

Article

Assessing the Efficacy of Vertical Deflection Versus Visual Signalling in Urban Transition Zones: A Field Study on Speed Compliance

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Abstract

Managing vehicle speeds in rural-to-urban transition zones—where two-lane roads traverse small population centres—remains a critical challenge for road safety engineering. While various traffic calming measures (TCMs) are employed to enforce speed limits, empirical evidence comparing their relative effectiveness in sequential applications is often limited. This study presents a field analysis conducted on the BI-2604 road in Gordexola (Spain). Using radar counters at 24 sequential control points, a dataset of 23,021 valid vehicle passages was analysed to evaluate seven distinct calming configurations. The results indicate that, within this corridor, purely visual countermeasures were associated with high non-compliance: standard crosswalks (paint only) recorded a non-compliance rate of 92.9%, while the Speed Monitoring Display (SMD) registered a 72.1% violation rate. Regarding physical measures, a safety–compliance paradox was identified. Speed humps located in 50 km/h zones achieved the highest statistical compliance (41.7% violation). However, raised crosswalks in 30 km/h zones, despite registering higher non-compliance (63.6%), achieved the lowest mean speeds (approximately 34 km/h; $V_{85} \approx 45$ km/h), a range that the previous literature associates with lower pedestrian injury risk. The findings suggest that, within the investigated corridor, physical vertical deflection was associated with lower speeds than the analysed visual/signalling measures, although it remains an imperfect solution that generates significant negative externalities (noise, emissions, and discomfort) and fails to guarantee strict legal adherence to 30 km/h limits. These limitations highlight the urgent need for alternative solutions, setting the stage for future research on optimised perceptual countermeasures.

Keywords: traffic calming; urban transition zones; speed compliance; vertical deflection; road safety



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1. Introduction

Road safety remains a globally critical concern, despite the notable decline in traffic fatalities recorded in developed countries over recent decades. However, this reduction has been unequal; for instance, in the European Union between 2012 and 2022, while total road fatalities decreased by 22%, the reduction was less pronounced for vulnerable road users in urban environments compared to vehicle occupants on rural roads [1]. This issue is particularly acute in urban transition zones, especially where two-lane rural roads traverse

small towns lacking suitable bypasses, creating fragmented urban segments. Spanish data confirms this disparity: although urban roads accounted for 65% of all traffic crashes in 2023, rural roads registered the vast majority—71%—of fatalities, highlighting the much higher average severity of non-urban incidents [2].

The main challenge in these transitional zones is ensuring drivers effectively reduce their speed from high rural rates to established urban limits of 50 km/h or 30 km/h upon entering built-up areas. Strict compliance with the lower limit is particularly critical, as the risk of pedestrian fatality increases drastically at impact speeds of 50 km/h compared to 30 km/h [3].

To manage excessive speeds, traffic calming measures (TCMs) are implemented. According to Lockwood [4], traffic calming is the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behaviour and improve conditions for non-motorised street users. Generally, vertical deflections follow a hierarchy of effectiveness whereby speed tables (flat-topped humps) impose the highest degree of restriction [5,6], followed by standard speed humps, chicanes, and cushions [7]. The existing literature supports their efficacy in forcing speed reduction by physically altering vehicle dynamics [8]; for instance, reductions of up to 71.6% have been documented in specific contexts [5]. The geometry of the device mediates this effect: in a before–after field study in Belgrade, Antić et al. [9] found that the height of speed humps governs the magnitude of the resulting speed reduction. Comparable evidence has been reported for Berlin-type speed cushions assessed before and after installation at varying distances from the device [10], and for combinations of raised crosswalks, lane narrowing and speed-camera signs deployed along rural-to-urban transition corridors, evaluated using an upstream/on-device/downstream measurement scheme comparable to the one adopted here [11]. However, their configuration is key; spacing vertical measures more than 200 m apart allows drivers to accelerate up to 10 km/h above the 50 km/h limit [12]. Ultimately, this effective speed management translates directly to safety improvements, with significant reductions in collision rates observed at treated intersections [13].

However, previous studies also detail the negative externalities associated with vertical measures [14]. These devices are frequently criticised for causing discomfort to occupants when crossed [5,15], and they contribute to elevated noise levels due to the abrupt deceleration and acceleration manoeuvres they induce [16]. Increased hump height leads to greater speed reduction but also causes higher noise peaks, particularly for passenger cars [16]. This aggressive driving profile also leads to increased fuel consumption and vehicular exhaust emissions [17]. Beyond speed and compliance, the wider effects of traffic calming on public health, travel behaviour and urban liveability have recently been synthesised in a PRISMA systematic review, which underlines that speed reduction is only one of several outcomes worth considering [18]. At the level of vehicle control, driving-simulator research has begun to characterise how drivers negotiate these devices through their braking, throttle and steering inputs [19], an approach that complements the spot-speed perspective adopted in most field studies.

To mitigate the negative externalities of vertical deflection, non-intrusive alternatives relying on psychological feedback or visual signalling are often deployed. Speed Monitoring Displays (SMDs) have been widely documented for their speed-reducing potential in controlled environments, such as work zones [20], school areas [21], and short urban segments [22,23]. Beyond informational devices, the efficacy of other non-physical interventions is often conditional. For instance, traffic lights designed to turn red if the speed limit is exceeded showed low standalone effectiveness but were enhanced when combined with a pedestrian crossing, indicating synergy between measures [22]. Similarly, perceptual countermeasures based on road markings are being explored as cost-effective

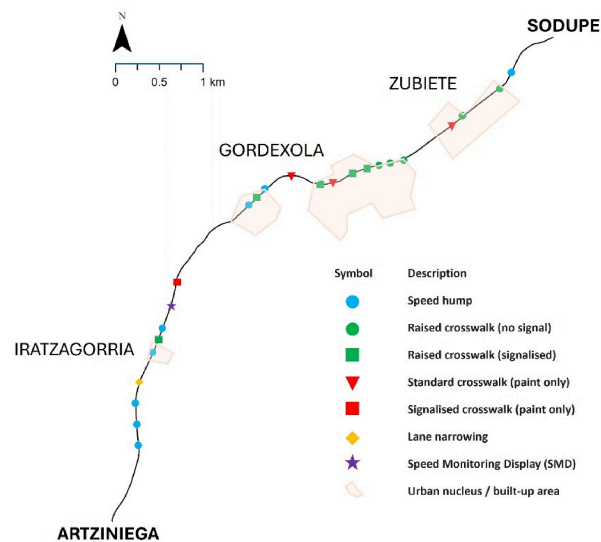
alternatives [24,25]; specifically, a recent study found that broken edge lines were the most effective design near a pedestrian crossing, achieving a significant speed reduction of 8.6 km/h at the critical point [25].

Despite the extensive body of work on individual measures' effectiveness, the specific dynamics of their sequential application in rural-to-urban transitions have received less attention. While it is established that drivers tend to exhibit the 'kangaroo effect'—decelerating at a measure and accelerating again once past it [12,26]—which can necessitate closely spaced consecutive measures to maintain compliance, field-based comparisons of vertical versus visual/signalling measures deployed along the same rural-to-urban corridor remain scarce. The contribution of this study is therefore a field-based comparison of seven traffic-calming configurations arranged sequentially along a single transition corridor, assessed under real operating conditions and against the applicable posted limits. It is important to delimit this contribution: the study does not track individual drivers through the sequence, nor does it adopt a controlled before–after design; the observational unit is the individual vehicle passage recorded at each site, and behaviour is characterised at the aggregate level rather than for identified vehicles. Within these bounds, the sequential single-corridor layout offers a consistent basis for comparing how a continuous traffic stream negotiates measures of contrasting type. Consequently, field-based empirical studies are essential to provide the data-driven evidence needed to inform effective road safety policy. The present study addresses this knowledge gap through a case study on the BI-2604 road as it traverses the municipality of Gordexola, Bizkaia (Spain). Unlike theoretical models, this research uses empirical data from 23,487 vehicle passages recorded via radar units across 24 sequential control points. The aim is to statistically evaluate the efficacy of seven distinct traffic calming configurations—ranging from vertical deflections to horizontal markings—to determine the most effective strategy for ensuring compliance with 30 km/h and 50 km/h limits in these critical transitional environments. This analysis is performed along a single continuous itinerary, implying that a consistent traffic stream interacts sequentially with the diverse measures.

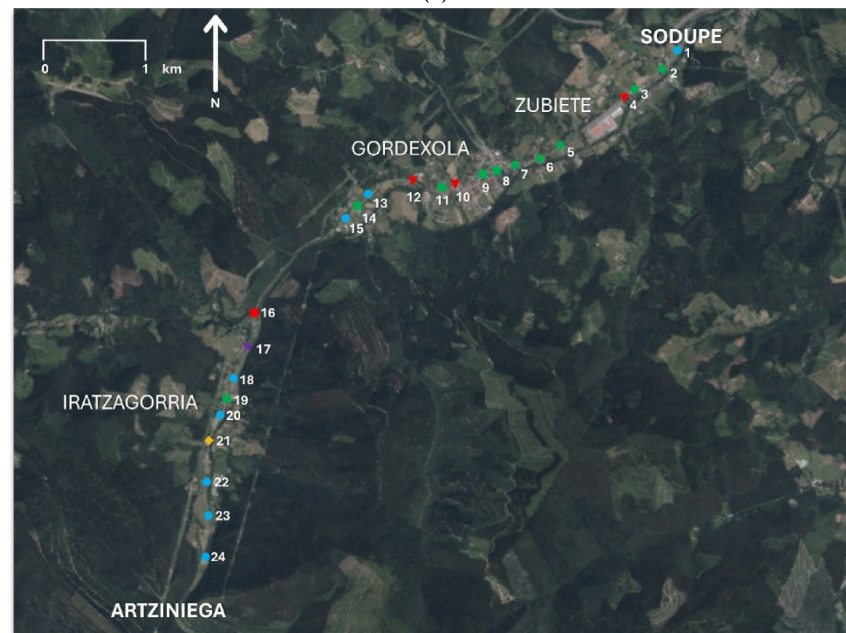
2. Methodology

2.1. Case Study

The research was conducted on the BI-2604 road as it traverses the municipality of Gordexola, Bizkaia (Spain). This road was selected as a representative case study of a transition zone, featuring multiple shifts between two-lane rural road regimes (50 km/h) and urban segments (30 km/h). The study area encompasses four distinct population nuclei, Zubiete, Gordexola town centre (comprising 2 urban nuclei) and Iratzagorria, spanning a total distance of 6.8 km between the initial and final measurement points. A total of 24 measurement points were established along the corridor to capture vehicle behaviour in both directions of travel (towards Artziniega and towards Sodupe), as illustrated in Figure 1. This figure combines a schematic layout of the measures with an orthophoto of the corridor to contextualise the intervention. Crucially, although data collection at these points was conducted sequentially rather than simultaneously, the linear constraints of this short route imply that the study captures the behaviour of a highly consistent traffic stream. As measurements were taken sequentially and vehicles were not individually identified, it cannot be established that the same drivers were observed at every point, nor can the repeated detection of the same vehicle be excluded; the observational unit is therefore the individual vehicle passage.



(a)



(b)

Figure 1. Study area along the BI-2604 road: (a) schematic diagram illustrating the location of the 24 measurement points categorised by TCM type. (b) Orthophoto of the corridor depicting the rural–urban transition context [27]. Note: Location IDs 1–24 identify the measurement points (radar positions) along the corridor, numbered in the direction of travel from Sodupe towards Artziniega.

2.2. Data Collection Instrument

Speed and vehicle classification data were collected using iCOMS TMS-SA mobile radar traffic counters (Icoms Detections S.A., Louvain-la-Neuve, Belgium), based on Doppler technology. These devices operate in the K-band (24.125 GHz) to measure spot speed, vehicle length, and time of passage non-intrusively. The units were mounted on existing street furniture at a standardised height of approximately 2.2 m. The equipment specifications offer a speed measurement range of 10 to 125 km/h with an accuracy of ± 3 km/h (for speeds < 100 km/h). Fieldwork was carried out exclusively under daylight conditions and favourable weather to ensure optimal visibility. The radar setup and its mounting on existing street furniture are illustrated in Figure 2.



Figure 2. Field equipment setup: (a) the radar unit mounted behind signage monitoring the approach to a speed hump (height ≈ 2.2 m); (b) view of the measurement zone from the radar's perspective.

2.3. Classification of Traffic Measures

To enable a comparative efficacy analysis, the infrastructure at the 24 measurement points was categorised into seven distinct typologies. For the statistical analysis, these were grouped into two categories based on their physical nature, physical measures (which impose vertical deflection) and visual/signalling measures (which rely on horizontal markings or vertical signs without physical obstruction), as shown in Table 1.

Table 1. Categorisation of measures.

Measure	Category	Description	Purpose-Built Calming Device?	Example of Implementation	Location IDs
Speed hump	Physical	Standard circular profile vertical deflection with uniform height, primarily located in 50 km/h zones.	Yes		1, 13, 15, 18, 20, 22, 23, 24
Raised crosswalk (no signal)	Physical	Trapezoidal vertical deflection functioning as a pedestrian crossing, marked with white stripes but lacking traffic light regulation.	Yes		2, 5, 6, 7, 19
Raised crosswalk (signalised)	Physical	Identical trapezoidal geometry but regulated by a push-button pedestrian traffic light.	Yes		3, 8, 9, 11, 14

Table 1. Cont.

Measure	Category	Description	Purpose-Built Calming Device?	Example of Implementation	Location IDs
Standard crosswalk (paint only)	Visual/signalling	Horizontal road marking only, with no vertical deflection or light regulation.	No		4, 10, 12
Signalised crosswalk (paint only)	Visual/signalling	Horizontal marking regulated by a traffic light, lacking physical vertical deflection.	No		16
Speed Monitoring Display (SMD)	Visual/signalling	Electronic sign displaying real-time vehicle speed (smiley/sad face), serving as a psychological rather than physical measure.	Yes		17
Lane narrowing	Visual/signalling	Horizontal deflection using central hatched markings or physical islands to channelise traffic and increase lane separation, creating a visual narrowing effect.	Yes		21

‘Purpose-built calming device?’ indicates whether the element was conceived specifically as a traffic-calming measure (Yes), as opposed to an element whose primary function is different, such as a standard painted pedestrian crossing (No).

2.4. Data Analysis

The raw dataset collected during the observation period comprised a total of 23,487 vehicle records. A filtering process was applied to ensure data integrity and isolate free-flow motorised traffic suitable for speed analysis. Records were excluded based on the following criteria:

- Low-speed outliers: Speeds below 5 km/h were removed to exclude parking manoeuvres or congestion events. This threshold was applied to ensure the analysis focused exclusively on free-flow operational speed, consistent with the methodological framework for assessing traffic calming effectiveness described by Obregón-Biosca [17].
- Length-based filtering: To exclude measurement errors and non-motorised traffic, records with lengths outside the 2.5–15.0 m range were discarded. This criterion, aligned with methodological principles for isolating unimpeded vehicles described by Barbosa et al. [7], removes bicycles and micromobility devices [16], as well as potential measurement artefacts caused by tailgating vehicles being detected as a single unit.

- Directional validity: For the Speed Monitoring Display (SMD), located at point 17, only data from the direction of travel facing the active screen was retained. Records from the opposing direction were excluded as drivers were not exposed to the feedback measure.

Following this cleaning process, a final valid sample of $n = 23,021$ vehicle passages was obtained.

To improve reproducibility, Table 2 summarises the 24 measurement locations. The monitoring campaign ran between 11 October and 24 November 2021, exclusively on weekdays (Monday to Friday) and under daylight conditions. Radar-to-device distance, measurement position (upstream, on the device or downstream), gradient, alignment and lane width are reported per site from the field records.

Table 2. Summary of the 24 measurement locations.

ID	Measure	Limit (km/h)	Dir.	Date	Day	Passages (n)	Radar Dist. (m)	Position	Gradient (%)	Alignment	Lane Width (m)
1	Speed hump	50	A/B	18 November 2021	Thu	1769	1.2	Downstream	1.0	Straight	7.0
2	Raised crosswalk (no signal)	30	A/B	18 November 2021	Thu	1790	0.2	Downstream	0.9	Straight	7.0
3	Raised crosswalk (signalised)	30	A/B	10 November 2021	Wed	1844	0.7	Downstream	0.6	Straight	7.0
4	Standard crosswalk (paint only)	30	A/B	10 November 2021	Wed	2132	6.0	Downstream	1.2	Straight	7.0
5	Raised crosswalk (no signal)	30	A/B	9 November 2021	Tue	945	1.6	Upstream	−4.3	Straight	6.0
6	Raised crosswalk (no signal)	30	A/B	9 November 2021	Tue	888	1.4	Upstream	−7.6	Straight	6.0
7	Raised crosswalk (no signal)	30	A/B	24 November 2021	Wed	950	1.1	Upstream	3.1	Straight	6.0
8	Raised crosswalk (signalised)	30	A/B	24 November 2021	Wed	950	0.7	Upstream	−0.3	Left-hand curve	6.0
9	Raised crosswalk (signalised)	30	A/B	9 November 2021	Tue	888	0.5	Upstream	1.5	Straight	6.0
10	Standard crosswalk (paint only)	30	A/B	24 November 2021	Wed	950	0.4	Upstream	8.7	Right-hand curve	6.0
11	Raised crosswalk (signalised)	30	A/B	24 November 2021	Wed	789	1.3	Upstream	2.5	Right-hand curve	6.0
12	Standard crosswalk (paint only)	50	A/B	19 November 2021	Fri	661	2.3	Upstream	0.0	Left-hand curve	7.0
13	Speed hump	50	A/B	19 November 2021	Fri	740	0.9	Upstream	1.0	Straight	7.0
14	Raised crosswalk (signalised)	30	A/B	19 November 2021	Fri	443	0.6	Upstream	1.1	Straight	7.0
15	Speed hump Signalised	50	A/B	19 November 2021	Fri	966	0.2	Downstream	1.9	Straight	7.0
16	crosswalk (paint only)	50	A/B	27 October 2021	Wed	687	3.1	Upstream	3.0	Left-hand curve	7.0
17	SMD	50	B	27 October 2021	Wed	567	4.2	Downstream	0.4	Straight	7.0
18	Speed hump	50	A/B	21 October 2021	Thu	636	2.1	Upstream	2.8	Straight	7.0
19	Raised crosswalk (no signal)	30	A/B	11 October 2021	Mon	1198	1.5	Downstream	1.0	Straight	7.0
20	Speed hump	50	A/B	21 October 2021	Thu	797	0.6	Upstream	1.6	Straight	7.0
21	Lane narrowing	50	A/B	20 October 2021	Wed	377	0.0	Upstream	1.2	Left-hand curve	7.5
22	Speed hump	50	A/B	20 October 2021	Wed	630	1.9	Upstream	0.8	Straight	7.0
23	Speed hump	50	A/B	19 October 2021	Tue	566	0.1	Upstream	−1.1	Left-hand curve	7.0
24	Speed hump	50	A/B	19 October 2021	Tue	858	1.3	Downstream	0.9	Right-hand curve	7.0

3. Results

The analysis was performed on the valid sample of $n = 23,021$ vehicle passages. The results are presented in three subsections: mean speed analysis by category, non-compliance rates, and speed distribution profiles comparing physical versus visual measures. All statistical analyses were carried out using Statgraphics Centurion XIX (Statgraphics Technologies, Inc., The Plains, VA, USA).

3.1. Analysis of Mean Speed

A one-way Analysis of Variance (ANOVA) was conducted to compare the effectiveness of the seven measures in reducing vehicle speeds. The analysis revealed statistically significant differences in mean speeds between the categories ($F(6, 23,014) = 1444.6, p < 0.001$).

To visualise these disparities, Figure 3 presents the speed distribution profiles (box-and-whisker plots) for each measure category, ordered by median speed.

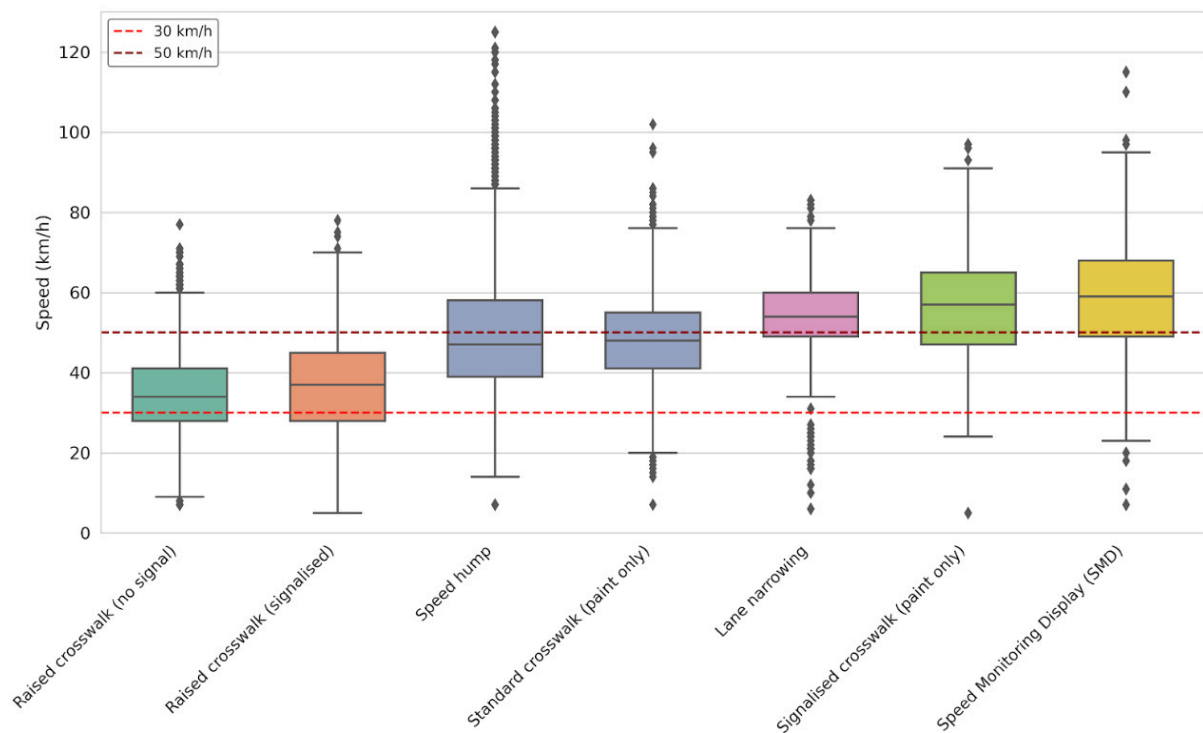


Figure 3. Box-and-whisker plot of speed distribution across the seven measures categories. (Colours represent homogeneous groups identified by Bonferroni post-hoc test, Table 3).

Table 3. Mean speed and homogeneous groups (Bonferroni Method, 95% Confidence).

Measures	<i>n</i>	Mean Speed (km/h)	Group
Raised crosswalk (no signal)	5771	34.37	A
Raised crosswalk (signalised)	4914	36.61	B
Standard crosswalk (paint only)	3743	48.16	C
Speed hump	6962	48.83	C
Lane narrowing	377	53.00	D
Signalised crosswalk (paint only)	687	56.24	E
Speed monitoring display (SMD)	567	59.13	F

Figure 3 illustrates a clear hierarchy: vertical deflections (particularly raised crosswalks) exhibit tight distributions concentrated below the 40 km/h mark, whereas visual measures display significantly higher medians and broader variability, with the upper quartiles frequently exceeding the 50 km/h limit.

Post-hoc comparisons using the Bonferroni method (95% confidence level) identified six homogeneous groups. Table 3 summarises these groups and the mean speeds.

The lowest mean speeds were recorded for raised crosswalks without signals (34.37 km/h, Group A), while the highest were observed for SMD (59.13 km/h, Group F). Standard crosswalks (paint only) and speed humps showed no statistically significant difference in their mean speeds (48.16 km/h and 48.83 km/h, respectively).

Table 4 reports the measure-specific descriptive statistics. The 85th-percentile speed (V85) is provided for each category; the previously reported value of approximately 35 km/h corresponded to the mean speed of the raised crosswalk without a signal (34.4 km/h), whose V85 is 44.5 km/h.

Table 4. Measure-specific descriptive statistics on the valid sample ($n = 23,021$ vehicle passages).

Measure	n	Mean (km/h)	95% CI	V85 (km/h)	Non-Compliance (%)	Posted Limit
Raised crosswalk (no signal)	5771	34.37	34.12–34.62	44.5	63.6	30
Raised crosswalk (signalised)	4914	36.61	36.31–36.94	49.0	68.6	30
Standard crosswalk (paint only)	3743	48.16	47.82–48.50	58.0	92.9	30/50
Speed hump	6962	48.83	48.48–49.18	63.8	41.7	50
Lane narrowing	377	53.00	51.69–54.32	64.6	67.1	50
Signalised crosswalk (paint only)	687	56.24	55.22–57.27	70.0	68.1	50
Speed monitoring display (SMD)	567	59.13	58.02–60.23	72.0	72.1	50

Given the large sample size, effect sizes are reported alongside the significance tests. The overall effect of measure type on speed was large ($\eta^2 = 0.274$), exceeding the 0.14 threshold that Cohen [28] proposed as a benchmark for a large effect. Levene's test indicated unequal variances across categories ($p < 0.001$); a Welch ANOVA therefore complemented the classical test and confirmed the result ($F(6, 2596) = 1566.0, p < 0.001$). For the principal non-confounded contrasts, Cohen's d was 1.21 (raised crosswalk without signal versus painted crosswalk, 30 km/h sections) and 0.70–0.71 (speed hump versus SMD and versus painted crosswalk, 50 km/h sections), indicating large to medium effects.

To address the confounding between measure type and posted speed limit, Table 5 reports the results separately for the 30 km/h and 50 km/h regimes. Within each regime the contrasts are not confounded by the applicable limit, and the standard crosswalk (paint only) appears under both regimes, providing an internal reference.

Table 5. Descriptive statistics stratified by posted speed limit.

Measure	n	Mean (km/h)	V85 (km/h)	Non-Compliance (%)
30 km/h sections				
Raised crosswalk (no signal)	5771	34.4	44.5	63.6
Raised crosswalk (signalised)	4914	36.6	49.0	68.6
Standard crosswalk (paint only)	3082	45.8	55.0	94.6
50 km/h sections				
Speed hump	6962	48.8	63.8	41.7
Lane narrowing	377	53.0	64.6	67.1
Signalised crosswalk (paint only)	687	56.2	70.0	68.1
Standard crosswalk (paint only)	661	59.1	67.0	84.7
Speed monitoring display (SMD)	567	59.1	72.0	72.1

Because observations are nested within the 24 locations, passages recorded at a single point are not independent replications of the intervention. Table 6 reports the descriptive statistics by location. Between-site variability within the same measure type is substantial: for speed humps, site mean speeds range from 41.5 to 61.8 km/h. Three categories are represented by a single location—the SMD (ID 17), lane narrowing (ID 21) and the signalised painted crosswalk (ID 16)—so the effect of the measure cannot be separated from that of the specific site; results for these categories are single-site observations that cannot be generalised.

Finally, to verify that the observed differences are not an artefact of the large sample size, a sensitivity analysis based on random subsampling was performed. One thousand stratified random subsamples of $n \approx 400$ vehicle passages were drawn, and a one-way ANOVA with Tamhane's T2 post-hoc test (robust to unequal variances) was recomputed on each. The global ANOVA remained significant ($p < 0.05$) in 100% of the subsamples, with a stable large effect size (mean $\eta^2 = 0.285$; 95% resampling interval 0.222–0.353).

Table 7 reports, for each pair of measures, the percentage of subsamples in which the two did not differ significantly. The pattern reproduces three stable clusters (the two raised crosswalks; the painted crosswalk and speed hump; and lane narrowing, the signalised painted crosswalk and the SMD), confirming that the group structure is robust rather than driven by sample size.

Table 6. Descriptive statistics by measurement location.

ID	Measure	Limit (km/h)	<i>n</i>	Mean (km/h)	V85 (km/h)	Non-Compliance (%)
1	Speed hump	50	1769	43.7	56.0	26.6
2	Raised crosswalk (no signal)	30	1790	35.2	44.0	70.5
3	Raised crosswalk (signalised)	30	1844	42.6	51.0	92.8
4	Standard crosswalk (paint only)	30	2132	46.7	56.0	95.7
5	Raised crosswalk (no signal)	30	945	33.5	42.0	64.4
6	Raised crosswalk (no signal)	30	888	30.0	37.0	47.0
7	Raised crosswalk (no signal)	30	950	43.9	53.0	92.3
8	Raised crosswalk (signalised)	30	950	44.3	53.0	92.4
9	Raised crosswalk (signalised)	30	888	30.8	37.8	47.8
10	Standard crosswalk (paint only)	30	950	43.8	53.0	92.2
11	Raised crosswalk (signalised)	30	789	28.1	36.0	37.6
12	Standard crosswalk (paint only)	50	661	59.1	67.0	84.7
13	Speed hump	50	740	41.5	52.0	18.5
14	Raised crosswalk (signalised)	30	443	23.9	31.0	15.8
15	Speed hump	50	966	54.9	68.2	61.5
16	Signalised crosswalk (paint only)	50	687	56.2	70.0	68.1
17	SMD	50	567	59.1	72.0	72.1
18	Speed hump	50	636	48.3	61.0	44.0
19	Raised crosswalk (no signal)	30	1198	29.5	38.0	42.2
20	Speed hump	50	797	46.7	60.0	37.3
21	Lane narrowing	50	377	53.0	64.6	67.1
22	Speed hump	50	630	61.8	80.6	74.0
23	Speed hump	50	566	51.9	68.0	53.7
24	Speed hump	50	858	49.6	64.0	41.5

Table 7. Stability of the homogeneous groups under random subsampling: percentage of 1000 subsamples ($n \approx 400$) in which each pair did not differ significantly (Tamhane's T2, $\alpha = 0.05$).

Measure	RC-Nosig	RC-Sig	Paint	Hump	Lane	Paint-Sig	SMD
Raised crosswalk (no signal)	—	90	0	0	47	2	4
Raised crosswalk (signalised)	90	—	0	0	50	8	8
Standard crosswalk (paint only)	0	0	—	99	92	84	69
Speed hump	0	0	99	—	94	88	75
Lane narrowing	47	50	92	94	—	100	99
Signalised crosswalk (paint only)	2	8	84	88	100	—	99
SMD	4	8	69	75	99	99	—

3.2. Non-Compliance Analysis

The effectiveness of each measure was evaluated by analysing the proportion of vehicles exceeding the posted speed limit. Figure 4 presents a comprehensive overview, combining the non-compliance rates with the absolute frequency of compliant and non-compliant vehicles for each category.

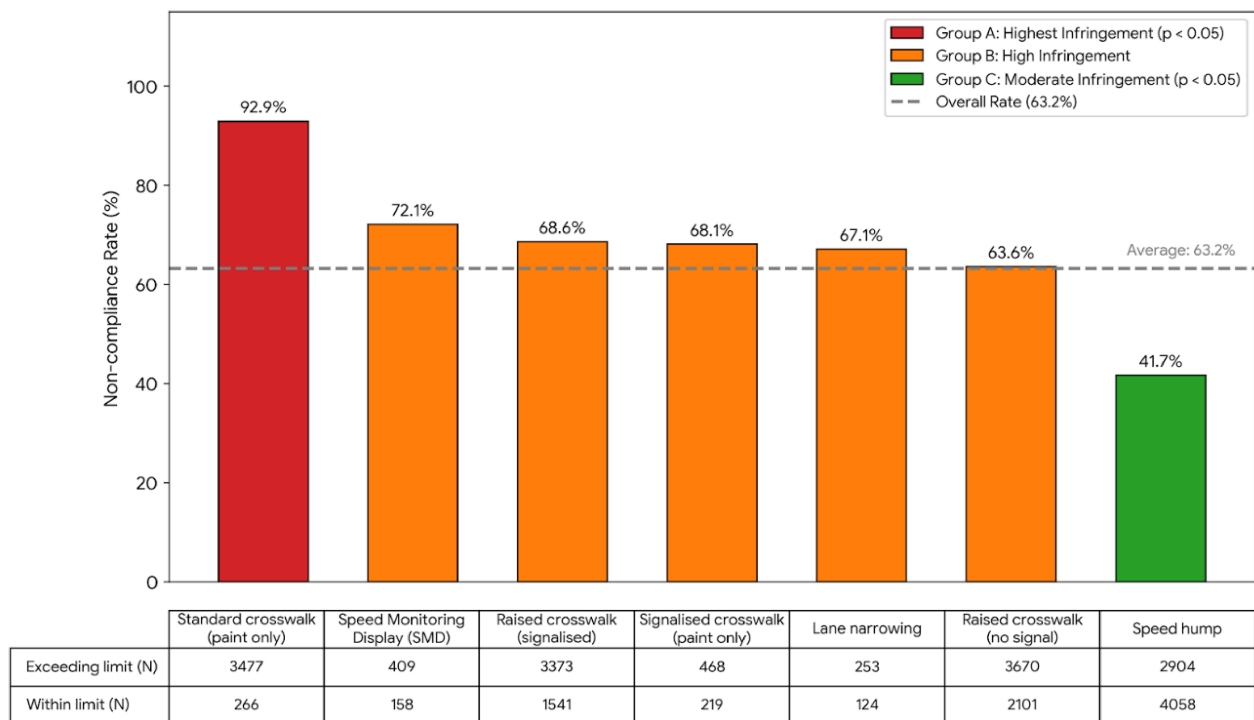


Figure 4. Non-compliance rate (%) and vehicle counts (within/exceeding limit) by measure type.

The analysis reveals that the overall non-compliance rate across the entire study area was 63.2%. A Chi-square test of independence ($p < 0.001$) confirmed that the distribution of compliant versus non-compliant drivers is statistically dependent on the type of infrastructure present. To verify the existence of distinct performance levels, a post-hoc analysis using pairwise Chi-square tests with Bonferroni correction was conducted.

The lowest non-compliance rate was recorded for speed humps (41.7%), which constituted the best-performing statistical group (Group C), being significantly different from all other measures ($p < 0.001$).

A broad intermediate group (Group B) was identified, showing high infringement rates ranging from 63.6% to 72.1%. Pairwise comparisons revealed no statistically significant differences ($p > 0.05$) between the measures in this cluster, which includes raised crosswalks (no signal) (63.6%), lane narrowing (67.1%), signalised crosswalks (paint only) (68.1%), raised crosswalks (signalised) (68.6%), and the Speed Monitoring Display (SMD) (72.1%).

Finally, the highest level of infringement was observed in standard crosswalks (paint only). This measure formed an independent statistical group (Group A) with a non-compliance rate of 92.9%, significantly higher than all other categories ($p < 0.001$).

3.3. Aggregated Speed Distribution

To further analyse the operational impact on driver behaviour, the data was aggregated into two categories: physical measures ($n = 17,647$) and visual/signalling measures ($n = 5374$). Figure 5 presents the Kernel Density Estimation (KDE) plots for both groups, illustrating the continuous probability distribution of vehicle speeds.

The distribution for physical measures is centred around a mean speed of 40.7 km/h. The operating speed (V_{85} , the 85th percentile of the speed) for this group was calculated at 54.0 km/h. In contrast, the visual/signalling measures exhibit a distribution shifted to the right, with a mean speed of 50.7 km/h and an operating speed (V_{85}) of 64.0 km/h, representing a 10 km/h increase compared to physical measures. Welch's t -test confirmed that this difference in mean speeds is statistically significant ($p < 0.001$).

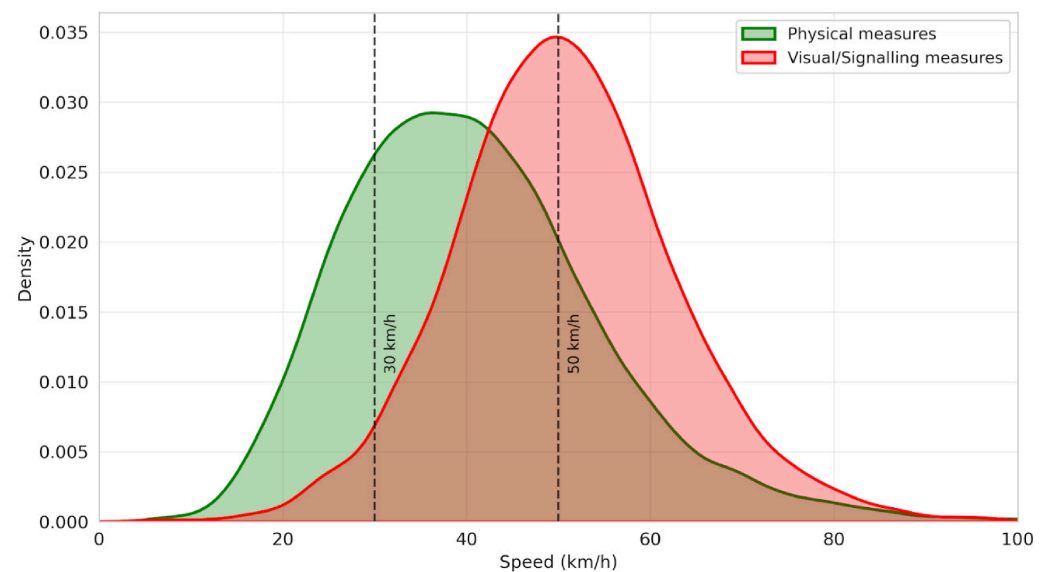


Figure 5. Speed distribution profile: physical measures (green) vs. visual/signalling measures (red).

4. Discussion

The findings of this study provide robust empirical evidence regarding the hierarchy of effectiveness of traffic calming measures in urban transition zones. The statistical analysis is consistent with the interpretation that, in this corridor, visual or informational signalling alone was associated with limited speed compliance in an environment where drivers approach from higher rural speeds, aligning with the challenges identified by the European Commission [1] regarding the lower reduction in fatalities in urban areas compared to rural roads.

A key finding concerns the limited effectiveness of measures lacking vertical deflection, particularly standard road markings, within this corridor. Standard crosswalks (paint only) recorded a critical non-compliance rate of 92.9%, forming the statistically worst-performing group. This suggests that, in this transition context and without physical reinforcement, horizontal markings alone had a limited association with speed compliance. Furthermore, the Speed Monitoring Display (SMD), despite being an active device designed to alert drivers, registered a high violation rate (72.1%), grouping statistically with other high-infringement measures rather than with effective physical barriers. This result stands in contrast to the previous literature documenting the efficacy of SMDs in controlled environments such as work zones or school areas [20,21]. One possible interpretation is that the SMD's purely informational feedback may be insufficient to offset the higher speeds carried over from the rural approach; this mechanism, however, was not measured directly. These results corroborate the conclusions of Pérez-Acebo et al. [22], who argued that the efficacy of signalling diminishes without physical constraints.

Regarding physical measures, the data reveal a paradox between compliance and absolute speed reduction. Statistically, speed humps achieved the best compliance record (only 41.7% violation). However, this success is contextual: they are located in 50 km/h zones, where reducing the mean speed to 48.8 km/h is sufficient to ensure compliance. In contrast, raised crosswalks, despite being the most effective devices in terms of absolute speed reduction (lowering mean speed to 34.4 km/h), registered higher non-compliance rates (63.6%). This indicates that while vertical deflection effectively forces deceleration, it is often insufficient to fully bridge the gap to a strict 30 km/h limit in a transition environment.

However, from a safety perspective, the raised crosswalk remains the superior device. By validating the hierarchy established by Barbosa et al. [7] (speed tables > speed humps),

this study confirms that flat-topped tables impose a significantly higher restriction than standard speed humps (34.4 km/h vs. 48.8 km/h). According to Tefft [3], the risk of pedestrian fatality decreases drastically at lower impact speeds. By achieving mean speeds close to 35 km/h ($V_{85} \approx 45$ km/h), raised crosswalks shift the conflict zone towards a more survivable range, whereas the mean speeds near 50 km/h that persist at standard humps still entail a substantially higher pedestrian mortality risk [3]. This supports the assertion by Batomen et al. [13] that physical modification is the primary driver of safety improvement.

The comparison between raised crosswalks reveals a counter-intuitive phenomenon. Raised crosswalks without signals achieved better compliance (63.6% violation rate) and lower mean speeds (34.4 km/h) than those with signals (68.6% violation, 36.6 km/h). This finding adds nuance to the work of Pérez-Acebo et al. [22], who suggested a synergy between signals and physical measures. As signal-phase data were not available, we advance only as a hypothesis that a possible “dilemma-zone” response at a green light might encourage drivers to maintain speed to clear the crossing, partially offsetting the deceleration induced by the vertical deflection. Conversely, a non-signalised raised crosswalk forces a precautionary approach due to the uncertainty of pedestrian presence, resulting in lower speeds.

Beyond mean speed reduction, the aggregated speed distribution for physical measures is shifted towards lower speeds than that of visual/signalling measures. However, this safety benefit comes at a significant cost. While authors like Shwaly et al. [14] and Obregón-Biosca [17] warn about the environmental impact (noise and emissions), vertical deflection devices also pose significant challenges for emergency services and the transport of passengers with reduced mobility. Consequently, while the results suggest that physical measures are currently a necessary trade-off to enforce compliance in transition zones given the failure of standard visual measures (standard crosswalks and lane narrowing, mean speed 48.16 km/h), there is an urgent need for alternative solutions. Recent findings by Martin-Castresana et al. [24] indicate that specific perceptual designs, such as broken edge lines, can achieve significant speed reductions without physical disruption, suggesting a future pathway to mitigate these negative externalities. Additionally, the phase state of the signalised crossings could not be recorded. As speed at signalised crossings depends strongly on the signal phase, the interpretation of driver behaviour at these locations—including the possible “dilemma-zone” response discussed above—remains hypothetical, and the two signal-controlled sites should be read with this constraint in mind.

Several limitations should be borne in mind when interpreting these results. First, measure type is partially confounded with the posted speed limit, as speed humps are located mainly in 50 km/h sections and raised crosswalks mainly in 30 km/h sections; the analysis stratified by regime (Table 5) mitigates this confounding but does not eliminate it. Second, the observations are not fully independent: passages are nested within the 24 measurement locations and are therefore not independent replications of each intervention, and because vehicles were not individually identified, neither the repeated detection of the same vehicle across successive points nor the possibility that the same drivers were observed at several sites can be excluded. Third, three categories—the SMD, lane narrowing and the signalised painted crosswalk—are represented by a single site, so for these the effect of the measure cannot be separated from that of the specific location and the corresponding findings cannot be generalised. Fourth, the radar counters have a measurement accuracy of ± 3 km/h, which introduces a small uncertainty into the individual speed records. Finally, the generalisability of the results is limited: a single rural-to-urban corridor was studied to ensure geometric comparability, vehicles longer than 15.0 m were excluded to avoid measurement artefacts caused by tailgating, and data collection was restricted to

daylight hours, so the efficacy of visual signalling under reduced visibility—where vertical retroreflectivity becomes critical—was not evaluated, even though drivers tend to travel faster at night [22]. Furthermore, as a cross-sectional study of a mixed traffic stream that probably includes a high proportion of local commuters, some drivers may be habituated to the specific sequence of measures and may react differently from transient drivers. The general trends observed are nonetheless consistent with the physics of vehicle dynamics over vertical deflections reported in the literature [8].

5. Conclusions

This study analysed the behaviour of 23,021 vehicles passages across 24 control points to evaluate the efficacy of traffic calming measures in urban transition zones. Based on the statistical evidence, the following conclusions are drawn:

1. Ineffectiveness of standard visual measures: Under current infrastructure standards, measures relying solely on horizontal marking or psychological feedback were associated with high non-compliance in this corridor. Standard crosswalks (paint only) recorded a critical non-compliance rate of 92.9%, while the Speed Monitoring Display (SMD) registered a 72.1% violation rate. This suggests that, in this corridor and without physical constraints, visual priority signs were frequently disregarded by drivers arriving at higher approach speeds.
2. The limitation of vertical deflection: While physical measures proved superior to visual ones in reducing speed, they are not a perfect solution. Although raised crosswalks achieved the lowest mean speeds (34.4 km/h), they still failed to ensure strict legal compliance with the 30 km/h limit (registering a 63.6% violation rate). This indicates that even the most aggressive measure currently available is insufficient to fully discipline traffic in transition zones without supplementary reinforcement.
3. The “Safety vs. Externalities” dilemma: Authorities currently face a difficult trade-off. Within this corridor, converting painted crosswalks into raised tables was the measure associated with the lowest mean speeds (approximately 34 km/h; $V_{85} \approx 45$ km/h), a range that the previous literature links to lower pedestrian injury risk. However, this safety benefit comes at a high cost. Considering the negative externalities identified—ranging from noise and emissions to discomfort and potential health risks for vulnerable passengers—vertical deflection may be regarded as a current trade-off rather than an optimal long-term solution.

Considering these drawbacks, future research will focus on evaluating the potential of perceptual countermeasures to replace vertical deflection. Specifically, a driving simulator study replicating the exact geometry of the BI-2604 road will be conducted. This virtual environment will allow for the risk-free testing of innovative marking patterns (as proposed by Martin-Castresana et al. [24,25]) to determine if they can replicate the compliance rates of physical humps while eliminating the associated negative externalities. The simulator to be used has been validated in previous work [29], confirming that driver speed behaviour in the virtual environment reproduces that observed in the field; this provides confidence in the internal validity of the planned experiment. The simulator study will reproduce the geometry of the corridor and evaluate each configuration under both the 30 km/h and 50 km/h regimes, and it will extend the present spot-speed analysis by recording driver-control responses—braking, throttle and steering inputs—that cannot be captured with roadside radar. Nevertheless, simulator findings will require confirmation through subsequent field testing before any operational recommendation is made, since absolute speeds and compliance rates obtained in a virtual environment may differ from those on the real road.

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Abbreviations

The following abbreviations are used in this manuscript:

TCM	Traffic Calming Measure
SMD	Speed Monitoring Display
ANOVA	Analysis of Variance
V ₈₅	85th percentile of the speed

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