Vehicular Speed Profiles on Raised Pedestrian Crossing to Inform 30 Km/h Zone Implementation

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Abstract. High vehicular speeds are likely to cause fatal crashes when a car hits a pedestrian. To reduce this probability, risk mitigation measures are required. A traffic calming device is a measure implemented to alter driver behavior and reduce speeds, thereby improving safety conditions for all vulnerable users. In this paper, a simplified methodology to evaluate vehicular speed profiles, according to vehicle type, is proposed. This is a crucial step in evaluating the effectiveness of the traffic calming measures for different types of road users and understanding their behaviours. The models show good prediction accuracy in terms of Pearson coefficient ($P \approx 0.7$). The results of this study demonstrate how the use of Raised Pedestrian Crossing (RPC) reduces speeds near its installation, but this reduction is lower for Sport Utility Vehicles compared to other vehicle types. Furthermore, the development of speed profiles for different vehicle types may be a new contribution to the implementation of speed models within traffic microsimulation models, thus studying the impact of using these measures on proper traffic flow. The application that could follow is to implement these measures to effectively create reduced speed zones (Zone 30), without the use of external enforcement for speed control.

Keywords: Sustainable Mobility · Road Safety · Pedestrian Safety

1 Introduction

Improving the safety conditions for vulnerable users and reducing the risks associated with interactions with motorized flows is an essential step in promoting and strengthening sustainable and smart mobility. As shown in the current literature [1], higher vehicular speeds are more likely to cause fatal crashes when a car hits a pedestrian. To reduce this probability, risk mitigation measures are required [2]. The most used devices are defined as Traffic Calming Devices, which aim to reduce speeds by applying some psycho-physical discomforts to drivers in the vicinity. In general, a traffic calming device is a measure implemented to alter driver behavior and reduce speeds, thereby improving safety conditions for all vulnerable users [3].

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A first classification of the most common traffic calming measures could be based on vertical and horizontal devices [4]. Among the first category, it is possible to find all devices that induce speed reduction by a vertical displacement that leads to discomfort, such as speed humps and raised platforms. To the second category, for instance, belong all the devices that induce speed reduction by causing a horizontal displacement of the vehicle: it is possible to find chicanes and carriageway narrowing (which also lead to a psycho-physical discomfort) [5].

Among the vertical devices that cause vertical deflections, there are Raised Pedestrian Crossings (RPC). RPCs are often used to allow pedestrians to cross streets safely and modify driver behaviours by reducing their travel speeds in urban areas. Traffic calming configuration, height or width, and finally materials, are strongly related not only to vehicle speed reduction, but also to measurement effectiveness [6]. In this context, evaluating crossing speeds and speed reduction efficiency and effectiveness are key to improving vulnerable road user safety [7].

According to Barbosa et al. [8], after RPC installation, the speed of the 85% percentile is reduced by 10%, and the number of crashes could be reduced by less by 10%. As shown by the study of Distefano [9], after analyzing crash data five years before and five years after the installation of an RPC, the authors found that after the installation of the device, the number of fatal crashes was reduced by 100%, while the number of injuries decreased by 50%. In another study conducted in the city of Burgos, Northern Spain [10], the author found, after analyzing several traffic calming devices, that both pedestrian RPC and Lane Narrowing lead to the greatest speed reduction. In particular, after evaluating the speed of the 85% percentile, the RPC led to a speed reduction of 20 km/h.

It is worth noting that the installation of such type of devices, in addition to speed reduction, could lead to a worsening of vehicular traffic conditions, by reducing road capacity and increasing traffic delays. As already shown by Garcia et al. [11], after the calibration of a microsimulation software with real data collected with GPS devices, the authors found that if the speed table has a more inclined entry ramp, the higher the speed reduction registered. In addition, the spacing between traffic calming devices is not only linked to a reduced speed but also to a reduced capacity. Another aspect to bear in mind is that, although traffic calming measures are useful to influence driver behaviours, they may not always be so effective in reducing speeds. According to Majer and Sołowczuk [12], poor speed table design could lead to unpredictable driver behaviours, or the presence of short length roads could be relevant.

From the analysis of the literature, two main gaps emerge that need to be addressed for future research. The first one regards the development of models that take into account the different vehicle typologies that cross the traffic calming devices. Previous studies have shown that there may be differences between crossing speeds, but without much strong evidence, and only with the use of statistical analyses and without the development of ad hoc models. Furthermore, no models emerge from the literature that allow for evaluating the mean and variance taking into account the different categories of vehicles, nor values of accelerations and speeds that have a low probability of being exceeded.

In this paper, a simplified methodology to evaluate vehicular speed profiles, according to vehicle type, is proposed. This is a crucial step in evaluating the effectiveness of

the traffic calming measures for different types of road users and understanding their behaviours. The innovative aspect that is proposed in this paper is to analyse this vehicular speed profile by considering different types of vehicles. In this perspective, the proposed modelling approach provides a quantitative support for the design of 30 km/h Zones, allowing practitioners to calibrate traffic calming measures according to different vehicle classes and to ensure that target speeds are consistently achieved under real operating conditions. Since this research is based on a single specific site alone, without replication across multiple sites, the entire work can be configured as a methodological case study rather than a generally transferable design paper.

The whole paper will be structured in this way: after the introductory Section with evidence from literature, a Sect. 2 on the methodological aspect will be proposed, and then the case study in Sect. 3; then the results in Sect. 4 will be shown, and in the following Sect. 5, a brief discussion will be reported; finally, a Sect. 6 with overall conclusions.

2 Methodology

This paper aims, as already stated, at vehicular speed profile evaluation in the vicinity of a raised pedestrian crossing (RPC). Evaluating the speed profile is essential for traffic microsimulation analysis and for traffic calming effectiveness assessment in reducing speeds. The methodology (see Fig. 1) involves using cameras on the edge of the road, near the raised pedestrian crossing, to collect speed data. Video data collection can be carried out using various devices equipped with video cameras. The necessary video quality must be quite high, as time measures must be taken at each milestone marked at the PRC to assess the travel speed at that milestone. Knowing the instants of time at which the vehicle passes the marked milestones, given the distance fixed a priori between them, it is possible to derive the speed. The optimal site of analysis should be selected, bearing in mind accessibility to camera positioning and relevance in terms of traffic considerations.

After the video editing phase, consisting of data collection and pre-processing, the video from the cameras has been analyzed. For each milestone, speed assessment in the vicinity of Traffic Calming Measures (TCM) had been carried out, and data have been labelled according to vehicle category, and only isolated vehicles have been considered eligible. The assumption of an isolated vehicle is important as the objective of reconstructing speed profiles is closely linked to the study of vehicle and user behavior in relation to RPC. Studying the isolated vehicle means reducing to zero any possible interactions with other users (other drivers and crossing pods), to isolate the real behavior assumed by the user. Based on average speed, all observations involving two different vehicles crossing the same finish line within 15 s were discarded. Above this 15-s time gap, isolated vehicle/ free-flow conditions were deemed met [13, 14].

Subsequently, for each vehicle, the speed profile for each vehicle was plotted using linear (Eq. 1) and parabolic (Eq. 2) mathematical functions in the access and exit branches of the RPC:

$$v_{deceleration,k} = \mathrm{m}_k \times s + q_k \tag{1}$$

Where:

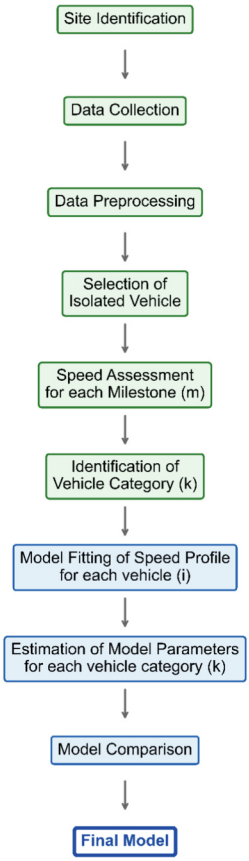


Fig. 1. Flow chart of the proposed methodology to reconstruct vehicular speed profile in the nearby of an RPC.

- $v_{deceleration,\,k}$ is the vehicle speed in the deceleration phase approaching the RPC;
- s is the abscissa;
- m_k and q_k are the model calibration coefficients;
- k is the vehicle category.

$$v_{acceleration,k} = a_k \times s^2 + b_k \times s + c \tag{2}$$

Where:

- $v_{acceleration,\,k}$ is the vehicle speed in the acceleration phase after crossing the RPC;
- s is the abscissa;
- a_k, b_k, and c_k are the model calibration coefficients;
- k is the vehicle category.

Given the actual speed values, the model was calibrated, and the estimates were evaluated for each vehicle that passed through. Once this was done, average parameters

were evaluated for each vehicle category, allowing for a single model per category. For each traffic calming approach branch and for each vehicle category, different models have been evaluated, and the best of these was chosen by comparing their performance in terms of Pearson Coefficient. Other types of functions (such as the exponential one, based on the real mechanics of locomotion) have been calibrated: only those with the best fit are reported in this article.

3 Case Study

The RPC under analysis is located in the city of Cassino, Lazio, Italy, in front of the Department of Civil and Mechanical Engineering (see Fig. 2). The RPC allows pedestrians to cross the road and so link directly to the multilevel parking located in the opposite direction to the entrance of the Department. The road on which is installed (Gaetano di Biasio Street) is characterized by elevated traffic flows. Additionally, the RPC is not only used by university students, but also by other school students and pedestrians. As it is possible to observe in Fig. 3, the RPC has a length of 6.00 m and a width of 3.75 m.



Fig. 2. Location of the RPC under study in the City of Cassino (red dot). The two directions of Analysis have also been reported (black arrows). Source; Open Street Map [15].

Video camera equipment had been installed on the rooftop of the Department's main building to have a clear overview of the RPC and the approaching vehicles, and also to avoid problems related to the privacy of road users. In addition, 8 milestones have been defined, and for each of them, speed values have been collected. The distance between milestones has been selected according to the camera acquisition frequency of 20 frames per second. An ad hoc software has been implemented in Python to analyze video recordings and collect vehicular speed values.

The data collection campaign, carried out on different days, in different lighting conditions, and during off-peak hours (to avoid excessive vehicle and pedestrian traffic

volumes and therefore minimize interactions between road users), led to the collection of 19,840 discrete speed measurements for 2,480 different vehicles and users. The forward collection has been differentiated by the two different directions of travel that are recorded near the RPC. This is mainly because RPC is not perfectly positioned on a zero-slope road, but there is a 1% slope.



Fig. 3. Detail of the RPC under study in the City of Cassino.

4 Results

After the video editing phase, data on predefined milestones have been collected for each vehicle category k. Five class vehicles have been defined: City Car (n = 1123), Sedan (n = 393), Station Wagon (n = 117), Sport Utility Vehicle (n = 627), and Heavy-Duty Vehicle (214). Other vehicle classes have not been analyzed (for instance, two-wheeler vehicles) due to the limited number of observations in the dataset. Before the models were created, the normality of the speed data at the RPC was taken into consideration. As can be seen from Figs. 4 and 5, the QQ plots show a normal pattern of the data.

For each vehicle class, the best model for speed profile is a combined model consisting of a linear model in the deceleration phase, while a parabolic model in the acceleration phase after crossing the RPC. Model description is provided in the "Methodology" section, while the estimated parameters are reported in Tables 1 and 2 for the incoming and outgoing direction, respectively. As already stated, the analysis has been made for the two travel directions due to the road slope (see Fig. 2).

In addition, from Fig. 6, 7, 8, 9, 10, the graphical output of the combined model is shown for each vehicle category. The vehicular speed profiles in grey represent the measured speed profile, while the red one is the estimated model.

As it emerges from all graphs, in the incoming direction (a), with a negative slope, vehicular speed at 20 m from the RPC is higher than the speed after 15 m from the RPC. While there is a reduction in speed in the entry branch, after crossing the RPC, the

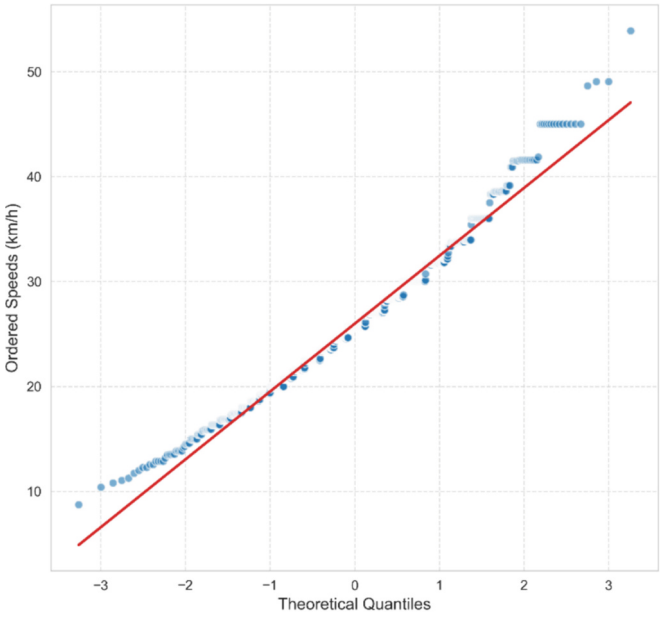


Fig. 4. Q-Q plot for crossing speeds in the outgoing direction.

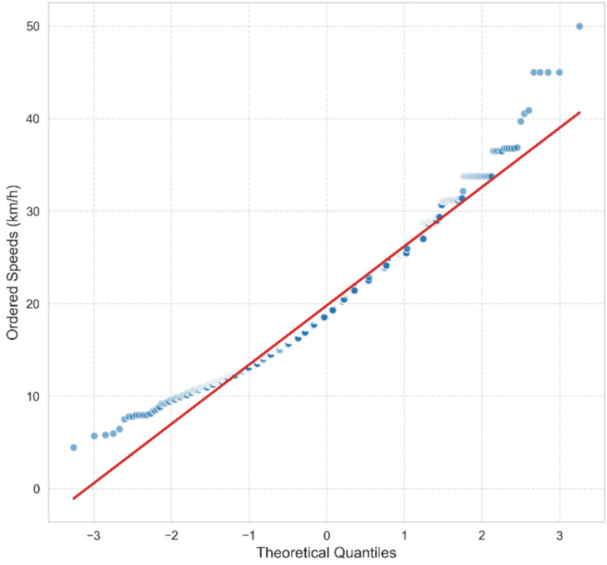
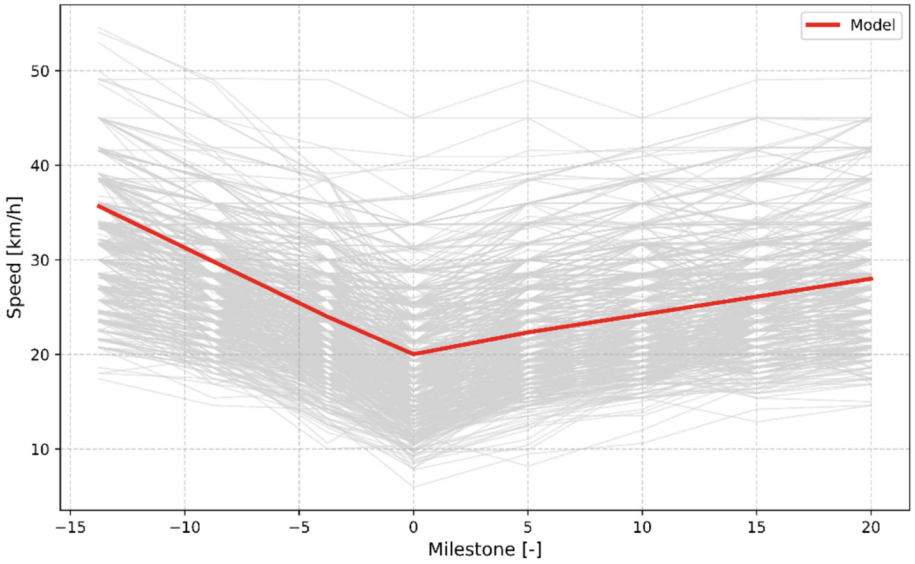
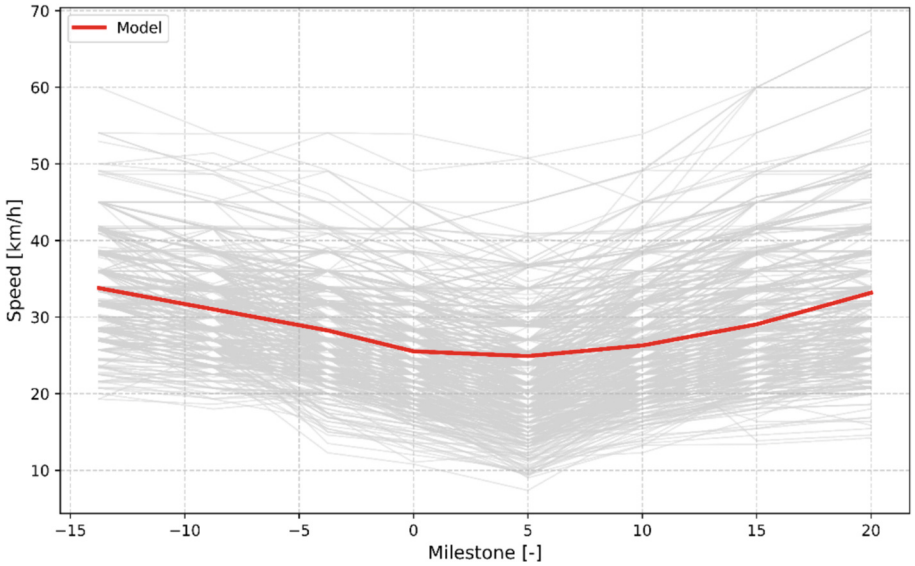


Fig. 5. Q-Q plot for crossing speeds in the incoming direction.

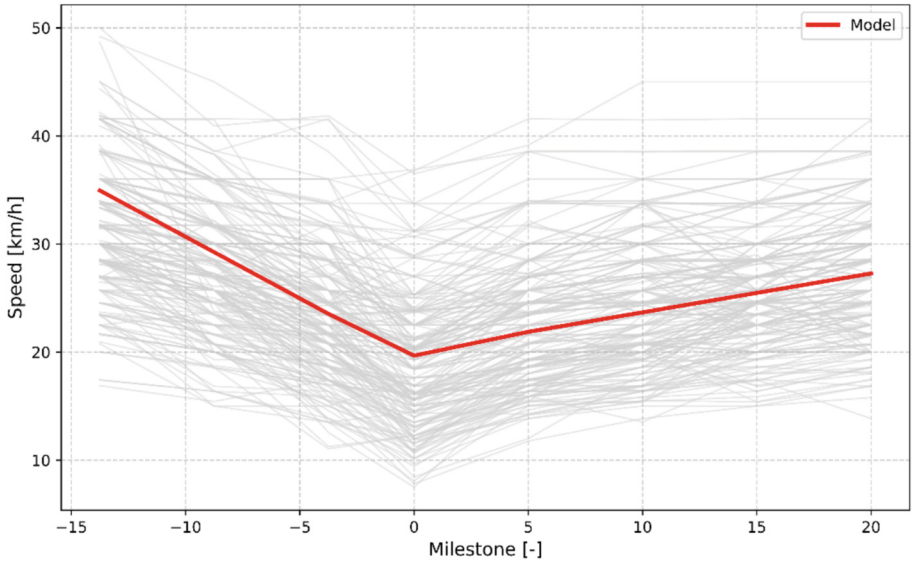


a)

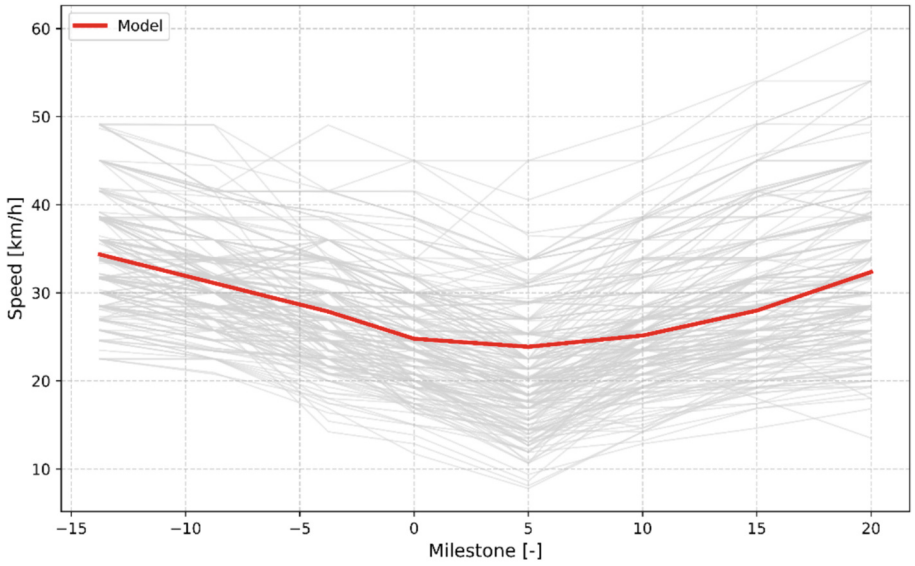


b)

Fig. 6. Graphical representation of the vehicular speed model for the city car: a) the speed profile in the incoming direction; b) speed profile of the city car in the outgoing direction.

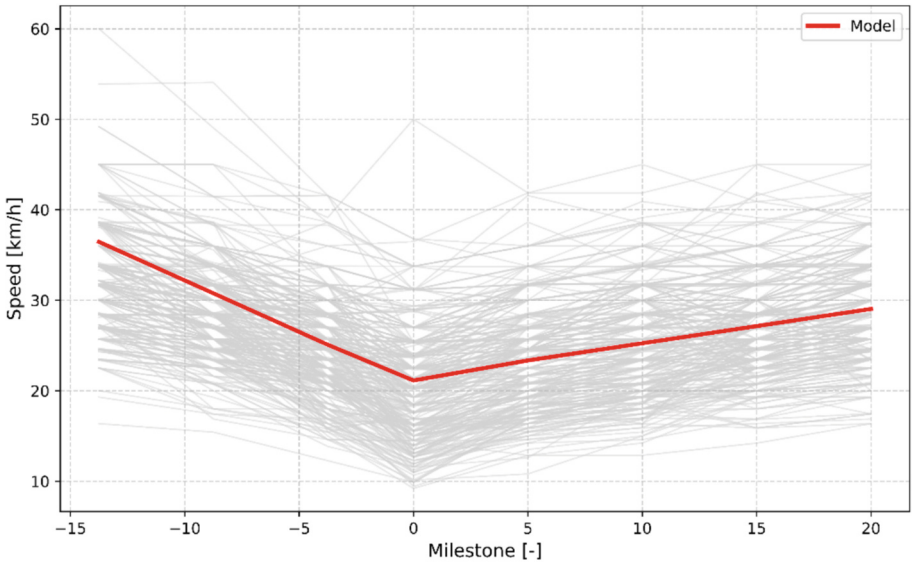


a)

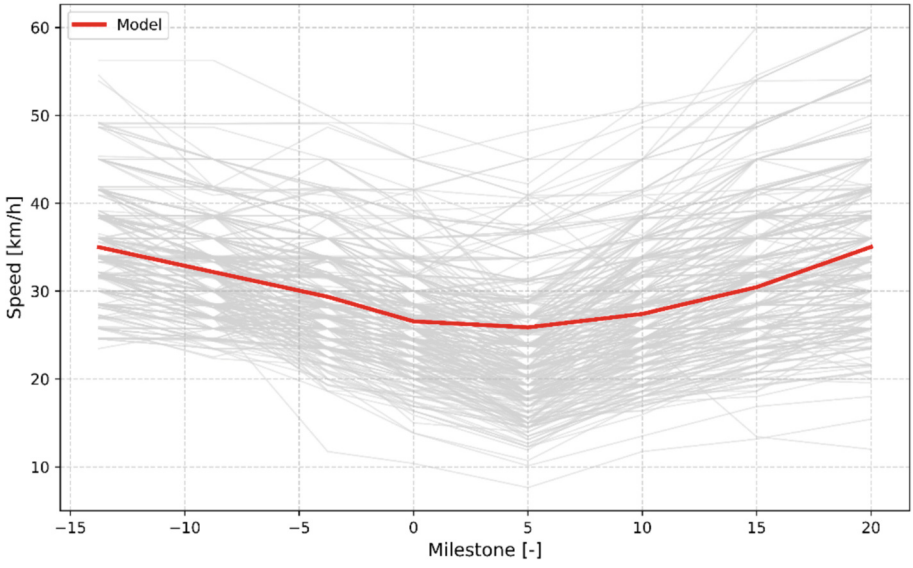


b)

Fig. 7. Graphical representation of the vehicular speed model for the sedan: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.

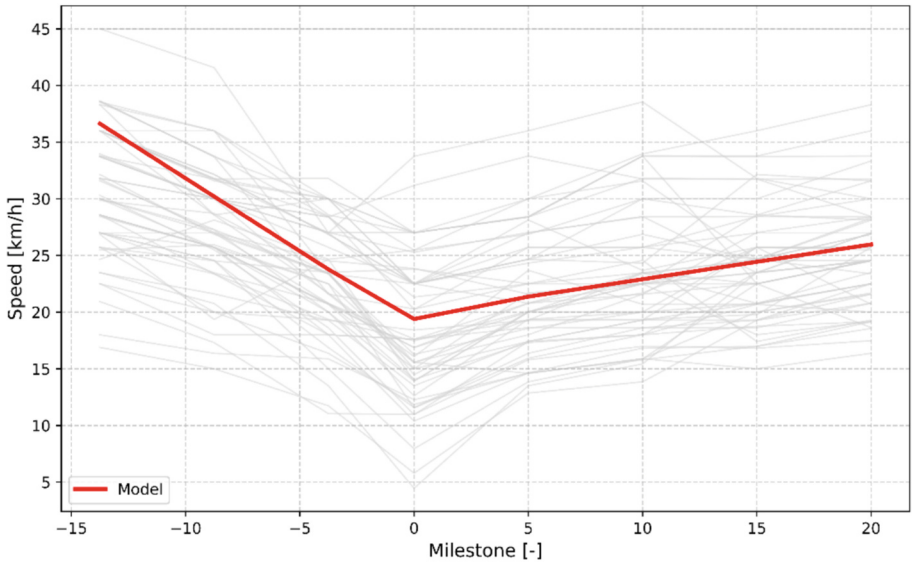


a)

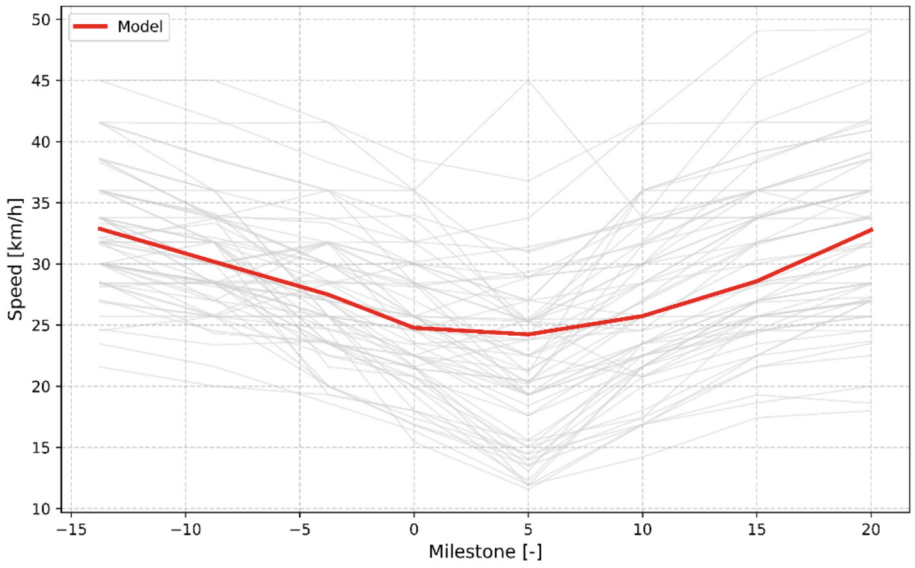


b)

Fig. 8. Graphical representation of the vehicular speed model for the SUV: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.

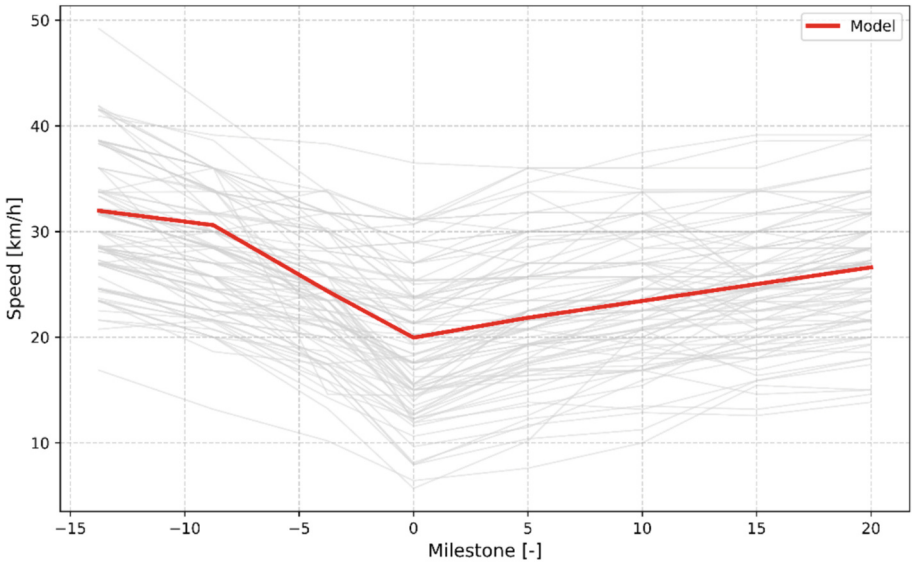


a)

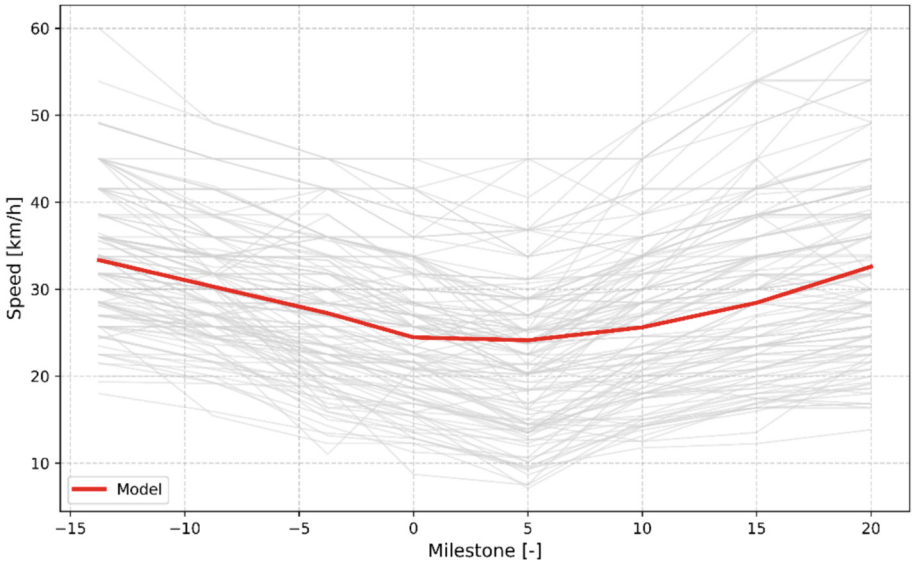


b)

Fig. 9. Graphical representation of the vehicular speed model for the Station Wagon: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.



a)



b)

Fig. 10. Graphical representation of the vehicular speed model for the Heavy-Duty Vehicle: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.

gradient with which the speed increases is higher than in the entry section. This shows that drivers tend to accelerate and reach high speeds after crossing the RPC, but this could be due to a widening of both the lane and the roadway.

In the opposite outgoing direction, with a positive slope (b), it is possible to observe in all graphs that the speed 15 m before and 20 m after the RPC is almost the same. In addition, in this direction, in the acceleration phase, it is possible to observe a more parabolic speed profile than the opposite direction (a) with a negative gradient.

Going to Tables 1 and 2, and specifically on the estimates of the linear model in the Deceleration Phase, it is worth noting, looking at the known term of the linear relationship (in particular q_k), that SUVs compared to other vehicle types, tend to cross PRC with a higher average velocity than other vehicle categories (the difference is more marked in the outgoing direction, described in Table 2). This could be due to the different stiffness of the suspension systems or the reduced visual perception of the structure from a raised driving position. It emerges that the negative slopes (Table 1) are beneficial in reducing crossing speeds that are lower than those in the opposite direction (b), with a positive slope. In Table 3 and 4, the Mean Absolute Error (MAE) for the linear and parabolic model in both directions have been reported.

Table 1. Estimation of the calibration coefficient of the linear and parabolic models to describe vehicular speed profile in the incoming direction.

Variable	Linear Model (Deceleration Phase)		Parabolic Model (Acceleration Phase)			
	m_k	q_k	a_k	b_k	c_k	Pearson (P)
City Car	0.378557	20.42865	-0.02175	-1.12472	19.6006	0.717159
Sedan	0.359991	20.07026	-0.01796	-1.10462	19.26042	0.736754
SUV	0.379507	21.44814	-0.01914	-1.09882	20.818	0.720141
Station Wagon	0.317725	20.25318	-0.02728	-1.19568	19.65861	0.717473
Heavy Duty Vehicle	0.307414	19.82455	-0.02667	-1.23205	18.95272	0.740551

Table 2. Estimation of the calibration coefficient of the linear and parabolic models to describe vehicular speed profile in the outgoing direction.

Variable	Linear Model (Deceleration Phase)		Parabolic Model (Acceleration Phase)			
	m_k	q_k	a_k	b_k	c_k	Pearson (P)
City Car	−-0.55261	26.18206	0.027296	-0.13103	24.8738	0.640476
Sedan	-0.64885	25.42485	0.031097	-0.21106	24.14558	0.69267
SUV	-0.56432	27.23512	0.030517	-0.15311	25.87957	0.646925
Station Wagon	-0.61014	24.95177	0.026642	-0.10177	23.97185	0.660369
Heavy Duty Vehicle	-0.5382	25.46817	0.026827	-0.1015	24.07225	0.671542

Table 3. Mean Absolute Error (MAE) for the linear and parabolic model in the incoming direction.

Variable	Linear Model (Deceleration Phase)	Parabolic Model (Acceleration Phase)
	MAE	MAE
City Car	5.32	4.68
Sedan	5.18	4.81
SUV	5.22	4.56
Station Wagon	4.92	4.64
Heavy Duty Vehicle	5.25	4.86

Table 4. Mean Absolute Error (MAE) for the linear and parabolic model in the outgoing direction.

Variable	Linear Model (Deceleration Phase)	Parabolic Model (Acceleration Phase)
	MAE	MAE
City Car	4.76	6.07
Sedan	4.71	5.95
SUV	4.52	5.89
Station Wagon	4.07	5.36
Heavy Duty Vehicle	6.16	7.54

5 Conclusions

From the literature analysis carried out, high vehicle speed values represent one of the main risk factors associated with fatal crashes, especially for pedestrians. Reducing road user speeds across all contexts is a strategy to reduce risk and increase safety for all vulnerable road users. Recently, traffic-calming measures have been implemented worldwide as a strategy to reduce the risk of road crashes. Among those that play an important role in pedestrian safety in urban areas, it is possible to find raised pedestrian crossings. These devices aim to induce a state of discomfort in the driver when crossing and to adapt the driving behaviour by reducing crossing speeds. The use of several RPCs, together with other traffic calming measures, could, in fact, control and reduce travel speeds in particular areas of the urban context. The application that could follow is to implement these measures to effectively create reduced speed zones (Zone 30), without the use of external equipment for speed control, but only by inserting devices that modify the driving behavior. Therefore, understanding how road users behave in the vicinity of a PRC is essential to understanding the extent of speed reduction. Obviously, a user's driving behavior is influenced by several very different factors, such as road width, road type, and vehicle type. To minimize the interference of external variables on behavior,

video camera data were collected in this study on a PRC located in the city of Cassino. The collected data were processed using appropriately developed software. Only some observations were considered suitable for the development of the analysis, namely, all those in which the condition of an isolated vehicle and no crossing pedestrians on the PRC occurred. All this was necessary to ensure that driving behavior was not conditioned by external factors.

Following the data collection and preprocessing phase, the data were analyzed with the aim of obtaining speed profiles, i.e., how the vehicles behave when approaching and exiting the PRC. This analysis was conducted for different vehicle types (small car, sedan, station wagon, SUV, and heavy vehicles), and then for each vehicle type, two speed profiles (in both directions) were evaluated. The best model in terms of Pearson coefficient (P) was found to be a mixed model consisting of two submodels: a linear one in deceleration and a parabolic one in the acceleration phase. What emerges from the analyses is that crossing speeds are strongly influenced by the type of vehicle: SUVs tend to cross the PRC in both directions at higher speeds than the other types analyzed. Furthermore, it can be noted that the speed of approach to the RPC is also influenced by the width of the road section.

The results of this study demonstrate how the use of RPCs reduces speeds near their installation. In addition to that, by analyzing acceleration and deceleration speed profiles, to guarantee 30 km/h, spacing between RPC should be 40/50 m (in line with previous studies [16]), but further analyses are needed to validate this spacing. Furthermore, the development of speed profiles for different vehicle types may be a new contribution to the implementation of speed models within traffic microsimulation models, thus studying the impact of using these measures on proper traffic flow. Furthermore, by knowing the velocity profiles and deriving the respective accelerations or decelerations, it is possible to understand how to space different RPCs so as to effectively create a zone in which the velocities do not exceed a certain value, as in Zone 30.

Author Contributions

Conceptualization, C.G. and N.S.; **methodology**, C.G. and N.S.; **software**, C.G. and N.S.; **validation**, C.G. and N.S.; **formal analysis**, C.G. and N.S.; **investigation**, C.G. and N.S.; **resources**, C.G. and N.S.; **data curation**, C.G. and N.S.; **writing—original draft preparation**, C.G. and N.S.; **writing—review and editing**, C.G. and N.S.; **visualization**, C.G. and N.S..; **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.

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