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Truck Equivalence Factors for Divided, Multilane Highways in Brazil

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Abstract

Trucks represent a high proportion of highway traffic in Brazil and are longer, heavier and have smaller engines than the trucks used in the development of HCM2000. Some users try to account for these differences by combining HCM2000 procedures with truck PCEs from prior versions. Generally, both this crude adaptation and use of the HCM2000 produce unsatisfactory results. This study focuses on estimating truck PCEs for divided multilane highways in Brazil. Truck characteristics (power, weight, etc.) were observed at several weigh stations on multilane highways. A sample of these trucks was tracked along road segments with multiple grades, using GPS units to collect vehicle performance data. Data on traffic composition and truck fleet mix were obtained from 17 toll plazas and a four-class truck classification scheme was created. Afterwards, CORSIM's heavy vehicle performance and car-following models were recalibrated using a genetic algorithm with truck performance data and traffic data collected on a divided multilane highway. The recalibrated CORSIM was then used to derive new PCEs using density as the measure of effectiveness, for scenarios in which grade magnitudes varied between 0% and 8%, with grade lengths between 0.5 and 2.0 km and truck percents ranging from 0% to 50%. Equivalence factors ranged from 1.0 to 10.9 pc. PCE tables for specific grades and for extended segments were created to replace those used in the HCM2000. The results point to the need for development of a Brazilian HCM.

Keywords: Passenger car equivalents; divided multilane highways; truck performance; CORSIM

1. Introduction

Since its inception in 1950, the Highway Capacity Manual (HCM) has become a fundamental tool to analyze highway quality of service. For a long time, the HCM has been used in many countries apart from the United States and Canada. The HCM2000 explicitly recognizes its international influence, incorporating research results from outside North America and making an effort to develop procedures more applicable to other countries. At the same time, the manual warns international users that its procedures and equations may require calibration to local

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conditions, due to possible significant differences in vehicle performance, traffic composition, driver characteristics, road geometrics and control measures [TRB, 2000].

HBS, the German version of the HCM, is the foremost example of adapting HCM procedures to local conditions and practice [Brilon, 1998; Wu, 2009], while retaining the overall concepts of the HCM. In Brazil, the use of the HCM is so widespread that even contracts of highway concession contain clauses mentioning that the concessionaire must assure that no "highway segment will exceed, for more than 50 hours/year, level of service D, as established by the Highway Capacity Manual" [DER-SP, 1997]. The adaptation of the HCM to Brazil has been a subject of research over the last few years. The first studies demonstrated that the direct use of the HCM caused errors in the level of service estimates of divided highways [Demarchi, 2000; Cunha, 2007] and rural, two-lane highways in the state of São Paulo [Egami, 2006; Mon-Ma, 2008; Bessa Jr., 2009]. These studies have shown that one of the main sources of errors in the level of service estimates is the effect of trucks, which account for a significant fraction of rural highway traffic in Brazil. Furthermore, Brazilian trucks are longer, heavier and have poorer performance than the trucks used in the development of the HCM2000 procedures.

This shortcoming has been tacitly acknowledged by users, who have resorted to combining procedures from the HCM2000 with truck equivalents from previous versions [ARTESP, 2000]. Users agree that results obtained from both this approach and from the direct use of HCM2000, however, can be highly unsatisfactory and may not reflect the real quality of service. The objective of the research reported here was to obtain passenger car equivalence factors (PCE) for Brazilian trucks to replace the ones provided by the HCM2000. This paper is structured as follows: a brief review of the literature follows this introduction; then an analysis of the traffic mix and typical trucks found in divided highways in Brazil is presented, followed by a description of the calibration to which CORSIM was submitted to better represent traffic flow in Brazilian highways; afterwards, the paper presents the procedure used for generating the data for this study and finishes with a discussion of the results.

2. Literature review

Vehicles travelling slower than the general vehicle population in a stream can impede the flow and lower the quality of service on a highway. This effect is more severe on upgrades, where speed loss is greater for vehicles with poorer performance characteristics. These impedance effects of slow-moving vehicles (usually trucks) are usually expressed in terms of the number of additional cars which, if added to the stream, would have the same impeding effect as a single truck [McLean, 1989]. This number of cars is called the passenger-car equivalent (PCE) for the truck. The impedance mechanisms associated with trucks derive from them having lower travel speeds. Therefore, it is harder for them to overtake and they require more road space than cars.

Huber [1982] proposed the basic concept for PCE derivation, which consists of comparing a base stream (containing only cars) and a mixed stream containing trucks and cars that present the same quality of service. The traffic stream quality of service is usually assessed by a measure of performance. The choice of the measure of performance depends on the purpose of the PCE derivation. The literature shows that several different measures have been used: the speed of the traffic stream [Huber, 1982; Elefteriadou *et al*., 1997]; the traffic stream density [Huber, 1982; Webster and Elefteriadou, 1999]; the passenger car speed in the stream [Huber, 1982]; and the number of vehicle-hours in the base and mixed streams, which is equivalent to density [Sumner *et al*., 1984]. Simulation has been used to derive PCEs for the HCM since the 1985 edition, as it simplifies obtaining equivalent flows for a wide combination of flows and grades.

Sumner *et al*. [1984] extended Huber's concept to allow the derivation of PCEs for streams with more than one type of truck. This approach requires the adoption of a fixed mix of trucks, which may result in inaccuracies in the estimation of PCEs [Demarchi and Setti, 2003], but is still widely accepted due to the lack of a better method.

3. Method used

Since the objective of the research was to replace the HCM2000 PCEs with PCEs derived for Brazilian divided, multilane highways, the method used for obtaining PCE values was basically the same used in the development of the HCM2000, which uses the traffic stream density to measure the quality of service [Webster and Elefteriadou, 1999]. Basically, the PCE value is obtained comparing two traffic streams with the same density. One of the streams, called mixed stream, consists of p trucks and $(1 - p)$ cars, while the other, called base stream, contains only passenger cars. The PCE of a truck is the number of passenger cars E that would have the same effect as the truck on the quality of service of the traffic stream.

Figure 1 illustrates the concept: for the same density k, q_b is the corresponding flow rate for the base stream and q_m is the corresponding flow rate for the mixed stream. Thus, if one assumes that these two streams present equivalent levels of service, it is possible to write that:

$$q_b = (1-p)\cdot q_m + E\cdot p\cdot q_m \tag{1}$$

Rearranging Equation 1, the PCE for the trucks in the mixed stream is:

$$E = \frac{1}{p}\left[\frac{q_b}{q_m}-1\right]+1. \tag{2}$$

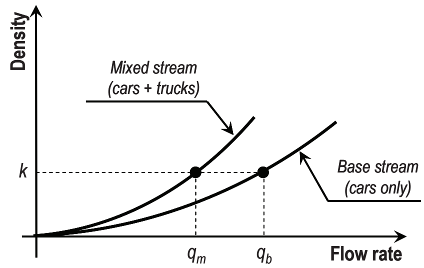

Figure 1: PCE derivation from two traffic streams with the same level of service (measured by density)

A simulation model is used to obtain the density-flow rate curves, because it would be nearly impossible to obtain these data empirically. By using a simulator, it is possible to control both traffic conditions (e.g., the fraction of trucks in the traffic, truck characteristics, etc.) and road geometry (e.g., magnitude and length of grades, number of lanes, etc.). The method used included the following steps:

1. Determine the range of truck percent in the traffic mix for typical divided, multilane highways in Brazil;
2. Characterize trucks travelling on divided highways in Brazil in terms of their performance and mass/weight ratios, both to calibrate the traffic simulator and to estimate the truck mix on these roads;
3. Collect traffic data and calibrate a traffic simulator so that it would be capable of representing the observed behavior of passenger cars and trucks in traffic streams on divided, multilane highways in Brazil;
4. Generate flow rate vs. density function for the scenarios chosen to represent combinations of road and traffic characteristics to obtain PCE for Brazilian trucks; and
5. Define service flow rates for each service level and calculate PCE values.

The next sections of this paper discuss these steps.

4. Characterization of traffic flow on Brazilian highways

Because road transportation plays such a significant role in the Brazilian economy, with more than 60% of all goods being transported by this mode [CNT, 2009], trucks are much more common on Brazilian highways than on North American or European roads. At this stage of the research, the objective was to estimate the range of truck percentages for which PCEs should be provided. Another aspect of interest was to define traffic composition on a typical working day on divided, multilane highways, as well as to determine the performance characteristics of truck configurations typically found on this type of road.

Data for the analysis was provided by ARTESP, the agency supervising the more than 5,300 km of highways operated by private companies in the State of São Paulo. The data consisted of hourly traffic volumes and composition at toll plazas along three of the most important highways in the state: SP330, SP348 and SP310. The region served by these roads generates a significant portion of Brazil's GNP. The network selected for data collection has a total extension of nearly 900 km and contains 17 toll plazas. The traffic data available is disaggregated in 8 toll classes: two passenger car classes (includes pick-up trucks, vans and cars pulling trailers) and six commercial vehicle classes (buses and trucks). Heavy vehicle classes are defined in terms of the number of axles.

Figure 3 shows the range of heavy vehicle percentages observed in the sample. The sample consisted of 148,920 classified hourly traffic counts for 17 toll plazas, covering the period from January 1st to December 31st, 2005. Heavy vehicle percentages ranged from 30% to 40% for nearly half of the observations in the sample. HCM2000 provides PCE values for heavy vehicle percentages varying from 2% to 25%, which represent less than 16% of the cases in the sample. Therefore, there was a clear need to derive PCEs for a greater range of heavy vehicle percentages.

A more detailed analysis was conducted to characterize traffic composition on a typical working day, eliminating the effect of holidays. The adopted approach consisted of selecting only observations made on Tuesdays, Wednesdays and Thursdays that were not holidays or immediately before or after holidays. The typical workday hourly traffic for each toll plaza was obtained using the corresponding average of all observations for each hour of the day. Figure 4 illustrates the results of the analysis, showing the variation of traffic throughout a typical workday for two typical toll plazas. The values shown at the top of the bars in Figure 4 represent the percentage of heavy vehicles during the hour.

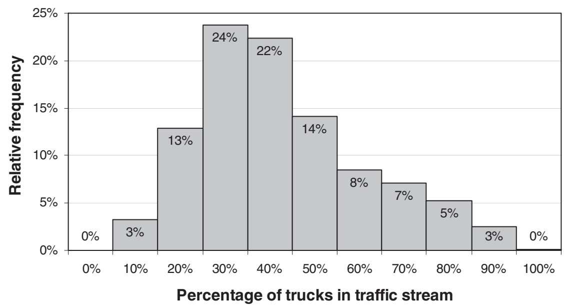

Figure 3: Distribution of observed heavy vehicle percentages in the traffic stream on the highway network used in the study

Figure 4(a) shows the daily traffic variation at a toll plaza representative of those located within the metropolitan region of São Paulo, where the hourly volumes are high and there is significant commuter traffic. Figure 4(b) illustrates the traffic variation at toll plazas located far away from any metropolitan region, thus not carrying commuter traffic. In the first type of location, heavy vehicles represent a smaller fraction of the traffic, due to the high number of passenger cars; in the other case, truck percentages are higher because the volume of passenger cars is smaller.

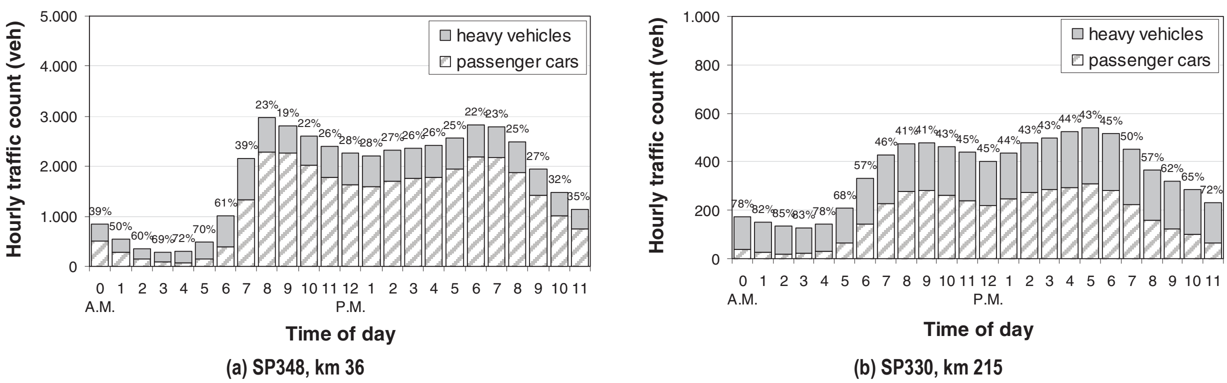

Figure 4: Variation of hourly traffic and traffic composition on a typical workday at two toll plazas: (a) toll plaza located within the metropolitan region of São Paulo; and (b) toll plaza located approximately 180 km from the metropolitan region of São Paulo

The analysis has also shown that the highest truck percentages are found between 8pm and 6am, due to the decrease in passenger car volumes and in overall vehicular traffic. During this period, truck percentages greater than 80% were observed, but with a smaller impact on the level of service, because this is the least congested period of the day. Truck volumes peak during the day from 7am to 7pm making the impact of heavy vehicles on traffic greater during this period of the day.

Heavy vehicle percentages observed between 7am and 7pm on a typical workday ranged from 17% to 50%. Therefore, the analysis indicated that PCE values must be derived for truck percentages between 10% and 50% with the recommendation that, in the absence of local data, heavy vehicle percentages may be assumed to be 30% for sites located within metropolitan regions and 40%, otherwise.

4.1. Truck performance characterization

Another important aspect for PCE derivation is to define the performance characteristics of the design truck (or trucks). The HCM2000 provides PCEs for multilane highways based on trucks with weight-to-power ratio of 100 kg/kW and for freeways, on trucks ranging from 75 to 90 kg/kW.

A study of the characteristics of the truck population on the highways selected for the project was carried out to support the calibration of the simulation model [Cunha, 2007]. The data collected included, among other aspects: gross vehicle weight, individual axle weights, nominal engine power, axle configuration and overall length. Data for 6,253 trucks were collected at several permanent and mobile weigh stations. Given that CORSIM and similar software can only handle four types of heavy vehicles, trucks were aggregated into four truck classes, using cluster analysis [Cunha *et al*., 2008]. Table 1 summarizes the characteristics of each truck class.

Table 1: Typical characteristics of the truck population on divided, multilane highways in Brazil

Truck class	*Number of axles*	*Percentage in fleet*	*Average length (m)*	*Weight/power ratio(kg/kW)*		
				Minimum	*Maximum*	*Median*
Light	2	30%	7	21	165	64
Medium	3 e 4	33%	10	33	269	97
Heavy	5 e 6	33%	15	33	302	144
Extraheavy	7 or more	4%	19	65	283	201

It can be noted that weight-to-power ratio varies widely among configurations and within configurations, thus precluding the use of the sample mean (105 kg/kW) as the weight-to-power ratio of the design truck. This, associated to the fact that CORSIM does not use weight-to-power ratio directly to simulate heavy vehicle locomotion, indicated that a different approach should be taken to derive PCE values for Brazilian trucks. The next section describes the approach adopted for the calibration of the traffic simulation model.

5. CORSIM calibration

The traffic simulation model chosen for the task was CORSIM version 5.1, part of the TSIS software. The choice was due to the use of CORSIM to develop the HCM2000. CORSIM, as any other traffic simulation software, has a set of parameters whose value can be adjusted by users to better represent the local driver behavior and traffic performance characteristics [Dowling *et al*., 2004]. CORSIM's calibration parameter default values were obtained in North America and might not be adequate to simulate traffic in Brazilian highways. Even assuming that the differences between the performance of North American and Brazilian passenger cars are negligible, the range of weight-to-power ratios, as well as possible differences in driver behavior, require the calibration of CORSIM to assure the quality of simulation results.

The calibration procedure used was based on a genetic algorithm (GA), which automatically searches the set of parameter values that best reproduce local traffic conditions. The calibration was carried out in two stages: the calibration of the heavy vehicle performance parameters [Cunha *et al*., 2009] and the calibration of the car-following parameters [Araújo, 2007]. This approach was chosen due to the way that CORSIM simulates the behavior of heavy vehicles on upgrades, which is based on average acceleration for predetermined speed ranges.

To calibrate CORSIM's heavy vehicle performance model, data on instantaneous speeds of trucks traveling along a road segment with several grades of different lengths and magnitudes were collected using differential GPS. A total of 89 trucks were used for the data collection; 8 were classified as light trucks (Table 1); 23 were of the medium truck class; 36 were heavy trucks and 22 were classified as extra heavy trucks. Motorists were approached at weigh scales and asked to drive normally during the data collection, which were carried out under light traffic conditions to assure that the traffic would affect the truck speed as little as possible. For each truck in the sample, a set of curves reflecting the loss of speed along the upgrades was obtained.

CORSIM stores the parameters used to characterize heavy vehicle performance in RT173, as the acceleration that the vehicle can produce for speeds vary from 0 to 110 ft/s, in 10 ft/s steps (12 values). CORSIM also allows the user to use up to four different truck types in a simulation. The calibration procedure consisted of using the GA to search for the best set of RT173 for each truck types separately. The quality of the parameter sets was assessed in terms of the differences between the observed and simulated performance of all trucks in a truck class. A complete description of the calibration procedure is beyond the scope of this paper. Cunha *et al*. (2009) describes the calibration procedure and its results in more detail. Figure 5 summarizes the results, showing the reduction on the mean absolute error ratio (MAER), a measure of the difference between observed and simulated truck speed along a grade, before and after the calibration of CORSIM's heavy vehicle performance model.

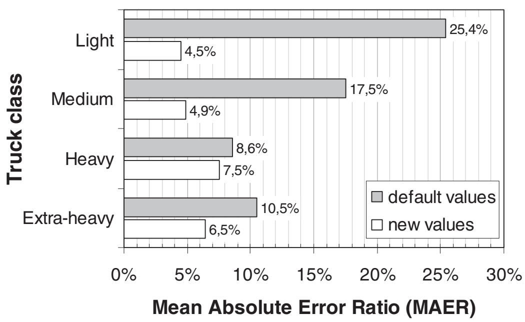

Figure 5: Improvement on CORSIM results after the calibration of RT173 values

In a second stage, the calibration focused on 20 parameters related to the models that define driver behavior. For this purpose, data were collected at a 7.5-km section of SP310 (a divided, multilane highway) on two different days, for five hours each day. The segment carries a mix of local and long-distance traffic, but predominantly the latter. Traffic was observed at 6 different points along the segment to collect data on travel times, traffic flows and traffic composition at each observation station, as well as the origin and destination of a sample of vehicles. Details about the data collection and the calibration procedure can be found in Araújo [2007].

CORSIM parameters selected for the calibration are stored in RT68 (car-following sensitive factors), RT69 (lag to accelerate and decelerate), RT70 (lane change parameters) and RT71 (vehicle type specifications). The performance measures used in the calibration were the average travel speed along the network and average headways at observation points. The calibration was based on a data set that covered 5 hours of continuous observation; the validation used a second data set, collected on a different day, covering 3 hours of continuous observation.

Before the calibration, the difference between observed and simulated flows was 9.1%, as measured by the mean average error ratio; after the calibration, MAER dropped to 6.3%. The validation of the calibrated model was done using a second set of data, collected in the same fashion. MAER, in this case, was 6.6% which was enough to consider the calibration process successful. Having the new set of parameters, the calibrated CORSIM was deemed capable of reproducing the traffic behavior on a typical divided, multilane Brazilian highway. This new version of CORSIM was used to generate the flow-density curves used to derive PCE values, as discussed in the next section.

6. Simulation experiments

The derivation of PCE values using density as a measure of performance requires the generation of flow-density curves for a base stream (passenger cars only) and a mixed stream (cars and trucks) using CORSIM. The truck population in the mixed stream was assumed to be similar to the truck population observed during the data collection: 30% light trucks, 33% medium trucks, 33% heavy trucks and 4% extraheavy trucks. To generate all the data required for PCE derivation, 2,340 scenarios combining the following conditions were used:

- number of traffic lanes: 2;
- free-flow speed (*FFS*): 110 km/h and 100 km/h;
- grade length (*L*): 0.50 km, 1.25 km and 2.00 km;
- grade magnitude (*i*): 0%, 2%, 4%, 6% and 8%;
- truck percentage (*p*): 0%, 10%, 20%, 30%, 40% and 50%; and
- flow rate (*q*): 500, 1000, 1400, 2000, 2100, 2200, 2500, 2900, 3100, 3200, 4050, 4400, and 5000 veh/h.

Figure 6 shows the characteristics of the road section used to simulate the scenarios. It reproduces the typical vertical profiles of highways in the state of São Paulo, characterized by low hills and rolling terrain. Only the middle segment was used to generate data for the flow-density curves used in PCE derivation. As each scenario was replicated 10 times, using different random number seeds, a total of 23,400 simulations were required to generate the data. The simulation runs were controlled by a computer program which was especially created. For each scenario, this program created the input files, called CORSIM to simulate it, and processed the simulation results. Figure 7 illustrates the flow-density curves obtained from the simulation experiments.

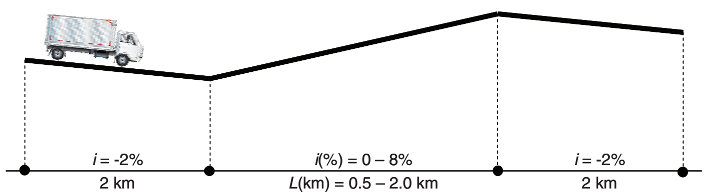

Figure 6: Profile of highway section used for PCE derivation

Figure 7(a) shows that the emerging capacity for base conditions is around 2100 pc/(h.lane). Density at capacity is less clear but was assumed to be 25 pc/(km.lane). Figure 7(b) illustrates the effect of 30% trucks on a traffic stream along a 4%, 0.5-km grade. The simulation experiments show a noticeable reduction in capacity and suggest that density at capacity was close to 25 pc/(km.lane).

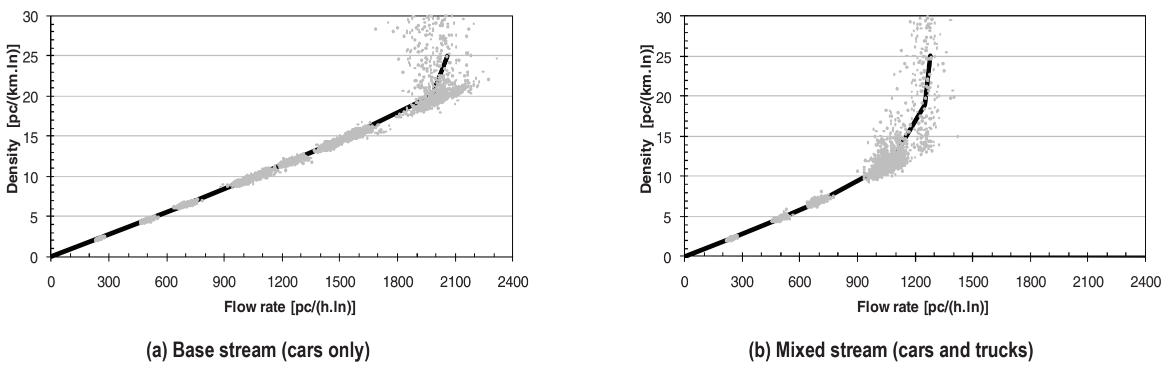

Figure 7: Flow-density curves obtained from the simulation experiments: (a) base stream, *FFS* = 110 km/h, *L* = 0.5 km, *i* = 0% and *p* = 0%; (b) mixed stream, *FFS* = 110 km/h, *L* = 0.5 km, *i* = 4% and *p* = 30%

The literature suggests that PCE values are not constant, but vary, depending on flow rate [Elefteriadou *et al*., 1997; Webster and Elefteriadou, 1999; Ingle, 2004]. Therefore, it is desirable to derive PCEs for conditions close to the limit of each level of service. Based on the density-flow curves obtained from the simulation experiments, thresholds for levels of service A to E and the corresponding service flow rates were defined. Although the HCM2000 criteria for levels of service (LOS) is the current version, it was decided that the 1994 HCM density criteria should be adopted, because it provides homogenous intervals of 5 pc/(km.lane) for levels B to E, given that the density at the capacity was assumed to be 25 pc/(km.lane). Another reason for the use of such criteria is that they are still used by ARTESP, the authority in charge of nearly all rural divided highways in the state of São Paulo (ARTESP, 2002). Table 2 shows LOS criteria adopted in this research.

Table 2: Level of service criteria for divided, multilane highways in Brazil

FFS	*Parameter*	*LOS A*	*LOS B*	*LOS C*	*LOS D*	*LOS E*
110 km/h	Density [pc/(km.lane)]	6	10	15	20	25
	Passenger car speed [km/h]	108	107	103	96	84
	Flow rate [pc/(h.lane)]	650	1070	1550	1920	2100
100 km/h	Density [pc/(km.lane)]	6	10	15	20	25
	Passenger car speed [km/h]	98	97	95	90	80
	Flow rate [pc/(h.lane)]	590	975	1425	1795	2000

7. Results

Tables 3 and 4 provide PCE values derived for divided, multilane highways in Brazil, for free flow speeds (*FFS*) of 110 km/h and 100 km/h. The observation of the results shows two differences from HCM2000 PCEs. First, PCE values found in this study increase, as the level of service worsens instead of being constant, as in the HCM2000. Other studies have also detected the same phenomenon [Elefteriadou *et al*., 1997; Webster and Elefteriadou, 1999; Ingle, 2004]. The second difference is that, in level segments, PCEs increase as the level of service deteriorates and the fraction of trucks in traffic increases. Otherwise, the variation of PCE values found in this study conforms to HCM2000.

Table 3: Passenger car equivalents for trucks in specific upgrades on Brazilian divided, multilane highways, for segments with *FFS* = 110 km/h

		Grade magnitude and length *(km)*														
	Percent	***0%***			***2%***			***4%***			***6%***			***8%***		
LOS	**trucks**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**
A	10%	1.0	1.1	1.1	1.1	1.2	1.4	1.2	1.7	2.8	1.3	3.0	4.5	1.9	4.9	6.3
	20%	1.0	1.1	1.1	1.1	1.3	1.4	1.2	1.7	2.4	1.3	2.5	3.7	1.6	3.9	4.9
	30%	1.1	1.1	1.1	1.1	1.3	1.4	1.2	1.7	2.3	1.3	2.5	3.3	1.5	3.4	4.2
	40%	1.1	1.1	1.1	1.1	1.3	1.5	1.2	1.7	2.3	1.3	2.4	3.2	1.5	3.2	3.9
	50%	1.1	1.1	1.2	1.1	1.4	1.5	1.2	1.7	2.3	1.3	2.4	3.0	1.5	3.1	3.6
B	10%	1.1	1.2	1.4	1.2	1.5	1.8	1.4	2.5	4.0	1.7	4.2	5.9	2.3	6.2	7.9
	20%	1.1	1.2	1.4	1.2	1.6	1.9	1.4	2.4	3.2	1.6	3.4	4.5	2.1	4.6	5.7
	30%	1.2	1.3	1.4	1.3	1.7	2.0	1.4	2.3	2.8	1.7	3.0	3.9	2.1	4.0	4.7
	40%	1.2	1.4	1.5	1.3	1.8	2.0	1.5	2.2	2.7	1.9	2.9	3.5	2.1	3.6	4.4
	50%	1.2	1.6	1.7	1.4	1.9	2.0	1.8	2.2	2.7	1.9	2.8	3.3	2.0	3.4	4.1
C	10%	1.3	1.5	2.0	1.5	2.6	3.0	1.9	3.7	5.3	2.5	5.6	7.9	3.2	8.1	10.0
	20%	1.5	1.8	2.0	1.8	2.3	2.8	2.0	3.1	4.1	2.4	4.3	5.4	2.9	5.6	6.6
	30%	1.7	1.9	2.0	1.8	2.3	2.6	2.1	3.0	3.6	2.4	3.8	4.4	2.8	4.6	5.3
	40%	1.7	2.0	2.0	1.9	2.3	2.6	2.1	2.9	3.3	2.7	3.4	3.9	3.1	4.1	4.8
	50%	1.8	2.0	2.1	2.0	2.5	2.7	2.5	2.9	3.1	2.6	3.2	3.6	2.9	3.9	4.5
D	10%	2.3	2.9	3.2	2.5	3.7	4.2	3.0	4.7	6.5	3.8	6.7	8.6	4.2	8.8	10.9
	20%	2.1	2.6	2.6	2.4	3.0	3.5	2.7	3.9	4.6	3.1	4.9	5.8	3.8	6.0	6.8
	30%	2.2	2.6	2.6	2.3	2.9	3.1	2.8	3.4	3.9	3.0	4.1	4.7	3.5	4.8	5.4
	40%	2.2	2.5	2.5	2.4	2.8	2.9	2.7	3.2	3.6	3.3	3.5	4.1	3.7	4.6	4.8
	50%	2.2	2.6	2.5	2.4	2.9	3.0	2.8	3.3	3.5	3.1	3.5	3.7	3.5	4.2	4.6
E	10%	2.6	3.5	3.9	3.0	4.2	4.6	3.7	4.8	6.3	4.0	7.3	7.9	4.4	7.9	10.1
	20%	2.4	3.0	2.9	2.7	3.3	3.5	2.8	4.1	4.4	3.5	4.9	5.5	4.1	5.5	6.1
	30%	2.3	3.0	2.8	2.6	3.0	3.1	3.1	3.4	3.6	3.5	4.2	4.5	3.6	4.6	4.9
	40%	2.3	2.7	2.6	2.6	3.0	2.9	2.9	3.2	3.3	3.5	3.5	3.9	3.8	4.5	4.6
	50%	2.4	2.8	2.6	2.6	3.0	3.0	2.9	3.4	3.3	3.2	3.5	3.6	3.7	4.0	4.2

Table 4: Passenger car equivalents for trucks in specific upgrades on Brazilian divided, multilane highways, for segments with *FFS* = 100 km/h

		***Grade magnitude and length** (km)*														
	Percent	***0%***			***2%***			***4%***			***6%***			***8%***		
LOS	***trucks***	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**	**0.50**	**1.25**	**2.00**
A	10%	1.0	1.0	1.0	1.1	1.2	1.3	1.2	1.7	2.4	1.4	2.9	3.9	1.7	4.4	5.5
	20%	1.0	1.0	1.0	1.1	1.2	1.3	1.2	1.7	2.3	1.3	2.5	3.4	1.6	3.6	4.4
	30%	1.1	1.1	1.1	1.1	1.2	1.3	1.2	1.7	2.2	1.3	2.5	3.1	1.5	3.3	3.8
	40%	1.1	1.1	1.1	1.1	1.2	1.4	1.2	1.7	2.2	1.3	2.3	2.9	1.5	3.1	3.5
	50%	1.1	1.1	1.1	1.1	1.3	1.4	1.2	1.7	2.2	1.3	2.3	2.8	1.5	2.9	3.3
B	10%	1.2	1.2	1.2	1.3	1.5	1.7	1.4	2.4	3.7	1.7	4.0	5.4	2.3	5.8	7.1
	20%	1.2	1.2	1.2	1.3	1.6	1.8	1.4	2.3	3.0	1.7	3.3	4.1	2.1	4.4	5.1
	30%	1.2	1.2	1.3	1.3	1.6	1.8	1.4	2.1	2.7	1.7	3.0	3.5	2.1	3.8	4.4
	40%	1.2	1.3	1.4	1.3	1.7	1.8	1.4	2.1	2.6	1.7	2.8	3.2	2.0	3.5	4.0
	50%	1.2	1.4	1.5	1.3	1.7	1.9	1.4	2.1	2.5	1.7	2.6	3.1	2.0	3.3	3.8
C	10%	1.3	1.4	1.5	1.6	2.1	2.6	2.0	3.7	4.8	2.3	5.4	7.0	3.4	7.4	9.0
	20%	1.4	1.5	1.6	1.6	2.1	2.6	2.0	3.0	3.7	2.3	4.1	5.0	2.8	5.2	5.9
	30%	1.5	1.8	1.8	1.8	2.1	2.4	2.0	2.8	3.3	2.3	3.6	4.1	2.7	4.4	5.0
	40%	1.7	1.9	1.9	1.8	2.2	2.4	2.0	2.7	3.0	2.3	3.2	3.7	2.7	4.0	4.4
	50%	1.7	1.9	1.9	1.9	2.2	2.4	2.1	2.6	2.9	2.4	3.1	3.5	2.7	3.7	4.1
D	10%	2.1	2.2	2.5	2.2	3.1	3.8	2.5	4.7	6.2	3.3	6.6	8.4	4.5	8.5	10.5
	20%	2.1	2.3	2.4	2.3	3.0	3.3	2.6	3.8	4.5	3.2	4.8	5.6	3.6	5.9	6.6
	30%	2.1	2.4	2.4	2.3	2.9	3.0	2.6	3.5	3.8	3.2	4.0	4.4	3.6	4.8	5.5
	40%	2.1	2.5	2.4	2.4	2.8	2.8	2.6	3.1	3.4	3.0	3.6	4.0	3.4	4.3	4.7
	50%	2.2	2.5	2.4	2.4	2.7	2.9	2.6	3.0	3.2	2.9	3.4	3.7	3.2	4.0	4.4
E	10%	2.2	2.6	3.3	2.8	3.5	3.9	3.1	5.0	6.4	3.3	6.5	8.5	4.8	8.5	10.8
	20%	2.2	2.7	2.8	2.7	3.0	3.5	3.0	3.8	4.7	3.3	5.0	5.5	3.9	5.8	6.4
	30%	2.3	2.7	2.7	2.7	3.0	3.2	3.0	3.7	4.0	3.6	4.1	4.3	3.9	4.7	5.2
	40%	2.3	2.7	2.6	2.7	3.0	3.2	3.0	3.3	3.4	3.3	3.5	3.8	3.5	4.3	4.4
	50%	2.3	2.7	2.6	2.7	3.0	3.2	3.0	3.1	3.2	3.1	3.3	3.5	3.4	4.0	4.3

PCEs to replace those in the table in HCM2000 to use in the analysis of specific grades were obtained from data shown in Tables 3 and 4 and are given in Table 5. Table 6 provides PCEs for extended general segments, according to terrain: level (grades less than 3%); rolling (grades between 3% and 5%); and mountainous (grades between 5% and 7%). The values were also rounded to the nearest 0.5 pc, following HCM tradition. PCEs for extended general segments were obtained averaging PCE values found for LOS C [Rakha *et al.*, 2007].

Table 5: Passenger car equivalents for trucks and buses in specific upgrades on Brazilian divided, multilane highways

Grade	***Grade length***	***Percentage of heavy vehicles***				
(%)	***(km)***	***10%***	***20%***	***30%***	***40%***	***50%***
< 2	≤ 0.50	1.5	1.5	1.5	1.5	1.5
	0.50 – 2.0	2.0	2.0	2.0	2.0	2.0
	≥ 2.00	2.0	2.0	2.0	2.0	2.0
≥ 2-3	≤ 0.50	2.0	2.0	2.0	2.0	2.0
	0.50 – 2.0	2.0	2.0	2.0	2.0	2.0
	≥ 2.00	3.0	3.0	2.5	2.5	2.5
> 3-4	≤ 0.50	2.0	2.0	2.0	2.0	2.0
	0.50 – 2.0	3.5	3.0	3.0	3.0	3.0
	≥ 2.00	5.0	4.0	3.5	3.0	3.0
> 4-6	≤ 0.50	2.5	2.5	2.5	2.5	2.5
	0.50 – 2.0	5.5	4.0	3.5	3.0	3.0
	≥ 2.00	7.0	5.0	4.0	4.0	3.5
> 6	≤ 0.50	3.0	3.0	3.0	3.0	3.0
	0.50 – 2.0	7.5	5.5	4.5	4.0	4.0
	≥ 2.00	9.5	6.0	5.0	4.5	4.0

The range of PCE values in Table 6 is greater than the range of PCEs in HCM2000 (1.5 to 7.5) and narrower than in the 1994 HCM (1.5 to 15.0). This fact has implications for the LOS analysis of highways in Brazil, as the current practice supported by ARTESP in the state of São Paulo is to use the HCM2000 procedure with the 1994 HCM PCEs. PCEs on Table 7, however, are only slightly higher than those presented in HCM2000.

Table 6: Passenger car equivalents for trucks and buses on extended divided, multilane highways in Brazil

Type of terrain		
Level	***Rolling***	***Mountainous***
2.0	3.0	4.5

8. Concluding remarks

In Brazil, the capacity and level of service analysis is carried out using the HCM2000 due to the lack of a local adaptation. Equivalence factors for heavy vehicles have been identified as one of the aspects of HCM2000 that require adaptation to local conditions. Trucks with poorer performance characteristics and higher percentages of trucks in traffic are some of the aspects that should be included in the derivation of PCEs for Brazilian trucks, which was the objective of the research presented in this paper.

The HCM provides PCE values as a function of truck percentage, grade magnitude and grade length. Furthermore, PCE values are derived for a "typical" truck. Therefore, the study initially investigated the percentage of trucks in the traffic on divided, multilane highways in the state of São Paulo. The results suggested that PCEs should be provided for truck percentages varying between 10% and 50%. Instead of a single "typical" truck, the truck population was represented by four truck types, based on data collected at weight stations.

PCE derivation requires the intensive use of simulation. For this study, the CORSIM model was calibrated in a two-phase procedure. Initially, the truck performance parameters were calibrated, using data collected with differential GPS; in the second stage, the car-following parameters were calibrated and validated, using two data sets collected on different days at a 7.5-km segment of a divided, multilane highway. In both stages, the calibration procedure used genetic algorithms to search for the best values for the model parameters.

After the calibrated model was considered capable to satisfactorily simulate the observed traffic behavior, a series of simulation experiments were run to provide data for the derivation of truck PCEs. The method adopted for PCE derivation was as close as possible to the one used in the HCM2000 and the traffic stream density was adopted as a measure of performance. Sets of PCEs for specific upgrades and extended segments were obtained

The PCE values obtained in this study should be taken as preliminary results. It would be desirable to have a greater sample of trucks and data from other highways. Further studies to adapt other aspects of the HCM to Brazilian divided, multilane highways might modify PCE values. The results obtained so far, however, indicate that, besides the need to adapt the HCM to Brazil, the use of the PCEs found in this result may improve LOS estimates.

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