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Adaptation of the HCM-7 for estimating the level of service on a Brazilian two-lane rural highway with passing lanes

Adaptação do HCM-7 para estimativa do nível de serviço em uma rodovia de pista simples brasileira com faixas adicionais

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ABSTRACT

The Highway Capacity Manual (HCM-7) is the primary document for analyzing capacity and level of service worldwide. The traffic data used in the development of the manual were obtained on North American roads, so adaptations must be made based on observed local conditions. The present study aimed to adapt the HCM-7 method to estimate the level of service on a Brazilian two-lane highway with passing lanes. The proposed method was based on traffic data produced with the Aimsun Next simulator, previously calibrated from traffic data obtained on a Brazilian highway (BR-040). Based on the simulation results, the coefficients of several equations in the manual were adjusted to assess the service measure Follower Density (FD) values in segments with passing lanes. It was observed that the adaptation of the HCM-7 method provided FD and Level of Service values close to the data found directly in the field.

RESUMO

O *Highway Capacity Manual* (HCM-7) é o principal documento para análise de capacidade e nível de serviço em âmbito mundial. Os parâmetros utilizados no desenvolvimento do manual foram obtidos em países norte-americanos e, por esse motivo, devem ser realizadas adaptações devido às condições encontradas localmente. O presente trabalho teve, como objetivo geral, adaptar o método proposto no HCM-7 para estimar o nível de serviço em uma rodovia de pista simples brasileira com faixas adicionais. O método proposto foi baseado em dados de tráfego produzidos com o simulador de tráfego Aimsun Next, previamente calibrado para dados obtidos em uma rodovia brasileira. A partir dos resultados das simulações, foi possível adequar os coeficientes de diversas equações presentes no manual que permitem obter a medida de serviço Densidade de Veículos em Pelotões (FD) em segmentos com faixas adicionais. Foi observado que a adaptação do método forneceu valores estimados de FD e Nível de Serviço próximos aos dados encontrados diretamente em campo.

1. INTRODUCTION

Two-lane highways are fundamental to any country's economy since they are a significant part of the road network. Therefore, finding ways to assess road performance in these locations to implement operational improvements is essential. To this end, it is common to estimate the level of service (LOS) on highways to support decision-making since it is related to the road's quality of operation, reflecting users' perception about aspects like traffic flow, the possibility of changing lanes, and spacing between vehicles (Al-Kaisy et al., 2017).

The Highway Capacity Manual, or HCM, is in its 7th edition (TRB, 2022) and is used worldwide to apply methods to analyze the level of service and capacity of various road elements. However, HCM is often applied without any adaptation to reproduce conditions observed locally. In this context, when the HCM methodology is misapplied, the results regarding the level of service and capacity of a given road system may be inaccurate. If the level of service results is underestimated, there may be unnecessary expenses with widening and improvements; in the case of overestimating the level of service, the system's performance may remain poor because the necessary investment will not be made.

In Brazil, some studies have been carried out to either adapt the methods proposed in the HCM or provide alternative approaches to the manual (mainly) for analyzing two-lane highway segments. Some research has proposed methods other than HCM (Silva et al., 2021; 2022), including evaluating alternative performance measures (Bessa Jr. and Setti, 2016; Bessa Jr. and Setti, 2018). Outside Brazil, there are studies of this nature carried out in Finland (Luttinen, 2000; 2001), Spain (Moreno, 2020; Moreno et al., 2016; 2018), Argentina (Maldonado et al., 2012) and India (Penmetsa et al., 2015).

In many works, including the development of the new HCM-7 method for two-lane highways (Washburn et al., 2018), the steps for adjusting to local conditions involved phases such as data collection, calibration of a traffic simulator and generation of synthetic data through the simulator. This type of approach can be seen in different works that aimed to evaluate the operational conditions of highways based on simulation data (Bessa Jr. et al., 2017; Šarić and Lovrić, 2021; Yin et al., 2022; Jeon and Benekohal, 2023; Brêtas et al., 2024; Chowdhury et al., 2024).

Oliveira and Bessa Jr. (2022) obtained a local version of HCM-7 focused only on segments without passing lanes. Before that, only Setti et al. (2011) had completely adapted the HCM method for two-lane highways for the 2000 version (TRB, 2000). With the publication of HCM-7, the manual's two-lane highway analysis method underwent the most considerable methodological change since the 1985 version (TRB, 1985). Therefore, the main objective of this work is justified, which was to carry out an adaptation of the methodology proposed in HCM-7 to obtain the level of service on a Brazilian two-lane highway with passing lanes.

The results of this research sought to contribute to obtaining a complete adaptation of the HCM-7 method for this type of highway (focused on motor vehicles). It is worth noting that the adapted method was based on traffic data produced with the Aimsun Next traffic simulator, previously calibrated for data obtained in three segments of a Brazilian highway, BR-040, which represents a limitation of the work. Details can be seen in subsequent sections.

2. ANALYSIS OF TWO-LANE HIGHWAY SEGMENTS WITH HCM-7

The HCM methodology for obtaining the level of service on two-lane highways with passing lanes is similar to the method for evaluating segments without passing lanes (TRB, 2022). The first step to applying the HCM method is to analyze the type of segment that will be studied. In addition to checking the existence of a climbing lane, the segment is assessed for overtaking restrictions and whether nearby passing lanes influence them.

The following steps include determining the vertical alignment class (from 1, which represents the least sloped terrain, to 5, which represents the most sloped terrain) and the segment type (with overtaking restrictions, without overtaking restrictions, or with passing lanes). These steps are necessary to calculate the performance measures – the percent followers (PF), the average travel speed (ATS, in km/h), and the traffic flow in the direction of analysis (v_d, in veh/h) for the highest 15-min traffic volume within the hour of analysis – that comprise the formulation of the service measure, the follower density (FD, in veh/km).

FD is the number of vehicles traveling in platoons per kilometer per lane. This performance measure demonstrates the opportunities for drivers to overtake and expresses the discomfort of traveling in platoons. The equation 1 gives it:

$$FD = \frac{PF}{100} \times \frac{v_d}{ATS} \tag{1}$$

If ATS needs to be estimated, then it is necessary to use the following formulation (equation 2):

$$ATS = FFS - m \times \left(\frac{v_d}{1{,}000} - 0.1 \right)^p \tag{2}$$

where: m_{ATS} and p_{ATS} = coefficients for estimating ATS; and FFS = free flow speed (in km/h). To find the parameter m_{ATS}, it is necessary to apply the following equations (equations 3, 4 and 5):

$$m_{ATS} = Max\left[b_5, b_0 + b_1 \times FFS + b_2 \times \sqrt{\frac{v_o}{1000}} + Max(0, b_3) \times \sqrt{L} + Max(0, b_4) \times \sqrt{HV} \right] \tag{3}$$

being:

$$b_3 = c_0 + c_1 \times \sqrt{L} + c_2 \times FFS + c_3 \times \left(FFS \times \sqrt{L} \right) \tag{4}$$

$$b_4 = d_0 + d_1 \times \sqrt{HV} + d_2 \times FFS + d_3 \times \left(FFS \times \sqrt{HV} \right) \tag{5}$$

where: $b_0 - b_2$; b_5 ; $c_0 - c_3$; $d_0 - d_3$ = adjustment coefficients of Equations 3 to 5; HV = percentage of heavy vehicles; L = segment length (km); and v_o = traffic flow in the opposite direction to the analysis (veic/h). In turn, to estimate the parameter p_{ATS} , the following formulation (equation 6) should be used:

$$p_{ATS} = \max\left[f_8, f_0 + f_1 \times FFS + f_2 \times L + f_3 \times v_o + f_4 \times \sqrt{\frac{v_o}{1000}} + f_5 \times HV + f_6 \times \sqrt{HV} + f_7 \times (L \times HV) \right] \tag{6}$$

where: $f_0 - f_8$ = adjustment coefficients of Equation 6. To find the FFS , the following equation should be used (equation 7):

$$FFS = BFFS - a \times HV - f_{LS} - f_A \tag{7}$$

where: $BFFS$ = base free flow speed (mi/h or km/h); a = angular coefficient of the linear relationship between FFS and HV (Equation 7); f_{LS} = adjustment factor for traffic lane and shoulder widths; f_A = adjustment factor for access density; $a_0 - a_5$ = adjustment coefficients. Being (equation 8):

$$a = Max\left[0.0333, a_0 + a_1 \times BFFS + a_2 \times L + Max\left(0, \left(a_3 + a_4 \times BFFS + a_5 \times L\right) \times \frac{v_o}{1,000}\right)\right] \quad (8)$$

HCM-7 recommends, for calculation purposes, that the $BFFS$ be obtained from the product of the posted speed limit of the highway segment by 1.14.

To obtain the FD value, it is necessary to estimate the PF value. This parameter consists of the percentage of vehicles that travel with headways equal to or less than a critical value of 2.5 seconds and can be obtained by the equation 9:

$$PF = 100 \times \left[1 - e^{\left(m_{PF} \times \left(\frac{v_d}{1000}\right)^{p_{PF}}\right)}\right] \quad (9)$$

where: m_{PF} and p_{PF} = coefficients to estimate PF.

The coefficients m_{PF} and p_{PF} are obtained based on PF in two different scenarios: one of them consists of the highway at its capacity, according to the equation 10:

$$PF_{cap} = b_0 + b_1 \times L + b_2 \times \sqrt{L} + b_3 \times FFS + b_4 \times \sqrt{FFS} + b_5 \times HV + b_6 \times FFS \times \frac{v_o}{1000} + b_7 \times \sqrt{FFS} \quad (10)$$

where: $b_0 - b_7$ are adjustment coefficients for calculating PF_{cap} (Equation 10); PF_{cap} is the percent followers at capacity.

The second scenario concerns the conditions in which the directional traffic flow is equal to 25% of the capacity (equation 11):

$$PF_{25cap} = c_0 + c_1 \times L + c_2 \times \sqrt{L} + c_3 \times FFS + c_4 \times \sqrt{FFS} + c_5 \times HV + c_6 \times FFS \times \frac{v_o}{1000} + c_7 \times \sqrt{\frac{v_o}{1000}} \quad (11)$$

where: $c_0 - c_7$ are adjustment coefficients for calculating PF_{25cap} (Equation 11); PF_{25cap} is the percent followers for a directional traffic flow equal to 25% capacity.

The slope coefficient m_{PF} and the power coefficient p_{PF} must be calculated according to the equations 12 and 13:

$$m_{PF} = d_1\left(\frac{0 - \ln\left(1 - \frac{PF_{25cap}}{100}\right)}{0.25 \times \left(\frac{cap}{1000}\right)}\right) + d_2\left(\frac{0 - \ln\left(1 - \frac{PF_{cap}}{100}\right)}{\left(\frac{cap}{1000}\right)}\right) \quad (12)$$

$$p_{PF} = e_0 + e_1\left(\frac{0 - \ln\left(1 - \frac{PF_{25cap}}{100}\right)}{0.25 \times \left(\frac{cap}{1000}\right)}\right) + e_2\left(\frac{0 - \ln\left(1 - \frac{PF_{cap}}{100}\right)}{\left(\frac{cap}{1000}\right)}\right) + e_3\sqrt{\left(\frac{0 - \ln\left(1 - \frac{PF_{25cap}}{100}\right)}{0.25 \times \left(\frac{cap}{1000}\right)}\right)} + e_4\sqrt{\left(\frac{0 - \ln\left(1 - \frac{PF_{cap}}{100}\right)}{\left(\frac{cap}{1000}\right)}\right)} \quad (13)$$

where: d_1, d_2 = adjustment coefficients for the calculation of m_{PF}; $e_0 - e_4$ = coefficients for calculating p_{PF} ; and cap = one-way capacity (veh/h).

In the method proposed by HCM-7 for analyzing segments with passing lanes, additional steps are carried out to obtain the performance measures that comprise FD at the midpoint of the segment with the passing lane. Therefore, the method proposes that the traffic flow be calculated in each of the lanes of the segment with a passing lane. To do this, first, the $PropFlowRateFL$, which is the proportion of traffic flow in the faster lane of the passing lane segment, according to the equation 14:

$$PropFlowRateFL = 0.92183 - 0.05022 \times \ln\left(v_d\right) - 0.0003 \times NUM_{HV} \quad (14)$$

where NUM_{HV} is the number of heavy vehicles (veh).

Traffic flow in the faster lane and the slower lane of the passing lane segment must also be obtained (equations 15 and 16):

$$FlowRateFL = v_d \times PropFlowRateFL \quad (15)$$

$$FlowRateSL = v_d \times \left(1 - PropFlowRateFL\right) \quad (16)$$

where $FlowRateSL$ is the traffic flow value in the slower lane, and $FlowRateFL$ is the traffic flow in the faster lane of the passing lane segment. The percentage of heavy vehicles in each traffic lane is also calculated using the equations 17, 18 and 19:

$$HVFL = HV \times HVPropMultiplierFL \quad (17)$$

$$NUM_{HVSL} = NUM_{HV} - \left(FlowRateFL \times HVFL \times 100\right) \quad (18)$$

$$HVSL = NUM_{HVSL} \times FlowRateSL \times 100 \quad (19)$$

where $HVPropMultiplierFL$ is the proportion of heavy vehicles in the faster lane, defined by HCM-7 as 0.4. $NUMHVSL$ is the number of vehicles in the slower lane, and $HVSL$ is the percentage of heavy vehicles in the slower lane. Applying the combination of the equations and coefficients to estimate average speed, the initial average speed in the faster lane (S_{init_FL}) and the initial average speed in the slower lane (S_{init_SL}) are calculated. Next, the average speed at the midpoint of the passing lane is computed using the equations 20, 21 and 22:

$$AvgSpeedDiffAdj = 2.750 + 0.00056 \times v_d + 3.8521 \times \frac{HV\%}{100} \quad (20)$$

$$S_{PLmid\_FL} = S_{init\_FL} + \frac{AvgSpeedDiffAdj}{2} \quad (21)$$

$$S_{PLmid\_SL} = S_{init\_SL} - \frac{AvgSpeedDiffAdj}{2} \quad (22)$$

where S_{PLmid_FL} is the average speed in the faster lane at the midpoint of the passing lane segment, and S_{PLmid_SL} is the average speed in the slower lane at the midpoint of the passing lane segment.

It is necessary to obtain the percent followers in each lane of the passing lane segment, similar to ATS. By applying all the equations above, it is possible to get the value of the FD in the segment; it is a simple average between the FD values obtained in the slower lane and the faster lane, as follows (equation 23):

$$FD = \frac{\left(\frac{PF_{FL}}{100} \times \frac{v_{d\ FL}}{ATS_{FL}}\right) + \left(\frac{PF_{SL}}{100} \times \frac{v_{d\ SL}}{ATS_{SL}}\right)}{2} \quad (23)$$

where all terms have already been previously defined; FL means the faster lane, and SL means the slower lane in the passing lane segment.

In addition, HCM-7 verifies the impact of a passing lane close to the analyzed passing lane. For this step, the equations 24 and 25 are used:

$$\%ImprovePF = \max\left(0; 27 - 8.75 \times \ln\left[\max\left(0.1; downstream\ length\ from\ passing\ lane\right)\right] + \right.$$
$$\left. + \ 0.1 \times \max\left[0; PF - 30\right] + 3.5 \times \ln\left[\max\left(0.3; passing\ lane\ length\right)\right] - 0.01 \times FlowRate\right) \quad (24)$$

$$\%ImproveATS = \max\left(0; 3 - 0.8 \times downstream\ length\ from\ passing\ lane + 0.1 \times \max\left[0; PF - 30\right] + \right.$$
$$\left. + \ 0.75 \times passing\ lane\ length - 0.005 \times FlowRate\right) \quad (25)$$

where $\%ImprovePF$ is the percentage of improvement to the percent followers, and $\%ImproveS$ is the percentage of improvement to the average speed. The improvement observed in both parameters is used as a multiplier adjustment in the calculation of the adjusted FD for the segment downstream of the passing lane, as follows (equation 26):

$$FD_{Adjusted} = \frac{PF}{100} \times \left(1 - \frac{\%ImprovePF}{100}\right) \times \frac{FlowRate}{S \times \left(1 + \frac{\%ImproveS}{100}\right)} \quad (26)$$

The level of service verified for the analyzed segment is found with the calculated FD value. If the analyzed section is composed of several types of segments, the FD is a weighted average of the FD values obtained for each subsection (equation 27):

$$FD = \sum_{0}^{i} \frac{FD_i L_i}{L_t} \quad (27)$$

where FD_i is the FD of the subsection, L_i is the length of the subsection, and L_t is the total length of the section.

3. ADAPTATION OF THE HCM-7 METHOD

Adapting the HCM-7 method consists of obtaining calibration parameters presented in the previous section, found in Equations 3 to 6, 10 to 14, and 24 to 25. It was necessary to generate a series of traffic data through microscopic simulation to adapt the method proposed in HCM-7 to evaluate Brazilian two-lane highways with passing lane segments. The simulation approach has been used since it is impractical to find different traffic and geometry conditions in the field, and it is more reasonable to calibrate a traffic simulator that can thus reproduce these various conditions. This adaptation method is found in other works, such as in Setti et al. (2011), Washburn et al. (2018), and Oliveira and Bessa Jr. (2022).

3.1. Aimsun next calibration and validation

The traffic data used to calibrate the chosen simulator, Aimsun Next (Aimsun, 2020), were initially collected by Silva et al. (2021) and Silva et al. (2022). The data were collected on BR-040, a vital highway connecting Brasília and Rio de Janeiro. From the sample obtained in these two studies, three segments with passing lanes were verified, all approximately 10 kilometers long, with different vertical and horizontal alignments. The three segments observed – between km 29 and 39, km 96 and 105, and km 288 and 298 of BR-040 – have posted speed limits equal to or above 80 km/h and are on the segment between two Brazilian municipalities: Cristalina, in the state of Goiás, and Paracatu, in the state of Minas Gerais. In the three sections, the directional traffic flows were between 108 and 308 veh/h, 156 and 632 veh/h, and 128 and 319 veh/h. In turn, the percentage of heavy vehicles, on average, was 14%, 11%, and 18%, respectively, for the three road segments.

The seven Aimsun Next behavioral parameters chosen for calibration are the same as those selected in the work of Oliveira and Bessa Jr. (2022):

- $MINCHEADMCAR$: minimum headway between the leading and following vehicles; considered in calculating the speed and deceleration of the vehicle at a given instant, for cars;
- $NDECMCAR$: average normal deceleration of the leading vehicle, for cars;
- $SNSTVTFCTRDCD$: sensitivity factor that changes the perception of visibility distance and, consequently, the aggressiveness in performing an overtaking maneuver;
- $SPDIFMAX$: maximum value of the speed difference between the leading and following vehicles that determines whether overtaking is desired;
- $SPDIFMIN$: minimum value of the speed difference between the leading and following vehicles that determines whether overtaking is desired;
- $DLTRSHLD$: maximum delay limit caused by a leading vehicle, which also affects the desire to overtake; and
- $RNKTRSHLD$: maximum position in the queue where vehicles still have some chance of overtaking.

Using data collected in the field, a Genetic Algorithm (GA) was applied to calibrate the Aimsun Next, considering each of the three mentioned segments. The best sets of calibration parameters obtained by the GA are illustrated in Table 1. A difference was observed in the results of applying the GA for each of the three road segments, with different degrees of aggressiveness of the parameters for each case. This is because the configurations and positions of the passing lanes in each segment are different, which causes drivers to travel through the locations with different aggressiveness. Other details about the geometry of the highway segments can be seen in Silva (2019).

Table 1: Aimsun Next parameters found with AG for each highway segment

	Segment (km)		
Parameter	**29-39**	**96-105**	**288-298**
NDECMCAR (m/s²)	3.73	4.12	2.74
MINCHEADMCAR (s)	0.84	0.31	1.04
DLTRSHLD (s)	161.51	64.13	260.72
SPDIFMAX (km/h)	42.23	24.45	51.78
RNKTRSHLD	4.66	5.57	2.62
SPDIFMIN (km/h)	12.64	7.20	16.03
SNSTVTFCTRDCD	0.92	0.28	1.70

To establish the typical driver's behavior on the BR-040 to simulate and subsequently adapt the HCM-7 methodology for segments with passing lanes, the parameters related to a high degree of aggressiveness were considered, as observed in the work of Oliveira and Bessa Jr. (2022). Therefore, the values used to develop this paper were from the segment between km 96 and 105.

Several experiments were carried out to produce simulation data to evaluate the impact of geometric characteristics and flow conditions on the behavior of the analyzed performance measures. Several scenarios were simulated by varying the slope and length of the segment with the passing lane, as performed to obtain the original method (Washburn et al., 2018) and adapt it to local conditions without passing lanes (Oliveira and Bessa Jr., 2022).

In the simulated model, illustrated in Figure 1, detectors were inserted in the section with the passing lane to position them in specific locations: at the beginning, in the center, and at the end of the segment. These detectors were intended to record performance measures in the section in the various simulated scenarios. In addition, in the third portion of the section, without a passing lane, detectors were added every 200 meters along its entire length (three kilometers) to obtain additional performance measures necessary for calibrating the method. The experimental section was simulated by combining several geometric and traffic parameters as follows:

- Segment length (km): 0.80; 1.60; 3.20; and 4.80;
- Free flow speed (km/h): 72; 80; 89; 97; 105; and 113;
- Directional traffic flow (veh/h): 100; 300; 600; 900; 1,200; 1,500; and 1,800;
- Percentage of heavy vehicles: 0; 5; 10; 15; 20; and 25;
- Traffic flow in the opposite direction (veh/h): 0.

A vertical alignment classification modified to local conditions is necessary to obtain more feasible results with the adaptation. Oliveira and Bessa Jr. (2022) obtained this classification, which details how this adaptation was carried out.

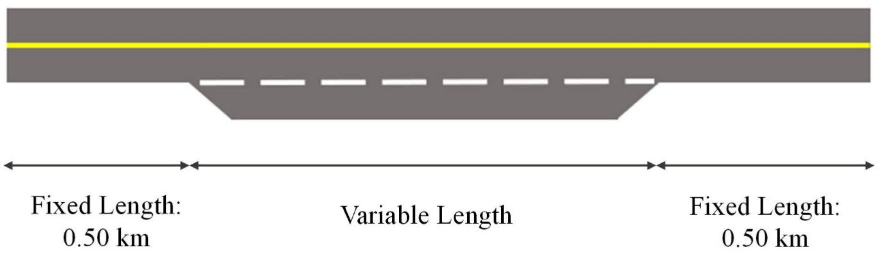

Figure 1. Simulated segment overview.

3.2. Coefficients obtained for local conditions

Since there are no differences in HCM-7 between the coefficients $a_0 - a_5$ (Equation 8) for segments with or without passing lanes, the adapted coefficients found by Oliveira and Bessa Jr. (2022) were maintained. The determination of the adjustment factors that comprise Equation 3 of the coefficient m_{ATS} was carried out similarly to the determination of the adjustment factors for the coefficient α during the FFS estimation stage. Then, using linear regression and considering the results of the simulations, the adjustment factors $b_0 - b_4$ were estimated (Equations from 3 and 5). The values obtained for these factors are shown in Table 2. Once these coefficients were determined, a linear regression was performed to obtain the coefficients necessary to calculate b_3 and b_4 (Tables 3 and 4).

Table 2: Adjusted $b_0 -\ b_5$ coefficients (Equation 3)

Vertical class	b_0	b_1	b_2	b_3	b_4	b_5
1	-0.91951	0.01659	0.00000	Equation 7	Equation 8	0.00000
2	-32.35779	0.34383	0.00000	Equation 7	Equation 8	0.00000
3	-16.28496	0.15284	0.00000	Equation 7	Equation 8	0.00000
4	5.94483	-0.04883	0.00000	Equation 7	Equation 8	0.00000
5	-44.90599	0.40213	0.00000	Equation 7	Equation 8	0.00000

Table 3: Adjusted c_0 c_3 coefficients (Equation 4)

Vertical class	c_0	c_1	c_2	c_3
1	1.4452	0.0000	0.0000	-0.0084
2	-14.2873	0.0000	0.1896	-0.0150
3	0.0000	0.0000	0.0000	0.0000
4	1.2018	0.0000	0.0000	0.0000
5	18.6382	0.0000	0.0000	0.0000

Table 4: Adjusted $d_0 -\ d_3$ coefficients (Equation 5)

Vertical class	d_0	d_1	d_2	d_3
1	-2.19530	0.55192	0.02892	-0.00716
2	-13.84137	0.75696	0.11523	0.00000
3	6.09632	-2.76009	-0.02786	0.02982
4	0.00000	0.02418	0.00122	-0.00042
5	26.42716	-4.96787	-0.21846	0.05350

The coefficients p_{ATS} and m_{ATS} also vary for each combination of geometry and traffic flow (Equation 9). The adjustment coefficients related to the calculation of p_{ATS} were also obtained through linear regression for the simulated data set, as shown in Table 5.

According to Equation 1, obtaining the value of PF is also necessary to determine FD. This performance measure can be calculated by Equation 9. The coefficients needed to find PF_{cap} and PF_{25cap} (Equations 10 and 11) are in Tables 6 and 7. Consequently, it is possible to calculate the parameters m_{PF} and p_{PF} , whose values are found from the parameters $d_1 - d_2$ and $e_0 - e_4$ (Equations 12 and 13), as seen in Tables 8 and 9.

Table 5: Adjusted $f_0 - f_8$ coefficients (Equation 6)

Vertical class	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
1	3.991854	-0.026442	0.000000	0.000000	0.000000	0.000000	0.000000	0.004841	0.000000
2	3.117196	-0.025481	0.146047	0.000000	0.000000	0.000000	-0.101704	-0.003379	0.000000
3	1.387571	0.000000	0.000000	0.000000	0.000000	0.000000	0.287007	-0.020939	0.000000
4	0.000000	0.031157	-0.249205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
5	1.995090	0.000000	-0.232032	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 6: Adjusted $b_0 - b_7$ coefficients (Equation 10)

Vertical class	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
1	61.730750	6.739220	-23.688530	-0.841260	11.445330	-1.051240	1.503900	0.00491
2	12.300960	9.574650	-30.794270	-1.794480	25.764360	-0.663500	1.260390	-0.003230
3	206.073690	-4.298850	0.000000	1.964830	-30.325560	-0.758120	1.064530	-0.008390
4	263.134280	5.387490	-19.048590	2.730180	-42.769190	-1.312770	-0.322420	0.01412
5	126.956290	5.957540	-19.222290	0.432380	-7.356360	-1.030170	-2.660260	0.01389

Table 7: Adjusted $c_0 - c_7$ coefficients (Equation 11)

Vertical class	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7
1	80.37105	14.44997	-46.41831	-0.23367	0.84914	-0.56747	0.89427	0.00119
2	18.37886	14.71856	-47.78892	-1.43373	18.32040	-0.13226	0.77217	-0.00778
3	239.98930	15.90683	-46.87525	2.73582	-42.88130	-0.53746	0.76271	-0.00428
4	223.68435	10.26908	-35.60830	2.31877	-38.30034	-0.60275	-0.67758	0.00117
5	137.37633	11.00106	-38.89043	0.78501	-14.88672	-0.72576	-2.49546	0.00872

Table 8: Adjusted $d_1 - d_2$ coefficients (Equation 12)

Segment type	d_1	d_2
Passing lane	-1.64353	0.05835

Table 9: Adjusted $e_0 - e_4$ coefficients (Equation 13)

Segment type	e_0	e_1	e_2	e_3	e_4
Passing lane	-0.33286	-7.58573	-0.17007	6.31609	0.42877

As described in the previous section, the additional steps of the method are aimed at segments with passing lanes to provide more representative results for a segment of this type. Therefore, with the synthetic data produced by traffic simulation for the experimental section, it was possible to adjust the equations for these extra steps (Equation 28 onwards). In this context, Equation 28, which is responsible for calculating the proportion of traffic vehicles traveling in the faster lane of the passing lane segment, now has the following form (equation 28):

$$PropFlowRateFL = 0.05584 - 0.04859 \times \ln\left(v_d\right) - 0.00014 \times NUM_{HV} \tag{28}$$

The presence of a passing lane can bring some benefits to the segment downstream of it. These effects are mainly perceived concerning the number of vehicles in platoons, which decreases, and the average speed, which increases. The same occurs for the percentage of vehicles in platoons. For a given effective length, which corresponds to the length whose effects of the passing lane are still observed, the PF values return to those observed at the beginning of the segment. However, if another passing lane segment begins before this effective length ends, the PF values obtained at the start of the section will be lower than those observed at the start of the first segment; this difference is called $ImprovePF$.

To obtain the adapted equations of $\%ImproveS$ and $\%ImprovePF$ (Equations 24 and 25), the simulation data of the average travel speed and the percent followers were evaluated for approximately 3 kilometers after the end of the passing lane sections; for this purpose, detectors were inserted in the final section of the simulated model (Figure 1). With the results of the traffic simulations, linear regressions were again performed, and the equations 29 and 30 were found:

$$\%\text{ImprovePF} = \max\begin{pmatrix} 0;\ 68 - 212.34 \times \ln\left[\max\left(0.1; \text{downstream length from passing lane}\right)\right] + \\ 0.6 \times \max\left[0;\ \text{PF} - 30\right] + 205.8 \times \ln\left[\max\left(0.3; \text{passing lane length}\right)\right] - \\ 0.02 \times \text{FlowRate} \end{pmatrix} \tag{29}$$

$$\%\text{ImproveATS} = \max\left(0; -9 + 34.0 \times \text{downstream length from passing lane} - 34.0 \times \max\left[0;\ \text{PF} - 30\right]\right). \tag{30}$$

4. VALIDATION OF THE PROPOSED METHOD

Once the coefficients for calculating FFS, ATS, and FD had been adapted, a validation step for the calibrated models was performed. A comparison was made with the FD and the LOS values between the traffic flows obtained in the field for the three observed segments and those obtained with the HCM-7 method with and without adaptations. As shown in Figure 2, more different values were found concerning what is observed in the field with the HCM-7 method without adaptation. The adapted model produces more realistic values with unidirectional volumes below 300 veh/h. However, above this, the results are still closer than concerning the method without adaptations. It is believed that this discrepancy between the predicted and field data, with unidirectional traffic flows above 300 veh/h, could be even smaller if the field sample size, in this volumetric range, were more significant. This could have better adjusted the HCM-7 method to local conditions.

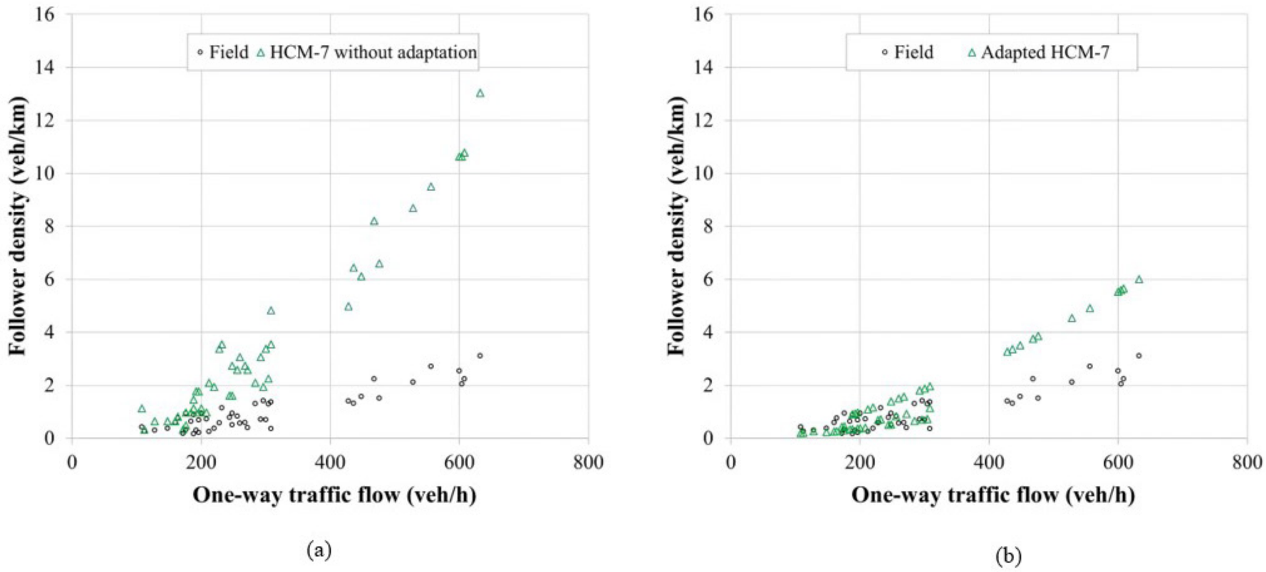

Figure 2: FD values obtained in the field and with the HCM-7 without (a) and with adaptation (b).

This comparison was also carried out using goodness-of-fit functions, as in previous works (Bessa Jr. and Setti, 2018; Silva et al., 2021; 2022; Oliveira and Bessa Jr., 2022), between the results obtained by the proposed models and those observed in the field (Equations 31 and 32): i) the mean absolute normalized error ($MANE$); and ii) the root mean square normalized error ($RMSNE$). The values of the adjustment functions are presented in Table 10. In both cases, the values of $MANE$ and $RMSNE$ were more than twice as high for the case without adaptations than for the FD data with adaptation of the HCM-7 method.

$$MANE = \frac{1}{N}\sum_{i=1}^{n}\frac{|x_i - y_i|}{y_i} \tag{31}$$

$$RMSNE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - y_i}{y_i}\right)^2} \tag{32}$$

Table 10: Goodness-of-fit functions for the analyzed FD models

	Goodness-of-fit functions	
***FD* Model**	***MANE***	***RMSNE***
Adapted HCM-7	1.17	1.56
HCM-7	2.66	3.48

According to TRB (2022), for highways with posted speed limits equal to or above 80 km/h (50 mi/h), the levels of service are determined based on FD (in followers/mile/lane) as follows: $LOS = A: FD \leq 2$; $LOS = B: 2 < FD \leq 4$; $LOS = C: 4 < FD \leq 8$; $LOS = D: 8 < FD \leq 12$; and $LOS = E: FD > 12$. From the FD data shown in Figure 2, the levels of service found with the HCM-7 with and without adaptations were obtained, using, as a reference for comparison, the levels of service obtained in the field. Table 11 illustrates these results.

Table 11: FD values obtained in the field and with the HCM-7 with and without adaptation

Level of service	FD in the field	Model		Difference to the field (%)	
		Adapted HCM-7	HCM-7	Adapted HCM-7	HCM-7
A	67.4%	63.0%	30.4%	-4.4%	-37.0%
B	26.1%	13.0%	21.7%	-13.1%	-4.4%
C	6.5%	15.2%	23.9%	8.7%	17.4%
D	0.0%	8.7%	8.7%	8.7%	8.7%
E	0.0%	0.0%	15.2%	0.0%	15.2%

The most common LOS in the field was A, with 67.4% of cases, followed by levels B (26.1%) and C (6.5%). With the adapted HCM-7, there was a high success rate in LOS A (63.0%), followed by B (13.0%), C (15.2%) and D (8.7%). Thus, the adapted HCM-7 tended to provide some service levels worse than the field, with an increase in cases in C and D (which was not observed in the field). However, with the HCM-7 without adaptation, the differences concerning the field are much more significant than concerning the manual with adaptation. The most remarkable differences were with LOS A (37%, in module), followed by LOS C (17.4%) and LOS E (15.2%).

The field LOS was better than or equal to that calculated with the HCM-7 without adaptation in all observed traffic flow streams. In 39% of the cases, the LOS was the same, mainly for the segment between km 288 and 298 and, secondly, between km 29 and 39. In 13% of the traffic flow streams, there was a difference of one level of service, practically all in the segment between km 96 and 105. In 39% of cases, there was a difference between the two levels of service, mainly in the segment between km 96 and 105. It was observed that, in 9% of the cases, the difference reached three levels of service (also in this segment). These significant differences in the LOS values found in the segment between km 96 and 105 probably occurred due to only one passing lane, causing FD values to emerge from a global behavior in the section not estimated by the HCM-7 without adaptation. With more passing lanes, as in the segment between km 288 and 298, the HCM-7, without adaptation, could reproduce the field behavior, having correctly predicted the LOS in 12 of 14 traffic flow streams.

5. FINAL REMARKS

The objective of this work was to adapt the HCM-7 method to the conditions found on a Brazilian highway to estimate the level of service of two-lane highways with passing lanes. Adapting the coefficients found in the model proposed by the manual to estimate ATS and PF , and consequently FD, was performed for traffic data produced by a traffic simulator, the Aimsun Next, calibrated for conditions found on a local highway, the BR-040. The differences between the proposed method and that of HCM-7 can be observed by comparing the parameters of Equations 3 to 6, 10 to 14, and 24 and 25, without adaptation (which can be found in HCM-7) and with adaptation (Tables 2 to 9 and Equations 28 to 30).

Scenarios were simulated under different geometric and traffic conditions, as presented in the final report of NCHRP *Project* 17-65 (Washburn et al., 2018). It is essential to mention that the HCM-7 method was maintained, with only the equations illustrated in section 2 of this paper being adjusted. The results demonstrate that this adaptation effort is necessary since the HCM-7 method (as in the manual) presented FD values closer to those collected in the field. It would be interesting, in future work, to apply the adapted method on a segment of a North American highway to compare the predicted FD values using the HCM-7 without and with local adaptations.

For future work, it is recommended that the data set be expanded to calibrate and validate the traffic simulator and the proposed models, especially with unidirectional traffic flows above 300 veh/h. In addition, the data set should be expanded by searching for more locations with different lengths of passing lanes (in this work, only three highway segments were used). This diversity may impact the simulator adjustment, adapted models, and estimated FD values.

The HCM-7 method for analyzing two-lane highways includes evaluating " $2+1$ " type two-lane highways and analyzing segments with and without passing lanes. Given that this type of solution is practically non-existent in Brazil, it would be interesting to adapt the manual's method for this type of highway and reflect on its applicability to Brazilian highways.

AUTHORS' CONTRIBUTIONS

ACFB: Formal analysis, Data curation, Writing – original draft, Investigation, Software, Validation, Visualization; JEBJ: Project administration, Formal analysis, Funding acquisition, Conceptualization, Writing – review & editing, Methodology, Resources, Supervision.

CONFLICTS OF INTEREST STATEMENT

Nothing to declare.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence tools were used in the research reported here or in the preparation of this article.

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