Evaluation of the vehicle dynamics, energy and environmental impacts of traffic calming measures

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Abstract

Traffic Calming Measures (TCMs) have been implemented to reduce vehicle speed and/or cut-through traffic in specific city areas; however they have also been associated with impacts on fuel consumption and air pollution. Thus, the objective of this study was to evaluate the impacts of TCMs on vehicle dynamics, fuel consumption and emissions (CO_2 and NO_x). Through on-road measurements (in a second-by-second basis), on a compression-ignition vehicle and one driver, four types of TCMs were tested: speed table, speed hump, continuous sidewalk and textured pavement. The TCMs were located on 30 km/h Zones and on a 50 km/h speed limit road in the city of Lisbon.

The results indicate that all TCMs studied slowed down the traffic and kept it under the speed limit (with exception of textured pavement), achieving speed reductions between 20% and 41%. On the 30 km/h Zones, the interventions increased fuel consumption and CO_2 emissions by 48%, and NO_x emissions by 92%, on average. On the 50 km/h speed limit road, the TCMs led to an average decrease of 4% for fuel consumption and CO_2 emissions, and to an average increase of 304% for NO_x emissions.

The 30 km/h Zones contribute to overall safer conditions due to low average speeds. However, road safety showed more significant improvements on the 50 km/h speed limit road, which are associated to the higher absolute speed reduction.

The methodology developed can support local authorities during the process of selecting the more appropriate TCM to implement, giving the existent circumstances and desired objectives.

Keywords: Traffic calming measures; Vehicle dynamics; Fuel consumption; Exhaust emissions; On-road vehicle monitoring; Portable emission measurement system

1. Introduction

Traffic calming measures (TCMs) are implemented with the goal of improving road safety and enhancing quality of life within the urban areas, by reducing vehicle speeds and/or cut-through traffic (Ghafghazi & Hatzopoulou, 2014).

Speed reductions have showed to be related with changes in accident frequency. According to Taylor, Lynam, & Baruya (2000) a reduction of 1.6 km/h in average vehicle speed results in 6% reduction in accident frequency. The reduction in speed increases peripheral vision of the driver, allows a shorter braking distance and consequently decreases the risk of death among pedestrians in case of collision (IMTT/Transitec, 2011). Figure 1 shows that the probability of pedestrian death exponentially increases after 30 km/h.

Despite the beneficial effects of TCMs, they have been associated with impacts on fuel consumption and exhaust emissions (Ahn & Rakha, 2009). This results from acceleration, deceleration and speed adjustments necessary to drive over the intervention. Also, vehicles driven at low average speeds provide increased levels of fuel consumption and pollutant emissions. In fact, low average speeds (i.e. urban speeds) characterized by frequent speed variations are known to produce the highest values. As the average speed increases from low to moderate, engine operation becomes more efficient. At much higher speeds (i.e. freeway speeds) much more fuel is consumed and more emissions produced (Krzyzanowski, Kuna-Dibbert, & Schneider, 2005; Boulter, 2001), as can be seen on Figure 2.

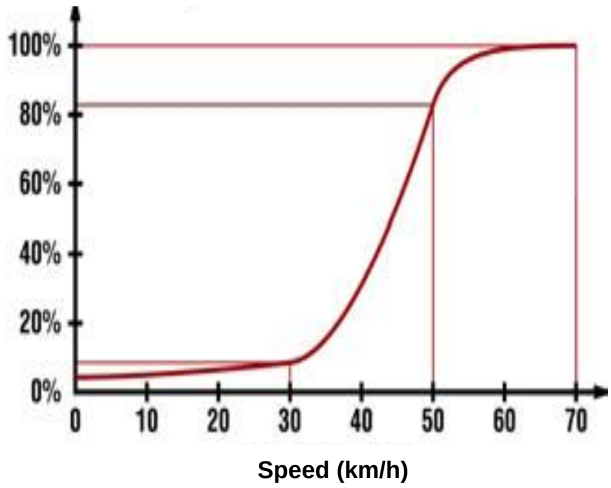

Figure 1 - Relation between the vehicles speed and the death probability of a pedestrian (adapted from OECD (2008))

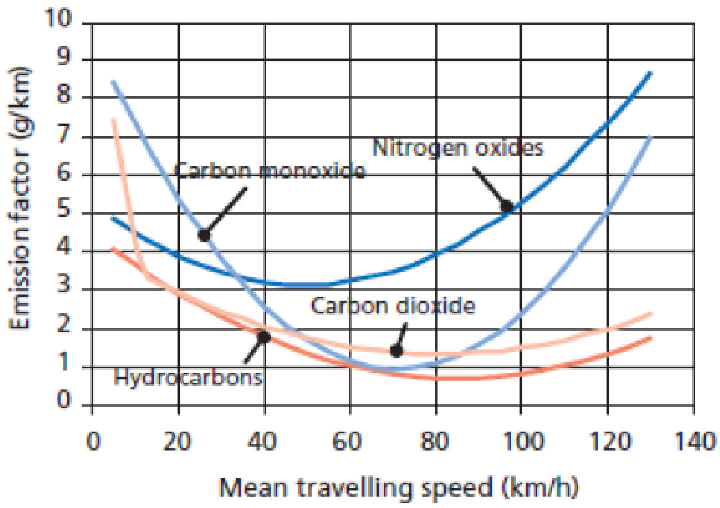

Figure 2 - Effect of average travelling speed on emission levels from passenger cars with catalysts - Euro-I petrol passenger cars (Ntziachristos & Samaras, 2000).

According to traffic characteristics (such as speed, volume and type of vehicle) and street function, different approaches are required for different sections of the road network. TCMs may be implemented individually or in combination in area-wide schemes (Boulter, 2001). The 30 km/h Zones aim to reduce motorized traffic volumes and improve travel safety conditions, particularly for pedestrians and cyclists, by imposing a low speed limit of 30 km/h and multiple physical measures at the urban design level. Limiting the speed to 30 km/h leads to changes in driver behavior that generates a circulation with more safety, less noise and less pollution, allowing a more equitable utilization of the public space (IMTT/Transitec, 2011).

While TCMs have been widely used, it’s still not clear how they impact vehicle dynamics, energy and environment. Consequently, the objective of this study was to evaluate the impacts of TCMs on vehicle dynamics, fuel consumption and exhaust emissions (CO_2 and NO_x), based on on-road measurements of a compression-ignition vehicle and one driver (performed in a second-by-second basis).

2. Methodology

2.1. Experimental Design

A series of experimental on-road tests were designed in the city of Lisbon, in order to achieve the objectives of this work. The TCMs from Lisbon were chosen according to their availability in the city, with the purpose of covering a wide and representative range of measures. Consequently, roads that allow an adequate evaluation of vehicle dynamics, energy and emissions impacts of traffic calming measures were selected, taking into consideration constraints regarding comparable conditions, such as speed limits, topography, travel speed and also, construction and surroundings (site conditions) and type of road and adjacent roads. The on-road tests were carried in three areas of Lisbon: Arco Cego, Alvalade and Parque das Nações.

Arco do Cego Neighborhood

The Arco do Cego neighborhood is located on a residential area of the Lisbon center. It was intervened and transformed into a 30 km/h Zone with several traffic calming measures. For this work, a speed table, textured pavement and three continuous sidewalks were selected, as presented in Figure 3. The speed table (TCM-A-1) is built of asphaltic concrete and is used as a raised pedestrian crosswalk. The textured pavement (TCM-A-2) is built with concrete blocks, is raised to the height of the surrounding curb and has around 75 m in length. Continuous sidewalks (TCM-A-3.3, TCM-A-3.4 and TCM-A-3.7) are built in the same material as the sidewalk (Portuguese stone pavement) and are also used as a raised pedestrian crosswalk. TCM-A-3.3 is on an intersection going uphill with a right turn; TCM-A-3.4 is an intersection with a right turn going downhill; and TCM-A-3.7 is on intersection going uphill.

Alvalade Neighbourhood

The Alvalade South/West neighbourhood belongs to a residential area of Lisbon and was also converted into a 30 km/h Zone. The street analysed was a one-way lane going uphill with two speed tables (TCM-B-1).

Parque das Nações

The Via do Oriente near Parque das Nações (located outside of the city center) is a street of about 1 km with two lanes in each direction, where the speed limit is 50 km/h. The street has multiple speed humps (TCM-C-4) and speed tables (TCM-C-1) separated roughly by 120 m and made of asphaltic concrete, as the indicated in Figure 4

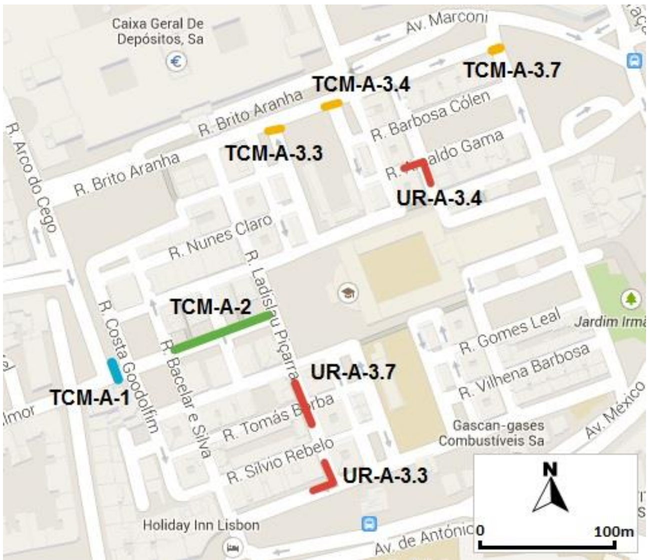

Figure 3 - Map of the Arco do Cego Neighborhood with the cases of study indicated. The red line represent the untreated sections the blue the TCM-A-1, the green the TCM-A-2 and the yellow the TCM-A-3.3, TCM-A-3.4 and TCM-A-3.7 (adapted from Google Maps).

Figure 4 - Map indicating the measures in Via do Oriente. The blue lines represent the TCM-C-1 and the purple lines the TCM-C-4 (adapted from Google Maps).

For each TCM a comparable road without intervention was selected, but with similar conditions (named untreated road), in order to evaluate the impacts of the intervention.

The comparative plan developed allows a comparison of traffic calming measures with each other and with the untreated roads, according to the following guidelines:

- The corridors with measures were compared with a comparable untreated road;
- The measures from Arco do Cego neighborhood were compared with each other;
- The measures from Parque das Nações were compared with each other; and
- The speed tables from different neighborhoods were compared with each other.

Table 1 shows the number of data seconds collected for each case study section and the reached combination of confidence level and margin of error. Sample size was based on the variable that required higher number of seconds to achieve a certain statistical confidence, which in most cases was NO_x.

Table 1 - Summary of Confidence Level and Margin Error Percentage achieved with measurements made the for all the scenarios

	Confidence Level and Margin of Error				**Number of Crossings**	**Number of seconds Measured (s)**
	95% and 15%	80% and 15%	80% and 20%	80% and 35%		
TCM-A-1: Speed Table of Arco do Cego			**x**		8	92
TCM-A-2: Textured Pavements of Arco do Cego		**x**			6	137
TCM-A-3.3: Continuous Sidewalks of Arco do Cego		**x**			10	133
TCM-A-3.4: Continuous Sidewalks of Arco do Cego				*	9	113
TCM-A-3.7: Continuous Sidewalks of Arco do Cego			**x**		9	97
UR-A-(1,2): Untreated Road for Arco do Cego;		**x**			-	158
UR-A-3.7: Untreated Intersection for Arco do Cego			**x**		9	82
UR-A-3.3: Untreated Intersection for Arco do Cego		**x**			7	65
UR-A-3.4: Untreated Intersection for Arco do Cego				**x**	7	79
TCM-B-1: Speed Tables of Alvalade				**x**	4	33
TCM-C-4: Speed Humps of Parque das Nações	**x**				53	293
TCM-C-1: Speed Tables of Parque das Nações		**x**			23	135
UR-C: Untreated Road for Parque das Nações	**x**				-	249

* Continuous Sidewalks (TCM-A-3.4) presented a Margin of Error of 55%.

2.2. Data Collection

The data was collected using a vehicle equipped with portable monitoring equipment to measure vehicle dynamics, fuel use and emissions under on-road conditions.

The vehicle is a Renault Mégane Sport Tourer with Diesel engine, which meets the Euro 4 emission limits with CO emissions of 0.284 g/km and NOx of 0.245 g/km, along with 124 g/km of CO2. The urban fuel consumption estimated was 5.8 l/100km (VCA, 2015).

The portable laboratory used consists of an on-board vehicle monitoring device (I2d) and a tailpipe gas analyzer. The I2d device is an experimental tool used for vehicle on-road monitoring. It collects, measures and automatically transmits in a second by seconds basis driving data from the vehicle, including driving dynamics (speed and acceleration), engine data (engine load, rpm, mass or air flow, etc.) and GPS data (Baptista, Duarte, Gonçalves, & Rolim, 2014). The exhaust emissions were measured in a seconds-by-seconds scale with a gas analyzer (Kane Auto 5), which determine the concentrations of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and nitrous oxides (NO_x).

The most important outputs of this combined monitoring system are vehicle dynamics, engine data, road topography, GPS location, fuel consumption, exhaust emissions.

2.3. Data Analysis

Some of the variables were obtained directly after being collected by the combined monitoring system, such as the coordinates (latitude and longitude), speed, engine load, rpm, air flow and road grade. While others, such as the case of distance traveled, acceleration, vehicle specific power (VSP), mass of exhaust gases (O_2, CO_2, CO, HC and NO_x) and fuel consumption had to be properly calculated.

Vehicle speed allows calculating acceleration and distance traveled. The measured gases were converted into mass flow and the fuel consumption calculated, both in grams per seconds, based on air mass flow (g/s) collected from the vehicle sensor, and also considering the composition of the fuel in terms of carbon and hydrogen (this method is described with more detail in Gonçalves (2009)). The Hydrocarbons (HC) emissions weren't considered in this work, due to the very low exhaust gas readings associated with Diesel engines.

The Vehicle Specific Power (VSP) methodology was also used to assess the instantaneous power per vehicle unit mass, which presents a good correlation with emissions. It was calculated to support the interpretation of the results, namely the fuel consumption and emissions. The equation used to calculate the VSP at each measured second was (Jimenez-Palacios, 1999):

$$VSP = v \cdot (1.1 \cdot a + g \cdot grade + 0.132) + 3.02 \cdot 10^{-4} \cdot v^3 \qquad \text{[Eq. 1]}$$

where v is the instantaneous speed (m/s); a is the acceleration (m/s^2); grade is the road slope; g is the acceleration of gravity (9.8 m/s^2); 1.1 is the inertial mass; 0.132 is the rolling resistance term coefficient; and 0.000302 is the aerodynamic drag term coefficient (Jimenez-Palacios, 1999).

With the GPS coordinates, the studied TCMs and untreated road sections were identified and isolated from all the information recorded during the trips. For each section the distance traveled was calculated; and in the case of the treated sections a segment of approximately 20 m before and after the intervention was selected. The TCMs sections were divided in segments: the approach area ("Before"), the measure itself ("Measure") and the exit area ("After"). A global analysis ("Total") was made as well for TCMs and untreated road sections.

The results of fuel consumption and exhaust gases were presented in l/100km and g/km, respectively, for the different segments ("Before", "Measure", "After" and "Total") considered.

With the aim of accomplishing the comparative plan defined earlier, a comparison percentage of change was developed for the final analysis, using the formula:

$$\text{percent change} = \frac{\text{B}-\text{A}}{\text{A}} \times 100 \qquad \text{[Eq.2]}$$

Where A is the comparative case study (TCM or UR) variable, basis of comparison; and B the same variable of the case study (TCM) being compared.

If percent change is positive an increase in the considered variable occurred, if negative a decrease occurred for that variable.

3. Results

3.1. Vehicle Dynamics

This section presents the results on the multiple TCMs considered regarding the impacts on vehicle dynamics. The evaluation of the variables on the TCMs was primarily divided in the four segments: “Before”, “Measure”, “After” and “Total”. Table 2 presents speed, acceleration, engine speed and calculated load parameters for the speed tables of Arco do Cego neighborhood and Parque da Nações road along with their respective untreated road.

Table 2 - Parameters of driving dynamics and engine operation for TCM-A-1: Speed Table with respective the UR-A-(1,2): Untreated Road of Arco do Cego; and TCM-C-1: Speed Tables with the respective UR-C: Untreated Road of Parque das Nações.

	TCM-A-1				**UR-A-(1,2)**	**TCM-C-1**				**UR-C**
	Before	**Measure**	**After**	**Total**	**Total**	**Before**	**Measure**	**After**	**Total**	**Total**
Speed										
Maximum (km/h)	20	18	24	24	31	38	39	44	44	62
Average (km/h)	14	13	17	14	24	30	32	37	33	47
Change (%)	-45	-47	-31	-41	-	-37	-34	-22	-30	-
Acceleration										
Average (m/s^2)	-0.21	0.26	0.42	0.09	0.02	-0.44	0.77	0.84	0.28	0.00
Engine Speed										
Average (rpm)	1028	1194	1360	1168	1433	1358	1457	1658	1503	1907
Calculated Load										
Average (%)	4	12	16	10	10	6	46	47	30	14

Through Table 2 it is noticeable the influence of the TCMs on the vehicle dynamics. The deceleration prior to the TCMs contributes to the lower speed before the measure or on it, while at the exit area the speed increases. This pattern is also noticeable on the engine parameters, which have lower values before and higher after the measure. The results presented on Table 2 are representative of other TCMs studied.

As presented also in **Error! Reference source not found.** untreated roads registered always higher average speed. According to the average speed percentage of change (%), on Figure 5, the TCM-A-1 is the TCM with more influence on speed reduction, achieving a total of 41%. The lowest reduction occurred at the TCM-A-3.3 with 20%. However this TCM along with the TCM-A-3.7 were the ones with the lower absolute average speed (12 km/h), which expected since they are at an intersection. The textured pavement (TCM-A-2) has higher average speeds when compared to speed table (TCM-A-1), which would be expected since the speed tables are usually more effective in speed reduction, as other studies such as Lee et al. (2013) have mentioned.

The speed table (TCM-C-1) and speed humps (TCM-C-4) from the 50 km/h speed limit road contributed to almost the same reduction of speed, of 30% and 31% respectively.

With different results all the TCMs were effective on slowing down the traffic on the roads where they were built and on maintaining it under the speed limit defined there. On average the TCMs on the 30 km/h Zone contributed to a speed reduction of 6.3 km/h on the interviened roads, while the TCMs on 50 km/h speed limit road lead to a 14 km/h reduction. These different values are strongly related with road characteristics such as intersections associated, slope and pavement conditions, speed limit, and not only with the traffic calming measure characteristics.

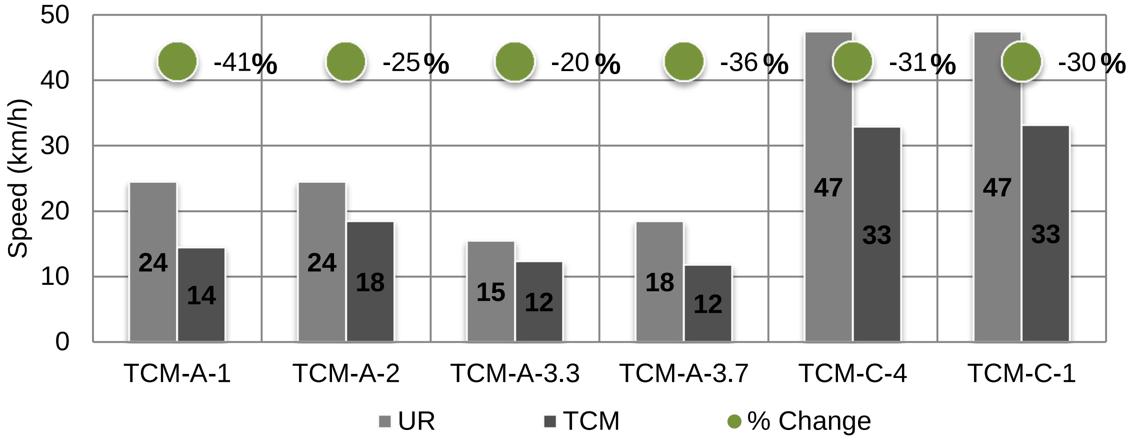

Figure 5 - Average speed (km/h) of the untreated roads or intersection (UR) and traffic calming measures (TCM); and of average speed percentage of change (%) associated to each TCM segment. The green color on the circle indicates a reduction in speed the red indicates an increase.

3.2. Fuel Consumption and Exhaust Emissions

This section analyzes the exhaust emissions (CO_2 and NO_x) and also its fuel consumption.

Table 3 presents the speed tables of Arco do Cego neighborhood and Parque da Nações road along with their respective untreated road. The table shows that exhaust emissions and fuel consumption are lower before the measure and higher after it, which is in line with the vehicle dynamics (speed and acceleration).

The absolute average results of fuel consumption and CO_2 were 48% higher on the TCMs of 30 km/h Zones (Arco da Cego and Alvalade neighborhoods), than on 50 km/h speed limit road (Parque da Nações), due to the lower average speed traveled there. On the other hand, the NO_x emissions were 38% lower.

Table 3 - Parameters of fuel consumption and emitted pollutants throughout TCM-A-1: Speed Table and respective UR-A-(1,2): Untreated Road of Arco do Cego; and TCM-C-1: Speed Tables and the respective UR-C: Untreated Road of Parque das Nações.

	TCM-A-1				UR-A-(1,2)	TCM-C-1				UR-C
	Before	**Measure**	**After**	**Total**	**Total**	**Before**	**Measure**	**After**	**Total**	**Total**
Fuel										
l/100km	3.9	8.2	10.6	7.9	3.8	2.4	3.8	4.4	3.7	4.0
%	3	114	178	107	-	-39	-5	12	-6	0
CO_2										
g/km	105	219	285	212	103	65	101	119	100	106
%	3	114	178	107	-	-39	-5	12	-6	-
NO_x										
g/km	0.07	0.23	0.39	0.25	0.08	0.09	0.20	0.37	0.25	0.07
%	-21	178	368	198	-	25	192	428	263	-
VSP										
W/kg	-1.0	1.5	3.0	0.8	1.5	-2.9	9.3	11.6	5.0	2.6

Figure 6

Figure 8 summarizes the “Total” average concentration for each exhaust gases emitted, fuel consumed, and their percentage of change between each TCM and its own untreated comparative road. The interventions on the Arco do Cego neighborhood caused an increase up to 107% on fuel consumption and CO_2 emissions and up to 198% on NO_x emissions. At the Parque da Nações case study there was, on average, a decrease in fuel consumption and CO_2 emissions of 4%. These decreases occurs because for the allowed speeds; the influence of the TCMs on the engine efficiency when the vehicle accelerates to its normal speed is balanced by the deceleration on the approach area. On the other hand, the NO_x emission presented, on average, strong increases around 304%, associated to acceleration patterns with higher average speeds.

Of all cases, speed table (TCM-A-1) contributed to the highest increase on energy and CO_2 impacts (107%) and to the third highest increase on NO_x impact (198%); however it was where speed presented the strongest decrease (41%). Textured pavement (TCM-A-2), also on the same 30 km/h zone, was not as effective as TCM-A-1 on speed reduction, but the impacts on fuel consumption and exhaust emissions were lower there.

TCM-A-3.3 registered the highest absolute values of fuel consumption (l/100km), CO_2 emissions (g/km) and NO_x emissions (g/km), mostly due to road characteristics (uphill slope and intersection). Nevertheless, the negative impacts associated with the implementation of a TCM did not have the highest increase there (just between 14% and 24%). This continuous sidewalk was the one with the lowest speed reduction (20%). On the other hand, TCM-A-3.7 caused a decrease of 20% on fuel consumption and CO_2 emissions, along with a decrease of 22% on NO_x emissions, while slowing down speed by 36% (the seconds highest).

The highest increase on NO_x emissions occurred on TCM-C-4 (345%), followed by TCM-C-1 (263%); both located on a road with 50 km/h speed limit. However, TCM-C-4 and TCM-C-1 also registered a small decrease on fuel consumption and CO_2 emissions, and the highest absolute reduction on average speed (14 km/h), contributing to slow down vehicles in about 30%.

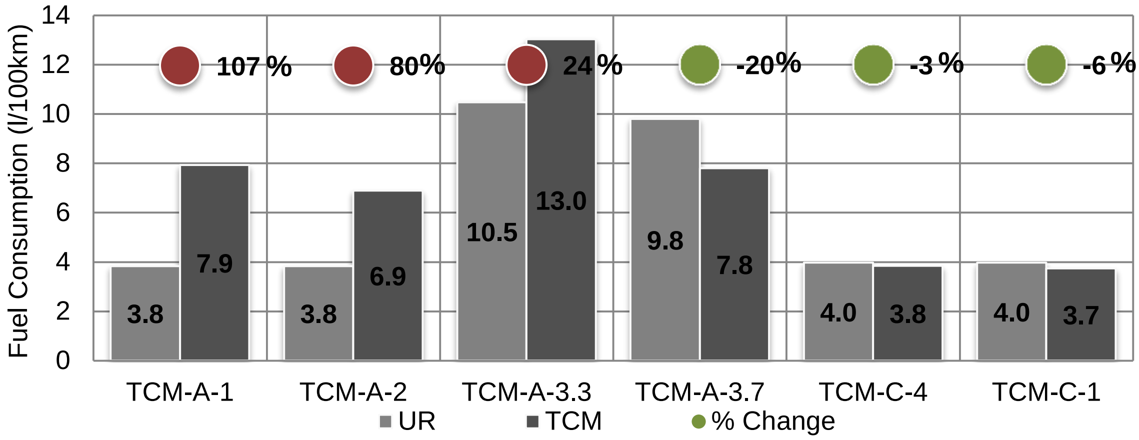

Figure 6 – Total average fuel consumption (l/100km) of the untreated roads or intersection (UR) and traffic calming measures (TCM); and percentage of change (%) for the total average fuel consumption associated with the implementation of each TCM. The green color on the circle indicates a reduction in fuel consumption and the red indicates an increase.

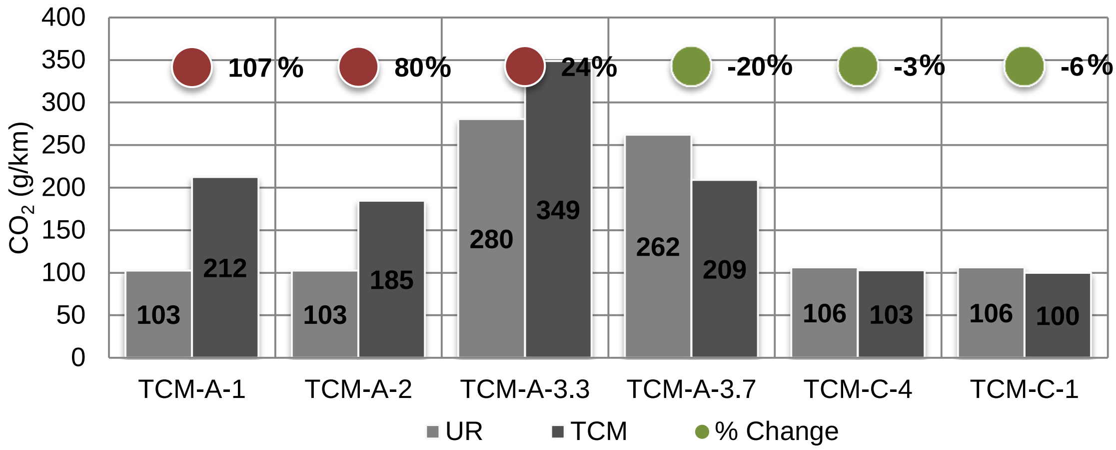

Figure 7 - Total average CO2 emissions (g/km) of the untreated roads or intersection (UR) and traffic calming measures (TCM); and percentage of change (%) for the total average CO2 emissions associated with the implementation of each TCM. The green color on the circle indicates a reduction in CO2 and the red indicates an increase.

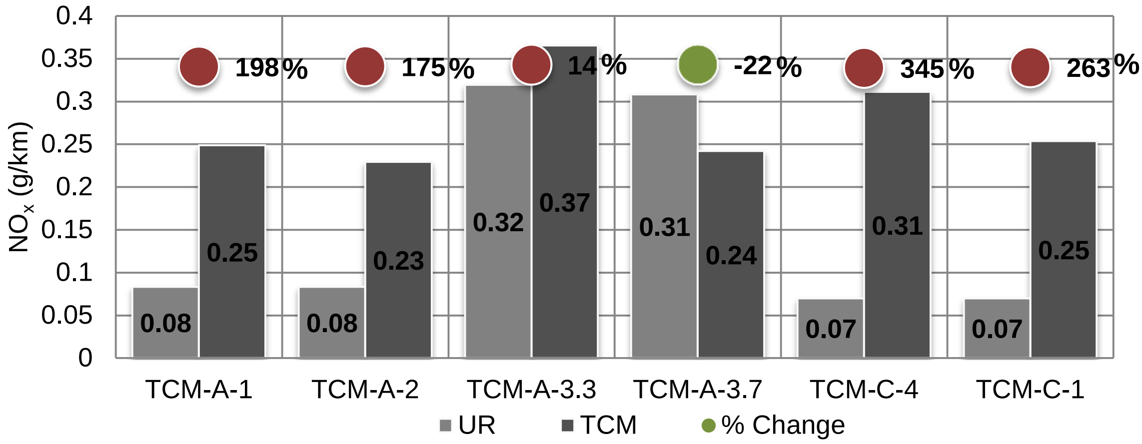

Figure 8 - Total average NO_x emissions (g/km) of the untreated roads or intersection (UR) and traffic calming measures (TCM); and percentage of change (%) for the total average NO_x emissions associated with the implementation of each TCM. The green color on the circle indicates a reduction in NO_x and the red indicates an increase.

3.3. Traffic Calming Assessment

This section assesses the traffic calming measures regarding a set of performance indicators based on their impacts, which can be used by local authorities when selecting the more appropriate measure, according to the existent circumstances and desired objectives.

Fuel consumption, exhaust emissions and speed reduction indicators were based on the percentage of change associated with the implementation of TCMs. The maximum speed indicator was based on the percentage of change between maximum speed on each TMC and its local speed limit.

The percentage of accident reduction is based on the Taylor et al. (2000) estimation indicating that a reduction of 1.6 km/h on average speed leads to a 6% decrease on accident frequency, on urban roads with low average speeds (lower than 50 km/h). The accident reduction (%) was obtained using this relation and the absolute speed reduction (km/h) associated with each TCM.

The pedestrian probability of death (%) in case of collision with a vehicle, associated with the vehicle average speed is based on Figure 1, from OECD (2008). The probability of death reduction results from the difference of probability of death related to the vehicle average speed before and after the implementation of each TCM.

Table 4 presents the results of the performance indicators assessment. A rating formed by black circles was adopted in order to simplify the large amount of information. Using the maximum and the minimum percentage of each performance indicator tercile groups were created. In Table 4, one circle represents the one third of the impact results with the worst performance, and three circles represent the one third of the impact results with the best performance.

Table 4 – Traffic calming measures assessment based on the performance indicator.

	TCM-A-1	TCM-A-2	TCM-A-3.3	TCM-A-3.7	TCM-C-4	TCM-C-1
Traffic Data						
Maximum Speed	●●	●	●●	●●●	●●	●●
Speed Reduction	●●●	●	●	●●●	●●	●●
Variables Impacts						
Fuel Consumption	●	●	●●	●●●	●●●	●●●
CO_2 Emissions	●	●	●●	●●●	●●●	●●●
NO_x Emissions	●●	●●	●●●	●●●	●	●
Safety						
Accident Reduction	●●	●	●	●	●●●	●●●
Probability of Death Reduction	●	●	●	●	●●●	●●●

Road safety on the Parque das Nações road with a speed limit of 50 km/h achieved the higher performance, with speed humps and speed tables. The results were based on an accidents reduction of 52% and a reduction on pedestrian probability of death during a collision of 54%, associated with the highest absolute speed reduction (km/h). In Arco do Cego neighborhood the speed table is the one with the best results on the safety indicators, with the accidents reduced by 37% and pedestrian probability of death during a collision reduced by 3%. This indicates that the vertical deflection measures on a straight road have a greater impact on road safety, mainly associated with the speed reductions. Nevertheless, the 30 km/h zones studied have in general higher safety conditions associated to the low average speed registered there. As shown in Figure 1, higher average speeds lead to higher probability of death of a pedestrian, in fact after 30 km/h the probability increases exponentially

The relative importance of the individual performance indicators can be defined by each local authority giving their interests and issues.

4. Conclusion

This paper evaluates the vehicle dynamics, energy and environmental impacts of traffic calming measures, using on-road measurements of a vehicle, performed in a second-by-second basis.

The results showed that all the TCMs studied contributed to slow down the traffic and keep it under the speed limit, achieving speed reduction between 41% (24 to 14 km/h) on a speed table and 20% (15 to 12 km/h) on a continuous sidewalk (TCM-A-3.3), both located in the 30 km/h Zone of Arco do Cego neighborhood. The higher absolute reduction on speed was 14 km/h on the speed humps and speed tables of Parque das Nações road with a 50 km/h speed limit.

Regarding fuel consumption and CO_2 emissions, the results indicate that the lower average speeds on 30 km/h Zones led to an overall increase on them. Actually, the highest increase was 107%, registered on the speed table located on the 30 km/h Zone, where the highest speed reduction also was registered (41%). On average, the TCMs on the 30 km/h Zone contributed to an increase of 48%, while on the road with a 50 km/h speed limit led to a decrease of 4% on fuel consumption and CO_2 emissions. The TCMs on the 30 km/h Zones tend to also contribute to higher absolute values of CO_2 emissions and fuel consumption, due to the lower speeds.

On the other hand, NO_x emissions presented an overall increase on most TCMs, although more significantly on the speed humps and speed tables located on the road with a 50 km/h speed limit, 345% and 263% respectively. On average, the TCMs of the road with a 50 km/h speed limit increased NO_x emissions by 304%, while the ones on the 30 km/h Zone increased NO_x emissions by 92%. The NO_x emissions showed to be more affected by higher average speeds, especially during acceleration patterns, resulting in more significant increases and higher absolute values.

Through the comparative analysis between the speed table and textured pavement of 30 km/h Zone and also between the speed tables and speed humps on the road with a 50 km/h speed limit, it was noticeable that under the same road characteristic (such as speed limit and slope), stronger vertical deflection measures tended to have higher exhaust emissions and fuel consumption, but lower average speed when comparing with more smother measures.

The 30 km/h Zones contribute to overall safer conditions due to the low average speeds. Though, according to the Traffic Calming Measures Assessment, safety on the 50 km/h speed limit road achieved the higher improvements, with accidents reduced by 52% and the pedestrian probability of death during a collision reduced by 54%, associated with the highest absolute speed reduction registered there.

The methodology developed can support local authorities during the process of selecting the most appropriate TCM to implement, according to the existent circumstances and the desired objectives.

5. References

Ahn, K., & Rakha, H. (2009). A field evaluation case study of the environmental and energy impacts of traffic calming. *Transportation Research Part D: Transport and Environment*, *14*(6), 411–424.

Baptista, P., Duarte, G., Gonçalves, G., & Rolim, C. (2014). ICT for mobility pattern and driver behavior characterization: trial case-study in the city of Lisbon, Portugal.

Boulter, P. G. (2001). *The impacts of traffic calming measures on vehicle exhaust emissions*. Middlesex University London.

Ghafghazi, G., & Hatzopoulou, M. (2014). Simulating the environmental effects of isolated and area-wide traffic calming schemes using traffic simulation and microscopic emission modeling. *Transportation*, *41*(3), 633–649. Retrieved from http://link.springer.com/10.1007/s11116-014-9513-x

Gonçalves, N. G. A. (2009). *Energy and Environmental Monitoring of Alternative Fuel Vehicles*. Universidade de Lisboa, Instituto Superior Técnico.

IMTT/Transitec. (2011). Acalmia de Tráfego - Zonas de 30 e Zonas Residenciais ou de Coexistência. *Pacote Da Mobilidade - Colecção de Brochuras Técnicas / Temáticas*.

Jimenez-Palacios, J. L. (1999). *Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing*. Massachusets Institute of Technology.

Krzyzanowski, M., Kuna-Dibbert, B., & Schneider, J. (2005). *Health effects of transport-related air pollution*.

Lee, G., Joo, S., Oh, C., & Choi, K. (2013). An evaluation framework for traffic calming measures in residential areas. *Transportation Research Part D: Transport and Environment*, *25*, 68–76. doi:10.1016/j.trd.2013.08.002

Ntziachristos, L., & Samaras, Z. (2000). Speed-dependent representative emission factors for catalyst passenger cars and influencing parameters. *Atmospheric Environment*, *34*(27), 4611–4619. doi:10.1016/S1352-2310(00)00180-1

OECD/ITF. (2008). *Towards Zero, Ambitious Road Safety Targets and Safe System Approach*.

Taylor, M. C., Lynam, D. A., & Baruya, A. (2000). The effects of drivers ' speed on the frequency of road accidents. *Transportation Research Laboratory*, 56.

VCA. (2015). Vehicle details - Directgov - Find fuel consumption and emissions information on a new or used car. Retrieved from http://carfueldata.direct.gov.uk/