Statistical Analysis of Experimental Crossing Speed on Vertical Traffic Calming Devices: Influence of Vehicle Category and Road Safety Implications

Sofia Nardoianni[1], Giuseppe Cappelli[1,2], Mauro D'Apuzzo[1(✉)], and Vittorio Nicolosi[2]

[1] University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
{sofia.nardoianni,giuseppe.cappelli1,dapuzzo}@unicas.it
[2] University of Rome "Tor Vergata", Via del Politecnico, 1, 00133 Rome, Italy
nicolosi@uniroma2.it

Abstract. The growing number of accidents involving pedestrians every year represents a critical issue for road safety in urban areas. These accidents are often caused by excessive speed and risky behaviour by the drivers of the vehicles involved. In this context, traffic calming devices, especially raised pedestrian crossings (RPCs), are installed to reduce the transit speed of vehicles and allow pedestrians to cross safely. This study aims to determine whether the transit speeds of vehicles on a traffic calming device depend on the category of the vehicle itself. To this end, an experimental data collection was conducted on an RPC case study, considering different collection days, in various time slots. Statistical tests, including ANOVA (F-test), Student's t-test, and Tukey's correction, were carried out on these data, showing a significant correlation between the crossing speed of the traffic calming device and the vehicle category. This study, therefore, lays the foundations for urban planning dedicated to pedestrian safety, enabling the adaptation of traffic calming device characteristics according to the vehicle fleet, maximizing their effectiveness.

Keywords: Traffic calming · ANOVA test · T-test · Traffic safety

1 Introduction

As awareness of sustainable mobility increases, it becomes necessary to implement measures to mitigate the risk that vulnerable road users incur during their mobility. Vehicular traffic, especially in urban areas, is one of the main factors affecting the safety of vulnerable users. Among the risk mitigation measures, the most widespread is the installation of traffic calming devices that induce the vehicle's driver to slow down in their vicinity. Risk mitigation measures such as speed bumps, raised platforms, and narrowing of the carriageway are designed to induce drivers to maintain speeds appropriate to the road context [1–3]. However, it is crucial to assess the effectiveness of these devices to understand whether they actually reduce the speed of vehicles passing over them and thus ensure the safety of vulnerable road users [4–6].

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O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15892, pp. 65–80, 2026.
https://doi.org/10.1007/978-3-031-97638-4_5

Nevertheless, the type of traffic calming device and its installation configuration greatly influence their effectiveness [4, 7–10]. The layout, height, width, and material with which they are made can directly affect the reduction of vehicular speed and the perception of safety by pedestrians [11–18].

Several studies have shown that vehicle speed in the presence of speed bumps varies according to the driver's perception of the severity of the traffic calming measure [19–23]. Therefore, the analysis of the behaviour of drivers and pedestrians is essential for the design of interventions that reduce the risk of collisions [10, 24]. Understanding the dynamics of interaction between vehicles and traffic calming devices, therefore, makes it possible to optimize the latter's design, ensuring a balance between effectiveness in reducing speed and driving comfort. In this context, Raised Pedestrian Crossings (RPCs) emerge as one of the most effective solutions for pedestrian protection and vehicle speed reduction [7].

This study aims to analyze driver behaviour near RPCs in detail, to identify design solutions that improve pedestrian safety and promote sustainable mobility. The objective of the present research is to evaluate whether the crossing speed of an RPC is affected by the category of the vehicle.

To address this question, an approach based on collecting and analysing experimental data obtained through video recordings was adopted. The vehicles were classified into three main categories: medium-sized cars, sedans, and SUVs. Data analysis was conducted through statistical tests such as the ANOVA test [25], followed by a t-Student test [26, 27], and, where necessary, Tukey correction [28, 29] to minimize the risk of Type I errors. The study was conducted on a specific case in a city in central Italy, near a university area, where it was possible to analyze the behaviour of drivers in real traffic conditions. The results obtained provide useful indications for the design of future traffic calming devices and for the optimization of road safety strategies. In particular, it is hoped that local administrations will utilize these findings to improve the design of traffic calming measures and raise awareness among drivers of their effectiveness.

The structure of the paper includes a Sect. 1 in which an overview of the focus of the case study is made, a Sect. 2 where the aspects of the current literature on this subject are explored, a Sect. 3 where the methodology adopted is illustrated, a Sect. 4 in which the site chosen for the case study is described, a Sect. 5 in which the processing of the data is defined with the related results appropriately commented and finally a Sect. 6 of conclusion.

2 Related Research

The installation of traffic calming devices involves a variation in the speed and flow of traffic at the site where they are installed [30]. Experimental studies have shown that the extent of the speed reduction that is obtained thanks to the installation of such devices depends on:

- Typology and geometry of the device [31–41]. In particular, for example, Parkill et al. [35] have highlighted how the geometry of the speed hump affects its performance by analyzing the longitudinal acceleration at the passage of a parabolic and a trapezoidal one. It has been shown that the parabolic speed hump produces a more progressive

reduction than the latter. Shauna et al. [39] have shown that, among the various types of traffic calming devices, speed humps and speed tables significantly reduce the number of vehicles exceeding the speed limit allowed on the road where they are installed and especially near the device itself. Similarly, Moreno et al. [40] investigate the influence of the geometry of the traffic calming devices on the induced speed reduction, noting that the latter is strongly influenced by the inclination of the entrance ramp and the length of the device.

- Area of influence where slowing occurs [3, 42, 43]. The possible presence of schools, parking areas, intersections, and shops significantly affects the speed reduction induced by the traffic calming device. Precisely about this, Distefano et al. [3] describe how the different installation context of traffic calming devices varies their effectiveness.
- Placement of devices with speed profile evaluation [44–47]. Namee et al. [46] have highlighted, for example, how traffic calming devices are extremely effective in intersection corners.

However, several studies confirm that the installation of such devices alters speeds and flows even on the roads adjacent to those in which they were installed [48–50].

The category of vehicles passing through the traffic calming device does not appear among the parameters listed above.

The current literature investigates the average effects on traffic flows by analyzing the effects produced and the effectiveness of traffic calming devices without distinguishing how the various categories of vehicles are subject to different effects. A study [51] showed that traffic calming devices affect personal and non-personal vehicles differently, with variations in average speed and acceleration and deceleration patterns.

So, in the literature this in-depth study is still rather unexplored, and this is precisely what we assume to do with this paper: to investigate how the different categories of vehicles significantly influence the speed reduction recorded in the vicinity of the traffic calming device and therefore how this parameter is essentially important to consider in the design phase of the latter.

3 Methodology

The present research aims to evaluate whether or not the crossing speeds of the traffic calming device depend on the category of vehicles in transit.

The methodology adopted follows a rigorous approach that integrates the collection, processing, and statistical analysis of experimental data concerning the speed of crossing a traffic calming device, which is differentiated according to the category of vehicles that surmount it.

The data was acquired via a video recording system, the position of which allows for a clear view of the various designated milestones, including the start and end of the device itself. The measurements were carried out for several typical weekdays and for different time slots in order to have a representative sample of real traffic conditions.

Subsequently, the collected videos were analyzed to extract the crossing speeds of vehicles at designated points. The data obtained was then subjected to a statistical analysis to determine whether there was a significant relationship between the vehicle category

and the crossing speed of the device. To explore these possible differences, an ANOVA (Analysis of Variance) statistical test is applied [25], which allows for verification of whether the average speeds of the different categories of vehicles are significantly different from each other. This test, known as an F-test, is specifically designed to compare multiple data groups simultaneously. If the ANOVA test indicates the presence of statistically significant differences, the analysis continues with a Student's t-test [26, 27], used for pairwise comparison between vehicle categories. If this test also confirms the significance of the differences, Tukey's correction is applied [28, 29] to reduce the risk of Type I errors (false positives). Conversely, the statistical tests do not detect significant differences, and the flow of analysis stops, concluding without further processing.

This methodology is illustrated in Fig. 1 through a flow chart.

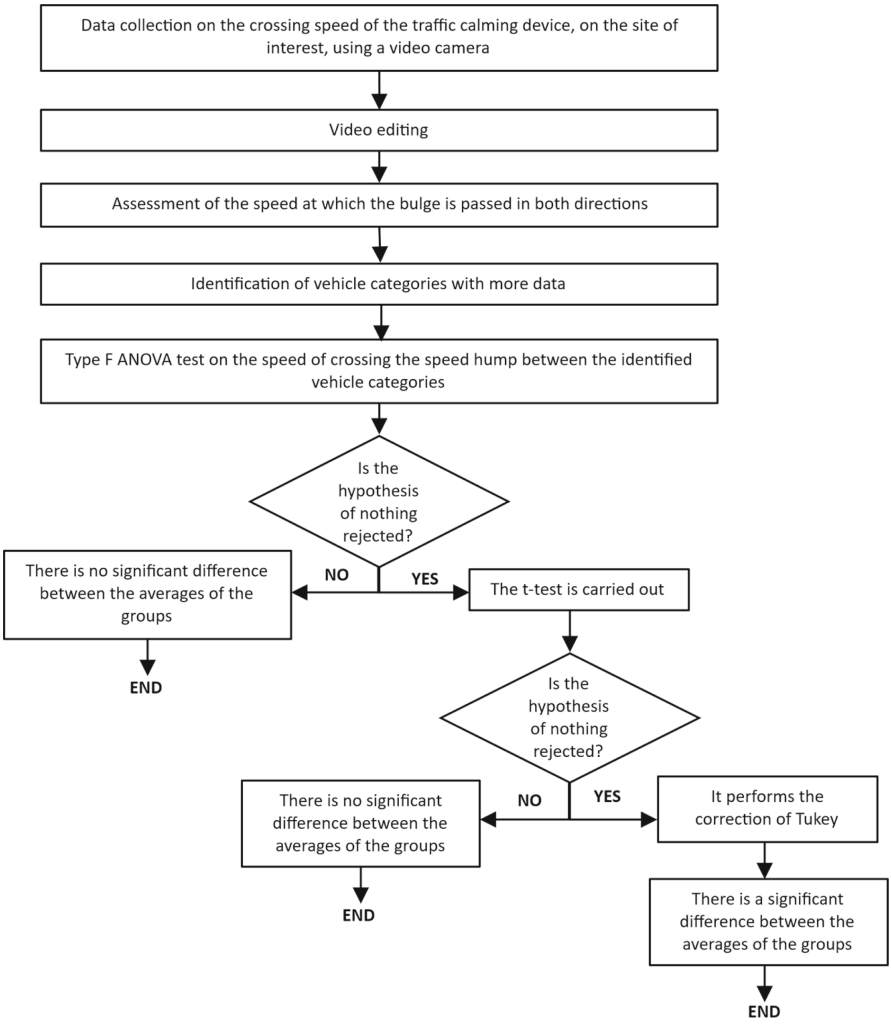

Fig. 1. Flow chart of methodology

4 Case Study

As previously mentioned, the research aims to assess whether there are differences in speed regulation when passing the traffic calming device, depending on the type of vehicle you are driving. The study was conducted on an RPC (Raised Pedestrian Crossing) located in a city in central Italy, in Cassino near a university facility.

The traffic calming device has a trapezoidal shape and a geometry illustrated in Fig. 2.

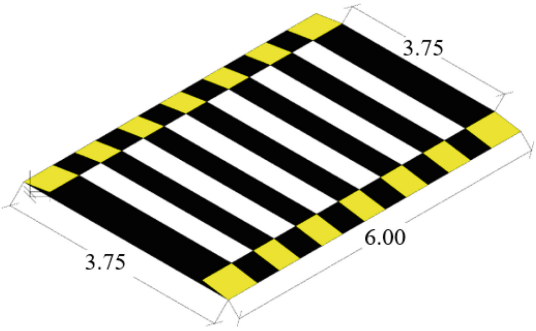

Fig. 2. Shape and geometry of the traffic calming device.

The identified site allows a significant amount of data to be collected for analysis, as it is characterized by a high vehicular flow. At the same time, it allows to have a clear shot for camera placement (see Fig. 3) without affecting driver behavior.



Fig. 3. Video camera position

For this reason, the recording equipment was installed at a strategic point (in red in Fig. 3) on the top of building B of the Engineering complex. This choice made it possible to obtain a wide overview of the area of interest, ensuring detailed and reliable footage.

To be able to process data regarding the speeds of vehicles passing through the site of interest, a series of milestones was defined, the distance of which was calculated based on the camera acquisition frequency (20 fps, i.e., one frame every 0.05 s) and an average transit speed of 10 m/s. Each frame, therefore, corresponds to a displacement of about 50 cm. To improve accuracy, an interval of 10 frames (0.5 s) was chosen, resulting in a distance between the finish lines of about 5 m. Next, with video modeling software, a digital grid was created to record the crossing times.

The analysis considered the two directions of travel separately, choosing as a reference point the upper limit of the vehicle for the direction "a" and the rear limit for the direction "b", in order to avoid obstacles to visibility.

Video recordings were collected over multiple days to account for variability in driver behaviour and traffic conditions, in particular, by carrying out data collection in different time slots, including the morning, early, and late afternoon, in order to obtain experimental data both in daylight and evening conditions. In addition, filming was carried out on sunny days with stable weather.

In the data analysis, the hypothesis of an 'isolated' vehicle was established, i.e., only vehicles maintaining a headway of at least 15 s compared to the previous vehicle were considered. Furthermore, data were excluded in cases where a vehicle's passage could have been influenced by obstacles on the sides of the roadway (such as parked vehicles) or by possible pedestrian crossings.

The acquisition of data also differentiates between directions of travel, indicating with the letter "a" the direction of travel that defines the entrance to the city of Cassino, while with the letter "b", the exit from the latter.



Fig. 4. Direction "a" in entrance to the city of Cassino [52]

For this case study, it is essential to analyze the data separately for the two directions of travel, as there is a significant elevation difference at the site of interest (see Figs. 4 and 5).

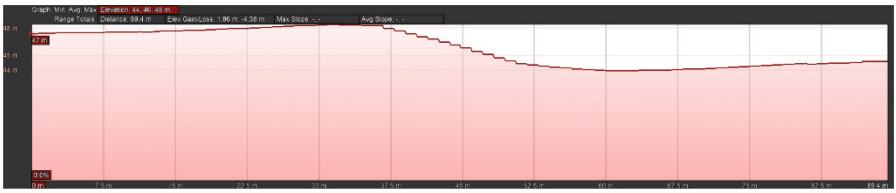

Fig. 5. Elevation profile of the site of interest in direction "a" [52]

Therefore, there is a decreasing slope in the direction of travel that defines the entrance to the city of Cassino, indicated with the letter "a" and, therefore, vice versa, an increasing slope in the direction "b" leaving the city.

5 Analysis of the Result

As regards the analysis of the experimental data collected, particular attention was paid to three categories of vehicles, as a greater amount of data is available on them, as shown in Table 1.

Table 1. Data collection about the category of vehicle

Category of vehicle	Amount of data in direction "a"	Amount of data in direction "b"
Medium-sized car	570	483
Sedans	185	187
Off-road/Sport Utility Vehicles	138	127

It was possible to derive the crossing speeds of the different vehicle categories, thanks to the processing of the data collected. Knowing the distance between the milestones set and being able to derive from the videos the time in which the vehicle reaches and exceeds the various milestones, it was possible to evaluate its speed, a parameter on which the following statistical tests were carried out.

To determine whether there was a significant statistical difference in the speed of crossing the RPC as the vehicle category varied, the F-test ANOVA test was performed on the aforementioned data. This statistical test estimates the variance between groups to assess whether differences in means are statistically significant. In particular, it assesses the probability that the null hypothesis (H_1), in the case in question, whether all vehicles have the same crossing speed, is rejected.

The ANOVA calculates the value of the F statistic as the ratio of the variability between groups ($MS_{between}$) and intra-group variability (MS_{within}):

$$F = \frac{MS_{between}}{MS_{within}} \tag{1}$$

where:

- $MS_{between}$: variability between the means of the groups;
- MS_{within}: variability within groups, due to random dispersion.

A high F value suggests that at least one group differs from the others.

However, to determine if the difference is significant, the F-value is compared to a critical F-distribution (F_c).

The probability that all vehicles have the same crossing speed is expressed through the p-value.

If this value is low (p-value$<\alpha$), it indicates a statistically significant difference between the means of the data groups. Otherwise, if the value is high (p-value$>\alpha$), no significant difference is observed.

For this analysis, a significance threshold (α) of 0.05 was adopted, as commonly recommended in statistical studies.

Another key parameter of the test is the F/F_C ratio, which indicates the ratio of variance between and within groups; if this ratio is greater than 1, there is a difference between the means of the data. Otherwise, there is no significant difference.

The test was carried out separately in both directions, for the reasons explained above, thus obtaining the results in terms of p-value and F/F_c (see Table 2).

Table 2. F-test results

Direction of travel	P-value	F/Fc
Inbound direction “a”	0.048	1.01
Outbound direction “b”	0.055	0.97

It is, therefore, clear that there is a significant difference in the mean speeds of the groups in the inbound direction towards Cassino “a” while in the outbound direction “b” there is a borderline situation. Given this, a more detailed investigation into the relationship between vehicle categories and crossing speed was conducted by carrying out statistical tests of the t-Student type.

This type of statistical test can be implemented if assumptions regarding the observed data are met:

- Independence;
- Normal or approximately normal distribution;
- Homogeneity of variances.

As regards the hypothesis of data independence, in the case study, the vehicle groups (SUVs, sedans, and medium-sized cars) are independent of each other as each vehicle is

considered an independent observation; moreover, no more than one measurement was carried out on the same vehicle.

The hypothesis of normal or approximately normal distribution is automatically satisfied since each observation group consists of several data observations greater than 30, for the Central Limit Theorem, the sample means are distributed in an approximately normal way [53].

The homogeneity of the variances was verified with the implementation of Levene's test, which compares the absolute deviations from the median within each observation group. The result of the test is expressed in terms of p-value; if it is less than 0.05 (threshold value), the variances are different; on the contrary, the variances can be considered equal.

The results obtained from this test for the case study data yielded the following results (see Table 3).

Table 3. Levene's test results

Category of vehicle	P-value (a)	P-value (b)
Medium-sized car vs Sedans	0.18	0.36
Sedans vs Off-road/Sport Utility Vehicles	0.74	0.51
Medium-sized car vs Off-road/Sport Utility Vehicles	0.42	0.12

Therefore, for both directions of travel and for each combination of groups of vehicle categories, the value of the p-value obtained by Levene's test is always greater than 0.05, confirming the homogeneity of the variances.

It is therefore possible to proceed with the implementation of the Student's t-test. The Student's t-test is a widely used statistical method for comparing the means of two groups to determine whether their difference is statistically significant. This test applies when the data are distributed in an approximately normal manner and the variances of the two groups are similar, although there are variants of the test to address situations where this assumption is not met.

The general formula of the t-test for independent samples is as follows:

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{2}$$

where:

- $\overline{X_1}$; $\overline{X_2}$ represent the means of the two groups;
- s_1^2; s_2^2 are the respective sample variances;
- n_1; n_2 indicate the size of the two samples.

The Student's t-test provides the p-value as output, which allows the statistical significance of the difference between the groups to be assessed, similar to the F-test in

ANOVA. A p-value below a set threshold (usually 0.05) indicates that the difference in the group means is significant.

Table 4 shows the p-value values obtained from comparing the recorded speeds of the vehicle categories of the case study.

Table 4. T-test results

Category of vehicle	P-value (a)	P-value (b)
Medium-sized car vs Sedans	**0.77**	0.03
Sedans vs Off-road/Sport Utility Vehicles	0.03	0.03
Medium-sized car vs Off-road/Sport Utility Vehicles	0.02	**0.60**

The test showed statistically significant differences between the categories considered, supporting the initial hypothesis. This shows that the drivers experience different perceptions when crossing the traffic calming device, which is different depending on the vehicle he is driving; this is because the vibration felt, which translates into a decrease in comfort and, therefore, in the speed maintained, is dissimilar.

However, since the comparison concerns all possible pairs of groups, it is necessary to apply a correction for the risk of Type I error, i.e., the probability of obtaining statistically significant results as a result of chance rather than for a real difference between the groups.

Among the available post-hoc test correction methods, the choice fell on Tukey HSD (Honestly Significant Difference) correction. This method is particularly suitable in contexts where all possible pairwise comparisons are made between groups, as in the case of this study, and ensures effective error rate control while maintaining high statistical power [54–60]. Tukey's test considers the joint distribution of errors and uses the statistics of the studentized range, making it less conservative than other corrections. Consequently, it enhances the ability to detect true differences between groups.

Therefore, the choice of Tukey's correction is motivated by the need to balance Type I error control and statistical power, reducing the risk of neglecting significant differences between the analyzed vehicle categories.

The formula behind this test is as follows:

$$HSD = q \cdot \sqrt{\frac{MS_{within}}{n}} \tag{3}$$

where:

- HSD: Honestly Significant Difference
- q: Critical value of Studentized Range deployment;
- MS_{within}: Mean intra-group variance;
- n: average sample size.

Once the HSD value has been assessed, it must be compared with the difference, in absolute terms, between the averages of the two groups.

Two cases can occur:

- If $|M_1 - M_2| > HSD \rightarrow$ The difference between the groups is **significant**.
- If $|M_1 - M_2| \leq HSD \rightarrow$ The difference between the groups is **not significant**.

This correction has been applied to the cases of comparison of the speed of vehicles previously defined, obtaining the results expressed in Table 5 for the direction "a" and in Table 6 for the direction "b".

Table 5. Tukey correction results for direction "a"

Category of vehicle	HSD	$\lvert M_1 - M_2 \rvert$	Outcome
Medium-sized car vs Sedans	0.91	0.15	**Not significant**
Sedans vs Off-road/Sport Utility Vehicles	1.40	1.57	Significant
Medium-sized car vs Off-road/Sport Utility Vehicles	0.96	1.42	Significant

Table 6. Tukey correction results for direction "b"

Category of vehicle	HSD	$\lvert M_1 - M_2 \rvert$	Outcome
Medium-sized car vs Sedans	1.06	1.30	Significant
Sedans vs Off-road/Sport Utility Vehicles	1.48	1.65	Significant
Medium-sized car vs Off-road/Sport Utility Vehicles	1.09	0.35	**Not significant**

Therefore, the application of Tukey's correction confirmed the results obtained by the t-test, effectively ruling out the possibility of Type I errors.

In particular, it is observed that there is a conspicuous difference between Off-road/Sport Utility Vehicles-Sedans in both directions. On the other hand, a more in-depth analysis is required for the results obtained for the Medium-sized car-Sedans and Medium-sized car-Off-road/Sport Utility Vehicles categories, as the results vary depending on the direction of travel. More specifically, as regards the Medium-sized car-sedans comparison, a p-value is obtained, in the direction defined as "b", such that there is a significant difference between the means of the groups and, therefore a statistically different crossing speed when passing the speed bump; on the contrary, for direction "a" this does not happen. It is important to note that direction "a", entering the city of Cassino, has a conspicuous downhill slope (see Figs. 3 and 4). This topographical feature may influence driver behaviour, leading to a natural reduction in speed while crossing the traffic calming device regardless of vehicle category as it would tend in any case to decrease his speed in the crossing section of the traffic calming device.

On the other hand, as regards the comparison between Medium-sized cars and Off-road/Sport Utility Vehicles, there is a p-value in the "a" direction, indicating a statistically significant difference between the means of the groups, confirming a difference in crossing speeds over the RPC. Conversely, in direction 'b', the p-value does not indicate a significant difference in the speed of crossing the traffic calming device as the car category varies.

This discrepancy may be attributed to the fact that uphill, the weight/power ratio is more important than the absolute power of the engine. Therefore, Off-road/Sport Utility Vehicles are generally heavier, and they also tend to have more powerful engines. Conversely, smaller cars have a lower weight but also less power; therefore, in terms of ratios, there are comparable quantities.

These results extend the analysis previously conducted on the same site of interest [38] in which the static analysis had stopped at the first step, i.e., at the ANOVA F-test, as there was no significant difference between the means of the groups. This was likely due to the smaller dataset analyzed in the earlier study; by making further measurements and having a large amount of data available, it was possible to hope for a more precise result.

6 Conclusion

The study conducted shows how the category of vehicles influences the extent of the speed of crossing the traffic calming device, confirming the initial hypothesis.

In particular, the results show that Off-road/Sport Utility Vehicles and Sedans have significantly different crossing speeds in the two directions considered.

To highlight a statistically significant difference in the crossing speeds of the traffic calming device as the vehicle category varied, an ANOVA F-test was first carried out, which showed a statistically significant difference between the vehicle categories analyzed.

Therefore, it was possible to subsequently implement a t-student test that identified the pairs of categories with the most marked differences in terms of crossing speed.

Finally, Tukey's correction excluded the risk of Type I errors, consolidating the reliability of the results and strengthening the interpretation of the observed differences.

The results obtained highlight some key trends.

Off-road/Sport Utility Vehicles have been observed to pass through the traffic calming device at higher speeds than sedans, while medium-sized cars show intermediate behavior. This phenomenon can be attributed to several factors, including power, suspension set-up, and the perception of ride comfort. Off-road/Sport Utility Vehicles, being designed for driving on rough terrain, suffer less impact in terms of vibrations and reduced comfort than Sedans, which could explain their higher average crossing speed.

A separate analysis of the two travel directions revealed a significant difference in the effect of RPC based on road gradient. Therefore, this aspect should also be explored in future developments since it could turn out that the morphology of the terrain plays a decisive role in the behaviour of drivers: in a downhill section, the natural tendency to slow down could standardize the crossing speeds between the different categories of vehicles, while uphill the specific characteristics of the vehicle become more relevant.

Another aspect that could be noted concerns the case of the uphill section or the "b" direction. It has been hypothesized that, in this case, the weight/power ratio may play an important role since the analyses carried out show that Off-road/Sport Utility Vehicles and Medium-sized cars have similar behaviour.

While Off-road/Sport Utility Vehicles, despite being heavier, generally have more powerful engines, lighter medium-sized cars tend to have less specific power, leading to similar behaviour on climbs.

The results obtained improve on the previous study on the same traffic calming device [61], where, however, the only statistical analysis conducted is the type F ANOVA test since, given the scarcity of data, there was no significant difference between the speeds of crossing the RPC as the category of vehicles varied.

The increase in the number of measurements and the application of more advanced statistical methodologies have made it possible to achieve greater accuracy in identifying significant differences between vehicle categories.

These results have important practical implications in the design of traffic calming devices, as currently, most speed bumps are designed according to uniform criteria without considering the differences in the dynamic behaviour of the various categories of vehicles.

Defining whether speed bump speeds depend on vehicle categories or not allows for drawing up new design procedures that can control crossing speeds for each vehicle category rather than in aggregate terms. This can be useful for public authorities and local administrations to manage new design criteria for traffic calming devices.

However, the study boasts good replicability, thanks to the methodology adopted, even in countries other than the case study.

Future developments could include the analysis of another site of interest to confirm or refute what statistically emerged for the case study in question.

Acknowledgments. This study was carried out within the MOST—Sustainable Mobility Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4—D.D. 1033 17/06/2022, CN00000023). The research leading to these results has also received funding from Project "Ecosistema dell'innovazione Rome Technopole" financed by the EU in the NextGenerationEU plan through MUR Decree n. 1051 23.06.2022—CUP H33C22000420001. This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Author Contributions. **Conceptualization**, N.S and C.G.; **methodology**, N.S and C.G.; **software**, N.S and C.G.; **validation**, N.S and C.G.; **formal analysis**, N.S and C.G.; **investigation**, N.S and C.G.; **resources**, N.S and C.G; **data curation**, N.S and C.G.; **writing—original draft preparation**, N.S and C.G; **writing—review and editing**, N.S and C.G; **visualization**, N.S and C.G.; **supervision**, D.A.M. and N.V.; **project administration**, D.A.M. and N.V.; **funding acquisition**, D.A.M. and N.V. All authors have read and agreed to the published version of the manuscript.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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