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USE OF SPEED PROFILE AS SURROGATE MEASURE: EFFECT OF TRAFFIC CALMING DEVICES ON CROSSTOWN ROAD SAFETY PERFORMANCE

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ABSTRACT

Urban road safety management is usually characterized by a lack of quantity and quality of crash data and low budgets. However, fifty four percent of road crashes in Spain take place on urban areas. Moreover, ten percent of urban fatal crashes occur on crosstown roads, which are rural roads that traverse small communities. So, traffic calming measures (TCMs) are often implemented in this part of a rural road that traverses a small community in order to reduce both crash frequency and severity by lowering speeds.

The objective of the research was to develop a methodology using continuous speed profile to evaluate safety effectiveness of TCMs on crosstown roads. Given the strong relationship between speed and crash experience, safety performance can be related to speed. Consequently, speed can be used indirectly as a surrogate safety measure.

Two indexes were defined as surrogate safety measures based on the continuous speed profile: *Ra* and *Ea*. *Ra* represents absolute accumulated speed variations relative to the average speed, and is inversely related to accumulated speed uniformity; and *Ea* represents accumulated speed variations above the speed limit, and is directly related to accumulated speeding. Naturalistic data was collected using GPS trackers on twelve scenarios with different TCMs spacing. Then, the indexes were applied to individual observed speed profiles (individual analysis) as well as the operating speed profile (global analysis). The values obtained from individual and global analysis were statistically different. Spacing lower than 110 m, which was found optimal on previous research, did not allow drivers to modify their speeds as accumulated speed uniformity was quite similar regardless average operating speed; and, accumulated speeding was also minimized. Consequently, scenarios with implemented TCMs according to technical criteria presented a better design quality. On the other hand, age and gender differences didn't seem to affect average speed, nor accumulated speed uniformity or accumulated speeding.

Key words: Surrogate safety measure; traffic calming; speed profile; consistency; speeding.

1. INTRODUCTION

Improving road safety in both urban and rural areas is a major objective of the Spanish Traffic Agency (Spanish General Directorate of Traffic). In 2010 in Spain, fifty four percent of severe road crashes, which include injury and fatal crashes, took place in urban areas. In crosstown roads occur one point three percent of urban severe crashes even though they have the ten percent of urban fatalities (Dirección General de Tráfico, 2011). Crosstown roads are the part of a two-lane rural road which traverses a small populated area. Consequently, most drivers are through traffic and should adapt from rural to urban driving conditions. Crosstown roads are common in Europe and they are characterized by low-median traffic volume (annual average daily traffic between 500 and 8,000 vehicles per day), which results in a relatively low number of crashes. Besides, Spanish databases usually lack reliable data. Thus, traditional urban road safety management based on road crashes and fatalities may not be the most appropriate approach due to a lack of crash data statistical significance.

Surrogate safety measures based on roadway characteristics are often defined to indirectly assess road safety management where historical crash data are limited or unavailable. In rural highways, the relationship between consistency and safety level was ascertained (Polus and Mattar-Habib, 2004; Polus et al., 2005). Some authors developed surrogate measures relating speed variation and crash rates on rural roads. The definition of the surrogate measures varied from difference between pre-crash and normal condition traveling speeds (Solomon, 1964) to standard deviation of speeds (Garber and Gadiraju, 1989; Aljanahi, 1999) or difference between the operating speed and the mean speed (Lave, 1985; Rodriguez, 1990). Lamm and Choueiri (1995) proposed two criteria: operating speed difference between two consecutive elements; and difference between operating speed and design speed. This second criterion was incorporated into the Interactive Highway Safety Design Model (IHSDM) of the Federal Highway Administration (2010) on the design-consistency module. Cafiso et al. (2007) used Lamm and Choueiri measures to assess two-lane rural road consistency on the Italian road network. Nevertheless, the former surrogate measures are calculated in one specific location and not along an entire section. Polus and Mattar-Habib (2004) introduced the analysis of operating speed profile to evaluate consistency and safety level. The main hypothesis was that improved speed uniformity along a roadway section resulted in better quality and less strain in driving, thus improving safety. Two consistency measures were defined: the relative area bounded by the speed profile and the average weighted speed (Ra); and, the standard deviation of operating speeds (σ). As design consistency increased, crash rates decreased significantly. Both consistency measures provided a similar assessment of consistency as Lamm and Choueiri measures. However, Polus and Mattar-Habib's measures are calculated for the entire segment under research. The Polus consistency model is based on operating speed prediction models on curves and tangents; and estimated acceleration and deceleration rates to complete the operating speed profile.

In urban areas, such as crosstown roads, operating speed models are fewer than in two-lane rural roads. In fact, only a few studies developed operating speed models in low-speed urban streets (Poe et al, 1996; Fitzpatrick et al., 1997; Poe et al., 1998; Bonneson, 1999; Poe and Mason, 2000; Fitzpatrick et al., 2001; Fitzpatrick et al., 2003; Wang et al., 2007). Poe et al. (1996) concluded that access and land use characteristics influenced operating speed. A regression model carried out by Poe et al. (1998) showed that alignment and traffic control explained a large part of the speed variation, although a high correlation between both variables was detected. Fitzpatrick et al. (2003) found that posted speed limits were the most significant variable for both curve and tangent sections. Wang et al. (2007) used in-vehicle GPS technologies to determine operating speed on urban streets. They found that operating speed was influenced by number of lanes, roadside object density, the density of T-intersections, raised curb, sidewalk, on-street parking, and land use. However, none developed a correlation between speed and crashes.

If one considers the previous speed models, the operating speed profile of a crosstown road could be estimated and evaluated using Polus measures. However, the speeding problem along rural roads going through populated areas is usually handled in Europe by using traffic calming measures (TCMs). TCMs only affect speeds because most of the drivers on the route are through traffic. Furthermore, possible detours to local streets with lower speed limits would lead to higher delays as travel distance is increased, speeds are reduced and merge priority to the rural road is lost. Given that TCMs involve traffic control in one location, specific operating speed models should be considered. Several studies have been conducted to evaluate the effectiveness on speed reduction and operating speed over individual TCMs; and their results have been summarized in several publications (Department for the Environment, Transport and the Regions, 2000; Elvik et al., 2009; Ewing and Brown, 2010; Federal Highway Administration, 2009; Transportation Research Board, 2011). TCMs' acceleration and deceleration rates have also been assessed. Barbosa et al. (2000) studied mean acceleration and deceleration rates by types of measures based on continuous speed profiles. Deceleration rates varied from -0.25 to -0.82 m/s2, while acceleration rates were set between 0.24 and 0.50 m/s2. Therefore, TCMs implementation usually produced an irregular speed profile with frequent, unnecessary, decelerations and accelerations. Studies showed that spacing between TCMs was a key factor on speed reduction (Ewing et al, 1996; Ewing, 1999; Barbosa et al., 2000; Cottrell et al, 2004; Torres et al., 2010; Bassani et al, 2011; Moreno et al, 2011). Hence, most of the guidelines and recommendations propose TCMs geometry and their optimal spacing to reduce speeding in urban areas. Then, the assessment of TCMs implemented along a segment is often characterized by average speed reduction rather than consistency of the resulted speed profile or accumulated speeding along the segment. Moreover, uniformity of a speed profile on a calmed crosstown road has never been assessed.

On the other hand, some authors (Poe et al., 1998; Freedman, 1999; Park and Saccomanno, 2006) mentioned that the use of aggregate statistics fails to recognize the probability distribution of the individual observed values. The apparent improvement in explaining variation of the parameter is given by the aggregation speed data which may reduce the individual extreme values and overestimate consistency and safety level. Therefore, individual speed profiles should be examined. However, practitioners may not have individual observations to determine design quality. Consequently, aggregate values should also be analyzed and determine whether the difference between individual and aggregate values is statistically significant.

Crosstown roads with adequate TCMs separated with optimal spacing would result in a more uniform speed profile and; therefore, more consistent design; which would likely lead to a safer crosstown road, in the same way as rural highways. This paper explores continuous speed profiles obtained from naturalistic driving to evaluate safety performance on calmed crosstown roads.

2. OBJECTIVES

The aim of the research was to develop a methodology using continuous speed profile to evaluate safety effectiveness of traffic calming measures (TCMs) on crosstown roads.

The main objectives of the research were: to observe drivers' behavior and characteristics on twelve different scenarios by using GPS trackers; to define two indexes as surrogate safety measure; to apply the surrogate measures to individual observed speed profiles and aggregated operating speed profiles; and to analyze the measures' values depending on the crosstown road characteristics, such as speed limit, operating speed or traffic calming density. Moreover, driver's age and gender influence on the proposed indexes would be also evaluated. It should be noted that with this approach TCMs were considered as an integrated system along an entire crosstown road rather than isolated measures.

3. FIELD STUDY

3.1. Site selection

For the research, six crosstown roads were selected. Five of the sites had TCMs installed; while the sixth location had no TCMs. The first five crosstown roads were selected according to the recommendations from a previous road safety study taking into account: annual average daily traffic (AADT); length of the cross-town road (L); and, type of TCMs. The selected towns were: Albalat de la Ribera (3,609 inhabitants); Chelva (1,683 inhabitants); Genovés (2,826 inhabitants); Quatretonda (2472 inhabitants); and Llutxent (2,538 inhabitants). TCMs included sixteen speed tables, five speed humps and one roundabout (Moreno et al., 2011).

The sixth location was Belgida (723 inhabitants). No TCMs were initially installed on Belgida's crosstown road. Two pedestrian crossings were located on a tangent section. The community asked the authorities to install TCMs to reduce speeding along the crosstown road. The road safety project was implemented by stages, which allowed deducing individual effect of different TCMs on the continuous speed profile: one speed hump; two speed tables; one speed bump; one chicane; and one set of dragon's teeth. The TCMs were implemented from the center of the crosstown road to the extremes: the first measures were located in the middle of the road while the last measures were the entrance gates of the traffic calming plan (first TCM of a crosstown road). A total of seven scenarios were considered: (0) no TCMs; (1) Southern speed table and speed hump construction; (2) Northern speed table and speed bump installation; (3) chicane construction; (4) dragon's teeth construction; (5) Northern speed table removal; and (6) stage 5 after one year. Consequently, a total of twelve different scenarios (5 observation and 7 experimentation) with different TCMs density were observed.

Crosstown road characteristics are summarized on Table 1. The speed limit was 40 or 50 km/h; while the AADT varied from 1,180 to 4,230 vehicles per day. According to Garcia et al. (2011), all crosstown roads would operate with free-flow conditions, as AADT was lower than 9,000 vehicles per day. Belgida's AADT reduction was caused by the construction of a highway segment near the area, instead of the TCMs implementation: the new highway segment diverted some traffic from the rural road which after goes through Belgida; however, many through traffic continued on Belgida. The length of the crosstown roads varied between 560 and 945 m from the beginning to the end of the town. In order to characterize the crosstown roads, TCMs density (*TcD*) was calculated. *TcD* was defined as the number of traffic calming devices per kilometer: *TcD* equal to 10 meant that TCMs were spaced 100 m on average. To calculate *TcD,* TCMs along the crosstown road were considered as well as entrance gates and curves with radius lower than 150 m.

Table 1 Scenarios characteristics

Scenario	Speed limit (km/h)	AADT (veh/day)	Length (m)	Curves (ud)	Number of TCMs (ud)	Entrance gate (ud)	TCM density (nº/km)	
							Bound 1	Bound 2
Albalat	40	4,230	765	1	5	0	7.8 (E)	7.8 (W)
Chelva	40	2,490	885	1	4	0	5.6 (W)	5.6 (E)
Genoves	40	4,550	945	2	4	1	7.4 (E)	6.3 (W)
Quatretonda	50	3,250	680	0	4	0	5.9 (E)	5.9 (W)
Llutxent	40	2,930	690	0	4	0	5.8 (E)	5.8 (W)
Belgida 0	50	2,650	560	1	0	0	1.8 (NE)	1.8 (SW)
Belgida 1	50	1,920	560	1	2	0	5.4 (NE)	5.4 (SW)
Belgida 2	50	1,920	560	1	4	0	8.9 (NE)	8.9 (SW)
Belgida 3	50	1,180	560	1	4	1	11.6 (NE)	8.9 (SW)
Belgida 4	50	1,180	560	1	4	2	11.6 (NE)	11.6 (SW)
Belgida 5	50	1,180	560	1	3	2	9.8 (NE)	9.8 (SW)
Belgida 6	50	1,180	560	1	3	2	9.8 (NE)	9.8 (SW)

All crosstown roads presented good pavement conditions and traffic lane widths vary from 3.10 to 3.25 m; which is common in Spanish crosstown roads. As crosstown roads are in urban areas, there were sidewalks on both sides and on-street parking was allowed. Grade is nearly horizontal in all scenarios.

3.2. Data collection

To collect drivers' behavior, passive GPS trackers were used. These data loggers stored GPS data gathered from the vehicles which were attached for one-second intervals. Consequently, individual continuous speed profile and acceleration profile could be deduced.

To collect the information, two road controls were placed before drivers approached the town from each direction (Moreno et al., 2011). Road controls were separated at least 1 km from the town to enable drivers to adopt their desired speed before entering. On each road control, all drivers were stopped and asked to collaborate in a road safety study if they were going until the second road control. So, only naturalistic drivers going about their normal business were used. Drivers were only told that a device had to be placed on their own vehicles and they were reminded not to drive differently. Only passenger cars were taken into account. A survey was conducted at the first control to collect age, gender and vehicle type. At the other road control, drivers were stopped to return the device and were asked whether they had been influenced on their speed by another vehicle or pedestrian.

The methodology was proved not to influence drivers' speed with spot speeds verification measures before and during the observed time. Thus, drivers were not induced to reduce their usual speeds or behave differently. Tests were performed between 9:00 a.m. and 2:00 p.m., on a working day and with good weather conditions. In Belgida, each data collection took place at least 14 days after the TCM implementation. Initial sample was 1,505 vehicles.

3.3. Data reduction

The data contained at every second: latitude; longitude; altitude; heading; time; and, date. A program developed for another research was used to determine the vehicle speed along the crosstown road (Moreno et al., 2011). Only vehicles in free-flow conditions that covered the entire crosstown road without stops were considered. Consequently, some data were removed because of: detours to local streets and stops; platooning; or speed reductions due to influence of pedestrians or other vehicles.

Speed profiles should be developed between the beginning and the end of the crosstown road without detours to another streets or stops. The GPS coordinates were plotted on Google Earth to verify if drivers followed the crosstown road. Then, the time sequence was analyzed to determine if they stopped along the crosstown road (i.e. take a coffee, get gas). Drivers that took another path to go through the community were discarded, as well as stopped drivers.

On the road controls, the vehicles whose driver accepted to participate on the study were stopped at least 2 minutes in order to give them enough free-space ahead. As stated, the AADT of the rural roads was not too high and if some platooning was detected on the road controls, the test was stopped until the traffic was lower. So, the staff tried to assure the free-flow conditions. However, drivers could find slower vehicles along the segment between the traffic controls. To overcome this problem, individual speed profiles were examined including the rural road sections before and after the crosstown road. The individual speed profiles were plotted on the same graph than the speed percentiles (15, 30, 50, 70 and 85). If the individual speed profile was “normal” it should be between two percentiles the whole segment or with slight variations. Individual speed profiles that are in a high percentile and varied from that one to a lower one and maintain it (i.e. 85 to 30) were meant to find a slower vehicle and be influenced by the platoon. So, that individual speed profile was removed. Moreover, if the individual speeds were locally reduced on one section but the percentiles did not present a speed reduction; only that vehicle was influenced somehow in that section. These vehicles were removed.

Nearly 30% of the initial sample was discarded due to non free-flow conditions, detour or stopping. Figure 1 shows an example of 25 vehicles’ observed speed profile obtained from the GPS trackers in Genoves’ scenario.

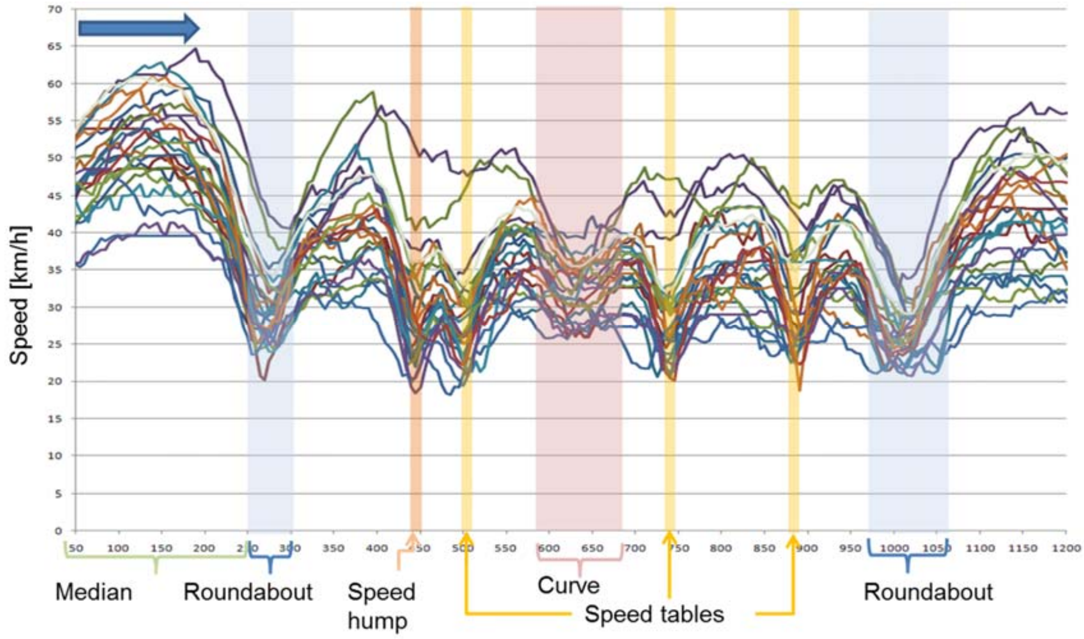


Figure 1 25 Individual speed profiles of Genoves

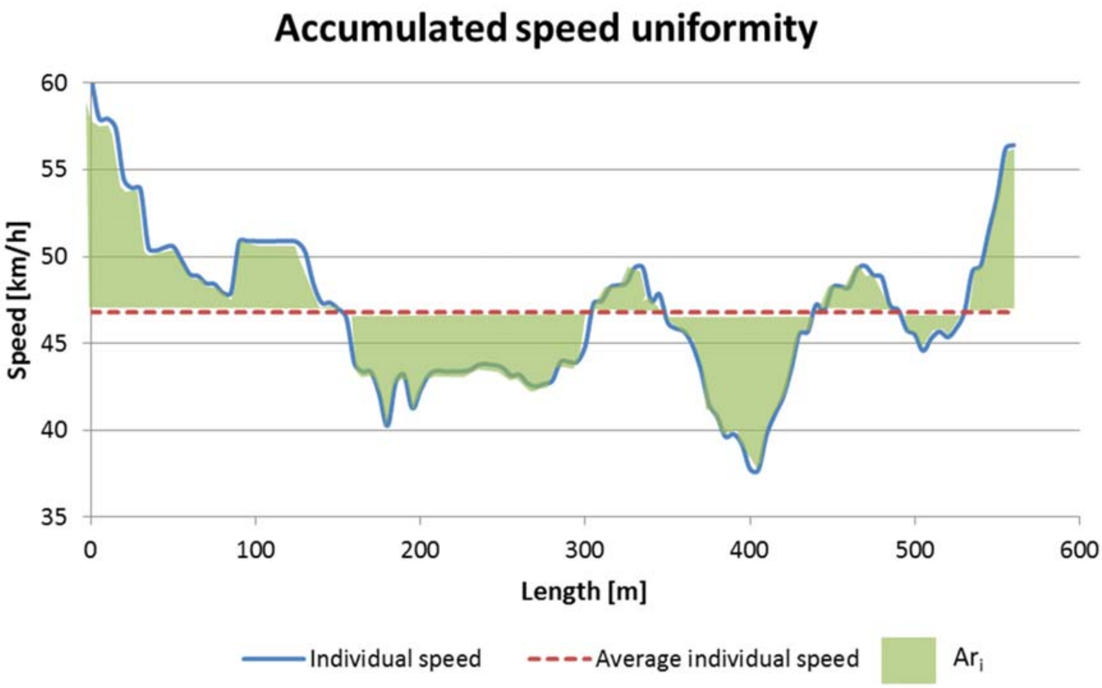
4. SURROGATE MEASURES

Two indexes are defined as surrogate safety measures based on the continuous speed profile: *Ra* and *Ea*. The first measure evaluates accumulated speed uniformity; while the second measure assesses accumulated speeding along the entire crosstown road. Accumulated speed uniformity is not enough to consider a good design quality if speed level is higher than the design speed; thus, both measures should be used to determine design quality. Figure 2 represents the concept.

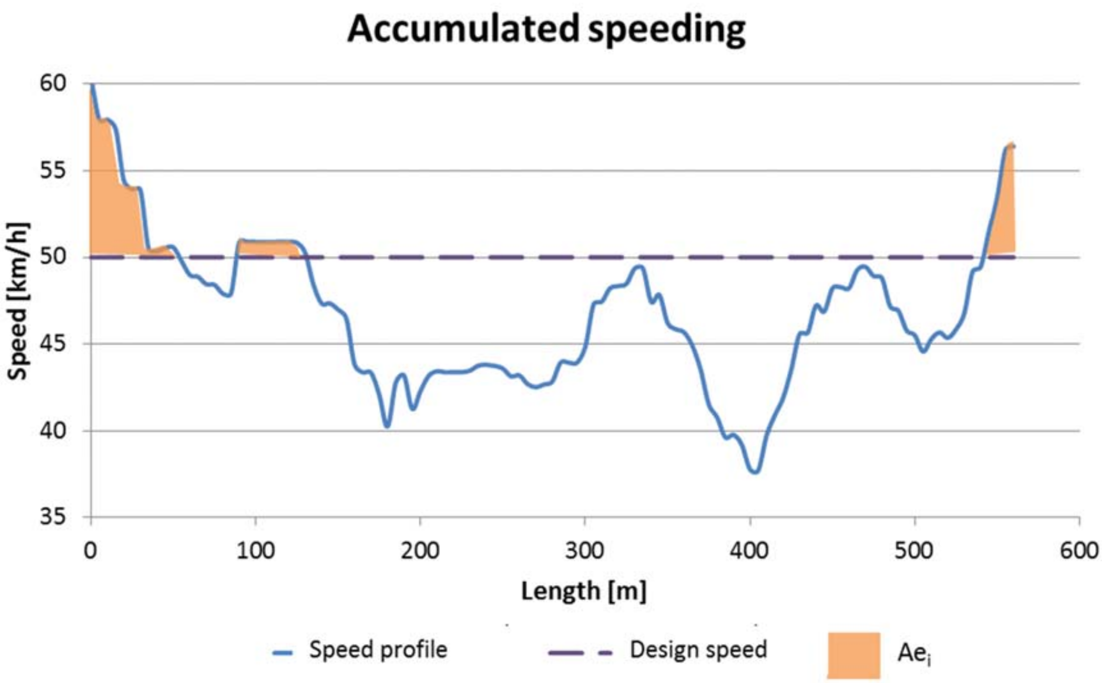
Ra is defined as the normalized relative area (per unit length) bounded between the speed profile and the average speed line. The measure can be applied to individual speed profiles or to the operating speed profile. The first step, is to calculate the average speed of the speed profile along the crosstown road. Then, the areas bounded between the speed profile and the average speed line (Ar_i) are obtained (Figure 2a). The consistency measure is given as the sum of the absolute value of the areas divided by the length of the segment (*L*). Therefore, *Ra* is reversely related to accumulated speed uniformity. Equation 1 can be applied.

$$Ra = \frac{\sum Ar_i}{L} \quad (1)$$

where:
Ra: relative area measure of uniformity (m/s) – speeds should be measured in m/s
ΣAr_i: sum of areas (absolute values) bounded between the speed profile and the average speed (m^2/s)
L: crosstown road length (m).



(a)



(b)

Figure 2 Speed profile and surrogate measures of Belgida 5 – NW: (a) accumulated speed uniformity; (b) accumulated speeding

Ea is the normalized relative area (per unit length) bounded between the speed profile values higher than the speed limit and the speed limit line. The measure can be applied to individual speed profiles or to operating speed profile. Given the speed limit, the areas bounded between the speed profile and the speed limit line are determined. Only the areas above the speed limit line (Ae_i) are considered in the measure (Figure 2b). The accumulated speeding is calculated applying Equation 2 as the sum of the areas divided by the length of the segment (*L*). Consequently, *Ea* is directly related to accumulated speeding..

$$Ea = \frac{\sum Ae_i}{L} \qquad (2)$$

Where:
Ea: relative area measure of speeding (m/s) – speeds should be measured in m/s
ΣAe_i: sum of areas bounded between the speed profile and the speed limit where speed is higher than speed limit (m^2/s)
L: crosstown road length (m).

The proposed measures are calculated based on continuous speed profile rather than individual speed differentials between consecutive elements. They provide an evaluation of accumulated speed uniformity and accumulated speeding along the whole crosstown road under study.

5. RESULTS AND ANALYSIS

As TCMs type and number varied on the same crosstown road depending on the traffic bound, each bound was considered as a different site. Consequently, 24 sites were analyzed on 12 scenarios. On each site, average speed, accumulated speed uniformity and accumulated speeding were calculated. Two approaches were considered:

- Individual speed profile analysis (individual analysis). From each individual speed profile, average speed, accumulated speed uniformity and accumulated speeding were calculated. Afterwards, 85^{th} percentile of each distribution was deduced ($Vm_{p85}, Ra_{p85}, Ea_{p85}$).
- Operating speed profile analysis (global analysis). Average speed, accumulated speed uniformity and accumulated speeding of the operating speed profile were calculated ($Vm_{v85}, Ra_{v85}, Ea_{v85}$).

All variables should be normally distributed among sites in order to fulfill the assumptions of the statistical tests. Moreover, the individuals' value of the variables should also be distributed as a normal distribution on each site. The probability plot, skewness and kurtosis were analyzed on each case.

Average speeds in all the sites were normally distributed. From each normal distribution, 85^{th} percentile was calculated (average individual speed - Vm_{p85}). Then, average individual speed among the sites was tested to be normally distributed. The probability plot, skewness and kurtosis values were within the limits of a normal distribution. Average speeds of the operating speed profile of each site were obtained (Vm_{v85}). Average operating speed among sites was also normally distributed.

Ra was calculated for each individual speed profile along the crosstown roads, except for Belgida 0 because of the absence of TCMs. Then, accumulated speed uniformity values were checked to be normally distributed on each site. The results indicate that *Ra* was distributed as a normal distribution on each site. Then, 85th percentile of individuals' accumulated speed uniformity was calculated in each site (individual accumulated speed uniformity - Ra_{p85}). The distribution of individual uniformity among sites was normally distributed. Afterwards, accumulated speed uniformity of the operating speed profile of each site was obtained (global accumulated speed uniformity - Ra_{v85}) and they were distributed as a normal distribution among sites.

Table 2 Average speed, uniformity and speeding results

Site	Speed limit (km/h)	Tc density (units/km)	Vm (km/h)		Ra (m/s)		Ea (m/s)	
			Vm_{v85}	Vm_{p85}	Ra_{v85}	Ra_{p85}	$Ea^{0.5}_{v85}$	$Ea^{0.5}_{p85}$
Albalat-W	40	7.8	40.68	38.82	1.31	1.68	0.87	0.75
Albalat-E	40	7.8	41.71	40.27	1.08	1.68	0.90	0.94
Belgida 0-SW	50	1.8	60.43	58.10	2.98	3.68	1.79	1.68
Belgida 0 -NE	50	1.8	64.53	63.62	3.18	3.64	2.06	2.06
Belgida 1-SW	50	5.4	53.98	54.79	3.72	4.18	1.55	1.55
Belgida 1-NE	50	5.4	55.95	53.26	4.04	4.05	1.65	1.49
Belgida 2-SW	50	8.9	48.33	44.58	2.94	3.36	1.14	1.08
Belgida 2-NE	50	8.9	48.42	45.98	3.27	3.72	1.22	1.22
Belgida 3-SW	50	8.9	44.66	43.56	2.17	2.53	0.81	0.82
Belgida 3-NE	50	11.6	43.42	41.80	1.30	1.86	0.33	0.40
Belgida 4-SW	50	11.6	45.27	43.49	2.33	2.67	0.88	0.79
Belgida 4-NE	50	11.6	44.43	41.88	1.29	1.93	0.36	0.40
Belgida 5-SW	50	9.8	48.51	46.77	2.06	2.45	0.95	0.96
Belgida 5-NE	50	9.8	46.79	45.05	0.98	1.88	0.42	0.47
Belgida 6-SW	50	9.8	50.94	49.74	2.33	2.59	1.24	1.14
Belgida 6-NE	50	9.8	48.84	47.83	1.08	1.79	0.65	0.70
Chelva-E	40	5.6	42.97	41.35	1.33	1.72	1.07	1.05
Chelva-W	40	5.6	43.10	41.30	1.54	2.06	1.13	1.06
Genoves-W	40	6.3	40.06	38.47	1.51	2.01	0.87	0.85
Genoves-E	40	7.4	42.35	40.95	1.69	2.13	1.07	1.04
Llutxent-W	40	5.8	45.50	43.90	0.98	1.52	1.25	1.20
Llutxent-E	40	5.8	43.61	43.14	1.25	1.63	1.10	1.07
Quatretonda-W	50	5.9	51.40	50.00	2.02	2.41	1.11	1.03
Quatretonda-E	50	5.9	48.06	45.82	2.10	2.66	0.89	0.82

Accumulated speeding was evaluated using *Ea*. The index is directly related to accumulated speeding. Equation 2 was applied to all the individual speed profiles. Then, it was verified if the individuals' accumulated speeding were distributed as a normal distribution on each site. The results were negative: the individuals' accumulated speeding did not follow a normal distribution. Consequently, the variable was transformed to the square root of the accumulated speeding, which was normally distributed on each site. Therefore, the variable under analysis was calculated as the square root of the accumulated speeding ($Ea^{0.5}$). From each normal distribution of $Ea^{0.5}$, 85th percentile was calculated (individual accumulated speeding – $Ea^{0.5}{}_{p85}$). From each operating speed profile, the accumulated speeding was calculated and then transformed to its square root (global accumulated speeding - $Ea^{0.5}$). The transformed global accumulated speeding was distributed as a normal distribution among sites.

Table 2 summarizes the results.

5.1. Average speed

Average speed reduction is a usual performance measure of traffic calming plans. The traditional analysis is to compare average speed before and after the TCMs implementation. This first analysis was carried out to determine the overall traffic performance on the evaluated sites.

The average speed results are shown in Table 2. Vm_{p85} was lower than Vm_{v85} in all the sites. To determine whether the difference between Vm_{v85} and Vm_{p85} was significant, a pairwise analysis was carried out. The results of the t-test of the difference between the values on each site indicated that the differences was that it was statistically significant (t-statistic = -8.87456, p-value $_{\text{t-statistic}}$ = 0.00000; α = 5%). Consequently, Vm_{v85} was systematically higher than Vm_{p85}. Aggregation of individual speed data into operating speed resulted in a higher value of average speed, as individual speed profiles distribution was not considered. However, global and individual values were close to each other.

Afterwards, an ANOVA test was executed to verify if average individual speeds had equal average value among sites. The results (F-statistic = 62.71; dg = 1002; p-value $_{\text{F-statistic}}$ = 0.0000; α = 5%) indicated that the average individual speeds had a different average value depending on the site.

As the assumptions of the multiple regression analysis were fulfilled, a forward-selection multiple regression analysis was performed to determine the variables that influenced on global average speed (Vm_{v85}) and individual average speed (Vm_{p85}).

The most important variable on average operating speed among sites was the posted speed limit (p-value $_{\text{model}}$ = 0.0003; p-value$_{\text{vlim}}$ = 0.0090; α = 5%, r^2_{adj} = 46 %). Speed limit is usually defined by crosstown road alignment. Moreover, traffic calming measures type and geometry has often been determined depending on speed limit. Given this common relationship among speed limit, crosstown road alignment and TCMs type, average speed analysis depending on speed limit also included crosstown road alignment and TCMs type. Equation 3 shows the prediction model of average operating speed. Then, traffic calming density (*TcD)* was introduced on the model (p-value $_{\text{model}}$ = 0.0000; p-value$_{\text{vlim}}$ = 0.0000; p-value $_{\text{TcD}}$ = 0.0000; α = 5%, r^2_{adj} = 77 %). Equation 4 shows the prediction model depending on both speed limit and *TcD.* As observed, the higher traffic calming density, the lower average operating speed; and the higher speed limit, the higher average operating speed.

$$Vm_{v85} = 18{,}488 + 0{,}600 \cdot V_{lim} \qquad R^2_{aj} = 46\ \% \qquad (3)$$

$$Vm_{v85} = 15{,}547 + 0{,}871 \cdot V_{lim} - 1{,}194 \cdot TcD \qquad R^2_{aj} = 77\ \% \qquad (4)$$

Where:
Vm_{v85}: average operating speed (km/h)
V_{lim}: speed limit (km/h).
TcD: traffic calming density (number/km).

On the other hand, average operating speed was compared to speed limit. Only crosstown roads with *TcD* higher than 9 presented an average operating speed lower than the speed limit. Thus, traffic calming density would be a key factor on controlling average operating speed accumulated speeding.

Individual analysis showed similar results with lower coefficient of determination. The models are given in Equation 5 (p-value $_{model}$ = 0.0011; p-value$_{vlim}$ = 0.0011; α = 5%, r^2_{adj} = 39 %). and Equation 6 (p-value $_{model}$ = 0.0000; p-value$_{vlim}$ = 0.0000; p-value $_{TcD}$ = 0.0001; α = 5%, r^2_{adj} = 72 %).

$$Vm_{p85} = 18{,}111 + 0{,}573 \cdot V_{lim} \qquad R^2_{aj} = 39\ \% \qquad (5)$$
$$Vm_{p85} = 14{,}965 + 0{,}863 \cdot V_{lim} - 1{,}278 \cdot TcD \qquad R^2_{aj} = 72\ \% \qquad (6)$$

Where:
Vm_{p85}: average individual speed (km/h)
V_{lim}: speed limit (km/h)
TcD: traffic calming density (number/km).

5.2. Accumulated speed uniformity

Uniformity of the speed profile along the entire calmed crosstown road was assessed by using the index *Ra*, which is inversely related to accumulated speed uniformity. Results are summarized on Table 2.

Global and individual values were compared. Global accumulated speed uniformity was always lower than individual accumulated speed uniformity. The results of the t-test on the variable Ra_{v85} - Ra_{p85} indicate that the difference was statistically significant (t-statistic = 12.4673, p-value $_{t\text{-}statistic}$ = 0.00000 α = 5%). Operating speed profile was obtained as the aggregated value of individual speeds, section to section. Consequently, the variability of the individual speed distribution was being lost through data aggregation into a single descriptive value. Thus, uniformity of operating speed profile resulted better than the uniformity of individual speed profile and its corresponding *Ra* was statistically lower; which statistically confirms the previous hypothesis (Poe et al., 1998; Freedman, 1999; Park et al., 2006).

An ANOVA test analyzed whether the individuals *Ra* average value in each site were equal. Statistical differences among average values of *Ra* were found (F-statistic = 76.10; dg = 862; p-value $_{F\text{-}statistic}$ = 0.0000; α = 5%).

Multiple regression assumptions were verified. Then, a forward-selection multiple regression analysis was carried out on global accumulated speed uniformity (Ra_{v85}) and individual accumulated speed uniformity (Ra_{p85}).

The parameter which better explained accumulated speed uniformity variation was the average operating speed. As seen in Equation 7 (p-value $_{model}$ = 0.0001; p-value$_{vlim}$ = 0.0001; α = 5%, r^2_{adj} = 53 %) and Equation 8 (p-value $_{model}$ = 0.0000; p-value$_{vlim}$ = 0.0000; α = 5%, r^2_{adj} = 55 %). The higher average operating speed, the higher *Ra*. So, higher average operating speeds caused lower accumulated speed uniformity, for both global and individual analysis. As stated before, average operating speed was influenced by TCMs type and speed limit. A lower uniformity within the profile may be caused by a lower consistency of the implemented TCMs. Consequently, drivers tended to accelerate and decelerate more aggressively; so, the inconsistency of speeds on the entire crosstown road was higher.

$$Ra_{v85} = -5{,}277 + 0{,}155 \cdot Vm_{v85} \qquad R^2_{aj} = 53\ \% \qquad (7)$$
$$Ra_{p85} = -4{,}157 + 0{,}141 \cdot Vm_{v85} \qquad R^2_{aj} = 55\ \% \qquad (8)$$

Where:
Vm_{v85}: average operating speed (km/h)
Ra_{v85}: global accumulated speed uniformity (m/s)
Ra_{p85}: individual accumulated speed uniformity (m/s).

TcD was also included on the multiple regression model. The results indicated that the values should be grouped depending on the traffic calming density. Hence, three groups were created. The first group contained the crosstown roads with *TcD* lower than 6 unit/km; which meant that the average spacing between TCMs was longer than 170 m. The second group was formed by crosstown roads with *TcD* between 6 and 9 unit/km, which included average spacing from 110 m to 170 m. The third group was crosstown roads with *TcD* higher than 9 unit/km and corresponded to optimal spacing according to Garcia et al. (2011). Valid regression models between accumulated speed uniformity and average operating speed were found on the first and second group. However, the p-value of the model on the third group was higher than 0.05. Consequently, no statistical relationship was found between average operating speed and accumulated speed uniformity on crosstown roads with spacing lower than 110; at 95% level of confidence. Thus, drivers could not vary significantly their speed; which results in better uniformity regardless of their speed.

On the other hand, global *Ra* values tend to accumulate around 1.5 m/s; and the lowest values were near to 1.0 m/s. Global values over 2.0 m/s presented high operating speed. Polus and Mattar-Habib (2004) determined thresholds of design consistency quality based on the design qualities of nine two-lane highway segments and the results of a sensitivity analysis. To consider a good consistency quality, *Ra* should be lower than 1 m/s; while *Ra* higher than 2 m/s was categorized as poor consistency quality. Between both thresholds, consistency was defined as acceptable. The thresholds proposed by Polus and Mattar-Habib were correlated then to safety.

Based on the traffic calming qualities of the twenty two sites considered, and using engineering judgment based on the observed conflicts of videos, two preliminary thresholds could be proposed to define uniformity quality along the crosstown road. Both thresholds are shown in Table 3. They are similar to the thresholds that can be estimated from this initial assessment of accumulated speed uniformity in calmed crosstown roads. It should be noted that *Ra* is inversely related to accumulated speed uniformity.

Table 3 Thresholds for the determination of design uniformity quality

Global accumulated speed uniformity	**Design quality**		
	Good	**Acceptable**	**Poor**
Ra (m/s)	$Ra < 1.5$	$1.5 \leq Ra \leq 2.0$	$Ra > 2.0$

The best of the observed sites could not be categorized as good uniformity design with Polus thresholds.

5.3. Accumulated speeding

Accumulated speeding was evaluated using the square root of the accumulated speeding index ($Ea^{0.5}$), which are on Table 2. Global accumulated speeding ($Ea^{0.5}_{v85}$) and individual accumulated speeding ($Ea^{0.5}_{p85}$) were similar to each other regardless the site. Firstly, a t-test on the variable $Ea^{0.5}_{v85}$ - $Ea^{0.5}_{p85}$ was carried out to determine whether the difference between both values was statistically significant. The results of the t-test indicated that the difference between those values was statistically significant (t-statistic = - 2.08462, p-value$_{\text{t-statistic}}$ = 0.049499; α = 5%).

Secondly, a ANOVA test was carried out to determine if the average values of accumulated speeding among sites were equal. The results indicated that the average values were statistically different (F-statistic = 1685; dg = 862; p-value $_{\text{F-statistic}}$ = 0.0000; α = 5%).

Thirdly, forward-selection multiple regression analysis was executed to identify the influence variables on global accumulated speeding ($Ea^{0.5}_{v85}$) and individual accumulated speeding ($Ea^{0.5}_{p85}$). The assumptions of the multiple regression analysis were fulfilled.

The most significant variable on global accumulated speeding was the traffic calming density (p-value $_{\text{model}}$ = 0.0003; p-value $_{\text{TcD}}$ = 0.0003; α = 5%, r^2_{adj} = 46 %). As $Ea^{0.5}_{v85}$ was directly related to accumulated speeding, lower spacing between TCMs reduced accumulated speeding (Equation 9). Then, average operating speed was introduce on the model of Equation 10 (p-value $_{\text{model}}$ = 0.0000; p-value$_{\text{vlim}}$ = 0.0032; p-value $_{\text{TcD}}$ = 0.0001; α = 5%, r^2_{adj} = 64 %). Accumulated speeding increased as average operating speed increased.

$$Ea^{0.5}_{v85} = 1.817 - 0.105 \cdot TcD \qquad R^2_{aj} = 46\ \% \qquad (9)$$

$$Ea^{0.5}_{v85} = 0.116 + 0.035 \cdot Vm_{v85} - 0.105 \cdot TcD \qquad R^2_{aj} = 64\ \% \qquad (10)$$

Where:

$Ea^{0.5}{}_{v85}$: global accumulated speeding (m/s)
TcD : traffic calming density (number/km)
Vm_{v85}: average operating speed (km/h)

Similar results were obtained on the individual accumulated speeding analysis. The models are given in Equation 11 (p-value $_{model}$ = 0.0004; p-value $_{TcD}$ = 0.0004; α = 5%, r^2_{adj} = 47 %) and Equation 12 (p-value $_{model}$ = 0.0000; p-value$_{vlim}$ = 0.0033; p-value $_{TcD}$ = 0.0001; α = 5%, r^2_{adj} = 63 %).

$$Ea_{p85}^{0.5} = 1.817 - 0.105 \cdot TcD \qquad R^2_{aj} = 47\ \% \qquad (11)$$

$$Ea_{p85}^{0.5} = 0.157 + 0.032 \cdot Vm_{v85} - 0.085 \cdot TcD \qquad R^2_{aj} = 63\ \% \qquad (12)$$

Where:
$Ea^{0.5}{}_{p85}$: individual accumulated speeding (m/s)
TcD: traffic calming density (number/km)
Vm_{v85}: average operating speed (km/h)

The global analysis was used to assess initial thresholds of accumulated speeding, as individual values would be more complicated to obtain for practitioners. Optimal spaced traffic calming measures gave $Ea^{0.5}{}_{v85}$: = 0.7 m/s at average operating speeds lower than 50 km/h; which is equivalent to Ea_{v85}:= 0.5 m/s. Moreover, $Ea^{0.5}{}_{v85}$ tend to concentrate around 1 m/s (Ea_{v85}:= 1 m/s). The two proposed preliminary thresholds to evaluate design speeding quality are reflected in Table 4. As the uniformity analysis, engineering judgment based on traffic conflicts observation and traffic calming qualities of the sites were taken into account.

Table 4 Thresholds for the determination of design accumulated speeding quality

Accumulated speeding	Design quality		
	Good	**Acceptable**	**Poor**
$Ea^{0.5}$ (m/s)	$Ea^{0.5} < 0.7$	$0.7 \leq Ea^{0.5} \leq 1.0$	$Ea^{0.5} > 1.0$

Common analysis to quantify the safety benefits of better design quality cannot be applied to the selected crosstown roads. Although ten percent of urban fatalities occur on crosstown roads, the available databases do not separate different traveling directions. Including both directions, the total number of crashes on the selected crosstown roads varied from 2 to 4 crashes during the last four years. Earlier data correspond to a previous situation where no TCMs were implemented. The low number of crashes on crosstown roads did not result in statistical insignificance. Furthermore, the regression to the mean and time trend biases cannot be eliminated since almost all the crosstown roads in Valencia started to implement traffic calming devices in the data collection period. Consequently, the initial assessment of uniformity and speeding thresholds was limited to observations of the design qualities and the results of sensitivity analyses while using traffic conflicts observation. Nevertheless, the influence of speed on safety has been widely studied. Polus and Mattar-Habib (2004) found the relationship between expected crash rate and consistency on two-lane rural roads: the higher the consistency, the lower the expected crash rate. The concept may be also applied to calmed crosstown roads with similar results. On the other hand, reducing traffic speeds can reduce the frequency and severity of vehicle crashes. According to Litman (1999), each 1-mph traffic speed reduction typically reduces vehicle collisions by 5%. Thereafter, the safety implications of both values were not assessed during the research.

5.4. Effects of drivers' characteristics

The effect of drivers' age and gender on average speed, uniformity and speeding was examined using the ANOVA test. Individual average speed, accumulated speed uniformity and the square root of accumulated speeding were considered. Each site and variable was considered separately; so, 144 ANOVA tests were carried out. Three groups of age were determined: young drivers; middle aged; and elderly drivers. The first group included drivers from 18 to 34 years; the second, from 35 to 59 years; and the third, 60 years and over.

Table 5 Summary of effect of driver characteristics

Site	Average speed		Accumulated speed uniformity		Accumulated speeding	
	Gender	Age	Gender	Age	Gender	Age
Albalat-W	0.6336	0.8115	0.5928	0.4150	0.3356	0.2656
Albalat-E	0.5129	0.4230	0.0057	0.2492	0.8982	0.9318
Belgida 0-SW	0.9797	0.1312	0.7730	0.3852	0.6707	0.7749
Belgida 0 -NE	0.7956	0.6410	0.9700	0.6673	0.9818	0.1940
Belgida 1-SW	0.7481	0.0035	0.6507	0.5275	0.6603	0.8751
Belgida 1-NE	0.5738	0.5056	0.8196	0.0802	0.9222	0.0081
Belgida 2-SW	0.8225	0.6646	0.3293	0.7114	0.4318	0.7732
Belgida 2-NE	0.5716	0.9111	0.3917	0.1552	0.4074	0.0081
Belgida 3-SW	0.5268	0.1657	0.9906	0.7611	0.9174	0.9327
Belgida 3-NE	0.4307	0.3635	0.8550	0.0435	0.5283	0.3015
Belgida 4-SW	0.2447	0.0402	0.5453	0.9473	0.3869	0.0543
Belgida 4-NE	0.8250	0.0608	0.6931	0.3924	0.0895	0.0113
Belgida 5-SW	0.6638	0.0185	0.8665	0.1742	0.5125	0.3616
Belgida 5-NE	0.1966	0.3888	0.8169	0.3759	0.0700	0.0187
Belgida 6-SW	0.1526	0.1025	0.6132	0.2654	0.2285	0.0687
Belgida 6-NE	0.2251	0.1545	0.7218	0.2849	0.0984	0.0454
Chelva-E	0.0406	0.2085	0.7615	0.2665	0.0092	0.1115
Chelva-W	0.3683	0.2186	0.0081	0.7406	0.6392	0.2529
Genoves-W	0.5531	0.8905	0.1232	0.0021	0.5898	0.2669
Genoves-E	0.2218	0.1099	0.5675	0.4203	0.9408	0.0738
Llutxent-W	0.8215	0.0297	0.4741	0.0094	0.4642	0.1115
Llutxent-E	0.4964	0.1730	0.1415	0.1619	0.4968	0.0550
Quatretonda-W	0.4247	0.0878	0.5640	0.2329	0.5937	0.2148
Quatretonda-E	0.5921	0.2589	0.7611	0.6460	0.8639	0.1015

The null hypothesis, Ho, of the test was that all the variables had equal means and the frequencies of drivers performances do not depend on the examined characteristic (ager or gender). The results of the tests are summarized on Table 5. To simplify the output data, p-values of the F-statistics are represented instead of F-statistics. P-value higher than 0.05 implied that the null hypothesis should not be rejected for 95% level of confidence. As shown in Table 5, Ho should not be rejected in almost all combinations. In addition, the cells in which the null hypothesis should be rejected were randomly distributed on average speed and uniformity. Thus, the results suggest that average speed and accumulated speed uniformity were independent of driver characteristics. Accumulated speeding results showed that for almost all Belgida – NE sites, accumulated speeding was statistically different depending on drivers' age. However, the null hypothesis should be accepted on the remaining sites. Consequently, age influenced accumulated speeding results in that specific location. More sites should be considered in order to verify accumulated speeding dependence on drivers' age.

6. CONCLUSIONS

Crosstown roads are rural roads that go through small communities; so, most drivers are through traffic and should adapt from rural to urban driving conditions. Traffic calming measures are often implemented in crosstown roads to reduce both crash frequency and severity. Commonly, traffic calming effectiveness has been assessed by means of speed reduction. Safety implications of traffic calming plans have usually been analyzed based on before-after studies or the Empirical Bayes (EB) method. However, Spanish crosstown roads are characterized by low traffic volume; which leads to a relatively low number of crashes. Given the lack of data, surrogate safety measures based on speed should be developed similarly to successful consistency measures applied to two-lane rural roads.

Two surrogate indexes of safety have been defined based on the continuous speed profile. The first index, *Ra*, reflects the accumulated absolute uniformity of the speed profile and it is reversely related to accumulated speed uniformity. It is calculated as the relative normalized area bounded between the speed profile and the average speed line. Nevertheless, speed uniformity is not enough to guarantee a good design quality: speeds should be moderated as well. Consequently, a second index is needed. The second index, *Ea*, indicates accumulated speeding and they are directly related. It is defined as the relative normalized area between the speed profile values higher than the posted speed limit and the posted speed limit line. Consequently, only areas over the posted speed limit line are considered.

The two surrogate measures have both been applied on twenty four different sites. Six crosstown roads were selected. Five of the crosstown roads had traffic calming measures implemented, while the sixth crosstown road was not calmed. On this site, a traffic calming plan was executed in five stages. The step-by-step plan implementation allowed varying the traffic calming density along the crosstown road. Initial scenario and one year after the last implementation stage were also evaluated. Consequently, twelve different scenarios with different TCMs type and location were observed. Continuous speed profiles collected under naturalistic conditions from more than 1500 different drivers were analyzed. Average speed, accumulated speed uniformity and accumulated speeding were calculated for each vehicle at each site. Two approaches were considered: individual analysis and global analysis. The individual value was calculated as the 85th percentile of the individual values of one site. The global value was calculated from the operating speed of the site. Even though global and individual values were similar; and they were statistically different at a level of confidence of 95%.

The indexes varied depending on crosstown roads traffic calming systems. Traffic calming density was found as key parameter to explain both average operating speed and accumulated speeding variability: the higher traffic calming density, the lower average operating speed and the lower accumulated speeding along the segment. On the other hand, both accumulated speed uniformity and accumulated speeding depended on average operating speed, which would be influenced by the crosstown road alignment, the speed limit and the type of traffic calming measures. As average operating speed increased, so did *Ra* and *Ea* indexes. Thus, the speed profile was less uniform and speeding was higher. However, the relationship between average operating speed and accumulated speed uniformity was found to be statistically not significant on crosstown roads with spacing similar to optimal (110 m). Consequently, once the optimal traffic calming density is achieved, accumulated speed uniformity is not dependent on average operating speed because drivers' capability of varying speeds is much reduced; so, accumulated speed uniformity index is similar. Hence, practitioners should determine TCMs type and geometry depending on the crosstown road design speed to achieve an operating speed similar to the speed limit and decrease speeding; then, locate TCMs with spacing similar to the optimal to maximize accumulated speed uniformity.

On the other hand, drivers' age and gender influence on the variables was evaluated. No statistical significance of age and gender on the variables was found. Therefore, drivers' characteristics did not appear to affect average speed, nor accumulated speed uniformity or accumulated speeding.

The paper presents an initial safety performance assessment of calmed crosstown roads based on continuous speed profiles obtained from naturalistic driving. The design quality evaluation was based on two surrogate measures: *Ra* and *Ea*, which represented accumulated speed uniformity and accumulated speeding along an entire calmed crosstown road. Initial thresholds to determinate quality design were proposed based on the global observed values of accumulated speed uniformity and accumulated speeding. With this approach TCMs were really considered as an integrated system rather than isolated or segregated measures, as up to now. Further development on safety implications of the surrogate measures needs to be elaborated in order to calibrate the design quality thresholds of *Ra* and *Ea* indexes, as well as more crosstown roads observations and speed profiles estimations from speed models with different TCMs type and spacing.

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