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ORIGINAL ARTICLE

Probabilistic evaluation of design live loads for Brazilian light-duty vehicle parking garages

Avaliação probabilística da carga variável de projeto para garagens brasileiras de veículos leves

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Abstract: Design loads for parking garages should be reviewed every few years due to changes in fleet characteristics and the impact of design loads on carbon emissions by the built environment. Specifically for Brazil, the authors are unaware of existing studies to justify the design values and corresponding exceedance probabilities stated in NBR 6120:2019 – Design Loads for Structures. In this paper, a simplified probabilistic model for live loads in parking garages is presented. A set of updated statistics characterizing the gross curb weight of the fleet in circulation was obtained based on technical specifications and sales reports between 2003 and 2022. These statistics and the probabilistic load model are employed to derive the equivalent uniform design load corresponding to a 30% probability of being exceeded in 50 years, according to the definition stated in NBR 6120:2019 and NBR 8681:2003. The results provide support for a significant reduction of the current design load for light-duty vehicle parking garages, from the current 3.0 kN/m^2 to at least 2.5 kN/m^2. Such a reduction has a significant impact on new building construction costs and carbon emissions and would not compromise the structural safety of parking garages built in Brazil.

Keywords: live load, garage load, Brazilian fleet, light-duty vehicles, design codes.

Resumo: Cargas de projeto para garagens devem ser periodicamente revisadas em função de mudanças nas características da frota de veículos, bem como devido ao impacto nas emissões de carbono do ambiente construído. Especificamente no caso do Brasil, os autores desconhecem estudos que justifiquem os valores de projeto e as probabilidades de excedência preconizados na NBR 6120:2019 – Ações para o cálculo de estruturas de edificações. Neste artigo, um modelo estocástico simplificado para cargas variáveis em garagens e estacionamentos é apresentado. Com base nas especificações técnicas dos veículos e em dados de vendas entre 2003 e 2022, foram obtidas estatísticas para caracterizar os pesos operacionais da frota de veículos em circulação. Estas estatísticas e o modelo probabilístico são utilizados para obter a carga uniforme equivalente que corresponde à probabilidade de 30% de ser ultrapassada em 50 anos, conforme a definição da NBR 6120:2019. Os resultados obtidos fornecem suporte para uma redução na carga de projeto para garagens, dos atuais 3.0 kN/m^2 para pelo menos 2.5 kN/m^2. Tal redução teria um impacto significativo no custo de novos edifícios-garagem/estacionamentos subterrâneos, bem como nas emissões de carbono, sem comprometer a segurança destas estruturas.

Palavras-chave: carga variável, carga em garagens, frota brasileira, veículos leves, normas de projeto.

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1 INTRODUCTION

Technological advances and changes in working environments resulted in rapid urbanization and fast population growth, leading to a rapid increase in vehicle numbers worldwide.

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Survey results in the United States show that the average time drivers spend driving on a typical day is about 1.2 hours, or 5% of the time in a day, which means that private cars usually stay parked the remaining 95% of the time [1]–[4]. Furthermore, each private car typically requires at least two parking spaces: one at home and another at work [5]. Consequently, vast amounts of land must be used to accommodate parking facilities for the ever-increasing vehicle fleet, whether it be on-street parking located on the sides of the road, or off-street parking with enclosed parking lots and multistory, underground or mechanized parking structures. For instance, parking facilities in the United States take up an amount of land roughly equal to the total land area of the state of Massachusetts, and in Europe, the area taken up by parking amounts to at least one-half of the entire land area of Belgium [2], [6].

According to publicly available data from the National Traffic Secretariat (SENATRAN) [7], the state of São Paulo reached 32.3 million registered vehicles in December 2022, between passenger cars, commercial vehicles, motorcycles, buses, trucks, and others. Of those, 19.6 million are passenger cars, which amounts to 32.5% of the registered passenger cars in the entire country. In the city of São Paulo alone, there were 6.2 million registered passenger cars as of December 2022. Considering that the city's population in the same year was approximately 12.2 million people, according to the preliminary results of the 2022 Population Census data collected by the Brazilian Institute of Geography and Statistics (IBGE) [8], this means that there is an average of one car per two people.

The amount of space dedicated to car parking in the city of São Paulo seems to be among its main priorities, even though motorized trips using private vehicles represent only 30,9% of the total daily trips in the city [9], with the remaining being made by public transport, bicycles or by foot. Data from EMBRAESP – a Brazilian private company specializing in real estate consulting – show that residential buildings constructed between 1985 and 2013 in the city of São Paulo have, on average, 1.5 parking spots per residential unit, or one parking spot per 99 m^2 of built area [10]. On the other hand, commercial buildings from the same period have, on average, one parking spot per 77 m^2 of built area [11].

Table 1 shows the total number of parking spaces and built area of residential and commercial buildings from 1985 to 2013 in the city of São Paulo. The total space required by a parking spot (including access lanes) depends on its dimensions and parking angle, but is typically within 23.2 m^2 to 32.5 m^2 (or 250 ft^2 to 350 ft^2) [12]. If we assume the median value of 27.9 m^2 (300 ft^2), it follows that about 28.8% of the gross built area of all real estate developments in the city of São Paulo during this period was dedicated to parking, or 53.5% of the net built area. This means that parking takes up more than half of the usable private space of buildings, which illustrates the relative importance of parking facilities in the built environment, especially in large urban centers.

Table 1. Parking in residential and commercial real estate developments in the city of São Paulo from 1985 to 2013.

Type of building use	Number of parking spots	Gross built area [m^2]	Gross area per parking spot [m^2]	Parking fraction of gross area*	Net built area [m^2]	Net area per parking spot [m^2]	Parking fraction of net area*
Residential	1,150,276	113,644,628	98.8	28.2%	61,626,189	53.6	52.1%
Commercial	107,631	8,287,281	77.0	36.2%	4,013,089	37.3	74.8%
Total	1,257,907	121,931,909	96.9	28.8%	65,639,277	52.2	53.5%

*To estimate the percentage of area dedicated to parking, an average of 27.9 m^2 per parking spot was used.
Data sources: EMBRAESP, datasets made publicly available by the Center for Metropolitan Studies (CEM) in references [10], [11].

Brazilian parking garages are designed to withstand the live loads stipulated in *NBR 6120:2019 – Design loads for structures* [13]. The superseded version of this design code [14], originally published in 1980, specified a design load of 3.0 kN/m^2 to be employed in parking facilities where the gross vehicle weight (GVW) is no more than 25 kN, but presented no further recommendations otherwise. It also specified a load amplification factor for beams and slabs with short spans that could go up to 1.43. The current version of the code [13] expanded these load recommendations, dividing parking garages into five categories according to vehicle weight and specifying different minimum load requirements for each.

For parking garages classified as Category I (that is, for vehicles with GVW ≤ 30 kN), which covers the vast majority of parking facilities, the minimum design load stipulated in NBR 6120:2019 [13] is still 3.0 kN/m^2. At first glance, this load may seem reasonable: if we assume the parking spot dimensions to be $2.2 \text{ m} \times 4.5 \text{ m}$ (which would be quite small but still suitable for compact vehicles), the heaviest allowed vehicle in Category I would produce a uniform load of $30/(2.2 \times 4.5) = 3.0 \text{ kN/m}^2$ distributed over this parking spot. However, a single occurrence of such a heavy vehicle in such a small parking spot is already a rare event, and the likelihood of all the parking spots within the influence area of a structural element being occupied by the heaviest possible vehicle is very small. Thus, without resorting to actual statistical analyses, we can conclude that the exceedance probability of the 3.0 kN/m^2 load given in NBR 6120:2019 [13] is expected to be much smaller than the range of 25% to 35% exceedance in 50 years stated in this code, in agreement with the definitions found in *NBR 8681:2003 – Actions and Safety of Structures – Procedure* [15].

The conservativeness of this design load becomes even more evident when we compare it to the loading requirements of foreign design codes. For instance, the American standard ASCE 7 prescribed a uniform design load of 50 psf (2.39 kN/m^2) for passenger vehicles parking garages up until ASCE 7-98 [16]. This load was then reduced to 40 psf (1.92 kN/m^2) in ASCE 7-02 [17] following the studies of Wen and Yeo [18], which conducted load surveys in nine parking garages in four cities in the states of Illinois and Massachusetts and carried out statistical analyses based on the survey data. The 40 psf minimum live load is still recommended today in ASCE 7-22 [19] and the 2021 IBC [20]. Furthermore, these codes allow for a load reduction of up to 20% for vertical members supporting more than one floor, resulting in a minimum load of 32 psf (1.53 kN/m^2), almost half of the load prescribed by NBR 6120:2019 [13]. It should be noted that ASCE 7-22 [19] does not explicitly state to what exceedance probability the design uniform load corresponds to, but it references Wen and Yeo [18] as a reasoning for the reduction from 50 psf to 40 psf, in which the mean load for a design life of 30 years was considered. If a Gumbel distribution is assumed, this corresponds to an exceedance probability of approximately 43% in 30 years, or 61% in 50 years.

Eurocode 1 [21], on the other hand, divides parking garages into categories F and G. Category F corresponds to traffic and parking areas for light vehicles, with gross weight up to 30 kN – the same as Category I in NBR 6120:2019 [13] – but with a minimum required load to be selected within the range of 1.5 to 2.5 kN/m^2, the former being the recommended value. These loads are backed up by studies such as Marten [22], Schmidt and Heimann [23], and Kemper et al. [24]. Unlike the American standards, no live load reduction is allowed for parking garages in the Eurocodes. Similar to ASCE 7-22 [19], the Eurocodes also make no reference to what return period or exceedance probability their design imposed loads correspond to.

Even though NBR 6120:2019 [13] has the largest parking garage design load among the aforementioned codes, vehicle data indicates that, on average, the Brazilian fleet is smaller in size, lighter, and less powerful than the North-American and European fleets [25], [26]. This is shown in Table 2, which presents a comparison of some key characteristics of the passenger vehicle fleets in Brazil, China, the European Union, India, Japan, Mexico, Saudi Arabia, South Korea, and the United States, all of which are among the top 15 vehicle markets worldwide.

Table 2. International market comparison of passenger vehicle fleet characteristics.

	Brazil (2013)	**China (2014)**	**EU-28 (2015)**	**India (2015)**	**Japan (2011)**	**Mexico (2014)**	**Saudi Arabia (2012)**	**South Korea (2014*)**	**USA (2015)**
Sales [million]	3.0	20.7	13.7	2.8	3.5	0.7	0.4	1.4	7.5
Engine displacement [L]	1.4	1.7	1.6	1.3	1.4	1.8	2.3	2.0	2.4
Engine power [kW]	76	98	93	59	78	95	120	120	149
Curb weight [metric ton]	1.1	1.4	1.4	1.1	1.2	1.2	1.4	1.5	1.6
Footprint [m^2]	3.7	4.1	4.0	3.5	3.7	3.8	4.2	4.2	4.3
Fuel consumption** [L/100 km]	6.8	7.3	5.1	5.3	5.8	6.3	6.8	6.4	6.8
CO_2 emission** [g/km]	154	171	120	123	136	147	158	148	158
Petrol	6%	98%	44%	47%	86%	99%	–	51%	94%
Diesel	0%	2%	52%	50%	0%	1%	–	39%	1%
Hybrid-electric	0%	0%	2%	0%	13%	0%	–	0%	5%
Others	94%	0%	2%	3%	1%	0%	–	10%	0%
Manual transmission	83%	49%	75%	92%	1%	56%	–	2%	5%
Automatic transmission	17%	51%	25%	8%	99%	44%	–	98%	95%

* South Korea footprint reflects 2011 fleet, engine power reflects 2013 fleet.
** Fuel consumption and CO_2 emission tested on the New European Driving Cycle (NEDC).
Data sources: International Council on Clean Transportation (ICCT) Reports [25], [26].

The arguments raised above indicate that there is some margin for improvement in the specification of design loads for Brazilian parking garages. This is particularly relevant to the challenge of promoting sustainability in construction, which demands that engineers reassess their design practices to reduce the embodied carbon of building structures by 10% each year in order to reach a goal of net zero emissions by 2050 [27]. Reexamining loading assumptions might be considered the "low-hanging fruit" for reducing material consumption and CO_2 emissions [28] when compared to improving material design choices and specifications or employing performance-based design methods instead of the conventional design practice. Hence, re-evaluating parking garage loads can have a significant impact toward reducing the embodied carbon of building structures, especially considering the current importance of parking facilities to the built environment, as demonstrated earlier.

In the present study, the minimum design load for light-duty vehicles parking garages (that is, those classified as Category I) given in NBR 6120:2019 [13] is reviewed using a probabilistic load model presented in Section 2. The analysis is limited to Category I parking garages because it is by far the most common category and the data for this weight range is more readily available. In Section 3, the methodology employed to construct a set of statistics, representative of the current state of the Brazilian fleet of passenger cars and light commercial vehicles in circulation, is presented. These statistics are the input of the probabilistic model, along with a set of parameters that describe the temporal variability of the loading process. In Section 4, the probabilistic model is used to obtain the equivalent uniformly distributed loads (EUDL) corresponding to specific exceedance probabilities or return periods, to be used in design code provisions. Results are then compared to the design load given in NBR 6120:2019 [13], and new loading requirements are proposed. The potential savings in embodied carbon due to the proposed load revision are examined in Section 5. The paper is finished with some concluding remarks presented in Section 6.

2 PROBABILISTIC LOAD MODEL FOR PARKING GARAGES

The study of live loads can be divided into two parts: data collection through load surveys and theoretical modeling. The latter can be traced back to the 1950s, with the work of Horne [29]. Although Horne's model was very simplified, ignoring spatial correlation and time variations, it marked the start of theoretical modeling of live loads. The current state of stochastic modeling of live loads, however, is primarily based on the work of Peir [30], who presented a more sophisticated and realistic probabilistic live load model for buildings and applied it employing data from the most extensive field survey up to that date, a load survey of 32 office buildings in London covering a total area of about 160,000 m^2 reported by Mitchell and Woodgate [31]. This model represented the live load on buildings as the sum of sustained and extraordinary loads modeled as Poisson rectangular wave and spike processes, respectively.

Peir's model [30] is also reproduced in the CIB Report 116 entitled *Actions on Structures: Live Loads in Buildings* [32] and in the Joint Committee on Structural Safety (JCSS) *Probabilistic Model Code* [33]. Costa et al. [34], [35] used this model to derive statistics for the average point-in-time and 50-year extreme live load in buildings that are consistent with the definition of NBR 6120:2019 [13] and NBR 8681:2003 [15] and employed these statistics in the reliability-based calibration of partial safety factors in Brazilian design codes.

The live load in parking garages can be represented, similarly to the sustained part of the live load in building floors, as a rectangular wave renewal process, but with a few key differences. First, while in the case of buildings the renewals of the sustained load intensity (pulse height) typically occur once every few years when the tenant or occupancy changes, for parking garages those renewals are much more frequent since usually many vehicles come in and out of the parking facility on a daily basis. Second, the load intensity in parking garages has a non-zero probability p of being in the "off" state in some of the pulses, since the parking spots might be unoccupied for some time, while in the case of buildings the sustained load is always "on" due to the presence of furniture. This means that the arbitrary point-in-time load intensity is represented by a mixed distribution, as shown in Figure 1.

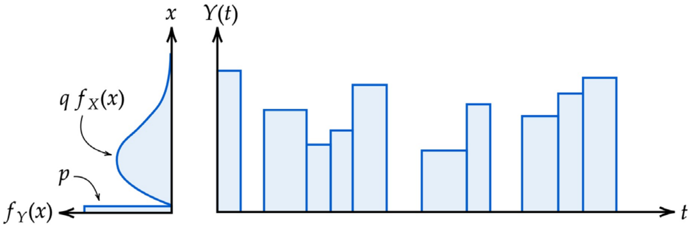

Figure 1. Typical realization of a mixed rectangular wave renewal processes with given probability density function.

A simplified stochastic model for the live load in parking areas is briefly described in the following sections. For more information, the reader is referred to the CIB Report 194 entitled *Actions on Structures: Floor Loads in Car Parks* [36].

2.1 Basic assumptions

Theoretically, one could establish a very sophisticated stochastic model to describe the load caused by parked vehicles in garages. Kemper et al. [24], for instance, employed a model where not only the weight but also vehicle dimensions such as width, length, and wheelbase (the distance between the axles of a vehicle) were treated as random variables, and the position of the car within the parking spot was also randomly determined. The concentrated loads were converted to structural effects and then to equivalently uniformly distributed loads (EUDL) using influence matrices obtained in a finite element analysis software for various configurations of single and continuous-slab systems, and extreme values of the EUDL were obtained via Monte Carlo simulation.

For the sake of determining the extreme value distributions of the load, however, a more refined model should not give considerably different results when compared with a more simplified model [36]. Hence, the simplified model described in the CIB Report 194 [36] is employed in this study. It is based on the following basic assumptions:

a) There are marked parking spots, and they have the same dimensions in the whole car park. This means that the pattern of possibly parked cars is determined;
b) The temporal and spatial variabilities of the loading may be treated independently of each other. This hypothesis may affect the excursion time of the stochastic process over a specified load level, but shouldn't have a considerable impact on the extreme value distribution;
c) The loads in individual parking spots contributing to a load effect are uncorrelated. This hypothesis is similar in principle to the white-noise assumption described in [34] for the sustained load in building floors, and can be considered valid in most cases, save for some very specific situations (for instance, a company that only uses a particular type of car renting a number of adjacent parking spots);
d) The model parameters that describe the spatial and temporal variabilities of the load acting on individual parking spots are the same for the entire car park and depend on its location and intended function (car parks situated in residential areas, office areas, connected to a shopping center, an airport, etc.). Furthermore, it is assumed that these parameters do not change with time. This disregards special conditions that might happen during weekends or holidays, for instance.

2.2 Spatial variability

Vehicles are seldom parked perfectly in a given parking spot – usually, there are deviations from the center of the vehicle and the center of the parking spot. The distances between the axles of the car (wheelbase) and between the centerlines of the tires on the same axle (average trackwidth) also vary from vehicle to vehicle.

Wen and Yeo [18] approximated the vehicle weight as a single concentrated load deterministically applied in the center of the parking spot. Kemper et al. [24], on the other hand, considered the weight distributed over the four wheels of the vehicle, regarding its dimensions as random variables and randomly determining its position within the parking spot using two normally distributed variables that describe eccentricities in both directions. The authors found that disregarding this deviation in the placement of the vehicle led to a slight decrease in extreme load amplitudes, which becomes more negligible the larger the area [24]. The model, suggested in [36] and employed herein, is a compromise between these two approaches, where the vehicle weight Q is deterministically distributed over its four wheels according to the reference arrangement shown in Figure 2.

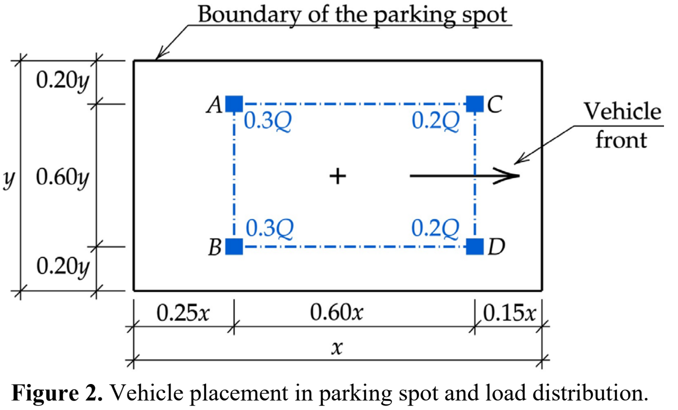

Figure 2. Vehicle placement in parking spot and load distribution.

Typically, different types of vehicles such as cars, buses and trucks are not mixed in the same parking building. Hence, the population of vehicles in a given parking building is usually reasonably homogeneous, and the weights Q_i of vehicles in different parking spots can be assumed to be independent and identically distributed.

2.3 Temporal variability

As discussed earlier, the load at individual parking spots can be modeled as a mixed rectangular wave renewal process (Figure 1). If we conveniently refer to a natural period of variability of 24 hours, the following quantities can be defined:

a) The possible time t_p in a day during which parking is expected to occur. For instance, the possible time for parking garages in residential buildings is 24 hours but is presumably lower for commercial areas, since car parks are often closed during nighttime. Similarly, we can define the number of busy days per year t_y during which parking is expected to occur;

b) The number ρ of cars in a parking spot during a 24-hour interval, which is a random variable with mean $\overline{\rho}$;

c) The dwell time t_u a parking spot is occupied continuously by the same car, which is a random variable with mean $\overline{t}_u$;

d) The total busy time t_d that a parking spot is occupied, which is a random variable with mean $\overline{t}_d = \overline{\rho}\,\overline{t}_u$;

e) The zero time t_0, that is, the difference between the possible time and the busy time, which is a random variable with mean $\overline{t}_0 = t_p - \overline{t}_d$.

The values of the parameters t_p, t_y, $\overline{\rho}$, $\overline{t}_u$ and $\overline{t}_d$ depend on the location and intended function of the parking garage (see Figure 3) and can be empirically estimated by observing the traffic in the car park over a large enough period. Suggested values taken from [36] are given in Table 3. Note that no values are given for the possible time t_p, since it is mainly conceptual and largely dependent on local circumstances.

Table 3. Temporal variability characteristics for different types of car parks.

Location of the parking garage	Number of busy days per year t_y [days/yr]	Mean busy time per day $\overline{t}_d$ [h/day]	Mean dwell time $\overline{t}_u$ [h]	Mean number of cars per day $\overline{\rho}$ [cars/day]
In a residential area	360	17	8	2.1
In a commercial area or an area with offices, factories, etc.	300	8 – 12	3 – 6	1.0 – 3.0
Connected to an assembly hall, to an area with sport facilities, etc.	50 – 360	2.5	2.5	1.0
Connected to an airport, railway station or other building associated with transports	360	13 – 18	10 – 14	1.3

Source: CIB Report 194 [36], from Gross and Rackwitz [37].

2.4 Load effects

Load effects of interest can be computed using the appropriate influence surface $I(x, y)$, where x and y are rectangular coordinates for a point on the floor of a car park. We can define I_i as the weighted sum of the values of the influence surface $I(x, y)$ under the four points A, B, C, and D indicated in Figure 2 for parking spot i, as shown in Equation 1:

$$I_i = 0.3\, I_A + 0.3\, I_B + 0.2\, I_C + 0.2\, I_D. \tag{1}$$

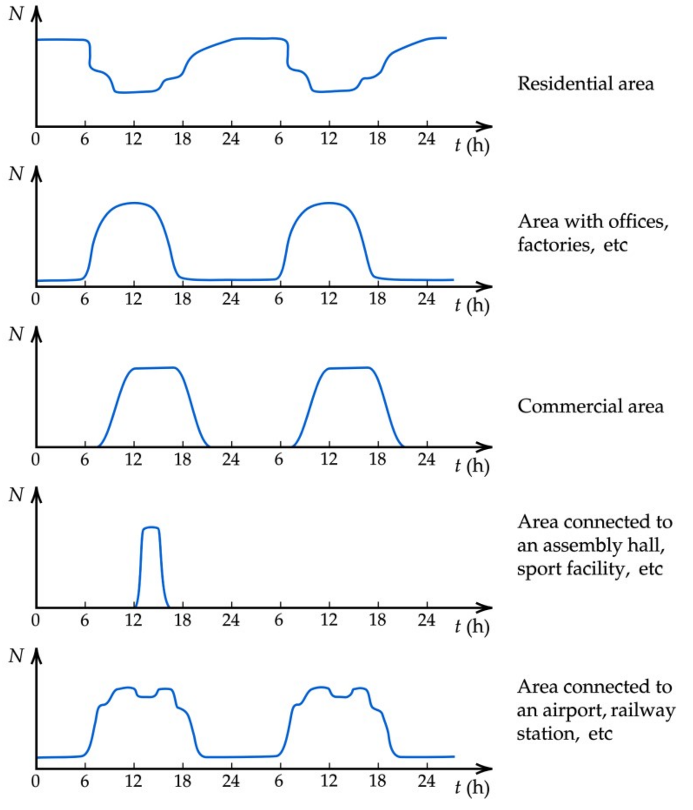

Figure 3. Schematic representations of the daily fluctuations of the total number of parked vehicles (N) in different types of car parks.

The load effect S caused by the weights Q_i of all of the n vehicles that contribute to the considered effect will be given by Equation 2:

$$S = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} I_i Q_i \,. \tag{2}$$

Since the weights are assumed to be identically distributed, it follows that the mean and variance of S are given by Equations 3 and 4, respectively:

$$\mathrm{E}[S] = \mu_Q \sum_{i=1}^{n} I_i \,, \tag{3}$$

$$\mathrm{Var}[S] = \sigma_Q^2 \sum_{i=1}^{n} I_i^2 \,. \tag{4}$$

where μ_Q and σ_Q are the mean and standard variation of vehicle's weights within the considered population. Although the distribution of Q is often assumed to be log-normal or other non-Gaussian distributions [18], [24], [38], the distribution of the load effect S will be close to Gaussian due to the central limit theorem.

2.5 Equivalently uniformly distributed load

Let q be a uniformly distributed load acting on the parking spot i with area A_i. The load effect S_i caused by this load is:

$$S_i = \int_{A_i} q\, I(x,y)\, dA = q \int_{A_i} I(x,y)\ dA = qA_i\bar{I}_i, \tag{5}$$

In Equation 5, the term $\bar{I}_i$ is the mean value of the influence surface $I(x,y)$ over the area A_i, defined as shown in Equation 6 below:

$$\bar{I}_i = \frac{1}{A_i}\int_{A_i} I(x,y)\ dA. \tag{6}$$

If we substitute the vehicle weights Q_i on the n parking spots that contribute to the considered load effect by an equivalent uniformly distributed load q, the total load effect S caused by q would be given by:

$$S = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} qA_i\bar{I}_i\,, \tag{7}$$

The total load effect expressed in Equation 7 would have to be the same as the effect produced by the concentrated loads Q_i (Equation 2). Assuming that all parking spots have the same area $A_i = A$, the mean and variance of S following the definition expressed in Equation 7 are:

$$\mathrm{E}[S] = \mu_q A \sum_{i=1}^{n} \bar{I}_i\,, \tag{8}$$

$$\mathrm{Var}[S] = \sigma_q^2 A^2 \left[\sum_{i=1}^{n} \bar{I}_i\right]^2. \tag{9}$$

If we define the ratio between the weighted sum I_i (Equation 1) and the mean value $\bar{I}_i$ (Equation 6) to be α_i, it follows that:

$$I_i = \alpha_i\, \bar{I}_i. \tag{10}$$

The values of α_i in Equation 10 depend on the load effect considered, the position of the parking spot, and the load distribution between vehicle wheels, but can be assumed to be constant ($\alpha_i = \alpha$) and close to one for most important load cases [36].

The mean and variance of the EUDL q can be obtained by making Equations 3 and 4 equal to Equations 8 and 9, resulting in:

$$\mathrm{E}[q] = \mu_q = \alpha \frac{\mu_Q}{A}, \tag{11}$$

$$\mathrm{Var}[q] = \sigma_q^2 = \alpha^2 \frac{\sigma_Q^2}{A^2}\frac{\kappa}{n}\,. \tag{12}$$

In Equations 11 and 12, κ is a factor given by:

$$\kappa = n\frac{\sum_{i=1}^{n}\bar{I}_i^2}{\left[\sum_{i=1}^{n}\bar{I}_i\right]^2}. \quad (13)$$

If the area A of the parking spot can be considered small in comparison with the total influence area A_{inf} that contributes to the load effect (that is, if the number n of parking spots within the influence area is sufficiently large), then the factor κ in Equation 13 can be approximated as shown in Equation 14 below:

$$\kappa \approx A_{\text{inf}}\frac{\int_{A_{\text{inf}}}[I(x,y)]^2\,dA}{\left[\int_{A_{\text{inf}}}I(x,y)\,dA\right]^2}. \quad (14)$$

In this case, κ will depend only on the shape of the influence surface and not on the arrangement of the parking spots. The values of κ will be the same as those presented in the CIB Report 116 [32], ranging from 2.0 to 2.7 depending on the load effect considered. Similar to the load effect S, the distribution of the EUDL q can also be assumed to be Gaussian.

2.6 Extreme value distribution

The extreme values of the loads in car parks may be determined using Monte Carlo simulation or analytically approximated. The latter approach is used herein, since it is found to provide accurate results with minimal computational cost.

Let $\nu(s)$ be the mean upcrossing rate per hour of a positive barrier level s by the stochastic process $S(t)$. This rate can be expressed as the sum of two components (Equation 15):

$$\nu(s) = \nu_+(s) + \nu_-(s), \quad (15)$$

where $\nu_+(s)$ is the contribution to the effect from cars entering the parking spots with positive influence surface values, and $\nu_-(s)$ is the contribution from cars leaving parking spots with negative influence values. Usually, $\nu_-(s)$ is much smaller than $\nu_+(s)$. Neglecting this term, it can be shown that [36]:

$$\nu(s) = \mathrm{P}[S > s]\sum_{i=1}^{n}\mu_i = \left(1 - F_S(s)\right)\sum_{i=1}^{n}\mu_i\,, \quad (16)$$

where μ_i is the mean number of vehicles per hour entering the parking spot i. Assuming that $\mu_i = \mu = 1/\bar{t}_u$ for all parking spots in Equation 16, it follows that the mean upcrossing rate can be calculated as shown in Equation 17:

$$\nu(s) = \frac{n}{\bar{t}_u}\left(1 - F_S(s)\right). \quad (17)$$

Finally, if independence between different days is assumed, the cumulative distribution of the maximum load effect in T years can be approximated as shown in Equation 18:

$$F_{\max\limits_{[0,T]} S}(s) \approx \exp\left[-\nu(s)\bar{t}_d t_y T\right] = \exp\left[-\bar{\rho} t_y n T\left(1 - F_S(s)\right)\right]. \quad (18)$$

The term $F_S(s)$ in Equation 18 is easily determined, since S is assumed to be normally distributed. A similar expression can be used to obtain the extreme value distribution of the EUDL q.

3 CHARACTERISTICS OF THE BRAZILIAN FLEET OF LIGHT-DUTY VEHICLE

In order to evaluate the extreme live loads in parking garages, it is necessary to have information on the distribution of vehicle weights Q, or at least their moments X and Y, since those are necessary to calculate the moments of the EUDL (Equations 11 and 12). For instance, Wen and Yeo [18] obtained this information directly by surveying nine multistory parking garages in the United States, while Kemper et al. [24] used data from the German Federal Motor Transport Authority (KBA).

Unfortunately, the Brazilian government authorities either do not have this kind of data or do not make it publicly available. A report by the International Council on Clean Transportation (ICCT) [25] says that the average curb weight of the Brazilian fleet of passenger vehicles in 2013 was 1106 kg (Table 2), based on their internal database. There is no information on the standard deviation, however. Furthermore, considering that the Brazilian automotive market has been undergoing a diversification trend in the last few years, slowly moving away from compact vehicles and toward larger and heavier models, as pointed out by Mosquim and Mady [39], [40], it would seem unwise to use outdated data such as this.

In the absence of data, the Probabilistic Model Code by JCSS [33] suggests that the mean weight of light-duty vehicles can be assumed to be about 15 kN, with a coefficient of variation between 15% and 30%. While this estimate may be appropriate for the European market, the Brazilian fleet is much lighter on average, as shown in Table 2. Other peculiar characteristics of the Brazilian automotive market are the preference for one-liter engine vehicles (Figure 4) and the absolute predominance of flex-fuel vehicles since their introduction in the market in 2003 (Figure 5). The data presented in Figures 4 and 5 are available in the Brazilian Automotive Industry Yearbook, yearly published by the Brazilian National Association of Automotive Vehicle Manufacturers (ANFAVEA) [41].

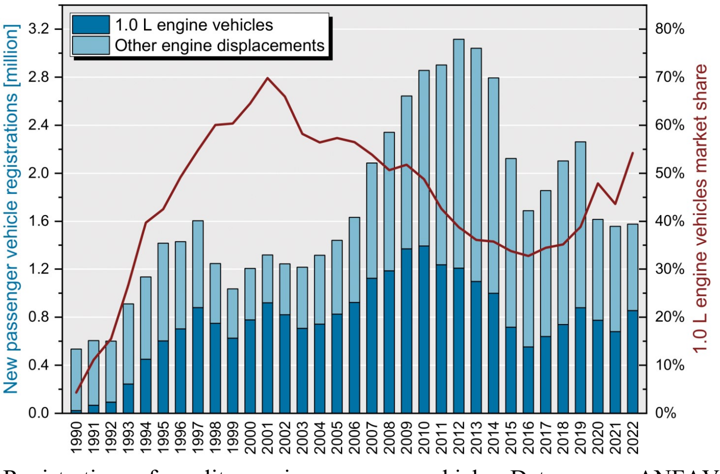

Figure 4. Registrations of one-liter engine passenger vehicles. Data source: ANFAVEA [41].

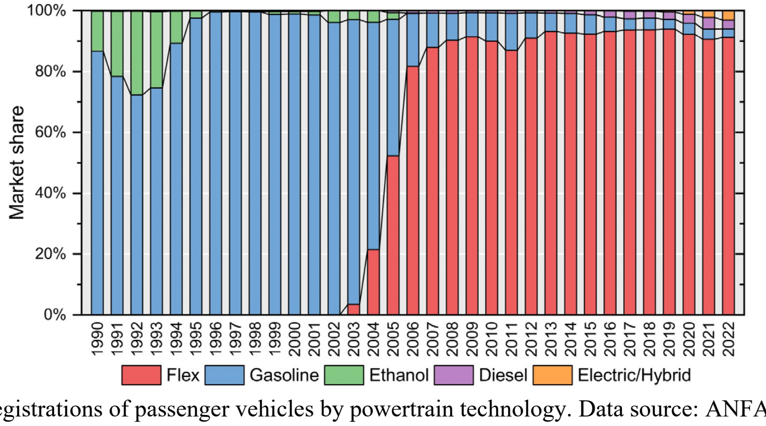

Figure 5. Registrations of passenger vehicles by powertrain technology. Data source: ANFAVEA [41].

Since no suitable data was found in the literature that is both recent and consistent with the characteristics of the Brazilian vehicle fleet, it was necessary to construct our own statistics on vehicle weight. To this end, a database with the characteristics of more than 11500 different vehicles was constructed using data gathered with web scraping techniques from various websites that aggregate the technical specifications of vehicles, such as CarrosNaWeb [42], iCarros [43] and FichaCompleta [44]. To guarantee the consistency of this data, some of it were checked against the information obtained directly from the manufacturers' websites and specialized research magazines. The resulting database is made publicly available as part of this study's findings (see the Data Availability statement).

Next, a second database was constructed with the 50 best-selling passenger car and light commercial vehicle models each month from January 2003 to December 2022. This information is made publicly available by the Brazilian National Federation of Automotive Vehicles Distribution (FENABRAVE) [45]. These best-selling models usually account for 90% to 95% of the total sales volume and can therefore be used to estimate a statistic representative of the entire fleet.

The sales data was then crossed with the vehicle data, associating each best-selling model with an entry in the technical specifications database. Since the sales data is more generic (with entries consisting only of a manufacturer and model name, such as VOLKSWAGEN/GOL), the heaviest vehicle within that model year was selected in the cases where there is more than one version for that model. For instance, the best-selling model in January 2020 is identified as CHEVROLET/ONIX, and the technical specs database has eight different versions of Chevrolet Onix corresponding to the model year 2020, with weights ranging from 1037 kg to 1113 kg, the latter being selected in this situation. Furthermore, some vehicles such as the Volkswagen Gol have different versions with one-liter and larger engine displacements under the same model name. To obtain a more realistic estimate, in these cases the total sales volumes was separated into 1.0 L engine vehicles and vehicles with larger engine displacements following the proportions plotted in Figure 4, and the heaviest version for each category was selected as described earlier.

Following this methodology, it was possible to obtain sales-weighted statistics for many vehicle characteristics such as curb weight (that is, the total mass of the vehicle, including all standard equipment and fluids necessary for regular operation), length, width, height, wheelbase, front and rear trackwidth, engine displacement and power, fuel tank capacity, among others. Some of the results for passenger vehicles are shown in Table 4. The full results for both passenger and light commercial vehicles are available in the repository listed in the Data Availability statement.

Table 4. Characteristics of the Brazilian fleet of passenger vehicles from 2013 to 2022.

Year	Sales Top50 [million]	Sales total [million]	Market share Top 50	Engine displ. [cm^3]	Curb weight [kg]	Length [mm]	Footprint [m^2]	Engine power [kW]	PTWR* [kW/kg]
2003	1.20	1.21	98.8%	1383	1032	3956	3.53	70	0.0638
2004	1.30	1.31	99.0%	1407	1039	3965	3.50	69	0.0637
2005	1.42	1.44	98.7%	1414	1052	3974	3.50	71	0.0645
2006	1.60	1.63	97.9%	1440	1064	4002	3.51	71	0.0646
2007	2.00	2.09	96.0%	1478	1077	4016	3.52	73	0.0644
2008	2.19	2.34	93.5%	1469	1080	4029	3.53	74	0.0654
2009	2.44	2.64	92.3%	1437	1078	4040	3.53	74	0.0654
2010	2.60	2.86	91.0%	1420	1076	4033	3.54	74	0.0659
2011	2.46	2.90	84.9%	1410	1081	4039	3.57	76	0.0678
2012	2.69	3.12	86.4%	1428	1091	4059	3.59	76	0.0678
2013	2.71	3.04	88.9%	1456	1108	4084	3.64	78	0.0683
2014	2.48	2.80	88.7%	1468	1123	4089	3.67	81	0.0690
2015	1.89	2.12	89.1%	1487	1133	4108	3.71	83	0.0707
2016	1.54	1.69	91.2%	1506	1149	4117	3.74	85	0.0716
2017	1.71	1.86	92.2%	1497	1159	4127	3.75	87	0.0729
2018	1.92	2.10	91.2%	1493	1166	4139	3.78	87	0.0729
2019	2.09	2.26	92.6%	1477	1179	4149	3.80	89	0.0730
2020	1.51	1.62	93.2%	1391	1211	4183	3.82	92	0.0737
2021	1.45	1.56	93.0%	1445	1243	4194	3.84	93	0.0722
2022	1.51	1.58	96.0%	1306	1245	4212	3.85	90	0.0704
Cumulative	38.72	42.17	91.8%	1445	1115	4074	3.64	79	0.0682

* Power to weight ratio.

It can be seen that the results obtained for the year 2013 are very close to the values reported by ICCT [25], with a difference of only 0.2% for the curb weight estimate (1108 kg *versus* 1106 kg) and a maximum difference of 2.7% for the engine power (78 kW *versus* 76 kW). This validates the consistency of the methodology employed herein. A monotonic trend of slow increase in the average weight over the last years can be identified, as shown in Figure 6. This trend can be attributed to the market shift toward larger and more powerful vehicles [39], [40] and the (still incipient) electrification of the fleet, since electric vehicles tend to be heavier due to significant battery masses.

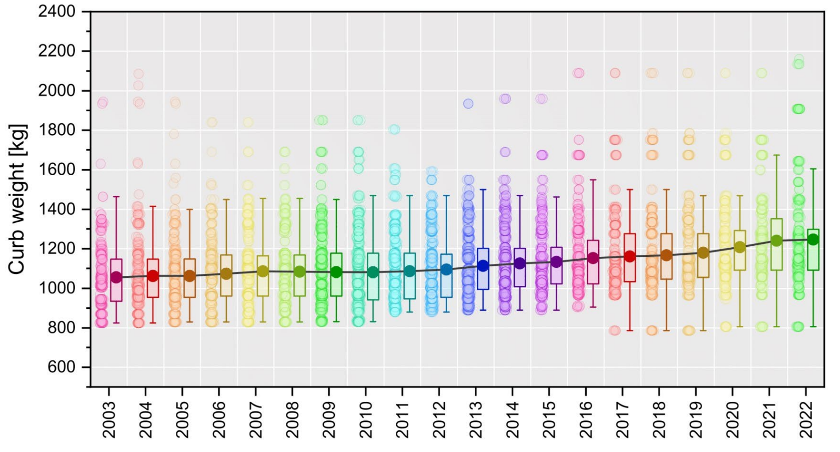

Figure 6. Evolution of the mean curb weight of the Brazilian fleet of passenger vehicles from 2003 to 2022 (each point represents 5000 vehicle sales).

One could simply use the statistics reported in the last line of Table 4, which represent the sales-weighted averages from January 2003 to December 2022. However, these values represent all the vehicles registered in this period, some of which may not be in circulation anymore. As some of the older (and lighter) vehicles stop circulating, the actual overall mean weight is expected to be skewed towards the higher values corresponding to the last few years. Alternatively, one may take μ_Q to be the mean weight of vehicles registered in 2022 as an upper bound, but this might be too conservative.

In order to obtain a more realistic estimate, a middle ground between these approaches is adopted herein. Figure 7 shows the distribution of the ages of passenger vehicles in circulation, according to a report published yearly by the National Syndicate of the Automotive Vehicle Parts Industry (Sindipeças) [46]. By averaging the annual statistics in Table 4 weighted by the relative frequency of each vehicle age, the distribution shown in Figure 8a is obtained for the curb weight of passenger vehicles. It should be noted that since the annual statistics start at the year 2003, the vehicles registered before this year (and therefore older than 20 years) were discarded from the average. This should not be of much importance, since 94.3% of the vehicles have 20 years of age or less. It can be seen that, similar to other studies in the literature [18], [24], [38], the curb weight of passenger vehicles can be reasonably adjusted by a log-normal distribution.

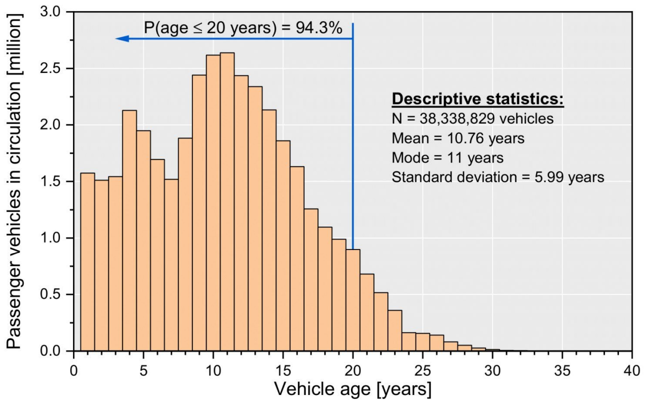

Figure 7. Age distribution of the Brazilian fleet of passenger vehicles in circulation. Data source: Sindipeças [46].

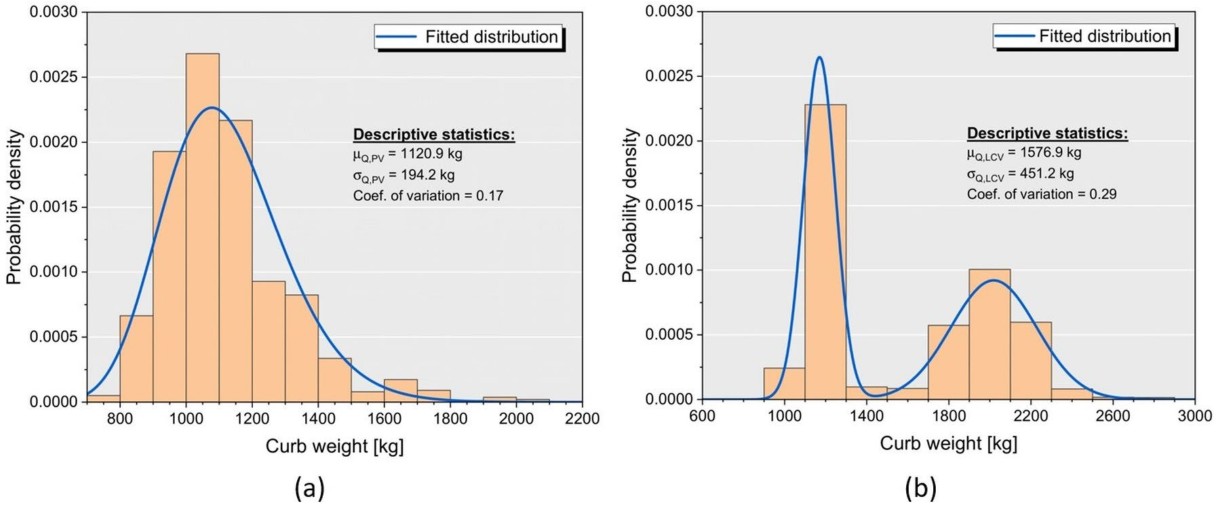

Figure 8. Curb weight distribution of the Brazilian circulating fleet of (a) passenger vehicles and (b) light commercial vehicles.

Following the same procedure of averaging by sales and by relative frequencies of vehicle ages, the distribution shown in Figure 8b is obtained for light commercial vehicles. Unlike the distribution for passenger cars, however, the curb weight of light commercial vehicles is bimodal, being well adjusted by a mixture of two normal distributions. This happens because the best-selling models are very clearly divided into compact pick-up trucks and vans (such as the Fiat Strada, Volkswagen Saveiro, Fiat Fiorino, and others), weighting between 1100 kg to 1300 kg, and medium or large pick-up trucks and vans (such as the Fiat Toro, Toyota Hilux, Chevrolet S10, and others) whose weights are around 2000 kg, with very few models in between. The coefficient of variation is also significantly higher for light commercial vehicles than for passenger cars.

Finally, a fleet-wide statistic can be obtained by constructing a mixture of the two distributions shown in Figure 8, with the weights being determined as the proportions of the fleet that correspond to passenger cars and light commercial vehicles. According to the data from Sindipeças [46], these proportions are around 86% and 14%, respectively. The resulting distribution is shown in Figure 9. While the mean curb weight of the fleet (1184.9 kg) is much closer to the mean weight of passenger vehicles alone, the standard deviation is significantly higher. Furthermore, the coefficient of variation of 25% found herein is consistent with the 15% to 30% recommendation of the JCSS [33] and close to the values obtained by Wen and Yeo [18] (31%) and Kemper et al. [24] (22%).

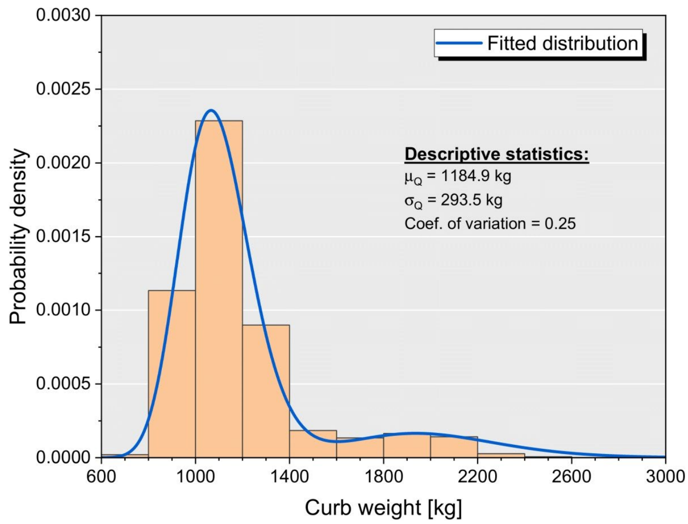

Figure 9. Curb weight of the Brazilian fleet of light-duty vehicles in circulation.

It should be noted that since a simplified analytical model is employed herein, it was not necessary to construct fleet-wide statistics for vehicle dimensions. Nevertheless, if a more refined model were to be used, the distributions of vehicle dimensions (and other characteristics that may be of interest for different kinds of problems) could be obtained using the methodology described in this section and the annual statistics and sales volumes reported in the Data Availability material.

4 DESIGN LIVE LOADS FOR BRAZILIAN PARKING GARAGES

The Brazilian design code *NBR 6120:2019 – Design loads for structures* [13] directly references the text found in NBR 8681:2003 [15] in stating that the nominal values for live loads are established by consensus and "have between 25% to 35% probability of being exceeded, in the unfavorable sense, in a period of 50 years". These exceedance probabilities would roughly correspond to a mean return period between 174 and 117 years, respectively, provided that the annual maxima are independent.

In the present study, we adopt the median of this interval as a reference, defining the characteristic live load as having a 30% exceedance probability in 50 years, corresponding to a mean return period of about 140 years. The characteristic load is herein calculated from the 50-year extremes but could be equally obtained as the mode of the 140-year extreme value distribution or as the $1 - 1/140 \approx 99.3\%$ fractile of the 1-year extremes, since the short time between load changes makes allows the annual maxima to be assumed independent, unlike live loads in buildings [34].

Using Equation 18 and recalling that the EUDL q is assumed to be normally distributed, as a consequence of the central limit theorem, it follows that the extreme value distribution of the maximum EUDL in T years can be approximated by Equation 19:

$$F_{\underset{[0,T]}{\max q}}(x) \approx \exp\left[-\overline{\rho} t_y n T \left(1 - \Phi\left(\frac{x - \mu_q}{\sigma_q}\right)\right)\right], \tag{19}$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function and the EUDL moments μ_q and σ_q are obtained from Equations 11 and 12.

The actual weight of vehicles in parking garages is expected to be higher than the curb weight determined in the previous section, since we have to account for possible additional weight due to passengers and cargo/luggage. Wen and Yeo [18] assumed this additional load to be about 17% of the car's weight, and Kemper et al. [24] found from live measurements that passenger and cargo load corresponds to 18% of the empty mass of the car. Herein, we adopted a weight amplification factor of 20%. Therefore, for the sake of calculating the EUDL moments, the mean and standard deviations of the curb weight are taken as (Equations 20 and 21):

$$\mu_Q = 1.20 \cdot 1184.9 = 1421.9 \text{ kg}, \tag{20}$$

$$\sigma_Q = 1.20 \cdot 293.5 = 352.2 \text{ kg}. \tag{21}$$

We consider initially a parking garage located in a commercial area, with $t_y = 300$ days/year and $\overline{\rho} = 2.0$ cars/day according to Table 3. It is also assumed that $\alpha = 1$, as recommended in the CIB Report 194 [36]. The value of κ can be taken from the CIB Report 116 for live loads in building floors, which recommends the following values:

a) $\kappa = 2.2$ to 2.7 for midspan moments in beams (the low values are valid for simply supported beams and the upper values for beams with both ends clamped);
b) $\kappa = 2.0$ for end moments in beams;
c) $\kappa = 2.5$ for end shear force in beams;
d) $\kappa = 2.2$ for column loads.

Herein, we take $\kappa = 2.4$ as an intermediate value. As for the area A of the parking spot, we initially consider three possible situations, in agreement with the dimensions defined in the Building and Construction Code of the city of São Paulo [47]:

a) Small vehicles: 2.2 m width by 4.5 m length ($A = 2.2 \times 4.5 = 9.9 \text{ m}^2$), ideal for compact vehicles;
b) Medium-sized vehicles: 2.4 m width by 5 m length ($A = 2.4 \times 5.0 = 12.0 \text{ m}^2$), ideal for sedans;

c) Large vehicles: 2.5 m width by 5.5 m length ($A = 2.5 \times 5.5 = 13.75\ \text{m}^2$), ideal for large pick-up trucks and utilitarian vehicles;

The results for each of the parking spot areas are shown in Figure 10, plotted as a function of the number n of parking spots within the influence area that contributes toward the considered load effect. The horizontal line at 3.0 kN/m^2 represents the current design load given in NBR 6120:2019 [13]. The area of the parking spot has a significant influence on the extreme live load. This is to be expected, since both the mean and the standard deviation of the EUDL depend on this parameter (see Equations 11 and 12).

It can be seen in Figure 10 that the nominal load stipulated by NBR 6120:2019 [13] for light-duty vehicles parking garages is rather conservative, being significantly surpassed only for the smallest area and $n = 1$ or 2. It should be noted, however, that there is some form of correlation between the size of the parking spot and the weight of the vehicles that might park in it, since larger and heavier vehicles cannot park in smaller parking spots and should therefore be excluded from consideration when taking the average vehicle weight. Since the overall average weight of the entire population of vehicles is being considered in this analysis irrespective of parking spot area, this correlation is being disregarded, leading to a certain degree of conservativeness in the predicted EUDL for the smaller parking spot.

While not that typical, an influence area so small that it only encompasses one or two parking spots might happen for short-span beams and slabs. However, it does not seem justifiable to maintain such a high equivalent uniform load just to be safe against this particular case, seeing as the 30% exceedance 50-year extreme load resulted significantly smaller for all the other cases.

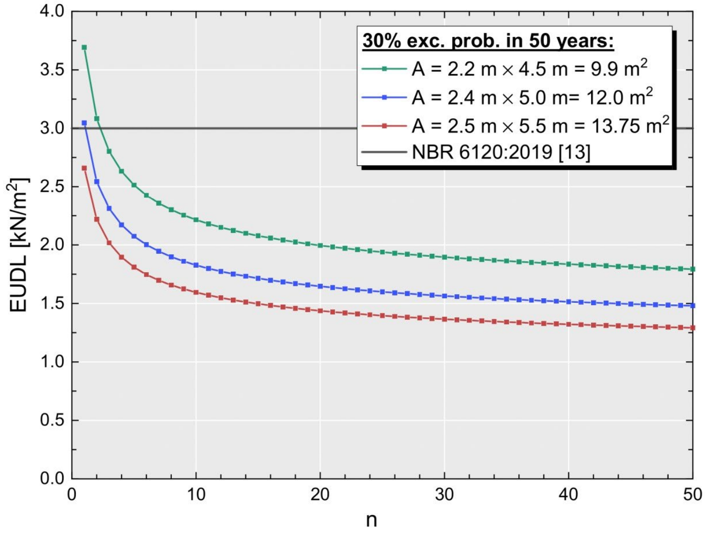

Figure 10. Characteristic live load for Brazilian light-duty vehicles parking garages.

There are more elegant ways of guaranteeing the safety of these structural elements with very small influence areas. The now obsolete NBR 6120:1980 [14], for instance, used to have a load amplification factor for beams and slabs with spans shorter than 5 m and 3 m, respectively, that could increase the uniform design load by up to 43%. The current version of this code [13] states that structural elements should also be checked for the isolated action of concentrated loads in the most unfavorable position, which for Category I parking garages is a single 12 kN load (close to the mean curb weight of the vehicles) acting in a 100 mm x 100 mm region. This is similar to the provisions of ASCE 7-22 [19] and EN 1991-1-1 [21].

4.1 Sensitivity analysis to load effect and temporal parameters

In order to evaluate the sensitivity of the maximum EUDL with respect to the considered load effect, we first adopted $A = 12.0\ \text{m}^2$ corresponding to the parking spot for medium-sized vehicles and calculated the design load for different values of κ, keeping the same temporal characteristics described earlier ($t_y = 300$ and $\overline{\rho} = 2.0$). The obtained results are shown in Figure 11. It can be seen that the sensitivity to the load effect is fairly low, especially for larger values of n, with an increase between 3.2% and 9.7% when κ goes from 2.0 to 2.7.

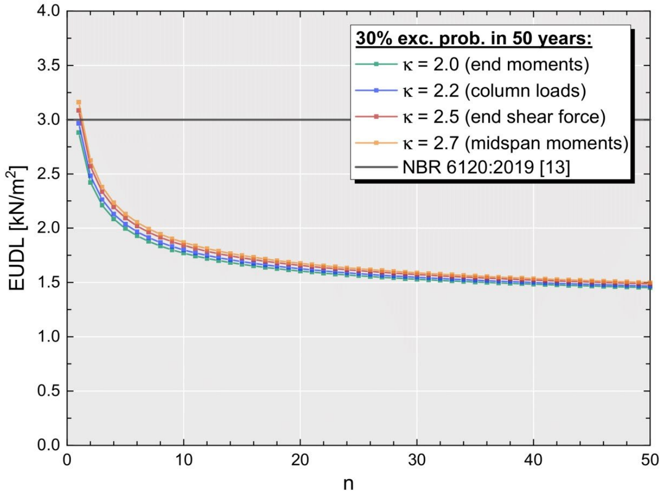

Figure 11. Sensitivity of the 50-year maximum EUDL with respect to the load effect.

As the temporal characteristics are very subjectively estimated, it is also interesting to analyze the sensitivity of the maximum EUDL with respect to these parameters, which is done in Figure 12 by defining $A = 12.0\ \mathrm{m}^2$, $\kappa = 2.4$, and taking $\overline{\rho}$ as 1.0, 2.0, and 3.0, according to Table 3. It is observed that the maximum EUDL is rather insensitive to the variation of $\overline{\rho}$, with an increase of only 1.0% to 3.7% when $\overline{\rho}$ goes from 1.0 cars/day to 3.0 cars/day. Similar results are obtained for the sensitivity of t_y. This means that, despite initially choosing the temporal parameters from Table 3 for a car park located in a commercial area, the results obtained for the other uses listed in this table are expected to be fairly similar to those shown in Figure 10.

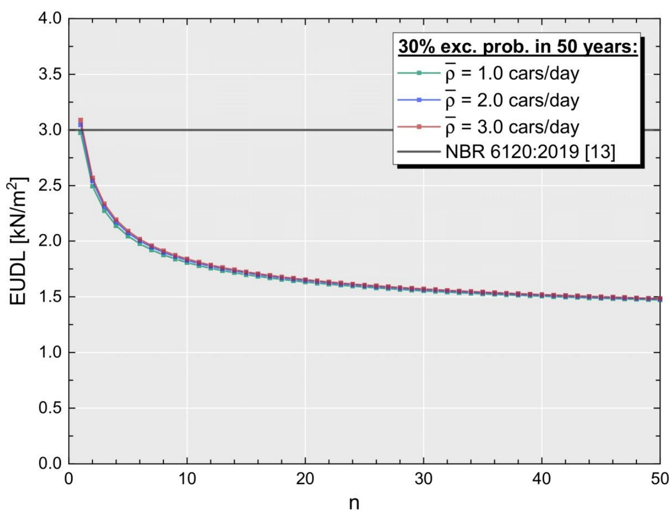

Figure 12. Sensitivity of the 50-year maximum EUDL with respect to temporal parameters.

4.2 Analysis for possible future scenarios

The data we collected for this study shows that electric or hybrid-electric vehicles are not very popular in the Brazilian market. In 2022, they accounted for only 3% of total sales [41] and are a negligible fraction of the current fleet. Despite this, there are expectations of a gradual transition towards electrification in the Brazilian vehicle fleet in the coming years. Because electric vehicles are heavier than internal combustion engine vehicles, it is important to perform a sensitivity analysis that considers different percentages of electric vehicles in the future Brazilian fleet.

ANFAVEA, in partnership with the Boston Consulting Group (BCG), has developed two forecast scenarios for the penetration of electric and hybrid-electric vehicles in the Brazilian automotive market [48]. These scenarios are called "Inertial" (L1) and "Global Convergence" (L2). According to the L1 scenario, xEVs – an umbrella term which includes mild hybrid

(MHEV), hybrid (HEV), plug-in hybrid (PHEV), and pure battery (BEV) electric vehicles – are expected to account for 12% and 32% of total light-duty vehicle sales in 2030 and 2035, respectively. In the L2 scenario, xEVs are projected to account for 22% and 62% of sales in 2030 and 2035, respectively. Despite this expected growth, flex-fuel vehicles are still expected to represent the majority of the future fleet of light-duty vehicles in circulation. Specifically, xEVs are projected to make up 2% to 4% of the fleet in circulation in 2030 and 10% to 18% in 2035 according to scenarios L1 and L2, as shown in Table 5.

Since the database of technical specifications constructed in this study includes a very small number of electric vehicles, the weight of xEVs needs to be estimated. Few studies compare the weight of vehicles by their powertrain technology. Timmers and Achten [49] found that, on average, electric vehicles are 24% heavier than internal combustion engine vehicles (ICEVs), based on their analysis of the literature on non-exhaust emissions of different vehicle categories. In another study, Bauer et al. [50] used an integrative vehicle simulation and modeling framework to perform a Life Cycle Assessment (LCA) of mid-sized European passenger vehicles with different powertrain technologies in 2012, as well as for a projected scenario in 2030. They found similar weight ratios, with HEVs and BEVs being up to 11% and 28% heavier than ICEVs, respectively.

In this study, we assume that xEVs are, on average, 40% heavier than conventional ICEVs. The higher weight ratio is justified on the basis that the average Brazilian ICEV is lighter than the European vehicles used as a base for comparison in the referenced studies. Taking the average weight of vehicles sold in 2022 as a basis (1308.0 kg, considering the contributions from both passenger cars and light commercial vehicles) and considering the forecasted xEV shares for scenarios L1 and L2 [48], the estimated average weights of the fleet in circulation in 2030 and 2035 shown in Table 5 are obtained. These weights are then amplified by a factor of 20% to account for extra weight due to passengers/cargo, and the standard deviation is calculated assuming that the coefficient of variation of 25% found for the present scenario is still valid.

Finally, the EUDL is calculated as before, considering medium-sized parking spots ($A = 12.0\ \mathrm{m}^2$), $\kappa = 2.4$, and $\overline{\rho} = 2.0$ cars/day. The results, shown in Figure 13, indicate that for these parameters, the current design load of 3.0 kN/m^2 is still conservative for all situations except for very small influence areas, even for the most optimistic scenario of electrification (Global Convergence, or L2, by 2035). In this scenario, the EUDL is about 19% larger than the corresponding reference results obtained using the statistics of the current fleet in circulation.

Table 5. Forecasted composition of the fleet in circulation in 2030 and 2035 [48] and corresponding estimated average weights and standard deviations

Year	Current	Inertial (L1)		Global Convergence (L2)	
	2022	2030	2035	2030	2035
xEVs	–	2%	10%	4%	18%
ICEVs	100%	98%	90%	96%	82%
Avg. weight [kg]	1184.9	1318.5	1360.3	1328.9	1402.2
Std. dev. Weight [kg]	293.5	329.6	340.1	332.2	350.5
Avg. weight +20% [kg]	1421.9	1582.1	1632.4	1594.7	1682.6
Std. dev. weight +20% [kg]	352.2	395.5	408.1	398.7	420.7

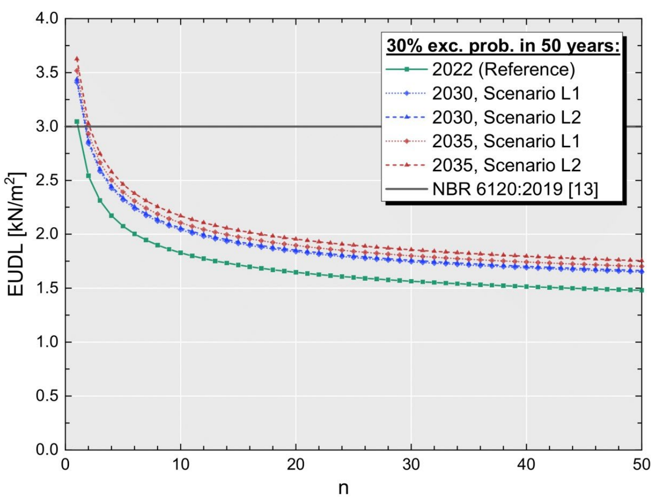

Figure 13. Sensitivity of the 50-year maximum EUDL with respect to forecast scenarios of fleet electrification in 2030 and 2035.

4.3 Recommended design loads

Based on previous results, it seems that the design load of 3.0 kN/m^2 given in NBR 6120:2019 [13] could be safely reduced without compromising the overall structural safety of parking garages, if it is meant to be consistent with the exceedance probabilities prescribed in the same code and in NBR 8681:2003 [15]. Based on the obtained results, the authors recommend that this design load should be reduced to at least 2.5 kN/m^2, maybe even lower. This is an upper bound arbitrarily chosen based on what the authors believe to be reasonable values of n and A (or, in other words, usual influence areas) for typical structural elements in parking garages. The concentrated load, on the other hand, could arguably be increased to somewhere around 15 kN to ensure that elements with very small influence areas are not underdesigned, bringing it more in line with the recommendations given by ASCE 7-22 [19] (13.35 kN) and EN 1991-1-1 [21] (10 to 20 kN, the latter being the recommended value). Area-based live load reduction could possibly also be allowed with reservations for vertical members supporting more than one floor, like in ASCE 7-22 [19], but this requires further analysis and should be discussed with caution.

4.4 Extreme value distributions

Using the probabilistic model described herein, we can also obtain statistics of interest to be used in reliability analyses. For instance, by adopting $A = 12\ \mathrm{m}^2$, $\kappa = 2.4$, and $n = 4$, the distributions for the 1-year, 50-year, and 140-year maxima shown in Figure 14 are obtained. The bias factors (mean/characteristic value) and coefficients of variation are obtained by numerical integration. Since the base distribution is Gaussian, with an exponential tail, the extreme value distribution tends to a Gumbel distribution. For other values of n, the distribution is shifted, but similar values are obtained for the bias factor and coefficient of variation. Comparison with the statistics of 50-year and 140-year extreme live loads in building floors reported by Costa et al. [34], [35] shows that the COV is much smaller for parking garages due to the frequency of load renovations.

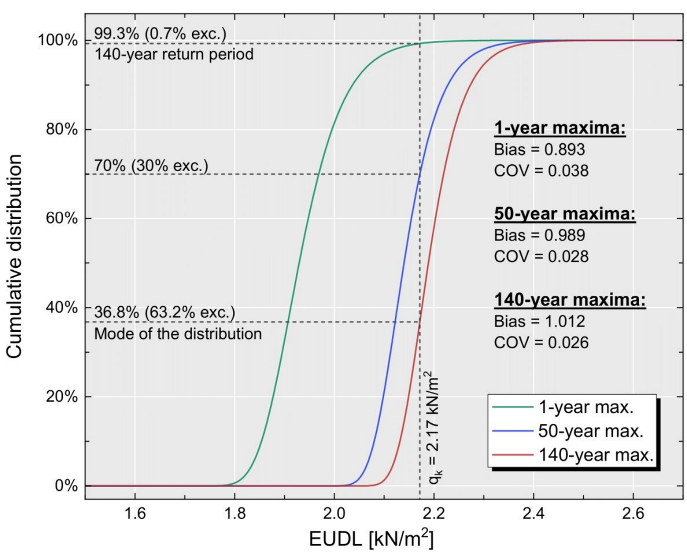

Figure 14. 1-year, 50-year and 140-year extreme value distributions for $A = 12\ \mathrm{m}^2$, $\kappa = 2.4$, and $n = 4$ and corresponding bias factors and coefficients of variation.

5 IMPACTS ON CARBON EMISSION

It is clear that the reduction of design loads has a positive economic impact on the designed buildings. What is often overlooked, however, is the potential savings in embodied carbon that can also be achieved, with engineers mainly focusing their efforts on improving material production [51] and specifications [52] or optimizing their designs [53]–[55].

To illustrate the impacts of reexamining floor loading assumptions on CO_2 emissions, Hawkins et al. [28] optimized the design of a four-story hypothetical reinforced concrete building with flat slabs, regular spans of 9 m, and a raft foundation for different live load values. For each floor loading level, the building was designed to be fully compliant with the provisions of Eurocode 2 [56] concerning both serviceability and ultimate limit states and optimized for minimum embodied carbon using a generative design software. The resulting CO_2 emissions of each design are plotted against the considered live load in Figure 15. The results show a linear relationship between imposed loading and embodied carbon, with savings of 12.6 $kgCO_2e/m^2$ for each 1.0 kN/m^2 reduced (or a 4% reduction over the base case of 3.0 kN/m^2), with most of these savings being attributed to the slabs (6.2 $kgCO_2e/m^2$) and foundations (5.5 $kgCO_2e/m^2$).

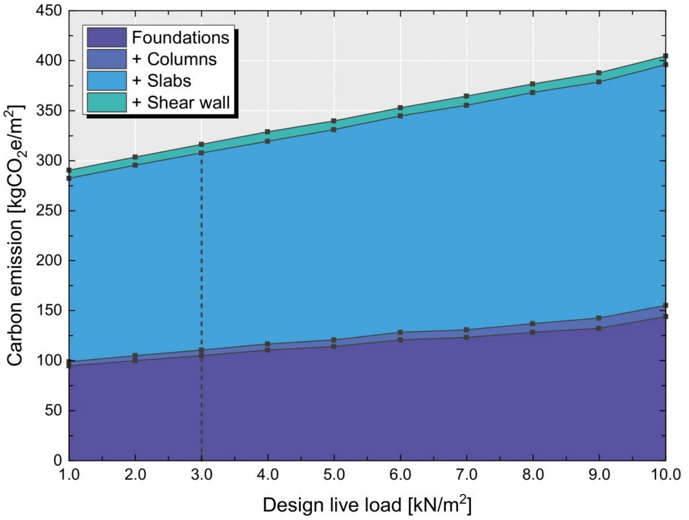

Figure 15. Variation of embodied carbon with design live load for a hypothetical four-story reinforced concrete building with flat slabs. Data source: Hawkins et al. [28].

Since there are many similarities with Eurocode 2, it is reasonable to assume that a similar reduction would be observed for buildings designed using the Brazilian design codes. The load reduction from 3.0 kN/m^2 to 2.5 kN/m^2 proposed herein would then correspond to an estimated carbon saving of about 6.3 $kgCO_2e/m^2$, or 2% over the base case.

While a 2% saving might seem modest, it can make an important contribution if we consider it over all the square meters of parking garages built over the country. According to the Center for Metropolitan Studies (CEM), the formal residential building stock in the city of São Paulo (both horizontal and vertical) amounted to 374.1 million m^2 [57] in 2020, while the commercial building stock was 112.8 million m^2 in the same year [58]. Assuming that the parking fractions of the gross area for residential and commercial buildings presented in Table 1 are valid, this would lead to a parking area of 146.5 million m^2. If the car parks of all those buildings were to be designed for 2.5 kN/m^2 instead of 3.0 kN/m^2, the estimated savings would be approximately 0.92 $MtCO_2$, and that is just considering the formal stock of regularized buildings in one city. To put this in perspective, the total CO_2 emissions of the energy sector in the city of São Paulo in 2021 was close to 11.9 $MtCO_2$ [59]. While it is too late for already existing buildings, this goes to show that reducing design loads is one of the simplest and quickest changes we can make to lower carbon emissions in new buildings in the future, moving toward the net zero emission goal.

6 CONCLUDING REMARKS

In the present paper, the current design live load for light-duty vehicle parking garages given in NBR 6120:2019 [13] is examined using a simple stochastic model that represents the load as a mixed rectangular wave renewal process. Statistics on the curb weight and other vehicle characteristics that represent the Brazilian fleet are obtained by crossing sales volumes data from 2003 to 2022 with a vast dataset of vehicle technical specifications, which are available in a public repository as part of this study's findings. The probabilistic model is then employed to analytically evaluate the equivalent uniformly distributed load (EUDL) corresponding to a 30% exceedance probability in 50 years.

It is found that the EUDL is primarily influenced by the area of the parking spots, being fairly insensitive to the load effect or temporal characteristics of the process, and that the minimum load requirements prescribed by NBR 6120:2019 [13] are somewhat conservative considering the characteristics of the Brazilian fleet. Based on the analyses presented herein, a reduction in the uniform design load for Category I parking garages is proposed, going from 3.0 kN/m^2 to 2.5 kN/m^2. The impact of this change on carbon emissions is also discussed, with estimated savings being around 6.3 $kgCO_2e/m^2$. The apparently meager 2% reduction over the base case is shown to be very significant due to the large participation of parking facilities in the total built environment. Due to the observed trends of market shift toward heavier models and electric vehicles, it is recommended that this analysis is repeated within the next ten years or so.

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