Developing and Calibrating Single-Regime Traffic Flow Models for Urban Multi-Lane Roads

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Abstract: The development of accurate mathematical relationships between the primary traffic flow parameters has a significant effect on the ability to accurately capture the operational characteristics on the roadway segment under different demand conditions. The focus of this research was on developing the functions relating those traffic flow parameters for multi-lane roadways. After the functions were developed, their output was compared to results provided by the Highway Capacity Manual (HCM) in addition to other models available in the literature and the results of the comparison are presented in this paper. The model output comparison showed that models developed by this research performed well for multi-lane roadways with speed limits of 60km/h and 80km/h compared to other models. However, the models also showed very high traffic density values compared to what is available in the literature. The results from this research could be used mainly for the calibration of the speed-flow model that could be used to enhance the accuracy of traffic simulation models and their different related applications.
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1.0 Introduction

The development of accurate mathematical relationships between the major traffic flow elements has a significant impact on the planning, design and comparison of different alternative traffic engineering measures on the roadway network. The functions relating traffic flow-density-speed provide quantitative estimate of the change in the traffic operations characteristics with the change of the demand on the roadway segments. In addition, the applications of those mathematical models is especially important in traffic simulation where they are used to study the effect of traffic flow changes on travel time and cost, vehicular emissions and expected travel demand.

In order to improve the accuracy of the traffic flow diagrams, data of speed, density and traffic flow values on urban multi-lane principal arterials were collected. This research focused on developing the functions relating those traffic flow parameters for the collected data. After the functions were developed, they were calibrated, validated and their output was compared to results provided by the Highway Capacity Manual (HCM) in addition to other models available in the literature. The results of the model comparison are presented in this paper.

2.0 Research Background

The mathematical relationships used to describe traffic flow are classified into macroscopic models and microscopic models based on the approach used to develop these relations. Macroscopic models consider flow-density relationships while microscopic models take vehicle spacing and individual vehicle speeds into account. Macroscopic traffic flow models could be further classified into single-regime models or multi-regime models. Single regime models provide mathematical relations between traffic flow, space mean speed and traffic density that are applicable to the different ranges of the parameters values. On the other hand, multi-regime models provide different mathematical functions describing the relation between those parameters for different ranges of the parameters values.

The focus of this research is on the development of single-regime macroscopic models that relate the traffic flow, space mean speed and traffic density parameters and comparing them to other models available in the literature such as Greenshields, Underwood, Northwestern and Greenberg models. However, it must be kept in mind that it is difficult for a single model to produce a good fit for different traffic states and traffic flow conditions. The validity for using a certain macroscopic model depends if the boundary criteria of the fundamental traffic flow diagram describing the traffic conditions is satisfied. It is important to choose the suitable functional form for the case being analyzed. For example, the Greenshields models could be used for light or dense traffic conditions while the Greenberg model could only be used for dense traffic conditions. Greenshields models are summarized using equations (1 & 2) while Greenberg model is summarized using equation (3).

$$V = V_F \left(1 - \frac{K}{K_J}\right) \ldots\ldots\ldots\ldots equation \quad (1)$$

$$q = V_F \left(K - \frac{K^2}{K_J}\right) \ldots\ldots\ldots\ldots equation \quad (2)$$

$$V = V_m * \ln\left(\frac{K_J}{K}\right) \ldots\ldots\ldots\ldots equation \quad (3)$$

Where,
V_F : space mean free-flow speed (km/h)
K_J: jam density (veh/lane/km)
V_m: space mean optimal speed (km/h)
K_m: optimal density (veh/lane/km)
K: traffic density (veh/lane/km)
V : space mean speed (km/h)
K_J: jam density (veh/lane/km)
q : traffic flow (veh/lane/h)

Traffic flow models are used to estimate the changes in the traffic operations characteristics and the level of service (LOS) on a roadway segment with different demand levels on that segment. Therefore, it is essential to have well calibrated models to produce high quality results that are suitable for further analysis and estimating the different measures of effectiveness needed for the different applications. The calibration of the traffic flow macroscopic models usually involves collecting data for a facility under specific traffic flow conditions and fitting those data points to an appropriate model. The most commonly used approach for model fitting is linear regression or multiple linear regression analysis.

The calibrated traffic flow models should have the ability to predict the traffic speed at different traffic volumes in addition to estimating of the capacity, optimum flow, and free flow speed for the roadway section.

The calibration of the speed-flow models performed in this research involved the determination of the parameters that will be calibrated, and what techniques will be used for calculating the values of these parameters. The research focused on the optimization of a quadratic speed-flow function using nonlinear regression and linear speed-density function utilizing linear regression as demonstrated for the different data sets used for this research. The developed models were also compared to other models available in the literature relating traffic speed, density and flow.

3.0 Methodology and Case Study

This research focused on the optimization of single-regime models relating the major traffic flow parameters for urban multi-lane roadways. To achieve the objectives of this study data were collected for six multi-lane roadway sections in the city of Amman, the capital of Jordan. The sections were on Zharan, Queen Alia, Al Aqsa, Al Shaheed, Prince Hashem and Al Urdon streets. The sections selected for the study had four and six total lanes with speed limits ranging from 60 km/h to 80 km/h with adequate spacing between the intersections for the case study objectives. The traffic flow data were collected for the case study sections during the month of October which represents average traffic conditions in Jordan.

For each of the case study sections, data on the number of lanes, lane width, median type, traffic volumes, speeds and vehicle classification were collected for analysis. Data related to the geometry of the case study sections were obtained through field observation and measurements while data related to traffic flow were collected from loop detector data and video camera recordings. To minimize the effect of traffic flow interruptions from vehicles in other lanes, traffic data were analyzed for left lane traffic only, where the average left lane width for the selected study section was 3.0 meters. After the data were collected, the traffic flow data were cleaned and corrected before they were used in the analysis. That was followed by model development, calibration and validation before those models were compared to other traffic flow models available in the literature.

Traffic flow data also included vehicle length information which was used to calculate the percentage of trucks and buses needed to determine the equivalent passenger car volumes for the different sections used for the study. In addition, it was observed that traffic volume data obtained from loop detectors were higher than actual traffic volume data obtained from digital video recordings performed randomly at the case study sections. This is attributed mainly to double counting of vehicles changing lanes at the loop detectors locations. Therefore, correction factors based on comparisons of traffic volumes from loop detectors and video recordings were used to modify the traffic volumes data obtained by loop detectors. The results of the traffic volume correction factors used are listed in table (1).

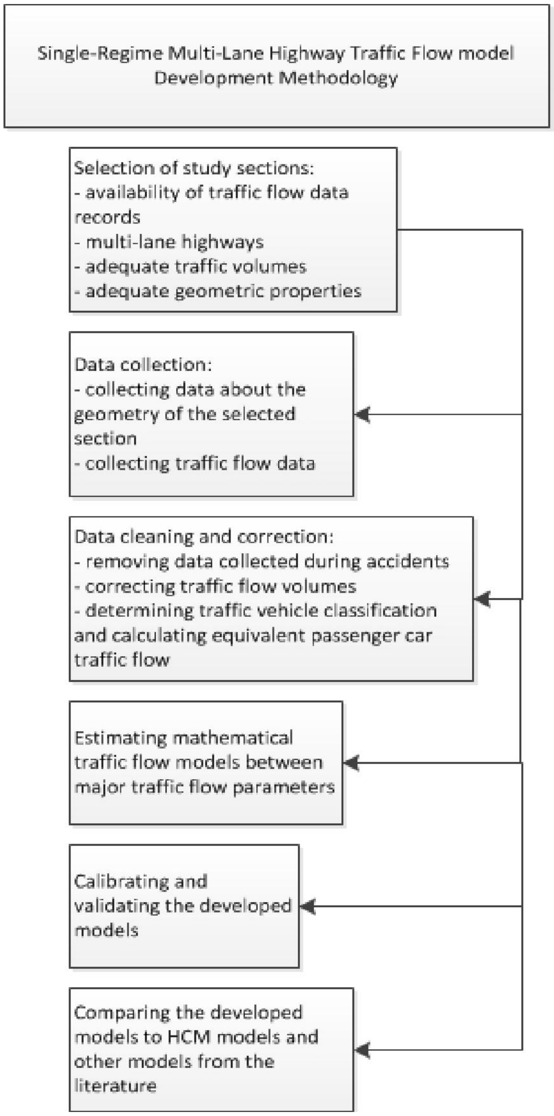

Figure (1): Research Methodology

After the traffic volume, equivalent passenger car volumes and space mean speed records were corrected, the data set was cleaned and all the outliers were removed from it and the data was ready to be used in the analysis and model development.

To achieve the objectives of this research traffic flow-space mean speed-traffic density data points were plotted and mathematical relationships between those parameters were developed for the case study sections. The research focused on the optimization of a quadratic flow-density function and linear speed-density function using linear and nonlinear regression as demonstrated for the different data sets used for this research. The calibrated speed-flow models should have the ability to predict the traffic speed at different traffic volumes in addition to estimating the capacity, optimum flow, and free flow speed of the roadway section.

That was followed by comparing the results from the developed models with values provided in the HCM for multi-lane highways in addition to Greenshields, Greenberg, Underwood and Northwestern models. The results of the model development and comparison are provided in the analysis of the results section. Figure (1) summarizes the methodology followed for this research.

4.0 Analysis of the Results

The data obtained for the left lane traffic in the case study sections were used to develop space speed vs. traffic density in addition to traffic flow vs. density models. Those models were used to obtain the values of free flow speed, jam density, density at capacity and optimal flow values for the case study sections with 60 km/h and 80 km/h speed limits. The developed traffic flow models for the 60 km/h sections are illustrated in figures (2 & 3) while the models developed for the 80 km/h sections are illustrated in figures (4 & 5).

Table (1): Data collected on case study sections

Street name	Number of lanes (in each direction)	Type of median	Number of traffic data points collected (before cleaning)	Speed limit (km/h)	Traffic volume % reduction for left lane traffic (based on video recordings)
Zahran	2	Divided	146	60	6%
Al-Aqsa	2	Divided	146	60	7%
Queen Alia	3	Divided	146	80	7%
Al-Shaheed	3	Divided	146	60	9%
Prince Hashim	3	Divided	146	60	5%
Al-Urdon	3	Divided	1,342*	80	4%

* Higher number of data points was recorded due to the high traffic volumes on this section

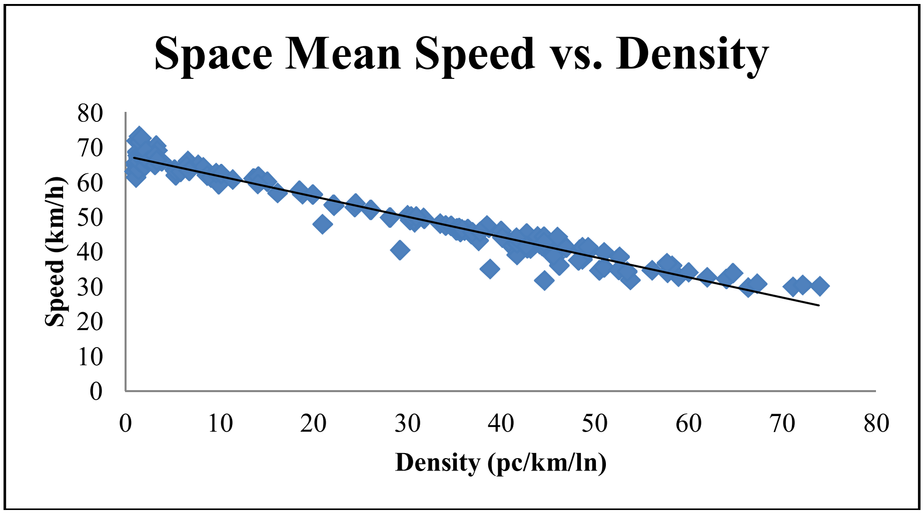

Figure (2): Space mean speed vs. traffic density for 60 km/h study sections

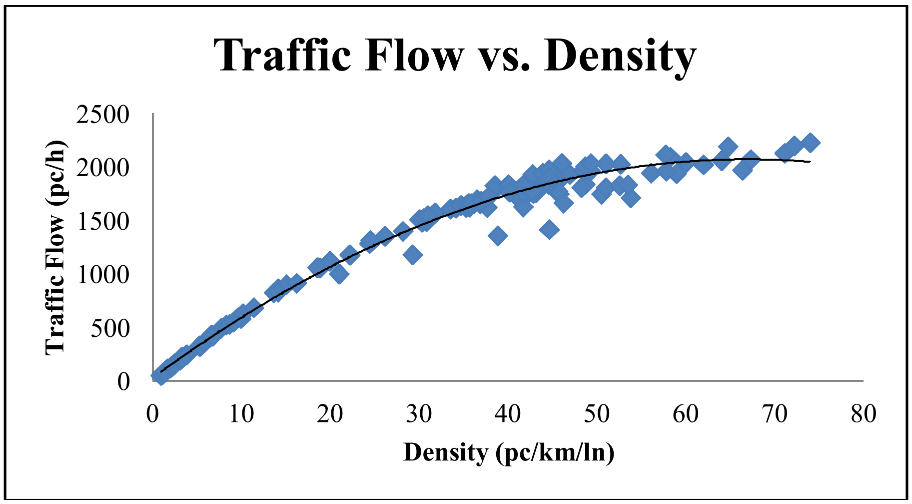

Figure (3): Traffic flow vs. traffic density for 60 km/h study sections

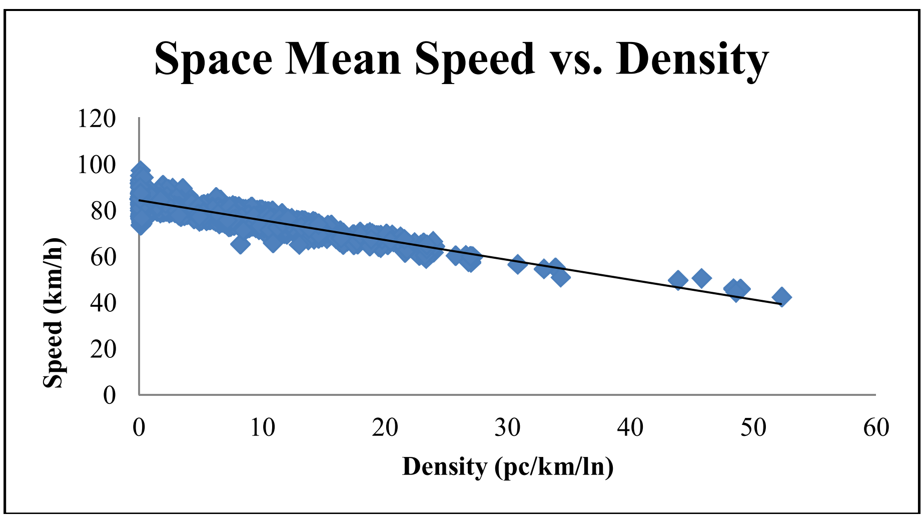

Figure (4): Space mean speed vs. traffic density for 80 km/h study sections

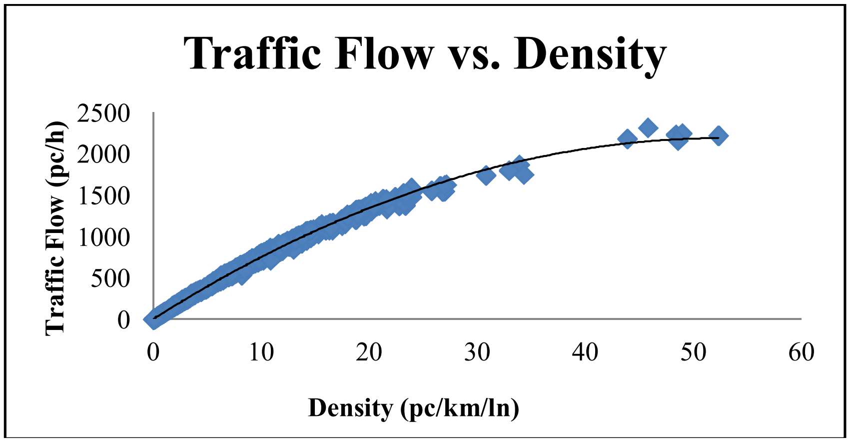

Figure (5): Traffic flow vs. traffic density for 80 km/h study sections

From the previous figures, the following models were obtained for case study sections with a speed limit of 60km/h:

$$V = 67.57 - 0.58\,k \;\dots\dots\dots equation \quad (4) \quad (R^2 = 0.953)$$

$$q = -0.46\,k^2 + 61.15\,k + 29.42 \;\dots\; equation\ (5) \quad (R^2 = 0.986)$$

Where,
K: traffic density (pc/lane/km)
V : space mean speed (km/h)
q : traffic flow (pc/lane/h)

Based on the models from equations (4 & 5) the following can be estimated for those sections:
Free flow speed (V_f) = 67.57 km/h
Jam traffic density (K_j) = 116.37 pc/km/ln
Density at capacity (K_m) = 66.84 pc/km/ln
Theoretical capacity (q_m) = 2072 pc/lane/h

Also, from figures (4&5), the following models were obtained for case study sections with a speed limit of 80km/h:

$$V = 84.35 - 0.86\,k \;\dots\dots\dots\dots equation \quad (6) \quad (R^2 = 0.81)$$

$$q = -0.78\,k^2 + 82.85\,k + 3.81 \;\dots\; (R^2 = 0.997) \dots\dots\dots equation \quad (7)$$

Where,
K: traffic density (veh/lane/km)
V : space mean speed (km/h)
q : traffic flow (veh/lane/h)

Based on the models from equations (6 & 7) the following can be estimated for those sections:
Free flow speed (V_f) = 84.35 km/h
Jam traffic density (K_j) = 98.05 pc/km/ln
Density at capacity (K_m) = 52.81 pc/km/ln
Theoretical capacity (q_m) = 2192 pc/lane/h

After theoretical models were developed for the different sections they were compared against the Greenshields (equation 1), Greenberg (equation 3), Underwood (equation 8) and Northwestern (equation 9) models. A graphical representation of the model comparison is illustrated in figures (6 & 7), and the results of the model comparison are discussed below.

$$V = V_f * e^{-\frac{k}{km}} \;\dots\dots\dots\dots equation \quad (8)$$

$$V = V_f * e^{-0.5\,(\frac{k}{km})^2} \;\dots\dots\dots\dots equation \quad (9)$$

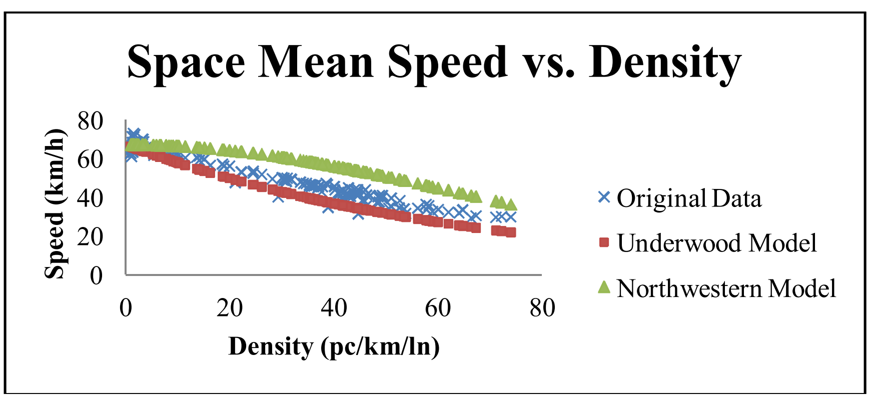

Figure (6): Space mean speed vs. traffic density model comparison for 60 km/h study sections

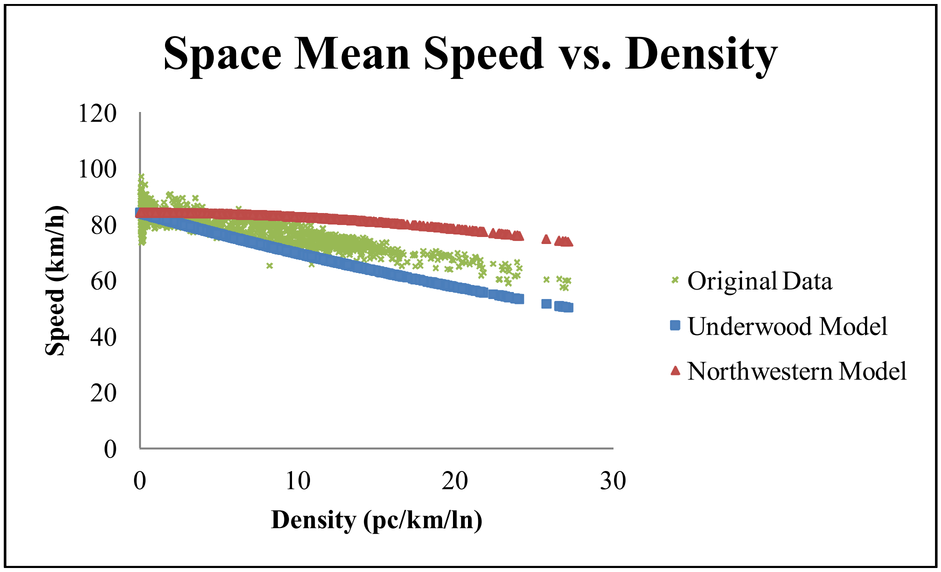

Figure (7): Space mean speed vs. traffic density model comparison for 80 km/h study sections

To compare the prediction ability of the developed models against other single regime macroscopic models available in the literature and the values of the root mean square error (RMSE) values were calculated for those models. The model comparison results are summarized in table (2).

Table (2): Model comparison results

Speed limit = 60 km/h		Speed limit = 80 km/h	
Model	RMSE	Model	RMSE
Greenshields	2.7	Greenshields	3.5
Greenberg	31.9	Greenberg	35.7
Underwood	5.8	Underwood	6.1
Northwestern	10.2	Northwestern	7.4

As can be seen from table (2), the developed models had high values for the RMSE. Also, it can be noticed that Greenshields and Underwood models provided good estimates compared to other models for the cases when the speed limit was 60km/h and 80km/h. In contrast, the Greenberg model had the highest RMSE value compared to other model. This is mainly because most of the data points were collected under uncongested traffic flow conditions.

The HCM provides speed flow models for different classes of freeway segments and multi-lane highways where the major parameters for those models include the free flow speed, the density at capacity and the capacity of the roadway section. For uninterrupted flow conditions on multi-lane highways the HCM 2000 suggests the values summarized in table (3) for the major traffic flow parameters.

By comparing the values provided in table (3) with values obtained from the developed models it is shown that values for the capacity of the roadway section and density at capacity provided in HCM are lower than values obtained from the models. This could be attributed mainly to the reduction in the headway between vehicles accepted by the driving population which is compatible with the finding of recent research in this area.

Table (3): HCM traffic flow parameter estimates

Traffic flow parameter	Multi-lane highways			
	Facility type			
	1	2	3	4
Free flow speed (km/h)	100	90	80	70
Capacity (veh/h)	2200	2100	2000	1900
Density at capacity (veh/km)	25	26	27	28
Speed at capacity (km/h)	88.0	80.8	74.1	67.9

5.0 Conclusion

The development of accurate mathematical relationships between the primary traffic flow parameters has a significant effect on the ability to accurately capture the operational characteristics on the roadway segment under different demand conditions. The focus of this research was on developing the functions relating those traffic flow parameters for the collected data. After the functions were developed, they were compared to results provided by the Highway Capacity Manual (HCM) in addition to other models available in the literature and the results of the comparison are presented in this paper.

The model comparison showed that models developed in this research performed well for multi-lane roadways with speed limits of 60km/h and 80km/h compared to other models. However, the models also showed very high traffic density values compared to what is available in the literature. This could be attributed (as suggested by recent research) to the aggressiveness of the driving population used for the development of the models. Also, it must be kept in mind that data used for the purposes of this research were mainly collected for uncongested traffic flow conditions, and this could lead to changing the functional form used to relate different traffic flow parameters.

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