Development of Capacity Estimation Models for Multi-lane Roads under Heterogeneous Traffic Conditions

D.N.D. Jayaratne, H.R. Pasindu and L.M.K. Rathnayaka

Abstract: The objective of this study is to develop capacity models to estimate the traffic carrying capacity of multi-lane roads with heterogeneous traffic flows. Since capacity is an important parameter in traffic engineering studies, it is vital that it is accurately estimated. Most of the current capacity estimation methodologies available are developed based on homogeneous traffic flows and hence not conducive for use in heterogeneous traffic conditions observed in Sri Lanka. Therefore, this study is done to fulfill the requirement of a capacity estimation model for this purpose. Fifty mid-block sections were surveyed using manual flow data collection methods and a novel Google Application Program Interface (API) based method for speed data collection. Based on the collected data, capacity values were developed following the fundamentals of traffic flow. Regression models were built to estimate four-lane and six-lane capacity values based on roadway characteristics such as effective lane width, access point density, median type, and built environment condition. Separate models were developed because the impact these characteristics have on four-lane and six-lane roads are different. The models showed good fit with R2 values of 0.81 and 0.86 for four-lane and six-lane roads, respectively. The base capacity value of a four-lane urban road was estimated to be 2044 pcu/h/l and for a six-lane sub-urban road section 2108 pcu/h/l. The outcomes of this study can be used to develop capacity guidelines in countries with heterogeneous traffic conditions for capacity estimation.

Keywords: Capacity estimation, Multi-lane highway, Heterogeneous traffic, Regression model

1. Introduction

1.1 Definitions

Highway capacity, defined as 'the maximum sustainable hourly flow rate at which vehicles reasonably can be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway and traffic conditions' by the US Highway Capacity Manual[1], is an important parameter in traffic and transportation studies. Highway capacity is used as an input parameter in many area studies such as highway design and planning, Level of Service (LOS) studies, network and route assignment studies, etc.

A multi-lane road is a highway with two or more lanes in one direction of travel. Multi-lane roads are located in road corridors with higher traffic flows, typically in and around urban settings.

A heterogeneous traffic stream is one that consists of vehicles with a wide range of static and dynamic characteristics with no spatial segregation. Arasan and Krishnamurthy (2008) proposed that heterogeneous traffic mixes exist when the percentage of the dominant vehicle mode is less than 80% of the traffic mix [2] while Fazio et al. (1999) suggest the value

to be slightly higher at 85%[3]. Heterogeneous traffic streams are commonly observed in developing countries like Sri Lanka where the dominant vehicle (passenger car) has a modal share of around 30% [4].

1.2 Background to Study

As implied in its definition, road capacity is dependent upon existing roadway and traffic conditions. Therefore, the magnitude of capacity varies with the locality in consideration. Understanding this, many countries including developing countries such as India, Malaysia, Thailand, Indonesia, etc.

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have developed indigenous guidelines and methodologies to estimate road capacity [5]. Even though the US Highway Capacity Manual (HCM) is the premier guideline used by the majority for capacity calculations, due to differences in the behaviour of traffic and roadway characteristics, this guideline is not universally applicable, especially in developing countries where traffic flows are heterogeneous in nature.

Sri Lanka has a road network of about 12,210km of A & B class roads, and over 31,000 km in the entire national road network [6]. A-class roads operate as arterials and are built to higher design standards. A majority of these roads in urban settings are multi-lane roads. At present, the guideline used for capacity estimation in Sri Lanka is the 'Geometric Design Standards of Roads' developed by the Road Development Authority of Sri Lanka in 1998 based on the US HCM published in 1985, which in itself is an outdated manual. In a study done by Jayaratne & Pasindu in 2019 it was established that the 2010 HCM multi-lane capacity methodology was not suited for estimation of capacity on Sri Lankan roads as the input criteria were not sufficiently fulfilled [4]. Since the ability to accurately estimate capacity is fundamental to maintain and develop the road network, this study is done with the objective of building a more up-to-date model to estimate capacity of multi-lane roads under heterogeneous traffic conditions. In order to do so, the impact roadway characteristics have on multilane capacity were evaluated and the models were built based on the most significant characteristics.

2.   Literature Review

It is understood that capacity is influenced by roadway characteristics and by traffic characteristics. Documented below is a summary of the information collected by reviewing literature.

2.1   Factors that Influence Capacity
HCM 2010 defines 3.6 m as the ideal lane width, with no increase to capacity when the lane width is increased further. This is an indicator of the lane discipline and car following behaviour observed in the United States of America. According to the guideline, the reduction in lane width by a range of 0.3 m -0.6 m would reduce the capacity

approximately 5% [1]. The Indonesian HCM (IHCM) suggests adjustment factors for lane width varying between 3.0 m and 4.0 m with a standard value of 3.5 m for both divided and undivided urban four-lane highways. The capacity shifts by ±8% and ±9% for divided and undivided four-lane highways when varying between 4.0 m and 3.0 m from the standard value, respectively. The increase in capacity with the increase in lane width is indicative of the loose lane discipline observed in Indonesia and prevalent especially in South Asian countries. In a study done on heterogeneous traffic flows in 2003, Chandra and Kumar suggested that the relationship between two-lane capacity and carriageway width is a quadratic function [7]. Many other studies suggested that lane width has an impact on traffic variables both at macro- and micro-level of analysis, indicating that lane width is a significant factor in traffic flow analyses ([8]-[12]).

In terms of median separation, HCM 2010 defines three median types, namely, divided, undivided and two-way left turn lane (TWLTL). The manual indicates that only undivided lanes adversely affect lane capacity and that too at an insignificant level which is unlikely to cause any major reductions in capacity. IHCM defines two median types, divided and undivided. The capacity may be reduced up to 6% on undivided sections based on the directional split of vehicles. In a study done by Moses &Mtoi, it is suggested that the presence of a median on the road has a statistically significant effect on the free-flow speed (FFS) [13].

The FFS itself is defined as a factor affecting capacity. HCM 2010 defines capacity based on FFS where sections with 97 km/h, 89 km/h, 80 km/h, 72 km/h FFS values have 2200 pcu/h/l, 2100 pcu/h/l, 2000 pcu/h/l, 1900 pcu/h/l capacity values, respectively. Hence, an 8 km/h reduction in FFS would reduce the capacity by approximately 5%. On the other hand, IHCM defines capacity independent of the FFS. Arun etal. in a study done on inter-urban highways under heterogeneous traffic conditions in 2016, estimated that for every 8km/h increase in FFS the capacity of six-lane and four-lane highways increased by a value of approximately 100 pcu/h/l [14]. In a study done by Satishkumar etal. in 2016, lane capacity was found to positively increase with

the increase in 'operating speed' of a section, where the operating speed was defined as the 85th percentile speed of FFS [15].

HCM 2010 states that the FFS is reduced by 0.25 km/h per access point per km indicating a minor negative impact on capacity. IHCM incorporates the effect of access points have on capacity by defining a factor named 'side friction class', which indicates that the capacity decreases with the increase in access point density. In other literature, Ch and et al. [16] studied the drop in capacity due to curb-side bus stops in India in 2014 and concluded that there is a drop of 8-13% in base capacity due to this phenomenon. Pallavi et al. in 2016, investigated the effect of side friction versus stream speed in urban multilane mid-block sections by categorizing side friction classes according to IHCM 1997 guideline [17]. They concluded that low to medium side friction classes do not have a significant effect on stream speed, whereas at sections with high side friction classes, the reduction in speed was significant. Similarly, in a study done in Australia in 2015, Wijerathna concluded that half hour on-street parking zones reduced the theoretical capacity of urban roads by a percentage up to 17% [18].

HCM 2010 methodology defines the vacant width on either side of the road as the lateral clearance. A lateral clearance of 3.6m in total is considered ideal with a minimum of 1.8m on either side. According to HCM, a four-lane highway with no lateral clearance will have approximately 5% reduction in capacity. IHCM incorporates the shoulder type and width to define its adjustment factors as part of the 'side friction class' parameter. This is more representative of roadside conditions in Asian countries. In other research, Leong measured speeds and capacity values on rural highway sections with varying lane width and shoulder width in New South Wales and suggested that the traffic stream speed increased with the increase in shoulder width [19]. The consensus on shoulder and lateral clearance is that the increase in width has a positive effect on roadway capacity [20].

HCM and IHCM do not incorporate the effect vehicle composition has on capacity directly. In a study done by Chandra et al. in 2015 using micro-simulation, it was shown that with the

increase in non-standard vehicles in the traffic stream the capacity decreases [21]. The issue of different vehicle classes operating in the same traffic stream is negated by incorporating the 'Passenger Car Unit' (PCU) or 'Passenger Car Equivalent' (PCE) to bring the unit of flow to a common denominator.

Further, it is understood that the effect various roadway and traffic characteristics have on capacity is a function of the locality and the country considered. This is exemplified by a study done by Li et al. in 2005 in Nanjing, China, where the air quality of the environment was found to significantly influence traffic capacity [22].
Smith et al. (2021) recently conducted a study to evaluate the LOS (level of service) and capacity of different segments of the Malik Mahmood Ring Road in Sulaymaniyah city, Iraq, under heterogeneous traffic conditions. The study used the latest methodology of HCM2016, and both the moving car method and stationary method were employed to collect traffic volumes and measure all necessary geometric parameters. The peak hour factor (PHF) was calculated for all segments using the stationary observer approach within the peak-hour. The peak hour volume was identified based on the highest traffic volume obtained from the test runs[23].

According to HCM2016, the PHF for all segments ranged from 0.92 to 0.95, which are normal values for multi-lane urban highways. The study found that the lane width was less than the standard value, which had a significant impact on reducing the value of free flow speed (FFS) and the number of access points affecting FFS. The speed limit observed during the study was over 42.5 miles per hour, which meant that all the sections investigated were considered to be similar to a multi-lane highway. As the proportion of heavy vehicles in the traffic flow increases, the efficiency of traffic operations and the level of service (LOS) are negatively impacted. Another finding of the study was that collecting traffic volume data using the moving car method was just as effective as using the stationary method[23].

2.2   Capacity Studies
Several studies have been done to find capacity values of multi-lane highways under heterogeneous traffic conditions. Sathishkumar et al. in 2016 estimated base capacity of urban Indian four-lane roads under ideal roadway conditions (3.5m lane width,

and no roadside friction) to be 1570 pcu/h/ln [15]. The composition of vehicles in this study were 64.8% cars, 3.7% heavy vehicles, and the rest motor cycles and three wheelers. Chandra et al. studied the effect of traffic composition in inter-urban multilane highways of India in 2014 using VISSIM simulation software and predicted that the lane capacity of a four-lane highway comprising entirely of passenger cars to be 2475 pcu/h/ln [21]. In a study done by Yang and Zhang in 2005 on multi-lane highways in Beijing, they observed that the lane capacity decreases with the increase in number of lanes on the road section [24]. The average roadway capacities of four-lane, six-lane and eight-lane highways were 2104 pcu/h/l, 1973 pcu/h/l and 1848 pcu/h/l, respectively.

In a study done by Semeida in 2013, on rural multi-lane highways in Egypt, the capacity, LOS and the factors affecting capacity were investigated [25]. Forty five highway sections were studied, and LOS and capacity were estimated using HCM 2000 methodology. Capacity values between 1477 pcu/h/l and 2200 pcu/h/l were observed on these sections. The study used lane width, directional pavement width, lateral clearance, number of lanes per direction, median width, side access availability, percentage of heavy vehicles in traffic stream as independent variables to estimate capacity.

2.3   Capacity Estimation Techniques

There are various techniques that have been used to estimate capacity in literature, ranging from speed-density models to empirically derived frameworks. Greenshields published the first major empirical model in the field of traffic engineering in 1935 [26]. This model was derived based on 'non-ideal' traffic flows and is applicable for both two-lane and multi-lane road sections [27]. The model is denoted by Equation 1.

$$u = u_f - \left[\frac{u_f}{k_j}\right]k \qquad \qquad ...(1)$$

where, u is the space mean speed, k is the density, u_f is the FFS, and kj is the jam density.

Similar single regime speed-density models such as Greenberg's model, Underwood's model, Pipes-Munjal model, Drake's model, etc., were developed to estimate the relationship between the speed and density of a traffic flow ([28] - [31]). These models are used along with the fundamental traffic flow equation (Equation 2), in order to estimate the speed-flow relationship of which capacity is the maximum.

$$Q = U * K \qquad \qquad ....(2)$$

where, Q is the flow, U is the space mean speed, and K is the density.

The maximum flowrate method is a simple technique where the highest observed flowrate of a given location during a specific time period is taken as the capacity. Here the time interval taken to calculate the flowrate (e.g. 5-min, 15-min, 60-min, etc.) and the total period of flow observation are important factors that affect the estimated capacity [32]. The maximum capacity method is shown in Equation 3.

$$C_i = \max(f_{i,t}) \quad for \; all \; t = 1,2,....,n \qquad ....(3)$$

where, C_i is the capacity (maximum flowrate) for location i, $f_{i,t}$ is the observed flowrate in time interval t, t is the time interval (e.g. 5-min), and n is the number of time intervals considered.

Van Aerde proposed a four-parameter model to estimate capacity which has more degrees of freedom to capture a range of behaviours on different facility types [33]. This model is designed specifically to be calibrated using Intelligent Transportation Systems (ITS) data such as inductive loop data, radar and video detector data [32]. Among other capacity estimation methodologies, two methods that are commonly used are the Breakdown capacity methodology and the Product Limit Method (PLM) for capacity estimation. The breakdown capacity is the flow when a breakdown occurs. A breakdown takes place when the traffic stream speed decreases past a pre-specified threshold between two consecutive time intervals and is sustained for a predefined length of time [34]. The product limit method is based on the findings by Brilon et al. that capacity based on daily observations of traffic data collected over several months is Weibull distributed [35]. Based on this finding other researchers have developed the PLM to estimate the capacity distribution function from empirical data. Li & Laurence relate the PLM to the flows that cause breakdown in flow and the flows that do not cause breakdown to develop the capacity distribution function [32]. The drawback with these methods and also the Van Aerde method is that they are data intensive methods. With

the limited resources and technology available, traffic data of such magnitudes are not easy to collect in developing countries like Sri Lanka.

3. Methodology

3.1 Data Collection

Given the constraints in resources, the data collection methods employed for the study were manual collection for flow data and a Google Distance Matrix Application Programming Interface (GDM-API) based data collection method for traffic stream speed data. The GDM-API can be used to acquire travel distances and travel times for specified origin and destination pairs. The API returns information based on the given route between origin and destination points, as calculated by the Google Maps API. The required input parameters include the Origin-Destination coordinate pair, and the API key. Optional calibration parameters, mode of travel (set to 'driving'), departure time (set to 'now') and traffic model (set to 'best guess'), were fixed accordingly. To collect data a PHP script was used. A study carried out by Kumarage estimated that the travel time can be predicted using Google Distance matrix API data to an accuracy of up to 99% [36]. This method was used in tandem with manual flow data collection to collect respective traffic stream speeds. The flow data were collected in 15-minute intervals by stationing enumerators on the roadside with handheld electronic tally counters to count vehicles. The traffic stream was classified into 11 categories: namely, Motorcycle (MC), Three-Wheeler (TW), Car, Van, Utility Vehicle (UV), Light Goods Vehicle (LGV), Medium Goods Vehicle (MGV), Heavy Goods Vehicle (HGV), Multi Axle Vehicle (MAV), Minibus (MB) and Large Bus (LB).

In addition to flow data and speed data, the following geometric details of the highway locations surveyed were also recorded: median type, number of lanes per direction of travel, lane width, effective lane width (this is the effective width of a lane available for vehicles to traverse, since some sections are blocked due to on-street parking, etc.), shoulder type (e.g., hard shoulder, soft shoulder and curb), lateral clearance, access point density (number of access roads and centre median gaps along a 400m section), and built environment type. The built environment is the environment along the side of the road. In South Asian countries such as Sri Lanka, direct access to developments along the side of the road is

allowed. Hence, ribbon developments are present along most roads. In order to capture this feature, the built environment factor is introduced and was classified into three types based on the percentage of built land along the road in a 400m section. The three types were named as Urban (>70% built up area), Sub-Urban (20-70% built up area), and Rural (<20% built up area) to represent the built environment of the section.

3.2 Survey Locations

Surveys were carried out across 60 locations in the western province of Sri Lanka. These included 49 four-lane sections and 11 six-lane sections. Of these, 50 locations (41 four-lane sections and 9 six-lane sections) were used for model development. A map of a set of locations is shown in (Figure 1).

Figure 1 - Study Survey Locations (Source: maps.google.lk)

The study locations were limited to mid-block sections, away from junctions, in order to minimize the effect of junction control measures on the collected data. Further, typical locations such as sites with construction work that impede the traffic flow were not selected to avoid misrepresentation of capacity values ([37],[38]).

3.3 Capacity Development Framework

Capacity values were developed using traffic flow fundamentals by calibrating a speed-density model for each location using the collected flow and speed data. Single regime speed-density models reviewed in literature were fitted to the empirical data and the best-fit model was selected for each individual

section. The framework followed for capacity estimation is shown below [4]:

i.   Collection of classified flow data and speed data;
ii. Conversion of classified flows to uniform flows using PCU factors;
iii. Obtaining density data using fundamental traffic flow equation, speed and flow data;
iv. Calibration of speed-density model to fit speed-density data;
v.   Computing speed-flow model based on fitted model and fundamental traffic flow equation; and
vi. Acquiring capacity from developed speed-flow model.

The classified heterogeneous flow data were converted to uniform flows using PCU factors developed in a study done on heterogeneous traffic flows in Sri Lanka by Jayaratne et al. in 2018, using Chandra's method of PCU estimation ([39],[40]). Table 1 presents the PCU factors used in this study. Equation 4 was used to convert the empirical flows to uniform flows.

Table 1 - PCU Factors Developed by Jayaratne et al. [39]

Vehicle Category	PCU factor
Motorcycle (MC)	0.2
Three-Wheeler (TW)	0.6
Car	1.0
Van	1.2
Utility Vehicle (UV)	1.7
Light Goods Vehicle (LGV)	1.0
Medium Goods Vehicle (MGV)	2.5
Heavy Goods Vehicle (HGV)	3.7
Multi Axle Vehicle (MAV)	6.5
Minibus	2.3
Large Bus	5.4

$$Flowrate = \Sigma \ Count \ of \ i^{th} \ vehicle \ category * PCU_i * 4 \quad \text{…(4)}$$

where the flowrate is in (pcu/h/l) and PCU_i is the PCU factor in Table 1 of the 15-min count of the ith vehicle category.

The best-fit speed-density model was calibrated to the existing speed-density data by minimizing the squared sum of errors (SSE) between the actual speed and the predicted model speed as shown in Equation 5, where u_i is the actual speed and u_i' is the predicted speed from the model.

$$SSE_{min} = Min \ \Sigma (u_i - u_i') \quad \text{….(5)}$$

4.   Results & Data Analysis

Capacity values varying from 1231 pcu/h/l to 2349 pcu/h/l were observed in the study with a mean capacity of 1829 pcu/h/l. In comparison to HCM 2010 capacity values, which range between 1900 pcu/h/l to 2200pcu/h/l, the obtained values have higher floor and ceiling values which can be attributed to the differences in the roadway conditions observed. Figure 2 depicts a histogram of the capacity values derived.

Further, the mean maximum traffic stream speed observed was 41 km/h with a standard deviation of 9.9 km/h. This exhibits another separating feature of the traffic streamed from traffic streams in countries like the USA where FFSs on multi-lane roads are in the range of 70 km/h – 100 km/h on multilane highways [1]. Consequently, the mean traffic stream speed at capacity was 19.2 km/h with a standard deviation of 5.1 km/h. This is a result of the heterogeneous nature of the traffic streams in Sri Lanka where the driver behaviour is erratic and lane discipline is rarely observed.
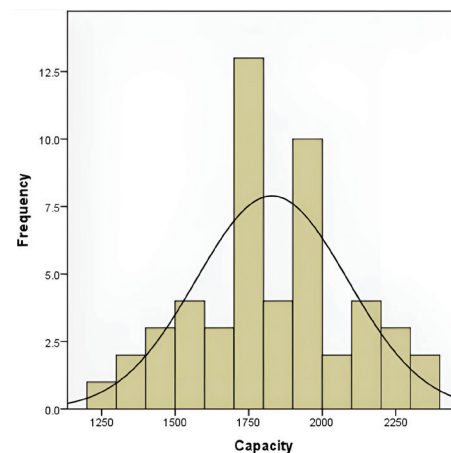
Figure 2 - Capacity histogram

4.1   Capacity Model Development

Capacity estimation models were separately developed for four-lane and six-lane highways since the influence roadway characteristics have on these roads are different. 'IBM SPSS Statistics 24' software was used for statistical analysis.

Capacity model for four-lane highways

A significance analysis was done for all collected roadway characteristics, namely, effective lane width, access point density (APD), median type, built environment, FFS, shoulder type, and lateral clearance. FFS, shoulder type, and lateral clearance were excluded as they were not statistically significant predictors of the dependent variable, lane capacity. Hence the following

factors were selected as the predictors of lane capacity (the extent of each variable is shown within brackets).

- Effective lane width (2.1m – 4.0m)
- Access point density (0-13 per 400m)
- Median type (Median separated, Divided)
- Built environment (Rural, Sub-Urban and Urban)

The effective lane width is the available width per lane. Hence, the total effective directional width for four-lane sections were 4.2m – 8.0m. The effective lane width was used for the analysis since capacity is predominantly represented per lane. Multiple linear regression analysis was performed to develop the capacity model. The pre-requisites to carry out the regression are documented below.

Linearity of independent variables and homoscedasticity of data were checked to satisfaction by visual observation of partial regression plots and the scatterplot between 'Studentized Residuals' and 'Unstandardized Predicted Values'. Next, the data was checked for multicollinearity by inspection of correlation coefficients and Tolerance/VIF values. Since there were no correlations greater than 0.7 (maximum value being 0.615) and no Tolerance values lesser than 0.1 (minimum being 0.333), it was established that there was no multicollinearity in the data set [40].Next, the data set was checked for outliers by running the 'Case wise diagnostics' function in the SPSS software. This produced no outliers in the data set (Cases where the standardized residual is greater than ±3 standard deviations). Next the data was checked for leverage points and influential points, both of which were absent in the data set. The normality of the data was verified by observing the Histogram and the P-P plot of the standardized residuals (see Figure 3). Since the mean is close to zero (= $-1.5*10^{-15}$) and standard deviation is approximately 1 (= 0.94), the data can be approximated to be normal. Since the data set was conducive to perform the analysis, it was carried out using effective lane width, access point density, and built environment as independent variables, and lane capacity as the dependent variable. The effective lane width and access point density were entered as 'scale' variables and the built environment which is a categorical variable (Urban, Sub-Urban and Rural), was entered as a 'nominal' variable to the software and dummy coded for the analysis.

The regression model coefficient of determination (R^2) was 0.81 (standard error of the estimate = 117.03) indicating that the independent variables account for a major portion of the variance of the dependent variable. Further, it was observed that the independent variables statistically significantly predict lane capacity from Table 2, as the P-value is less than 0.05.

Table 3 shows the results of the regression analysis. The unstandardized coefficients of the independent/ predictor variables and the significance of each of them are seen in columns two and six, respectively. Since the P-values of each of the predictor variable is less than 0.05, the variables were accepted to the model. Hence the four-lane capacity model can be written as shown in Equation 6.

$$C_4 = 1467 + 190\,C_L + 118\,C_M - 39\,C_A - 206\,C_{BE} \quad ….(6)$$

where, C_4 is the four-lane capacity (pcu/h/l), C_L is the effective lane width (m), C_M is the median Type (0,1), C_A is the access point density (per 400m section), and C_{BE} is the built environment type (0, 0.7, 1). Since the built environment is entered as a categorical variable, the model is modified in such a way that a variable (C_{BE}) explains all three categories, rural, sub-urban and urban. Hence the values 0, 0.7 (= 145.7/206.1 from (Table 3)), and 1 (= 206.1/206.1 from (Table 3)) will be used to indicate rural, sub-urban and urban sections, respectively. Similarly, for the 'Median Type (C_M)' variable, values 0 or 1 should be substituted for divided and median separated sections respectively

Table 3 also portrays the coefficients of the predictor variables and their significance values which are less than 0.05, indicating that the predictor variables can be accepted to the model.
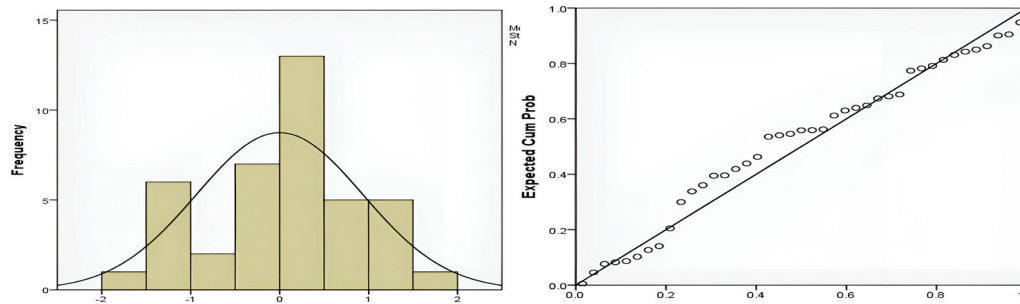
Figure 3 - Four-lane Capacity Histogram (left), and Normal P-P Plot of Regression Standard Residuals

Table 2 - ANOVA Table for Regression

Model	Source	Sum of Squares	df	Mean Square	F	Significance
4-lane model	Regression	1991917.967	5	398383.593	29.088	0.000
	Residual	479360.911	35	13696.026		
	Total	2471278.878	40			
6-lane model	Regression	126466.815	2	63233.407	18.19	0.003
	Residual	20858.074	6	3476.346		
	Total	147324.889	8			

Table 3 – Coefficients of Regression

Model	Factor	Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.
		B	Std. Error			
4-lane model	(Constant)	1467.12	145.218		10.103	0.000
	Effective lane width	189.547	41.111	0.392	4.611	0.000
	Access point density	-38.859	7.359	-0.519	-5.281	0.000
	Sub_Urban	-145.775	63.371	-0.297	-2.3	0.028
	Urban	-206.158	65.044	-0.398	-3.17	0.003
	Median Type	118.014	57.93	0.157	2.037	0.049
6-lane model	(Constant)	833.835	319.243		2.612	0.040
	Effective lane width	363.505	99.594	0.63	3.65	0.011
	Access point density	-23.12	8.85	-0.451	-2.612	0.040

Capacity model for six-lane highways

This analysis was carried out in a similar manner to the four-lane model development. The study sections were all median separated and predominantly 'Sub-Urban', hence the median type and built environment variables were not factored into the model. Similar to the four-lane capacity model developed in the previous section, the pre-requisite tests to assess of the data were done, and the data set was found to be suitable. Hence the six-lane capacity model can be written as shown in Equation 7. The developed model's regression model coefficient of determination (R^2) was 0.86, (standard error of the estimate = 58.961) indicating that the independent variables account for a major

portion of the variance of the dependent variable Further, the independent variables statistically significantly predict lane capacity as the P-value was less than 0.05 as seen in Table 3.

$$C_6 = 834 + 364 C_L - 23\, C_A \qquad \qquad \text{.... (7)}$$

where, C_6 is the six-lane capacity (pcu/h/l), C_L is the effective lane width (m), and C_A is the access point density (per 400m section).

4.2   Model Validation
For the task of verifying developed models, 10 multilane road sections (8 four-lane roads and 2 six-lane roads) were surveyed, collecting both classified flow data and traffic stream speed data as well as relevant roadway characteristics.

Capacity values were developed employing the technique explained section 3.3.

Using Equations 6 and **7**, the capacity values of the 10 sections were calculated. The Mean Absolute Percentage Error (MAPE) (Equation 8) of the estimated capacities was 8.2% and 5.3% (<10%) for the four-lane capacity model and the six-lane capacity model, respectively. This confirms that the models accurately predict capacity. Further, the Mean Absolute Error (MAE) (Equation 9) of the test data set was 128 pcu/h/l (137 pcu/h/l and 90 pcu/h/l for four-lane and six-lane models, respectively). The models show an acceptable fit with the test data with an R^2 value of 0.81 as seen in Figure 4.

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| x \ 100\% \qquad \text{.... (8)}$$

$$MAE = \frac{1}{n}\sum_{t=1}^{n}|A_t - F_t| \qquad \text{.... (9)}$$

where A_t is the actual value, F_t is the calculated value and n is the number of data points.

5.   Discussion

Table 4 presents a summary of the base capacity values in capacity estimation guidelines along with base capacity values obtained through the models developed in this study. The base capacities were estimated by maintaining the effective lane width at 3.5m, access point density at zero, and the median type as median separated. This ensures that the capacity values are on par with the base conditions defined in literature.

Table 4 - Capacity Comparison

Guideline	Base Capacity (pcu/h/ln)
HCM 2010	2200 (FFS = 100km/h)
IHCM	1650
Aust Roads	2200
Road Development Authority Guideline (Sri Lanka)	2000 (HCM 1985)
Four-lane capacity model	2250 (Rural) 2106 (Sub-Urban) 2044 (Urban)
Six-lane capacity model	2108 (Sub-Urban)

Figure 5 graphically represents how different roadway characteristics influence capacity. The top-left graph depicts the lane capacity variation

of four-lane roads with effective lane width under different built environment conditions. The top-right graph depicts the variation of capacity with increase in access point density on four-lane and six-lane roads when all other conditions are same. It is observed that the effect access point density has on four-lane roads is higher than that for six-lane roads.

The bottom-left graph presents the variation of capacity of six-lane roads with effective lane width and access point density. Finally, the bottom-right graph presents a comparison of typical capacities of rural, sub-urban and urban sections. These were derived by obtaining mean values of empirical roadway characteristics in
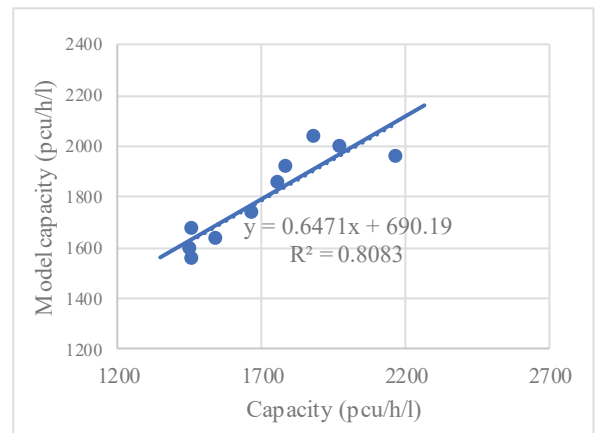
each built environment category.

Figure 4 - Scatter Plot of Model Capacity and Actual Capacity used for Validation

A summary of the captured empirical data is presented in Table 5.

Table 5 - Typical Capacity Values

Built Envionment type	Effective lane width (m)	Median availability	Access point density (/400m)	Typical capacity (pcu/h/l)
Rural	3.3	Yes	0	2212
Sub-Urban	3.3	Yes	5	1873
Urban	2.9	Yes	6	1696

Table 6 presents a comparison of the impact capacity reduction factors derived in this study have with respect to HCM and IHCM guidelines. It is observed that the six-lane capacity is comparably more sensitive to the lane width and on par with IHCM lane width factor.
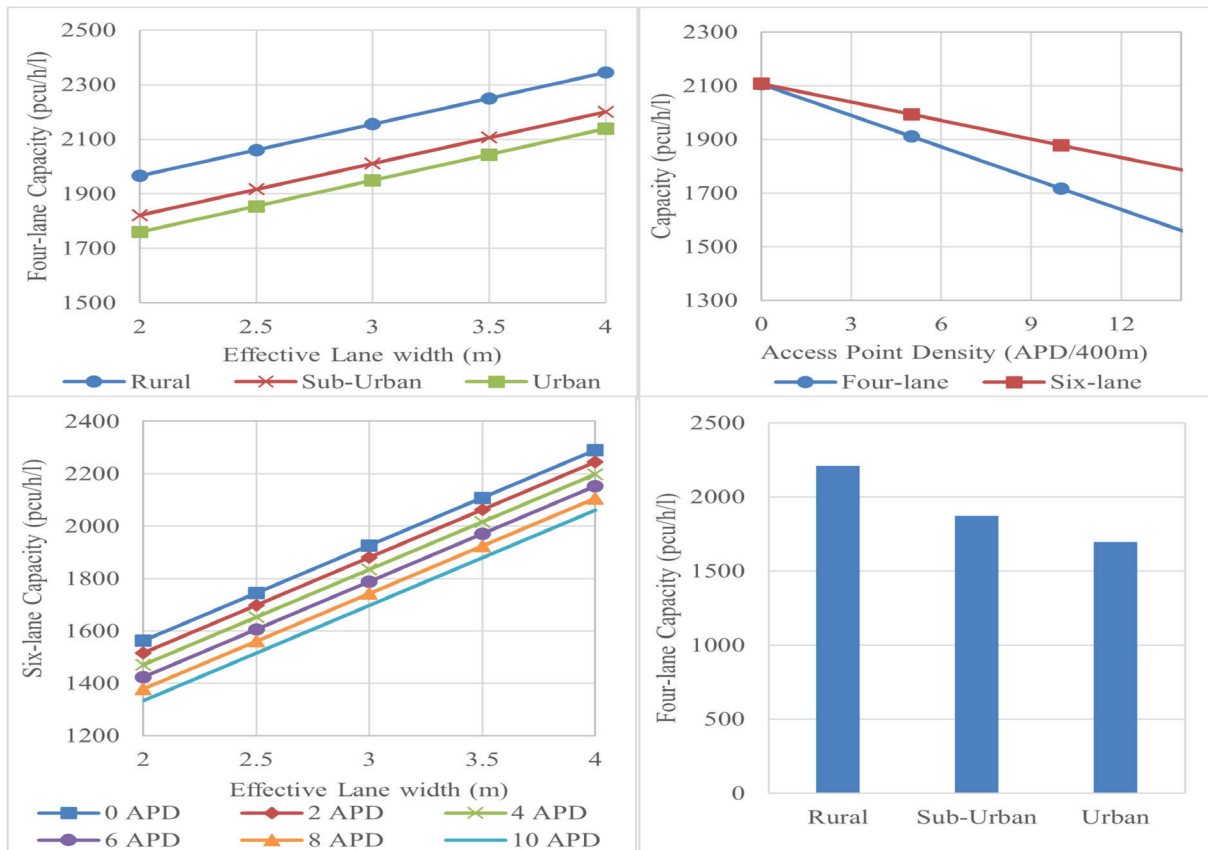
Figure 5 - Capacity Variations with Roadway Characteristics

The differentiating factor from HCM lane width adjustment factor is the variation of capacity with the increase and decrease of lane width since lane discipline is not strictly followed ([8],[11]).Reduction in lane widths upto 0.9m were observed due to on-street parking of vehicles on some urban and sub-urban roads. This phenomenon will reduce the lane capacity by approximately 8% - 20% on local multi-lane roads. From Table 6,it is observed that the impact access point density (APD) has is significantly higher on four-lane roads than the impact on six-lane roads. However, the impact of the APD observed is higher than what is specified in HCM. This can be attributed to the indiscipline driving etiquettes, where vehicles from minor roads enter the traffic stream, forcing through moving vehicles to slow down significantly. Similarly, it is observed that the absence of the median separation has a higher negative impact in this study (and in IHCM), in comparison to HCM.

This is another consequence of indiscipline driving, where drivers execute overtaking and turning manoeuvres at the expense of the through moving traffic. The impact of the median separation slightly increases when the built environment gets urbanized.

6.   Conclusions

It is understood that capacity is a vital parameter in transport planning and traffic management. Hence many transport authorities around the world have developed guidelines to evaluate capacity because the traffic carrying capacity of a road varies with new developments in vehicle technology, road construction, etc. The capacity value needs to be re-evaluated periodically. Further, since it has been established that capacity is a parameter that depends upon roadway and traffic characteristics unique to the road section and the locality of study, proper methodologies should be in place to accurately estimate capacity. Presently, this is not the case in Sri Lanka. Hence, this study was designed with the aim of developing a model which can predict the capacity of multi-lane roads in Sri Lanka.

Table 6 - Comparison of Capacity Adjustment Factors

Capacity adjustment factor	This study		HCM		IHCM	
	Absolute value	Percentage value	Absolute value	Percentage value	Absolute value	Percentage value
Effective/ Lane Width	Four-lane ±190 pcu/h/l/m Six-lane ±364 pcu/h/l/m	Four-lane ±4% Six-lane ±8.5%	-132 pcu/h/l for 0.6m lane width reduction	-5%	Four-lane ±264 pcu/h/l/m Six-lane ±211 pcu/h/l/m	Four-lane ±8% Six-lane ±8%
Access Point Density (AP - access point)	Four-lane -16 pcu/h/l/AP/km Six-lane -9 pcu/h/l/AP/km	Four-lane -0.7% (rural) -0.8% (sub-urban) -0.8% (urban) Six-lane -0.4% (sub-urban)	-5 pcu/h/l/AP/km	-(0.2-0.3)%	-	-
Median Type (undivided)	Four-lane -118 pcu/h/l	Four-lane -5.2% (rural) 5.6% (sub-urban) -5.8% (urban)	-32 pcu/h/l	-(1.5-1.7)%	-99 pcu/h/l (four-lane and six-lane)	-6% (four-lane and six-lane)
Built Environment	Four-lane -146 pcu/h/l (Sub-Urban) -206 pcu/h/l (Urban)	Four-lane -6.5% (Sub-Urban) -9% (Urban)	-	-	-	-

Considering the factors that affect multi-lane capacity, it was observed that the effective lane width, access point density, median separation, and roadside built environment have a significant impact on lane capacity. The factors that did not have a statistically significant impact were shoulder type, lateral clearance, and FFS. The six-lane capacity model which was developed from a limited data set, which included only median separated road sections in sub-urban environments, was based on the effective lane width and access point density. This area of the study can be strengthened through further research.

Whilst it was observed that the base capacities of four-lane and six-lane roads are on par with the values observed in literature, the significant findings of this study are the regression models developed based on the factors that affect capacity, and the extent to which the factors have an impact on roadway capacity which have not been quantified previously. In terms of four-lane roads, which are the most commonly found multi-lane road types in Sri Lanka, all capacity factors have a similar impact on capacity. In six-lane road sections the governing factor was the effective lane width. Through this study the impact of on-street parking in the Sri Lankan context was quantified and it was observed that it can reduce the lane capacity by a range of 8%-20%. The typical base capacity for a four-lane urban road was found to be 2044 pcu/h/l. The base capacities for four-lane rural and sub-urban sections were estimated to be 2250 pcu/h/l and 2106 pcu/h/l, respectively, and the base capacity for a six-lane sub-urban road section was estimated to be 2108 pcu/h/l.

Finally, the outcomes of this study can be used in traffic and transportation studies and, in a wider sense, in the development of capacity guidelines in areas with heterogeneous traffic conditions for capacity estimation as it is important given the incompatibility of guidelines developed based on homogeneous traffic streams. Further, studies can be done on other criteria that may influence capacity in future studies using these outcomes as a foundation.

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