# Traffic calming along rural highways crossing small urban communities: Driving simulator experiment

Francesco Galante[a], Filomena Mauriello[a], Alfonso Montella[a,*], Mariano Pernetti[b], Massimo Aria[c], Antonio D'Ambrosio[c]

[a] Department of Transportation Engineering "Luigi Tocchetti", University of Naples Federico II, Italy
[b] Second University of Naples, Italy
[c] Department of Mathematics and Statistics, University of Naples Federico II, Italy

## ARTICLE INFO

## ABSTRACT

The paper investigated drivers' speed behaviour in a section of a rural highway crossing a small urban community in the existing scenario without any traffic calming device and in two different design scenarios with traffic calming in the urban community. Two gateways and four integrative traffic calming devices along the route within the urban area were tested. The gateways were aimed at slowing down the vehicles entering in the built-up area, while the traffic calming devices were aimed at complementing the gateway effect inside the built-up area. Two design options were tested: first option (alt1) is a combination of low cost measures, whereas the second option (alt2) is more expensive as includes a chicane and requires land acquisition.

Drivers' behaviour was investigated by means of a driving simulator experiment. The VERA dynamic-driving simulator operating at the TEST Road Safety Laboratory located in Naples (Italy) was used. Simulation results were validated by the comparison of speed behaviour in the real world and in the driving simulator, in the scenario without traffic calming.

Analysis of the driving simulator experiment results was performed using two different approaches: (a) explorative description of data by cluster analysis; (b) inferential procedures about population using statistical tests. Cluster analysis was carried out in order to test if the drivers' speed behaviour in the different design alternatives was substantially different. Statistical tests were performed in order to verify if speeds in specific sections were significantly different. Cluster analysis looked at speed profiles, whereas statistical tests looked at speed data in specific points.

The obtained results showed a different behaviour of drivers approaching the urban community in the existing scenario and in the design scenarios. In the south direction, mean speed reduction ranging between 16 and 17 km/h, with 5% level of significance, was observed. In the north direction, mean speed reduction equal to 11 km/h, with 10% level of significance, was observed. Differences between the two design alternatives were not statistically significant. Along the urban community, a statistically significant mean speed reduction ranging between 9 and 15 km/h was observed in the south direction. In the north direction, speed reduction was not statistically significant.

Overall, combined results of cluster analysis and statistical tests showed that the treatments were more effective in the direction with higher speeds in the base scenario.

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## 1. Introduction

Rural highways crossing small urban communities are used by pedestrians, cycles, powered two wheelers, and different types of vehicle users with substantial differences in speed, mass, and degree of protection. This produces inconsistency between the mobility of motor vehicle users and the safety of pedestrians and cyclists. In rural highway sections, the drivers maintain high operating speeds and generally they do not adequately reduce speeds crossing the small urban areas (DfT, 2000, 2005; Hallmark et al., 2007; NRA, 2005). Frequently, the transition from the rural environment to the urban one consists only on the posted speed limit (Van Schagen, 2003), and this condition is totally inadequate to induce appropriate behaviours.

The aim of the paper was to investigate drivers' speed behaviour in a section of a rural highway crossing a small urban community in the existing scenario without any traffic calming device and in two different scenarios with traffic calming in the urban community. Drivers' behaviour was investigated by means of driving simulator experiments. Simulation results were validated by the comparison of speed behaviour in the real world and in the driving simulator, in the scenario without traffic calming.

The remainder of the paper summarizes the state-of-the-art, the main features of the design site, the two alternative designs of perceptual measures and physical devices for traffic calming, and the results of the driving simulator experiments.

## 2. Previous studies

In Italy, crashes in rural highways crossing small urban centres account for 14.5% of the total urban crashes, causing 33.2% of the total fatalities in urban area (Lamberti et al., 2009). In these highway sections, main crash risk factors (high severity of pedestrian crashes, over-representation of wet-road crashes, run-off-road crashes, and crashes at curves) are strictly related to operating speeds inconsistent with the urban environment. Thus, measures aimed at speed reduction might give rise to substantial safety improvement.

The European Transport Safety Council (1995) defined design principles for the transition zones located on the approaches to towns and villages on major routes. One principle is that measures in such transition zones must be complemented by measures along the urban area. A second principle is that these measures should be such that they achieve a cumulative effect culminating at the gateway. Gateways are the combination of traffic calming devices, such as traffic islands, road narrowing, coloured surfaces, change in pavement material, horizontal deflections, trees and shrubs, lighting, etc. (CROW, 1998; Highways Agency, 2004; NRA, 2005; Road Directorate, 1999). The UK Department for Transport (2005) suggests two conditions in which gateways can result particularly effective: (a) high operating speeds approaching small villages; (b) city centres where the beginning point of the built-up area is not clearly recognizable.

The gateway treatment effect depends on the context and on the type of the implemented measures. In the UK, speed reduction equal to 10 km/h was found if the gateway was not followed by further devices in the urban centre and equal to 15 km/h if there were other devices (VISP, 1994). Still in the UK, the Department of the Environment, Transport and the Regions (2005) found operating speed reductions equal to 25 km/h at gateways with other traffic calming devices in the urban area. Taylor and Wheeler (1998) evaluated the effectiveness of nine projects. They found a speed reduction between 5 and 24 km/h at gateways and between 5 and 22 km/h in the city centre. In a following study extended to 56 cases, in the projects with only gateways (2000), crash reduction equal to 10% for slight injury crashes and equal to 43% for fatal and serious injury crashes were found. In the cases in which the gateways were integrated with additional provisions inside the city centres, greater crash reductions were achieved: 37% for the slight injury crashes and 70% for fatal and serious injury crashes.

In the US, a recent evaluation of two gateways and five isolated traffic calming devices was carried out (Hallmark et al., 2007). The results showed up to 10 km/h reduction in the operating speed.

The effectiveness of traffic calming treatments has been assessed also by means of driving simulator experiments. Indeed, driving simulators have the potential to explain interaction between drivers and roadway surroundings, and more important, to explore effective countermeasures (Godley et al., 2002; Yan et al., 2008). In support of this concept, many validation studies related to driving speed behaviours have shown that drivers have similar speed performances in driving simulators as those measured in the real world or in real instrumented cars.

Yan et al. (2008) replicated a signalized intersection with as many important features into a high-fidelity driving simulator. A driving simulator experiment with eight scenarios at the intersection was conducted to determine if the subjects' speed behaviour in the driving simulator was similar to what was found at the real intersection. The experiment results showed that speed data observed from the field and in the simulator experiment have equal means for each intersection approach.

In the Netherlands, a project to simulate the impact of a series of measures (coloured asphalt, gateway, and median strip, either separately and in combination) aimed at reducing the speed of traffic approaching the village of Weiteveen was performed (Riemersma et al., 1990). Real world and driving simulation experiments were compared. The comparison showed the feasibility of using a driving simulator to analyse the effectiveness of speed-reducing measures as a suitable alternative to full-scale field-trials.

Traffic calming road treatments were also investigated in the TRL driving-simulator (Lockwood, 1997). The entrance of three villages was simulated. All the villages presented different infrastructural measures. Sixteen subjects participated to the study, driving on the simulated village with and without treatments. The resulting speeds were compared with data collected before and after the measures implementation in the real village. The simulated and real speed data were extensively comparable.

Various traffic calming treatments were simulated in the Leeds Driving Simulator (Jamson et al., 1999). Traffic calming measures were simulated in entrance to sharp bends and rural villages. Significant reductions in speed and in speed variance were observed in both situations.

Godley et al. (2002) used an advanced driving simulator for the evaluation of speeding countermeasures. Using drivers with a minimum of 3 years driving experience, 24 participants drove an instrumented car and 20 participants drove the simulator in two separate experiments. Participants drove on roads which contained transverse rumble strips at three sites (approaches to stop sign intersection, right curve, and left curve), as well as three equivalent control sites. At the treatment sites, speeds were slower than at the control sites in both experiments. The authors found a close correlation between the speeds in the simulator and in the real driving situations.

Katz et al. (2008) investigated several alternative peripheral transverse bars designs in the Highway Driving Simulator (HDS) at Turner-Fairbank Highway Research Center (TFHRC). Four curves and two tangent sections were treated with peripheral transverse bars including four different design patterns. First, the participants drove the roadway under baseline conditions. Second, the participants drove the roadway with one set of experimental treatments. The results showed that treatments were effective in reducing speeds but there were no overall significant differences between the different treatments.

Still using the HDS at TFHRC, Molino et al. (2010) investigated five low cost traffic calming treatments directed at slowing traffic on rural roads in small towns. Thirty-six participants completed three drives. In each drive participants crossed six towns, each with one treatment (plus the base scenario) in a quasi-random order. The town consisted of a main two-lane roadway with marked parking spaces on each side. Each town segment was 137 m long, and was preceded and followed by a long rural tangent. There was no traffic on the roadway in either direction. There were no pedestrians in the town. Curb and gutter chicanes offered the most potential safety benefit, with a mean speed reduction equal to 14 km/h in the beginning of town and 8 km/h in the middle of town.
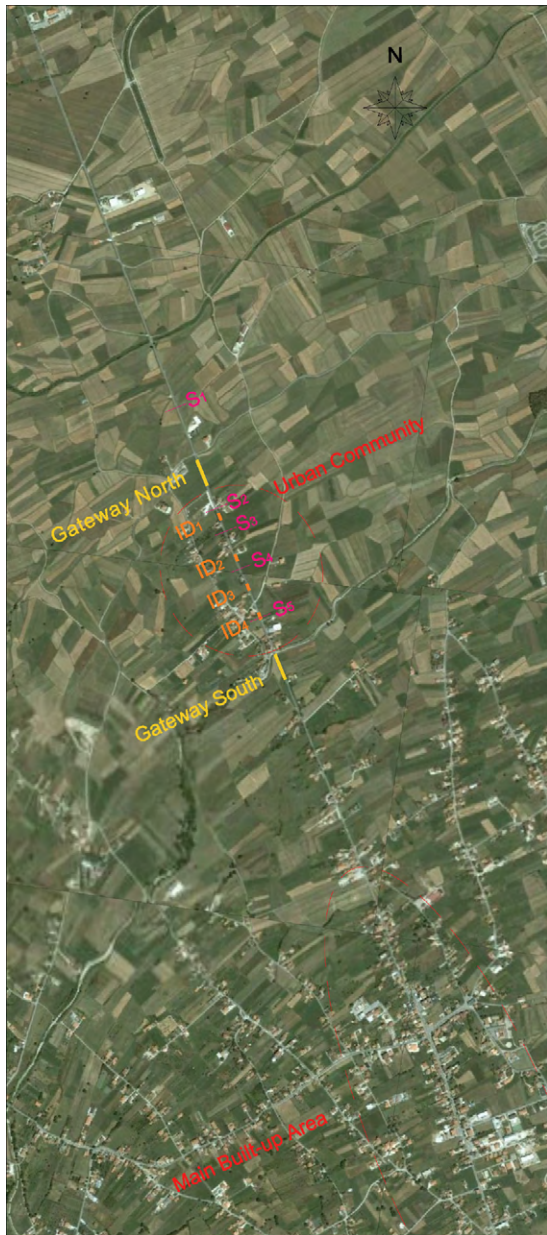
**Fig. 1.** Study area.

## 3. Design alternatives

In order to select the study site, speed measurements were collected along six transitions between rural highways and small urban communities located in Province of Salerno, in the South of Italy. The urban community with the greater entering speeds was selected as the study site. The study site is a small urban community, along the highway SP39 (see Fig. 1), in level terrain and with speed limit equal to 50 km/h. SP39 is a two lane highway with lane width equal to 3.0 m and shoulder width equal to 0.3 m. In the section between the station 3 + 200 and the station 3 + 900 there is a small urban community. Vehicles entering the community directed to south (gateway north in Fig. 1) come from a rural environment and pass through a tangent 3 km long. Vehicles directed to north (gateway south in Fig. 1) exit from the main built-up area and pass through a rural tangent 1 km long.

Real world speeds were collected at five measurement stations (S1–S5 in Fig. 1): 850 vehicles at S1, 2031 vehicles at S2, 1109 vehicles at S3, 762 vehicles at S4, and 872 vehicles at S5. Speed measurement were conducted using three Light Detection and Ranging (Lidar) guns. Operating speeds ($V_{85}$, 85th percentile of the speed distribution) in entrance to the urban community were equal to 91 km/h in the south direction and equal to 78 km/h in the north direction.

Each design alternative consists of two gateways and four integrative traffic calming devices along the urban area. The gateways are aimed at slowing down the vehicles entering in the built-up area, while the traffic calming devices are aimed at complementing the gateway effect inside the built-up area.

Two gateway alternatives were designed: alternative 1 is a combination of low cost measures, whereas alternative 2 is more expensive since includes a chicane and requires land acquisition.

### 3.1. Gateway alternative 1

#### 3.1.1. Overview

In the alternative 1 (see Figs. 2 and 3), the gateway is made by the following elements: (a) transverse rumble strips; (b) transverse optical bars; (c) peripheral transverse bars; (d) roadside fence; (e) coloured brick strip; (f) gantry.

The gateway is composed by a combination of devices that achieve a cumulative effect culminating at the gantry (see Fig. 2). The design is different from the state-of-the-art gateways, even if some elements have already been successfully used as speed-reducing devices.

First, there are two series of rumble strips aimed at alerting drivers approaching the urban community (see Fig. 2a). Second, a set of transverse bars bounds the beginning of a series of peripheral transverse bars with spacing decreasing in the travelling direction (see Fig. 2b). Peripheral bars (see Fig. 2c) give the illusion of road narrowing and increasing of the travel speed, thus providing to the drivers a feeling of discomfort and a greater risk perception. The device is integrated by a roadside fence converging towards the roadway in order to reduce the optical road width and focus the drivers' attention on the gantry (see Fig. 2d).

Last, the entrance in the build-up area is delimited by a steel gantry covered with grass (see Fig. 2f). The gantry is further highlighted by a coloured brick strip (see Fig. 2e).

#### 3.1.2. Transverse rumble strips

Two sets of transverse rumble strips are installed 255 and 185 m before the gantry (see Fig. 2a). Each set is composed by 10 raised rumble strips, with length (perpendicular to roadway edge) equal to 2.76 m, width (parallel to roadway edge) equal to 0.15 m, and spacing equal to 0.50 m.

#### 3.1.3. Transverse optical bars

Transverse optical bars (see Fig. 2b) are installed 70 m after the rumble strips. The transverse optical bars consist on a set of 5 bars, with length (perpendicular to roadway edge) equal to 2.00 m, width (parallel to roadway edge) increasing in the travelling direction (0.20, 0.30, 0.40, 0.50, and 0.60 m), and spacing decreasing in the travelling direction (1.25, 1.15, 1.05, and 0.95 m).

#### 3.1.4. Peripheral transverse bars

Nineteen couples of peripheral transverse bars (see Fig. 2c) are inserted immediately after the transverse bars. The bars are 0.44 m long (perpendicular to roadway edge) and 0.30 m wide (parallel to roadway edge). Spacing equal to 4 bars per second was selected. Spacing between each pair of bars was determined using a constant deceleration rate, equal to 1.2 m/s², basing on beginning speed equal to 90 km/h. Total length of the device is equal to 100.40 m.
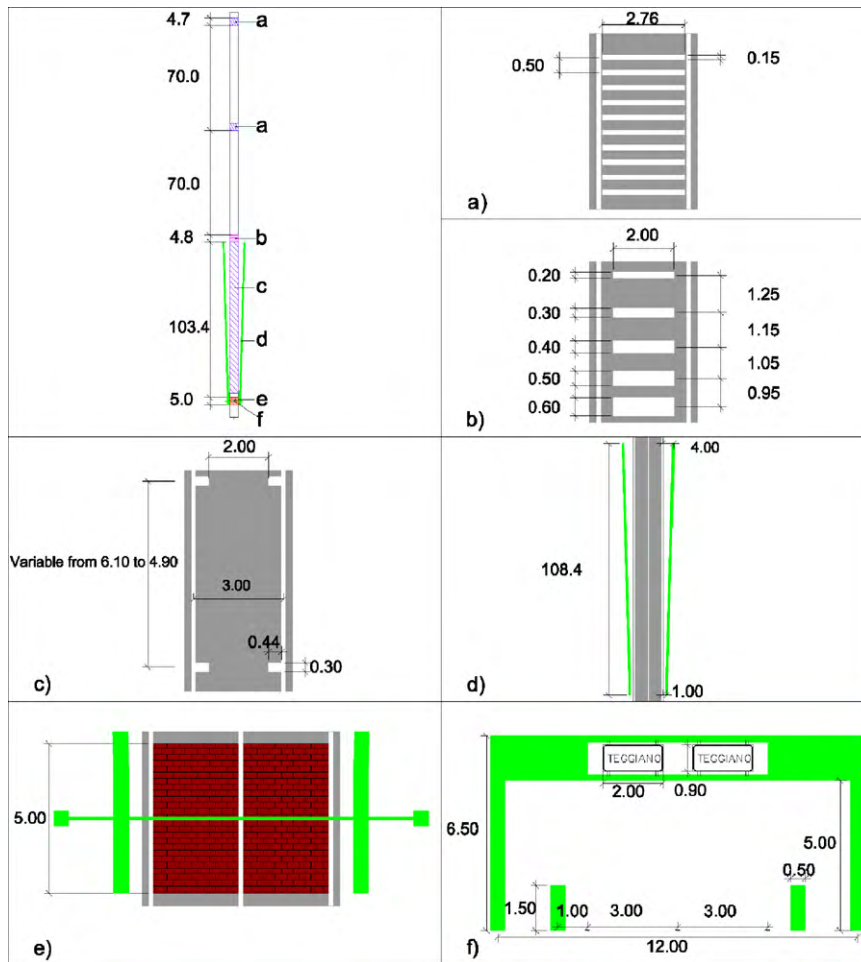
**Fig. 2.** Gateway in south direction, alternative 1: a) transverse rumble strips; b) transverse optical bars; c) peripheral transverse bars; d) roadside fence; e) coloured brick strip; f) gantry.

### 3.1.5. Roadside fence

In the section between the beginning of the peripheral transverse bars and the end of the gateway device, a roadside fence is planted in both sides of the roadway (see Fig. 2d). The fence dimensions ($L \times W \times H$) are equal to $108.40\,\text{m} \times 0.50\,\text{m} \times 1.50\,\text{m}$. At the beginning of the fence, offset from carriageway is equal to 4.00 m; it reduces to 1.00 m after 103.40 m in order to give feeling of road narrowing. The last 5.00 m are parallel to the road to give a better delineation of the gantry.

### 3.1.6. Coloured brick strip

In the gantry area, for a length equal to 5.00 m, a transverse strip of red colour surface with printed bituminous concrete appearing as brick pavers is laid (see Fig. 2e).

### 3.1.7. Gantry

In the centre of the coloured brick strip there is a steel gantry covered with grass (see Fig. 2f). The gantry width is equal to 12.00 m, the height is equal to 6.50 m. The minimum height below the gantry is 5.00 m. The steel structure of the gantry is dressed in ivy to increase the visual impact, the shielding effect, and the impression of the entrance in an urban area. The gantry contains the sign "urban centre beginning".

### 3.2. Gateway alternative 2

In the alternative 2, a chicane is introduced (see Figs. 4 and 5). The chicane is made by a raised island. Length of the deflection towards right is 37.50 m, where a shift towards right equal to 2.50 m is carried out. The section is composed by three stretches with length equal to 12.50 m: (1) circular with radius equal to 125.00 m; (2) tangent; (3) circular with radius equal to 125.00 m. The gantry is installed in the centre of the chicane. Re-entry in the original lane is symmetrical to the preceding deflection.



**Fig. 3.** Gateway in south direction, alternative 1: view from the simulation.
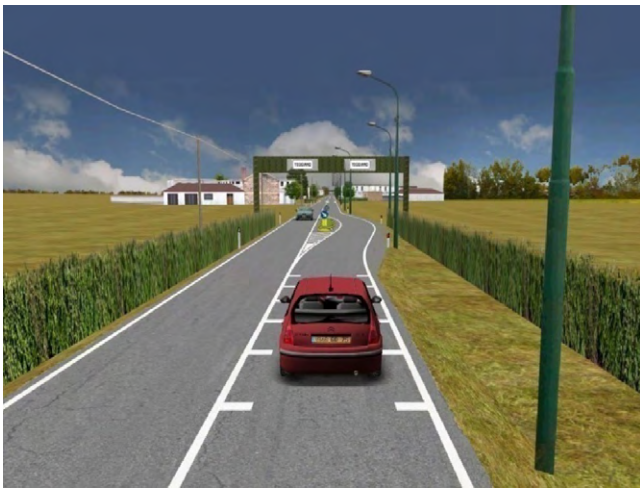
**Fig. 4.** Gateway in south direction, alternative 2: view from the simulation.

The raised island is separated from the traffic lanes by two shoulders 0.50 m wide, where permanent raised pavement markers are installed. In the nose, a yellow reflective obstacle delineator, coupled with the sign "passage allowed to the right", is installed. To avoid aggravating the impact of losses of control by light vehicles or motorcycles, a traversable curb is installed. The curb width is 0.30 m. The curb height is 0.12 m, where the vertical face is 0.05 m and the remaining face is sub-horizontal (0.20 m horizontal and 0.07 m vertical). The curb is delineated with black and yellow reflective strips. The surface of the island is covered with grass.

The coloured brick strip of coloured surface is not carried out in order to avoid changes of skid resistance in a road section characterized by high curvature. In comparison with the alternative 1, the peripheral transverse bars have different characteristics. Spacing equal to 5 bars per second was selected, assuming a constant deceleration rate, equal to 2.5 m/s$^2$ (greater than in the solution 1, considering the warning effect induced by the chicane), and an initial speed equal to 70 km/h (smaller than in the solution 1). Total length of the device is equal to 44.60 m.
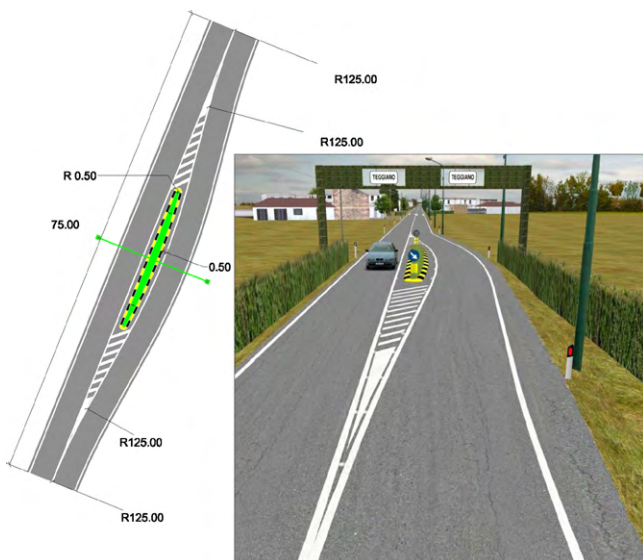


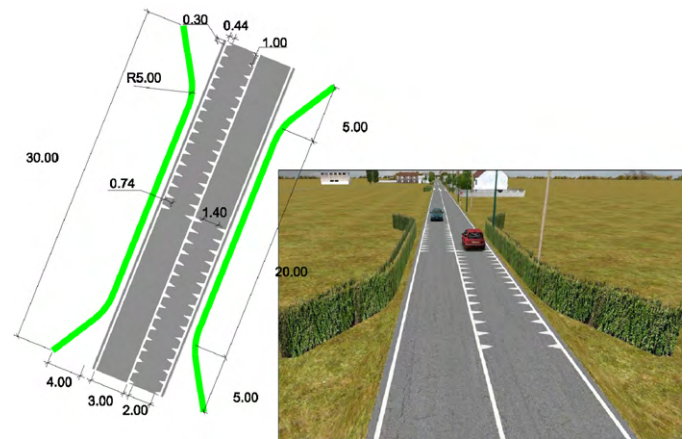**Fig. 5.** Detail of the gateway in south direction, alternative 2.



**Fig. 6.** Integrative traffic calming device.

### 3.3. Integrative devices

Four integrative traffic calming devices (see Figs. 1 and 6) are installed inside the built-up area in order to complement the gateway effect. Each device (with length equal to 30.00 m) is composed by two series (one per direction) of 15 dragon's teeth markings, with constant base and spacing, equal respectively to 0.30 m and 1.00 m, and increasing height (2 cm/m): 0.44 m the first one and 0.74 m the last one. Dragon's teeth with increasing height give the impression of roadway narrowing. Perceptual narrowing is strengthened by two fences convergent toward the roadway. Fence height is equal to 1.50 m, fence width is equal to 0.50 m, distance between fence axis and carriageway is equal to 4.00 m in the beginning section and is equal to 1.00 m in the central section (length equal to 20.00).

## 4. Driving simulator experiment

### 4.1. VERA driving simulator

The VERA (Virtual Environment for Road sAfety) dynamic-driving simulator, operating at the TEST (Technology Environment Safety Transport) Road Safety Laboratory (see Fig. 7) located in Naples (Italy), was used.

Three flat screens (3.00 m × 4.00 m) are fixed at the simulation room floor in order to surround the motion platform. The visual scene is projected to an high-resolution three channel 180° × 50° forward field of view with rear and side mirror views replaced by 6.5″ LCD monitors. The visual system allows a resolution equal to 1400 × 1050 for each channel and a refresh rate equal to 60 Hz. To minimize the flickering effect and enhancing the image quality of the driving scenarios, an 8× antialiasing and an 8× anisotropic filtering are enabled. The cockpit is a half real Citroen C2. The audio system can reproduce various sounds that can normally be heard while driving, including the rolling, engine, and exhaust noise produced by the driving vehicle as well as the surrounding sound field from other vehicles. Feedback is provided by a force feedback system (SENSO-Wheel SD-LC) on the steering and a six d.o.f. electric motion platform. The torque feedback at the steering wheel is provided via a motor fixed at the end of the steering column. The motion system consists of an hexapod with six electric actuators, able to reproduce most of the accelerations that real car occupants feel, in particular those arising from turning and braking manoeuvres and from dynamic interaction between the vehicle and the pavement surface unevenness (D'Apuzzo et al., 2008, 2009). The driving simulation software used in VERA is SCANeR®II r2.22 from Oktal company.

**Fig. 7.** The VERA driving simulator.

### 4.2. Procedure

Thirty participants, 18 men and 12 women, ranging in age from 23 to 54 years with valid Italian driving licenses from more than 4 years, were recruited. Participants were selected after a preliminary screening based on a questionnaire relative to health, gender, age, education, job position, release date of the driving license, annual driving distance covered, crash experience, and traffic offences. Although the sample of participants was balanced for age and gender, these factors were not analyzed in the experiment.

Upon their arrival in the laboratory, each participant was briefed on the requirements of the experiment and all read and signed an informed consent document. Consistently with previous studies, each subject drove 10 min a learning route. After a rest, each participant drove three times trough the small urban community in south direction and three times in north direction. Three scenarios were tested: Alt0, existing urban community; Alt1, design alternative 1; Alt2, design alternative 2. In the simulation there was other traffic in the opposing lane, but there was no traffic in the driving lane and there were no pedestrians in the urban communities. The urban communities were separated by sections 4 km long in a rural environment.

Each scenario was driven three times by 10 participants. More runs through the same scenario were carried out in order to study the behaviour of both drivers familiar and non-familiar with the treatment. Three participants stopped because of sickness discomfort, leaving 27 drivers (9 for each scenario). Speed measurements

were continuously recorded with a sampling frequency equal to 20 Hz.

### 4.3. Validation of the VERA driving simulator for speed measures

The use of driving simulators offers several positive elements, such as experimental control, efficiency, safety, and ease of data collection (Shinar and Ronen, 2007; Rosey et al., 2008), but simulators must have appropriate validity to be useful as research tools. In order to validate the VERA driving simulator speed data, comparison between real world and driving simulator speed data was performed.

Speed measures at stations 1, 2, 3, 4, and 5 in south and north direction were used (see Fig. 1). Real world speed measures of 5624 vehicles were compared with the speed measures in the driving simulator experiment. The Kolmogorov–Smirnov and Chi-squared ($\chi^2$) tests showed that not all the speed data fit the Gaussian distribution at the level of significance of 5%. Thus, non-parametric tests were performed. The two-tailed Kolmogorov–Smirnov test was used to determine whether the two independent samples (real world and driving simulator speeds) were drawn from populations with the same distribution (the null hypothesis). Results of the test (see Table 1) showed that the null hypothesis can be rejected at the 5% level only in station 1, south direction. Thus, except this station, there was not significant difference between the real and simulated speed samples. Maximum difference in mean speed was equal to

**Table 1**
Comparison between real world and driving simulator speed data.

| Station | Mean Speed (km/h) | | | Standard Deviation (km/h) | | | Kolmogorov–Smirnov *p*-value |
|---------|------|-----------|------------|------|-----------|------------|------|
| | Real | Simulated | Difference | Real | Simulated | Difference | |
| South direction | | | | | | | |
| 1 | 81.26 | 74.07 | 7.19 | 17.06 | 21.19 | −4.13 | 0.036 |
| 2 | 73.98 | 71.54 | 2.44 | 16.25 | 19.55 | −3.30 | 0.398 |
| 3 | 76.87 | 71.42 | 5.45 | 15.76 | 19.93 | −4.17 | 0.087 |
| 4 | 76.29 | 69.11 | 7.18 | 18.07 | 17.55 | 0.52 | 0.162 |
| 5 | 71.63 | 68.64 | 2.99 | 16.01 | 17.40 | −1.39 | 0.333 |
| North direction | | | | | | | |
| 1 | 77.39 | 80.85 | −3.47 | 16.84 | 24.30 | −7.46 | 0.113 |
| 2 | 73.49 | 79.61 | −6.13 | 17.04 | 26.26 | −9.22 | 0.181 |
| 3 | 75.04 | 78.01 | −2.97 | 15.96 | 26.31 | −10.35 | 0.175 |
| 4 | 64.19 | 71.34 | −7.14 | 13.16 | 18.91 | −5.75 | 0.092 |
| 5 | 65.81 | 71.39 | −5.58 | 12.99 | 20.11 | −7.11 | 0.118 |

7.19 km/h. Standard deviations of drivers' speed were greater in the simulation.

## 5. Results

Analysis of the driving simulator experiment results was performed using two different approaches: (a) explorative description of data by cluster analysis; (b) inferential procedures about population using statistical tests. Cluster analysis was carried out in order to test if the drivers' speed behaviour, in the different design alternatives, was substantially different. Statistical tests were performed in order to verify if speeds in specific sections were significantly different. Cluster analysis looked at speed profiles, whereas statistical tests looked at spot speed data.

### 5.1. Cluster analysis

Cluster analysis is a multivariate statistical methodology aimed at partitioning N observations into K disjoint groups in a such way that they are both maximally internally homogeneous and externally heterogeneous. In the definition of these groups, a distance measure must be defined. In this case, a non-hierarchical cluster analysis was performed, namely the number K of the groups is a-priori defined.

Cluster time-series methods were used. According to the nature of data, several categories of time-series clustering are distinguished in literature (Liao, 2005): raw time series, feature-based methods, and model-based approach. In the analysis, raw time series of driving speed shape were used. A fundamental step in each clustering method is the choice of a similarity measure for two individuals, two series in the present study. Similarity measures used for time-series clustering are: the Euclidean distance, the Minkowski metric, the Pearson's correlation coefficient, the short time series distance (Moller-Levet et al., 2003), the dynamic time warping distance (Myers and Rabiners, 1981), the probability-based distance function (Kumar and Patel, 2002), and the cluster shape distance (Goldin et al., 2006). Driving speed time-series of the study are sufficiently large in dimension and can be considered as time aligned. As the Pearson's correlation coefficient is invariant both to the scale and the mean of the series, it was adopted as similarity measure for the experiment. Consistently with literature studies (Saunier and Sayed, 2007), clustering was performed by the K-means algorithm.

Each part of each series was normalized. Let $DS_i(t)$ be the $i^{th}$ raw series, $\mu_i$ and $\sigma_i$ their mean and standard deviation, $T$ the length of the series, and $M$ the number of the series. Data transformation consists of the standardization of each series as follows:

$$ds_i(t) = \frac{DS_i(t) - \mu_i}{\sigma_i} \tag{1}$$

for all $1 \leq t \leq T$ and $1 \leq i \leq M$.

The similarity measure is the Pearson's correlation coefficient between each series and the mean of the time series cluster. The latter is defined as:

$$\overline{DS_j}(t) = \sum_{k=1}^{N_j} ds_{jk}(t) \tag{2}$$

for all $1 \leq t \leq T$ and $1 \leq i \leq K$. and where $K$ is the number of clusters, $K_j$ is the number of series belonging to the $j^{th}$ cluster and $jk$ is the index of the series belonging to the $j^{th}$ cluster. The Pearson's correlation coefficient between the $i^{th}$ series and the $j^{th}$ cluster is:

$$\rho_{ij} = \frac{\sum_{t=1}^{T} ds_i(t)\overline{DS_j}(t)}{\sqrt{ds_i(t)^2 \overline{DS_j}(t)^2}} \tag{3}$$

for all $1 \leq i \leq M$ and $1 \leq j \leq K$.

The K-means algorithm works as follows: (1) the number of clusters $K$ is chosen; (2) random $N$ initial means as starting points for the clusters are selected; (3) for each series, the similarity measure with each mean series is computed. Each series is assigned to the cluster whose mean series has the highest similarity with the time series; (4) means are updated; (5) step 3 is repeated until no reallocation in the clusters occurs after the updating step or a maximum number $p$ of iterations is performed.

After cluster analysis, a silhouette analysis was performed. Silhouette refers to a method of interpretation and validation of clusters of data. The technique provides a concise graphical representation of how well each object lies within its cluster.

Let's assume that the data have been clustered into $K$ clusters. For each object $I$, let $a_{(i)}$ be the average distance of $i$ with all other data within the same cluster that measures how well matched $i$ is to the cluster it is assigned (the smaller the value, the better the matching). Let $b_{(i)}$ the minimum average distance of $i$ with the data of another single clusters. Let's define:

$$S_{(i)} = \frac{b_{(i)} - a_{(i)}}{\max\{b_{(i)}, a_{(i)}\}} \tag{4}$$

with the silhouette value $s_{(i)}$ being bound between $-1$ and 1.

The average $s_{(i)}$ of a cluster is a measure of how all the data in the cluster are tightly grouped. If there are too many or too few clusters, such as a poor choice of $K$ in the K-means algorithm, some of the clusters will display much narrower silhouettes than the rest. Thus silhouette plots and averages are a powerful tool for determining the natural number of clusters within a dataset. Values of $s_{(i)}$ higher than 0.6 are considered acceptable, values higher than 0.8 are considered very good. Further, the good classification ratio, which is the ratio between the number of elements in the cluster which belong to the analyst's specified group and the total number of elements in the cluster, is used as a measure of the effectiveness of the analysis.

Each alternative was divided into six segments: (1) from $-500$ to $-340$ m; (2) from $-340$ to $-200$ m; (3) from $-200$ to $-130$ m; (4) from $-130$ m to 0 (gantry section); (5) from 0 to 400 m (village midpoint); (6) from 400 to 800 m (village end).

In the south direction (vehicles entering the community from the north), cluster analysis worked better with $K = 2$ than with $K = 3$. In the latter case, several silhouettes were negative. Silhouette mean values were greater than 0.8 with $K = 2$ between $-500$ m and 0 and were always smaller than 0.8 with $K = 3$ (see Table 2). With $K = 2$, cluster 1 was mainly composed by the alternative 0 (existing scenario) and cluster 2 by the alternatives 1 and 2 combined (design scenarios), as shown by the cluster quality indexes in terms of good classification ratio (see Table 3). In the north direction (vehicles entering the community from the south), the cluster analysis was not successful because of the low values of the good classification ratios (see Table 4).

**Table 2**
Silhouette mean values for cluster analysis (south direction).

| Segments (m) | K = 2 | K = 3 |
|---|---|---|
| [−500,−340] | 0.707 | 0.589 |
| ]−340,−200] | 0.802 | 0.691 |
| ]−200,−130] | 0.776 | 0.677 |
| ]−130,0] | 0.800 | 0.674 |
| ]0,400] | 0.592 | 0.589 |
| ]400,800] | 0.453 | 0.449 |

**Table 3**
Clusters quality in terms of good classification ratio (south direction).

| Segments (m) | Cluster 1 | Cluster 2 | Overall ratio |
|---|---|---|---|
| [−500,−340] | 73.3% | 63.6% | 69.3% |
| ]−340,−200] | 76.6% | 82.4% | 80.7% |
| ]−200,−130] | 64.3% | 55.2% | 59.1% |
| ]−130,0] | 89.6% | 77.8% | 85.8% |
| ]0,400] | 78.9% | 71.4% | 73.9% |
| ]400,800] | 33.3% | 58.2% | 49.3% |

**Table 4**
Clusters quality in terms of good classification ratio (north direction).

| Segments (m) | Cluster 1 | Cluster 2 | Overall ratio |
|---|---|---|---|
| [−500,−340] | 68.7% | 36.4% | 55.5% |
| ]−340,−200] | 53.3% | 76.2% | 63.2% |
| ]−200,−130] | 63.1% | 25.0% | 47.6% |
| ]−130,0] | 68.7% | 46.1% | 55.3% |
| ]0,400] | 55.5% | 21.1% | 32.7% |
| ]400,800] | 47.3% | 74.1% | 58.6% |

Overall, the cluster analysis showed a quite different behaviour of drivers approaching the urban community in south direction in the base scenario (alt0) and in the design scenarios (alt1 and alt2), even thought the differences between the two design alternatives were not significant. In the north direction, cluster analysis showed that the differences in driving behaviour between the alternatives were less significant than in south direction.

### 5.2. Statistical tests

Since speed data did not fit the Gaussian distribution, statistical analyses were performed by non-parametric tests: the Mann–Whitney test and the Kolmogorov–Smirnov test. The first one was used to study the relative positions of the samples. The second one was used to determine if the samples come from identical distributions. Since three treatments were compared, there are $[3 \times (3 - 1)]/2$ possible comparisons. Thus, the correction of the significance level proposed by Bonferroni was applied. The significance level used for pairwise comparisons was corrected using the formula $\alpha' = \alpha \times 2/[3 \times (3 - 1)]$.

**Table 5**
Speed data.

| Section | Mean Speed (km/h) | | | Standard Deviation (km/h) | | |
|---|---|---|---|---|---|---|
| | Alt 0 | Alt 1 | Alt 2 | Alt 0 | Alt 1 | Alt 2 |
| South direction | | | | | | |
| Control | 79.40 | 75.25 | 72.37 | 26.39 | 20.43 | 20.83 |
| Rumble strips 1 | 78.89 | 62.57 | 66.83 | 24.32 | 20.87 | 20.81 |
| Rumble strips 2 | 78.78 | 62.75 | 66.53 | 24.09 | 20.41 | 20.92 |
| Gantry | 76.99 | 61.01 | 60.06 | 23.02 | 21.16 | 20.10 |
| Integrative device 1 | 76.55 | 63.17 | 62.61 | 22.95 | 21.00 | 16.59 |
| Integrative device 2 | 75.82 | 65.35 | 61.48 | 22.39 | 19.72 | 15.48 |
| Integrative device 3 | 74.97 | 65.89 | 62.08 | 22.42 | 18.45 | 15.13 |
| Integrative device 4 | 75.49 | 60.19 | 63.06 | 22.32 | 18.51 | 16.29 |
| Village end | 71.33 | 59.61 | 61.68 | 23.04 | 17.81 | 15.41 |
| North direction | | | | | | |
| Control | 82.12 | 80.92 | 75.59 | 27.33 | 36.41 | 32.76 |
| Rumble strips 1 | 73.53 | 66.99 | 65.75 | 23.45 | 24.29 | 23.66 |
| Rumble strips 2 | 72.63 | 63.41 | 62.94 | 21.61 | 22.19 | 22.26 |
| Gantry | 72.04 | 61.00 | 61.63 | 20.46 | 17.70 | 20.12 |
| Integrative device 1 | 70.66 | 61.93 | 61.66 | 22.78 | 16.16 | 15.26 |
| Integrative device 2 | 72.45 | 64.58 | 62.76 | 23.46 | 14.39 | 14.09 |
| Integrative device 3 | 75.23 | 67.39 | 63.60 | 25.85 | 16.71 | 14.91 |
| Integrative device 4 | 78.09 | 68.91 | 65.78 | 26.77 | 16.84 | 13.90 |
| Village end | 81.42 | 69.02 | 66.09 | 26.34 | 20.97 | 16.74 |

Speed data in the following sections were analyzed (see Tables 5 and 6): control section (section 500 m before the gantry which should not be affected by the gateway treatment), rumble strips 1, rumble strips 2, gantry, integrative device 1, integrative device 2, integrative device 3, integrative device 4, and village end. Overall, Kolmogorov–Smirnov test showed significant effects only in some sections.

In the control sections, as expected, the speed distributions in the three alternatives did not show statistically significant differences.

Overall, rumble strips were effective in speed reduction. In the south direction, Mann–Whitney test and Kolmogorov–Sminorv test showed a significant effect only for alt1 compared to alt0 (mean speed reduction equal to 16 km/h). Mann–Whitney test showed level of significance for either treatments less than 5%, while Kolmogorov–Smirnov's level of significance was less than 10%. In north direction, only rumble strips 2 in alt2 showed a significant speed reduction with 10% level of significance.
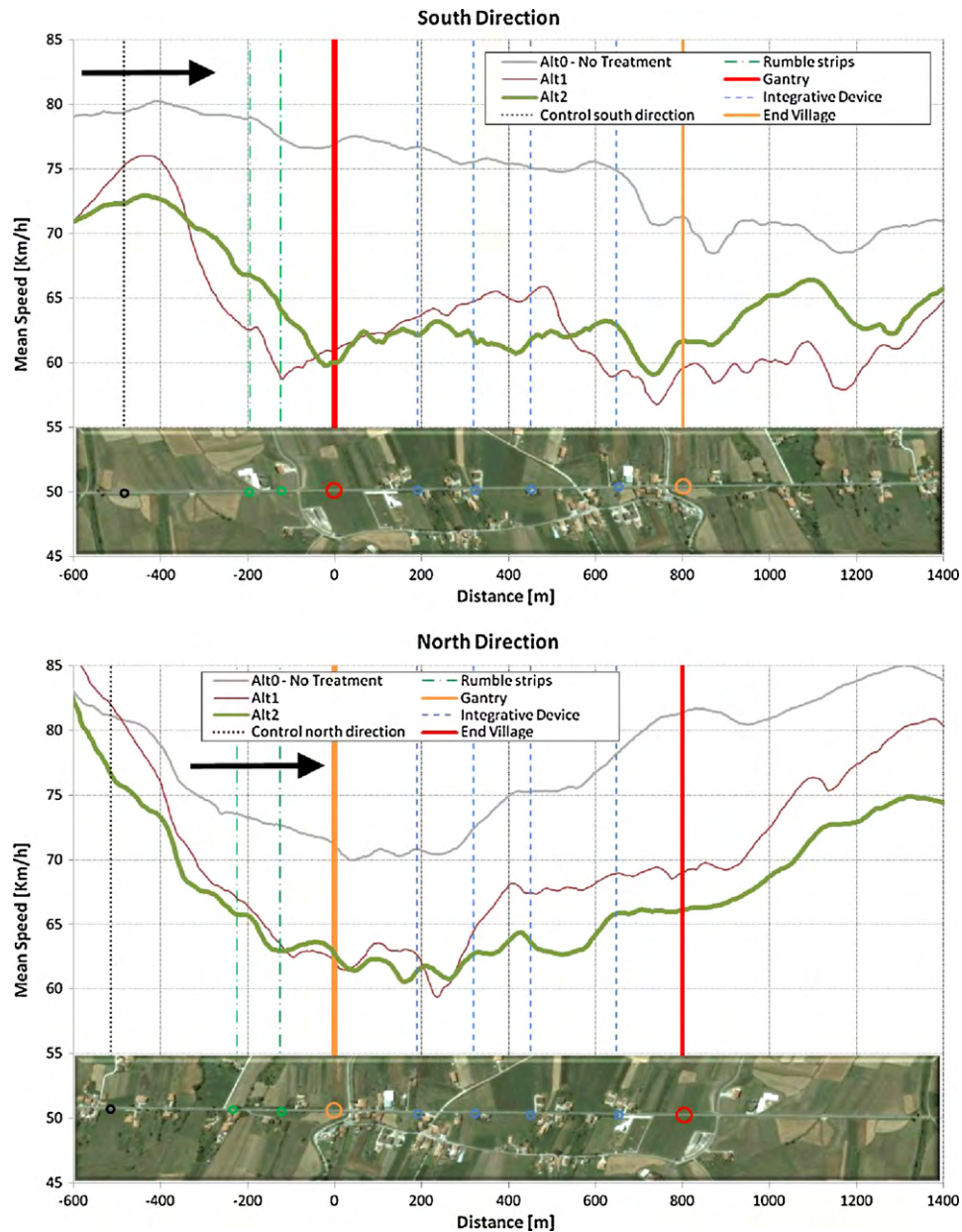
**Table 6**
Test results.

| Section | Mann–Whitney p-value | | | Kolmogorov–Smirnov p-value | | |
|---|---|---|---|---|---|---|
| | Alt 0 vs Alt 1 | Alt 0 vs Alt 2 | Alt 1 vs Alt 2 | Alt 0 vs Alt 1 | Alt 0 vs Alt 2 | Alt 1 vs Alt 2 |
| South direction | | | | | | |
| Control | 0.731 | 0.481 | 0.492 | 0.754 | 0.526 | 0.526 |
| Rumble strips 1 | 0.008 | 0.078 | 0.344 | 0.022 | 0.100 | 0.329 |
| Rumble strips 2 | 0.009 | 0.061 | 0.39 | 0.022 | 0.189 | 0.526 |
| Gantry | 0.006 | 0.005 | 0.932 | 0.022 | 0.022 | 0.997 |
| Integrative device 1 | 0.019 | 0.017 | 0.548 | 0.022 | 0.048 | 0.329 |
| Integrative device 2 | 0.078 | 0.020 | 0.693 | 0.189 | 0.100 | 0.936 |
| Integrative device 3 | 0.124 | 0.052 | 0.701 | 0.526 | 0.189 | 0.754 |
| Integrative device 4 | 0.004 | 0.006 | 0.046 | 0.022 | 0.189 | 0.329 |
| Village end | 0.075 | 0.142 | 0.571 | 0.189 | 0.100 | 0.329 |
| North Direction | | | | | | |
| Control | 0.683 | 0.313 | 0.567 | 0.526 | 0.329 | 0.936 |
| Rumble strips 1 | 0.179 | 0.124 | 0.706 | 0.329 | 0.329 | 0.936 |
| Rumble strips 2 | 0.097 | 0.031 | 0.631 | 0.329 | 0.048 | 0.526 |
| Gantry | 0.028 | 0.020 | 0.864 | 0.100 | 0.022 | 0.754 |
| Integrative device 1 | 0.202 | 0.138 | 0.719 | 0.526 | 0.189 | 0.526 |
| Integrative device 2 | 0.286 | 0.179 | 0.631 | 0.189 | 0.100 | 0.329 |
| Integrative device 3 | 0.318 | 0.120 | 0.706 | 0.526 | 0.329 | 0.329 |
| Integrative device 4 | 0.318 | 0.152 | 0.583 | 0.329 | 0.189 | 0.329 |
| Village end | 0.087 | 0.016 | 0.757 | 0.189 | 0.048 | 0.329 |

*Note*: boldface indicates statistically significant values with 5% level of significance ($\alpha'$ = 1.67%), underline indicates statistically significant values with 10% level of significance ($\alpha'$ = 3.33%).

**Fig. 8.** Driving simulator mean speed profile.

In the gantry section, both gateway treatments were highly effective. In south direction, mean speed reduction was equal to 16 km/h (20.8%) for alt1 and equal to 17 km/h (22.0%) for alt2, with 5% level of significance. The drivers deceleration started about 400 m before the gantry (see Fig. 8), highlighting a good perception of both gateways. Speed standard deviations were slightly reduced in the treatment alternatives. In the north direction, mean speed reductions (11 km/h, with 10% level of significance) were lower than in the south direction. Both in the south and in the north direction, differences between alternatives 1 and 2 were not statistically significant.

Along the urban community, a statistically significant speed reduction in south direction was observed. Compared to alt0, speed reduction ranged between 9 and 15 km/h. Further, standard deviations of speed also showed a significant decrease. Speed reduction with 5% level of significance was observed at integrative device 4, speed reductions with 10% level of significance were observed at integrative devices 1 and 2 (only for alt2).

At the village end, speed differences between the alternatives were not significant. In north direction, only for alt2 a significant speed reduction (12 km/h, 5% level of significance) was observed.

## 6. Discussion

Combined results of cluster analysis and statistical tests showed that both design alternatives were effective in south direction at the gantry section and along the urban community, whereas in north direction the treatments were effective only at the gantry section. This difference mainly depends on the different speeds in the base scenarios, where both in the real world and in the simulator experiment speeds were substantially higher in south direction than in north direction because of the different road environment before the urban community.

In the south direction, the mean speed reduction at the gantry was equal to 16 km/h for alt1 and equal to 17 km/h for alt2. The drivers deceleration started about 400 m before the gantry section,

highlighting a good perception of the systems. In the north direction, mean speed reductions at the gantry were equal to 11 km/h. Along the urban community, mean speed reduction in the design alternatives ranged between 9 and 15 km/h in the south direction and between 8 and 12 km/h in the north direction. Both cluster analysis and statistical tests showed that the speed-reducing effect of the two design alternatives was effective along the urban community only in south direction. Differences between the alternatives 1 and 2 were not significant.

## 7. Conclusions

The paper investigated drivers' speed behaviour in a section of a rural highway crossing a small urban community in the existing scenario without any traffic calming device and in two different scenarios with traffic calming in the urban community. Two gateways and four integrative traffic calming devices along the route within the urban area were tested. The gateways were aimed at slowing down the vehicles entering in the built-up area, while the traffic calming devices were aimed at complementing the gateway effect inside the built-up area. Simulation results were validated by the comparison of speed behaviour in the real world and in the driving simulator, in the scenario without traffic calming.

Analysis of simulation results showed a different behaviour of drivers approaching the urban community in the existing scenario and in the design scenarios. In the south direction, mean speed reduction ranging between 16 and 17 km/h, with 5% level of significance, was observed. In the north direction, mean speed reduction equal to 11 km/h, with 10% level of significance, was observed. Differences between the two design alternatives were not significant.

Along the urban community, a statistically significant mean speed reduction was observed only in the south direction. In the north direction, mean speed reduction was not statistically significant.

Overall, combined results of cluster analysis and statistical tests showed that the treatments were more effective in the direction with higher speeds in the base scenario.

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