Best HCM deterministic model calibrated for capacity analysis of basic segments of freeways in Lima

Tania Lizeth Cubas Gonzales
Facultad de Ingeniería Civil
Universidad Peruana de Ciencias Aplicadas
Lima, Perú
u201520139@upc.edu.pe

Rousbel Ricardo Rondon Alcedo
Facultad de Ingeniería Civil
Universidad Peruana de Ciencias Aplicadas
Lima, Perú
u201520293@upc.edu.pe

Fernando Mauricio Tarquino Torres
Facultad de Ingeniería Civil
Universidad Peruana de Ciencias Aplicadas
Lima, Perú
pcciftar@upc.edu.pe

Abstract

In traffic engineering, the assessment of capacity in basic segment of freeway is a critical factor for planning, design and operational analysis of the freeway facilities. Thereby, the Highway Capacity Manual – HCM is the main guide used in many countries of the world including Perú that contain the methodology to estimate freeway capacity in traffic studies. Nevertheless, the information of vehicular traffic used for the construction of the models proposed by the HCM, reflect the characteristics of North American features. Therefore, its application in other traffic conditions, must be backed by studies of the local conditions and calibrations of the models proposed, hereby, adjusting to each city. The objetive of this research, is calibrate and compare of the HCM 2010 and HCM 2016 models, starting off the traffic engineering study in Panamericana Sur freeway located in Lima, Perú. The report will recommended the application of a calibrated model that best represents the local Peruvian conditions. The results of this study suggest that the model of calibrated capacity HCM2016, is the best representation, with a reliability of 97%, the local behavior of the basic freeway segments in function of the speed and the flow intensity. After applying the calibrated model into basic freeway segments concessioned by Rutas de Lima SAC, it was reflected that the use of the HCM2000, employed by this Company, show flow intensities within a level of service – LOS D, while, the calibrated HCM2016 shows us that those values are found, in reality, within a level of service – LOS E.

Keywords— road capacity, free flow speed, intensity, calibration, basic segment of freeway

I. INTRODUCTION

The HCM Manual is the only guide used in Peru for operational analysis and estimation of urban road infrastructure capacity. The deterministic model proposed by the HCM is based on the determination of the free flow speed, and with help from the graphics for basic freeways segments that are in function of the speed and flow intensity, it helped us to predict the capacity of the freeways [1]. Nevertheless, the factors and parameters utilized to obtain these freeway capacity models are based in traffic studies of North American roads, which in turn have not been verified for local peruvian conditions, this entails the fact that there may be inadequate application of the Manual of Freeway Capacity HCM to the reality of the basic segments in peruvian freeways. By consequence, studies can produce incorrect diagnostics for the decision process in the increase of road capacity of the freeways and perform inadequate investments in the urban freeways projects in Lima.

In diverse researchs there are authors like Arun and Velmurugan [2], who proposed a framework for the estimation of the capacity of Indian freeways, because of the heterogeneity and the behavior of the driver its enormously unique for Indian freeways so much that it's not favorable for the direct application of the HCM.

Likewise in Italy, Pompigna and Rupi [3], raised data of velocity and flow rates of the Italian freeway A4 and they were calibrated according to the models of longitudinal control [4] and the Van Aerde model [5]. The results have demonstrated that the two models of calibration estimate values of road capacity, velocities and critical densities, very close between each other, but inferior to those proportioned to HCM2010. As well, the authors Riente de Andrade and Pitombo [6], performed a calibration of the model proposed by the HCM, through data of velocity and flow obtained in 36 sites on the Brazilian freeways, together with information about variables that describe segment characteristics such as: The limit of velocity, the curvature, the type of freeway, the number of lanes and the density of points of access, with the objective of adjusting the models of free flow speed (FFS), and adapt to the use of Brazilian conditions.

In India, Matthew, Dhamaniya and Arkatkar [7] investigated the suitability of the equations of the HCM to determine the capacity of entrance in one segment, in conditions of mixed traffic and proposed a methodology to validate and calibrate the equations of the HCM. With this, they discovered that the capacity obtained from the HCM 2010 equation was 11.8% less, than that obtained by using the calibrated equation. At the same time; Asgharzadeh and Kondyli [8], performed a comparison of estimation methods of the capacity of freeways, from which were included the method of Van Aerde, the method of limited product, the index of sustainable flow and the proposed by the HCM2016, using as a base of data of various bottlenecks of the city of Kansas City. It was revealed that the limited product method and the sustainable index of flow method showed a significant coherence in comparison with the HCM2016 method.

In the case of Poland, Dibinski and Janusz [9], based on the results of the evidence obtained for the one segment of national freeway, indicated that there exist problems to apply

978-1-7281-9466-0/20/$31.00 ©2020 IEEE

the HCM, since, the differences between the conditions in Poland and the United States of America already occur in the division stage of the freeways into groups. This could be the direct cause of making erroneous decisions and actions for the betterment of the flow of traffic in the sections of freeway, given that there are significate differences between the level of service defined for the freeways of class I, II, & III, proposed by the HCM2016. In this same manner, Ana Tsui Moreno [10], performed the calibration and validation of the simulation of traffic TWOPAS model, that which is the model used by the HCM. With this study they indicated that the methodology proposed by Tsui provides more precise estimations than the HCM on freeways with two real lanes in operation.

In this research, the HCM 2010 and 2016 methodology were used to study the traffic operation in two basic segments of the Panamericana Sur freeway. The Panamericana Sur freeway possesses a length of 54.1 km, located along of the Lima coast and counts with a velocity of design of 90 km/h and a central separator with three lanes per direction.

The results of the study permitted to develop calibration tools and obtain models of capacity calibrated for each version of the manual. From which, is recommended the application for the operational analysis of freeways in Lima, the calibrated model HCM2016, since it adjusts with a reliability from 97% to local behavior of the basic segments in function of the velocity and the intensity.

II. Methodology and Tools

A. Recollection of traffic inofrmation

This study consisted of capturing field data on two basic segments of the Panamericana Sur freeway. They were carried out vehicle speed and counting measurements cars, trucks and buses. The vehicle count was carried out manually with the support of two video cameras, the which were at the entrance and exit of the segment. This allowed to record the vehicular flow in the basic segments and determine the travel time of light vehicles, necessary to calculate the average circulation speeds.

Volume and speed measurements were made at a first stage, Fig. 1, at km 12 between the Pedestrian Bridge Maria Auxiliadora and Amauta, sector that was called basic segment I. And in a second stage, Fig. 2, at km 17 between the Pedestrian Bridge La Capilla and Lechon, sector called basic segment II. In both segments, proceeded to edit the videos in the Flimora9 program to count by vehicle type and lane in 15-minute intervals.

Fig. 1. Basic segment I of the Panamericana Sur freeway, Lima-Peru

Fig. 2. Basic segment II of the Panamericana Sur freeway, Lima-Peru

B. Processing traffic data

To calibrate of the capacity model, it's necessary to determine the average circulation speeds (km/h) and the intensity (veh/h/lane) corrected by the rush hour and heavy vehicle factors per lane and at 15-minute intervals.

B.1. Calculation of average speed of circulation

The representative circulation speed of each intensity shall be valid for a measurement of 100 light vehicle speeds per hour per lane. From this, the calculation of the average travel time of light vehicles was made in one hour, for the distance of 174m from basic section I and 130m of basic section II, using (1) obtains the representative circulation speed for each intensity.

$$V_s = \frac{L}{\frac{t_1 + t_2 + t_3 + \ldots + t_{100}}{100}} \ (m/s) \quad (1)$$

Where:
t_n: Travel time of each light vehicle (s)
L: Basic section length (m)
V_s: Average circulation speeds (m/s)

B.2. Calculation of vehicular intensities

From the vehicle count performed for each basic segment, the intensity (veh/h/lane) recorded in each lane measurement is determined. This calculation was determined by the estimates proposed by HCM 2010 and HCM 2016, which are shown in (2) and (3) respectively.

<u>HCM 2010</u>

$$Intensity\ (veh/\ h\ /lane) = \frac{volume\ (veh/h)}{PFH\ x\ N\ x\ f_{HV}\ x\ f_c} \quad (2)$$

<u>HCM 2016</u>

$$Intensity\ (veh/\ h\ /lane) = \frac{volume\ (veh/h)}{PFH\ x\ N\ x\ f_{HV}} \quad (3)$$

Where:
PFH: Rush hour factor
N: Number of lanes per direction of analysis
f_{HV}: Heavy vehicle adjustment factor
f_C: Adjustment factor by type of conductor

As the main differences between the calculation of intensities by HCM 2010 versus that presented by HCM 2016 are the adjustment factor by type of conductor, which for HCM 2016 is no longer considered within (3). In turn, for this latest version of the HCM, another change in the equivalent light vehicle factor is shown in accordance with Table 1 and 2, for estimating the adjustment factor for heavy vehicles according to (4) and (5).

Table 1: Light vehicle equivalence factor for heavy vehicles for segments on general terrain, HCM 2010

Passenger Car Equivalent	Terrain type		
	Level	Rolling	Mountainous
E_T (trucks and buses)	1.5	2.5	4.5
E_R	1.2	2.0	4.0

Table 2: Light vehicle equivalence factor for heavy vehicles for segments on general terrain, HCM 2016

Passenger Car Equivalent	Terrain type	
	Level	Rolling
E_T	2.0	3.0

HCM 2010

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \quad (4)$$

HCM 2016

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \quad (5)$$

Where:
f_{HV}: heavy vehicle adjustment factor
P_T: percentage of heavy vehicles
P_R: percentage of recreational vehicles
E_T: light vehicle equivalence factor for heavy vehicles (buses, trucks)
E_R: light vehicle equivalence factor for heavy vehicles (recreational vehicles)

It should be noted that the calibration for HCM 2000 was performed, however, according to the methodology presented by HCM 2010 there were no differences between them. As a result, only HCM 2010 and HCM2016 were studied.

Fig. 3 and Fig. 4 show the data processed for each version of the HCM manual. It can be seen that produces a similar trend to the classic model proposed by HCM for the graphical representation between transit intensity and speed of circulation.

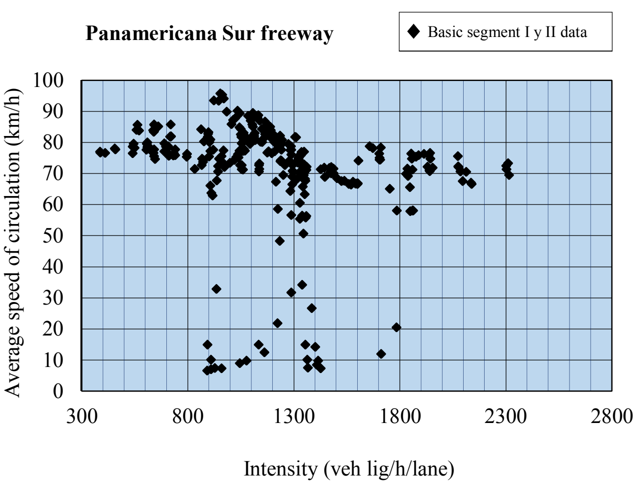

Fig. 3. Intensity and velocity distribution for HCM 2010

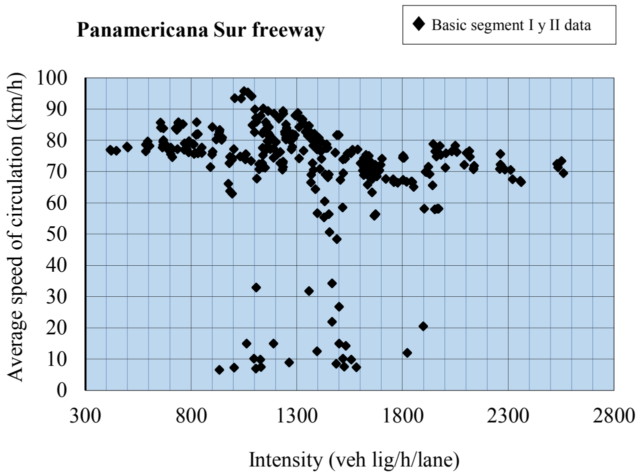

Fig. 4. Intensity and velocity distribution for HCM 2016

C. Data regression and adjustment curve calculations

The analysis of the field data was performed through adjustment curves that relate the intensity and speed variables of vehicles and their derivations. Thus, to find the best correlation of variables of all adjustment curves, with the value of R^2, that allows to calibrate the capacity model for basic segments of freeways.

When performing the respective regression adjustments, for the velocity and intensity variables, curves with very low correlation were obtained. It was then tested to adjust the logarithms and reciprocals of both variables, which also did not deliver very high correlation values. Due to the low determination factor found, the option to use the density variable was raised, which is calculated according to (6).

$$Density\ (veh/km) = \frac{Intensity\ (veh/h)}{Velocity\ (km/h)} \quad (6)$$

The adjustment curves between density and intensity showed a higher correlation than those obtained between density and velocity. In turn, adjustments were made to the logarithms and reciprocals of these variables, obtaining better results with correlations equal to 0.9727 for HCM 2010 and 0.9741 for HCM 2016, which lead to determining that the ratio of the reciprocal intensity vs density would be used to find the adjustment curve for each version of HCM. It should be noted that, in order to make these adjustment curves, data whose values had a speed less than 58 km/h were deleted, as these points varied too much compared to the other data.

What is in the interest of determining is the behavior of speed when volumes are moderate to high and there is congestion on the track, assuming that when there are lower volumes, drivers are not influenced by others. It is assumed, then, that for intensities less than 1000 veh/h, the circulation speed remains constant allowing to know the free flow speed. So, for each version of the HCM, its adjustment curve allows to obtain the capacity curve for basic segments of freeway associated with the free flow speed of field, whose value for HCM 2010 is 80.58 km/h and for HCM 2016 is 79.77 km/h. Fig. 5 and Fig. 6 show the adjustment curves for each version of the manual

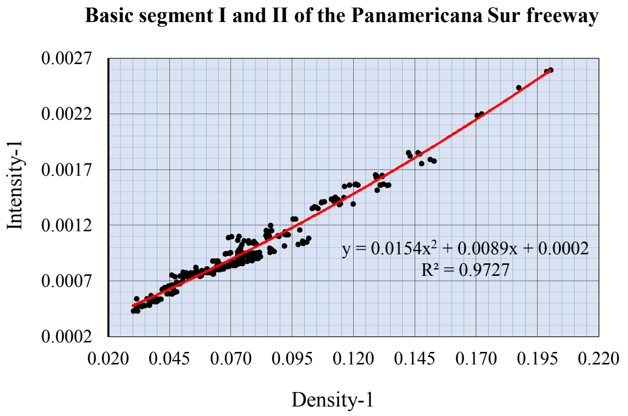

Fig. 5. Intensity and density reciprocal adjustment curve for HCM 2010

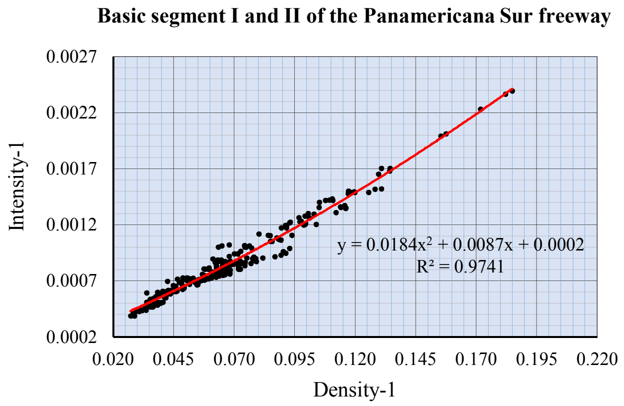

Fig. 6. Intensity and density reciprocal adjustment curve for HCM 2016

III. Results

A. Construction of calibrated capacity models for each version of the HCM

Once the adjustment curves for each version of the HCM were obtained, the relationship between speed and intensity was sought. Because of this, fixed density values were taken and their reciprocals replaced in the equation representing the adjustment curve, to obtain the intensity-1 values. The velocity was then determined through (6) that relates intensity, density, and velocity.

After having the speed data with their respective intensities, the intensity that marks the point of descent was determined. That is, for values greater than this, the velocity versus intensity behavior is governed by the adjustment curve. Whereas, for values less than the point of offspring the curve is governed by the free flow speed. So, HCM 2010 and HCM 2016 the intensities at the point of descent are 709 and 766 veh/h/lane, for values of intensities less than indicated, the curve remains constant, and is governed by the free flow speed values which are 80.58 km/h and 79.77km/h respectively.

With this capacity curve built for the free flow speed for each version of the manual, the capacity model was built for free flow speed equal to 90, 100, 110, 120 km/h, following the principle of parallelism, used in versions of the HCM. In turn, the capacity model is sectored, by service levels A to F, according to density (veh/km). Fig. 7 and Fig.8 show the capacity models for basic segments of freeways for each version of the HCM manual.

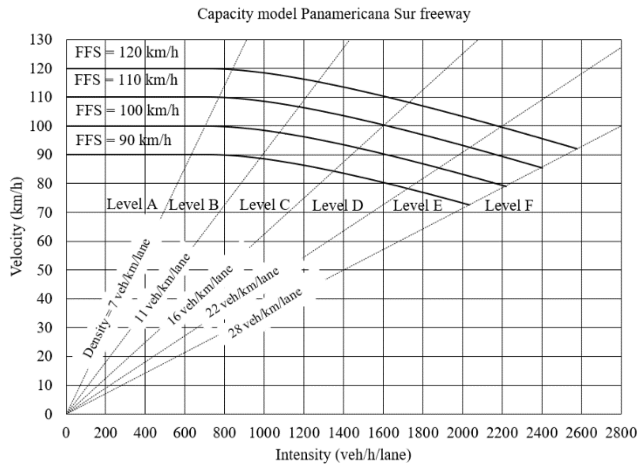

Fig. 7. Calibrated capacity model for basic segment of the Panamericana Sur freeway, HCM 2010

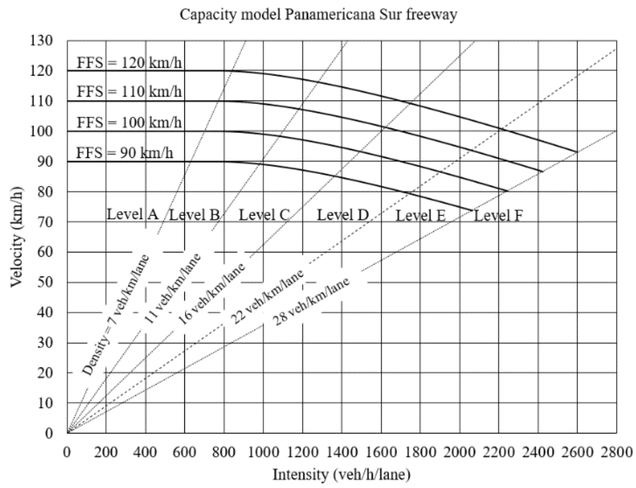

Fig. 8. Calibrated capacity model for basic segment of the Panamericana Sur freeway, HCM 2016

The following lines present the HCM 2016 model calibrated with their respective representative equations, for transit engineering studies.

$$V = \begin{cases} FFS, \quad 0 \le I \le Pd \\ \dfrac{-[87\,I \; - (6097I^{\,2} + 7360000I)^{0.5}]}{368} + (FFS - 79.77), Pd < I \le C \end{cases} \quad (7)$$

$$Pd = 766$$

$$C = 18.12\; FFS + 431.85 \qquad (8)$$

Where:
FFS=Free flow speed (km/h)
I=Intensity (veh/h/lane)
Pd=Point of descent (veh/h/lane)
V= Velocity (km/h)
C= Lane capacity (veh/h/lane)

B. Comparison of capacity models for basic segments of freeways

B.1. Comparison between the adjustment curves of calibrated models

According to Table 3, it is apparent that the behavior of speed with respect to intensity, derived from an adjustment of the reciprocal density and intensity of the data from basic sections I and II, shows a correlation of 0.9727 for HCM 2010 and for HCM 2016 is 0.9741. These values determine that the latest version of HCM 2016 calibrated to Peruvian reality , from the study of basic segments of the Panamericana Sur freeway, has a better representation of the data compared to previous versions.

Table 3: Equation of fit and correlation for the calibrated models of the HCM2010, HCM2016

Adjustment curves	Equation	Correlation R^2
HCM 2010	$Y = 0.0154X^2$+0.0089X +0.0002	0.9727
HCM 2016	$Y = 0.0184X^2$+0.0087X +0.0002	0.9741

B.2. Comparison of capacities between calibrated models and those proposed by the HCM

According to Table 4, for the free flow speed (FFS) of 90km/h, the capacity is 2050 veh/h/lane on average for the HCM2010 and HCM2016 calibrated models. Conversely, for the capacity models proposed by each HCM you have a capacity of 2255 veh/h/lane on average. This means that if we used these manuals for the planning and operation of the basic segments of the Panamericana Sur freeway, capacity would be overestimated by 205 veh/h/lane. The same verification is performed for speeds of 120, 110 and 100 km/h.

Moreover, when comparing the North American HCM2016 model for a free flow speed of 90 km/h, we would be indicating that unstable traffic from the basic segment would occur from 2260 veh/h/lane, which in local reality unstable traffic occurs for an intensity of 2060 veh/n/lane according to HCM2016 calibrated data, and Peruvian drivers would not reach speeds of 81 km/h as indicated by the HCM2016, if they do not reality reach speeds of 74 km/h according to the data obtained in this study.

IV. Conclusions

From the studies of operation of vehicle traffic to two basic segment of the Panamericana Sur freeway. Calibration tools could be developed and obtained calibrated capacity models for each version of the manual. Of which, the HCM 2016 calibrated capacity model, for basic segments of freeway, is the one that best represents with adequate reliability of 97%, according to the adjustment curve obtained, the local behavior of the basic segments depending on the speed and intensity.

In turn, when performing the validation of the HCM2016 model calibrated by applying it in the basic segments of freeways granted by Rutas de Lima SAC, it was reflected that the use of the HCM2000, employed by this company, show intensities within a service level D, which according to HCM2016 calibrated tells us that these values would actually be within a service level E. This means that Rutas de Lima, by applying the HCM 2000 model, which is not in line with the local conditions of Peru, would be taking action measures for the expansion of the physical capacity of the subsegment, no longer preventively as its premise assumes in its model, but that these actions would be when the level of service is actually close to collapse - LOS E.

This concludes that it is advisable to use the calibrated HCM 2016 capacity model, for future road concessions, as this will result in capacity values according to local conditions and preventive action measures will be implemented in a timely manner, as real capacity values would be available for the level of service to be offered.

The differences found in the comparison made between the internationally proposed models and the calibrated models for Lima may be due to various factors, which were not studied in this research. Among them, the little habit that users have of circulating at high speeds, respecting fast tracks and feeling safe on the roads. Also, aspects related to speed control systems and regulations, risk levels at which drivers in each region are willing to take, among others.

In this study, the calibration carried out can be considered preliminary, despite the significant number of measurements made, due to this it is recommended to carry out more studies of this type to represent the behavior of freeways in Lima with greater reliability than that obtained in the present research.

Table 4:Capacities of the calibrated models and the models proposed for each manual HCM2010, HCM2016

Capacity Curves	HCM 2010 Calibrated					HCM 2016 Calibrated					HCM 2010					HCM 2016				
	LOS					LOS					LOS					LOS				
Criteria	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
FFS = 120 km/h																				
Maximum density (veh/km/lane)	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28
Minimum speed (km/h)	120	115	108	100	92.1	120	116	109	101	92.9	120	120	115	99.6	85.7	120	118	110	97.3	85.7
Maximum v/c	0.33	0.49	0.67	0.85	1.00	0.32	0.49	0.67	0.85	1.00	0.35	0.55	0.77	0.92	1.00	0.35	0.54	0.73	0.89	1.00
Maximum service flow (veh/h/lane)	840	1260	1720	2200	2580	840	1280	1740	2220	2600	840	1320	1840	2200	2400	840	1300	1760	2140	2400
FFS = 110 km/h																				
Maximum density (veh/km/lane)	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28
Minimum speed (km/h)	110	105	100	92.7	85.7	110	107	101	93.6	86.4	110	110	109	97.2	83.9	110	109	106	96.4	85
Maximum v/c	0.32	0.48	0.67	0.85	1.00	0.32	0.49	0.67	0.85	1.00	0.33	0.51	0.74	0.91	1.00	0.33	0.51	0.72	0.90	1.01
Maximum service flow (veh/h/lane)	770	1160	1600	2040	2400	770	1180	1620	2060	2420	770	1210	1740	2135	2350	770	1200	1700	2120	2380
FFS = 100 km/h																				
Maximum density (veh/km/lane)	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28
Minimum speed (km/h)	100	98.2	92.5	85.5	79.3	100	98.2	93.8	86.4	80	100	100	100	93.8	82.1	100	100	100	92.7	82.9
Maximum v/c	0.32	0.49	0.67	0.85	1.00	0.31	0.48	0.67	0.85	1.00	0.30	0.48	0.70	0.90	1.00	0.30	0.48	0.70	0.89	1.01
Maximum service flow (veh/h/lane)	700	1080	1480	1880	2220	700	1080	1500	1900	2240	700	1100	1600	2065	2300	700	1100	1600	2040	2320
FFS = 90 km/h																				
Maximum density (veh/km/lane)	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28	7	11	16	22	28
Minimum speed (km/h)	90	89.1	83.8	78.2	72.9	90	89.1	85	79.1	73.6	90	90	90	89.1	80.4	90	90	90	89.1	80.7
Maximum v/c	0.31	0.48	0.66	0.84	1.00	0.31	0.48	0.66	0.84	1.00	0.28	0.44	0.64	0.87	1.00	0.28	0.44	0.64	0.87	1.00
Maximum service flow (veh/h/lane)	630	980	1340	1720	2040	630	980	1360	1740	2060	630	990	1440	1955	2250	630	990	1440	1960	2260

REFERENCES

[1] TRB, Highway Capacity Manual. Madrid: National Academy of sciencies, 2010.

[2] A. Arun, S. Velmurugan, and M. Errampalli, Methodological Framework Towards Roadway Capacity Estimation for Indian Multilane Freeways, Procedia- Social and Behavioral Sciences, 2013, 477-486.

[3] A. Pompigna, and F. Rupi, Differences Between HCM Procedures and Fundamental Diagram Calibration for Operational LOS Assessment on Italian Freeways. Transportation Research Procedia, 2015, 103-118.

[4] D. Ni, Multiscale Modeling of Traffic Flow. Mathematica Aeterna, 2011, 27-54.

[5] M. Van Aerde, Single Regime Speed-Flow Density Relationship for Congested and Uncongested Freeways. Presented at the 74th Transportation Research Board Annual Conference (pág. Paper No. 950802). Washington: Washington, D C, 1995.

[6] G. Riente de Andrade, C. Souza, A. Luiz, and J. Reynaldo, A Model for Estimating Free-Flow Speed on Brazilian Expressways. Transportation Research Procedia, 2016, 378 - 388.

[7] S. Mathew, A. Dhamaniya, G. Joshi, and S. Arkatkar, Roundabout Capacity in Heterogeneous Traffic Condition:Modification of HCM Equation and Calibration. Transportation Research Procedia , 2017, 985-992.

[8] M. Asgharzadeh, and A. Kondyli, Comparison of Freeway Capacity Estimation Methods. Tranportation Research Record , 2018, 1-10.

[9] M. Dębińskia, J. Bohatkiewicza, and J. Ziębowicza, Classification of roads according to the HCM6 method and its aplication in polish conditions. Transportation Research Procedia, 2019, 1017 - 1022.

[10] A. Tsui, Estimating traffic performance on Spanish two-lane freeways. Case study validation. Case Studies on Transport Policy, 2020, 119 - 126.

[11] TRB, Highway Capacity Manual: A guide for multimodal mobility analysis. Washintong: Washintong D.C 20001, 2016.