

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 both a lack of quantity and quality of crash data and low budgets. However, fifty three percent of road crashes in Spain take place on crosstown roads and urban areas. Moreover, ten percent of fatal crashes on urban areas occur on crosstown roads. In order to reduce both crash frequency and severity, traffic calming measures (TCMs) are often implemented on crosstown roads.

The objective of the research is to develop a methodology using continuous speed profile on free-flow conditions to evaluate safety effectiveness of traffic calming measures 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 , related to speed uniformity and speeding, respectively. The indexes were applied to both individual observed speed profiles and aggregated operating speed profile. Twenty four global values of both indexes were obtained. The scenarios with implemented TCMs according to technical criteria, such as a traffic calming density close to nine TCMs per km, presented lower values. Age and gender differences have also been evaluated. More scenarios based on speed predictions over the TCMs will be modeled to propose Ra and Ea safety threshold values.

The paper explores continuous speed profiles obtained from naturalistic driving to assess safety performance of crosstown roads with traffic calming devices. With this approach, speed is in effect used as a surrogate safety measure formulated in two new indexes: Ra and Ea .

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

INTRODUCTION

Improving road safety in both urban and rural areas is a major objective of the Spanish General Directorate of Traffic. In 2009, fifty three percent of severe road crashes, which includes injury and fatal crashes, took place on urban areas. Despite severe crashes on crosstown roads represent only one point three percent of severe crashes on urban areas, ten percent of fatalities occur on this specific road type (Dirección General de Tráfico, 2010). Crosstown roads are the part of a two-lane rural road which goes through a populated area. Consequently, drivers should adapt their driving from rural road conditions to urban environment. 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, databases have usually lack of reliable data. Thus, traditional urban road safety management based on road crashes may not be the most appropriated approach due to a lack of statistically significance of crash data.

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 have developed surrogate measures relating speed variation and road safety on rural roads. Given the different purpose of the studies and data collection method, the definition of the surrogate measures in each case was different: from the difference between pre-crash and normal condition traveling speeds (Solomon, 1964), to the standard deviation of speeds (Garber and Gadiraju, 1989; Aljanahi, 1999); and the difference between the operating speed and the mean speed (Lave, 1985). 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) 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 were calculated at one specific location and not along an entire roadway 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 measures were calculated for the entire segment under investigation.

The Polus consistency model was based on operating speed prediction models on curves and tangents; and estimates acceleration and deceleration rates. In urban areas, such as crosstown roads, developed operating speed models are fewer than in two-lane rural roads. In fact, only a few studies have developed operating speed models in low-speed urban streets (Poe et al, 1996;; Poe et al., 1998; Bonneson, 1999; Poe and Mason, 2000; Fitzpatrick et al., 2003; Wang et al., 2007). Poe et al. (1996) concluded that access and land use characteristics influenced on operating speed. A regression model carried out by Poe et al. (1998) showed that alignment and traffic control explained a large portion 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 for the first time to determine operating speed on urban streets. They found that operating speed was influenced by number of lanes, roadside objects density, the density of T-intersections, raised curb presence, sidewalk presence, on-street parking, and land uses.

Considering the previous models, operating speed profile of a crosstown road could be developed. However, the speeding problem along roads running through populated areas is usually handled by using traffic calming measures (TCMs), which were not included in the previous research. Given that TCMs involve traffic control at one location, specific operating speed models should be considered. Several studies have been conducted to evaluate effectiveness on speed reduction and operating speed over individual TCMs; and their results have been summarized on several publications (Department for Transport, 2004; 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/s^2 , while acceleration rates were set between 0.24 and 0.50 m/s^2 . Therefore, TCMs implementation usually produced an irregular speed profile with frequent decelerations and accelerations. The 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; Bassani et al, 2011). Hence, most of the guidelines and recommendations propose geometry and spacing of traffic calming devices 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.

Similar to rural roads, crosstown roads with adequate TCMs and optimal spacing would result in a more uniform speed profile and; therefore, more consistent design; which would likely lead to a safer crosstown road. This paper explores continuous speed profiles obtained from naturalistic driving to assess safety performance of calmed crosstown roads.

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 measures to both individual observed speed profiles and 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 were also evaluated. It should be noted that TCMs were considered as an integrated system along an entire crosstown road rather than isolated or segregated measures.

FIELD STUDY

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 cross-town roads were selected according to the recommendations of a previous road safety study, taking into account: annual average daily traffic (AADT); length of the cross-town road (L); and type of existing traffic calming measures. The selected towns were: Albalat de la Ribera; Chelva; Genovés; Quatretonda; and Llutxent. TCMs included speed tables, speed humps and one roundabout.

The sixth location was Belgida. No TCMs were initially installed on Belgida's crosstown road. Two pedestrian crossings were located on a tangent section. The community asked the responsible agency to install TCMs to reduce speeding along the roadway. The road safety project was implemented by stages on Belgida, which allowed deducing individual effect of diverse TCMs on the continuous speed profile: one speed hump; two speed tables; one speed bump; one chicane; and one set of dragon's teeth. 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 with different TCMs type and location were observed.

Crosstown road characteristics are summarized on Table 1. The posted speed limit was 40 or 50 km/h; while the AADT varied from 650 to 4,230 vehicles per day. Belgida's AADT reduction from 1,920 veh/day to 1,180 veh/day was caused by the construction of a highway segment near the area, not the TCMs implementation because the new highway segment diverted traffic from the rural road which goes through Belgida. The length of the crosstown roads was between 560 and 945 m, considering only the urban area of the rural road. Thus, the length was obtained from the beginning to the end of the town. In order to classify the crosstown roads, TCMs density (TcD) was calculated. TcD was defined as the percentage of traffic calming devices per unit length. TcD equal to 1 meant that TCMs were spaced 100 m on average. Entrance gates were also considered as one TCM on the parameter, as well as curves with radius lower than 150 m, which also controlled speed below 50 km/h.

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 (ud/m/%)	
							Bound 1	Bound 2
Albalat	40	4,230	765	1	5	0	0.78 (E)	0.78 (W)
Chelva	40	2,490	885	1	4	0	0.56 (W)	0.56 (E)
Genoves	40	4,550	945	2	4	1	0.74 (E)	0.63 (W)
Quatretonda	50	3,250	680	0	4	0	0.59 (E)	0.59 (W)
Llutxent	40	2,930	690	0	4	0	0.58 (E)	0.58 (W)
Belgida 0	50	2,650	560	1	0	0	0.18 (NE)	0.18 (SW)
Belgida 1	50	1,920	560	1	2	0	0.54 (NE)	0.54 (SW)
Belgida 2	50	1,920	560	1	4	0	0.89 (NE)	0.89 (SW)
Belgida 3	50	1,180	560	1	4	1	1.16 (NE)	0.89 (SW)
Belgida 4	50	1,180	560	1	4	2	1.16 (NE)	1.16 (SW)
Belgida 5	50	1,180	560	1	3	2	0.98 (NE)	0.98 (SW)
Belgida 6	50	1,180	560	1	3	2	0.98 (NE)	0.98 (SW)

All the crosstown roads presented good pavement conditions and their lane width varied from 3.10 to 3.25 m; which is common on Spanish crosstown roads. As crosstown roads were in urban areas, they were sidewalks on both sides of the road and on-street parking was allowed. Grade was nearly horizontal in all scenarios.

Data collection

To collect drivers' behavior, passive GPS trackers were used. The available passive GPS tracking equipment recorded GPS location information and vehicle speed for one-second intervals. Consequently, an individual continuous speed profile and acceleration profile could be deduced.

To collect the information at each scenario, two road controls were placed before drivers' approach the town from each direction. The road controls were separated at least 1 km from the town to enable drivers to adapt their desired speed before entering the town. On each road control, drivers were asked to collaborate in a road safety study. Drivers were only told that a device had to be fitted on their vehicles and they were encouraged to drive in a normal way. 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 or not on their speed by another vehicle or pedestrian.

The methodology was proven not to influence drivers' speed selection 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 during morning period between 9:00 a.m. and 2:00 p.m., on a working day and with good weather conditions. In Belgida, data collection took place at least 14 days after the TCM implementation.

Data reduction

The data collected by the GPS trackers contain latitude, longitude, altitude, heading, time and date, every 1 second. After importing data from the devices, a coordinate's conversion to UTM (x, y) was carried out before a successive data debugging process. Firstly, the data storage errors were found by analyzing the recorded time sequence. Secondly, a transversal positioning debugging was carried out. The diverted points were discarded. After, a longitudinal positioning debugging was done by taking into account abnormal speeds, accelerations or decelerations. Finally, vehicles which had left the track were discarded.

Only free-flow conditions were considered; so, stopped vehicles and vehicles conditioned by other vehicles or pedestrians were removed from the sample. Therefore, traffic flow was not conditioning drivers' speed; and, drivers were individually selecting their own desired speed. Three second headway is often considered enough to determine if a driver is driving at free-flow speeds. However, GPS did not record traffic conditions or headway. To overcome this interrupted flow problem, individual speed profile and 15th, 30th, 50th, 70th, and 85th percentile were plotted. Abnormal speed profiles were removed. Besides, the response on the second survey about conditioning was considered. Nearly 30 % of the initial sample was discarded due to non free-flow conditions, detour or stopping. The total sample was 925 drivers. Figure 1 shows an

example of 25 vehicles' observed speed profile obtained from the GPS trackers in Belgida's sixth scenario.

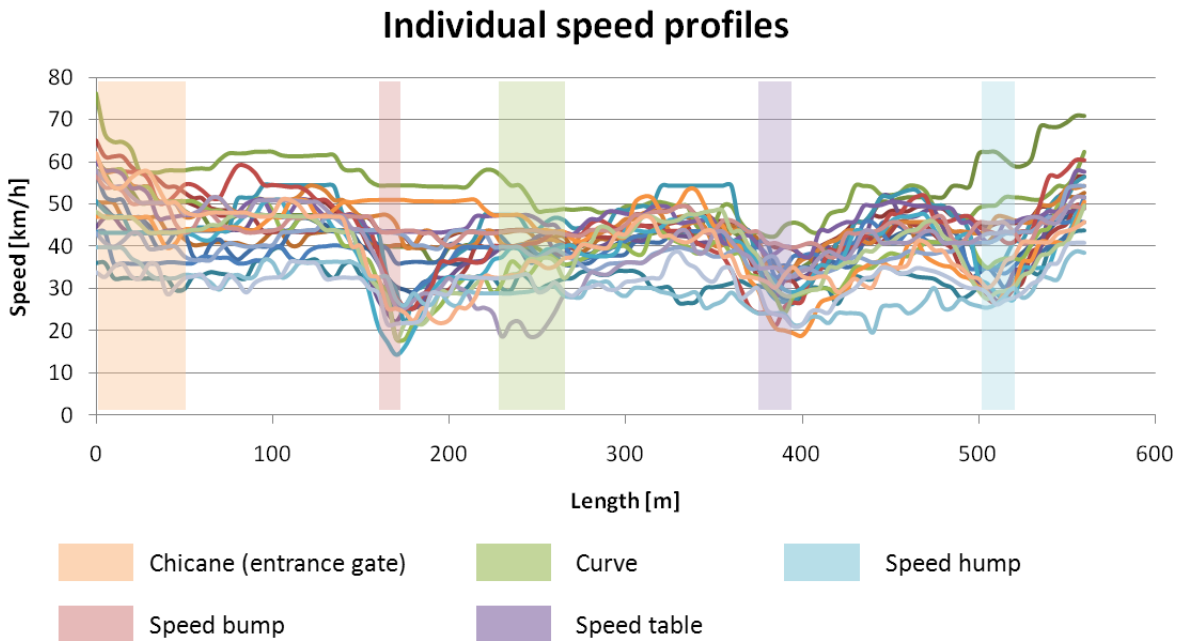


Figure 1 25 Individual speed profiles of Belgida 5 -NW

SURROGATE MEASURES

Two indexes are defined as surrogate safety measures based on the continuous speed profile: Ra and Ea . The first measure evaluates uniformity of the speed profile; while the second measure assesses speeding along the entire crosstown road. Uniformity of the speed profile is not enough to consider a good design quality if speed level is higher than the speed limit. Both measures should be accomplished to determinate design quality.

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; considering operating speed as the speed which is only exceeded by 15% of drivers. 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 lines (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, the inconsistency of speeds increases as Ra increases. Equation 1 can be applied.

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

where:

Ra : relative area measure of uniformity (m/s)

ΣAr_i : sum of areas (absolute values) bounded between the speed profile and the average speed (m^2/s)

L : entire crosstown road length (m).

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 also applied to individual speed profiles or to the operating speed profile. Given the speed limit, the areas bounded between the speed profile and the speed limit lines are determined. Only the areas over the speed limit line (Ae_i) are considered in the measure (Figure 2b). The consistency measure is calculated applying Equation 2 as the sum of the value of the areas divided by the length of the segment (L). Consequently, the higher the Ea , the higher speeding magnitude along the crosstown road.

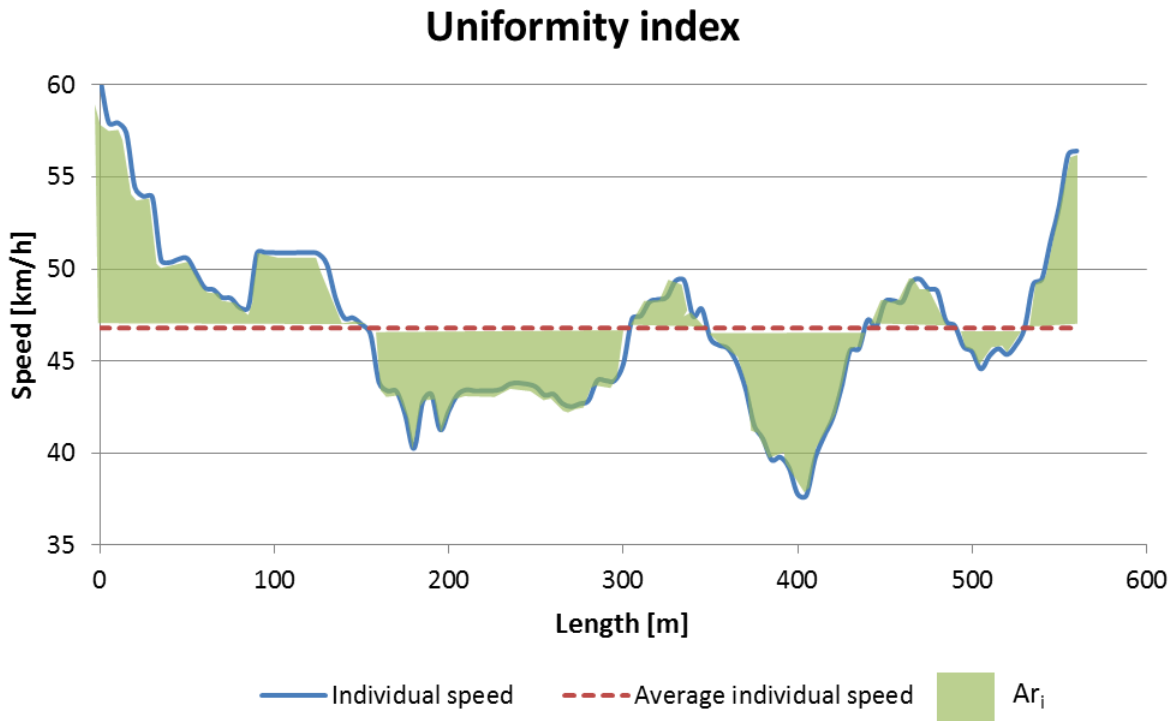
$$Ea = \frac{\Sigma Ae_i}{L} \tag{2}$$

Where:

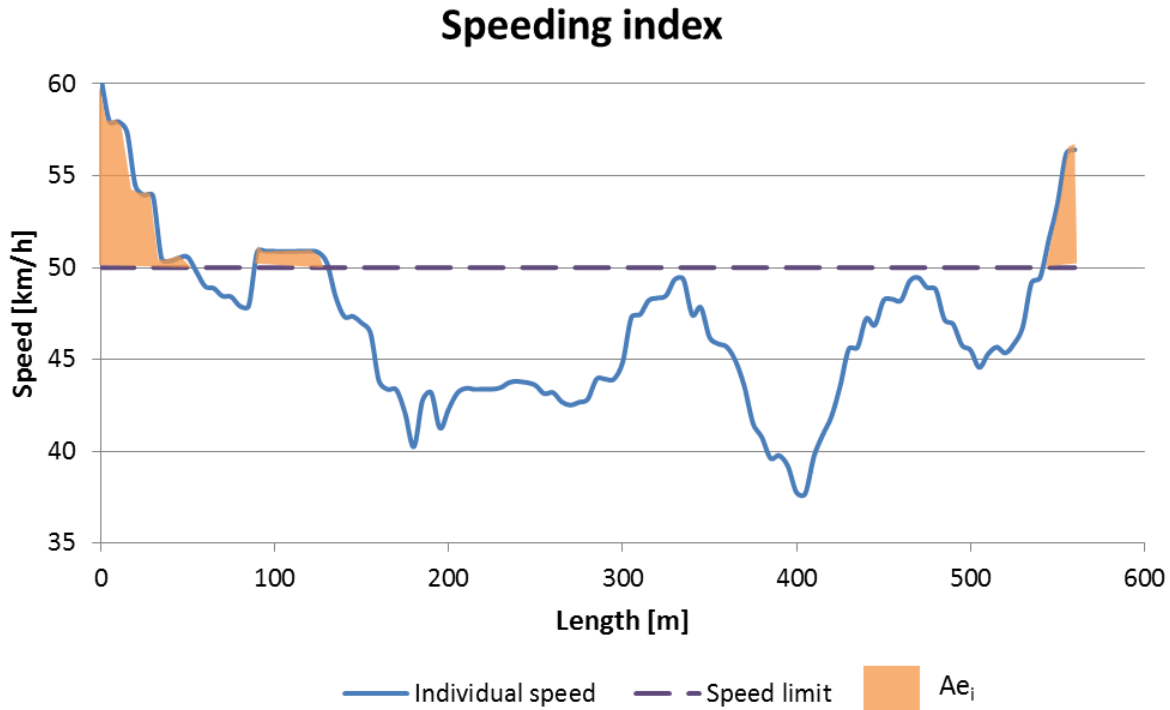
Ea : relative area measure of speeding (m/s)

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 : entire crosstown road length (m).



(a)



(b)

Figure 2 Speed profile and surrogate measures of Belgida 5 - NW

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

RESULTS AND ANALYSIS

Each direction was analyzed separately, as TCMs type and quantity varied. At each scenario and direction (site), operating speed profile was obtained. Then, average operating speed, uniformity and speeding were calculated. At each individual speed profile, average speed, uniformity and speeding were calculated along the crosstown road. After, 85th percentile of each site was deduced. Consequently, two values were considered: (1) a global value from the operating speed profile; and (2) an individual value as the 85th percentile of the individual values' distribution. Table 2 summarizes global and individual values of the analyzed variables.

According to Poe et al. (1998), 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. Given that the methodology allows studying individual speed profiles, individual values were examined. However, practitioners may not have individual observations to determine design quality; and, only global estimates from the literature could be used to approximate the operating speed profile. Consequently, global values should also be analyzed. Thus, both individual and global values are considered on the following analyses.

Table 2 Average speed, uniformity and speeding results

Site	Speed limit (km/h)	Tc density (m^{-1})	Vm (km/h)		Ra (m/s)		Ea (m/s)	
			Global	Individual	Global	Individual	Global	Individual
Albalat-W	40	0.78	40.68	38.82	1.31	1.68	0.75	0.56
Albalat-E	40	0.78	41.71	40.27	1.08	1.68	0.81	0.89
Belgida 0-SW	50	0.18	60.43	58.10	2.98	3.68	3.21	2.82
Belgida 0-NE	50	0.18	64.53	63.62	3.18	3.64	4.23	4.24
Belgida 1-SW	50	0.54	53.98	54.79	3.72	4.18	2.39	2.41
Belgida 1-NE	50	0.54	55.95	53.26	4.04	4.05	2.73	2.22
Belgida 2-SW	50	0.89	48.33	44.58	2.94	3.36	1.30	1.17
Belgida 2-NE	50	0.89	48.42	45.98	3.27	3.72	1.50	1.50
Belgida 3-SW	50	0.89	44.66	43.56	2.17	2.53	0.65	0.68
Belgida 3-NE	50	1.16	43.42	41.80	1.30	1.86	0.11	0.16
Belgida 4-SW	50	1.16	45.27	43.49	2.33	2.67	0.77	0.63
Belgida 4-NE	50	1.16	44.43	41.88	1.29	1.93	0.13	0.16
Belgida 5-SW	50	0.98	48.51	46.77	2.06	2.45	0.90	0.93
Belgida 5-NE	50	0.98	46.79	45.05	0.98	1.88	0.18	0.22
Belgida 6-SW	50	0.98	50.94	49.74	2.33	2.59	1.55	1.29
Belgida 6-NE	50	0.98	48.84	47.83	1.08	1.79	0.42	0.49
Chelva-E	40	0.56	42.97	41.35	1.33	1.72	1.15	1.10
Chelva-W	40	0.56	43.10	41.30	1.54	2.06	1.28	1.13
Genoves-W	40	0.63	40.06	38.47	1.51	2.01	0.76	0.73
Genoves-E	40	0.74	42.35	40.95	1.69	2.13	1.14	1.09
Llutxent-W	40	0.58	45.50	43.90	0.98	1.52	1.56	1.44
Llutxent-E	40	0.58	43.61	43.14	1.25	1.63	1.22	1.15
Quatretonda-W	50	0.59	51.40	50.00	2.02	2.41	1.23	1.07
Quatretonda-E	50	0.59	48.06	45.82	2.10	2.66	0.80	0.68

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. A first analysis was carried out to determine the overall traffic performance on the evaluated sites. Average global and individual speed of the different sites was calculated from the beginning to the end of the crosstown road. 85th percentile of individual average speed was lower than average operating speed in all the sites. Aggregation of individual speed data into operating speed resulted in a higher value of average speed, as individual speed profiles distribution was not considered. Individual speed profiles may result higher at one location; however, the distribution along the entire road segment showed lower average values. Consequently, average operating speed was higher than 85th percentile of individual average speeds. However, global and individual values were close to each other and no statistical differences were found between them.

The analyzed sites presented the same number of lanes, roadside objects density, intersections density, raised curb, sidewalks, on-street parking, and residential land use. Therefore, according to Wang et al. (2007), the operating speed would be equal on all the sites. Nevertheless, the global and individual average speeds were different among the sites. The main difference between the sites was the posted speed limit, which differed from 40 to 50 km/h; and the implemented TCMs. Considering TCMs as traffic control devices, Poe et al. (1998) models application would result in different operating speeds; which agreed with the results.

A Chi-square test was executed to verify if average operating speed had equal means among the sites. The resulted p-value indicated that the null hypothesis had to be rejected. Thus, average operating speed was statistically different between sites.

A multiple regression analysis was performed to determine the variables that influenced on global and individual average speed. The multiple regression analysis showed that the values should be grouped depending on the speed limit. Speed limit was 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. Hence, two groups were created: crosstown roads with speed limit equal to 40 km/h and crosstown roads with speed limit equal to 50 km/h (Figure 3). A linear regression was calculated within the two groups. The regression analysis of the crosstown with speed limit of 50 km/h showed that traffic calming density (TcD) explained 73% of the variability of the average operating speed. The coefficient of determination of the second group was only 31%. Consequently, average operating speed depended on TcD ; which was an important parameter on average operating speed and average individual speed.

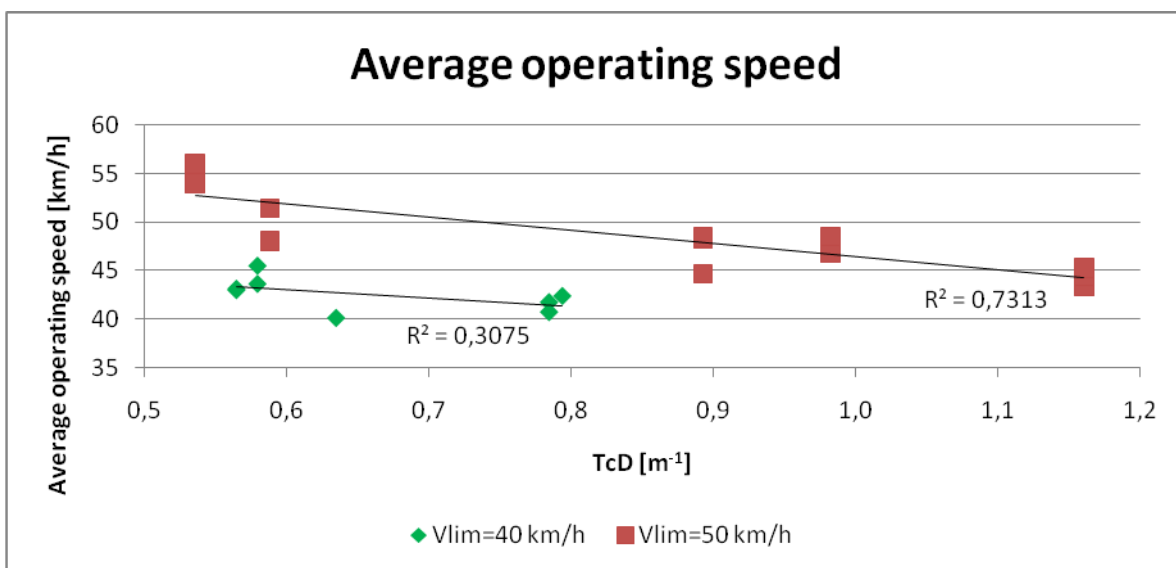


Figure 3 Average operating speeds depending on speed limit and traffic calming density

On the other hand, average operating speed was compared to speed limit. Only crosstown roads with TcD higher than $0,9 \text{ m}^{-1}$, which is equivalent to 9 traffic calming measures per km, presented an average operating speed lower than the speed limit. Thus, traffic calming density

results a key factor on average operating speed; and it seems that calmed crosstown roads with TcD higher than $0.9 \% m^{-1}$ would have an average operating speed similar to the posted speed limit.

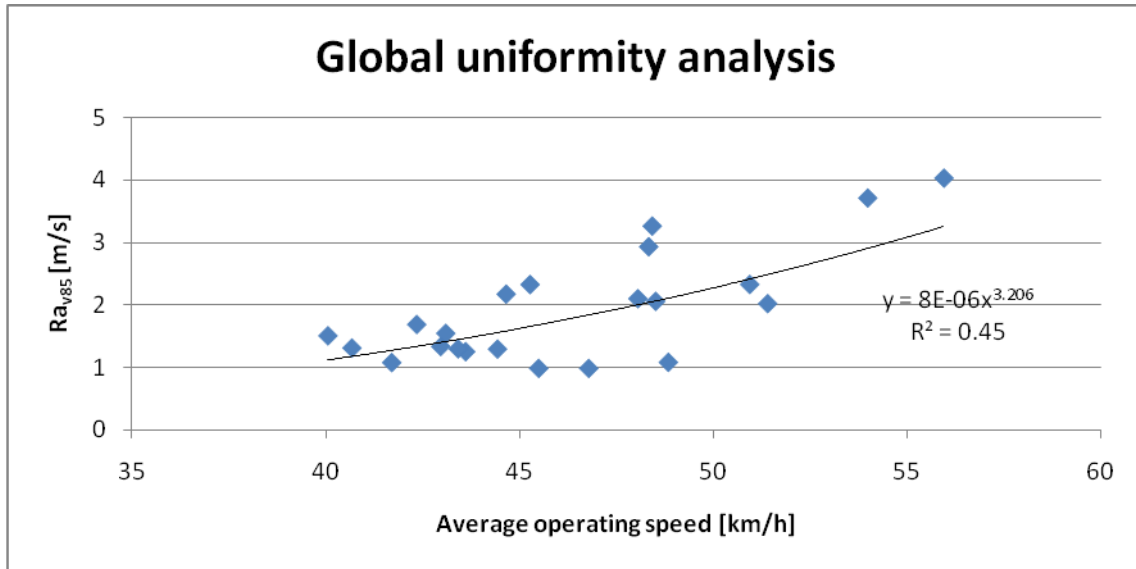
Uniformity

Uniformity of the speed profile along the entire calmed crosstown road was assessed by using the index Ra . A global value per site was calculated applying Equation 1 to the operating speed profile. Individual Ra values were also calculated. Then, 85th percentile of the individual Ra values at each site was obtained to carry out the individual uniformity analysis. Results are summarized on Table 2.

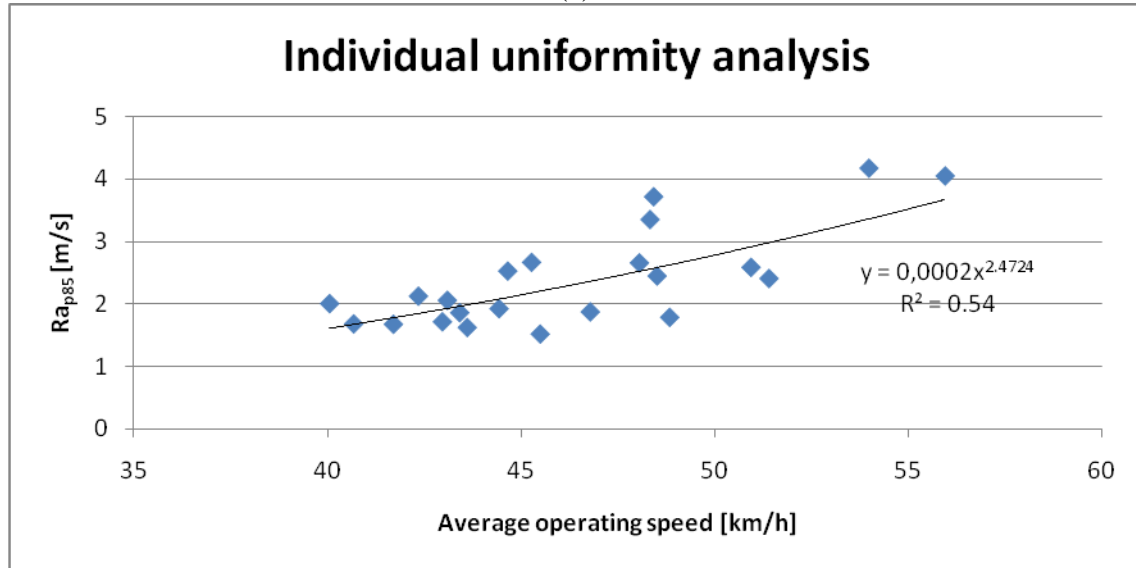
Global and individual values were compared. Global uniformity values were always lower than individual uniformity values regardless of the speed limit, average operating speed or traffic calming density. Operating speed profile was obtained as the aggregated value of individual speeds, section to section. 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 lower.

The uniformity values were analyzed to determine if they were statistically different between the sites. Belgida 0 was removed from the analysis since no TCMs were installed; and only a comparison between calmed crosstown roads was intended. A Chi-Square test was performed with the H_0 hypothesis that all the uniformity values had equal means and the differences observed in the data were because of randomness. The obtained P-values indicate that the null hypothesis should be rejected for both global and individual value. Thus, the uniformity of speeds along the crosstown roads can be statistically distinguished between sites.

A statistical analysis of the Ra based on multiple regression was carried out to determine which variables affected uniformity, for both global and individual value. The parameter which better explained uniformity variation was the average operating speed. As seen in Figure 4, the higher average operating speed, the higher Ra , so, the lower uniformity along the crosstown road. 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; as well as a lower number of TCMs. Consequently, drivers tended to accelerate and decelerate more aggressively; so, the inconsistency of speeds on the entire crosstown road was higher. Coefficients of determination of 45% and 54% were obtained for global and individual uniformity, respectively.



(a)



(b)

Figure 4 Uniformity results: (a) global analysis; (b) individual analysis

Global Ra values tend to accumulate around 1.5 m/s; and the lowest values were near to 1 m/s. Global values over 2 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 in a qualitative analysis of the conflicts along the observed crosstown roads, two preliminary thresholds could be proposed to define uniformity quality along the crosstown road. Both thresholds are shown in Table 3. The lowest threshold differed from Polus and Mattar-

Habib (2004) because global Ra values were concentrated around 1.5 m/s; and, even on the best quality sites, they were higher than 1 m/s.

Table 3 Thresholds for the determination of design uniformity quality

Uniformity	Design quality		
	Good	Acceptable	Poor
Ra (m/s)	$Ra < 1.5$	$1.5 \leq Ra \leq 2$	$Ra > 2$

We can see that even the best of the observed sites could not be categorized as good uniformity design with Polus' thresholds. Further validation of the proposed thresholds will be required. Operating speed profile simulations will be carried out by means of traffic microsimulation. The traffic microsimulation model will be calibrated using the observed speed profiles. Then, different scenarios will be elaborated varying: traffic calming device type; traffic calming density; posted speed limit; traffic calming device geometry; crosstown road length; and heavy goods vehicles rate. The analysis of the operating speed profile will be considered to improve the determination of Ra thresholds.

Speeding

Speeding density was also evaluated using Ea . Equation 2 was applied to individual speed profiles and operating speed profiles. One Ea global value per site was obtained from the operating speed profile. From the individual speeding results, 85th percentile was calculated. Thus, one individual value of Ea was deduced per site. The values are presented on Table 2.

A comparison between global and individual values was carried out. Both values were similar to each other regardless of the site. No statistical differences were found between the values.

Similar to the uniformity analysis, a statistical analysis was carried out to determine if the differences on speeding among the sites were due to randomness. As the previous analysis, Belgida 0 was removed because of the lack of TCMs. A Chi-Square test with the Ho hypothesis that all the speeding values had equal means was elaborated. The resulting P-value indicated the rejection of the null hypothesis. Consequently, speeding among the sites was statistically different at a level of confidence of 95%.

The next step was to detect which variables affected speeding. A multiple regression analysis was performed to both global and individual values. The results indicated that speeding depended on traffic calming density. Figure 5 shows the relationship between the two values on the global analysis, the higher TcD , the lower Ea . In other words, as the spacing between TCMs decreased, so did the accumulated speeding along the crosstown road. TcD explained 51% of speeding variation.

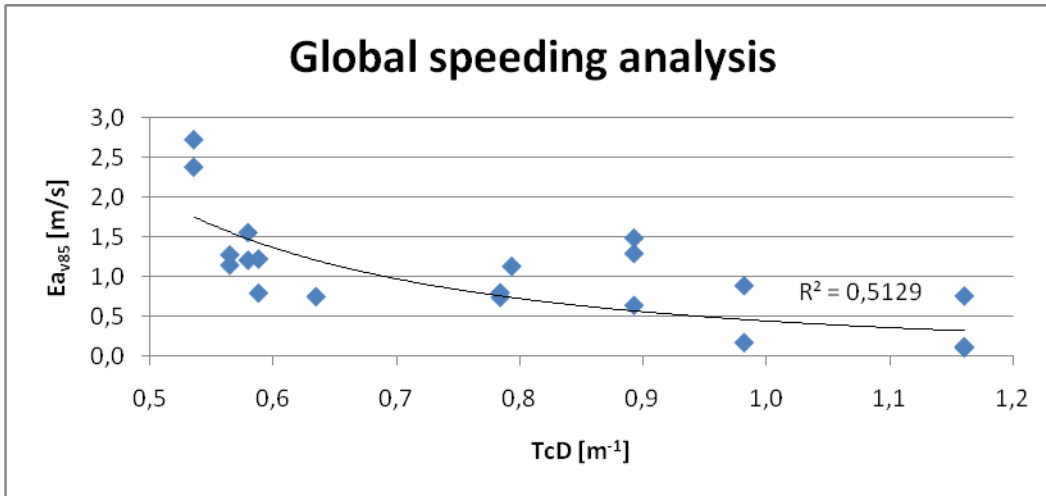
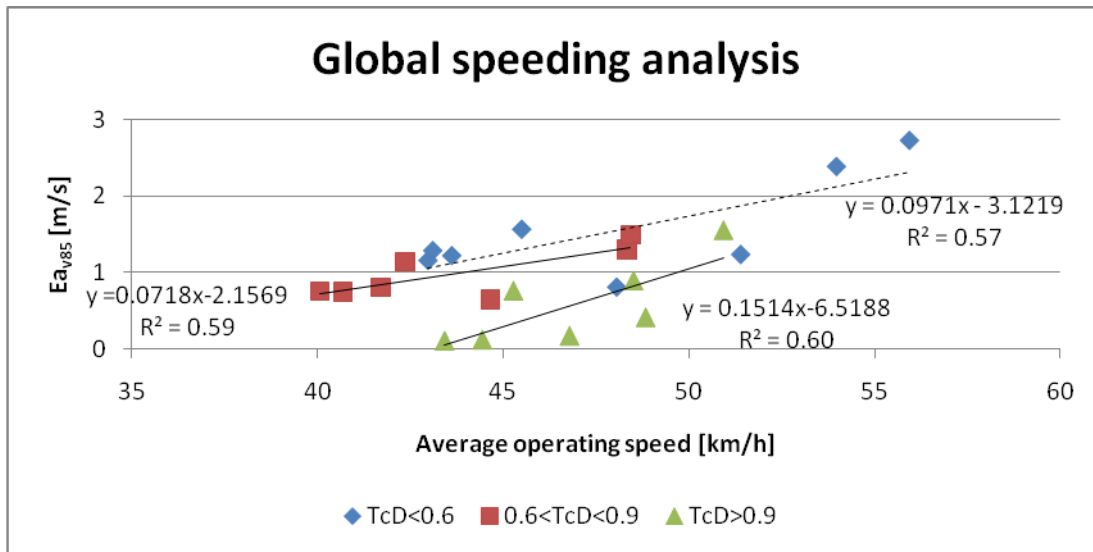


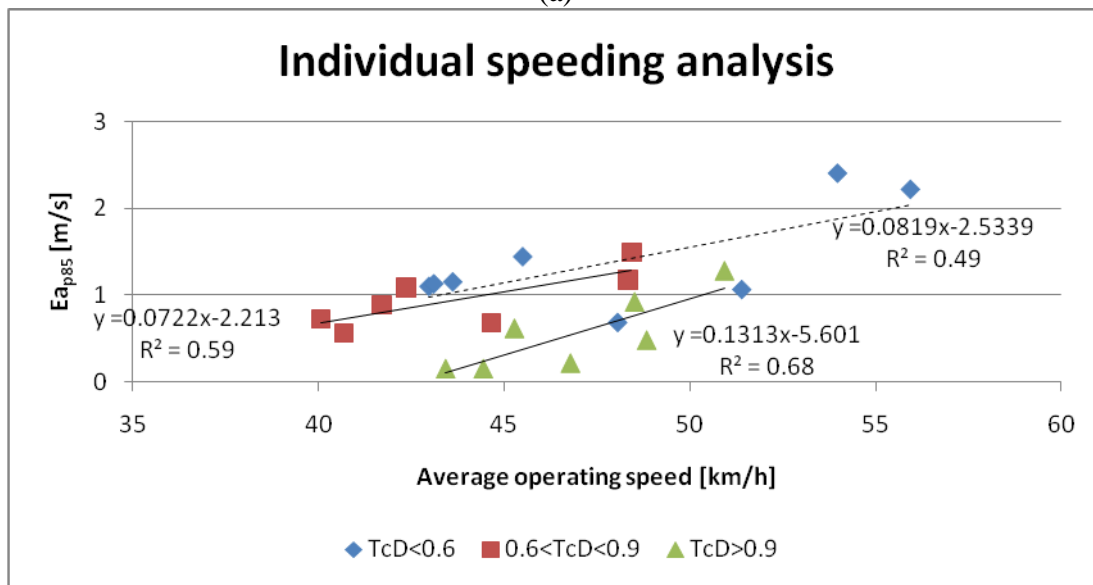
Figure 5 Speeding depending on traffic calming density

Another multiple regression analysis was carried out considering TcD and average operating speed as independent values. Figure 6 shows the trend that crosstown roads with higher average operating speed had higher speeding, as Ea was higher. Given the dependence of speeding on TcD , three groups were formed to calibrate the relationship between the average operating speed and speeding. The first group contained the crosstown roads with TcD lower than 0.6 m^{-1} , which meant that the average spacing between traffic calming measures was longer than 170 m. The second group was formed by crosstown roads with TcD between 0.6 m^{-1} and 0.9 m^{-1} , which included average spacing from 110 m to 170 m. The third group was crosstown roads with TcD higher than 0.9 m^{-1} ; which represented crosstown roads with 9 or more TCMs per km. According to Garcia et al. (2011), optimal spacing between elements is around 110 m. Consequently, group three represented crosstown roads with spacing near the optimal spacing. The three similar trends can be observed in Figure 6 for both individual and global analysis.

As observed in Figure 6, lower TcD resulted in higher speeding. The regression analysis of the second and third group presented a higher coefficient of determination than the initial speeding assessment. The best correlation between average operating speed and global speeding for the three groups was linear. The linear correlation for crosstown roads with spacing higher than 110 m presented a similar slope. However, the slope of the linear correlation of the third group was higher; so, the dependence of speeding on average operating speed value was higher. The intersection of the three linear correlations was close to 60 km/h. Thus, optimal spacing was a guarantee of lower speeding as average operating speed remained under 60 km/h. Consequently, not only traffic calming density had to be appropriated to reduce speeding, but also traffic calming type. However, average operating speed on calmed crosstown roads should vary between 35 and 55 km/h; where spacing is a key factor on speeding.



(a)



(b)

Figure 6 Speeding results for: (a) global analysis; (b) individual analysis

The global analysis was used to assess initial thresholds of speeding. Optimal spaced traffic calming measures gave $Ea=0.5$ m/s at average operating speeds lower than 50 km/h. Moreover, Ea tend to concentrate around 1 m/s. The two proposed preliminary thresholds to evaluate design speeding quality are reflected in Table 4. As the uniformity analysis, qualitative analysis of the conflicts and traffic calming qualities of the sites were taken into account.

Table 4 Thresholds for the determination of design speeding quality

Speeding	Design quality		
	Good	Acceptable	Poor
Ea (m/s)	$Ea < 0.5$	$0.5 \leq Ea \leq 1$	$Ea > 1$

Further validation of the thresholds will be required. *Ea* thresholds will be also determined using traffic microsimulation, as well as engineering judgment.

Surrogate measures correlation

Uniformity and speeding were proposed as measures of traffic calming design quality; and both indexes had to be accomplished. The correlation between both indexes was also analyzed.

Uniformity and speeding global values are plotted on Figure 7. As global values were selected to define the design quality, this variable was introduced on the Figure. The colored areas represent the design quality: green means good design quality; yellow represents acceptable design quality; and red highlights poor design quality.

Given that traffic calming density was a key parameter on speeding analysis, the parameter was included on the global correlation. Therefore, three groups were determined depending on *TcD*: lower than $0.6 \% m^{-1}$; between 0.6 and $0.9 \% m^{-1}$; and higher than $0.9 \% m^{-1}$. A regression analysis was carried out within each group. A relationship between uniformity and speeding was found on crosstown roads with TCMs spacing longer than 110. However, optimal spacing of 110 m presented a potential relationship of the values. The higher *Ra*, the higher *Ea*. Thereafter, crosstown roads with less uniformity of speeds may suffer higher speeding. The relationship is stronger on crosstown roads with lower traffic calming density. Individual analysis showed similar results.

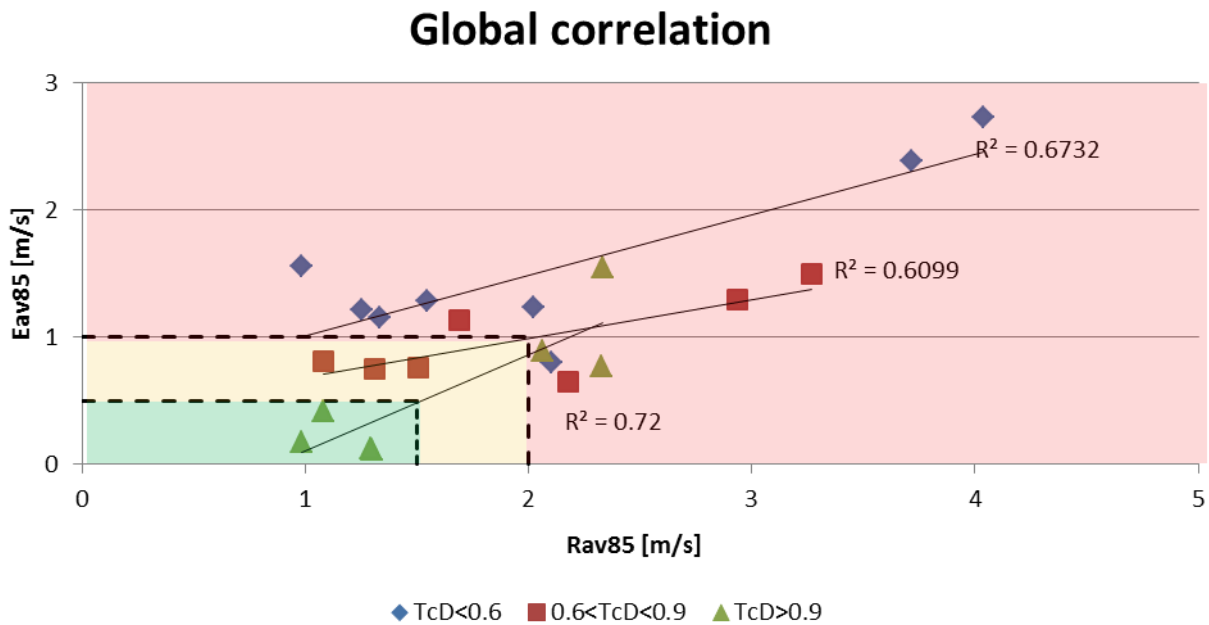


Figure 7 Global uniformity and speeding correlation analysis

Traditional analysis to quantify the safety benefits of better design quality cannot be applied to the selected crosstown roads. Even ten percent of the fatalities occur in crosstown roads, the available databases do not separate different travel 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. This low number of crashes on crosstown roads may 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 engineering judgment and qualitative conflict analysis.

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 but state-of-the-art and qualitative conflict analysis confirm the initial hypothesis.

Effects of drivers' characteristics

The effect of age and gender on average speed, uniformity and speeding was examined using the Chi-square test. Individual average speed, uniformity and speeding were considered. Each site and variable was considered separately. Three groups of age were determined: young drivers; middle aged; and older drivers. The first group included drivers from 18 to 35 years; the second, from 35 to 60 years; and the third, older than 60 years.

Table 5 Summary of effect of driver characteristics

Site	Average speed		Uniformity		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, H_0 , of the test was that all the variables had equal means and the frequencies of drivers performances do not depend on the characteristic being examined. The results of the test are summarized on Table 5. P-value higher than 0.05 implied that the null hypothesis had to be accepted for 95% level of confidence. As shown in Table 5, for almost all combinations of site, variable and driver characteristic, H_0 should be accepted. 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 uniformity were independent of driver characteristics. Speeding results showed that for almost all Belgida –NE sites, speeding was statistically different depending on drivers' age. However, the null hypothesis should be accepted on the remaining sites. Consequently, age influenced speeding results in that specific location. More sites should be considered in order to verify speeding dependence on drivers' age.

CONCLUSIONS

Traffic calming measures are often implemented in crosstown roads to reduce both crash frequency and severity. Traditionally, traffic calming effectiveness has been assessed by means of speed and/or volume 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, similar to successful consistency measures applied to two-lane rural roads.

Two surrogate indexes of safety have been defined based on continuous speed profile analysis. The first index, Ra , reflects the uniformity of the speed profile. It is calculated as the relative normalized area bounded between the speed profile and the average speed line. Nevertheless, uniformity of speeds is not enough to guarantee a good design quality: speeds should be moderated as well. Moreover, calmed crosstown roads where traffic calming measures were implemented without technical criteria are usually characterized by a sharp speed profile and low speeding. Thereafter, a second index is needed. The second index, Ea , indicates speeding. 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. Both surrogate measures should be checked in order to determine quality design.

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. The continuous speed profiles collected under naturalistic conditions were analyzed. Moreover, only free-flow conditions were considered; hence, a possible reduction of traffic volume should not impact on speed profile and its uniformity. Average operating speed, uniformity and speeding were calculated at each site. Both global and individual values were considered. The global value was obtained from the aggregated operating speed, while the individual value was calculated as the 85th percentile of individual values. Traffic calming density was found as key parameter to explain both average operating speed and speeding variability: the higher traffic calming density, the lower average operating speed and the lower speeding along the segment. Both uniformity and speeding depended on average operating speed. The average operating speed represented the alignment of the crosstown road, the speed limit and the type of traffic calming measures. A relationship between average operating speed and both indexes was deduced: as average operating speed increased, so did *Ra* and *Ea* indexes. Thus, the speed profile was less uniform and speeding was higher. Initial thresholds to determinate quality design were proposed based on the global observed values. Based on the initial results, traffic calming density higher than 9 per km presented a better quality design of calmed crosstown roads. However, sample should be increased in order to confirm this hypothesis.

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 the average speed, uniformity and speeding.

The paper presented an initial safety performance assessment of calmed crosstown roads. The design quality evaluation was based on two new surrogate measures: *Ra* and *Ea*, which represented uniformity and speeding along an entire calmed crosstown road. 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 observations and models of speed profiles with different traffic calming measures type and spacing.

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