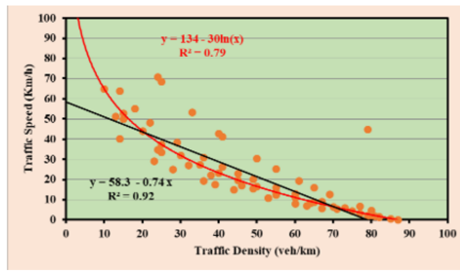
The model, depicted in Fig. 4, shows a relationship with an R-squared value of 0.92 for the linear relationship of the left and right lanes, and 0.91 for the center lane. These values indicate a high correlation as they are close to 1, and they exceed the R-squared value of 0.8 for the nonlinear relationship for each lane of the study highway segment.



(a) Speed-Density relationships (left lane)



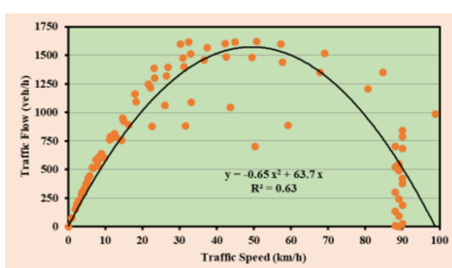
(b) Speed-Density relationships (center lane)



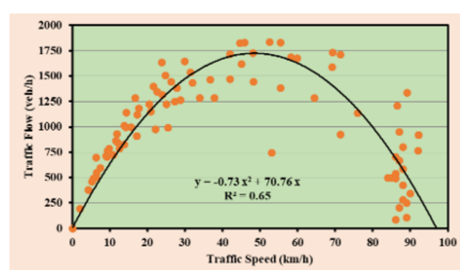
(c) Speed-Density relationships (right lane)

Fig. 4 Linear and nonlinear relationships between speed and density with R-square values.

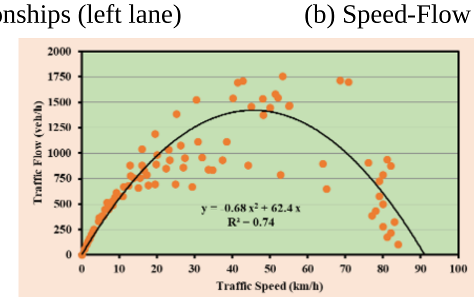
The relationship between traffic flow and space mean speed is quadratic, demonstrating that flow increases with speed up to a critical point. For the left and center lanes, this critical speed is 50 km/h, while for the right lane it is 45 km/h. Beyond these speeds, flow decreases, as illustrated in Fig. 5. This indicates that traveling above the critical speed results in a weaker service level for highway traffic in the study area.



(a) Speed-Flow relationships (left lane)



(b) Speed-Flow relationships (center lane)



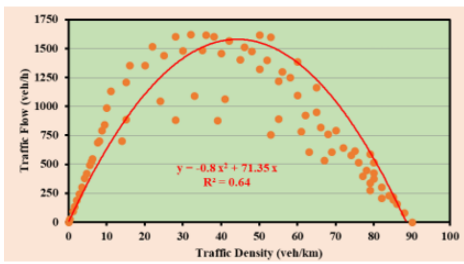
(c) Speed-Flow relationships (right lane)

Fig. 4 Quadratic relationships between space mean speed and traffic flow with R-square values.

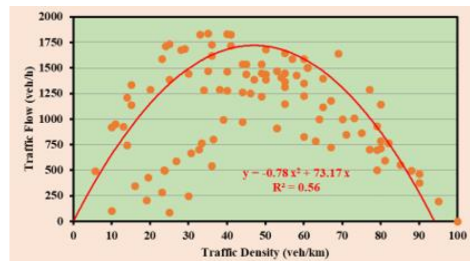
Fig. 5 shows that flow has two values at the same speed. The upper points represent stable flow, while the lower points indicate unstable flow.

According to the traffic flow classification by Al-Ghamdi (2001), which categorizes traffic flow into low, medium, and heavy levels, the level of traffic flow in this study can be considered high, as the minimum observed flow is greater than 1200 vehicles per hour. Additionally, the traffic flow in the center lane is higher than in the left and right lanes due to various factors, such as entering and exiting vehicles from the service road, and temporary parking for 15 minutes, which creates randomness in traffic flow on the right lane, thereby decreasing its flow.

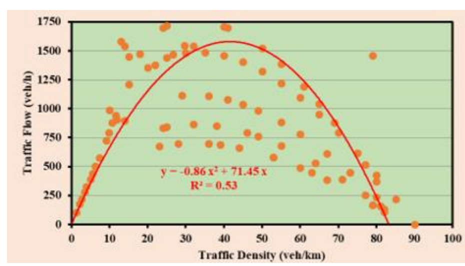
The models of flow-density, as shown in Fig. 6, depict a quadratic relationship for each lane. They start from zero, with density increasing as flow increases, representing stable flow. The flow reaches its maximum at the critical density, which is 40 vehicles per kilometer for the left and right lanes, and 50 vehicles per kilometer for the center lane. Beyond these points, flow decreases, indicating unstable flow.



(a) Flow-Density relationships (left lane)



(b) Flow-Density relationships (center lane)

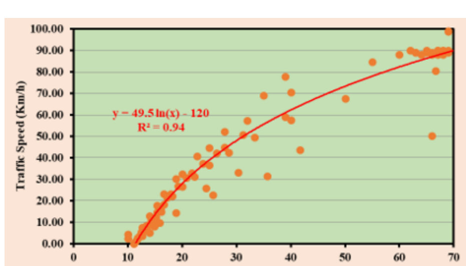


(c) Flow-Density relationships (right lane)

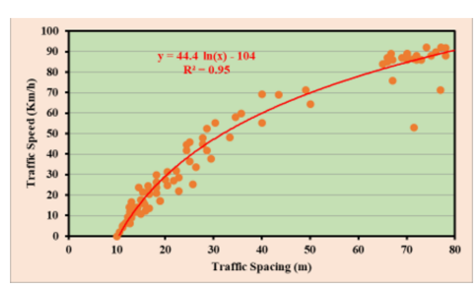
Fig. 5 The relationship between traffic flow and density for each lane with R-square values.

3.1.2. Speed-Headway-Spacing model

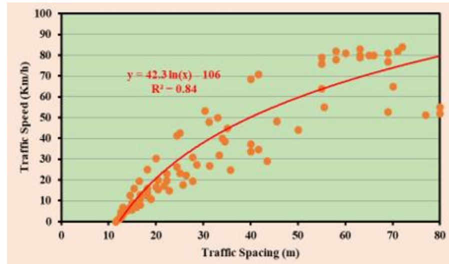
Regression models are powerful tools commonly used to predict a dependent variable based on a set of predictors. In microscopic traffic analysis, headway time and spacing distance are crucial for assessing traffic performance, as they represent vehicular behavior in the traffic stream. Specifically, spacing distance is the inverse of traffic density, and time headway is the inverse of flow. Therefore, regression models were developed to explore the relationships between speed and spacing, speed and headway, and headway and spacing. Fig. 7 illustrates the speed-spacing model for each lane within the study area.



(a) Speed-Spacing relationships (left lane)



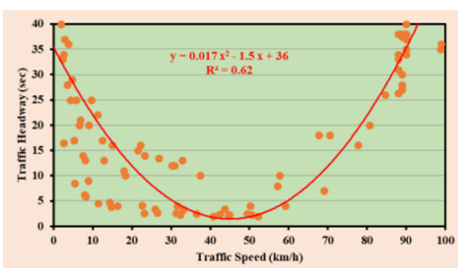
(b) Speed-Spacing relationships (center lane)



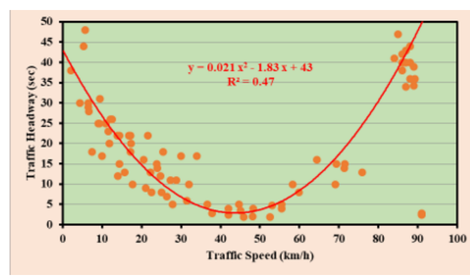
(c) Speed-Spacing relationships (right lane)

Fig. 6 Logarithm relationship between space mean speed and traffic spacing for each lane with R-square values.

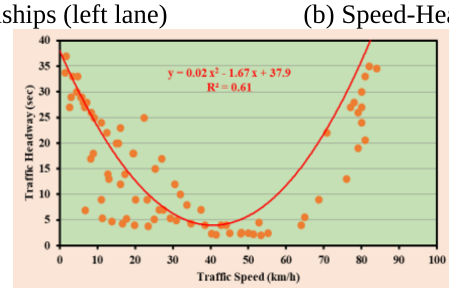
The space distance between successive vehicles increases as speed increases, demonstrating a relationship opposite to that of speed-density, as spacing can be represented as the inverse of density. Additionally, the speed values in the left and center lanes are higher than those in the right lane. The same analysis was performed to develop a model predicting the relationship between traffic speed and headway for each lane, as illustrated in Fig. 8. The relationship begins with the maximum headway, which decreases as speed increases until it reaches the critical speed, between 40-50 km/h, where the headway is at its minimum. This opposes the speed-flow relationship, as headway can be represented by the inverse of the flow.



(a) Speed-Headway relationships (left lane)

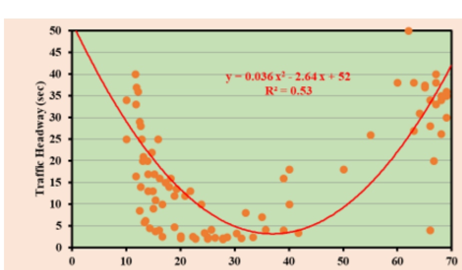


(b) Speed-Headway relationships (center lane)

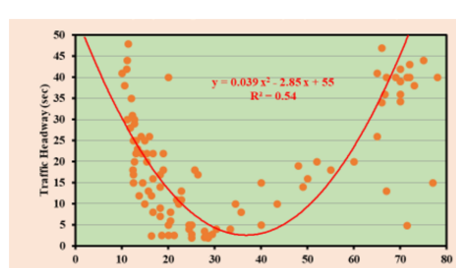


(c) Speed-Headway relationships (right lane)

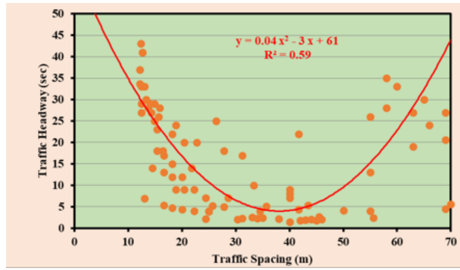
Fig. 7 Quadratic relationship between space mean speed and time headway for each lane with R-square values.



(a) Headway-Spacing relationships (left lane)



(b) Headway-Spacing relationships (canter lane)



(c) Headway-Spacing relationships (right lane)

Fig. 8 Quadratic relationship between traffic headway and traffic spacing for each lane with R-square values.

A regression model was developed to examine the relationship between headway and spacing, as shown in Fig. 9. Fig. 9 illustrates that headway is unstable on the left side of the line until it reaches the critical spacing. Beyond this point, the headway becomes increasingly stable as spacing increases, eventually reaching the maximum spacing, which represents the inverse of jam density.

The critical spacing is identified to be between 30 and 40 meters. Vehicles maintaining a distance of less than 30 meters from each other are likely to experience unstable flow conditions.

3.1.3. Validation of the models

To validate the model, a new dataset was collected from another highway segment and compared with the results of the developed models. The correlation between them was tested using the coefficient of determination and Chi-square methods.(Qasim et al., 2020) In summary, the models are evaluated using R-square as the coefficient of determination and the chi-square test for goodness of fit, as shown in Table 1. The null hypothesis at a 95% confidence interval is H0: there is no significant difference between the observed and expected frequencies.

Table 1 – The summary of models and calibration.

Traffic Characteristics	**Left lane**		**Center lane**		**Right lane**		**Chi-square value for observed data and predicted model**	**df**
Y-X	The model	R-square	The model	R-square	The model	R-square		
Speed-Density	Y=89 - 1.09 x	0.92	Y= 80 - 0.9 x	0.91	Y=58.3-0.74 x	0.92	90	81
Flow-Speed	Y= -0.65 x^2 + 63.7 x	0.63	Y= -0.73 x^2+70.76 x	0.65	Y=-0.68 x^2+62.4 x	0.74	80	72
Flow-Density	Y= -0.8 x^2 + 71.35 x	0.64	Y= -0.78 x^2+73.17 x	0.56	Y= -0.86 x^2+ 71.5 x	0.53	80	72
Speed-Spacing	Y= 49.5 ln(x) - 120	0.94	Y= 44.4 ln(x) - 104	0.95	Y= 42.3 ln(x) - 106	0.84	90	81
Headway-Speed	Y= 0.017x^2-1.5x+36	0.62	Y=0.021x^2-1.83x+43	0.47	Y= 0.02x^2-1.67x+37.9	0.61	60	54
Headway-Spacing	Y= 0.036x^2-2.64x+52	0.53	Y= 0.039x^2 - 2.85x+55	0.54	Y= 0.04 x^2 - 3x + 61	0.59	60	54

The models for each lane, as shown in the table, pertain to each lane of the multi-lane highway segment. The coefficient of determination (R-square) indicates the correlation strength of the models, with values close to 1 representing a strong correlation. Additionally, the goodness of fit test, using chi-square values, shows that all models have chi-square values less than the critical values from the table. This means the null hypothesis (H0) is accepted, indicating no significant difference between the predicted models and the observed data collected in the study area.

4. Conclusion

This research aims to model the relationship between traffic characteristics based on lane position. Macroscopic and microscopic models were developed for a six-lane divided highway. For each lane, speed-flow-density models were established to examine speed-density, speed-flow, and flow-density relationships, which deviate from traditional models for the study area. Also, the lane position shows a significant impact on the speed-flow-density relationships. Traffic flow was observed on each lane, with the center lane exhibiting higher flow levels than the right lane due to area conditions such as land use, vehicle entry and exit points, and illegal parking. At the same time, the presence of service roads increased the use of the right lane, as drivers frequently entered the service roads to access universities, schools, and other facilities. This resulted in relatively minor differences in traffic characteristics between lanes, allowing the main road to maintain higher speeds as a route connecting two cities. This contrasts with the studies by Qasim et al. (2020), Srikanth et al. (2020) and Singh & Santhakumar (2021), which were conducted on a highway without service roads, where the lack of service roads significantly affected the traffic characteristics between lanes.

Microscopic models were also developed to analyze speed-spacing, speed-headway, and headway-spacing relationships, highlighting critical values for each parameter on each lane of the highway. These models enhance understanding of vehicular behavior and driver patterns. Statistical indicators, including the R-square coefficient and chi-square test, were used to validate the models. All models showed no significant differences between the predicted results and the observed data, indicating strong model accuracy. By simply knowing the speed data, these models can help obtain microscopic data such as headway and spacing, which will make it easier for future research to collect microscopic data.

Acknowledgments

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