Case Studies on Transport Policy 22 (2025) 101591

Contents lists available at ScienceDirect

Case Studies on Transport Policy

journal homepage: www.elsevier.com/locate/cstp

Average speed dynamics on urban roads and highways: Influence of traffic infrastructure, vehicle and road characteristics on driving behavior

Alan Ricardo da Silva *, Rodrigo Nunes Cavalcante

Graduate Program in Transportation, University of Brasília, Brazil

A R T I C L E I N F O

Keywords:
Average speed
Optical character recognition
Driver behavior

A B S T R A C T

Vehicle speed control is important for road safety, directly influencing the frequency and severity of traffic accidents. Proper speed management can significantly reduce the number of accidents and save lives, and is an essential strategy in public road safety policies. The study of driver speed is a pervasive theme in scientific studies, as well as the consequences of high speeds. However, few of them correlate drivers' behavior with traffic infrastructure and road characteristics. This study aimed to analyzed what can be learned from the radar data about driving behavior related to speeding on urban roads and highways in Brazil, by using average speeds. To do that, it was adopted an observational approach, using data collected from radars with Optical Character Recognition (OCR) operated by traffic agencies on different types of urban roads and highways in the Federal District, Brazil. The results indicated that while OCR radars are effective in reducing the average speed at specific points, challenges persist due to adaptive driver behaviors, such as the "kangaroo jump", where drivers slow down before the radars and accelerate after passing through them and sometimes the driver's speed is reduced traffic infrastructure and road characteristics. Another result was that vehicle power is not the main factor for speeding and that drivers are the ones who want to accelerate more, regardless of where they are. This study, of zero cost and replicable on a large scale, suggests that cooperation between traffic agencies for data sharing can enhance efforts in speed moderation, contributing to a safer road environment.

1. Introduction

Vehicle speed is a critical factor that directly influences road safety, traffic efficiency, and quality of life in urban areas and highways. As highlighted by Aarts and Van Schagen (2006), speed affects both the probability of accidents occurring and the severity of them when they occur. Studies such as that of Elvik et al. (2004) show that there is an exponential correlation between speed and the probability of fatalities in traffic accidents. Thus, speed management can lead to a significant improvement in traffic flow and congestion reduction, which, in turn, contributes to the reduction of pollutant emissions and improved urban environmental quality (Schrank et al., 2012).

Understanding speed patterns is critical to planning and implementing traffic control measures. The variability of speed between vehicles, known as the difference in speeds, is an important factor that can increase the likelihood of claims. Studies indicate that greater disparities in driving speeds contribute to a higher occurrence of collisions (Taylor et al., 2000). Traffic moderation, in turn, is an approach that seeks to promote a gradual and controlled reduction of speeds on urban roads and highways, considering aspects such as user safety, traffic flow, and environmental impact. This approach is in line with the idea that reducing speeds contributes to reducing the severity of accidents and promoting safer and more humanized traffic.

In this context, it is clear that speed management is an important factor in reducing claims, although its implementation does not eliminate the occurrence of claims. The Vision Zero approach (Trafikverket, 2012) recognizes the inevitability of these occurrences, but aims to eliminate deaths and serious injuries. It can also be said that human behavior, especially the risk associated with high speeds, remains a concern, even with speed control devices, and will still be a latent variable in this equation.

Although fixed radars reduce the average speed of vehicles, risky behaviors continue, such as deceleration before radars and acceleration after passing through the equipment, and these behaviors limit their effectiveness (Retting et al., 2003; Montella et al., 2012; De Pauw et al. 2014; Høye, 2014). Knowing that speeding is one of the main causes of traffic accidents, influenced by behavioral and other factors such as road type, traffic volume, weather conditions and road infrastructure (Elvik

* Corresponding author.
E-mail address: alansilva@unb.br (A.R. da Silva).

https://doi.org/10.1016/j.cstp.2025.101591
Received 1 October 2024; Received in revised form 4 March 2025; Accepted 20 August 2025
Available online 21 August 2025

et al., 2019; WHO, 2018), this study seeks to investigate the dynamics of speed on the interstate, state highways and urban roads, using radar data with Optical Character Recognition (OCR) technology in the Federal District, Brazil.

So, the main purpose is to analyze what can be learned from the radar data about driving behavior related to speeding on urban roads and highways in Brazil, by using average speeds. The analysis will allow us to evaluate how different traffic infrastructure and road characteristics influence speed patterns, as stated by Sadia et al. (2018), and the effectiveness of enforcement equipment, as highlighted by Wilson et al. (2010) and Job et al. (2020). The manuscript has been organized as follows: Section 2 gives the background of the research topic investigated in this study, and Section 3 presents the proposed method. Section 4 presents the analysis of the results of a case study and Section 5 presents the concluding remarks obtained from this study.

2. Background

Risky traffic behavior refers to actions by drivers, passengers, cyclists, or pedestrians that increase the likelihood of accidents, injuries, or fatalities. This behavior can include a variety of dangerous practices, such as speeding, driving under the influence of alcohol or drugs, inappropriate use of mobile devices, disregarding traffic signs, and other reckless attitudes (WHO, 2018). This section aims to show some important aspects of speed enforcement and the risk behaviors related to the driver's speed.

2.1. Speed enforcement

Speed enforcement is crucial for road safety, as it helps to reduce the frequency and severity of traffic accidents. Devices such as electronic radars and monitoring cameras encourage drivers to respect speed limits, promoting safer behavior on the roads. Fixed speed controllers and fixed speed reducer radars must be equipped in Brazil with OCR technology, according to Contran (2020). The regulation distinguishes these two types of equipment: the speed controller radar is designed to monitor the speed of vehicles along a road segment, to keep the speed below the allowed speed; and the speed reducer radar is implemented specifically in places that require a punctual reduction in speed for safety reasons, such as near of school or hospital areas. The integration of these fixed radars is important for the inspection and improvement of road safety.

Fig. 1 (left) shows a fixed controller-type radar used in Brazil configured to monitor multiple lanes of traffic simultaneously and can be installed on poles or elevated structures that span multiple lanes. The structure of this equipment is robust, designed to work uninterruptedly, and withstand adverse weather conditions. Fig. 1 (right) represents a fixed reducer-type radar also used in Brazil often installed in strategic locations where it is easy for drivers to see it. They can include additional elements such as variable message displays or light signals that indicate the vehicle's current speed, serving as an immediate alert to the driver.

Fig. 1. Fixed controller-type (left) and reducer-type (right) radars.

Although speed controllers and speed reducers have different purposes in traffic control and moderation, the integration of these technologies with OCR systems allows a real and safe analysis of the speed dynamics of vehicles along different road segments. This combination makes possible to collect relevant data on driver behavior, such as maintaining consistent speeds in controlled areas or abruptly reducing speeds near speed bumpers. Based on the study of Jiménez-Bravo et al. (2022), it can be said that using OCR to track vehicles at multiple checkpoints helps to identify behavioral patterns that would be difficult to capture with the isolated application of a single type of equipment, contributing to a more comprehensive understanding of how different enforcement mechanisms influence driver behavior over time.

Article 218 of the Brazilian Traffic Regulation (Brazil, 1997) defines the penalties for speeding according to the severity of the infraction. If a driver exceeds the speed limit by up to 20 %, they commit a medium infraction, resulting in a fine. If the speed exceeds the limit by more than 20 % to 50 %, the infraction is classified as serious and also results in a fine. When the speed exceeds the limit by more than 50 %, the violation is considered very serious, resulting in a tripled fine and the immediate suspension of the right to drive. This article is important for traffic safety, as it establishes penalties proportional to the severity of the violation, encouraging compliance with speed limits and contributing to the reduction of accidents.

It is important to note that the implementation of large-scale OCR and monitoring systems can be costly, requiring significant investment in infrastructure and technology. However, it is necessary to implement effective measures to change the traffic culture and promote road safety (WHO, 2004). While the initial implementation of OCR systems can be costly compared to traditional systems, the long-term benefits, including reduced claims and operational efficiency, justify the investment. A report from ETSC (2021) highlights that the costs of installing and maintaining OCR systems are offset by the decrease in claims and infractions, resulting in savings for public administrations and society.

2.2. Risky behavior related to the driver's speed

Fig. 2 illustrates a flow in and out of an urban area, highlighting how the behavior of vehicle speeds is influenced by different factors, such as traffic density, the presence of adequate signage, and the geometric characteristics of the roads. It should be noted that the study of Rao et al. (2017) pointed out that maneuvers entering and exiting main roads cause a significant reduction in vehicle speed. This is because drivers need to slow down when entering and accelerate when exiting these roads.

Bastos et al. (2021) conducted a naturalistic study of driving in Brazil and found that drivers who exhibited risky behaviors, such as dangerous overtaking, were more likely to exceed the speed limit. Van Nes et al. (2019), conducted a study on driver behavior and concluded that the presence of reckless and overspeed drivers can lead to an increase in irritability and hostile behavior among other drivers.

In an environment with high average traffic speed, drivers tend to adapt to this speed, increasing risky behaviors such as dangerous overtaking and sudden lane changes (Stradling et al., 1994; Cooper and Novaco, 1986). Sudden variations in traffic speed can increase the likelihood of risky behaviors, such as sudden braking, sudden acceleration, and sudden lane changes (WHO, 2004).

In the context of speed analysis, several road aspects are important for a comprehensive and accurate assessment, aiming at the implementation of effective control and safety measures. These aspects include road geometry, signage, pavement type, the presence of traffic calming devices, and electronic enforcement infrastructure (Faiz et al., 2022). The geometry of the road, including the number of lanes, the width of lanes, and the presence of curves and inclines, directly affects

Fig. 2. Illustration of the behavior in approaching and distancing from urban areas.

the speed of vehicles. Studies such as Dai (2012) show that narrower roads with a greater number of curves tend to reduce the vehicle's average speed. Geometric configuration is important to identify risk areas and implement corrective measures.

The dynamics of speed on urban roads and highways are influenced by several factors, including the presence of enforcement radars. Drivers tend to alter their driving behavior when they approach electronic enforcement devices, resulting in acceleration and deceleration patterns that can have implications for road safety. When approaching speed cameras, many drivers slow down to avoid fines, a behavior that has been widely documented in the literature. For example, (AASHTO, 2006, 2010) highlights that the installation of radars is effective in reducing the average speeds of vehicles, contributing to the reduction of traffic accidents. However, after passing the radar, some drivers resume acceleration quickly, a phenomenon known as the "kangaroo jump effect", as described by Høye (2014).

Ogden (1996) argues that rapid acceleration can lead to loss of control of the vehicle, especially in adverse weather conditions or on sharp curves. It is important to note that frequent and sudden acceleration and deceleration causes excessive wear on vehicle components, such as the engine, brakes, and tires, shortening the vehicle's lifespan and increasing maintenance costs. To reduce the risks associated with acceleration and deceleration behavior near radars, several measures can be implemented, highlighting sectional control systems, which monitor the average speed along a longer segment of the road. These are recommended to reduce the "kangaroo jump effect" (Høye, 2014). Educational campaigns can raise awareness about the risks of sudden acceleration and the importance of maintaining a constant and safe speed (WHO, 2017). In addition, according to the WHO (2018), improvements in infrastructure, such as the implementation of adequate and visible signage, impact mitigation devices, can contribute to the reduction of traffic accidents and deaths.

Lastly, Melman et al. (2022) explored the impact of vehicle sport modes on driver behavior, specifically concerning the driver's speeds. The premise of the study was that sports modes, often available in modern vehicles, can influence the way drivers behave behind the wheel, potentially inducing higher speeds. The research was carried out using a driving simulator, allowing control of the variables and the possibility of directly observing the driver's behavior under different driving conditions. The study did not find a significant increase in drivers' perception of danger when driving in sport mode, which indicates that the feeling of control provided can encourage faster driving without drivers feeling more unsafe. In terms of road safety, this raises concerns, as greater acceleration and higher speeds can increase the risk of accidents.

The findings of Melman et al. (2022) suggest that vehicle characteristics such as power play an important role in how drivers adapt their behavior, particularly in speeding. Therefore, information on the displacement, power, and maximum speed of engines of different vehicle categories offers a broad view of the relationship between engine power and the performance of a vehicle in different contexts. For example, small engines, such as 1.0 L, with horsepower between 75hp and 88hp, reach speeds of up to 175 km/h and are ideal for urban use due to fuel economy. In contrast, large engines, such as the 2.0 L turbo, reach horsepower up to 250 hp and speeds more than 240 km/h, making them effective for sporty performance and situations where high power is required. This categorization is useful for consumers and engineers in choosing the most suitable vehicle according to the need for power, economy, and type of use, whether urban or highway.

3. Material and methods

Although the analysis of road safety behavior is traditionally conducted through questionnaires, driving simulators, and statistical analysis of accidents, this study adopts an observational approach based on statistical analysis of the data collected from OCR equipment. The method allows you to accurately capture vehicle speeds and other relevant information, making it possible to carry out detailed analyses that aim to identify patterns of driver behavior in real traffic conditions. In this study, data analyses were made using the SAS 9.4 software.

In Brazil, the public institutions (federal and state traffic agencies) responsible for traffic management have an extensive database on vehicular flow, collected through fixed radars with OCR technology installed on public roads, and in most cases underused. The methodological flowchart of this study is presented in Fig. 3 and the steps are described below:

3.1. Stage 1: Road section selection

The first step of the study consists of selecting road sections or segments and the period to be analyzed. It is recommended to choose sections or segments that have distinct characteristics in terms of traffic, road geometry, and speed limits, among other relevant factors. In addition, these sections must have at least two radars equipped with OCR technology, which is essential for the accurate collection of vehicle speed data. Equipment with OCR technology must have its times properly synchronized, to ensure the accuracy of the data and avoid records of extreme speeds that can distort the results.

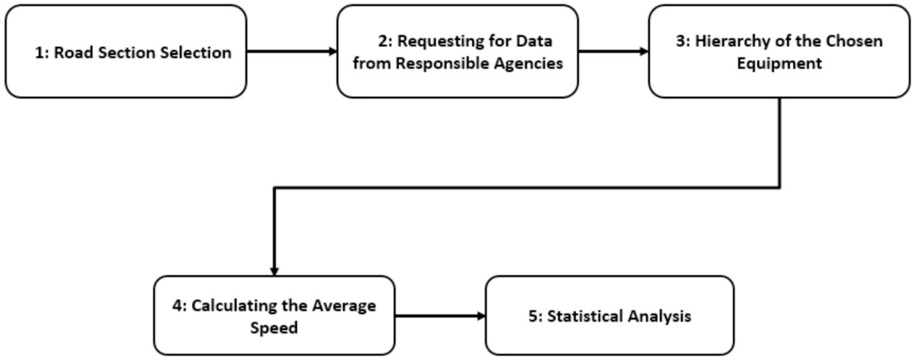

Fig. 3. Methodological Flow Diagram.

3.2. *Stage 2: Requesting for data from responsible agencies*

After selecting the road sections, it is necessary to request the data from the responsible agencies. This data should include, essentially, the records of the geographic coordinates of the equipment with OCR technology (latitude and longitude), date and time (including minutes and seconds), the vehicle's license plate, and the speed recorded by the OCR radars. Geographic coordinates are the key to calculating the distance between points, while time allows us to determine the traveling time spent between these points. With this information, it is possible to calculate the average speed between two equipment. The vehicle's license plate is the most important data, as it allows us to identify the same vehicle in different equipment records. If it is also possible to obtain the characteristics of the vehicles, such as type (automobile, truck, pickup truck, motorcycle, etc.) as well as brand, model, and horsepower, this data can enrich the analysis, allowing segregation by type and power of the vehicles.

3.3. *Stage 3: Hierarchy of the chosen equipment*

Radars equipped with OCR technology must be arranged in a logical sequence to ensure accuracy in calculating the average speed, ensuring that the records are consistent and representative of the analyzed section. As the objective is to follow the vehicle along the different road segments and between radars, it is essential to determine the order of passage of vehicles between them, as well as the direction of travel in the section. This ordering will allow the identification of vehicle acceleration and deceleration patterns, contributing to a more detailed analysis of driver behavior along the route.

3.4. *Stage 4: Calculating the average speed*

With the collected data, it is possible to calculate the average speed (as) between the equipment with OCR technology using Eq. (1):

$$as = \frac{Distance}{Time} \tag{1}$$

The analysis can be segmented by vehicle type, excluding, for example, trucks and other heavy vehicles, to focus only on cars and pickup trucks. In addition, it is possible to segment the data by traffic direction and by period of the day, allowing a more detailed and specific analysis of speed patterns in different conditions and times.

3.5. *Stage 5: Statistical analysis*

With the average speeds calculated, several analyses can be carried out to identify the factors that influence the behavior of drivers about speed dynamics. An initial analysis may involve verifying the association between the average speed practiced and the occurrence of infractions, categorizing the average speed into different ranges (such as "below the regulated speed", "up to 10 % above the regulated speed", "between 10 % and 20 % above the regulated speed", etc.) and categorizing the infraction into "Yes" or "No", that is, whether the vehicle has exceeded the regulated speed limit or not. Other analyses may include:

- Vehicle power: Examine whether there is a relationship between vehicle power and speed dynamics.
- Direction of the road: Analyze the average speed in different directions of the road to identify variations in the behavior of drivers during the approach or departure from an urbanized area.
- "Kangaroo jump effect": Graphically analyze the phenomenon in which drivers tend to accelerate after passing through radar and brake when approaching the next, evidencing the behavior of adaptation to the presence of radars.
- Road comparison: Compare the speeds of the same vehicles in different segments (urban and rural) to identify variations in behavior in different road contexts.

These analyses allow for a deeper understanding of driver behavior and the factors that influence speed dynamics in different conditions. In general, chi-square and Z tests can be used for categorical variables, and ANOVA and Student's t or Wilcoxon's tests for quantitative variables.

4. Analysis of the results

The proposed method was applied in several segments of interstate and state highways and urban roads under the jurisdiction of the Federal District (DF) and Goiás (GO), Brazil, which surrounds the Federal District. The steps of the method used to conduct this study are described below, highlighting the particularities of each type of road and how they influence the observed results.

4.1. *Stage 1: Road section selection*

The choice of sections considered the strategic presence of radars equipped with OCR technology, which are essential for collecting data on vehicle speeds. In addition, sections with allowed speeds ranging from 60 km/h to 80 km/h were selected, to capture a representative range of driver behaviors in different road conditions. This approach aimed to ensure comprehensive coverage of the monitored areas, allowing a robust analysis of speed dynamics in diverse contexts, considering both rural and urban environments, and how different speed regulations impact safety and traffic flow.

The study covered 4 segments of interstate highways located in the Federal District and Goiás (BR 251, BR 020, BR 080, BR 070); 10 segments of state highways belonging to the Federal District (DF 003, DF 002, DF 001, DF 075, DF 085, DF 095, DF 007, DF 079, DF 463, DF 025) and all available urban road segments that connected with any of the aforementioned highways, allowing a comprehensive evaluation of the average speed dynamics in the different types of roads. All state highways monitored by the DER/DF are in urban environments, with three lanes each side, while the roads managed by DETRAN/DF are also part of the urban environment, with two lanes each side. On the other hand, the highways under DNIT jurisdiction are located in predominantly rural environments, with two lanes each side, and which allows the comparison between different road contexts and driver behavior patterns related to average speed. In general, these selected highways and roads are the ones in and out of the Federal District and they represent the main roads of the Federal District, essential for urban and regional mobility, connecting urban and rural areas.

Fig. 4 shows the segments of highways under the jurisdiction of the National Department of Transport Infrastructure (DNIT), Department of Highways (DER/DF), and Traffic Department (DETRAN/DF), all public agencies in Brazil, highlighting the segments selected and the location of OCR equipments.

4.2. Stage 2: Requesting for data from responsible agencies

The database provided by DNIT, DER/DF, and DETRAN/DF, presented in Table 1, has a total of more than 59 million records (vehicle passage), involving more than 5 million different vehicle license plates and occupying 15.9 GB. They are relative to the first 10 days of March 2024 and are 24 h uninterrupted. It is worth mentioning that the DNIT has both equipments (controller and reducer), which is not ideal, but without the reducer-type, it would not be possible to measure the average speed in some segments, due to the lack of controller-type in these same segments. This is a limitation of the study since the reducer-type tends to slow down more than the controller-type equipment, but unfortunately, this is an infrastructure restriction.

Data include the geographic coordinates of the equipment with OCR technology (latitude and longitude), date and time (including minutes and seconds) of the passage of the vehicles, the vehicle's license plate, and the speed recorded by the OCR radars. From the license plate, and based on the administrative records, it was possible to obtain the model and power of the analyzed vehicles.

Table 1
Summary of the data gathered.

Jurisdiction	Records	License Plate	Size
DNIT	11.390.940	748.188	1,8GB
DER/DF	28.429.243	2.835.522	7,8GB
DETRAN/DF	20.177.187	1.892.253	6,3GB
TOTAL	59.997.370	5.475.963	15,9GB

4.3. Stage 3: Hierarchy of the equipment chosen

The hierarchization stage of the radars represents one of the pillars of the results obtained, given the absence of a sequential logic provided by the responsible agencies. Fig. 5 shows an example of how the equipment was initially provided for the study, without a defined logical sequence. In fact, these codes are randomly distributed in the database.

In contrast, Fig. 6 shows the logical sequence created specifically for this study, aiming at a more structured analysis. The illustration shown in Fig. 6 uses only two pieces of equipment for instance, but some segments have up to 18 pieces of equipment in sequence This step was important not only to optimize the quality of the data but also to overcome the limitations imposed by the absence of a pre-established sequential logic, ensuring that the results accurately and reliably reflected the speed dynamics on the studied roads.

Based on the hierarchy, it was possible to analyze the distance between the radars. Table 2 shows some descriptive statistics of the distance between radars under the jurisdiction of DNIT, DER/DF and DETRAN/DF. Note that DNIT has the longest distances between

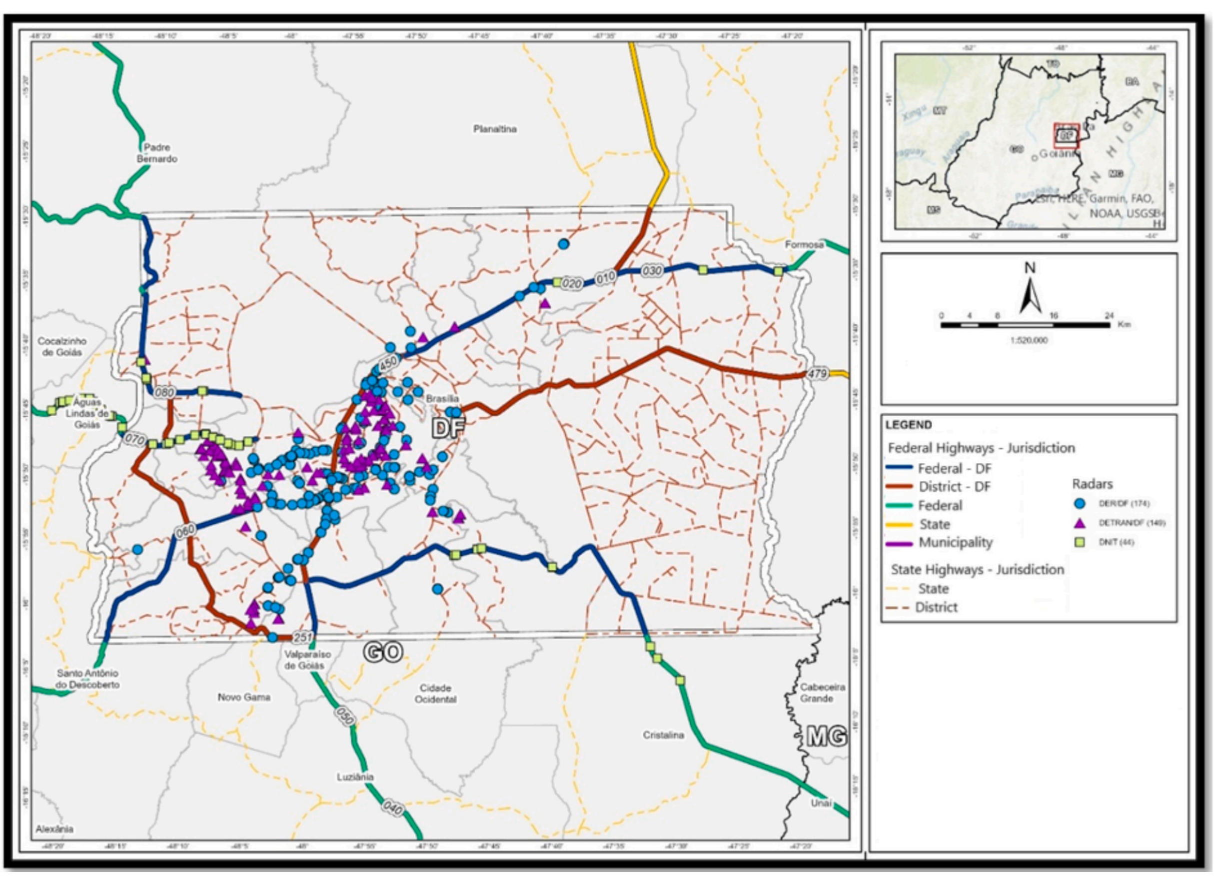

Fig. 4. Segments and locations of OCR equipment used in the study.

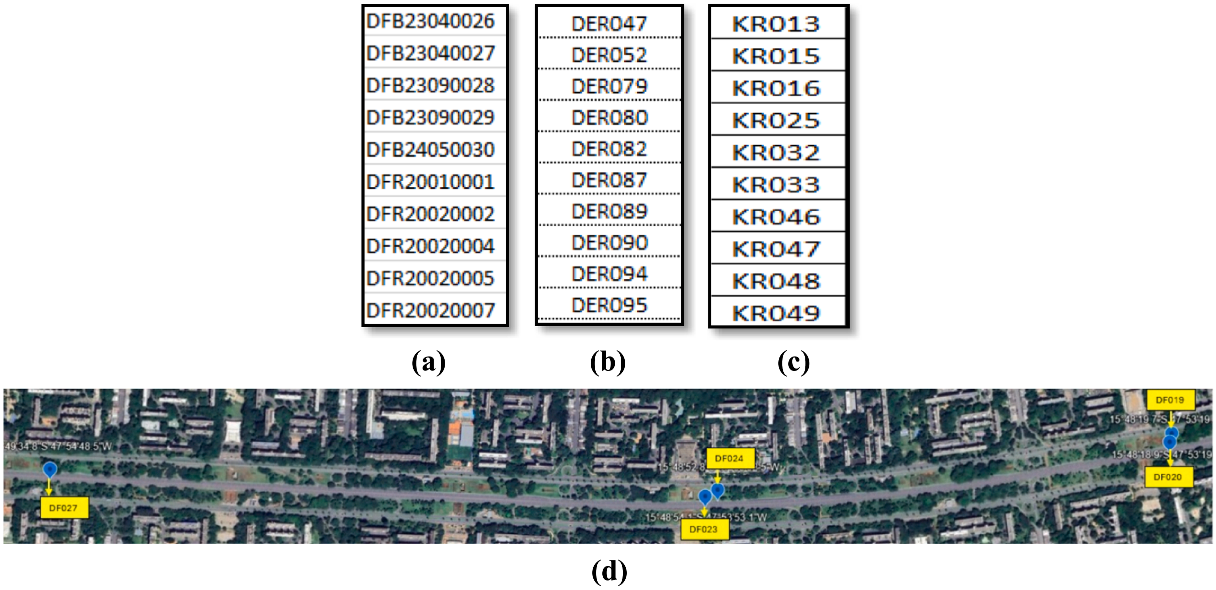

Fig. 5. Identification of some equipment provided by the traffic agencies. (a) DNIT, (b) DER/DF, and (c) DETRAN/DF (d) spatial distribution (DER/DF).

Radar	seq	km	Type
DFB20020010	1	14,6	reducer
DFB23090028	2	4,9	reducer

(a)

Radar	seq	km	Type
DER447 (KM 0,8)	1	0,8	controller
DER454 (KM 4,0)	2	4	controller

(b)

Radar	seq	Address	Type
KRB171	1	EIXO W SQS 103 SENT SUL/NORTE, BrasÃ-lia, DF	controller
KRB175	2	EIXO W SUL ALTURA EQS 106/107 PROX. AO CINE BRASILIA SENT. SUL/NORTE, BrasÃ-lia, DF	controller

(c)

Fig. 6. Example of hierarchization and sequencing of the equipment: (a) DNIT, (b) DER/DF and (c) DETRAN/DF.

equipment, with an average of 5.47 km, revealing a greater spacing between control points on federal highways, while DETRAN/DF has the shortest distances between equipment, with an average of 1.61 km, which makes sense since it is in the urban environment.

4.4. Stage 4: Calculating the average speed

From the calculation of the average speed, the analysis was deepened and segmented into different categories of vehicles, excluding trucks and other heavy vehicles. This strategy allowed them to focus on utility cars and pickup trucks, providing a more refined and specific view of the speed patterns of these vehicles. After merging the three databases, with the vehicles that traveled in the three jurisdictions on the same days, the database had 206,677 records and 9050 different license plates. The data of these vehicles (model and horsepower) was then requested to clean the dataset.

To ensure that the same vehicles were traveling between the segments, without stops, it was stipulated that to remain at the database, the total time between the DNIT and DETRAN/DF equipment could not be more than 4 h, and to avoid uncertainties of extreme speeds in the case of DETRAN/DF, which had equipment with uncalibrated times, only vehicles with an average speed of less than or equal to 140 km/h were considered. Thus, filtering only the categories “Automobile”, “Pickup Truck”, and “Utility”, the database had 16,184 records, generating a total of 2061 different license plates, as can be seen in Table 3.

Still concerning average speeds, the phenomenon known as

Table 2
Descriptive statistics of the distance between radars (km).

Jurisdiction	Observations	Min	Q1	Q2	Average	Q3	Max
DNIT	22	1.04	1.22	1.66	5.47	2.69	54.33
DER/DF	75	1.00	1.65	2.55	3.47	3.47	23.72
DETRAN/DF	29	0.98	1.30	1.42	1.61	1.50	7.66

Table 3
Vehicle types and frequencies, after filtering.

Type	Frequency	Percent
Automobile	14,878	91.93
Pickup Truck	1,228	7.59
Utility	78	0.48
Total	16,184	100.00

"kangaroo jump" was graphically analyzed, revealing the tendency of drivers to accelerate after passing a radar and brake when approaching the next equipment. In Figs. 7–9, the horizontal axis represents radars, while the vertical axis represents speed (average and at the point). In DETRAN/DF, it was possible to analyze more than 8 sequential points, in DER/DF more than 10 pieces of equipment, and in DNIT highways, more than 20 sequential pieces of equipment. This behavior showed an adaptation of drivers to the presence of radars, which suggests that the mere presence of this equipment may not be enough to maintain safe speeds along the entire monitored segment. Note the up and down of the speed, where drivers reduce speed approaching the radar, accelerate after passing through it, and reduce again when approaching to another radar. The presence of multiple peaks highlights the importance of considering the strategic positioning of equipment (or some optimal distance) to increase the effectiveness of speed enforcement.

These plots demonstrate the perception that, in general, drivers brake close to the inspection equipment, and then accelerate, and this process is repeated along the road. And more, they show the capacity to work with observational data having pretty much the same result as one from a trial study. Once the descriptive analysis of the data is completed, the following section will perform a more in-depth statistical analysis of the data.

4.5. *Stage 5: Statistical analysis*

Several analyses were carried out to identify the factors that influence the behavior of drivers about speed dynamics. Among them, the analyses by speed ranges on different roads, speeding, direction of the road, and vehicle characteristics.

4.5.1. *Speed ranges*

The initial and main analysis of this study involved verifying the association between the average speed in different jurisdictions, considering the same driver (paired analysis). For this, the average speeds were categorized into different ranges, so that different speeds can be compared, such as: "1. Below the allowed speed", "2. Between 0 % and 10 % above the allowed speed", "3. Between 10 % and 20 % above the allowed speed" and "4. Above 20 % of the allowed speed". Thus, it is intended to verify whether drivers who travel at high speeds (or low speeds) on a certain road do so on other roads. Table 4 shows the joint distribution of drivers who travel on the highways under the jurisdiction of the DER/DF and DNIT. It is noted that the highest percentages among the categories of the DER/DF "1. Below the allowed speed" and "4. Above 20 % of the allowed speed", also occur in the DNIT categories, showing the same behavior of drivers driving at low or high speed on the DER/DF and DNIT highways. The chi-square test for independence confirms this hypothesis, as it is rejected (p-value $<$ 0.0001), considering a 5 % significance level.

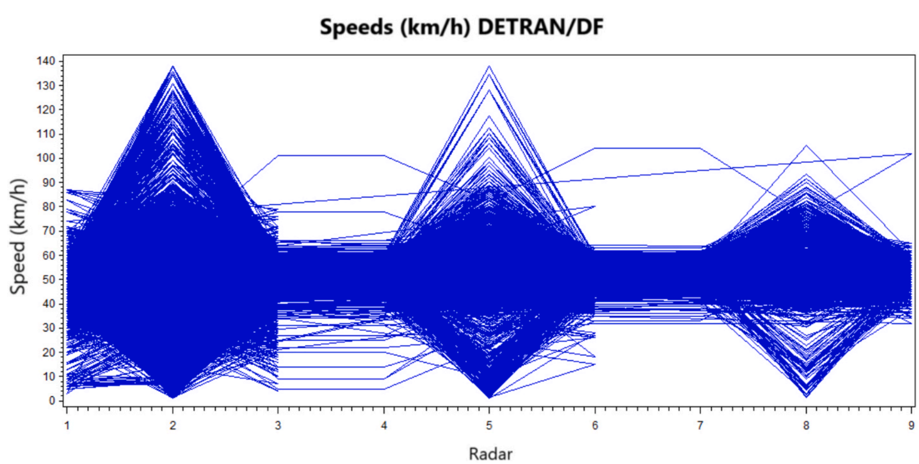

Fig. 7. Graphic representation of the kangaroo jump effect on the DETRAN/DF roads.

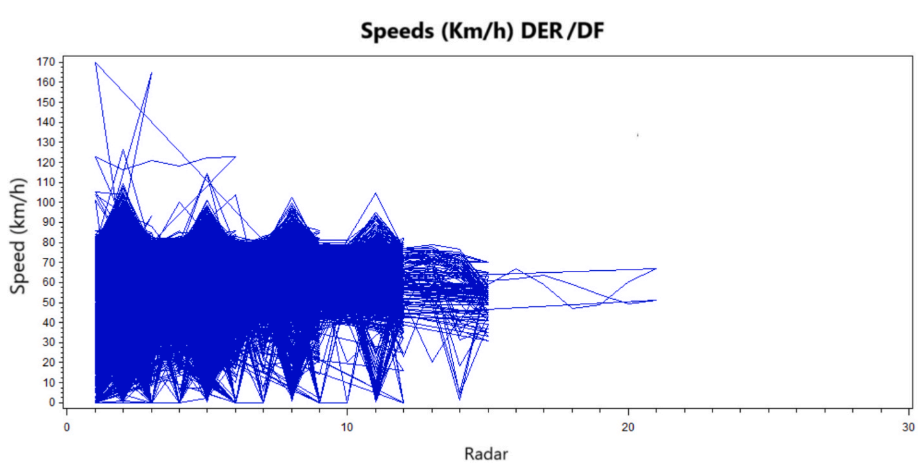

Fig. 8. Graphic representation of the kangaroo jump effect on the DER/DF highways.

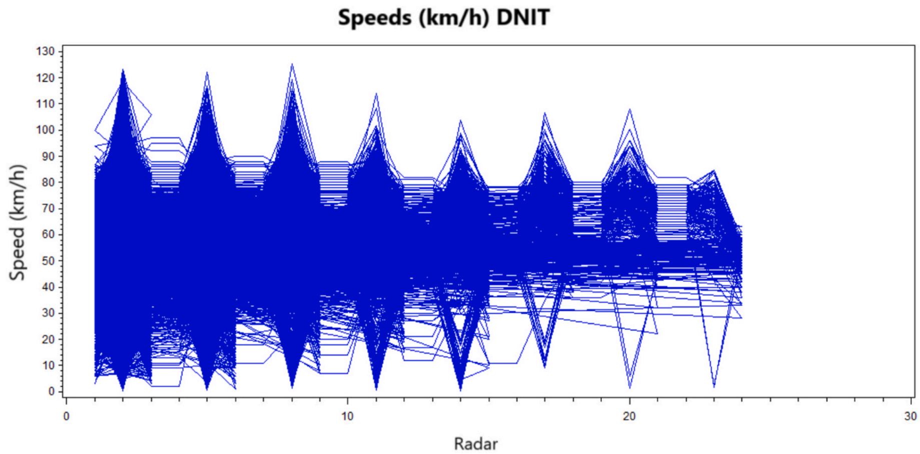

Fig. 9. Graphic representation of the kangaroo jump effect on the DNIT highways.

Table 4
Speed ranges DER/DF x DNIT.

Speed Range DER/DF Frequency Percent (row)	Speed Range DNIT				Total
	1. Below Allowed Speed	2. Between 0 % and 10 % Above Allowed Speed	3. Between 10 % and 20 % Above Allowed Speed	4. Above 20 % Allowed Speed	
1. Below Allowed Speed	4,878 39.22	1,850 14.87	1,830 14.71	3,881 31.20	12,439 100.00
2. Between 0 % and 10 % Above Allowed Speed	907 31.81	434 15.22	381 13.36	1129 39.60	2,851 100.00
3. Between 10 % and 20 % Above Allowed Speed	215 28.94	115 15.48	99 13.32	314 42.26	743 100.00
4. Above 20 % Allowed Speed	21 13.91	16 10.60	29 19.21	85 56.29	151 100.00
Total	6,021 37.20	2,415 14.92	2,339 14.45	5,409 33.42	16,184 100.00

$\chi_9^2 = 171.57(\text{p-value} < 0.0001)$

Analyzing now the association between the roads under the jurisdiction of the DER/DF and DETRAN/DF, the same behavior can be observed in Table 5, that is, drivers who are traveling below the allowed speed and above 20 % of the allowed speed also do so on both roads. The chi-square test for independence is also rejected (p-value < 0.0001), considering a 5 % significance level.

$\chi_9^2 = 311.99(\text{p-value} < 0.0001)$

Finally, Table 6 shows the association between the roads under the jurisdiction of DNIT and DETRAN/DF, where the same dynamics presented in Tables 4 and 5 can be found, except for the high speeds practiced (above 20 % of the allowed speed) on the highways under the jurisdiction of DNIT, which in the case of DETRAN/DF roads, most drivers tend to travel below the allowed speed. These results confirm the research hypothesis that the driver's behavior in driving at low or high speed happens regardless of where they are traveling, that is, there is a driver's desire to drive at high speeds, or to stay within the regulated speed limit. And that in the case of the DETRAN/DF roads, the traffic infrastructure and road characteristics that were responsible for reducing the drivers' speed who like to accelerate on free flow highways.

Table 5
Speed ranges DER/DF x DETRAN/DF.

Speed Range DER/DF FrequencyPercent (row)	Speed Range DETRAN/DF				Total
	1. Below Allowed Speed	2. Between 0 % and 10 % Above Allowed Speed	3. Between 10 % and 20 % Above Allowed Speed	4. Above 20 % Allowed Speed	
1. Below Allowed Speed	4,689 37.70	3,465 27.86	2,730 21.95	1,555 12.50	12,439 100.00
2. Between 0 % and 10 % Above Allowed Speed	842 29.53	815 28.59	703 24.66	491 17.22	2,851 100.00
3. Between 10 % and 20 % Above Allowed Speed	196 26.38	208 27.99	180 24.23	159 21.40	743 100.00
4. Above 20 % Allowed Speed	23 15.23	13 8.61	41 27.15	74 49.01	151 100.00
Total	5,750 35.53	4,501 27.81	3,654 22.58	2,279 14.08	16,184 100.00

$\chi_9^2 = 258.69(\text{p-value} < 0.0001)$

Table 7 provides a detailed analysis of speed violations in DNIT, DER/DF, and DETRAN/DF jurisdictions, highlighting the percentages of vehicles not notified of violations at the location of radar, to different average speed ranges. Note as expected, 100 % of the vehicles that traveled at an average speed below the allowed speed were not notified of a violation. But for the other average speed ranges, even the highest ones, the percentage of vehicles notified was very low, being 0 % for DER/DF, 0.07 % for DNIT, and 0.57 % for DETRAN/DF. This result corroborates the behavior of accelerating and braking shown in Figs. 7–9, i.e, drivers conscientiously slow down so as not to be fined.

4.5.2. Direction of entry and exit

The next analysis will refer to the direction of entry and exit from the urban environment to the highway environment. To verify whether the speed practiced by the same drivers entering the Federal District and leaving the Federal District is the same, the difference between the average entry speed and the average exit speed of the same drivers who travel both routes was calculated, which reduced the amount of data to 63 observations (Table 8). The null hypothesis of this paired test is that H0) the average speeds at entering and exiting the city are the same, versus the alternative that H1) the average speeds at entering and exiting the city are different. When the distribution of these differences follows a normal distribution, the Student's *t*-test is used for paired data, otherwise, the non-parametric Wilcoxon test is used.

The results presented in Table 8 show that for the highways under the jurisdiction of DER/DF, the mean difference in average speeds was 8.62 km/h, which according to the Student's *t*-test (the distribution was considered normal), the null hypothesis of equality can be rejected, considering a 5 % significance level. This shows that the average speed of drivers entering the urban environment from a highway is, on average, 8.62 km/h higher than the average speed of these same drivers when they are leaving the urban environment, which allows us to conclude that the perception of speed depends on the direction of the highway and suggesting that factors such as urban interventions (traffic lights, radars, crosswalks, roundabouts, speed bumps) and absence of traffic affect the driver's speed.

In the case of the highways under the jurisdiction of DNIT (Table 8), the mean difference in average speeds was −3.13 km/h and the null hypothesis of equality was not rejected, according to the Wilcoxon test (the distribution was not considered normal), considering a 5 % significance level. This result was expected since the driver is already in a highway environment far from the urban area, and the driver's speed no matter the direction of the road.

The results indicate that there is a significant difference in the entry and exit speeds in the jurisdiction of the DER/DF, which supports the hypothesis that traffic infrastructure and road characteristics influence speed (Fig. 2). Specifically, the entry speeds on the DER/DF highways are higher, possibly because drivers are coming from DNIT highways, which have higher allowed speeds. This leads to perceptual inertia, where drivers take time to realize the need to reduce speed when entering urban areas. In contrast, at the exit of the urban area under the jurisdiction of the DER/DF, the speeds do not show much difference, since drivers are already at low speeds when approaching a road with higher speed limits, such as those of the DNIT.

This research reflects the importance of the traffic infrastructure and road characteristics, where drivers adjust their speeds according to site conditions, especially in areas with and without urban interventions (traffic lights, radars, crosswalks, roundabouts, speed bumps). On DER/DF highways, the need for adaptation is greater when entering the city, while at the exit, the transition to higher speeds is more natural and gradual due to the preparation to access DNIT highways.

4.5.3. *Comparison of speeds with vehicle characteristics*

Another dimension explored in this study to better understand the factors that determine speed dynamics was the relationship between vehicle power and average speed. The intention is to check whether vehicles with higher horsepower tend to exceed speed limits more frequently than vehicles with lower horsepower, just as made in naturalist studies. This analysis, from an observational point of view, can better quantify this behavior since there is a broader range of investigation.

The analysis of data on the speed of less powerful vehicles exemplified with basic models, and most used in Brazil, such as Fiat MOBI, Hyundai HB20, and Chevrolet ONIX, in DNIT, DER/DF, and DETRAN/DF jurisdictions, reveals important information on the speed-related behavior of these vehicles in the 3 jurisdictions, as shown in Table 9.

In the jurisdiction of DNIT, a considerable percentage of the less powerful vehicles traveling below the allowed speed was observed, which is around 41.89 % of the records. However, a significant percentage of 30 % of vehicles exceeding the allowed speed by more than 20 % stands out. This high percentage suggests that, despite these vehicles being less powerful, drivers still tend to exceed speed limits significantly. The high frequency of speeding in this category may be associated with more open road conditions or a perception of lower risk or enforcement, encouraging higher speed behaviors even in less powerful vehicles.

In the context of DER/DF, most of the less powerful vehicles (70.06 %) travel below the allowed speed, indicating a more cautious or regulated behavior in the areas under this jurisdiction (remember that the drivers are in the urban environment already). The presence of vehicles above 20 % of the speed limit is significantly low (only 1.19 %), which suggests tighter control or greater awareness of the risks associated with speeding. The road characteristics, urban interventions (traffic lights, radars, crosswalks, roundabouts, speed bumps), and inspection seem to be more effective in the sections of DER/DF to maintain safer speeds, especially for less powerful vehicles.

On DETRAN/DF roads, a more varied distribution is observed, with 34.40 % of less powerful vehicles traveling below the limit. This variation indicates that less powerful vehicles in DETRAN/DF areas show mixed behavior, with a relevant tendency to exceed speed limits. Reasons may include road features that encourage higher speeds, or a difference in risk perception among drivers.

Table 6
Speed ranges DNIT x DETRAN/DF.

Speed Range DNIT Frequency Percent (row)	Speed Range DETRAN/DF				Total
	1. Below Allowed Speed	2. Between 0 % and 10 % Above Allowed Speed	3. Between 10 % and 20 % Above Allowed Speed	4. Above 20 % Allowed Speed	
1. Below Allowed Speed	2,456 40.79	1,645 27.32	1,270 21.09	650 10.80	6,021 100.00
2. Between 0 % and 10 % Above Allowed Speed	906 37.52	670 27.74	538 22.28	301 12.46	2,415 100.00
3. Between 10 % and 20 % Above Allowed Speed	826 35.31	680 29.07	486 20.78	347 14.84	2,339 100.00
4. Above 20 % Allowed Speed	1,562 28.88	1,506 27.84	1,360 25.14	981 18.14	5,409 100.00
Total	5,750 35.53	4,501 27.81	3,654 22.58	2,279 14.08	16,184 100.00

Table 7
Comparison of the average speed range and no violation at the radar point.

Speed Range	DNIT		DER/DF		DETRAN/DF	
	Freq.	%	Freq.	%	Freq.	%
1. Below Allowed Speed	6,021	100.00	12,439	100.00	5,750	100.00
2. Between 0 % and 10 % Above Allowed Speed	2,414	99.96	2,851	100.00	4,501	100.00
3. Between 10 % and 20 % Above Allowed Speed	2,337	99.91	743	100.00	3,654	100.00
4. Above 20 % Allowed Speed	5,405	99.93	151	100.00	2,266	99.43
TOTAL	16,184	–	16,184	–	16,184	–

Table 8
Comparison statistics of average speeds on entry and exit of urban area.

Jurisdiction	Observations	Average difference	Statistic	p-value	Decision
DER/DF	63	8.62 km/h	$t = 3.29$	0.0017	Reject (5 %)
DNIT	63	−3.13 km/h	Wilcoxon = -183	0.2129	Do not Reject (5 %)

Table 9
Comparison of average speeds of less powerful vehicles.

Speed Range	Less powerful vehicles (MOBI, HB20, ONIX)					
	DNIT		DER/DF		DETRAN/DF	
	Freq.	%	Freq.	%	Freq.	%
1. Below Allowed Speed	666	41,89	1,114	70.06	547	34.40
2. Between 0 % and 10 % Above Allowed Speed	225	14.15	343	21.57	441	27.74
3. Between 10 % and 20 % Above Allowed Speed	222	13.96	114	7.17	392	24.65
4. Above 20 % Allowed Speed	477	30.00	19	1.19	210	13.21
Chi-squared test (p-value)	$\chi^2_3 =$ 349.60 (< 0.0001)		$\chi^2_3 =$ 1861.57 (< 0.0001)		$\chi^2_3 =$ 149.50 (< 0.0001)	

Table 10
Comparison of average speeds of more powerful vehicles.

Speed Range	More powerful vehicles (COROLLA, CIVIC, JETTA, AUDI, BMW)					
	DNIT		DER/DF		DETRAN/DF	
	Freq.	%	Freq.	%	Freq.	%
1. Below Allowed Speed	118	34.10	241	69.65	110	31.79
2. Between 0 % and 10 % Above Allowed Speed	57	16.47	83	23.99	113	32.66
3. Between 10 % and 20 % Above Allowed Speed	32	9.25	17	4.91	42	12.14
4. Above 20 % Allowed Speed	139	40.17	5	1.45	81	23.41
Chi-squared test (p-value)	$\chi^2_3 =$ 87.73 (< 0.0001)		$\chi^2_3 =$ 408.72 (< 0.0001)		$\chi^2_3 =$ 37.74 (< 0.0001)	

The chi-square tests of homogeneity indicate that the differences in speed distributions between the categories are statistically different (rejection of the null hypothesis of equality of proportions), considering 5 % of significance. This confirms that there are relevant and non-random variations in the driver's speed behavior of less powerful vehicles in different jurisdictions, reflecting the influence of road, regulatory, and inspection factors specific to each jurisdiction. These results show that, even for less powerful vehicles, in DER/DF, there is a clear trend towards lower speeds, while in DNIT and DETRAN/DF, a significant part of the vehicles exceeds the limits, especially above 20 % in the DNIT, being an acceptable result for the latter.

On the other hand, the analysis of more powerful vehicles, such as Toyota COROLLA, Honda CIVIC, Volkswagen JETTA, AUDI, and BMW, highlights different behaviors regarding speed limits, reflecting the specific characteristics of each jurisdiction and the potential influences of higher performance vehicles, as shown in Table 10.

On DNIT highways, a significant proportion of 40.17 % of more powerful vehicles travel above 20 % of the allowed speed, which indicates more aggressive behavior and a fuller use of the capacity of more powerful vehicles. Only 34.10 % travel below the speed limit, suggesting that the road structure or traffic conditions in DNIT areas may be encouraging drivers to exceed the speed limits. This high percentage of speeding in the highest lane suggests the need for greater enforcement or specific interventions for traffic calming.

In the context of DER/DF, 69.65 % of more powerful vehicles travel below the allowed speed, which reflects a considerably more cautious or well-regulated behavior within this jurisdiction. Only 1.45 % of vehicles are above 20 % of the allowed speed, indicating that road interventions (traffic lights, radars, crosswalks, roundabouts, speed bumps), enforcement, or other control measures in DER/DF are particularly effective in maintaining safe speeds, even for vehicles with higher acceleration capacity and performance.

On the urban roads under the responsibility of DETRAN/DF, there is a more balanced distribution between the speed ranges, with 31.79 % of more powerful vehicles traveling below the limit, while 23.41 % exceed the allowed speed by more than 20 %. The distribution also shows 32.66 % of vehicles in the range up to 10 % above the limit, which suggests moderate behavior, but with a tendency to high speed. The differences in behaviors can be attributed to variations in inspection, road characteristics, or even in the profile of the drivers who driving these vehicles in DETRAN/DF jurisdiction.

The results of the chi-square testing for each jurisdiction indicate that the differences in speed distributions between the categories are statistically different (rejection of the null hypothesis of equality of proportions), considering a 5 % significance level. This indicates that the speed behavior of drivers of more powerful vehicles varies significantly in different jurisdictions, reflecting specific influences of the road and regulatory context.

Data shows that more powerful vehicles have a greater tendency to exceed speed limits, especially on highways under the jurisdiction of DNIT, where almost half of vehicles run above 20 % of the limit. In contrast, on highways under the jurisdiction of DER/DF, most drivers remain below the speed limits, suggesting effectiveness in speed control measures or driver awareness. On the roads under the jurisdiction of DETRAN/DF, the behavior is intermediate, with a balanced distribution, but still a significant presence of speeding.

The comparative analysis of Tables 9 and 10 provided for less and more powerful vehicles in DNIT, DER/DF and DETRAN/DF jurisdictions, offers important insights into how vehicle power and traffic infrastructure and road characteristics influence the speed practiced by drivers, about the hypotheses of this research. The main hypothesis is that vehicular and traffic infrastructure and road characteristics influence driver speed, with drivers tending to accelerate more in environments without traffic retention and to reduce speed in areas with urban interventions (traffic lights, radars, crosswalks, roundabouts, speed bumps). The data support this hypothesis, especially when looking at the difference in behavior between less and more powerful vehicles in different jurisdictions.

The comparison between the two groups of vehicles shows that, regardless of the power, there is a variation in the behavior of drivers according to the traffic infrastructure and road characteristics. In DNIT, where there are fewer restrictions, drivers of more powerful vehicles significantly exceed the speed limits. In DER/DF, even more powerful vehicles remain mostly below the allowed limit. This indicates that, despite the vehicle's capabilities, the driver's behavior is strongly determined by the traffic infrastructure and road characteristics and the interventions present, suggesting that the speed practiced is not only a function of the vehicle characteristics but also of the road conditions and the current regulations. This information supports understanding how vehicle power interacts with the regulatory and traffic infrastructure and road characteristics, directly influencing driver behavior in terms of compliance with speed limits.

To verify an association between a possible average speed violation notification, classes "1. Below Allowed Speed" and "2. Between 0 % and 10 % Above Allowed Speed" were aggregated to "1. Up to 10 % Allowed Speed", and classes "3. Between 10 % and 20 % Above Allowed Speed" and “4. Above 20 % Allowed Speed” were aggregated to “2. Above 10 % Allowed Speed”, as shown in Table 11. On roads under the jurisdiction of DNIT, the speed pattern indicates a slight tendency of more powerful vehicles to exceed speed limits more frequently. However, this difference is not statistically significant (p-value = 0.8297), which suggests that, although the power of the vehicle may exert some influence on the speed behavior, it is not a determining factor in all situations.

On the other hand, on the roads under the jurisdiction of DER/DF, it is observed that the speed behavior is quite consistent between the power categories, indicating that most drivers maintain speeds close to the regulated limit, regardless of the vehicle’s power. On the roads under the jurisdiction of DETRAN/DF, the behavior is like that observed in DER/DF, where most vehicles, regardless of horsepower, maintain speeds within or close to the allowed limit. This analysis reinforces the conclusion that vehicle power is not a determining factor for speed behavior, in line with the idea that drivers of more powerful vehicles do not necessarily always travel at high speeds, just as drivers of less powerful vehicles do not necessarily maintain lower speeds.

Still, on the relationship between speed behavior and vehicle power, Table 12 allows us to evaluate whether vehicle power has a statistically significant relationship with speed behavior, performing hypothesis tests to compare the proportions of vehicles traveling at up to 10 % of the allowed speed between less and more powerful vehicle categories (see data in Table 11). The hypotheses are: H0) the proportion of vehicles traveling at up to 10 % of the allowed speed is the same between less and more powerful vehicles; H1) the proportion of vehicles traveling at up to 10 % of the allowed speed is different between less and more powerful vehicles.

The results of the tests show that in all cases, the null hypothesis cannot be rejected, considering 5 % of significance. This means that it cannot be said that vehicle power significantly influences the tendency to exceed speed limits in different jurisdictions. Thus, the data indicate that, regardless of the vehicle’s power, speed behavior tends to be consistent on different road segments, with most vehicles, either less powerful or more powerful, remaining close to the allowed limits. Therefore, vehicle power is not a determining factor for speed behavior in the circumstances analyzed, suggesting that fast vehicles do not always go fast and slow vehicles do not always go slow. That is, the behavior of having more aggressive or more cautious driving is always more related to the drivers.

5. Concluding remarks

This study used an observational approach to analyze the speed dynamics on different types of roads, differing from naturalistic and experimental studies, such as those conducted by Amancio et al. (2024), for example, which involve data collection under controlled conditions or continuous monitoring of drivers. The observational method applied in this work allowed an analysis of the behavior of drivers using real data collected by radars equipped with OCR, which are comparable to experimental and naturalistic studies. In addition, it has much lower costs than the latter and allows for much greater coverage. However, it did not allow the control of external variables, such as weather conditions, temporary works or events that alter the flow of traffic, which could improve the analyses, having a better understanding of the dynamics of the average speed. And of course, it is not capable of covering “human fator” variables that explain driving behaviors, such as age, driving experience or history of violations, which limits the correlation between speed patterns and driver characteristics.

Table 12
Comparison of the proportions of vehicles traveling up to 10% of the allowed speed.

Vehicle Power	Jurisdiction					
	DNIT		DER/DF		DETRAN/DF	
	Freq.	%	Freq.	%	Freq.	%
Less Powerful	891	56.04	1,475	91.14	988	62.14
More Powerful	175	50.58	324	93.64	223	64.45
Z Test (p-value)	Z = 1.32774(0.18455)		Z = −1.46690(0.14258)		Z = −0.64382(0.51981)	

Unlike naturalistic studies, which often require a complex infrastructure for the installation of equipment in vehicles or simulated scenarios, the present study had zero cost, being carried out exclusively with data made available by traffic agencies. This approach not only significantly reduces costs, but also demonstrates the feasibility of large-scale replication, both in Brazil and overseas, provided there is effective cooperation between the agencies responsible for managing traffic data.

Thus, the analysis of speed dynamics on different types of roads using OCR technology revealed important information about driver behavior and the effectiveness of electronic enforcement mechanisms. The results indicate that, although OCR systems are effective in reducing speed and improving road safety, there are still challenges related to the adaptive behavior of drivers, such as the phenomenon of “kangaroo jump”, where drivers accelerate after passing through radars and decelerate before approaching the next equipment. This behavior suggests that the presence of radars is not enough to maintain safe speeds along the entire monitored segment, highlighting the need for average speed enforcement, which can maintain a constant speed. In line with this, a finding of this study is that vehicle power is not a determining factor for high speeds, but the driver’s desire.

An important finding of this study is the importance of the traffic infrastructure and road characteristics, where drivers adjust their speeds according to site conditions, especially in areas with and without urban interventions. A classical urban area has several factors that decrease speed such as traffic lights, radars, crosswalks, roundabouts, number of lanes, speed bumps, which create a barrier to drivers who want to high speeds. Therefore, these geometry aspects of the roads alone do not eliminate accidents, as the human factor is always present, but they contribute to road safety. For example, speed limits can be more effective in some areas than others when there are not as many geometric aspects as those discussed above or when there are facilities around the road such as schools, hospitals, etc. In addition, the implementation of signage showing for example “average speed monitored in this road section” can be used to improve road safety.

Table 11
Comparison of less powerful and more powerful vehicles.

Speed Range	Less Powerful Vehicles vs More Powerful Vehicles											
	DNIT				DER/DF				DETRAN/DF			
	Less Powerful		More Powerful		Less Powerful		More Powerful		Less Powerful		More Powerful	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
1. Up to 10 % Allowed Speed	891	56.04	175	50.58	1,457	91.64	324	93.64	988	62.14	223	64.45
2. Above 10 % Allowed Speed	699	43.96	171	49.42	133	8.36	22	6.36	602	37.86	123	35.55
Chi-squared test (p-value)	χ^2_1 = 23.1849(<0.0001)		χ^2_1 = 0.0462(0.8297)		χ^2_1 = 1102.501(<0.0001)		χ^2_1 = 263.5954(<0.0001)		χ^2_1 = 93.7082(<0.0001)		χ^2_1 = 28.9017(<0.0001)	

However, drivers should be more aware of the dangers of higher speeds and the importance of traffic infrastructure and road characteristics in influencing average speeds. The studies by Da Silva and Santos (2020) and Da Silva and Dos Santos (2025) reinforce the importance of educational and visual interventions in speed management, such as sending educational letters to drivers caught speeding and exposing injured vehicles as visual reminders of traffic hazards. These actions showed initial effectiveness in changing the behavior of drivers, leading to temporary reductions in the average speed. However, the effects of these measures tend to dissipate over time, highlighting the need for more sustainable and long-term solutions to control the regulatory speed limits on each segment.

Regarding the effectiveness of OCR radars, the study shows that, despite the high initial costs, the long-term benefits, such as the possible reduction of speeding-related claims and operational efficiency, justify the investment. However, the implementation of these systems must be accompanied by measures that promote safer behavior in traffic, in addition to road interventions that reinforce the need for speed control in critical areas. One further investigation is about an optimal distance that is particularly effective for measuring average speeds.

Therefore, based on this study, it is highlighted that the best approach for the control and moderation of speeding is the average speed enforcement, which is effective in minimizing speed peaks, observed in acceleration and deceleration behaviors near radars. Monitoring the average speed along a segment promotes a more linear and consistent control of vehicle speed, reducing the risk behaviors associated with temporary speed adjustments, common in scenarios where enforcement is perceived as punctual.

CRediT authorship contribution statement

Alan Ricardo da Silva: Software, Conceptualization, Writing – original draft, Funding acquisition, Validation, Formal analysis, Investigation, Supervision, Writing – review & editing, Methodology, Data curation. **Rodrigo Nunes Cavalcante:** Writing – review & editing, Investigation, Formal analysis, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research received funding from the National Council for Scientific and Technological Development (Cnpq), grant number 306120/2021-6, and from the Universidade de Brasilia, grant number 23106.084484/2024-34.

References

Aarts, L., van Schagen, I., 2006. Driving speed and the risk of road crashes: a review. Accid. Anal. Prev. 38 (2), 215–224.
AASHTO, 2006. Roadside Design Guide, 3rd ed. American Association of State Highway and Transportation Officials, Washington, DC.
AASHTO, 2010. Highway Safety Manual, First Edition, HSM-1. American Association of State Highway and Transportation Officials, Washington, DC.
Amancio, E.C., Gadda, T.M.C., Corrêa, J.N., da Bonetti, G., Oviedo-Trespalacios, C., Bastos, O., 2024. Impact of speed limit enforcement cameras on speed behavior: Naturalistic evidence from Brazil. Transp. Res. Record.
Bastos, J.T., dos Santos, P.A.B., Amancio, E.C., Gadda, T.M.C., Ramalho, J.A., King, M.J., Oviedo-Trespalacios, O., 2021. Is organized carpooling safer? Speeding and distracted driving behaviors from a naturalistic driving study in Brazil. Accid. Anal. Prev. 152, 105992.
Brazil (1997) Lei 9.503. Institui o Código de Trânsito Brasileiro. Available at: https://www.planalto.gov.br/ccivil_03/leis/l9503.htm. Access in mar. 2024.
Contran (2020) Resolução CONTRAN n° 798. Available at: https://www.legisweb.com.br/legislacao/?id=401145 . Access in aug. 2024.
Cooper, P.J., Novaco, R.W., 1986. Eliminating aggressive driving: A cognitive-behavioral approach. J. Consult. Clin. Psychol. 54 (2), 226–232.
da Silva, A.R., Santos, M.M., 2020. Impact on average vehicle speed with the introduction of educational actions and optical character recognition equipment in the Federal District, Brazil. Transportes 28, 294–308.
da Silva, A.R., dos Santos, T.M., 2025. Impact of traffic campaigns on the average speed of vehicles on urban roads. Travel Behav. Soc. 39, 100976.
Dai, D., 2012. Identifying clusters and risk factors of injuries in pedestrian-vehicle crashes in a GIS environment. J. Transp. Geogr. 24, 206–214.
de Pauw, E., Daniels, S., Brijs, T., Hermans, E., Wets, G., 2014. Behavioural effects of fixed speed cameras on motorways: Overall improved speed compliance or kangaroo jumps? Accid. Anal. Prev. 73, 132–140.
Elvik, R., Christensen, P., Amundsen, A., 2004. Speed and Road Accidents. an Evaluation of the Power Model. Institute of Transport Economics TOI, Oslo.
ETSC (2021) European Transport Safety Council, Automated Enforcement Strategies for Road Safety. ETSC Annual Report, 45–49.
ELVIK, R., VADEBY, A., HELS, T., VAN SCHAGEN, I., 2019. Updated estimates of the relationship between speed and road safety at the aggregate and individual levels. Accident Analysis & Prevention 123, 114–122.
Faiz, R.U., Mashros, N., Hassan, S.A., 2022. Speed behavior of heterogeneous traffic on two-lane rural roads in Malaysia. Sustainability 14, 16144.
Høye, A., 2014. Speed cameras, section control, and kangaroo jumps-a meta-analysis. Accid. Anal. Prev. 73, 200–208.
Jiménez-Bravo, D.M., Lozano Murciego, A., Sales Mendes, A., Sánchez San, A., Blás, H., 2022. Tracking multiple objects in traffic environments: A systematic literature review. Neurocomputing 494, 43–55.
Job, S., Cliff, D., Fleiter, J., Flieger, M., Harman, B. (2020) Guide for determining readiness for speed cameras and other automated enforcement. Geneva: Global Road Safety Facility and the Global Road Safety Partnership. Available at: https://documents1.worldbank.org/curated/en/794451581062198463/pdf/Guide-for-Determining-Readiness-for-Speed-Cameras-and-other-Automated-Enforcement.pdf. Access in feb. 2024.
Melman, T., Tapus, A., Jublot, M., Mouton, X., Abbink Winter Joost de, D., 2022. Do sport modes cause behavioral adaptation? Transport. Res. F: Traffic Psychol. Behav. 90, 202–214.
Montella, A., Persaud, B., D'Apuzzo, M., Imbriani, L.L., 2012. Safety evaluation of automated section speed enforcement system. Transp. Res. Rec. 2281, 16–25.
Ogden, K. W. (1996) Safer Roads: A Guide to Road Safety Engineering. Melbourne: Ashgate Publishing Ltd. Available at: https://trid.trb.org/View/459597. Access in May. 2024.
Rao, A.M., Velmurugan, S., Lakshmi, K.M.V.N., 2017. Evaluation of influence of roadside frictions on the capacity of roads in Delhi, India. Transp. Res. Procedia 25, 4771–4782.
Retting, R.A., Ferguson, S., 2003. A review of evidence-based traffic engineering measures designed to reduce pedestrian-motor vehicle crashes. Am. J. Public Health 93 (9), 1456–1463.
Sadia, R., Bekhor, S., Polus, A., 2018. Structural equations modelling of drivers' speed selection using environmental, driver, and risk factors. Accid. Anal. Prev. 116, 21–29.
Schrank, D., Eisele, B., Lomax, T., (2012) Urban Mobility Report. College Station: Texas Transportation Institute. Available at: https://static.tti.tamu.edu/tti.tamu.edu/documents/umr/archive/mobility-report-2012.pdf. Access in may. 2024.
Stradling, S.R., Cooper, P.J., Charlton, S.G., 1994. The effects of stress and anger on driving performance. Accid. Anal. Prev. 26 (4), 473–484.
Taylor, M. C., Lynam, D. A., Baruya, A. (2000) The effects of drivers' speed on the frequency of road accidents. Wokingham: Transport Research Laboratory. (TRL Report 421). Available at: https://trl.co.uk/uploads/trl/documents/TRL421.pdf. Access in apr. 2024.
Trafikverket (2012) Road Safety: Vision Zero on the move. Borlänge: Grafisk Form. 20 p. ISBN 978-91-7467-231-2. Available at: https://static.pmg.org.za/140218roadsafety.pdf. Access in mar. 2024.
van Nes, N., Bärgman, J., Christoph, M., van Schagen, I., 2019. The potential of naturalistic driving for in-depth understanding of driver behavior: UDRIVE results and beyond. Saf. Sci. 119, 11–20.
Wilson, C., Willis, C., Hendrikz, J.K., Le Brocque, R., Bellamy, R., 2010. Speed cameras for the prevention of road traffic injuries and deaths. Cochrane Database. Syst. Rev. 10, CD004607.
WHO (2004) World Health Organization. World report on road traffic injury prevention. Available at: https://www.who.int/publications/i/item/world-report-on-road-traffic-injury-prevention. Access in May. 2024.
WHO (2017) World Health Organization. Save LIVES: a road safety technical package. Geneva: World Health Organization. Available at: https://www.who.int/publications/i/item/save-lives-a-road-safety-technical-package. Access in May. 2024.
WHO (2018) World Health Organization. Global status report on road safety. Geneva: World Health Organization. Available at: https://www.who.int/publications/i/item/9789241565684. Access in May. 2024.