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Impact of speed bumps and raised crosswalks on passenger vehicles speed based on naturalistic data

Impacto de lombadas e travessias elevadas na velocidade de veículos de passeio baseado em dados naturalísticos

Eduardo Cesar Amancio[1,2], Gabriele Tres[3], Manoela Branco Ehlke Silva[3], Paulo Guimarães[4], Jorge Tiago Bastos[3]

[1]Institute for Research and Urban Planning of Curitiba, Curitiba, Paraná – Brazil
[2]Curitiba University of Technology, Curitiba, Paraná – Brazil
[3]Federal University of Paraná, Curitiba, Paraná – Brazil
[4]National Observatory for Road Safety, São José dos Campos, São Paulo – Brazil

contato: eamancio@ippuc.org.br, (ECA); gabrieletres@ufpr.br (GT); manoelaehlke@ufpr.br (MBES); paulo.guimares@onsv.org.br (PG); jtbastos@ufpr.br, (JTB)

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ABSTRACT

The implementation of speed bumps (SB) and raised crosswalks (RCW) has been a popular speed management strategy widely used in Brazil. Despite the imperative speed reduction imposed by such measures, little is known about the practical magnitude of this reduction or even about the speeds practiced in the segments before, during, and after passing through the device. The objective of this work was to evaluate the impact of SB and RCW on passenger vehicles speed practiced in their surroundings. The methodology included (i) the mapping of SB and RCW on structural, priority, and sectorial 1 and 2 roads of the road system in Curitiba (PR); (ii) collection and processing of instantaneous speed naturalistic data from a sample of drivers; (iii) elaboration of speed profiles in the segments before, during and after passing through the devices; (iv) application of criteria for excluding trips from the sample due to confounding factors; and (v) statistical analysis. The segments before, during, and after were defined as three Speed Analysis Ranges (SAR): 1, 2 and 3, respectively. The mean speed in SAR 2 was of the same magnitude as for SB and RCW (26 km/h), as well as for the variation of speed between the SAR 1 and 2 – a reduction about 43%. The speed in SAR 1 was higher on structural roads. Higher speed reductions between SAR 1 and 2 were found for roads with higher hierarchy. There were no statistically significant differences between the two devices for speed compliance distances less than or equal to 30 km/h or 40 km/h, though the average distance was 15.41% greater for 30 km/h and 5.57% higher for 40 km/h in the case of RCW. In terms of urban planning, such information can better support decisions about the implementation and positioning of the speed management device.

RESUMO

A implementação de lombadas e faixas de pedestres elevadas tem sido uma estratégia popular de gerenciamento de velocidade amplamente utilizada no Brasil. Apesar da redução de velocidade imposta por tais medidas, pouco se sabe sobre a magnitude dessa redução ou mesmo sobre as velocidades praticadas nos trechos antes, durante e após a passagem pelo dispositivo. O objetivo deste trabalho foi avaliar o impacto de lombadas e faixas de pedestre elevadas na velocidade praticada de veículos de passeio. A metodologia incluiu (i) o mapeamento de lombadas e faixas de pedestre elevadas em vias estruturais, prioritárias e setoriais 1 e 2 do sistema viário de Curitiba (PR); (ii) coleta e processamento de dados naturalísticos de velocidade instantânea de uma amostra de condutores; (iii) elaboração de perfis de velocidade nos segmentos antes, durante e após a passagem pelos dispositivos; (iv) aplicação de critérios de exclusão de viagens da amostra por fatores de interferência; e (v) análise estatística. Os segmentos antes, durante e depois foram definidos como três faixas de análise de velocidade (FAV): 1, 2 e 3, respectivamente. A velocidade média na FAV 2 foi da mesma magnitude que para lombadas e faixas de pedestre elevadas (26 km/h), assim como para a variação de velocidade entre a FAV 1 e 2 – uma redução de cerca de 43%. A velocidade na FAV 1 foi maior nas vias estruturais. Maiores reduções de velocidade entre FAV 1 e 2 foram encontradas para vias com maior hierarquia. Não houve diferenças estatisticamente significativas entre os dois dispositivos para distâncias de conformidade de velocidade menores ou iguais a 30 km/h ou 40 km/h, embora a distância média tenha sido 15,41% maior para 30 km/h e 5,57% maior para 40 km/h h no caso de faixas de pedestre elevadas. Em termos de planejamento urbano, tais informações podem subsidiar melhor as decisões sobre a implantação e posicionamento do dispositivo de gerenciamento de velocidade.

1. INTRODUCTION

According to the World Health Organization (WHO, 2012), speeding is one of the main risk factors for both the occurrence and severity of crashes. At high speeds, a shorter reaction time is required from the driver, the required braking distance is longer, and the possibility of an emergency maneuver is reduced (Elvik et al., 2009). A suitable speed occurs when it is compatible with traffic safety, based on several aspects, such as physical characteristics of the road, traffic volume, types of road users, environmental issues, and the impact on the quality of life (WHO, 2012).

Speed management consists of a group of measures that aim the at improvement of road safety with the efficiency of vehicle speeds on a road network (WHO, 2012). Therefore, speed management intends to reduce crashes, resulting in a reduction of serious trauma and deaths. A strategy used in urban areas for speed management is traffic calming, which consists of a set of interventions on the roads aimed safety through speed reduction (Gitelman et al., 2016; Jateikiené et al., 2016; Pérez-Acebo et al., 2020). According to Lockwood (1997), the term “traffic calming” can be defined as a group of measures that aim to reduce the negative impacts of motor vehicles, promoting better conditions and greater protection for pedestrians and other non-motorized users.

In some countries, as the United States (Cupolillo, 2006), India (Rokade et al., 2017) and Australia (Candappa et al., 2014; Cupolillo, 2006), this technique is used to reduce problems of accessibility, high motorized traffic, and speeding – factors that affect circulation in urban areas and generate insecurity for pedestrians and cyclists, among other vulnerable users (Vieira et al., 2007). Some of the traffic calming measures involve physical intervention in the roads, such as vertical deflections (with changes in the longitudinal profile of the road) and horizontal deflections (which modify the layout). Both interventions are designed to induce speed reduction and improve driver attention (Kiran, Kumar and Abhinay, 2020). Among the vertical deflections, there are speed bumps (SB) and raised crosswalks (RCW), which are the subject of this paper.

According to Resolution no. 600 of May 24, 2006 of the National Traffic Council - CONTRAN (Brasil, 2006), speed bumps (SB) can be used where there is a need to reduce the speed of motorized traffic, in cases where traffic studies show a high risk of crashes due to speeding and where other traffic engineering measures can not be deployed. According to the same resolution, two types of SB can be used: Type I, to obtain a speed of 20 km/h; and Type II, to obtain a speed of 30 km/h, both when passing through the device. SB was the type of speed calming measure most commonly used in Brazil in the 1990s. As long as there are other traffic calming measures, there are still several SB in Brazilian cities (Barbosa, 2006). Often, SB are deployed based on public demand, mainly in residential areas and school zones, representing an isolated measure without composing a greater traffic calming plan (Barbosa and Moura, 2008a).

In addition to SB, another popular traffic calming measure is the raised crosswalk (RCW), also known as a platform, which is defined by CONTRAN Resolution No. 738 as a location where the pavement is raised in accordance with the criteria and signage outlined in the same Resolution (Brasil, 2018). According to the Traffic Calming Measures Manual of Belo Horizonte Transport and Transit Company - BHTrans, RCW is very effective to controlling the speed of vehicles, reinforcing the preference for pedestrians when crossing the road (BHTrans, 1999).

However, in many scenarios, SB and RCW are deployed without effective control of their traffic calming effect (Vieira et al., 2007). The lack of monitoring and communication of the impacts of traffic calming measures contributes to a limited understanding of public opinion regarding such interventions, as well as makes it difficult for policymakers to adequately justify new interventions. The aim of this study was to evaluate the impact of speed bumps and raised crosswalks on passenger vehicles speed based on the database of the Brazilian Naturalistic Driving Study (NDS-BR). The database contains the monitoring of more than 5,000 km of the real driving task, without experimental control. The work is justified by the potential to contribute to the improvement of the speed management strategy in urban areas by providing more information for monitoring and evaluating these measures. Moreover, the investigation of SB and RCW effectiveness in different road types and through a naturalistic data is scarce.

2. LITERATURE REVIEW

Few studies in the Brazilian scenario investigated the impacts of SB on vehicle speeds. Barbosa and Moura (2008b) evaluated eight SB on streets with low traffic volume in the urban area of Belo Horizonte city (MG). Using speed data obtained with a speed camera, a mean speed reduction of 20.7 km/h was observed, and a mean speed at the device site of 19.5 km/h.

In the international scenario, although the effectiveness of SB in reducing speed is well known, there is considerable amplitude in the values found by different studies. Huang et al. (2011) in a study in China found a reduction in mean speed from 6.7 km/h to 7.0 km/h caused by SB. Also in China, Wang et al. (2017) found a 20% reduction in the mean speed in segments with SB. In a study with sensors for speed measuring installed on the road, including several measures of traffic calming, Barbosa, Tight and May (2000) found values for the median speed in SB around 20 km/h in the city of York, UK. In India, Kiran, Kumar and Abhinay (2020) point out that the speed in SB resulted in an average of 16 km/h for cars, below 15 km/h for commercial vehicles and close to 20 km/h for motorcyclists. In the same study, the speed of cars was kept below 30 km/h for a zone of about 80 m. In China, Wang et al. (2017) found mean speed values when passing through SB corresponding to approximately 20 km/h, so that the speed reduction caused by the device was of the order of 5 km/h, taking as a reference an input speed measured between 10 and 30 m before the SB. Handayani et al. (2020) found an 80.17% reduction in speeds caused by SB. Regarding the zone of influence, the Italian study by Pau and Angius (2001) indicated that speeds remained low in a stretch between 30 and 60 m around the device.

Geometric characteristics of SB were also investigated. Purnomo, Handayani and Syafi'i (2018) concluded that the height of the device showed the greatest correlation with speed reductions. Chandra, Begum and Sekhar (2022) observed that for SB with a parabolic design the vehicle speed at the crown of the SB presented great values (13 to 28 km/h) than for those with circular design (5 to 21 km/h). Reduction in crashes was also a well established point regarding SB implementation (Gyaase et al., 2023).

In Spain, Gonzalo-Orden et al. (2018) measured the speed of vehicles before, during, and after passing through a series of speed reduction devices, including RCW. The analysis was performed regarding the median and 85th percentile speed. The authors found a reduction of 10 km/h in the median and 85th percentile speeds, followed by an increase in speed to values above the speed limit. Badiger, Kuldeep and Anjaneyappa (2022) in a study conducted in India concluded that buses showed the biggest reduction in speed caused by the presence of RCW (34.9%), and motorbikes showed the smallest reduction (22.8%). Passenger vehicles presented a reduction about 33.9% in speed. In addition, pedestrians are more likely to cross the road in places where RCW are installed (Candappa et al., 2014; Torres et al., 2020). The association of these two effects explains the reduction in the number of crashes involving pedestrians. Jateikiené et al. (2016) analyzed the impact of RCW in reducing crashes. The results showed a 65% reduction in non-fatal crashes and an 83% reduction in fatal crashes.

The most suitable distance between two traffic calming measures (TCM) was also investigated. After a study in Poland and Spain Pérez-Acebo et al. (2020) recommended a maximum distance of 200 m between TCM's for a 85th percentile of speed under 50km/h, and 75 m for a value of 40 mk/h. In addition, Gitelman et al. (2016) found that the association between RCW and SB produces a positive effect on increasing pedestrian safety.

Despite this well-know reduction effect on vehicle speed caused by SB and RCW, studies using naturalistic data to investigate this effect are scarce, especially in Brazilian scenario. According to van Nes et al. (2019), the naturalistic study is a research methodology in the field of road safety that allows the analysis of several factors associated with the driver's behavior, the vehicle, and the environmental conditions. In the naturalistic study, it is possible to obtain real driving data, as the participating driver's vehicle is equipped with cameras, GPS (Global Positioning System), and other sensors, where the driver's actions are recorded in order to perform a later analysis.

NDS have been used internationally since the 2000s, including initiatives in the United States (Neale et al., 2005; Njord and Steudle, 2015), Europe (van Nes et al., 2019), Canada (CNDS, 2021; Marshall et al., 2013), Australia (ANDS, 2017; Larue et al., 2018), China (Zhu et al., 2018), Japan (Uchida et al., 2010) and Iran (Sheykhfard et al., 2021). In order to reproduce an NDS in a low- or and middle-income country, a low-cost naturalistic data collection platform (NDCP) was developed for the analysis of human and environmental factors, as part of the first Brazilian Naturalistic Driving Study (NDS-BR). The scenario of the NDS-BR was the city of Curitiba (PR) and its metropolitan region, in a predominantly urban area. The monitoring was carried out through a platform for collecting naturalistic driving data, which allowed the georeferencing of the routes and the acquisition of instantaneous speed data by a sample of drivers.

3. METHODOLOGY

3.1. Study area

For this study, the roads of the structuring axis, priority roads, and sectoral roads 1 and 2 were used, according to the road classification system of the city of Curitiba, based on Municipal Law no. 15.511 of 2019 (Curitiba, 2019). According to this municipal legislation, the structuring axis are areas where the expansion of the traditional center occurs, which is based on the road system (arterial roads), zoning, and transport. In relation to the priority roads, these are characterized by a large volume of traffic and connections between the structural axes and other streets of the road system, discouraging the presence of parking spaces on these roads. On the other hand, the sectoral roads 1 are classified as long-distance roads, covering several regions of the city and also the municipalities of the metropolitan region. These roads have great importance in the integration and articulation of the road system. In relation to sectoral roads 2, which are roads or parts of roads connecting the metropolitan region to Curitiba, as part of the old city accesses, whose parameters of land use and occupation need to respect the limitations of the road structure. In Figure 1, it is possible to observe the location of arterial, priority, and sectoral roads 1 and 2 and the location of the mapped devices.

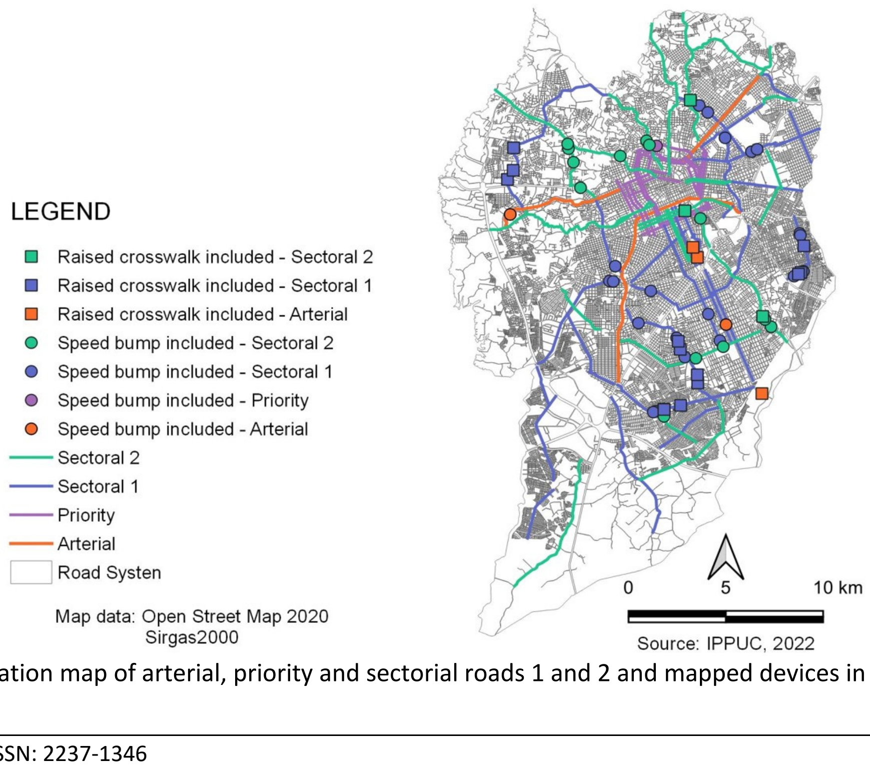

Figure 1. Localization map of arterial, priority and sectorial roads 1 and 2 and mapped devices in Curitiba, Brazil

Due to the unavailability of a georeferenced base of SB and RCW for the city of Curitiba, a mapping of these devices was first carried out with Google Earth, using the Street View tool (Google Earth, 2021). Further, it was necessary to import the road system database provided by the Institute for Research and Urban Planning of Curitiba (IPPUC, 2015) to Google Earth with the road type in shapefile format. From this data, all the roads characterized in the IPPUC database, such as those mentioned earlier, were remotely analyzed with the Street View tool.

3.2. Naturalistic Data Collection Platform (NDCP)

The Naturalistic Data Collection Platform (NDCP) was constituted by the following equipment: 01 USB GPS, with INF-GT62, in order to record geographic coordinates and instantaneous speed, 03 Webcam HD cameras, with USB connection (Universal Serial Bus), for recording images; 03 magnetic vehicle holders with silicone suction cups, to fix the cameras inside the vehicle (data collection system); 01 laptop, to process the images of the cameras and coordinates from the GPS (data storage system); and 01 voltage inverter 500 W 12 V to 110 V, to power the laptop battery (electric supply system). The frequency of GPS records was 1 second. Figure 2 contains a schematic representation of the data collection platform being built.

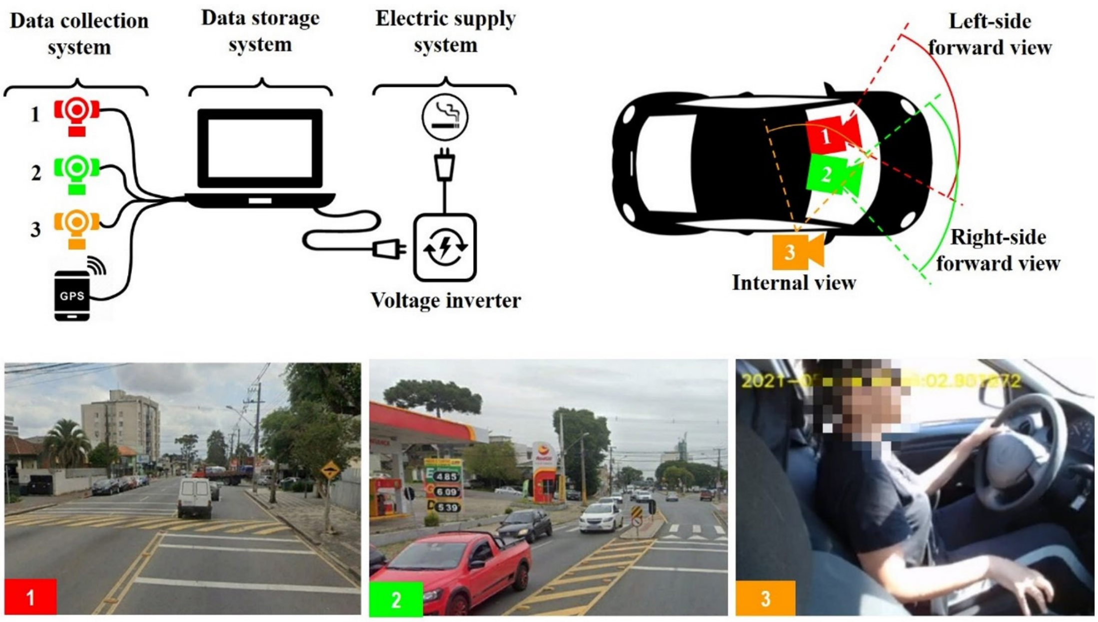

Figure 2. Naturalistic data collection platform (NDCP), cameras positioning and images captured

Cameras 1 and 2 were positioned to capture the environment outside the vehicle, one for the right side and the other for the left side in order to record the roads, the environment and their characteristics. Camera 3, on the other hand, was used to capture the driver's interactions with the steering wheel, gearshift, and vehicle dashboard. It is important to point out that no audio recordings were made, in order to preserve the privacy of the drivers. More information on NDCP can be found in Bastos et al. (2020; 2021).

Data processing was performed using electronic spreadsheets and the free software QGIS (QGIS Development Team, 2021). Speed profiles were created in electronic spreadsheets, with the distance traveled and speed at each point in the approach, passage, and distance from the traffic calming device, as described in the following section.

3.3. Drivers' profile

A total of 16 drivers were recruited to participated in the study. An amount equivalent to 50 USD was paid to each driver. Table 1 shows some demographic information and the collection period of each driver.

Table 1: Demographics and collection period of each driver

Driver	Demographics			Collection period		
	Age	Gender	Driver license experience (years)	Begin	End	Duration (days)
C1	31	F	9	24th August 2019	6th September 2019	13
C2	38	M	<1	07th September 2019	19th September 2019	13
C3	19	M	<1	22nd September 2019	30th September 2019	9
C4	23	M	4	29th October 2019	13th November 2019	16
C5	38	F	21	24th August 2019	06th September 2019	13
C6	25	M	7	07th September 2019	20th September 2019	14
C7	43	M	16	23rd September 2019	29th September 2019	7
C8	31	F	8	30th September 2019	08th October 2019	10
C9	28	M	7	21st November 2020	08th December 2020	18
C10	60	M	35	23rd November 2020	05th December 2020	13
C11	27	F	9	25th January 2021	06th February 2021	13
C12	45	F	25	15th February 2021	01st March 2021	15
C13	21	F	1	19th February 2021	13th March 2021	23
C14	32	M	14	12th December 2020	20th December 2020	9
C15	47	F	22	10th January 2021	24th January 2021	15
C16	26	M	2	10th January 2021	24th January 2021	15

Drivers' ages varied from 19 to 60 years, and driver's license between 1 to 35 years. The collection period was initiated in August 2019 and ended in February 2021. To guarantee usual drivers performance and realistic driving behavior each driver used his/her own vehicle. Also, information regarding the objective of the research was not provided to drivers to avoid study bias. All vehicles had manual gear transmission.

3.4. Analysis of traffic calming devices

A segment of 100 meters before and 100 meters after the device was considered to analyze its influence on the vehicle speed. This value was based on similar analysis found in the literature, which indicated that this 100 meter buffer is sufficient to include a speed profile within the devices' zone of influence (Pau and Angius, 2001; Barbosa and Moura, 2008a; Kiran, Kumar and Abhinay, 2020). The reference studies used to adopt this range of analysis did not consider different road hierarchies and speed limits, even though all of them were also carried out in urban areas. The considered range (100m) satisfied the larger influence distances found in the literature. As can be seen in Figure 3, the zero point represents the device and from there this segment was divided into three other Speed Analysis Ranges (SAR). First SAR occurs when the driver is between 100 m and 50 m before the device. Second SAR occurs when the driver is between 25 m before and 25 m after the device. Finally, the third SAR occurs with speeds recorded between 50 m and 100 m after the device.

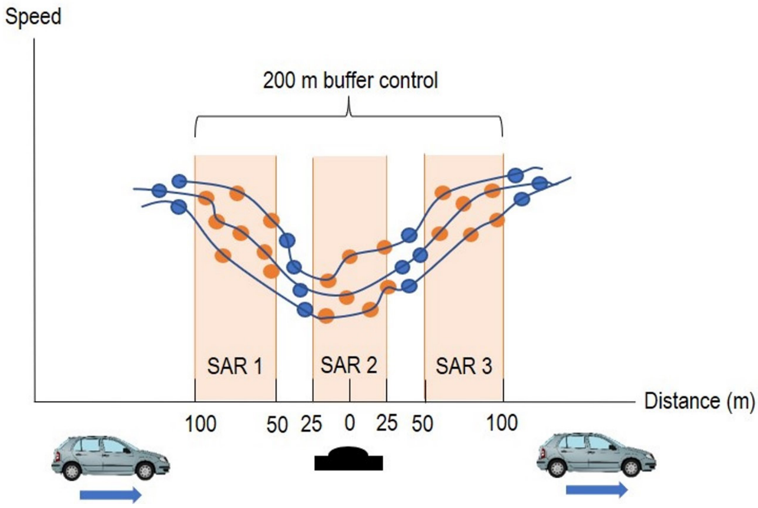

Figure 3. Distances from devices for each Speed Analysis Range (SAR)

Flow chart in Figure 4 shows the process to create the speed profile and descriptive statistics from naturalistic data and traffic calming device's location.

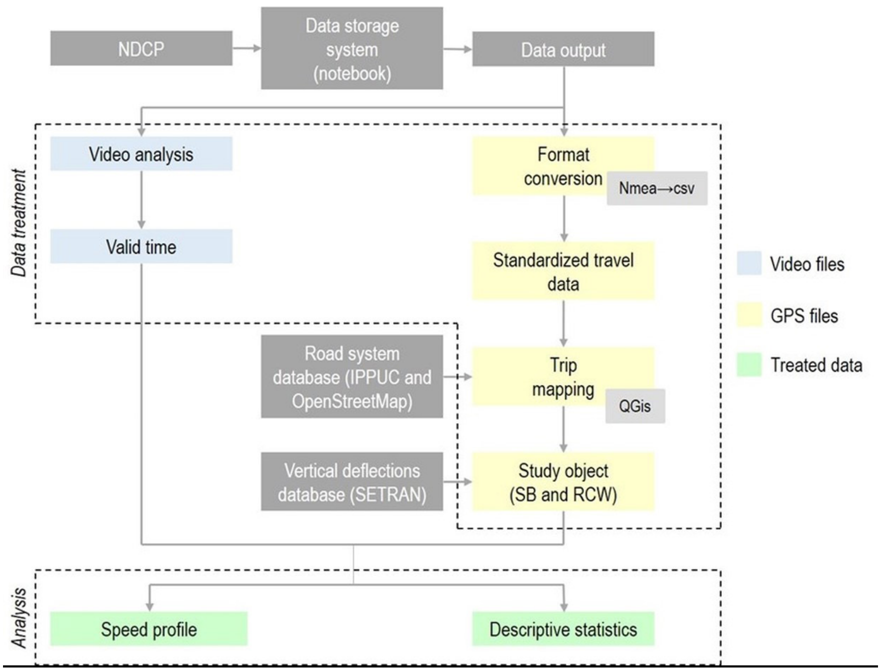

Figure 4. Flow chart of naturalistic data analysis

3.5. Data processing

Speed profiles were created through graphs that relate the speed in kilometers per hour (km/h) and the distance from the device in meters (m). In Figure 5, it is possible to observe an example of a speed profile with two trips in SB 62 of a sectoral road 1 and the marks of 100 meters before and 100 meters after. Lines X2 and X22 represent the trips number 2 and 22 of driver X, respectively. As can be seen, the profile for SB presents the following pattern: an approach at a higher speed, followed by a decrease in speed when passing through the device, and an increase in speed again after passing the SB.

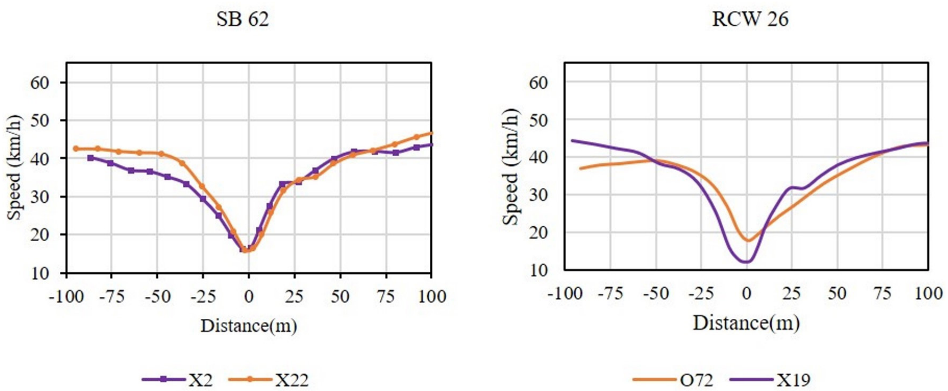

Figure 5. Speed profile on SB 62 (Sectoral road 1) and on RCW 26 (Sectoral road 1)

A speed profile at the raised crosswalk (RCW) 26, located on a sectoral road 1, where the demarcation of the segment 100 meters before and 100 meters later is also shown in Figure 5. The line O72 represents the trip 72 of driver O, similarly X19 represents the trip number 19 of driver X. In the speed profile it can be seen that there is a considerable speed reduction when the driver passes through RCW, reaching the initial speed again after the device.

After the elaboration of all profiles for all SB and RCW with recorded trips, the valid data was filtered. This step involved checking the speed profile created for each device. In cases where the speed profile showed a pattern different from that shown in Figure 5, for example, with speeds close to zero, the video verification allowed us to identify that such interferences were generally associated with stopping at traffic lights with red light indication, turning maneuvers, speed reductions caused by pedestrian crossings, devices in sequence (not properly spaced) and congestion. Aiming to isolate the influence of the device in speed choice, all trips with these situations in the stretch between 100 m before and 100 m after the device were excluded from the analysis.

Initially, 150 SB and 68 RCW were identified in the road system to be analyzed. Most of the devices mapped were located on sectoral roads 1 or 2 (95% in the case of SB and 65% in the case of RCW). From 150 SB only 37 had passages of drivers with valid data, being 02 on arterial roads, 02 on priority roads, 20 on sectoral 1 and 13 on sectoral 2 roads. Meanwhile, from 68 RCW, only 18 had valid trips, being 03 on the arterial roads, 12 on the sectoral 01 and 03 on the sector 2 roads. After applying the previously mentioned trip exclusion criteria, 33 SB and 14 RCW remained, totaling 47 devices. It analyzed 75 speed profiles for SB and 29 for RCW, totaling 104 speed profiles analyzed. The distribution of this sample by road type can be seen in Table 2.

Table 2: Amount of vertical deflections and trips according to road type

Road type	Vertical deflections			Trips		
	Speed bumps (SB)	Raised crosswalks (RCW)	Total	Speed bumps (SB)	Raised crosswalks (RCW)	Total
Arterial	02	03	05	11	04	15
Priority	01	00	01	06	00	06
Sectorial 1	18	08	26	35	17	52
Sectorial 2	12	03	15	23	08	31
Total	**33**	**14**	**47**	**75**	**29**	**104**

3.6. Statistical analysis

The Anderson-Darling normality test was used to check the statistical distribution of the data in each analysis. For cases in which the normal distribution was not identified, nonparametric comparison tests were applied. As for all the analyses carried out, it was identified that the data distribution did not follow normality. The non-parametric Mann-Whitney tests were adopted for the comparison of two samples and the non-parametric Mood Medians test for comparisons of three or more samples. All tests were performed with a confidence level of 95%.

4. RESULTS

After speed profile analysis, the general mean speed from the trips included in the device for each SAR was calculated, regardless of the road type. Next, the mean speed for the same SAR were calculated for each road type and traffic calming device. Finally, once 30 km/h or 40 km/h are reference speeds for passing through vertical deflection, the distance traveled with a speed below these two values was also obtained.

4.1. General mean speed

The mean speed per SAR in each device was calculated from 75 trips through SB and 29 trips through RCW. The results are shown in Table 3. Considering all trips by each device, the speeds in SAR 1, 2 and 3 were very similar. The speed reduction due to SB in SAR 2 was on average 43.90%, from 47.28 km/h to 26.11 km/h. This value is similar to the results found by Barbosa, Tight and May (2000) and Wang et al. (2017). In the case of RCW, the average reduction was 43.62%, from 46.35 km/h to 26.08 km/h, values considerably higher than those found by Gonzalo-Orden et al. (2018). The nonparametric Mann-Whitney test revealed that the difference in speed variation between SAR 1 and 2 for SB and RCW was not statistically significant - $W (N = 104) = 3941.0$, $p < 0.983$.

Table 3: Mean speed and standard deviation in each speed analysis range (SAR)

Device	Speed analysis ranges (SAR)					
	1 (before)		2 (during)		3 (after)	
	Mean speed (km/h)	Standard deviation (km/h)	Mean speed (km/h)	Standard deviation (km/h)	Mean speed (km/h)	Standard deviation (km/h)
Speed bumbs SB (n = 75)	47,28	7,63	26,11	4,33	44,60	6,06
Raised crosswalks RCW (n = 29)	46,35	8,70	26,08	6,20	42,76	5,67

4.2. Mean speed by road type

Table 4 shows the values of the mean speeds in SAR 1, 2 and 3 as well as the values of the percentage variation of the mean speed between SAR 1 and 2 according to each device and road type.

Table 4: Mean speed in each SAR and speed variation (ΔSpeed) between SAR 1 and 2 for each road type

Road type	Device	Speed			
		SAR 1 (km/h)	SAR 2 (km/h)	SAR 3 (km/h)	Δspeed SAR 1 X SAR 2 (%)
Arterial	SB (n = 11)	55.67	25.69	45.71	53.84
	RCW (n = 04)	57.40	33.30	48.03	42.70
Priority	SB (n = 06)	44.69	26.36	48.68	40.59
	RCW (n = 0)	-	-	-	-
Sectoral 1	SB (n = 35)	43.71	25.45	43.97	41.15
	RCW (n = 17)	44.56	24.49	42.47	45.03
Sectoral 2	SB (n = 23)	49.39	27.27	43.97	44.20
	RCW (n = 08)	44.63	25.83	40.73	41.09

From the verification of the mean speeds according to road type, it was identified that the speed in SAR 1 on arterial roads was the highest among the four types of analyzed roads, for both SB and RCW (55.67 and 57.40 km/h, respectively); the lowest mean speed measured in SAR 1 was for SB on sectoral road 1 (43.71 km/h). However, the results of Mood's Medians – $\chi^2(6, N = 104) = 20.97$, $p = 0.002$ – indicated that the mean speed in SAR 1 is only statistically higher in the case of SB in the arterial roads when compared to SB in the priority and sectoral roads 1 and RCW on sectoral roads 1. It is expected that once both speed limits and geometric alignments induce drivers to practice higher speeds.

Regarding the speed in SAR 2, the lowest mean speed was identified in sectoral road 1 (24.49 km/h); the highest mean speed was identified for RCW on arterial roads (33.30 km/h). However, the results of Mood's Medians test indicated that such differences were not statistically significant – $\chi^2(6, N = 104) = 4.94$, $p = 0.551$.

The lowest mean speed in SAR 3 was found for the RCW located on the sectoral roads 2 (40.73 km/h), while the highest mean speed was found for the SB located on the priority roads (48.68 km/h) and the RCW on arterial roads (48.03 km/h). However, the results of Mood's Medians test indicated that such differences were not statistically significant – $\chi^2(6, N = 104) = 5.89$, $p = 0.435$.

Regarding the percentage variation in speed between SAR 1 and 2, the smallest variation was identified for the SB on the priority roads (reduction of 40.59%), while the greatest variation was identified for the SB on the arterial roads (reduction of 53.84%). According to the Mood Median test 2(6, N = 104) = 19.14, p = 0.004, only the greatest speed reduction for the SB on arterial roads was statistically significant. It is expected as well, as the mean speed in SAR 1 for these roads was considerably high and there is no statistical difference in mean speed in SAR 2 for all road types. The values found in this research for sectoral roads 1 and 2 are similar to the average reduction of 7 km/h found by Huang et al. (2011) for SB deployed on local roads in a city in China.

4.3. Low speed compliance distance

From the analysis of the speed profile and by interpolation between the points corresponding to the speeds immediately below and above 30 and 40 km/h, it was possible to obtain the distance traveled by the driver at speeds less than or equal to 30 km/h or 40 km/h (see Table 5). This value represents the influence distance or compliance distance of the traffic calming device.

Table 5: Speed compliance distance for speeds below 30 km/h and 40 km/h

Device	30 km/h		40 km/h	
	Average (km/h)	Standard Deviation (km/h)	Average (km/h)	Standard Deviation (km/h)
SB (n = 75)	35.44	12.05	100.27	40.70
RCW (n = 29)	40.90	24.28	105.86	51.41

For SB speeds less than or equal to 30 km/h were maintained for an average distance of 35.44 meters, while on RCW speeds lower than or equal to 30 km/h were maintained for an average distance of 40.90 meters. However, from the non-parametric Mann-Whitney test considering the 95% confidence level – W(N = 104) = 3741.0, p = 0.077 – it was found that such values do not present a statistically significant difference. Speeds less than or equal to 40 km/h were maintained for an average distance of 100.27 meters in SB and of 105.06 meters in RCW. However, from the non-parametric Mann-Whitney test considering the 95% confidence level – W (N = 104) = 3865.0, p = 0.302 – it was found that such values do not present a statistically significant difference. These values are within the findings of Huang et al. (2011), who found a maximum influence distance of 120 meters of influence of SB.

Also, it was noted that high values for the standard deviation in the case of speeds less than or equal to 40 km/h. In the histograms of Figures 6 and 7 this great dispersion is shown. The results of the Mood Medians test – $\chi^2(6, N = 104) = 15.42$, $p = 0.017$ – for the speed compliance distance less than or equal to 30 km/h indicate that there is only a statistically significant difference between the combinations of device and road type between: (i) SB on arterial roads and RCW on sectorial roads 1, the distance in question being smaller in the case of SB on arterial roads; (ii) SB on the sectorial roads 2 and the RCW on the sectorial roads 1, being the distance in question smaller in the case of the SB on the sectorial roads 2.

Mood's Medians test – for the speed compliance distance less than or equal to 40 km/h did not present a statistically significant result for a confidence level of 95% – $\chi^2(6, N = 104) = 11.25$, $p = 0.081$.

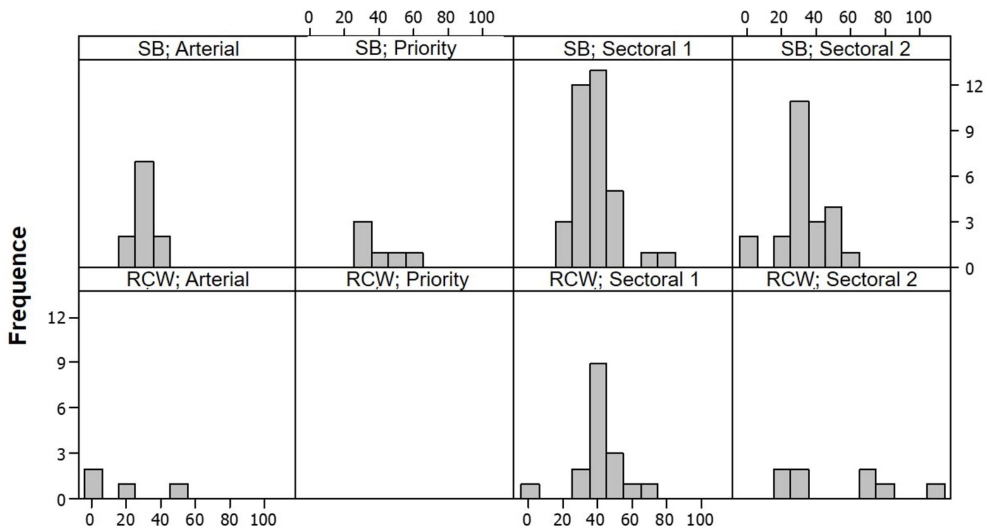

Figure 6. Distances histogram for speed less or equal to 30 km/h for SB and RCW

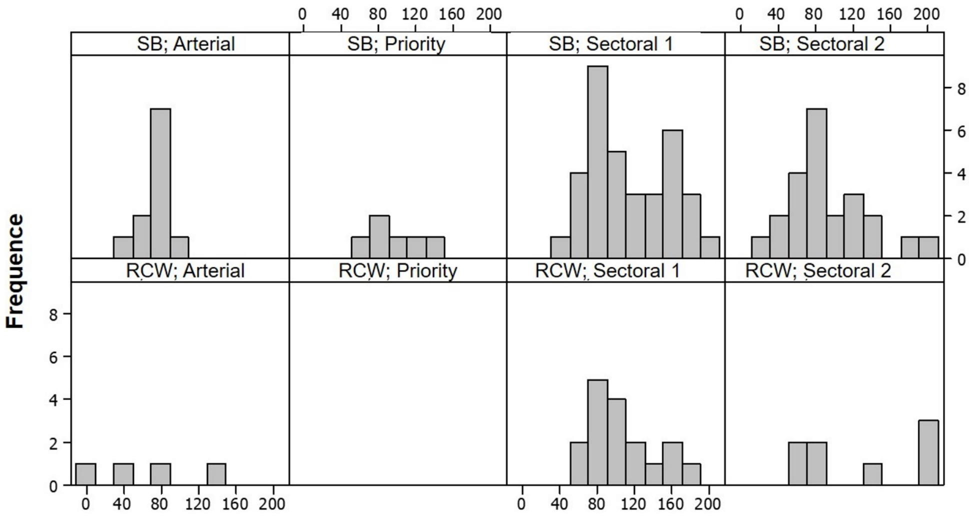

Figure 7. Distance histogram for speed less than or equal to 40 km/h for SB and RCW

5. CONCLUSIONS

This study investigated driving behavior in terms of the speed choice in segments with speed bumps (SB) and raised crosswalks (RCW), both widespread traffic calming devices in Brazil and many other developing countries. The use of naturalistic driving data allowed the analysis of the speed profile through continuous recording of the speed practiced, allowing a better understanding of the impact of the devices in real driving situations. The methodology applied also made it possible to better isolate the effect of the device by eliminating situations of speed reduction for any other reason than passing through the vertical deflection.

The mean speed in the SB and RCW sites analyzed (SAR 2) showed similar values (around 26 km/h), as well as for the variation of speeds between the segments before (SAR 1) and during the passage through the device (SAR 2) - a reduction of around 43% in mean speed. This result demonstrates the effectiveness of such devices in reducing the speed at their surroundings.

Although the geometry of the vertical deflections was not taken into account in this study, the comparison of the mean speed values during the passage through SB indicates that only the objective of speeds lower than or equal to 30 km/h has been reached (associated with Type II SB according to CONTRAN Resolution nº 600/2006), since only in seven of the 75 analyzed passages (9.33%) speeds above 30 km/h were identified in the segment during. On the other hand, the results of this study indicate that the objective of speeds less than or equal to 20 km/h of the SB type I has not been reached, since only one of the 75 passages through SB had a speed lower than 20 km/h in the segment during the passage.

In the case of RCW, the target speed of less than or equal to 30 km/h provided for by CONTRAN Resolution Nº 738/2018 was verified in 22 of the 29 analyzed passages, that is, in 75.86% of the cases. This result demonstrates the great effectiveness of RCW as a traffic calming measure.

The analyzes considers the type of device and the road where it is deployed. It allows us to draw the following conclusions: (i) the speed in the segment before (SAR 1) tends to be higher on arterial roads, possibly due to the higher operational speed practiced on these roads; (ii) higher speed reductions between before (SAR 1) and during segments (SAR 2) were found for roads with higher road type level, which demonstrates the greatest impact on vehicle speeds by the implementation of vertical deflections on roads with a higher road type level. (iii) the greater dispersion in the speed profile found, from the perspective of road safety, should be viewed with caution, since the positive effect of the speed reduction at the device site may, eventually, have counterbalanced by the negative effect of the sudden speed reduction.

With regard to the speed compliance distance less than or equal to 30 km/h or 40 km/h, no statistically significant differences were found between SB and RCW, although numerically the average distance was 15.41% higher for 30 km/h and 5.57% higher for 40 km/h in the case of RCW. However, the high dispersion associated with these distances is probably associated with the differences in geometric characteristics of the device and the personal characteristics of the drivers. In terms of urban planning, information on the speed compliance distance below a certain threshold may be useful to define the most suitable positioning of the traffic calming device.

The absence of an analysis of the impact of drivers' personal characteristics on the speed practiced is one of the limitations of this study. The sample size of 16 drivers did not allow the performance of disaggregated analyzes considering the age range or gender of the drivers, for example. This subdivision of the sample would imply a loss of statistical significance in the analysis of the results. However, bearing in mind the continuity of the NDS-BR data collection process, analyzes considering such characteristics may be contemplated in future studies. In addition, the choice of speed is also influenced by circumstantial aspects, such as "being in a hurry" or "being more aggressive on a given day". Land use characteristics surrounding each speed control device may also affect drivers' speed choice. Such factors were also not addressed in this study and may be the subject of future research.

Future research may also include the evaluation of the geometric characteristics of the devices and the existing vertical and horizontal signaling conditions in the area where they are deployed. Additionally, increasing the sample size of drivers and, consequently, the number of passes through the devices, is important to increase the representativeness of the obtained results, both in terms of the number of drivers, as well as through the replication of the methodology in other Brazilian cities and in the Global South.

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