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Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Empirical study on capacity evaluation of urban multi-lane roads under heterogeneous traffic conditions

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Abstract

The capacity of a highway facility is defined as the maximum hourly flow rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or a roadway during a given time period under prevailing roadway and traffic conditions (HCM, 2010) (Transport Research Board 2010). Even though the definition of capacity is universal capacity is a value dependent upon various traffic and roadway characteristics. Hence different countries have developed indigenous guidelines to estimate the traffic carrying capacity of their roads. This study is a stepping stone to the development of such a guideline for Sri Lanka. The study looks into the applicability of the HCM 2010 guideline for local conditions and observes the empirical evidence. It is found that the HCM guideline is not applicable to local conditions given the low traffic stream speeds. Further, capacity values of 25 four-lane highway sections are estimated using first principles assuming Greenshields' model. Capacity values ranging from 2399 pcu/h/l to 1346 pcu/h/l were observed. Even though they are comparable with capacity values observed in homogeneous traffic streams in developed countries the speeds at capacity were found to be drastically low.

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Keywords: Capacity estimation; Emperical capacity; heterogeneous traffic; developing country

1. Introduction

The capacity of a highway facility is defined as the maximum hourly flow rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or a roadway during a given time period under prevailing roadway and traffic conditions (HCM, 2010) (Transport Research Board 2010). Multilane highways are those where two or more lanes are provided in each direction of travel. The Highway Capacity Manual (HCM) developed in the United States of America, with all its revisions since 1950, is the pioneer document in this respect as it quantifies the concept of capacity for transport facilities. Unfortunately, the HCM methods developed in the US are

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not directly applicable around the world due to the heterogeneities arising out of prominently varying local conditions. Likewise, Sri Lankan highways are also not conducive for the application of HCM methods, predominantly due to the heterogeneous traffic conditions and vastly unique driver behaviour found on its roads.

Traffic streams that consist of vehicles with a wide range of static and dynamic characteristics with no spatial segregation are called heterogeneous traffic streams (see Figure. 1). This is opposed to homogeneous traffic streams observed in developed countries where the majority of the traffic stream is passenger cars. Arasan and Krishnamurthy (Arasan and Krishnamurthy 2008) suggest that heterogeneous traffic mixes exist when the percentage of the dominant vehicle mode is less than 80% of the traffic mix. While Fazio, Hoque, and Tiwari (Fazio, Hoque and Tiwari 1991) suggest the value to be slightly higher at 85%.

At the international level varying amounts of research have been found to be done in the area of capacity evaluation. Countries such as Germany, China, Indonesia, Malaysia, Thailand among other countries have developed indigenous Highway Capacity Manuals whereas neighbouring India is currently in the process of developing the Indo-HCM. Velmurugan S. et al. (2014) used microscopic simulation to evaluate capacity for four-lane inter-urban highways in India which is a research done focusing the development of the Indo-HCM (Yadav, Arun and Velmurugan 2014). Therefore, this research has significance to the current state of knowledge in the area of highway capacity evaluation, in evaluating how road capacities vary under heterogeneous traffic conditions and roadway characteristics which are prevailing in developing countries such as Sri Lanka.

Figure. 1. Heterogeneous traffic stream observed in Sri Lanka

Since the transport industry is essentially a service sector component, it is of paramount importance for the traffic engineers, transport planners, and engineers alike to understand and evaluate the ‘quality’ of service being provided by the transport facilities designed by them. In this regard, it is imperative to understand first the ‘capacity’ of such facilities. This is especially important in the urban context given the high interdependency of the movement of traffic flows in its highways. Knowledge of capacity is important in the design and maintenance of highways as it is governed by geometric parameters such as the number of lanes, width of lanes, median type, access point density etc. Further, it is used as an input in transportation planning studies such as traffic demand modelling in network analysis.

2. Literature review

2.1. Base capacity

Base capacity is defined as the capacity of a road section under 'ideal' conditions. The conditions to be met for a section to be considered ideal depend on the guideline followed. For example, the Highway Capacity Manual (HCM) 2010 requires the following key conditions to be met for a multilane highway to be considered as ideal,

- Lane width – 3.6m
- Lateral clearance – 1.8m
- Median – available
- Access point density – zero access points
- Traffic stream consisting of passenger cars

When the above conditions are met the base capacity is said to be a function of the free flow speed observed across the given section of road. Free flow speed (FFS) is defined as 'The average speed of vehicles on a given segment, measured under low-volume conditions, when drivers are free to travel at their desired speed and are not constrained by the presence of other vehicles or downstream traffic control devices' by the HCM 2010 (Transport Research Board 2010). The base capacity values given in the HCM 2010 vary from 2200-1900 pcu/h/lane depending the FFS. The Indonesian Highway Capacity Manual (IHCM) of 1997 proposes a base capacity value of 1650 pcu/h/lane for a median separated road and 1500 pcu/h/lane for a non-divided lane (Directorate General of Highways 1997). The Geometric Design Standard of Roads (1998) proposes a base capacity of 2000 pcu/h/lane (Road Development Authority 1998). Hence it is understood that base capacity is a variable dependent upon the locality. Considering research carried out into establishing base capacity Sathishkumar et. al (2016) (Sathishkumar , Rao and Velmurugan 2016) estimated base capacity of Urban Indian 4-lane roads under ideal roadway conditions (3.5m lane width, and no road side friction). The composition of vehicles were 64.8% Cars, 3.7% Heavy vehicles and the rest motor cycles and three wheelers. The lane capacity was estimated to be 1570 pcu/h/ln. The operating speed which was defined as the 85th percentile value of free flow speed of passenger cars was estimated to be 64kmph. Anamika Y. et al studied the Capacity of inter-urban multi-lane highways in India in 2014 proposing that the capacity per lane on a 4-lane highway is 2250 pcu/h/ln. The capacity value was derived based on the assumption that capacity occurs at half of the free flow speed (Anamika, Ashutosh and Velmurugan 2014).

2.2. Factors that affect lane capacity

The survey of literature indicates that the 'base' capacity value varies with different roadway and traffic parameters. Hence the empirical capacity values of non-standard locations will differ from the base value. The HCM 2010 guideline has capacity reduction factors in terms of lane width, median type, free flow speed, access point density and lateral clearance. The effect of these factors is seen in independent research publications as well. Effect of lane width on capacity (Chandra and Kumar 2003, Nakamura 1994), Effect of the Median type on FFS and thereby capacity (Moses and Mtoi 2013), Effect of FFS on capacity (Arun, et al. 2016, Sathishkumar , Rao and Velmurugan 2016), Effect of access point density/ curbside parking/ bus stops/ pedestrian activity (Chand, Chandra and Dhamaniya 2014, Salini, Sherin and Ashalatha 2014, Wijerathna 2015) and effect of lateral clearance (Leong 1978, Prakash 1970) are observed in published literature. In addition to these factors, the vehicle composition is also found to be having a significant impact on capacity (Chandra, Mehar and Senathipathi 2015).

2.3. Data collection methodologies

Various traffic data collection methods which are either manual or automated are used at present for the purpose of data collection. Manual traffic data collection is the primary and the oldest method currently in practice. This is usually done by employing enumerators to collect the necessary types of traffic data as per the requirement. This method is still useful as at present automated methods do not accurately gather some data types such as vehicle occupancy, vehicle classification, pedestrian details etc. (Leduc, 2008). The Google Distance Matrix Application Programming Interface (API) is a service that provides travel distance and time for a matrix of origins and destinations. The API returns information based on the recommended route between start and end points, as calculated by the Google Maps API, and consists of rows containing duration and distance values for each pair. This feature can be used for traffic stream speed estimations of road segments of varying length. 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% (Kumarage, et. al. 2017). The same methodology can be extended to predict traffic stream speeds of road links.

3. Data collection

Manual Classified Counts (MCC) were done on 25 four-lane highway sections. Enumerators with handheld counting devices were employed for traffic flow data collection for a time period of at least 12 hours at each location. Flow data were collected in 15-min intervals. Flow data were collected at mid-block sections such that the flow was not affected by junction access control. The vehicles were classified into 10 distinct categories. Namely, Motor Cycles (MC), Auto rickshaws commonly known as Three Wheelers (TW), Cars, Light Commercial Vehicles (LCV), Light Goods Vehicles (LGV), Medium Goods Vehicles (MGV), Heavy Goods Vehicles (HGV), Multi Axle Vehicles (MAV), Mini Buses, and Buses.

Speed data were collected parallel to the collection of flow data. A novel method was used to collect space mean speeds of the relevant sections using Google Distance Matrix API (Google Developers n.d.). The speed was calculated indirectly by getting the time travelled for a traffic stream over a known distance. The required input parameters include the Origin-Destination coordinate pair, and the API key. Optional calibration parameters Mode of travel, departure time and traffic model were fixed. The mode of travel was set to ‘driving’, departure time to ‘now’ and traffic model to ‘best guess’. Travel time is retrieved in JSON (JavaScript Object Notation) format which is a human readable text format. To collect data a PHP (Hypertext Preprocessor) script was used. The accuracy of collected speed data using this method was examined by Sakitha et. al. (2018). Speed data for was collected in 5-minute intervals and averaged across 15 mins to establish the 15 min traffic stream speeds.

4. Analysis

4.1. HCM 2010 comparison

A study was carried out to establish the applicability of the HCM 2010 multilane methodology for capacity estimation. The base capacity of a multilane highway is dictated by its free flow speed (FFS) in the HCM 2010 guideline. The methodology defines capacity values for free flow speeds ranging from 72km/h (45 mi/h) to 97km/h (60mi/h) where the free flow speed is the speed of vehicles when the flow is less than 1400 pcu/h/lane or as represented by equation (1) (Transport Research Board 2010).

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A \tag{1}$$

Where, FFS is the free flow speed. BFFS is the base free flow speed, f_{LW} is the lane width adjustment, f_{LC} is the lateral clearance adjustment, f_M is the median type adjustment and f_A is the access point density adjustment.

5 multilane sections were considered for the study and the relevant geometric details of the sections are as shown below in table 1. The Google Distance matrix (GDM) API and equation 1 both were used to calculate the Free Flow Speeds at each location. 24-hour speed data were collected across 25 days at each location at 10 minute intervals. The 95th percentile speed obtained from the Google Distance matrix API was considered to be equivalent to the FFS. Figure. 2 shows the comparison between speed values obtained via equation 1 and GDM API.

Table 1. Geometric details of sections considered

Location	Posted Speed (mi/h)	Lane width range (ft)	Lateral Clearance (ft)	Median Type	Access Point Density (per mile)	FFS (mi/h)
A1 Highway Loc 1	31 (50km/h)	11-12 (3.35-3.65m)	4 (1.2m)	Divided	0 (0 per km)	34 (55 km/h)
A1 Highway Loc 2	31 (50km/h)	11-12 (3.35-3.65m)	8 (2.4m)	Divided	13 (8 per km)	32 (52 km/h)
A3 Highway	31 (50km/h)	11-12 (3.35-3.65m)	8 (2.4m)	Divided	23 (14 per km)	30 (48 km/h)
Marine Drive	31 (50km/h)	11-12 (3.35-3.65m)	6 (1.8m)	Undivided	24 (15 per km)	27 (44 km/h)
New Panadura Road	43.5 (70km/h)	11-12 (3.35-3.65m)	12 (3.6m)	Divided	23 (14 per km)	42.5 (69km/h)
A4 Highway	31 (50km/h)	11-12 (3.35-3.65m)	4 (1.2m)	Undivided	9 (6 per km)	32 (52km/h)

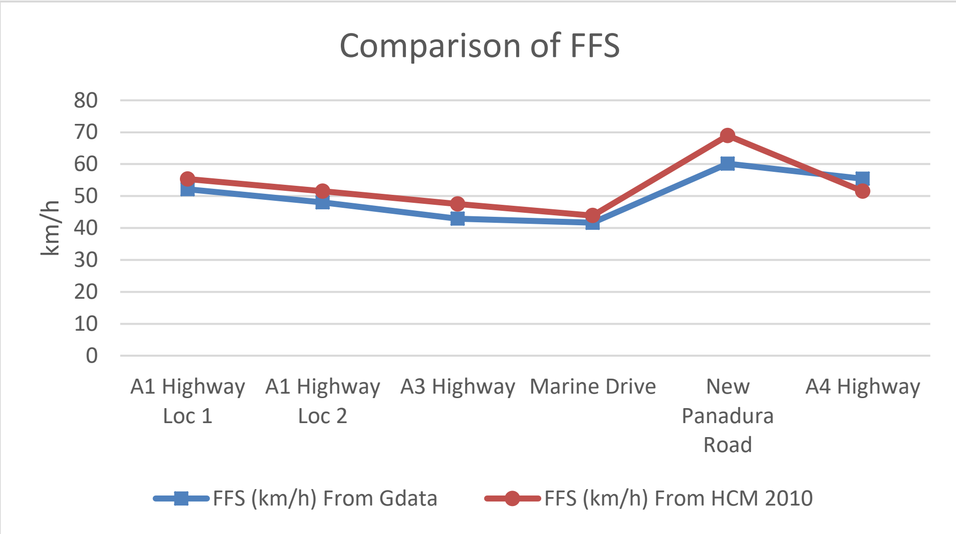

Figure. 2. Comparison of observed speed data with HCM 2010 model

Considering the values, it was observed that the HCM methodology satisfactorily predicts the FFS of roads under heterogeneous traffic conditions. But the observed FFS values are much lower than the FFS range defined by the HCM guideline for further analysis. Hence base capacity cannot be obtained for Sri Lankan roads using the HCM guideline.

4.2. Empirical data

A histogram of the empirical flow data collected is shown in Figure 3. The maximum flow observed is 2414 pcu/h/l. And the 95th percentile flow being 1492 pcu/h/l. For conversion of heterogeneous flow data to homogeneous flow data the Passenger Car Unit (PCU) factors developed by Jayaratne et. al based on the method proposed by Chandra et. al were used (Jayaratne, et. al. 2018, Chandra et. al. 1995). The PCU factors used are shown in table 2.

The traffic composition is shown in Figure. 4. The vehicle split observed is typical to what is observed in Sri Lanka where heterogeneous traffic flows are the norm (Jayaratne et. al 2018). Light Goods Vehicles (LGV), Medium

Goods Vehicles (MGV), Heavy Goods Vehicles (HGV) and Multi Axle Vehicles (MAV) are binned together as Goods Vehicles. Buses and Mini Buses are binned together as Buses in the pie chart. As is the norm in traffic flows observed in the country the majority (50%) of the traffic stream consisted of motor cycles and three wheelers. The standard vehicle which is the passenger car only catered to 28% of the entire traffic stream. This is a major difference from the homogeneous traffic streams observed in developed countries.

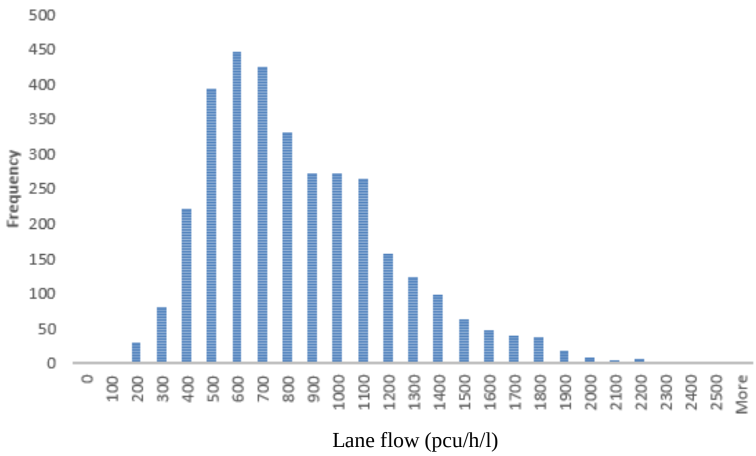

Figure. 3. Empirical flow histogram

Table 2. PCU values used in study

Vehicle category	PCU value
Motor Cycles (MC)	0.23
Three Wheelers (TW)	0.56
Cars	1.00
Light Commercial Vehicles (LCV)	1.00
Light Goods Vehicles (LGV)	1.70
Medium Goods Vehicles (MGV)	2.52
Heavy Goods Vehicles (HGV)	3.65
Multi Axle Vehicles (MAV)	6.53
Mini Buses	2.32
Buses	5.36

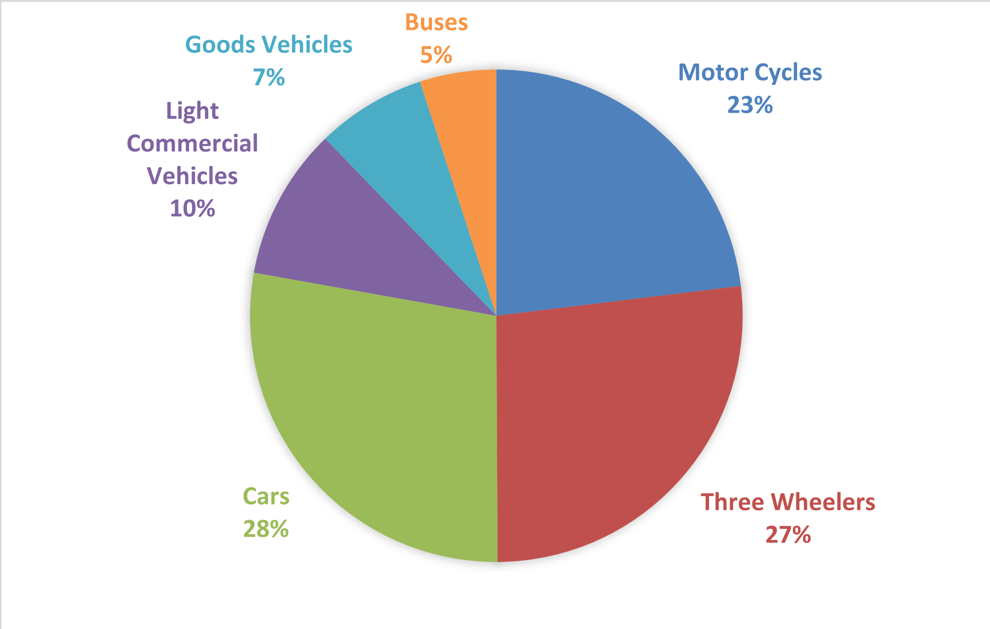

Figure. 4. Traffic composition pie chart

4.3. Capacity estimation methodology

Capacity values were estimated for each location from first principles assuming Greenshields model shown by equation 2 (Greenshields, et al. 1935). The following steps were followed to find capacity values for each location.

1. Heterogeneous traffic flow was converted to a homogeneous traffic flow using PCU factors developed by Jayaratne et. al 2018.
2. Corresponding traffic speed data for each 15-minute flow interval was obtained from GDM API.
3. The density value for each 15-minute interval was calculated using the fundamental traffic flow equation 3
4. Speed vs density points were plotted, and Greenshields model was fitted to the data
5. The speed flow model was derived using the calibrated Greenshields model and the fundamental traffic flow equation for each location.
6. The maximum flow value predicted for the derived speed flow model was taken as the Capacity of that location.

$$v = v_f(1 - \frac{k}{k_j}) \quad (2)$$

$$Q = v * k \quad (3)$$

Table 3. Derived capacity values and Greenshields' calibration parameters

Location Code	Max 12-hour stream speed (km/h)	Greenshields' model				
		Rsq	FFS (Uf) (km/h)	Jam Density (Kj) (pcu/km/l)	Speed at Capacity (Uc) (km/h)	Capacity (pcu/h/l)
Loc_01	51	0.85	50	190	25	2399
Loc_36	30	0.71	32	290	16	2349
Loc_02	56	0.45	56	164	28	2274
Loc_13	56	0.50	56	159	28	2243
Loc_60	25	0.58	19	415	10	1995
Loc_65	43	0.79	45	179	22	1992
Loc_23	49	0.70	47	168	24	1983
Loc_12	49	0.84	49	162	24	1965
Loc_35	26	0.45	28	281	14	1961
Loc_32	50	0.56	42	187	21	1957
Loc_66	41	0.44	34	229	17	1943
Loc_11	57	0.90	54	144	27	1941
Loc_50	39	0.63	38	199	19	1916
Loc_49	45	0.71	44	172	22	1908
Loc_03	35	0.62	37	202	19	1884
Loc_57	38	0.51	29	241	15	1775
Loc_31	28	0.44	22	322	11	1760
Loc_41	41	0.92	43	161	22	1730
Loc_42	49	0.40	50	139	25	1727
Loc_43	46	0.72	46	148	23	1717
Loc_53	29	0.42	25	268	13	1705
Loc_04	35	0.73	38	177	19	1690
Loc_30	32	0.49	31	220	15	1690
Loc_52	44	0.56	48	132	24	1569
Loc_25	34	0.69	28	194	14	1346

Table 3 shows the capacity values derived for each of the 25 locations surveyed along with the actual maximum speeds observed, the r-squared value when fitting Greenshields' model, U_f, U_c, and K_j. The capacity values ranged from 2399 pcu/h/l to 1346 pcu/h/l. Figure. 5 shows a comparison between the actual maximum speed observed and the FFS derived via Greenshields' model. It can be observed that the model accurately maps the actual speeds observed given the Root Mean Square Error (RMSE) is 4.698 and the r-square value of 0.9. Figure 7 shows the speed-flow relationships of six road sections surveyed. This displays a key a limitation of the study where for a majority of the road sections investigated flow data in the congested sections have not been observed.

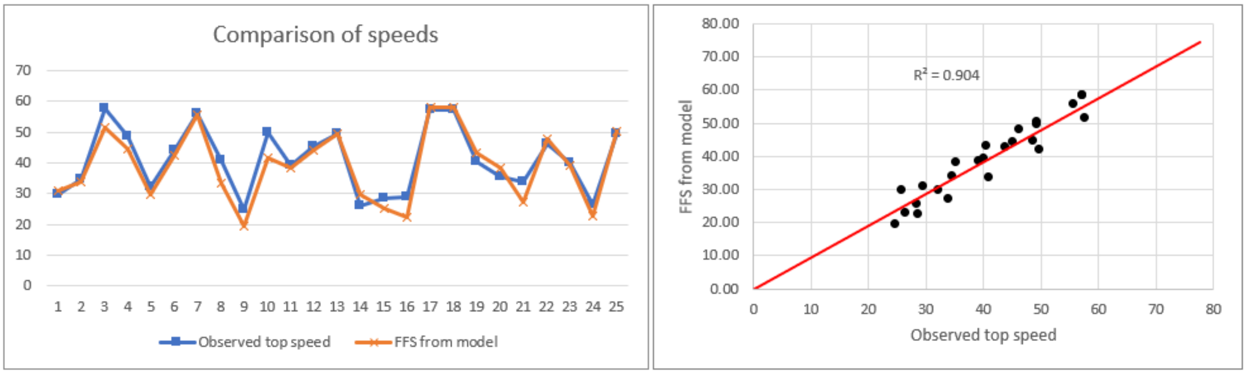

Figure. 5. Comparison of observed top speeds with free flow speeds from Greenshields' model

A histogram of the observed capacities is shown in figure 6. A The 85th percentile capacity was 2246 pcu/h/l. 50th percentile capacity value or the median of the capacity data was 1943 pcu/h/l. The empirical average capacity is 1922 pcu/h/l. These values are comparable with capacity values observed in literature. A study carried by Jayaratne et. al in 2018 observed that the base capacity of a four-lane highway was 2309 pcu/h/l (Jayaratne et. al 2018). Even though the values obtained are similar in value to the base capacity values suggested in the HCM 2010 guideline the speed at capacity is vastly different. The speeds at capacity given in the HCM guideline are in the range of 70-90 km/h whereas the speeds at capacity observed are between 10-30 km/h. This is a major difference in the dynamics of the traffic stream.

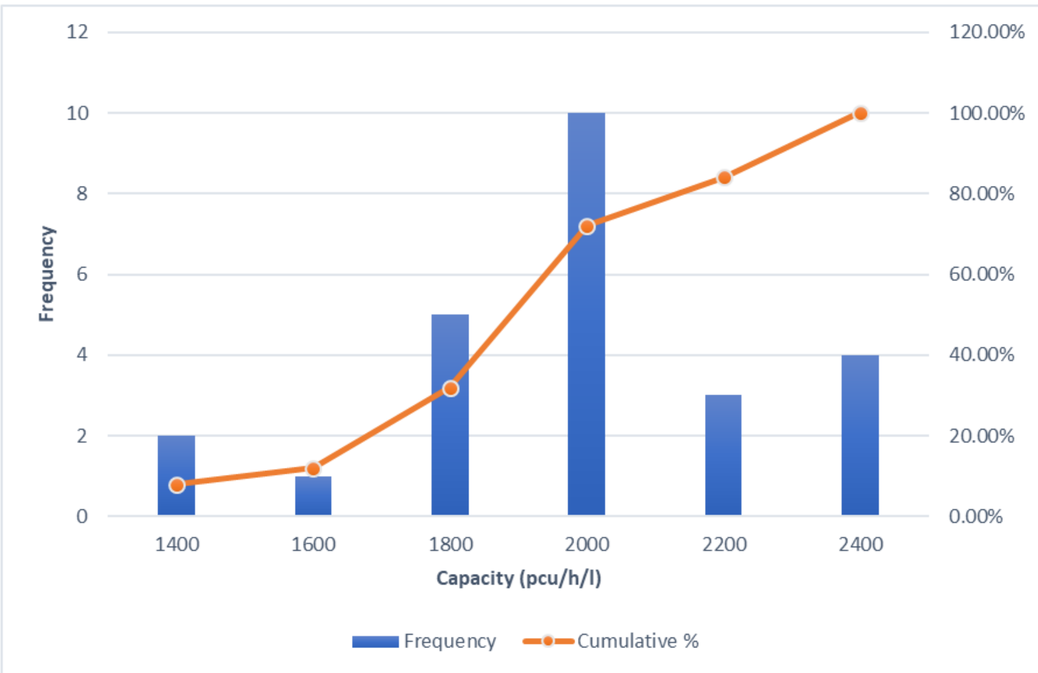

Figure. 6. Histogram and cumulative frequency curve

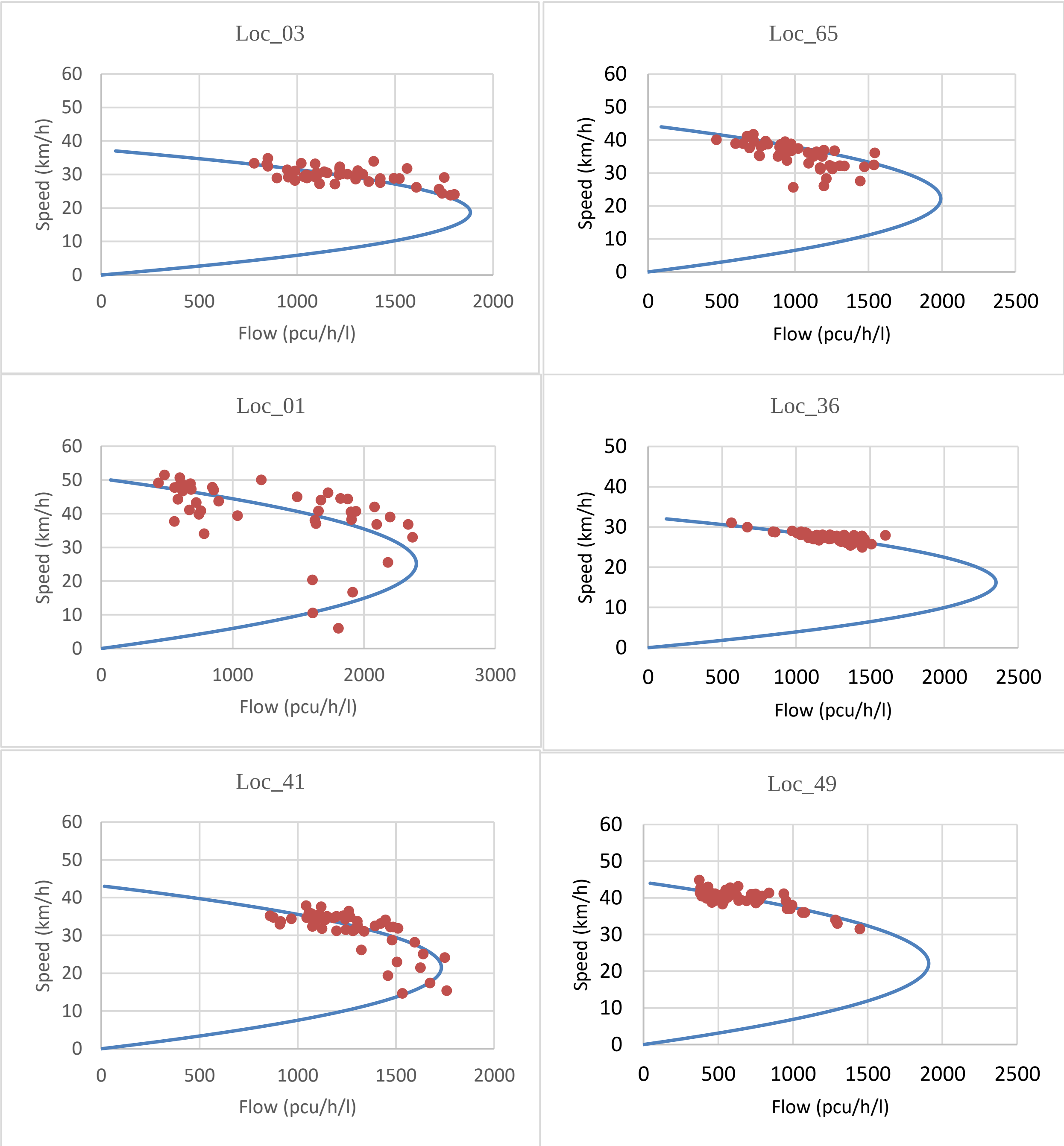

Figure. 7. Speed-flow plots used to derive capacity values (at selected locations)

5. Conclusion

This study was carried out to develop an understanding about multilane highway capacity under heterogeneous traffic conditions. Through the literature review an understanding about approximate lane capacity values and the factors that affect capacity was gained. Collection of flow data was carried out manually by employing enumerators. Speed data was collected using a novel method via Google traffic data. This was understood to be an easy and data intensive method that can be utilized in future studies. An initial analysis was done to check if methodology proposed by the HCM 2010 guideline was applicable to local conditions. But it was observed that the speeds observed on local roads are much less than what the guideline defines. Hence it was understood that the HCM guideline was not applicable to the heterogeneous traffic streams observed in Sri Lanka. The average maximum speed of the 25 sections observed was 42km/h with a standard deviation of 10.5 km/h. The traffic composition observed during the study conformed to the norm in which the majority of vehicles being motor cycles and three wheelers. 50% vehicles of the traffic stream were motor cycles and three wheelers where as only 28% of the traffic stream consisted of passenger cars.

Considering the capacity values derived from first principles, a wide range of values were observed. Greenshields' linear model was used to calculate the capacity. Values ranging from 2399 pcu/h/l to 1346 pcu/h/l were observed. The average capacity value was 1922 pcu/h/l whereas the 85^{th} percentile capacity value was 2246 pcu/h/l. These values were comparable with values observed in literature including the HCM guideline where capacity varied between 2200-1900 pcu/h/l. But the main difference being the speeds at capacity which were very low in comparison. All in all, the study covers basics of capacity estimation under heterogenous traffic conditions in developing countries. Further work needs to be done to understand the influence different traffic and geometric parameters have on capacity.

Acknowledgements

This research was funded by University of Moratuwa Senate Research Grant.

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