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Adaptation of the HCM for the analysis of two-lane rural highways without passing lanes in Brazil

Adaptação do HCM para análise de rodovias de pista simples sem faixas adicionais no Brasil

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ABSTRACT
The Highway Capacity Manual (HCM) is the main document used to analyze the level of service and capacity of highway facilities. However, applying its methodology without adjustments to local traffic and road conditions and vehicle and driver characteristics can result in discrepancies between the performance measures calculated using the manual and those observed in the field. This paper aimed to adapt the new HCM method (7th edition) to the conditions of Brazilian two-lane rural highways without passing lanes. With a recalibrated version of Aimsun Next, simulation results were generated for hypothetical segments to adjust the traffic models to obtain the follower density (*FD*), the new service measure proposed for evaluating two-lane highway segments. The *FD* results found with the proposed method showed that the HCM traffic models need to be adapted to evaluate Brazilian highways to avoid levels of service that underestimate what is observed in the field.

RESUMO
O *Highway Capacity Manual* (HCM) é o principal documento utilizado para a análise do nível de serviço e da capacidade de componentes rodoviários. Todavia, a aplicação de sua metodologia sem que sejam realizadas adaptações às condições locais de tráfego e das vias e às características dos veículos e dos motoristas pode resultar em discrepâncias entre as medidas de desempenho calculadas por meio do manual e as observadas em campo. Este trabalho teve como objetivo adaptar o novo método do HCM (7ª edição) às condições das rodovias de pista simples brasileiras sem faixas adicionais. De posse de uma versão recalibrada do Aimsun Next, foram gerados resultados de simulação para segmentos hipotéticos com o intuito de ajustar modelos de tráfego para obter a densidade de veículos em pelotões (*FD*), a nova medida de serviço proposta para avaliar segmentos de rodovias de pista simples. Os resultados de *FD* encontrados com o método proposto mostraram que os modelos de tráfego do HCM necessitam de adaptações para avaliar rodovias brasileiras, evitando-se níveis de serviço subestimados em relação ao que é observado em campo.

1. INTRODUCTION

The road mode has a key role in the freight and passenger transportation in Brazil, being responsible, according to the Confederação Nacional do Transporte (CNT, 2020), for the movement of more than 60% of the transportation of goods and 95% of the transportation of people. Its importance is based on, among other factors, the extensive road network in Brazil, which comprises approximately 1.7 million kilometers, with 92.7% of this total composed of two-lane highways and 21.5% composed of paved highways (CNT, 2020). In addition, in 2020, the country had a fleet of approximately 108 thousand vehicles, an increase of 81% compared to that in 2009 (CNT, 2021). In this context, investments in road infrastructure to improve the traffic conditions of the highways are of paramount importance for the economic development of Brazil.

The Highway Capacity Manual (HCM) is the main document used worldwide to evaluate the capacity and the level of service of various road elements, such as highways. In Brazil, the manual has a strong appeal for use by agencies that manage road traffic, especially in the context of road concessions (Pereira and Bessa Jr., 2017). However, the HCM was developed based on research conducted on highways in Canada and especially in the USA (TRB, 2022). When it is applied in different regions, including Brazil, without any adaptations fitting its equations, parameters, and methodologies to the reality of these locations, several deficiencies and limitations are presented in the analyses (Setti *et al.,* 2011).

In the Brazilian scenario, the National Department of Transport Infrastructure (DNIT, 2006) – or Departamento Nacional de Infraestrutura de Transportes, for its abbreviation in Portuguese – highlights that the methodology proposed by the HCM is used in its entirety, without any modification or adjustment. From this perspective, an incorrect assessment always negatively impacts the road system: underestimations can lead to unnecessary costs for improvements; overestimations imply a lack of implementation of necessary improvements for the proper functioning of the highway system (Paula, 2006).

In Brazil, studies by Egami (2006), Utimura *et al.* (2007), Mon-Ma (2008), Bessa Jr. (2015), Pereira and Bessa Jr. (2017), Bessa Jr. and Setti (2018), and Silva (2019) concluded that the adoption of the method provided in previous editions of the manual without adaptation to local conditions tends to underestimate the level of service on Brazilian highways. Therefore, these authors propose a search for alternative methods to the HCM for the analysis of Brazilian highways or even adaptations of the methodology and parameters presented in the manual.

The HCM is in its seventh edition (TRB, 2022). A new chapter of the manual focuses on the analysis of two-lane highways based on the final report of National Cooperative Highway Research Program (*NCHRP*) Project 17-65 (Washburn *et al*., 2018), with emphasis on the use of a new service measure, the follower density (*FD*). Given the above, the objective of this study was to adapt part of this new method to address two-lane highway segments without passing lanes.

To achieve this goal, field traffic data were collected to calibrate and validate the Aimsun Next traffic simulator. With this, simulation data were generated for a range of scenarios with different geometric and traffic flow compositions according to Washburn *et al*. (2018). From this information, the coefficients of the models that are part of this new method were estimated. Then, again using traffic data collected in the field, the degree of proximity of the *FD* values found with the adapted model and without adaptation was verified, and these results were compared with what was observed in the field and with two other models found in the literature (Bessa Jr., 2015; Silva, 2019). The details of these steps are shown below, as well as an overview of the new HCM method for the operational analysis of two-lane highway segments.

2. ANALYSIS OF TWO-LANE RURAL HIGHWAYS BASED ON THE HCM-7

The final report of NCHRP Project 17-65 (Washburn *et al*., 2018) proposed that the new HCM-7 method for evaluating the capacity and level of service of two-lane highways eliminates tables that need interpolations, treating heavy vehicles explicitly through the percentage of heavy vehicles (*HV*) instead of measuring them using the vehicle equivalent. In addition to proposing *FD* as a new service measure, another significant change was the categorization of highways into only two classes according to their regulatory speeds: high-speed highways (posted speed limit equal to or greater than 80 km/h) and low-speed highways (posted speed limit less than 80 km/h).

The first step of the method consists of identifying the segment types that make up the section under analysis, as follows: i) passing constrained; ii) passing zone; or iii) passing lane. The equations and coefficients of the method differ according to the segment type. Another step is the determination of the classifications for vertical alignment, which are grouped into five classes according to the segment slope and the segment length (*L*), as shown in Table 1.

Table 1 – Classifications for vertical alignment (downgrades in parentheses)
(Washburn *et al.*, 2018; TRB, 2022)

L (km)	Segment slope (%)									
	≤ 1	> 1 ≤ 2	> 2 ≤ 3	> 3 ≤ 4	> 4 ≤ 5	> 5 ≤ 6	> 6 ≤ 7	> 7 ≤ 8	> 8 ≤ 9	> 9
≤ 0.16	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	2 (1)	2 (2)	2 (2)
> 0.16 ≤ 0.32	1 (1)	1 (1)	1 (1)	1 (1)	2 (1)	2 (2)	2 (2)	3 (2)	3 (3)	3 (3)
> 0.32 ≤ 0.48	1 (1)	1 (1)	1 (1)	2 (1)	2 (2)	3 (2)	3 (3)	4 (3)	4 (4)	5 (5)
> 0.48 ≤ 0.64	1 (1)	1 (1)	2 (1)	2 (2)	3 (2)	3 (3)	4 (4)	5 (4)	5 (5)	5 (5)
> 0.64 ≤ 0.80	1 (1)	1 (1)	2 (1)	2 (2)	3 (3)	4 (3)	5 (4)	5 (5)	5 (5)	5 (5)
> 0.80 ≤ 0.96	1 (1)	1 (1)	2 (1)	3 (2)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)
> 0.96 ≤ 1.12	1 (1)	1 (1)	2 (1)	3 (2)	4 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.12 ≤ 1.28	1 (1)	1 (1)	2 (1)	3 (3)	4 (4)	5 (4)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.28 ≤ 1.44	1 (1)	1 (1)	2 (1)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.44 ≤ 1.60	1 (1)	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.60 ≤ 1.76	1 (1)	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.76	1 (1)	1 (1)	2 (2)	4 (4)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)

The measures of effectiveness that make up the *FD* formulation, which is defined as the number of vehicles traveling in platoons per kilometer per lane, should be obtained. The *FD* was originally proposed by Van As (2003) for the analysis of two-lane highways in South Africa. It reflects the opportunities for drivers to execute passing maneuvers and expresses the discommodity of users who travel in platoons (Catbagan and Nakamura, 2006). *FD* is obtained through the combination of two performance measures – the percentage of followers (*PF*) and average travel speed (*ATS*), in addition to the traffic flow rate in the direction of analysis (v_d) for the peak 15-min volume within the hour of analysis, according to the equation:

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

Although the HCM-7 method presents the equations that can obtain *FD*, this performance measure can also be obtained directly in the field. If the *ATS* needs to be estimated, then it is necessary to obtain the free-flow speed (*FFS*), which can be achieved through field data or the following equation:

$$FFS = BFFS - a \times HV - f_{LS} - f_A \tag{2}$$

where:

$$a = Máx\left[0.0333, a_0 + a_1 \times BFFS + a_2 \times L + Máx\left(0, \left(a_3 + a_4 \times BFFS + a_5 \times L\right) \times \frac{v_o}{1{,}000}\right)\right] \tag{3}$$

where *BFFS* = base free-flow speed (mi/h or km/h); *a* = slope of the linear relationship between *FFS* and *HV*; *HV* = percentage of heavy vehicles; f_{LS} = adjustment factor for the width of the traffic lane and the shoulder (which should be calculated only if the width of the traffic lane is between 9 feet and 12 feet and the shoulder width is between 0 feet and 6 feet; otherwise, it should be equal to zero); f_A = adjustment factor for the access-point density; a_0 to a_5 = fit coefficients; L = segment length (mi or km); and v_o = traffic flow rate in the direction opposite that of the analysis for the peak 15-min volume within the hour of analysis (veh/h). The *BFFS* represents the speed expected to be reached when a vehicle travels on a road with basic geometric and flow conditions. The HCM-7 recommends, for calculation purposes, that the *BFFS* be obtained from the product of the maximum regulatory speed of the road and 1.14.

ATS, in turn, has been the main performance measure used to determine the level of service of two-lane highways since the first versions of the HCM and is a well-known and studied measure. This measure is easily obtained in the field, which is advantageous. However, the *ATS* alone cannot represent the discommodity of drivers who travel in platoons. *ATS* can be calculated according to the equation:

$$ATS = FFS - m \times \left(\frac{v_d}{1{,}000} - 0.1 \right)^p \tag{4}$$

where m = slope coefficient; v_d = traffic flow in the direction of analysis (veh/h); and p = power coefficient. To find the parameter m, the following equations can be applied:

$$m = Max\left[b_5, b_0 + b_1 \times FFS + b_2 \times \sqrt{\frac{v_o}{1{,}000}} + Max(0, b_3) \times \sqrt{L} + Max(0, b_4) \times \sqrt{HV} \right] \tag{5}$$

where:

$$b_3 = c_0 + c_1 \times \sqrt{L} + c_2 \times FFS + c_3 \times \left(FFS \times \sqrt{L} \right) \tag{6}$$

$$b_4 = d_0 + d_1 \times \sqrt{HV} + d_2 \times FFS + d_3 \times \left(FFS \times \sqrt{HV} \right) \tag{7}$$

In turn, to estimate the parameter p, the following formulation should be used:

$$p = \max\left[f_8, f_0 + f_1 \times FFS + f_2 \times L + f_3 \times v_o + f_4 \times \sqrt{\frac{v_o}{1{,}000}} + f_5 \times HV + f_6 \times \sqrt{HV} + f_7 \times \left(L \times HV \right) \right] \tag{8}$$

where v_o = the traffic flow of vehicles in the direction opposite that of the analysis (veh/h); b_0, b_1, b_2 and b_5 = model coefficients; b_3 = length adjustment coefficient; $c_0 - c_3$ = coefficients relative to the calculation of b_3; b_4 = adjustment coefficient for the percentage of heavy vehicles; $d_0 - d_3$ = coefficients relative to the calculation of b_4; and $f_0 - f_8$ = coefficients for finding p.

PF is defined as the percentage of vehicles that travel with headways equal to or less than one critical headway, which is equal to 2.5 seconds, according to NCHRP Project *17-65* (Washburn *et al.*, 2018) and HCM-7 (TRB, 2022). This measure is easily obtained in the field but is dispersed, which can generate a certain degree of uncertainty in the results, especially if not used in combination with other performance measures (Al-Kaisy *et al.*, 2018). This measure is calculated by:

$$PF = 100 \times \left[1 - e^{\left(m \times \left(\frac{v_d}{1{,}000} \right)^p \right)} \right] \tag{9}$$

Unlike the equation that determines *ATS*, the coefficients m and p are calculated based on the *PF* in two different scenarios: the first, when the road is at capacity (Equation 10), and the second, when it has a directional flow at 25% of capacity (Equation 11):

$$PF_{cap} = b_0 + b_1 \times L + b_2 \times \sqrt{L} + b_3 \times FFS + b_4 \times \sqrt{FFS} + b_5 \times HV + b_6 \times FFS \times \frac{v_o}{1{,}000} + b_7 \times \sqrt{FFS} \quad (10)$$

$$PF_{25cap} = c_0 + c_1 \times L + c_2 \times \sqrt{L} + c_3 \times FFS + c_4 \times \sqrt{FFS} + c_5 \times HV + c_6 \times FFS \times \frac{v_o}{1{,}000} + c_7 \times \sqrt{\frac{v_o}{1{,}000}} \quad (11)$$

where *PF* PF_{cap} = percentage of vehicles in platoons at capacity; b_0 – b_7 = fit coefficients for the calculation of PF_{cap}; PF_{25cap} = percentage of vehicles in platoons for flow equal to 25% of capacity; and c_0 – c_7 = adjustment coefficients for the calculation of PF_{25cap}. The slope coefficient *m* and the power coefficient *p* must be calculated according to Equations 12 and 13.

$$m = d_1 \left(\frac{0 - \ln\left(1 - \frac{PF_{25cap}}{100}\right)}{0.25 \times \left(\frac{cap}{1{,}000}\right)} \right) + d_2 \left(\frac{0 - \ln\left(1 - \frac{PF_{cap}}{100}\right)}{\left(\frac{cap}{1{,}000}\right)} \right) \quad (12)$$

$$p = e_0 + e_1 \left(\frac{0 - \ln\left(1 - \frac{PF_{25cap}}{100}\right)}{0.25 \times \left(\frac{cap}{1{,}000}\right)} \right) + e_2 \left(\frac{0 - \ln\left(1 - \frac{PF_{cap}}{100}\right)}{\left(\frac{cap}{1{,}000}\right)} \right) + e_3 \sqrt{\left(\frac{0 - \ln\left(1 - \frac{PF_{25cap}}{100}\right)}{0.25 \times \left(\frac{cap}{1{,}000}\right)} \right)} + e_4 \sqrt{\left(\frac{0 - \ln\left(1 - \frac{PF_{cap}}{100}\right)}{\left(\frac{cap}{1{,}000}\right)} \right)} \quad (13)$$

where d_1 and d_2 are fit coefficients for the calculation of *m*; e_0 and e_4 are coefficients for calculating *p*; and *cap* is the unidirectional capacity (veh/h). All tables with the coefficients proposed for the use of Equations 3 to 13 can be found in Washburn *et al.* (2018) and TRB (2022), with the values obtained in the units of the American system of measurements (speed in mi/h and distance in mi).

After the *ATS* and *PF* performance measures are calculated and the traffic flow v_d is obtained in the field, *FD* (Equation 1) is calculated for one direction of analysis, and the level of service estimate is obtained according to Table 2. At level F, the operational conditions are unstable, with the road operating in the congested traffic flow regime, corresponding to a higher demand than the unidirectional capacity, which is, for the base conditions, equal to 1,700 passenger car equivalent (pce)/h (except for segments with passing lanes).

Table 2 – Follower density thresholds for measuring the level of service (Washburn *et al.,* 2018; TRB, 2022)

Level of Service	FD (veh/km/lane) High-speed highways (Posted speed limit ≥ 80 km/h)	Low-speed highways (Posted speed limit < 80 km/h)
A	≤ 3.20	≤ 4.00
B	> 3.20–6.40	> 4.00–8.00
C	> 6.40–12.8	> 8.00–16.00
D	> 12.8–19.2	> 16.00–24.00
E	> 19.2	> 24.00

3. TRAFFIC DATA COLLECTION AND CALIBRATION AND VALIDATION OF AIMSUN NEXT

The traffic data were used in this study to calibrate and validate the Aimsun Next simulator. In addition, some of these data were used to validate the adaptation of the NCHRP Project 17-65 method. The traffic data and geometric characteristics used were obtained from Silva (2019) and collected on BR-040, an important highway that connects Brasília-DF to Rio de Janeiro-RJ. Six highway segments of approximately 10 km in length with different vertical and horizontal alignments were observed.

The six road segments of BR-040 in which the traffic data were collected do not have passing lanes and correspond to the following kilometer milestones: i) 19 to 29; ii) 97 to 105; iii) 130 to 140; iv) 140 to 150; v) 359 and 369; and vi) 389 to 399. More detail regarding the geometry and traffic data of these segments can be found in Silva (2019). In turn, regarding considering the effects of the presence of heavy vehicles in the traffic stream in the simulations, parameters related to the performance of these vehicles were used.

The input data in Aimsun Next that determined the vehicle performance in the simulated networks were obtained from mass and power data used in the study by Silva (2019). The vehicle power data were collected by recording the models of 450 trucks obtained near km 554 of BR-040 in a single day. Subsequently, a survey of the vehicle characteristics was performed using the catalogs of the models and engines of each truck found on the manufacturers' websites. The vehicle mass data (of 30,839 trucks) were recorded by a mobile scale installed on BR-040 located near km 554. With this information, the trucks of each category were classified, as shown in Table 3.

Table 3 – Heavy vehicle characteristics used on Aimsun Next

		Mass (kg)		Mass/Power ratio (kg/cv)		Mass/Frontal area ratio (kg/m²)	
Heavy vehicle category	Frontal area (m²)	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Light	5.39	9,113	3,418	58	22	1,691	634
Medium	6.56	18,190	6,100	68	23	2,773	930
Heavy	7.20	3,994	10,466	101	27	5,409	1,454
Extra-heavy	7.96	55,966	17,296	128	40	7,031	2,173

The desired speed distributions of the road segments observed in the field is also very important in simulations with Aimsun Next. In the simulator, the desired speed is randomly assigned to each vehicle that enters the network based on the mean value and standard deviation entered by the user, limited by the maximum and minimum values reported. The desired speed distributions observed in the field per road segment were obtained considering vehicles that traveled with headways longer than 2.5 seconds, which is the critical value established by NCHRP Project 17-65 to define platoons (Washburn *et al.*, 2018; TRB, 2022). In addition to the information on the desired speed, the vehicle performance model, and the demand, the behavioral parameters of the simulator that are most significant for calibration had to be adjusted. This was performed for the road segment with the highest traffic volumes observed in the field (km 130 to km 140), given that, in these cases, the number of vehicle interactions tends to be higher than that when the volumes are low.

To identify the most relevant parameters, the method proposed in Lacerda (2016) was applied, in which simulations were performed with the default values of the calibration parameters and then with the minimum and maximum values of the search intervals of each parameter. The differences between the values of a given performance measure (travel times of all vehicles, by direction, of each traffic stream, as they were influenced by different behavioral submodels of the simulator) were calculated with the minimum and maximum values of each parameter in relation to the results obtained using all the default parameters. With the samples of the travel time differences, for each parameter analyzed, Student's t test was performed for dependent samples (paired), with a significance level of 5%. Of the parameters subjected to sensitivity analysis, four needed to be adjusted, mainly related to passing maneuvers:

- *MINCHEADMCAR*: minimum headway between the leader and follower vehicles; considered in the calculation of vehicle speed and deceleration at a given time;
- *NDECMCAR*: mean normal deceleration of the leading vehicle for automobiles;
- *SNSTVTFCTRDCD*: sensitivity factor altering the perception of the visibility distance and, consequently, the aggressiveness in the execution of a passing maneuver; and
- *SPDIFMAX*: maximum value of the speed difference between the leader and follower vehicles, which determines whether passing is desirable.

As the sensitivity analysis was conducted for each parameter individually, the definitions of the parameters that could be linked to the four parameters were evaluated. *SPDIFMAX* is strongly related to the minimum value of the speed difference between the leader and follower vehicles (*SPDIFMIN*), which determines whether passing is desirable. Therefore, this parameter was included in the parameters to be calibrated. In this same sense, because they are closely related to passing, two more parameters related to the maneuvers were adjusted: the maximum delay limit caused by a leading vehicle (*DLTRSHLD*), which also determines whether passing is desirable, and the maximum position in the queue in which vehicles still have a chance of passing (*RNKTRSHLD*), totaling seven parameters chosen for calibration.

The calibration of the seven parameters was performed with a genetic algorithm (GA) adapted from Sousa *et al*. (2019), which, in turn, is strongly based on the algorithm developed in the work of Silva (2019). The GA was applied to each of the six road segments observed in the field, where the target measure was to reduce the sum of the quadratic errors of the average travel speeds observed by traffic stream and by road direction. As seen in Table 4, the application of the GA (best result) for the segments between km 389 and km 399 represented less aggressive driver behavior than the others, which may have occurred because the segment had a larger number of horizontal curves (which limited passing maneuvers). For this reason, in the attempt to establish a typical Brazilian driver for performing simulations in Aimsun Next, the average of the best parameters found (representing an individual of high aggressiveness) did not include the GA result for the segment between km 389 and km 399. Further details on the analysis of the relevant calibration parameters, as well as a brief description of the Aimsun Next behavioral models and the calibration and validation process of the simulator, can be found in Oliveira (2021).

Table 4 – Aimsun Next parameters found after applying the GA to each segment

Parameter	Segment (km)						Average*
	19-29	97-105	130-140	140-150	359-369	389-399	
NDECMCAR (m/s^2)	4.58	4.12	4.39	4.31	4.82	2.15	4.45
MINCHEADMCAR (s)	0.39	0.34	0.32	0.31	0.38	1.17	0.35
DLTRSHLD (s)	33.17	37.25	57.00	37.13	44.95	297.77	41.90
SPDIFMAX (km/h)	21.03	20.81	21.51	26.29	22.94	58.04	22.52
RNKTRSHLD	5.11	6.52	6.29	5.88	5.87	2.16	5.94
SPDIFMIN (km/h)	9.18	9.23	9.21	9.19	7.09	17.48	8.78
SNSTVTFCTRDCD	0.55	0.50	0.36	0.43	0.53	1.36	0.47

*without the segment between km 389 and km 399

4. HCM-7 ADAPTATION

The adaptation proposed in this study for HCM-7 follows the premise of maintaining the original structure of the method focused on two-lane highways found in the final report of NCHRP Project 17-65 (Washburn et al., 2018) and in HCM-7 (TRB, 2022). The first step is to adjust the vertical alignment classification. Next, the tables with the coefficients used to estimate FFS, used to obtain ATS and the PF, which are the performance measures necessary to calculate the FD, should be adapted (as shown in Section 2).

4.1. Classifications for vertical alignment

For this purpose, several scenarios were simulated, varying the slope and the length of a hypothetical section of analysis preceded by an input section, and followed by an output section, both with a slope equal to 0%. In the section of the analysis, the vertical grades were simulated with slopes between -10% and 10% and lengths ranging from 0 km to 1.9 km, with increments of 1% and 160 m, respectively. Detectors were inserted to obtain the instantaneous speed of the heavy vehicles that traveled along the segment in each sensor and, consequently, the vehicle performance model in each scenario. In this analysis, we used a medium (typical)-type truck of mass/power ratio equal to 68 kg/cv, as it is the most common in the sample collected in BR-040. The performance curves obtained by simulation can be found in Oliveira (2021).

The speed of this typical vehicle, entering the analysis segment at 65 mi/h (105 km/h), decreases along the section of analysis until the vehicle reaches an equilibrium speed. This effect is reproduced by the simulator due to the implemented TWOPAS model, in which the speed of vehicles in upgrade sections is affected by their mass and weight, which determines the vehicle performance (Aimsun, 2020). The classification of the vertical alignment of the upgrades is obtained as a function of this reduction: for class 1, the reduction is less than 11.3 km/h; for class 2, the reduction is between 11.3 km/h and 22.5 km/h; for class 3, the reduction should be between 22.5 km/h and 33.8 km/h; for class 4, the reduction should be between 33.8 km/h and 45 km/h; and class 5 is defined as the segments that cause a typical truck to reduce its initial speed by more than 45 km/h.

For downgrades, the method of obtaining the classes considers that the drivers want to maintain a speed in these places, for safety, equal to an equilibrium speed on a section whose upgrade is equal to the downgrade (in the module). According to Washburn *et al.* (2018), the hypothesis is that truck drivers, in this case, use the same gear for upgrade and downgrade segments. Thus, the process for obtaining the classes for downgrades has five steps: i) determine which upgrade performance curve should be selected according to the segment slope analyzed; ii) increase the length of the downgrade section if the desired initial speed is less than 75 mi/h (120 km/h); iii) determine whether the vehicle reaches the crawl speed on the downgrade segment; iv) calculate the desired speed on the downgrade segment, which must be less than or equal to the crawl speed; and v) adjust the desired speed for sections with low slopes once drivers, in this case, admit higher desired speeds without compromise safety. More details on the application of the method for obtaining the classes for the downgrades can be found in Oliveira (2021) and Washburn *et al*. (2018).

The resulting classification for the vertical alignments obtained from this study is shown in Table 5, which is an adapted version of that found in the NCHRP Project 17-65 and HCM-7 (Table 1). Note that the geometric conditions impact a typical Brazilian heavy vehicle more than the heavy vehicle used in Washburn *et al.* (2018), which has a mass/power ratio of 50 kg/cv.

Table 5 – Revised classifications for vertical alignment (downgrades in parentheses)

L (km)	Segment slope (%)									
	≤ 1	> 1 ≤ 2	> 2 ≤ 3	> 3 ≤ 4	> 4 ≤ 5	> 5 ≤ 6	> 6 ≤ 7	> 7 ≤ 8	> 8 ≤ 9	> 9
≤ 0.16	1 (1)	1 (2)	2 (3)	2 (4)	2 (4)	2 (4)	2 (5)	2 (5)	2 (5)	2 (5)
> 0.16 ≤ 0.32	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	4 (5)	4 (5)	4 (5)	4 (5)
> 0.32 ≤ 0.48	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 0.48 ≤ 0.64	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 0.64 ≤ 0.80	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 0.80 ≤ 0.96	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 0.96 ≤ 1.12	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.12 ≤ 1.28	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.28 ≤ 1.44	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.44 ≤ 1.60	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.60 ≤ 1.76	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
> 1.76	1 (1)	1 (3)	2 (4)	3 (5)	4 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)

4.2. Free-flow speed estimation

As in the method proposed in the NCHRP Project 17-65 report, a series of experiments was performed from which the impact of geometric characteristics and traffic conditions on the behavior of the performance measures analyzed could be evaluated, and thus, the traffic relationships could be developed, and the coefficients for each of these different conditions could be obtained. The scenarios proposed by the report are derived from the combination of the following variables:

- Segment length (km): 0.40; 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 directional heavy vehicles: 0; 5; 10; 15; 20; and 25;
- Traffic flow in the opposite direction (veh/h): 0; 200; 400; and 1,500; and
- Percentage of heavy vehicles in the opposite direction: 10.

In addition to these variables, to create the scenarios, the vertical classification (upgrade and downgrade segments) and the possibility of performing passing maneuvers (passing zones and no-passing zones) were considered. In this context, 1,260 scenarios with no-passing zones and 5,040 scenarios with passing zones were simulated, totaling 6,300 possible scenarios.

In addition, as predicted in the report of NCHRP Project 17-65, for scenarios with passing zones, this maneuver was authorized only for vehicles that traveled in the analysis direction and was prohibited for the other vehicles that traveled in the network. Therefore, the opposite flow was inserted only in scenarios where there are passing zones since vehicles traveling in the opposite direction limit the possibilities of executing passing maneuvers. On the other hand, in no-passing zones, it is understood that vehicles in the direction of analysis cannot pass and are restricted by vehicles traveling in the same direction, with no influence from vehicles traveling in the opposite direction.

The model proposed in Equations 2 and 3 involves a series of variables that influence the *FFS* estimate, such as the classifications for vertical alignment, the possibility of performing passing maneuvers, the segment length, the percentage of heavy vehicles, the *BFFS*, and the flow in the opposite direction. In this context, the coefficients present in the model are strongly related to the geometry and traffic flow conditions of the highways. Using linear regression and values of the *FFS*, *BFFS*, and *HV* of each simulated scenario, the values for a_0 to a_5 were obtained

(Table 6) according to the vertical classification; they are necessary to obtain the parameter *a* in Equation 2 (considering the international system of units). For the cases in which the fit coefficients showed regression with a p-value greater than 5%, it was concluded that this fit coefficient is not applicable (denoted by N/A). In these cases, the coefficients are considered zero, as occurs in the proposed method without adaptations (Washburn *et al.*, 2018; TRB, 2022). The equations in HCM-7 for calculating the adjustment factors f_{LS} and f_A were not adapted in this study given that Aimsun Next is not able to reproduce the traffic behavior from the road elements associated with these adjustment factors.

Table 6 – Coefficients for *FFS-HV* slope model (used in Equation 3)

Vertical Class	a_0	a_1	a_2	a_3	a_4	a_5
1	N/A	0.0005	-0.0088	0.0002	-0.0012	0.0240
2	N/A	0.0008	-0.0222	0.0003	-0.0019	0.0295
3	-0.1382	0.0025	-0.0076	0.0002	-0.0012	0.0291
4	-0.2206	0.0042	0.0104	N/A	N/A	0.0750
5	-0.3737	0.0058	0.1645	-0.0005	0.0073	0.0001

The *a* coefficient of Equation 2 proved to be quite sensitive, especially to the opposite traffic flow and for the classes that demand a higher vehicle performance, in particular class 5. For classes 1 and 2, this coefficient remains practically constant regardless of *BFFS*, the length of the segment, and the opposite flow observed. It is possible to observe these behaviors when the parameters of Table 6 are applied to obtain the coefficient *a*, as can be observed graphically in Oliveira (2021).

4.3. Average travel speed estimation

After estimating the *FFS*, we proceeded to obtain the mean travel speed (*ATS*) using Equation 4 per direction of analysis. The coefficients *m* and *p*, as well as the factors that compose these coefficients, were also obtained by linear regression. Regressions whose parameters had a p-value of less than 5% were considered valid. The coefficients b_0 to b_5, c_0 to c_3, d_0 to d_3, and f_0 to f_8, all presented in Section 2 of this study, can be seen in Tables 7 to 9 (considering the international system of units).

Table 7 – Coefficients used in the speed-flow slope model (used in Equation 5)

Vertical Class	b_0	b_1	b_2	b_3	b_4	b_5
1	8.0094	0.0147	0.6955	Equation 6	Equation 7	0.0000
2	6.5971	0.0323	N/A	Equation 6	Equation 7	0.0000
3	7.9158	0.0151	0.5354	Equation 6	Equation 7	0.0000
4	-14.7240	0.1542	-0.9976	Equation 6	Equation 7	0.0000
5	-3.4100	0.0612	-1.1008	Equation 6	Equation 7	0.0000

Table 8 – Coefficients used to calculate b_3 and b_4 (used in Equations 6 and 7)

Vertical Class	c_0	c_1	c_2	c_3	d_0	d_1	d_2	d_3
1	-1.1051	0.6502	0.0210	-0.0100	0.0391	N/A	0.0017	N/A
2	-7.3641	4.1854	0.1737	-0.0920	1.4795	-0.3131	0.0051	0.0012
3	-1.2244	0.7529	0.0197	-0.0109	N/A	N/A	0.0022	-0.0001
4	19.8716	-7.0122	-0.1226	0.0743	N/A	N/A	0.0021	N/A
5	0.9487	3.9602	0.0770	-0.0381	7.7582	N/A	0.0524	-0.0165

Table 9 – Coefficients used to calculate *p* (used in Equation 8)

Vertical Class	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
1	0.2458	0.0037	0.0199	-0.0168	-0.0578	0.0006	-0.0051	N/A	0.0000
2	0.2563	0.0036	0.0116	N/A	N/A	-0.0040	N/A	0.0021	0.0000
3	0.2835	0.0033	0.0203	-0.0208	-0.0605	0.0011	-0.0067	N/A	0.0000
4	N/A	0.0050	0.0490	N/A	-0.0136	-0.0124	0.0891	-0.0002	0.0000
5	0.3271	0.0033	-0.0081	-0.1500	0.0033	-0.0448	0.2213	-0.0008	0.0000

4.4. Estimation of the percentage of followers

For the *PF,* the determination of the coefficients was performed similarly to those related to the *ATS*, using the results of simulations for the scenarios presented at the beginning of Section 4.2. To calculate the values of PF_{cap} and PF_{25cap}, the adjusted parameters present in Tables 10 and 11, respectively, should be used. With *m* and the PF_{cap} and PF_{25cap} values of the simulations, it was possible to obtain the coefficients d_1 and d_2. These factors are independent of the vertical alignment class and are shown in Table 12. Similarly, the coefficients for obtaining *p* were found (e_0 to e_4), as shown in Table 12. With the coefficients necessary to calculate the variables that compose the equation for estimating the *PF*, this parameter can then be determined with Equation 9.

Table 10 – Coefficients used to calculate b_0 to b_7 to obtain PF_{cap} (used in Equation 10)

Vertical Class	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
1	52.4935	1.4447	-5.5774	-0.7541	11.7585	0.0227	0.0335	-2.7041
2	104.6865	N/A	-0.9500	-0.1154	N/A	0.0215	0.0500	-5.4326
3	95.2025	0.9376	-3.4024	N/A	N/A	N/A	0.0262	-2.8645
4	93.3619	N/A	-0.5463	N/A	N/A	-0.0273	0.0330	-3.4926
5	97.5721	2.3595	-7.6294	N/A	N/A	N/A	0.0268	-2.6145

Table 11 – Coefficients used to calculate c_0 to c_7 to obtain PF_{25cap} (used in Equation 11)

Vertical Class	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7
1	201.3322	3.3078	-13.4633	0.5634	-18.8788	N/A	0.1191	-11.6081
2	144.0636	-1.1471	N/A	N/A	-8.0622	N/A	0.1394	-16.3385
3	249.0668	5.1240	-14.5436	1.1099	-28.9537	-0.1088	0.0955	-11.4463
4	295.4739	N/A	-4.1813	1.6336	-39.1909	-0.1789	0.1872	-22.0521
5	241.4376	N/A	-4.5154	1.1465	-28.7855	-0.1169	0.1600	-20.7451

Table 12 – Coefficients used to calculate $d_1 – d_2$ and $e_0 – e_4$ to obtain *m* and *p* (used in Equations 12 and 13)

Segment type	d_1	d_2	e_0	e_1	e_2	e_3	e_4
Passing zone and no-passing zone	-0.4887	-0.4390	1.0096	0.2940	-0.5712	-1.4138	1.6083

4.5. *FD* obtained in the field and level of service calculation

Once the adaptation of the coefficients for calculating *FFS*, *ATS,* and *FD* was obtained, a validation process of these models was performed. It consisted of calculating the *FD* for half of the traffic streams obtained in the field (the same sample used in the Aimsun Next validation) and then determining the level of service of the segment according to Table 2. In addition to the values of *FD* found in the field, the results were obtained with the NCHRP Project 17-65 method with and without the proposed adaptation and with the methods found in Bessa Jr.

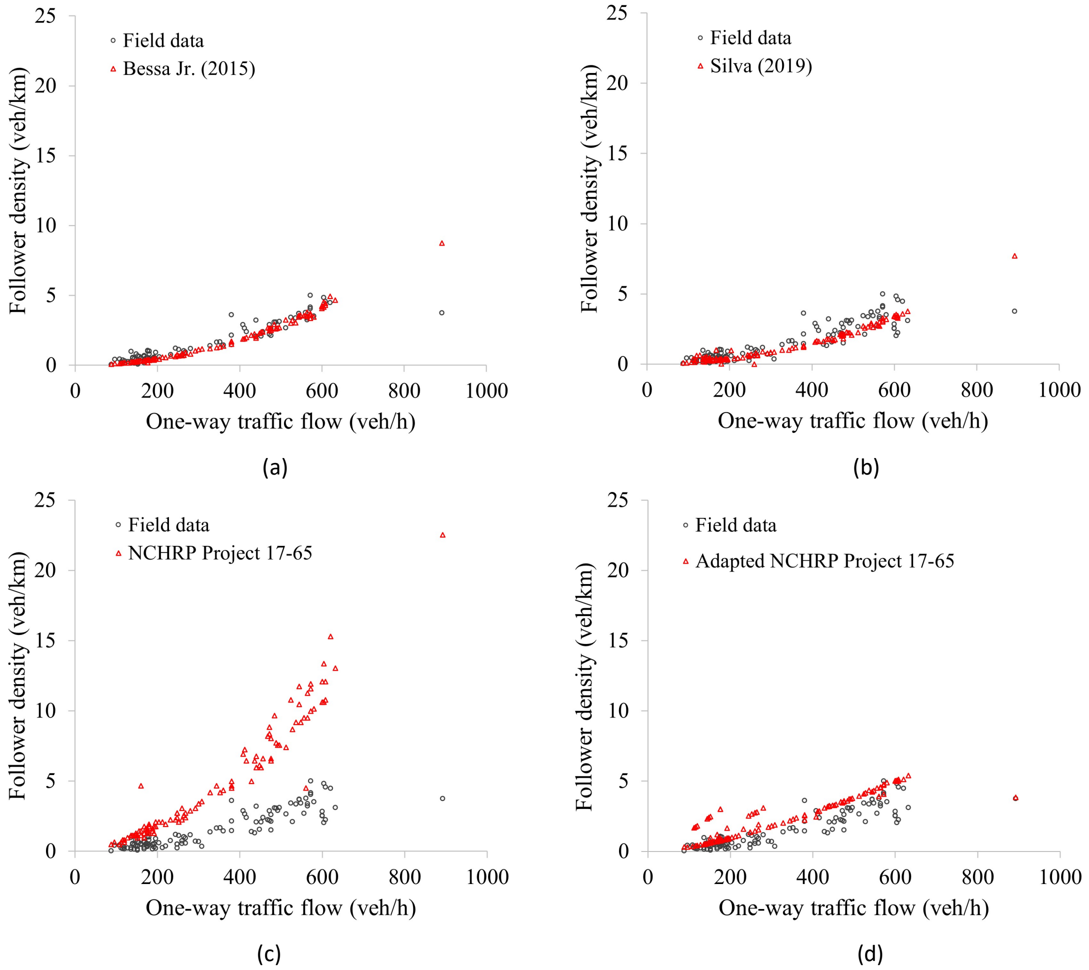
(2015) and Silva (2019), who proposed alternative traffic models to the HCM (which do not follow the same structure found in the manual) for the calculation of *FD* (for Brazil). The *FD* results calculated with the models were compared with the *FD* obtained directly in the field, as shown in Figure 1, which shows that values found with NCHRP Project 17-65 method without adaptations are overestimated compared with those observed in the field.

The quality of the estimates of each model was also evaluated using goodness-of-fit measures between the results obtained by the proposed models and those observed in the field (Equations 14 to 16): i) the mean absolute normalized error (*MANE*); ii) root mean square normalized error (*RMSNE*); and iii) correlation coefficient (*r*), as defined in Hollander and Liu (2008). The values of the fit functions are shown in Table 13.

$$MANE = \frac{1}{N}\sum_{i=1}^{n}\frac{|x_i - y_i|}{y_i} \tag{14}$$

$$RMSNE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - y_i}{y_i}\right)^2} \tag{15}$$

$$r = \frac{1}{N-1}\sum_{i=1}^{N}\frac{\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sigma_x \sigma_y} \tag{16}$$



(a)

(b)

(c)

(d)

Figure 1. FD values obtained in the field and with (a) Bessa Jr. (2015), (b) Silva (2019), (c) NCHRP Project 17–65, and (d) adapted NCHRP Project 17-65

Table 23 – Goodness-of-fit measures for the analyzed FD models

FD Model	Goodness-of-fit measure		
	MANE	*RMSNE*	*r*
Adapted NCHRP Project 17-65	59.7%	1.15	0.91
Silva (2019)	55.3%	0.90	0.86
Bessa Jr. (2015)	33.0%	0.46	0.87
NCHRP Project 17-65	219.9%	2.95	0.89

The goodness-of-fit measures obtained, especially *MANE* and *RMSNE*, show that there is a similarity between the *FD* values calculated with the adapted NCHRP Project 17-65 and the models of Bessa Jr. (2015) and Silva (2019) in relation to those from the field. The same can be seen in Figure 2, which compares the percentage of levels of service obtained with the NCHRP Project 17-65 method with and without adaptations and those obtained in the field, which reinforces the need to adjust the HCM method to the Brazilian conditions so that the results are more representative of what occurs on the highways.

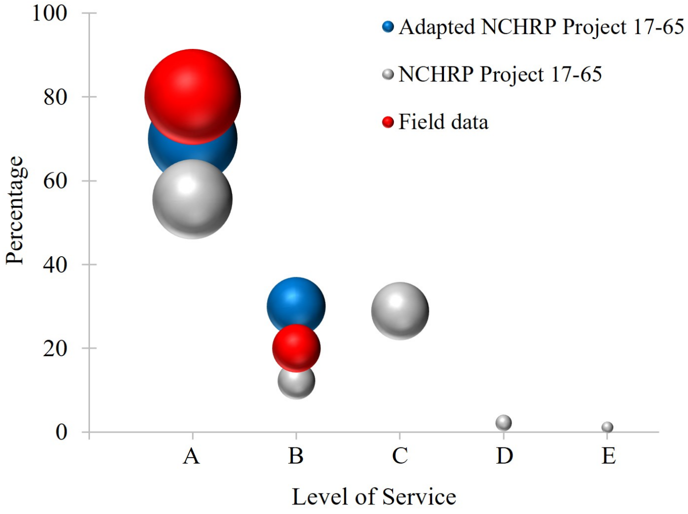


Figure 2. Level of service obtained in the field and with and without adaptation of the NCHRP Project 17–65

5. FINAL REMARKS

The objective of this study was to adapt the new HCM method to Brazilian conditions to estimate the level of service of two-lane highways without passing lanes. To make this possible, a set of traffic data collected in BR-040 segments was used to calibrate and validate Aimsun Next and, subsequently, to validate the adapted models found in the final report of NCHRP Project 17-65 (Washburn *et al*., 2018) and in HCM-7 (TRB, 2022).

Scenarios were simulated under different geometric and traffic conditions, and the generated data were used to fit the parameters of the models used to estimate the performance measures (*ATS* and *PF*) that make up the *FD* formulation, which is the service measure proposed in the new method. The structure of the HCM method was maintained, adjusting only the coefficients of the traffic models, as well as the classification for the vertical alignment. The results obtained reinforce the need to adjust the HCM to local conditions since the adapted NCHRP Project 17-65 method provided *FD* and levels of service values more compatible with the values obtained in the field than those found from the method without adaptations.

The traffic streams with the highest traffic volumes observed were on the order of 1,000 veh/h per direction of traffic, still far from the unidirectional capacity cited in the HCM of 1,700 cpe/h (most were below 600 veh/h per direction). Thus, calibration and validation were performed with traffic streams below capacity, and congested scenarios were not evaluated. The results found in this study strongly reflect what was found in the road segments observed in BR-040. For future studies, it is suggested to increase this traffic data sample, especially with a focus on other highways and, if possible, with traffic volumes closer to capacity. Thus, the most relevant Aimsun Next behavioral parameters can be reassessed, including considering *FD*, which is the measure of performance of interest to obtain the level of service on two-lane highways. The GA could also be reapplied to assess whether the results found in this study would be different.

For future studies, it is recommended to complement the adaptation of the method for the analysis of segments with passing lanes, and with the presence of horizontal curves. Another important part of the method that could be adapted concerns “2+1” highways, which requires a reflection on the possibility, or not, of using the recalibrated Aimsun Next in this study.

It is known that maintaining the structure of the HCM, with only adaptations of the coefficients associated with the traffic models, increases the appeal to the use of the results obtained in this study for management agencies in Brazil (even if in part). However, a new structure can always be proposed, which opens up possibilities for new research, such as those involving the user’s opinion. Studies of this nature may provide different criteria for determining the level of service based on *FD* or even for defining the classes for the vertical and horizontal alignments of the highway.

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REFERENCES

Aimsun (2020) *Aimsun Next 20: Dynamic Simulators User’s Manual*. Barcelona, Espanha.

Al-Kaisy, A., Jafari, A., Washburn, S.S. and Luttinen, T. (2018) Traffic operations on rural two-lane highways: a review on performance measures and indicators. *Transportation Record Record: Journal of the Transportation Research Board*, n. 2672: p. 66–74. DOI:10.1177/0361198118774743.

ANTT (2020) *Concessões Rodoviárias*. Disponível em: https://www.antt.gov.br/concessoes-rodoviarias. Acessado em: 07 de ago. de 2020.

Bessa Jr., J. E. (2015) *Medidas de desempenho para avaliação da qualidade de serviço em rodovias de pista simples no Brasil*. Tese (Doutorado), Universidade do Estado de São Paulo, São Carlos.

Bessa Jr, J. E. and J. R. Setti (2018) Evaluating measures of effectiveness for quality of service estimation on two-lane rural highways. *Journal of Transportation Engineering, Part A: Systems*, v. 144, n. 9, p. 04018056.1-04018056.10. DOI: 10.1061/JTEPBS.0000178

Catbagan, J. and Nakamura, H. (2006) Evaluation of performance measures for two-lane expressways in Japan. *Transportation Research Record: Journal of the Transportation Research Board*, v. 1988, p. 111–118. DOI:10.3141/1988-16

CNT (2020) *Pesquisa CNT de Rodovias 2019*. Confederação Nacional dos Transportes. Brasília, FD. Disponível em: https://pesquisarodovias.cnt.org.br/downloads/Galeria%20de%20Fotos/2019/Mapas/UF/MG.pFD. Acesso em: 12 de ago. de 2020.

CNT (2021) *Painel CNT do Transporte - Rodoviário*. Confederação Nacional dos Transportes. Brasília, FD. Disponível em: https://www.cnt.org.br/painel-cnt-transporte-rodoviario. Acesso em: 09 de dez. de 2021.

DNIT (2006) *Manual de Estudos de Tráfego*. Ministério dos Transportes, Departamento Nacional de Infraestrutura e Transportes. Rio de Janeiro, RJ

Egami, C. Y. (2006) *Adaptação do HCM-2000 para determinação do nível de serviço em rodovias de pista simples sem faixas adicionais no Brasil*. 240f. Tese (Doutorado). Universidade de São Paulo, São Carlos.

Hollander, Y. and R. Liu (2008) The principles of calibrating traffic microsimulation models. *Transportation*, v. 35, n. 3, p. 347–362. DOI: 10.1007/s11116-007-9156-2.

Lacerda, V. M. (2016) *Estimação da velocidade média em vias urbanas com o uso do microssimulador VISSIM*. Dissertação de mestrado. Universidade Federal do Ceará.

Mon-Ma, M. L. (2008) *Adaptação do HCM-2000 rodovias de pista simples com faixas adicionais típicas do estado de São Paulo*. 73f. Tese (Doutorado em Engenharia de Transportes), Universidade de São Paulo, São Carlos, SP.

Oliveira, J. K. S. (2021) *Adaptação do HCM-6 para análise de rodovias de pista simples sem faixas adicionais no Brasil*. 100f. Dissertação (Mestrado em Geotecnia e Transportes), Universidade Federal de Minas Gerais, Belo Horizonte, MG.

Paula, F. S. M. (2006). *Proposta de adaptação da metodologia do Highway Capacity Manual 2000 para análise de vias arteriais urbanas de Fortaleza.* 158f. Dissertação (Mestrado em Engenharia de Transporte), Universidade Federal do Ceará, Fortaleza, CE.

Pereira, H. M. and J. E. Bessa Jr. (2017) Análise comparativa de métodos para cálculo do nível de serviço em rodovias de pista simples. In: *Anais do XXXI Congresso de Pesquisa e Ensino em Transportes*, Rio de Janeiro, RJ.

Setti, J. R., J. E. Bessa Jr., C. Y. Egami and M. L. Mon-Ma (2011) Adaptação do HCM 2000 para análise da capacidade e do nível de serviço em rodovias de pista simples no Brasil. *Transportes*, v.19, n. 2, p. 66-78. DOI: 10.14295/transportes.v19i2.510

Silva, F. A. (2019) *Determinação do impacto de zonas de ultrapassagens proibidas e de faixas adicionais de subida em segmentos de rodovias de pista simples.* 185f. Dissertação (Mestrado em Transportes), Universidade Federal de Minas Gerais, Belo Horizonte, MG.

Sousa, V. C., J. E. Bessa Jr., J. K. S. Oliveira and F. C. Bethonico (2019) Modelos para obtenção da capacidade e do nível de serviço em rotatórias urbanas. In: *Anais do 33º Congresso de Pesquisa e Ensino em Transportes*, Balneário Camboriú, SC.

TRB (2022) *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis.* Transportation Research Board. National Academies of Sciences, Engineering, and Medicine. Washington, D. C. DOI: 10.17226/26432.

Utimura, F. S., J. R. Setti, C. Y. Egami and M. L. Mon-Ma (2007) Verificação da acurácia de estimativas de nível de serviço em rodovias de pista simples no estado de São Paulo. In: *Anais do XXI Congresso de Pesquisa e Ensino em Transportes*. Rio de Janeiro, RJ.

Van As, C. (2003) *The development of an analysis method for the determination of level of service of two-lane undivided highways in South Africa.* Project Summary. South Africa National Roads Agency Limited.

Washburn, S. S., D. Watson, Z. Bian, T. Luttinen, A. Al-Kaisy, A. Jafari, R. Downling and A. Elias (2018) *Improved Analysis of Two-Lane Highway Capacity and Operational Performance*. Final Report for NCHRP Project 17-65 National Cooperative Highway Research Program, TRB, Washington, Web-Only Document 255.