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

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Resumo

As medidas de acalmia de trafego (MATs) têm sido implementadas para reduzir a velocidade dos veículos e/ou o tráfego de atravessamento em áreas especificas das cidades. Contudo estas têm sido associadas a impactes no consumo de combustível e poluição atmosférica. Desta forma, o objectivo deste estudo foi avaliar os impactes de MATs na dinâmica, consumo de combustível e emissões (CO_2, CO e NO_x) de veículos. Através de monitorização em estrada (numa base segundo-a-segundo) de um veículo a gasóleo e um condutor, quatro tipos de MATs foram testadas: sobrelevação da via, lomba, passeio contínuo e plataforma sobrelevada. As MAT estavam localizadas em Zonas 30 e numa estrada com limite de velocidade de 50 km/h, da cidade de Lisboa.

Os resultados indicam que todas as MATs abrandam o tráfego e mantêm-no abaixo do limite de velocidade (com excepção da plataforma sobrelevada), obtendo-se reduções de velocidade entre 20% e 41%. Nas Zonas 30 as intervenções aumentaram o consumo de combustível e emissões de CO_2 em 48% e as emissões de NO_x em 92%, em média. Na estrada com limite de velocidade de 50 km/h as MAT levaram em média a uma redução de 4% no consumo de combustível e emissões de CO_2, e a um aumento de 304% nas emissões de NO_x.

As Zonas 30 contribuem de forma geral para condições de segurança mais elevadas, devido às suas velocidades mais baixas. Contudo, a análise à segurança rodoviária registou melhorias mais significativas na estrada com limite de velocidade de 50 km/h, que estão associadas a uma maior redução dos valores absolutos da velocidade.

A metodologia desenvolvida pode apoiar as autoridades locais durante o processo de selecção da MAT mais apropriada a implementar, de acordo com as circunstâncias existentes e os objectivos desejados.

Palavras-chave: Medidas de acalmia de trafego; Dinâmica do veículo; Consumo de combustível, Emissões de veículos, Monitorização em estrada do veículo; Sistema portátil de medição de emissões

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

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List of Abbreviations

AAQD – Ambient Air Quality Directive

ANSR – Autoridade Nacional de Segurança Rodoviária (National Authority of Road Safety)

C_6H_6 – Benzene

CH_4 – Methane

CI – Compression Ignition

CML – Câmara Municipal de Lisboa

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DoT – Department of Transportation

EEA – European Environmental Agency

EP – European Parliament

EPA – United States Environmental Protection Agency

EU – European Union

FHWA - Federal Highway Administration

GHG – Greenhouse Gases

GPS – Global Positioning System

H_2O – Water

HC – Hydrocarbons

I2d – Intelligence to drive

IMTT – Instituto da Mobilidade e dos Transportes (Institute of Mobility and Transports)

ITE – United States Institute of Transportation Engineers

MAT – Modelo de Acalmia de Tráfego (Traffic Calming Model)

MOVES – Motor Vehicle Emission Simulator

N_2 – Nitrogen

NECD – National Emission Ceilings Directive

NH_3 – Ammonia

NMHC – Non-Methane Hydrocarbons

NMVOC – Non-Methane Volatile Organic Compounds

NO – Nitrogen Monoxide

NO_2 – Nitrogen Dioxide

NO_x – Nitrogen Oxides

O_3 – Ozone

OECD – Organization for Economic Co-operation and Development

PAP – Plano de Acessibilidade Pedonal (Pedestrian accessibility Plan)

Pb – Lead

PDM – Plano Diretor Municipal

PI – Positive Ignition

PM – Particulate Matter

rpm – Revolution per Minute

SO_2 – Sulfur Dioxide

TCM –Traffic Calming Measure

THC – Total Hydrocarbon

UR – Untreated Road

VKT – Vehicle Kilometers Traveled

VOC – Volatile Organic Compounds

VSP – Vehicle Specific Power

1. Introduction

1.1. Background

Considering the growing mobility needs, priority has been given to passenger vehicle transport for a long time. In many places, the solutions found mostly involved the construction of road infrastructure, with wider roads allowing higher traffic volumes and higher travel speeds.

However, the externalities associated with the excessive use of motorized transport and the progressive consciousness of its environmental, social and economic impacts, has led to the reconsideration of the urban mobility models (IMTT/Transitec, 2011a). More recent approaches support the balance between accessibility and mobility, contributing to urban environment and its users protection, as well as the rehabilitation of streets for the people (F. N. da Silva & Custódio, 2011).

The poor condition of pedestrian infrastructure limits accessibility of significant population groups, especially the most vulnerable ones, such as children and elderly people. In combination with the decrease of safe public spaces due to motorized traffic, these lead to a reduced presence of people and consequent social activities on the streets (IMTT/Transitec, 2011a). Inappropriate road safety measures accompanied by the growing number of motorized vehicles are contributing factors to an increase in road accidents (Mohan, Tiwari, Khayesi, & Nafukho, 2006).

In 2013, 73% of accidents with victims in Portugal happened within localities and 27% outside, occurring 79% of pedestrian fatalities within those areas, as presented in Table 1. About 80% of the accidents were registered in local roads and *Estradas Nacionais* (ANSR, 2013).

Table 1 – 2013 victims of car accidents according to its location and the type of user, in Portugal (adapted from ANSR, 2013).

	Driver			Passenger			Pedestrian			Total
	Killed	Seriously Injured	Slightly injured	Killed	Seriously Injured	Slightly Injured	Killed	Seriously Injured	Slightly Injured	
Within Localities	52.2%	58.6%	71.6%	34.9%	46.5%	64.6%	78.5%	94.0%	97.8%	72.6%
Outside Localities	47.8%	41.4%	41.1%	65.1%	53.5%	35.4%	21.5%	6.0%	2.2%	27.4%

Changes in traffic speed have been shown to be related to changes in accident occurrence. According to Taylor, Lynam, & Baruya (2000) a reduction of 1.6 km/h on average speed typically provides circa 6% decrease on accident frequency, when considering urban roads with low average speeds (inferior to 50 km/h).The reduction in speed increases peripheral vision of the driver, allows for a shorter braking distance and consequently decreases the risk of death among pedestrians in case of collision. Figure 1 shows that the probability of pedestrian death exponentially increases after 30 km/h.

On the other hand, vehicle speed and its variations are key factors of vehicles energy consumption and respective level of exhaust emissions. Aggressive driving and excessive idling in stop-and-go traffic, characterized by events of acceleration and braking have higher energy consumption and emissions. A general speed reduction promotes the reduction of intense speed variation, which also improves the perception of the urban environment context (IMTT/Transitec, 2011a). Figure 2 presents a general curve of fuel consumption according to vehicle speed, the highlighted bar between 65 km/h and 85 km/h is the optimal speed where the lowest fuel consumption occurs.

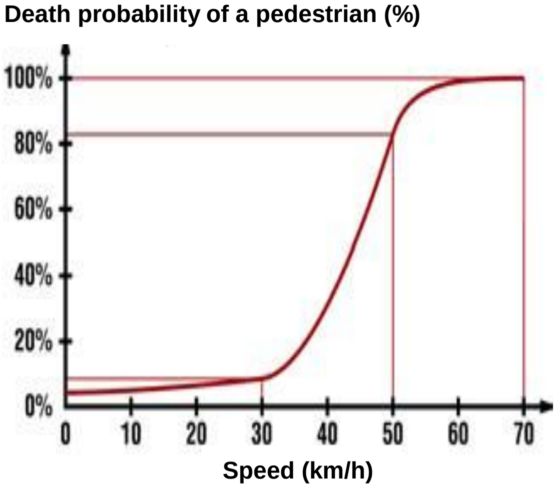

Figure 1 – Relation between the vehicles speed and the death probability of a pedestrian (adapted from OECD (2008))

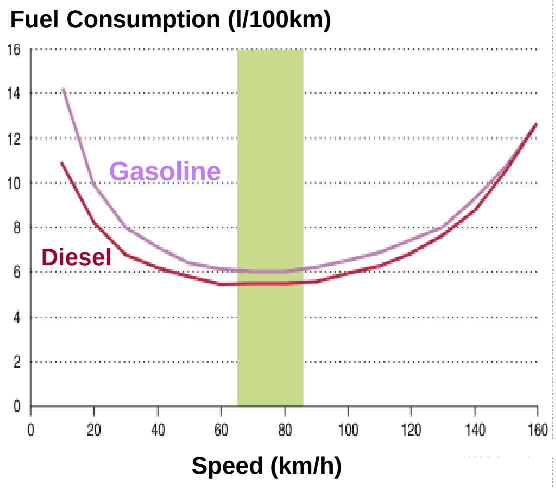

Figure 2 – Fuel Consumption according to vehicle speed, where the green bar represents the optimal speed. (adapted from (DREALLimousin, 2010)).

The increasing concern about environmental issues associated with the transportation sector is highly related to its contribution to air pollution. Air pollution is the top environmental cause of premature death in Europe, due to the increased concentration of hazardous air pollutants such as nitrogen oxides (NO$_x$), carbon monoxides (CO), volatile organic compounds (VOCs) including hydrocarbons (HC), and particulate matter (PM). These local pollutants increase the incidence of a wide range of diseases and have several environmental impacts, affecting the quality of fresh water and soil, and the ecosystem services they support (EEA, 2014a). According to the national annual emissions of air pollutants, reported in 2014 by countries of the European Environment Agency (EEA) or cooperating with it, the road transport sector was responsible for 24%, 12% , 32%, 9%, 13% of the CO, NMVOCs (non-methane volatile organic compounds), NO$_x$, PM$_{10}$ and PM$_{2.5}$ emissions, respectively, being the majority caused by 'road transport exhaust', as presented in Figure 3 (EEA, 2014c; EEA, 2014b).

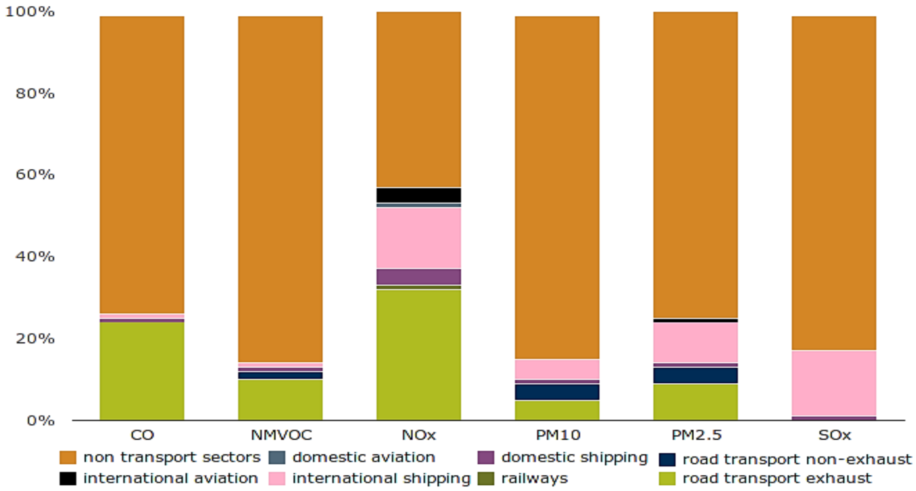

Figure 3 – Contribution of the transport sector to total emissions of the main air pollutants (adapted from EEA, 2014b).

The increase of road traffic in urban centers has led to the deteriorations of their air quality, in fact air pollution has become one of the factors contributing to the degradation of life quality in urban centers (CML, 2015).

Once, air pollution affects the human health and the environment, reducing exposure to it by setting limits on emissions and target values for air quality has been the aim of multiple policies. The European Union (EU) has been concerned with air pollution since the late 1970s. More recently, between 2011 and 2013, the European Commission developed the 2005 Thematic Strategy on Air Pollution, based on a comprehensive review of the existing EU air policies. From that, in December 2013, a Clean Air Policy Package was adopted (EU, 2015). It is a new Clean air Programme for Europe which aims to fulfill the air quality legislation by 2020 and further improvements by 2030, through: revising the National Emission Ceilings Directive 2001/81/EC (NECD) with upper limits for each Member State on total emissions of the six main pollutants (SO_2, NO_x, NMVOC, NH_3, $PM_{2,5}$ and CH_4) to decrease background concentrations and limit transboundary air pollution; a proposal for a new Directive on Medium Combustion Plants; and also proposed actions focusing on air quality in cities, supporting research and innovation, and promoting international cooperation (European Commission, 2013).

The air quality policy framework of the EU also integrates the Ambient Air Quality Directives, which establish local air quality limits that should not be exceeded anywhere; and other legislation aimed to limit emissions from specific sources, such as the Euro standards for vehicles, energy efficiency standards, Industrial Emissions Directive, among others.

The Directive 2008/50/EC on ambient air quality and cleaner air (AAQD) merges most of the existing legislation into a single directive (except for the Directive on heavy metals and polycyclic aromatic hydrocarbons in ambient air, 2004/107/EC). It describes principles concerning the assessment and management of local air quality in relation to a set of pollutant concentrations thresholds (of SO_2, NO_2, NO, PM_{10}, $PM_{2.5}$, Pb, C_6H_6, CO and O_3) that should not be exceeded. If exceeded, air quality management plans must be developed and implemented (EEA, 2014c; EU, 2008). Assessment thresholds, on ambient air quality, applied to NO_2, NO_x and CO are presented in Table 2.

Table 2 - Determination of requirements for assessment of NO_2 and NO_x, and CO concentrations in ambient air within a zone or agglomeration (EP & Council EU, 2008).

	Lower assessment threshold[1]	**Upper assessment threshold**[2]
NO_2: Hourly limit value[3] for the protection of human health	50% of limit value (100 μg/m^3, not to be exceeded more than 18 times in any calendar	70% of limit value (140 μg/m^3, not to be exceeded more than 18 times in any calendar year)
NO_2: Annual limit value for the protection of human health	65% of limit value (26 μg/m^3)	80% of limit value (32 μg/m^3)
NO_x: Annual critical level[4] for the protection of vegetation and natural ecosystems	65% of critical level (19.5 μg/m^3)	80% of critical level (24 μg/m^3)
CO: Eight-hour average	50% of limit value (5 mg/m^3)	70% of limit value (7 mg/m^3)

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[1] Lower assessment threshold: “level below which modelling or objective-estimation techniques alone may be used to assess ambient air quality.” (Footnotes 1 to 4 according to EP & Council EU (2008))

[2] Upper assessment threshold: “level below which a combination of fixed measurements and modelling techniques and/or indicative measurements may be used to assess ambient air quality.”

[3] Limit value: “level fixed on the basis of scientific knowledge, with the aim of avoiding, preventing or reducing harmful effects on human health and/or the environment as a whole, to be attained within a given period and not to be exceeded once attained.”

[4] Critical level: “level fixed on the basis of scientific knowledge, above which direct adverse effects may occur on some receptors, such as trees, other plants or natural ecosystems but not on humans.”

As part of the EU objectives on air quality, reducing emissions from the transport sector has its place on the overall strategy. Motorized vehicle emissions were initially regulated by Directive 70/220/EEC (light-duty vehicles) and 88/77/EC (heavy-duty vehicles). After several updates, Euro 6 is the latest standards for light-duty vehicles (EP & Council EU, 2007), which emission limit values for CO, THC, NMHC, NO_x and PM are presented in Table 3. Euro 6 became effective in 2014, for light-duty vehicles, to mainly add a reduction to the emissions of NO_x from diesel vehicles, from 180 mg/km to 80 mg/km.

On another hand, the Regulation (EC) No 443/2009 sets standards on CO_2 emissions from new passenger cars of 130 g/km and of 95 g/km after 2020.

Table 3 – Euro 6 emissions limits for passenger cars (Category M1) (EP & Council EU, 2007).

Limit Values (mg/km)											
CO		**THC**		**NMHC**		**NO_x**		**THC + NO_x**		**PM**	
PI	CI	PI	CI	PI	CI	PI	CI	PI	CI	PI	CI
1000	500	100	-	68	-	60	80	-	170	5	5

Key: PI= Positive ignition (Gasoline); CI=Compression ignition (Diesel)

The interest of authorities and citizens in dealing with the progressive loss of local safety and environmental quality caused by increasing traffic has resulted in experiments to divert and slow the traffic in urban areas. Thus, to solve the opposing goals of providing mobility while enhancing residential livability the implementation of physical measures has been encouraged – namely Traffic Calming Measures.

1.2. Traffic Calming Measures

Traffic calming measures (TCMs) are mainly used to address speeding and high cut-through traffic volumes on neighborhood streets, with the goal of increasing both real and perceived safety of pedestrians and cyclists, and also improve the quality of life within neighborhoods. High speeds and traffic volumes can create an atmosphere in which non-motorists are intimidated, or even endangered, by motorized traffic. Along with the additional amount of traffic generated within the neighborhood, cut-through drivers are often perceived as driving faster than local drivers (PennDoT, 2001).

Traffic calming measures tend to improve pedestrian and cycling travel conditions, as reduced vehicle speeds and traffic volumes tend to make walking and cycling safer, more comfortable and convenient. Street design features that improve safety and mobility encourage walking and promote pedestrian travel. Better walking conditions are particularly important for people with disabilities, the elderly, and children, who often have more difficulties for travelling (WSDOT, 1997). Street environment conditions affect how people interact in a community. Traffic calming helps make public streets lively and friendly, encourages community interaction and attracts customers to commercial areas. Projects that reduce the amount of land devoted to road and parking, allowing the increase of green spaces (or other types of landscaping) can make the urban environment more beautiful and aesthetically pleasing (Litman, 1999).

The USA Institute of Transportation Engineers (ITE) defined traffic calming in the following way: *“the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behavior and improve conditions for non-motorized street users.”* (Ewing, 1999a)

Although, traffic calming measures are typically limited for use on local streets, they have been incorporated on collector streets[5] with predominantly residential land uses and, less frequently, on streets through downtown business districts. TCM are generally not suitable to use on arterial streets which are intended to accommodate larger traffic volumes with higher speeds (PennDoT, 2001). Since, traffic calming measures intend to adapt traffic characteristics to the functions of the streets where they are implemented, different approaches are required for different sections of the road network. These measures may be implemented individually or in combination in area-wide schemes (Boulter, 2001). When they are applied to identified neighborhoods, instead of isolated locations, the behavior of drivers tends to be more influenced and the traffic problems of the area are more noticeably improved (WSDOT, 1997).

An example of combined TCMs schemes in specific areas is, for instance, the 30 km/h Zones that can be considered by itself a traffic calming measure. Through the imposition of a low speed limit of 30 km/h and multiple physical measures at the urban design level, it aims to reduce motorized traffic volumes and improve road safety conditions, particularly for pedestrians and cyclists. Limiting the speed to 30 km/h aims at changing driver behavior to improve driving with more safety and less noise, allowing a more equitable utilization of public space. The entrances and exits of the zone are identified with signage and the whole area has public space planning coherent with the speed limitation applied (IMTT/Transitec, 2011a).

As previously indicated, in addition to the reductions in traffic volume and speed typical of TCMs, the safety benefits associated with them are significant (Zein, Geddes, Hemsing, & Johnson, 1997). Driving speed is an important factor in road safety. Speed not only affects the severity of a crash, but is also related to the risk of being involved in one. Moreover, a reduction of speed translates into reductions in the impact speed during collisions with a pedestrian (or cyclist) and often to the extent of preventing the collisions altogether. In some traffic calming areas, pedestrian injury accidents have been reduced by 60-70% following speed reductions of about 14 km/h (DfT, 2007). Still, the exact relationship between speed and crash frequency depends on the actual road and traffic characteristics, including road width, intersection density and traffic flow (Aarts & Van Schagen, 2006).

When used properly, traffic calming measures will address and solve existing traffic issues. However, they may also bring some disadvantages to the neighborhood that will impact the residents and other users. The two more relevant disadvantages of TCMs are the impacts on emergency services and transit, and the impacts on environment.

Physical traffic calming measures can affects the emergency services, along with general motorized traffic. The concerns of fire and emergency medical services associated with TCMs are mainly related with the vertical deflection measures, such as speed humps. The delay per speed hump is usually under 10 seconds per hump (Leslie W. Bunte, Jr., 2000). Even though in isolation this time seems short, the total delay can present a considerable increase when speed

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[5] Local street or road - A street or road designated to provide access to residences, business, or other adjacent properties.

Collector street or road - A street or road designated to carry traffic between local streets and arterials, or from local street to local street.

Arterial or arterial street - A road or street serving major traffic movements (high speed, high volume) for travel between major points (FHWA, 2014).

humps are installed in series along a road. Emergency medical services also have concerns about the discomfort that may be suffered by patients as ambulances drive over these vertical measures. Thus, the biggest challenge is to keep the effects of TCMs on emergency response times within acceptable limits or to find new ways of slowing and diverting traffic without substantially disturbing emergency response (Ewing, 1999a). Ideally, maintaining the primary response routes free of obstructions.

Furthermore, the installation of traffic calming measures on roads where public transportation services circulate, such as on bus routes, can increase journey times, passenger discomfort, concerns about passenger safety and about maintenance cost of the vehicles (DfT, 2007). Also noteworthy is that TCMs on one road may cause vehicles to shift their trips to other roads, increasing traffic congestion there, or can sometimes increase the distance required to drive to the destinations, increasing travel time as well (Litman, 1999).

The physical nature of traffic calming measures can also have a negative impact on vehicle fuel consumption which leads to impacts on environment, such as higher emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM). The increase of the exhaust emissions results from speed adjustments (acceleration and deceleration) necessary to drive over an intervention, making it dependent on the type and extent of the TCMs implemented. Also, vehicles driven at low average speeds provide increased levels of fuel consumption and emissions. In fact, low average speeds (i.e. neighborhood speeds) characterized by frequent vehicle stops and starts as well as accelerations and decelerations leading to speed variations are known to produce the highest values. As the average speed increases from low to moderate, engine operation becomes more efficient, since there is less speed variations associated. 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 and Figure 4.

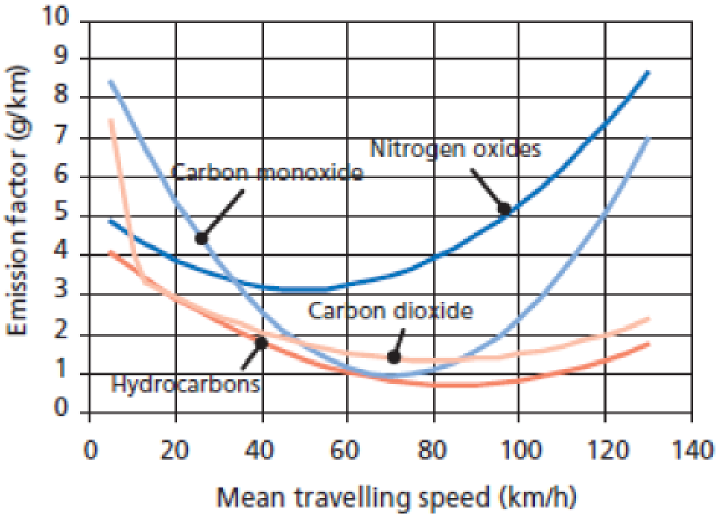

Figure 4 – Effect of mean travelling speed on emission levels from passenger cars with catalysts - Euro-I petrol passenger cars (Ntziachristos & Samaras, 2000).

Regarding noise pollution, vehicles accelerating and decelerating over physical measures increase noise in comparison with constant speeds, because of the additional tire noise and engine operations. The noise level depends on the vehicle type, heavy vehicles generate more noise, partly due to their frame construction but also due to the loads they carry. The noise level is also negatively affected when brick or other textured materials are used in surfaces at traffic calming areas. On the other hand, an overall decrease in speed results in a decreased noise pollution (Schagen, 2003; TSD, 2010). This way, smoother driving patterns should be encouraged to minimize air and noise pollution.

The potential increase in air and noise pollution as well as other negative impacts resulting from the implementation of traffic calming measures have to be weighed against the benefits by the local residents and authorities. Careful studies need to be performed to identify and minimize any adverse effects.

1.2.1. Type of Traffic Calming Measures

The process of selecting a correct traffic calming measure is of great importance and is unique for each section of the road network. Planning, consultation and execution of the correct TCM must be done according to the existent circumstances and desired objectives.

The main traffic calming measures used are separated in three categories:

- **Horizontal Deflection** – Traffic calming measures that force the driver to maneuver around the horizontal obstacle and create perception of narrower roads. There are two types of horizontal deflection: the first type prevents the driver from moving in a straight line by creating a horizontal shift in the road, which forces drivers to slow their vehicles in order to safely drive through the measure; and the second type that is designed to narrow the width of the travel lane. By doing so the usable surface of the road is reduced, causing drivers to slow their vehicles to maintain the level of comfort. Additionally, schemes that narrow the travel lane can improve pedestrian safety by reducing the width of the crossing. These measures can also have the effect of reducing traffic volumes; however, the effects will typically be lower than on speed reduction (CCL, 2014).

- **Vertical Deflection** – Traffic calming measures that create a change in the height of the road. Vehicles slow down to avoid the discomfort from the bumping sensation when travelling over it. Vertical deflection measures are mainly used to reduce vehicle speeds, with lower effects on traffic volumes. They can also be used to improve the safety of pedestrian crossings. These measures typically perform better if implemented in series, than when isolated. The number and spacing of vertical traffic calming measures in a series influences the deceleration and acceleration intensity of a vehicle traveling over them (CCL, 2014).

- **Physical Obstructions** – Traffic calming measures that stops specific vehicle movements, thus discouraging or eliminating cut-through traffic. The traffic volume reduction depends on the type of the TCM implemented and the number of movements obstructed (PennDoT, 2001).

Table 4 summarizes the most common traffic calming measures used separated into categories. Next each TCM is described and illustrated, according to Ewing (1999) and other reports from local authorities or national institutes providing information on traffic calming (CCL, 2014; DfT, 2007; EPAP, 2014b; PennDoT, 2001 and A. B. Silva & Santos, 2011).

Table 4 – List of commonly used traffic calming measures. Based on Ewing, 1999.

Horizontal Deflection
Curb Extension
Curb Radius Reduction
Chicane
Lateral Shifts
On-street Parking
Raised Median Island
Gateway
Traffic Circle
Roundabouts
Vertical Deflection
Textured Pavement
Speed Hump
Speed Cushion
Speed Tables / Raised Crosswalk
Raised Intersection
Continuous Sidewalk
Physical Obstruction
Diagonal Diverter
Directional Closures
Right-in / Right-out Island
Raised Median Through Intersection
Full Closure

The following information describes each type of traffic calming measure on its main physical characteristics, effects on traffic volumes and speeds, and appropriated location. Figures with a scheme representing the design of the TCMs when implemented are presented to all types.

Curb Radius Reduction

Curb radius reduction is horizontal intrusion of the curb on the intersection corner, creating a smaller radius, as shown in Figure 5. This measure slows down vehicle right-turn speed due to the tighter corner caused by the smaller radius. It can also improve pedestrian safety by decreasing the crossing distance. Curb radius reduction is acceptable primarily on local roads, but also on collector roadways with inferior extent. In addition, curb radius reductions should not be used on transit routes requiring a right turn (CCL, 2014; PennDoT, 2001).

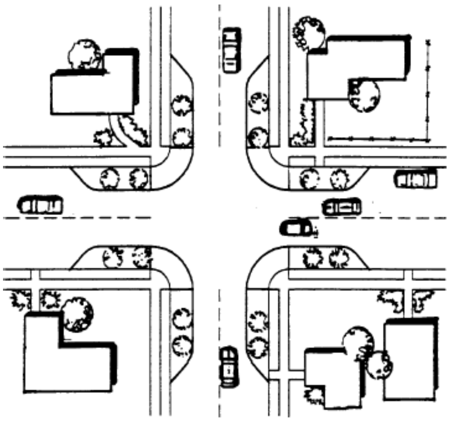

Figure 5 – Scheme of Curb Radius Reduction (Ewing, 1999).

Curb Extension

Curb extension identified in Figure 6 is a horizontal intrusion of the curb into the road. It reduces road width and causes a physical perception of a narrower road on the driver, which reduces speed. Curb extensions can improve pedestrian safety by providing refuge and shorter crossing distance (CCL, 2014). Curb extension is appropriate for all street classifications (local roads, collectors and arterials), but works particularly well in locations with significant pedestrian activity, such as schools zones where they also have the benefit of defining the parking area (PennDoT, 2001).

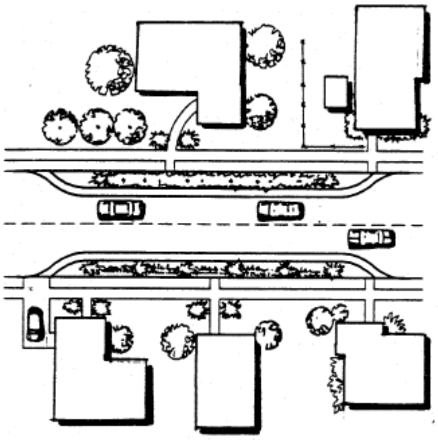

Figure 6 – Scheme of Curb extension (Ewing, 1999).

Raised Median Island

Raised Median Island is an elevated median constructed on the centerline of a two-way road to reduce the overall width of the adjacent travel lanes, as presented in Figure 7 . It results in speed reduction, due to the perception of a narrow road that driver experience. The medians can be landscaped to improve aesthetics. With adequate width this measure can also serve as a pedestrian refuge, when located at a crosswalk and the median is accommodating for pedestrians, according with Figure 8. Raised median islands may be appropriate for all classifications of streets: local, collector and arterial (CCL, 2014; PennDoT, 2001).

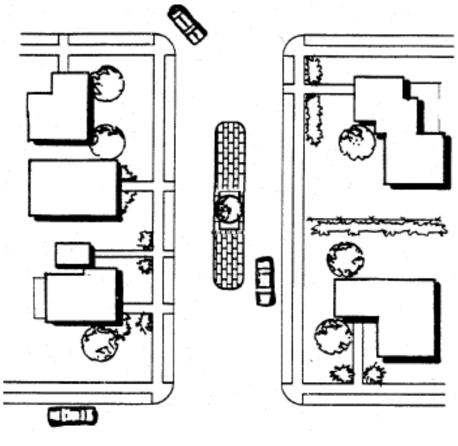

Figure 7 – Scheme of raised median island (Ewing, 1999).

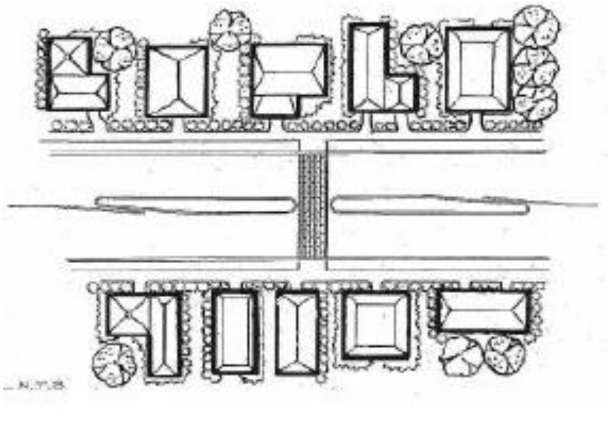

Figure 8 – Scheme of raised median island and textured crosswalk (PennDoT, 2001).

Chicane

Figure 9 presents a chicane, which comprehends a series of curb extensions on alternating sides of the road. It narrows the road and requires drivers to maneuver from one side of the road to the other, creating S-shaped patterns. Typically, a series of 3 curb extensions is constructed at mid-block location on alternating sides of the street. Raised landscaped islands or delineators are usually provided at both ends of a chicane in order to increase the drivers awareness of the need for a lateral shift. Along the road sections containing a chicane the street parking may be restricted. They are most appropriate on local streets, with two-lane on two-way streets or with one-lane on one-way streets (CCL, 2014; PennDoT, 2001).

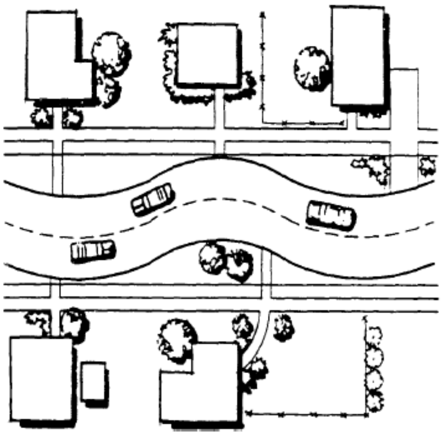

Figure 9 – Scheme of chicane (Ewing, 1999).

Lateral Shifts

Lateral Shifts presented in Figure 10 are half of a chicane. To cause travel lanes to bend one way and then bend back to the original direction of travel are implemented on the street curb extensions or pavement markings. It’s typically used to slow vehicles down by forcing drivers to maneuver through the bend. They can be used on collectors or even arterials, when implemented with the right degree of deflection. Lateral shifts can be considered when high traffic volumes and high speed limits prevent the use of other traffic calming measures (CCL, 2014) .

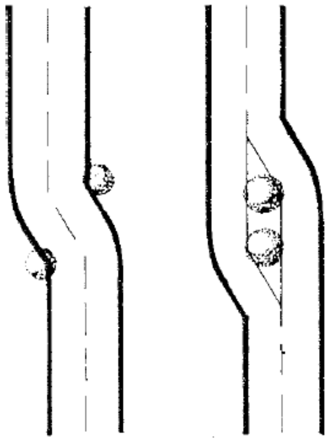

Figure 10 – Scheme of lateral shifts (Ewing, 1999).

On-street Parking

On-street parking is the reduction of the road width available for travelling vehicles by allowing motorized vehicles to park adjacent and parallel to the curb, as Figure 11 shows. The main use of this measure is to decrease the vehicle speed. On-street parking may be appropriate for all streets classifications (PennDoT, 2001).

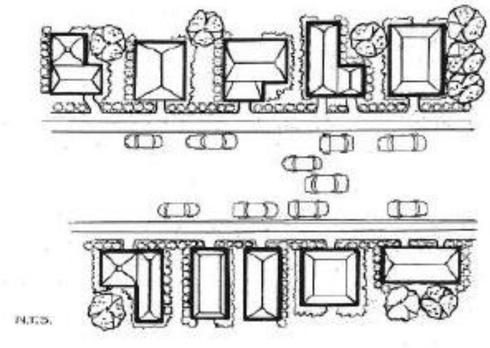

Figure 11 – Scheme of on-street parking (PennDoT, 2001).

Gateway

Gateways such as presented in Figure 12 are entrance treatments, typically using physical and textural changes that provide identity to an area. Entrance treatments alone such as landscaping and signing do not reduce speeds or total volumes; they need to be combined with other physical measures, such as curb extensions, textured pavement treatments and median islands. However, they can increase driver awareness of the environment in which they are driving. The appropriate location for this measure is on local roads only, primarily at the entrance of residential communities (PennDoT, 2001).

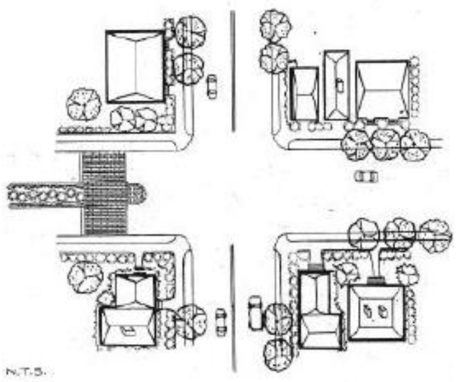

Figure 12 – Scheme of gateway (PennDoT, 2001).

Traffic Circle

Traffic Circle is a raised island located in the center of an intersection. It forces vehicles to travel through the intersection in a counter-clockwise direction around the raised island, as shown in Figure 13. The traffic circle typically has a circular shape, measuring between 5 m and 7 m in diameter, and can include landscaping within the circle. Traffic circles prevent drivers from speeding through intersections by blocking the through movement. They are most effective when there is a vertical landscaping design in the center, since it increases its visibility to the drivers and provides aesthetics to the neighborhood. Traffic circles are more suitable for intersections of local streets without high pedestrian or left-turn traffic volumes (CCL, 2014; PennDoT, 2001).

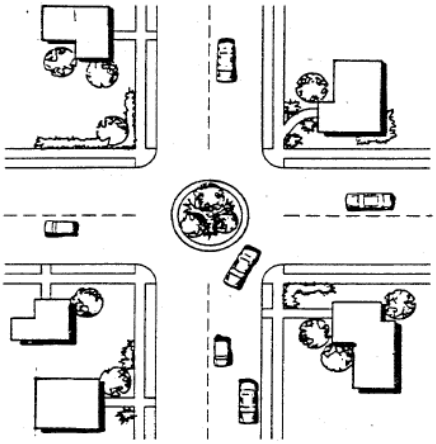

Figure 13 – Scheme of traffic circle (Ewing, 1999).

Roundabout

Roundabout is a measure similar to the traffic circle, but they are larger and typically require additional right-of-way for the vehicles circulating on it. The central island diameter of a single-lane roundabout can measure between 17 and 33.5 m. As Figure 14 indicates, raised splitter islands are need at roundabouts to channel approaching traffic to the right. They are found primarily on arterial and collector streets, often substituting intersections that were controlled by traffic signals or stop signs (CCL, 2014; PennDoT, 2001) .

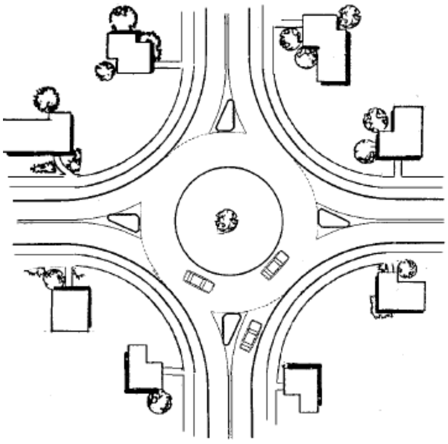

Figure 14 – Scheme of roundabouts (Ewing, 1999).

Speed Hump

Speed hump is a raised area placed across the entire road as presented in Figure 15, which deflects both the wheels and frame of a crossing vehicle. It has a rounded top with 75 to 100 mm of height and 3.5 or 7 m of travel length. The height and length of the speed hump determines how fast it can be crossed without causing discomfort to the driver. As the speed of the vehicle traveling over the measures increases, the discomfort increases as well, causing the driver to slow down to a safe speed (PennDoT, 2001). Speed humps as short as 1.5 to 2.5 m tend to function more like Speed Bumps. Speed bumps have around 75 to 150 mm in height and a travel length of 150 mm to 1 m, they are typically used on private residential streets, driveways and parking lots and it is not considered a traffic calming measure, since it require vehicles to travel much slower to attain a comfortable travel speed, creating a safety hazard otherwise (CCL, 2014).

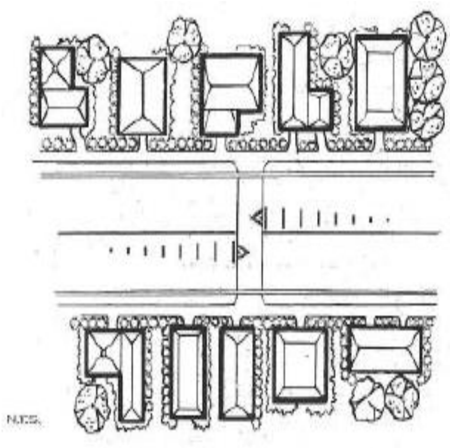

Figure 15 – Scheme of speed hump (PennDoT, 2001)

Speed Cushion

As seen in Figure 16, speed cushions are narrower speed humps that are typically installed in the center of each travel lane. Speed cushions are typically 2 m in width and range in length from 2 to 3 m. Passenger vehicles cross the speed cushions in the same way as speed humps, while emergency vehicles are able to drive through the measure without having to step over it, due to their wider wheel track. Thus, emergency services response times are not affected as much, if at all.

Figure 16 – Speed cushion (A. B. Silva & Santos, 2011)

Speed Tables

The speed table presented in Figure 17 is a flat-topped speed hump. They typically measure between 75 and 100 mm in height and 7 m in length, with the flat portion being 3 m in length. Speed tables are typically long enough for the entire wheelbase of a passenger vehicle to rest on its flat top. Their long flat area allows higher design speeds than speed humps. Textured materials can be used to improve the appearance and draw attention to them, reduce speed and possibly enhance safety. Discomfort increases as the speed of the vehicle traveling over them increases, like with the speed humps. Speed tables are good for locations where low speeds are desired but a smoother driving is needed for larger vehicles.

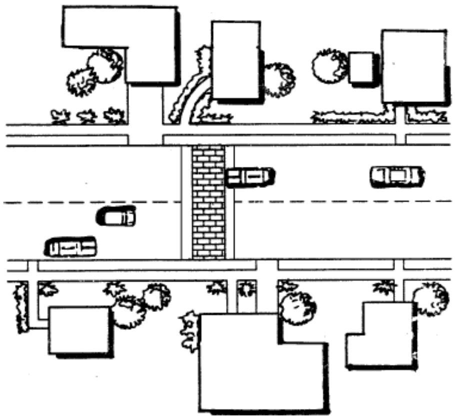

Figure 17 – Scheme of speed tables (Ewing, 1999)

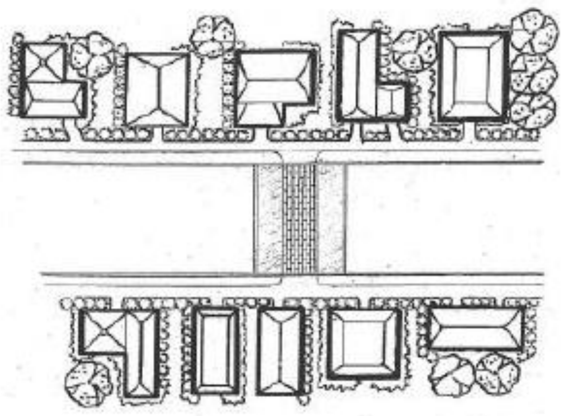

Figure 18 – Scheme of raised crosswalks (PennDoT, 2001)

If marked for pedestrian crossing, speed tales are called raised crosswalks or raised crossings. They should be elevated to a height that matches the adjacent sidewalk, such that the raised crosswalk is leveled with the curb or top of the sidewalk elevation at each end. Appropriate sidewalk transitions on both sides of the road must be installed with the raised crosswalks (CCL, 2014; PennDoT, 2001).

Textured Pavement

Textured pavements as in Figure 19 are road surfaces paved with brick, concrete pavers, stamped asphalt, or other surface materials that produce constant small changes in vertical alignment. Drivers tend to slow down when crossing textured pavement due to the vibration created by the surface material, which also contributes to alert the drivers that they are entering a pedestrian friendly area. However, this measure can have the disadvantage of generating noise pollution (CCL, 2014).

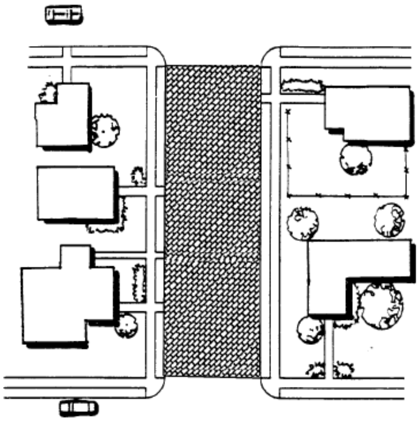

Figure 19 – Scheme of textured pavement (Ewing, 1999)

Continuous Sidewalk

Continuous sidewalk, as presented the Figure 20, is an extension of the sidewalk across a local street intersection. A “raised” continuous sidewalk is extended at its original elevation, with the local road raised to the level of the sidewalk at the intersection, similarly to a raised crosswalk at the middle of a street. On an “unraised” continuous sidewalk, the sidewalk is lowered to the level of the road (ToW, 2011). The extension becomes a crosswalk incorporating a textured and/or patterned surface which contrasts with the adjacent road creating textured crosswalk. These measures decrease conflicts between vehicles and pedestrians by better defining the crossing area and also elevating pedestrians above the road level (EPAP, 2014b).

Figure 20 – Continuous sidewalk (EPAP, 2014b)

Raised Intersection

The raised intersection, shown in Figure 21, is an intersection constructed at a higher elevation than the adjacent road. Similarly to speed tables it elevates to a height of about 75 mm. They have a long ramp on all approaches and a flat top throughout the entire intersection. Raised intersections can also be used to alert drivers to the possibility of pedestrians or other vehicles in the area. They are most appropriate to commercial areas and business districts with high pedestrian activity, but also to local streets and collectors (CCL, 2014; PennDoT, 2001).

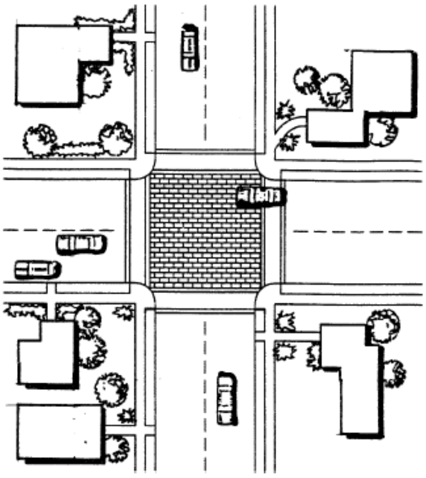

Figure 21 – Scheme of raised intersection (Ewing, 1999)

Diagonal Diverter

Diagonal diverter is a raised barrier placed diagonally across an intersection, as shown in Figure 22. The barrier forces traffic to turn and prevents it from travelling straight through the intersection, creating two unconnected intersections. It can incorporate gaps for pedestrians, wheelchairs and bicycles and can be designed to allow crossing of emergency vehicles. The typical use is to eliminate unwanted through traffic. They are most appropriate in local streets (CCL, 2014; PennDoT, 2001).

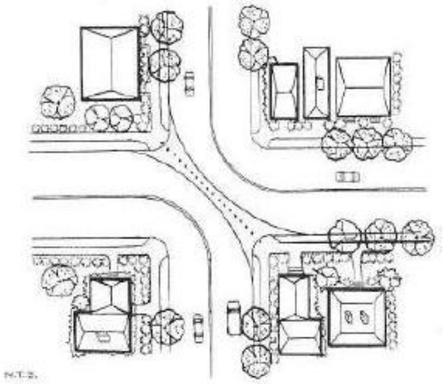

Figure 22 – Scheme of diagonal diverter (PennDoT, 2001)

Directional Closure

Directional closure is a curb extension or vertical barrier extending to approximately the centerline of a road, as presented in Figure 23. It obstructs one side of the road and prohibits vehicles from entering in that direction of traffic. This obstruction is especially useful for controlling non-compliance of one-way road and preventing cut-through traffic, by eliminating movements. Some directional closures have a pathway built through them specifically for bicycles, so they can travel in both directions of the obstructed road. The directional closure appropriate locations are local streets and minor collectors, at their intersection with collectors and arterials (CCL, 2014; PennDoT, 2001).

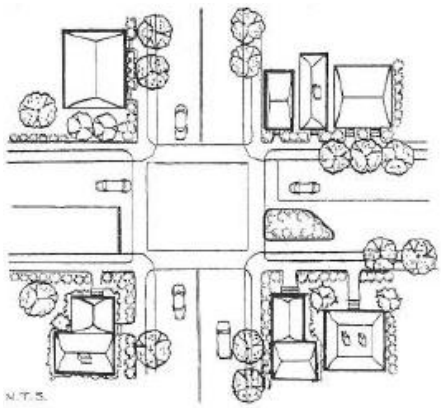

Figure 23 – Scheme of directional closures (PennDoT, 2001)

Right-in/Right-out Island

Right-in/right-out islands are raised triangular island at an intersection approach, as presented in Figure 24. They obstruct left turns and through movements to and from the intersection street or driveway. The main purpose of this type of intervention is to reduce cut-through traffic on local streets. Right-in/right-out islands are appropriate on local streets at intersections with arterials and major collectors. The island needs to be designed properly or vehicles will drive left around it (CCL, 2014; PennDoT, 2001).

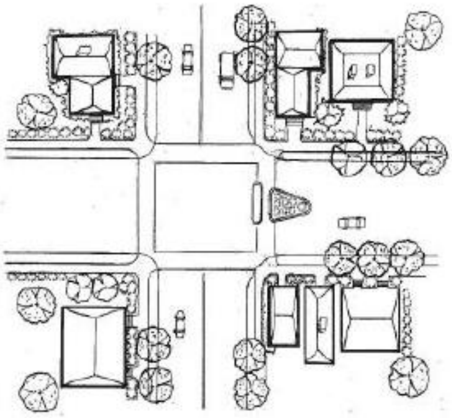

Figure 24 – Scheme of right-in / right-out island (PennDoT, 2001)

Raised Median Through Intersection

Raised median through intersection is an elevated median located on the centerline of a two-way road through an intersection, as shown in Figure 25. It prevents left turns and through movements to and from the intersection road. This type of measure is especially effective at preventing cut through traffic in residential areas, while improving pedestrian safety. It is most appropriate on arterials and major collectors at their intersection with local streets.

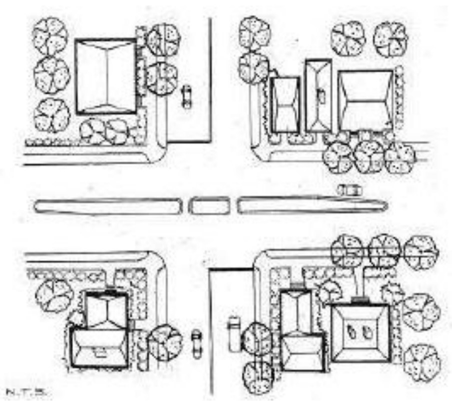

Figure 25 – Scheme of raised median through intersection (PennDoT, 2001)

Street Closure

Street closure is a barrier extending across the entire width of a road, as presented in Figure 26. It obstructs all motor vehicles from continuing along the road. A closure can change a four-way intersection into a three-way intersection, or a three-way intersection into a non-intersection. Gaps can be provided for cyclists and they are typically crossable by emergency vehicles. Street closures are intended to change traffic patterns by eliminating unwanted through traffic.

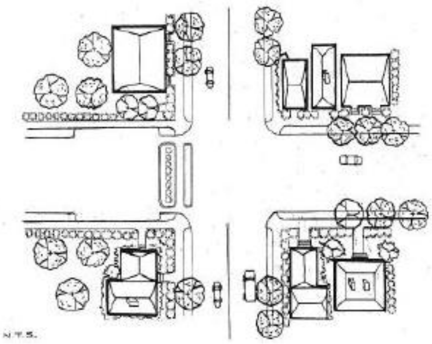

Figure 26 – Scheme of street closure (PennDoT, 2001)

Traffic calming measures have been successful at reducing the frequency and severity of accidents and increase the overall safety of the street users; however some of them affect negatively vehicles' fuel consumption as well as exhaust emissions. Thus it is important to investigate the relationship between the TCMs and their effects on multiple levels, especially the environmental and energy impacts.

1.3. Traffic Calming Measures in Lisbon

Municipality of Lisbon (CML) want to transform Lisbon into a “city of neighborhoods”, where should be given priority to pedestrians and promoted the quality and comfort of public spaces (Mendonça, Farias, Afonso, & Seixas, 2009). The ability of walk freely and safety is a human right that CML supports. Traffic calming measures were considered by CML as the best way to enforce this right in residential areas, historical centers, school areas and streets with many pedestrians; since they decrease vehicle speed, they also reduce of the number of collisions with pedestrians and their severity. Additionally, TCMs promote the reduction of cut-through traffic, with benefits in safety, coexistence between all street users, urban environment and quality of life of the residents (EPAP, 2014a).

The Traffic Calming Model (*Modelo de Acalmia de Tráfego*, MAT) is a working tool developed by a team of the municipality focused on promoting the pedestrian accessibility in the city of Lisbon (*Plano de Acessibilidade Pedonal*, PAP), to support municipal services and Parish Councils that are interested in implementing traffic calming measures (EPAP, 2014a). Three types of TCMs are currently covered by MAT: speed tables, raised crosswalk and continuous sidewalk. Two other working tools are being developed: curb extensions with raised crosswalks and 30 km/h Zones (Rodrigues, 2015). The type of measures considered to install on Lisbon streets are dependent on: hierarchy of the road network, access roads to hospitals, bus routes, street lighting conditions, road slope and existing drainage systems. The Municipality’s Plan of Lisbon (*Plano Diretor Municipal*, PDM), which is a municipal regulatory document concerning spatial planning, defined the introduction of TCMs on local distribution roads and local access roads (4th and 5th level[6]), and allows for the possibility of considering their introduction on secondary distribution roads (3rd level) (EPAP, 2014a). Lisbon city already has some traffic calming measures implemented in its neighborhoods and problematic roads. The types of TCM that can be found in Lisbon are: speed humps, speed table, continuous sidewalk, textured pavement, raised intersection, raised median islands, curb extension and chicanes. Most of these measures are integrated in 30 km/h Zones created in multiple Lisbon neighborhoods.

The implementation of 30 km/h Zones in Lisbon is an extremely important measure that aims at the requalification of the neighborhoods public spaces, by imposing a speed reduction and a spatial planning coherent with a speed limit of 30 km/h. It involves the delimitation of different spaces and the use of different traffic calming measures. The fundamental objectives of 30 km/h Zones in Lisbon are: reduction of accidents in urban areas; reorganization and increased parking for residents; and education to a more friendly mobility for pedestrians and environment (F. N. da Silva & Custódio, 2011).

In 2013, CML had thirty one proposals for 30 km/h Zones in residential neighborhoods, six of which had the project management completed and whose implementation were schedule to begin. These neighborhoods were Encarnação, São Miguel, Estacas, Carnide, Charquinho and Arco do Cego, as presented in Figure 27. In 2015, these interventions were completed along with those in Bairro Azul, Alvalade Norte/Poente and Alvalade Sul/Poente neighborhoods.

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[6] 3rd level – Consist of distributer roads on urban centers. It provides proximity distribution and lead traffic flows to superiors’ road levels (Secondary collectors).
4th level – Consist of distributer roads at a neighborhood level, with some capacity to traffic flow, but where pedestrians have priority (Local Collectors).
5th level – Provides access to residences, business, or other adjacent properties. It promotes conditions for pedestrian mobility (Local road) (IMTT/Transitec, 2011b).

Figure 27 – The green shows the neighborhoods in Lisbon with the project management completed and the yellow the ones to be developed (JFLumiar, 2014).

1.4. Objectives

Considering that traffic calming measures have been associated with negative impacts on fuel consumption and exhaust emissions, and considering the importance given by Lisbon Municipality to the TCMs, the main goal of this study was to quantify the impact of different traffic calming measures on vehicle’s dynamics, fuel consumption and exhaust emissions (CO_2, CO and NO_x). For that purpose, a vehicle was monitored in real travel conditions in several TCMs of the city of Lisbon, in order to obtain real on-road measurements.

This is justified by the fact that the impacts on fuel consumption and exhaust emissions have been less studied than other variables. Moreover, the fact that Lisbon has been very recently implementing TCMs in some of its neighborhoods made it more relevant to study the impacts of TCMs.

More specifically, the objectives of this study were:

- To elaborate a review of the impacts on speed, traffic, safety and most significantly on fuel consumption and exhaust emissions of the different type of TCMs.
- Based on the data collected from the on-road measurements, to individually study each TCM, in order to evaluate how it affects vehicle dynamics, exhaust emissions and fuel consumption while travelling on it, as well as on its approach and exit area. Then, compare the different TCMs with each other and with an equivalent road without intervention, in order to evaluate the influence of the each TCM on the impacts studied; and
- To perform an assessment based on driving speed, speed reduction, pedestrian safety, exhaust emissions and fuel consumption associated to each studied TCM, with the purpose of creating guidelines to support local authorities when choosing the most appropriate one to implement.

2. State of the Art

This section analyzes the impacts on fuel consumption and exhaust emissions due to the introduction of traffic calming measures. These impacts have been less studied and tested than the driving speed and traffic volume changes, which are the main purposes of TCMs. While TCMs are widely used, their energy and environmental impacts are still not clear. Furthermore, not all of the existing measures have been studied.

Traffic calming measures influence fuel consumption and exhaust emissions by reducing vehicle speed, speed variation and traffic volume. As presented in Figure 2 and Figure 4, emissions and fuel consumption present the same trend, which appears graphically as a U-shaped curve. At lower and at higher speeds, fuel consumption and emissions per kilometer travelled are higher (Krzyzanowski et al., 2005; Ntziachristos & Samaras, 2000; Owen, 2005). Thus, a reduction of traffic speed with TCMs will most probably be accompanied by an increase in tailpipe emissions. Additionally, accelerations, decelerations and idling time also negatively influence vehicle emissions, because the frequent variations in speed can result in an increase of fuel consumption and the accelerations in a more incomplete fuel combustion (Boulter, 2001; Pulkrabek, 2004). Consequently, interventions that reduce speed variations can contribute to decrease exhaust emissions. On the other hand, emissions from vehicles depend on the number of trips and the distance travelled by each one. As a result, traffic calming measures that are intended to reduce traffic volume of motorized vehicles, while increasing walking, for example, can result in a reduction of the total emissions. However, exhaust emissions may simply be displaced if traffic is diverted from one area to another.

Most of the studies mention vehicle speed, speed variation or traffic volume, as factors that influence fuel consumption and air pollutant emissions; but only some types of TCMs were investigated by their authors. The TCM studies cover curb radius reduction and curb extension, traffic circles, roundabouts, speed humps, speed cushions, speed tables, chicanes and raised intersections, along with other types of traffic control such as speed bumps, speed limits and stop signs. Some authors studied them individually, while others did so in small groups, examining the isolated and the area-wide effects.

A table summarizing the expected impacts associated with the implementation of each traffic calming measure defined in the Introduction section is presented. The tables cover not only the effects on fuel consumption and air pollutant emissions identified by the authors, but also the effects on speed, traffic, safety, among others, based on Ewing (1999d), PennDoT (2001), A. B. Silva & Santos (2011), DfT (2007), CCL (2014) and EPAP (2014b). These studies are reports provided by local authorities or national institutes (from different countries) that offer information on traffic calming, its place on the road and the impacts of specific measures.

2.1. Curb Radius Reduction and Curb Extension

A study by Boulter (2001) evaluated the impacts of multiple traffic calming measures on exhaust emissions. The TCMs selected were: speed tables, speed humps, raised intersections, speed cushions, chicanes, curb extensions and traffic circles. For each of the TCMs driving cycles to represent vehicles operation before and after their implementation were formulated. The CO, HC, NO_x and CO_2 emissions were measured on a chassis dynamometer using the cycles, from a sample of vehicles. The TCMs were studied individually, in order to also evaluate their performance on vehicle speed. The curb extension indicated a speed reduction of 8 km/h, as presented in Table 5 along with other impacts. It was the one with the lowers speed reduction registered. The emissions increased by 39% in CO, 35% in HC, 9% in NO_x and 14% in CO_2. The curb extension, along with the chicane and speed cushion tended to have relatively lower change in emission impacts.

Table 5 – Expected impacts associated with curd radius reduction and curb reduction extension.

Speed	• Can reduce speed. Most curb extensions result in speed reductions of 1.6-3.2 km/h. Potential to reduce speeds by up to 8 km/h, when applied significant narrowing the travel lanes (Boulter, 2001; PennDoT, 2001). • Slow vehicles making a right turn by reducing the curb radius (PennDoT, 2001).
Traffic	• Curb radius reduction increased difficulties associated with the operation of long vehicles (A. B. Silva & Santos, 2011).
Safety	• Reduce the crossing distance for pedestrians (A. B. Silva & Santos, 2011). • Improve the line-of-sight of pedestrians and make pedestrians more visible to oncoming traffic (PennDoT, 2001). • Can reduce accidents by 25% (in relation to a speed reduction of 8 km/h) (Boulter, 2001).
Exhaust Emissions	• Increase of pollutant emissions. The increase can be around 39% for CO, 35% for HC, 9% for NO_x and 14% for CO_2 (Boulter, 2001).
Other	• Can result in loss of one on-street parking space on each side of the road and can prevent illegal parking close to intersections (PennDoT, 2001; A. B. Silva & Santos, 2011). • May make it difficult to accommodate full bicycle lanes (PennDoT, 2001). • Improve neighborhood appearance with landscaping and/or textured treatments(A. B. Silva & Santos, 2011).

2.2. Chicanes

The chicanes were studied by Lee, Joo, Oh, & Choi (2013). This paper considers two types of speed humps, speed tables and chicanes, which had similar characteristics and were already installed in roads with speed limits of 50 km/h. It uses vehicles equipped with GPS devices to collect trajectory data, in order to obtain speed profiles every second, reflecting the driving behaviors. The data collected was used in simulations with a vehicle emissions model (MOVES[7]), to evaluate environmental and public health impacts. To study the TCMs three criteria measures were considered: speed, acceleration noise8 and emissions. The speed was considered to capture traffic calming performance and acceleration noise to evaluate road safety. Vehicle exhausts emissions, CO_2 and $PM_{2.5}$, were considered to assess environmental and public health impact. At the chicanes the approaching speeds were reduced smoothly and kept low at the crossing (like in the case of speed tables). Additionally it had the lowest average

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[7] MOVES (Motor Vehicle Emission Simulator) is an emission modeling system developed by US Environmental Protection Agency to estimate emissions for mobile sources. It covers a broad range of pollutants and allows multiple scale analysis (EPA, 2015).

[8] Acceleration noise is measured from speed profiles of individual vehicles and it is often used as a traffic parameter to quantify the interaction between driver, road, and traffic condition. Acceleration noise can be used to study safety because it provides an indication of the smoothness/stability of traffic flow. Traffic conditions with higher acceleration noise indicate higher potential for traffic accidents. Acceleration noise is defined as the standard deviation of acceleration or deceleration (Lee et al., 2013).

speed and standard deviation in the speed reduction area. The chicane had the total lowest average speed, 31.6 km/h, of all TCM considered in the Lee, Joo, Oh, & Choi (2013) study. When compared to the speed limits of 50 km/h, the average speed decreased by approximately 37%. The chicane had the lowest acceleration noise suggesting drivers maintain more uniform speeds when approaching and passing the chicane. However, it generated the highest level of vehicle emissions (23.3 kg/100veh in CO_2 and 1.3 g/100veh in $PM_{2.5}$) among the TMCs studied, because the average speeds were the lowest. On the other hand, the speed variations of chicanes were smaller than on the speed humps, speed tables.

Boulter (2001) also studied the impacts of chicanes. A single lane chicane showed a speed reduction of 11 km/h, being the second with the lowest reduction after the curb extension. The emissions increased by 126% in CO, 72% in HC, 10% in NO_x and 13% in CO_2 (results shown in Table 6). According to this study the chicanes presented lower emissions than speed tables and speed humps.

Table 6 – Expected impacts associated with chicanes.

Speed	• Speed reduction of vehicles. A 8 to 20.9 km/h reductions in the chicanes and 1.6 to 9.7 km/h in the surrounding area (A. B. Silva & Santos, 2011).
Traffic	• Reduction in traffic volumes, with records where the reduction reached 20%(A. B. Silva & Santos, 2011). • Easily negotiable by emergency vehicles (CCL, 2014).
Safety	• Trend to reduce the number of accidents, by approximately 35% (in relation to a speed reduction of 11 km/h), though with increased potential for accidents by screening of vehicles (A. B. Silva & Santos, 2011).
Exhaust Emissions	• Contribute to the increase of pollutant emissions. Can result in more 126% of CO, 72% of HC, 10% of NO_x and 13% of CO_2 emissions (Boulter, 2001; Lee et al., 2013).
Other	• Reduction of the noise level due to lower speeds and traffic volumes (A. B. Silva & Santos, 2011). • Landscape rehabilitation improves street appearance (PennDoT, 2001). • Require loss of on-street parking spaces (PennDoT, 2001).

2.3. Traffic Circles

A study by Ahn & Rakha (2009) evaluates the energy and environmental impact of a selection of traffic calming measures. It firsts characterizes the driver behavior with and without the implementation of TCMs, using portable GPS devices to measure second-by-second in-field driver behavior. Secondly, with a mathematic model (VT-Micro[9]) estimates the fuel consumption and emission levels using the vehicle speed and acceleration measurements from the GPS. The driving data were collected from a road with a speed limit of 40 km/h, containing multiple traffic circles and speed humps, as Figure 28 shows. This case study highlighted the comparisons between untreated intersections and the various traffic calming measures (traffic circles or speed humps). Regarding the traffic circles results, it presented a 34% increase in fuel consumption rates relative to the base case (untreated intersections). Traffic circles also generated 31%, 20%, 56%, and 35% higher HC, CO, NOx, and CO2 emissions, respectively. Speed decreases from 39 km/h at the untreated intersections to 28 km/h at the traffic circles.

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[9] VT-Micro model is a mathematical model that uses second-by-second speed and acceleration measurements as input variables, in order to predicts fuel consumption and emission rates for individual and/or multiple vehicles (Ahn & Rakha, 2009).

The intersections with traffic circles had 62% higher acceleration levels, when compared to intersections without traffic calming measures, suggesting the increase on vehicle fuel consumption and emission rates.

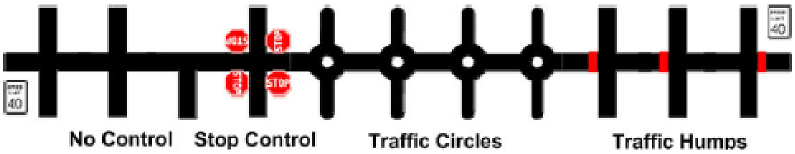


Figure 28 – Key Boulevard. Study corridor from Ahn & Rakha, 2009.

Another paper by Várhelyi *(*2002) analyzed the effects of traffic circles on emissions and fuel consumption using a “car-following” method (the cars were selected randomly and followed with an instrument-equipped vehicle, with the driver trying to imitate the followed vehicles driving pattern) in a before/after implementation approach. The total CO and NO_x emissions and fuel consumption were calculated based on emission and fuel consumption factors corresponding to different levels of speed and acceleration. Replacing signalized intersections with traffic circles made the speeds lower and more even. CO and NO_x emissions and fuel consumption decreased significantly on all approaches, while on the exits they suffered a small increase. The emissions per vehicle decreased 29% for CO, 21% for NO_x and 28% for fuel consumption. At the intersection with yield regulation rebuilt as traffic circles the average speed along their major streets decreased on average 48 to 35 km/h, while on minor streets the average speed increased on average from 17 to 21 km/h. Along major streets of traffic circles replacing yield regulated intersection the CO and NO_x emissions and fuel consumption increased per vehicle (13%, 8% and 8%, respectively). Along the minor streets occurred a decrease on CO, NO_x and fuel consumption per vehicle (20%, 15% and 21% respectively). Considering average traffic volumes, in total, the intersection (with major and minor streets) suffered on average increase by 6% on CO emissions, 4% on NO_x emissions and 3% on fuel consumption. In Várhelyi (2002) one concludes that a traffic circle replacing a signalized intersection results in decrease of CO and NO_x emissions and fuel consumption within the influence area of the intersection. A traffic circle replacing a yield regulation, in general results in a small increase of the total volumes emitted and of fuel consumed, as presented in Table 7 among other expected impacts.

Traffic circles also were studied by Boulter (2001), in a before/after implementation approach. It indicated a speed reduction of 13 km/h. The emissions estimated decreased by 9% in CO, but increased by 21% in HC, 17% in NO_x and 23% in CO_2. The results showed a trend, although weak, of higher impact emissions for vertical deflection measures than to horizontal deflection measures.

2.4. Roundabouts

A paper by Coelho, Farias, & Rouphail (2006) quantified the traffic and emissions impacts of single lane roundabouts on urban areas, based on experimental measurements of traffic and using Vehicle Specific Power (VSP) methodology to estimate emissions (CO, NO_x and HC). The variables used to calculate traffic performance and to conduct the speed profile include the approach traffic volume, its conflating volume and the resulting vehicle dynamics. Two types of stop and go cycles were observed: short (SSG) and long (LSG). Three representative speed profiles were identified: (I) unstopped vehicle approaching the TCM; (II) vehicle experiences one stop, with full deceleration at yield line while waiting for a gap to enter the TCM; (III) vehicle experience multiple stops on the approach queue. The results indicated that the acceleration from zero to cruise speed cause 25% of the total CO emissions (other pollutes show similar patterns). The relative increase of emissions is highest in short stop and go modes and acceleration modes. When queuing occurs with conflicting traffic flow, the emissions generally increase; although when there is no queuing a small increase in CO, NO_x and HC emissions also occur. This can be explained by the acceleration to cruise speed at the TCM exit. If the conflicting traffic flow at the roundabout exit increase the acceleration rate decrease, which positively influences the emission, since higher speed changes contribute to higher emissions. Thus, emissions increased also when there was a large difference between cruise and circulating speed on the TCM area. An increase in cruise speed from 30 km/h to 90 km/h corresponded to an increase in emissions of 677%, 262%, 179% and 88% for CO, NO_x, HC and CO_2, respectively. The deceleration from cruise speed to a stop and then the final acceleration back to cruise speed showed to be especially relevant for CO emissions.

Table 7 presents the expected impacts associated with the implementation of traffic circle and roundabouts.

Table 7 – Expected impacts associated with traffic circle and roundabouts.

Speed	• Speed reduction of vehicles. On average, speeds are reduced from 6.4 to 9.6 km/h (PennDoT, 2001). However, depending on the street intersection case can occur a higher speed reduction (13 km/h) or an increase in speed (4 km/h) (Várhelyi, 2002).
Traffic	• Increased capacity and fluidity. When compared with yield regulated intersections it results in an increase of about 40% on the capacity of the intersection and corresponding reduction in waiting times (A. B. Silva & Santos, 2011). • May make it difficult for emergency vehicles, buses, and trucks to turn left (PennDoT, 2001). • May be inappropriate on major emergency response routes. Emergency service vehicles are delayed by 1 to 11 seconds per traffic circle, with most delays falling between 5 and 8 seconds (PennDoT, 2001).
Safety	• Can significantly reduce motor vehicle collisions, by reducing the number of potential conflict points at an intersection (PennDoT, 2001). Replacing conventional intersections resulted in a reduction of collisions by 39% and 76% in overall accidents and with injuries, respectively. The reduction of accidents with fatalities was over 90% (A. B. Silva & Santos, 2011). • May make pedestrian crossing more confusing at the intersection (Leslie W. Bunte, Jr., 2000).
Exhaust Emissions and Fuel Consumption	• When replacing signalized intersection with traffic circle, the emissions can decrease 29% for CO, 21% for NO_x and 28% for fuel consumption. However, traffic circles replacing yield regulated intersections can suffer an increase by 6% on CO emissions, 4% on NO_x emissions and 3% on fuel consumption (Várhelyi, 2002). According Ahn & Rakha (2009) this increase can be higher (31% for HC, 20% for CO, 56% for NO_x, and 35% for CO_2 emissions). • In general, a potential decrease of exhaust emissions and fuel consumption when replacing a signalized intersection, and an increase when replacing a yield regulated intersection (Várhelyi, 2002).
Other	• Enhances neighborhood appearance when properly landscaped (PennDoT, 2001). • May require removal of some on-street parking (PennDoT, 2001). • A potential reduction in noise levels up to 4 dBA (A. B. Silva & Santos, 2011).

2.5. Speed humps

Ahn & Rakha (2009) also studied speed humps at the intersection area in comparison with untreated intersection. It showed an increase of 53% in fuel consumption, as well as an increase of 51%, 44%, 110%, and 52% in HC, CO, NO_x, and CO_2 emissions, respectively. Results demonstrate that speed humps tend to increase fuel consumption and emissions more than traffic circles, while being more effective in reducing speed. The average intersection speed for speed humps was 27 km/h and acceleration levels were 126% higher when compared to untreated. The data also demonstrates that speed humps increase acceleration levels by 39% when compared to traffic circles. In general, traffic circles allow smoother driving patterns with minor acceleration behavior when compared to speed humps and stop signs.

Lee, Joo, Oh, & Choi (2013) studied speed humps with 3 m long and speed humps with 4 m long. Their speed reduction area was relatively short and approaching speeds dropped more sharply than for speed tables and chicanes. The average speeds were between 40.9 and 41.5 km/h, with an average speed reduction rate of about 18%, which were the lowest between the TCMs in this paper. The speed humps had higher acceleration noise (1.1 m/s^2), suggesting drivers have less uniform speeds when approaching and exiting the speed humps. The estimated emissions of CO_2 and $PM_{2.5}$ were lower for the speed humps than for the other two TCMs (between 22.5 and 22.1 kg/100veh for CO_2 and between 0.93 and 0.90 g/100veh for $PM_{2.5}$). The shorter speed humps lower lead to lower average speeds and higher emissions.

An article by Ghafghazi & Hatzopoulou (2014) used a microscopic traffic simulation and emission modeling system (MOVES) to quantify the effects of different types of traffic calming measures on vehicle emissions (CO_2, CO, and NO_x), as well as traffic volumes and speeds. It had two objectives: capture the effects of TCMs at a localized level where the measure was implemented (link-level analysis) and capture the effects of isolated TCMs and area-wide schemes across the entire network (network-level analysis). Different scenarios were simulated: multiple speed bumps on a street; network wide speed limit of 30 km/k, multiple speed bumps along four streets (area-wide); multiple speed humps along four streets (area-wide); multiple speed bumps along four streets with speed limit of 30 km/k (area-wide) and multiple speed humps along four streets with speed limit of 30 km/k (area-wide). The base case scenario of the network-wide had a speed limit of 50 km/h.

Regarding the network level analysis with the reduction in traffic flow the TCMs decrease the total vehicle kilometers traveled (VKT) in the area under all scenarios compared to the base case (except for speed bumps along the four streets, because vehicles avoided the treated roads which resulted in traveling longer distances). In terms of emissions all scenarios had higher total emissions (g/VKT) with respect to the base case due to the resulting changes in speed. The speed bumps and humps combining lower speed limits along four different streets generate higher emissions on a network level than the TCMs along individual corridors. Both speed humps and bumps lead to higher emissions when combined with lower speed limits, in fact the speed bumps with lower speed limits showed the highest increase in emissions (7.9% for CO_2) on the network level analysis.

The investigation of the link-level effects identified that certain roads experience significant changes in driving patterns and emissions. The link-level evaluations of the multiple speed bumps on a street (isolated measures) presented an increase on total CO_2 emissions along the street by 15 to 81% compared to the base case; while the rest of the network did not experience significant changes. Also, even though the VKT on these links decreases, the CO_2 emissions rates (g/VKT) increase 35–74%, indicating that the increase in emissions is associated with changes in driving patterns. The area-wide TCMs, speed humps and bumps along four different streets, not only increase emissions along treated roads but also worsen emissions across the entire network. Treated streets shift some of the traffic to alternative routes thus worsening their emissions. Speed bumps generated more severe increases in emissions (10–83%) than speed humps (1–38%). The network wide 30 km/k speed limit, speed humps and bumps with lower speed limit increase emissions along most of the roads in the network. The speed bumps with lower speed limit suffered a substantial increase in CO_2 emission rates with respect to the base case scenario, mostly along its treated roads (37–96% change in CO_2 g/VKT). Lowering network-wide speed led to increase of emissions, as vehicles move slower.

In conclusion from Ghafghazi & Hatzopoulou (2014), the total VKT on the network were lower due to the implementation of traffic calming measures, however the network emissions were higher. Both isolated and area-wide measures led to lower increases in network-wide emissions compared to the base case. At link-level, emissions along roads with TCMs and nearby alternative routes increased by up to 83%, indicating that localized air quality impacts are inevitable. Under both isolated and area-wide TCMs, speed bumps produced higher increases in emissions than speed humps.

Other paper by Höglund & Niittymäki (1999) studied TCMs on two specific streets within a central area and a semi-central urban area, with the aim of comparing the exhaust pollution (CO, NO_x, HC and particles) and fuel consumption related to the traffic flow before and after speed humps were implemented. Traffic efficiency performance parameters, such as average speed was analyzed. Two speed limits (50 km/h and 30 km/h) were considered for both streets and also different flow intensities. The methodology used was traffic simulation and calculation of emission associated to single vehicles' driving patterns. Different flow intensities during the day were considered: peak hour traffic, mid-day traffic and low hour intensity. Results showed that different traffic flow conditions at different times of the day and different speed limits with or without TCMs lead to different performances in emissions and fuel consumption. However in general the introduction of TCMs contributed to the increase of exhausts emissions and fuel consumption. Both lower constant speed at 30 km/h and the speed changes between 50-20-50 km/h and 50-0-50 km/h gave considerably higher amounts of emissions and fuel consumption. In most cases the best performance regarding capacity, flow efficiency and air pollution occurred at speed level 50 km/h without TCMs.

Daham et al. (2005) used a road with seven speed cushions distanced from each other by 140 m. However, this road was used to test speed humps, by adapting the driving patterns. The vehicle was slowed down to 16 km/h and then accelerated back to 30-50 km/h in 2nd gear in order to simulate the speed humps. The TCMs were compared to an untreated road with smooth driving patters at a similar average speed of 50 km/h, in order to determine the effect of the speed humps on emissions. A vehicle was used in the study, it was fitted with a portable Fourier Transform Infrared (FTIR) spectrometer, capable of measuring multiple components in real-time on the road. From the results of the untreated road it was possible to observe that a smother trip led to lower overall emissions and that higher CO_2 was emitted for lower average speeds. The results from the road with TCMs showed a peak in emissions corresponding to each speed humps crossed. The results showed an increase in CO_2 (90%), CO (117%), NO_x (195%) and TCH (148%) in comparison to a smooth untreated road.

The speed humps were also studied by Boulter (2001). They indicated a speed reduction of 16 km/h. The emissions estimated increased by 40% in CO, 48% in HC, 22% in NO_x and 32% in CO_2. The speed humps along with speed tables and raised intersection tended to have high overall emissions impacts.

Table 8 presents potential impacts on vehicle speed, traffic, road safety, exhaust emissions and fuel consumption and noise.

Table 8 – Expected impacts associated with speed humps.

Speed	• Slow vehicles down to 24 - 32 km/h at each hump and 40 - 48 km/h in between properly spaced humps. It also can reduce speeds by about 8 km/h in the vicinity of humps (PennDoT, 2001).
Traffic	• Volumes are reduced, on average by about 18% (PennDoT, 2001). • Not recommended for major emergency service routes. 7 m speed humps caused 0 to 9 seconds of delay and 4 m speed humps caused 1 to 9 seconds of delay (PennDoT, 2001). • Negative impact on the wear of buses and other long vehicles (CCL, 2014).
Safety	• Can reduce vehicle conflicts; and lead to an accident reduction up to 50% (if there is a speed reduction of 16 km/h) (Boulter, 2001). • Should not be a problem for cyclists or motorcyclists, except at high speeds (PennDoT, 2001).
Exhaust Emissions and Fuel Consumption	• Some studies show increases around 51% in HC, 44% in CO, 110% in NO_x and 52% in CO_2 emissions, as well as increases around 53% in fuel consumption (Ahn & Rakha, 2009). But, there are other studies that indicate higher emissions (Daham et al., 2005).
	• May increase noise, due to vehicle deceleration and acceleration (CCL, 2014)

2.6. Speed Cushions

Speed cushions were analyzed as well in Ahn & Rakha, 2009. However, in this case, two different streets were involved containing newly installed speed cushions. The GPS driving data were collected before and after their implementation. When vehicles traveled after the implementation of speed cushions, an extra 54% in HC, 47% in CO, 98% in NO_x and 48% in CO_2 were produced and an increase of 48% on fuel consumption was registered, as indicated in Table 9 among other expected impacts. This TCM significantly reduced the average speed by 27% from 46 km/h to 34 km/h.

Boulter (2001) also studied the impacts of two types speed cushions. A speed cushion, 1.7 m wide, indicated a speed reduction of 13 km/h. The estimated emissions increased by 79% in CO, 36% in HC, 19% in NO_x and 32% in CO_2. Another speed cushion, 1.9 m wide, showed a speed reduction of 14 km/h. The estimated emissions increased by 41% in CO, 21% in HC, 6% in NO_x and 15% in CO_2. As mentioned before on the analyses of this work, speed cushions along with curb interventions and chicanes tended to have lower emission impacts.

Table 9 – Expected impacts associated with speed cushion.

Speed	• Reduction travel speed. Can slow vehicles down by 12 - 14 km/h (Ahn & Rakha, 2009; Boulter, 2001).
Traffic	• Reduction in vehicle traffic volumes (A. B. Silva & Santos, 2011). • Allows passage for emergency vehicles, buses or other large vehicles, and bicycles (CCL, 2014).
Safety	• Reducing the number of road accidents. Can contribute to an accident reduction of 40% - 45 % (if there is a to speed reduction of 13 km/h - 14 km/h) (Boulter, 2001).
Exhaust Emissions and Fuel Consumption	• Increases exhaust emissions. Can lead to an extra 54% in HC, 47% in CO, 98% in NO_x and 48% in CO_2, and an increase of 48% in fuel consumption (Ahn & Rakha, 2009). There are other studies that indicated lower emissions (Boulter, 2001).
Other	• May increase noise pollution, due to vehicle deceleration and acceleration (CCL, 2014).

2.7. Speed Tables

The paper by Lee, Joo, Oh, & Choi, 2013 also studied five speed tables. This measure allowed the highest average speed in its speed reduction area, among the speed humps and chicanes analyzed. The approaching speeds were reduced smoothly and kept low at speed tables and chicanes, contrary to the speed humps. The overall average speed was 38.55 km/h (an average reduction around 12 km/h), acceleration noise registered was 1.02 m/s^2 and the estimated emissions of CO_2 and $PM_{2.5}$ were 22.64 kg/100veh and 1.31 g/100veh respectively.

Boulter (2001) studied the impacts of speed tables as well. They resulted in a speed reduction of 16 km/h, like the speed humps. Of all the analyzed measures in this study (curb extensions, chicanes, speed humps, speed cushions, speed tables, traffic circles and raised intersections) only the raised intersection showed higher speed reduction. The estimated emissions increased by 157% in CO, 67% in HC, 42% in NO_x and 32% in CO_2, as mentioned in Table 10. The speed tables tended to have high overall emissions impacts than speed humps, in the Paul Graeme Boulter (2001) study.

Table 10 – Expected impacts associated with speed tables and raised crosswalks.

Speed	• Slow vehicles down to 38 - 48 km/h at the intervention, and approximately 56 km/h in between them (PennDoT, 2001). • Can reduce speeds by around 12 - 16 km/h (Ahn & Rakha, 2009; Boulter, 2001).
Traffic	• Discourage through-traffic. Reduce volume by 12% (PennDoT, 2001). • May be considered for emergency routes, but only after close coordination with emergency service providers. Slows emergency vehicles by 4 to 6 seconds, on average (PennDoT, 2001).
Safety	• Raised crosswalks improve visibility for and of pedestrians. Reducing the number of accidents by 45% (A. B. Silva & Santos, 2011).
Exhaust Emissions and Fuel Consumption	• Generate additional exhaust emissions and fuel consumption from vehicle deceleration and acceleration. Can result in more 157% of CO, 67% of HC, 42% of NO_x and 32% CO_2, according to a study (Boulter, 2001).
Other	• May generate noise from vehicle deceleration and acceleration (PennDoT, 2001). Variations in noise levels with an increase of 6 dBA to 8 dBA (A. B. Silva, Santos, & Seco, 2011) . • Addition of brick or textured materials can improve aesthetics (CCL, 2014).

2.8. Raised Intersection

The article by Boulter (2001) was the only one to analyze raised intersections. They resulted in a speed reduction of 19 km/h, the highest among all studied TCMs on this study. The estimated emissions increased by 75% in CO, 55% in HC, 39% in NO_x and 33% in CO_2, as presented in Table 11, along with other expected impacts. In general, this measure was the one with the worst emissions impacts, relative to speed humps, speed cushions, curb extensions and traffic circles studied.

Table 11 – Expected impacts associated with raised intersection.

Speed	• Reduce vehicle speeds on all approaches. The reduction can possibly go up to 19 km/h (Boulter, 2001).
Traffic	• Can reduce the cut-through traffic (F. N. da Silva & Custódio, 2011). • Result in an average delay of 4 to 6 seconds for emergency vehicles (PennDoT, 2001).
Safety	• Decrease conflicts between vehicles and pedestrians by better demarcating crossing areas and elevating pedestrians above the street (PennDoT, 2001). Can contribute to an accident reduction of 60% (in relation to speed reduction of 19 km/h) (Boulter, 2001). • Alert drivers to the possibility of pedestrians (PennDoT, 2001).
Exhaust Emissions	• Increases air pollution in neighborhood. Can lead an increase by 75% in CO, 55% in HC, 39% in NO_x and 33% in CO_2 (Boulter, 2001).
Other	• If pavement treatments and bulb extensions with landscaping are incorporated, the visual environment will be enhanced (PennDoT, 2001). • Increase in noise if textured pavement is used (CCL, 2014).

2.9. Other Traffic Calming Measures

This section contains a set of tables (Table 12 to Table 22), which present the expected impacts associated with the traffic calming measures that did not have studies regarding fuel consumption and exhaust emissions. The TCMs analyzed are: raised median island, lateral shifts, on-street parking, gateway, textured pavement, continuous sidewalk, diagonal diverter, directional closures, right-in / right-out island, raised median through intersection and full closure.

Table 12 – Expected impacts associated with raised median island.

Speed	• Vehicle speeds can decrease, especially if the median islands make the road narrower. Reductions in speed can range from 1.6 to 8 km/h, with reductions of 3.2 - 4.8 km/h being the most dominant (PennDoT, 2001).
Traffic	• Contribute to the reduction of traffic volumes. The reduction of traffic flow can reach 20%(A. B. Silva & Santos, 2011). • Increase delays imposed on traffic flows, particularly in solutions requiring the reduction of the number of lanes (PennDoT, 2001).
Safety	• Reduce the crossing distance for pedestrians by allowing them to cross half the street at a time (PennDoT, 2001). • Increased visibility of pedestrians (they see and are seen better), reducing the vehicle-pedestrian conflicts. Can reduce the accidents related to pedestrian crossings, from 57% to 82%(A. B. Silva & Santos, 2011). • Separate opposing vehicle travel lanes and prevent passing movements. • Can be used on curves to prevent vehicles from swinging wide at excessive speeds (PennDoT, 2001).
Other	• Can require removal of on-street parking to create room for median (PennDoT, 2001). • Can visually enhance the street if landscaped (PennDoT, 2001).

Table 13 – Expected impacts associated with lateral shifts.

Speed	• Reduce vehicle speeds. Discourage high speeds by forcing horizontal deflection (A. B. Silva & Santos, 2011).
Traffic	• Reduce traffic volumes, but can accommodate higher traffic volumes than many other traffic calming measures (CCL, 2014). • Easy to travel for emergency vehicles (CCL, 2014).
Safety	• Tendency to reduce the number of accidents, though with potential increase in accidents by screening individual vehicle. Drivers may deviate out of the appropriate lane (A. B. Silva & Santos, 2011).
Other	• Reduction of the noise level because of reduced speeds and traffic volumes. • Tendency to reduce the number of parking spaces (A. B. Silva & Santos, 2011). • Can visually enhance the roads and surroundings if landscaped (A. B. Silva & Santos, 2011).

Table 14 – Expected impacts associated with on-street parking.

Speed	• Reduce vehicle speeds, depending on the extent of road width reduction (PennDoT, 2001).
Traffic	• Increase delays imposed on traffic flows, particularly if solutions require the reduction of the number of lanes (PennDoT, 2001).
Safety	• Parked vehicles provide a protection between traffic and pedestrians on sidewalks (PennDoT, 2001). • Can reduce the visibility of pedestrians and vehicles to each other (PennDoT, 2001). • Increased risk to cyclists, when a vehicle door is opened suddenly, hitting them, where the adjacent travel lane is narrow (PennDoT, 2001).

Table 15 – Expected impacts associated with gateways.

Speed	• Reduce entry speed, depending on the inclusion of other measures such as curb extension and median islands (PennDoT, 2001).
Traffic	• Can discourage truck entry, depending on the extent of narrowing and inclusion of median islands at the intersection (PennDoT, 2001).
Safety	• Help identify the neighborhood. Emphasize a change in environment (PennDoT, 2001).
Other	• Create additional streetscape area for landscaping (PennDoT, 2001). • If textured pavements are used some, noise will result (CCL, 2014).

Table 16 – Expected impacts associated with textured pavement.

Speed	• Reduce traffic speed. Adoption of moderate speeds by the drivers (A. B. Silva & Santos, 2011).
Traffic	• Reduce traffic volumes, as many drivers choose alternative routes (A. B. Silva & Santos, 2011).
Safety	• Alert motorists that they are in a pedestrian-friendly area (PennDoT, 2001). • Heavily textured surface may present a traction problem for bicyclists, wheelchairs or disabled persons (PennDoT, 2001). • Increase respect for pedestrians and cyclists (A. B. Silva & Santos, 2011).
Other	• Improve street appearance. Create pleasant spaces and areas, with urban and landscape quality (PennDoT, 2001). • Can increase noise due to the pavement, but the reduction in traffic volumes can lead to a counter reduction of noise (A. B. Silva & Santos, 2011).

Table 17 – Expected impacts associated with continuous sidewalk.

Speed	• Reduce traffic speeds (EPAP, 2014b).
Traffic	• Discourage through-traffic (EPAP, 2014b).
Safety	• When used in combination with other measures, alert motorists to the possible presence of pedestrians (PennDoT, 2001). • Avoid interruptions in the pedestrian route (EPAP, 2014b). • Allow the pedestrian to continuously walk at the same level (EPAP, 2014b). • Create a visual continuity of the pedestrian space (EPAP, 2014b). • Heavily textured surface may present a traction problem for cyclists, wheelchairs or disabled persons (PennDoT, 2001).
Other	• Improve street appearance (PennDoT, 2001). • Can cause noise if applied incorrectly (e.g., excessive slope, inadequate pavement) (EPAP, 2014b).

Table 18 – Expected impacts associated with diagonal diverter.

Speed	• Slight speed reductions may occur within the immediate vicinity of the measure (PennDoT, 2001).
Traffic	• Reduce traffic volumes by 20 to 70% (most reductions are around 35%) (PennDoT, 2001). • Restrict resident access to the neighborhood, increasing distance traveled and time need (CCL, 2014). • Possible increases in traffic volumes in the surrounding streets as a result of search for alternative routes (A. B. Silva & Santos, 2011).
Safety	• Reduce crash potential by eliminating conflicting traffic movements (PennDoT, 2001). • Increased safety of pedestrians at crosswalks located on the intersection area (A. B. Silva & Santos, 2011).
Other	• Can enhance visual environment when landscaped (PennDoT, 2001).

Table 19 – Expected impacts associated with directional closures.

Speed	• Lower travel speed around the intersection. Speeds can be reduced from 3.2 to 8 km/h (PennDoT, 2001).
Traffic	• Expected to reduce traffic volumes by at least 40%. However, volume reductions up to 60% are common (PennDoT, 2001). • Reduce cut-through traffic without restricting bicycle and pedestrian access. • Restrict resident access to the neighborhood (CCL, 2014). • Traffic shift to alternative routes, resulting in worsening traffic conditions in adjacent streets (A. B. Silva & Santos, 2011). • Permit emergency vehicles to go around them in the wrong direction (PennDoT, 2001).
Safety	• Increase safety of pedestrians at crosswalks located on the intersection area (A. B. Silva & Santos, 2011).
Other	• Can enhance visual environment when landscaped (PennDoT, 2001). • Loss of on-street parking opposite the measure in order to permit emergency vehicle access (PennDoT, 2001).

Table 20 – Expected impacts associated with Right-in / Right-out Island.

Speed	• Little or no impact on speed (PennDoT, 2001).
Traffic	• Reduce cut-through traffic on local streets. May reduce volumes from 20 to 60% (PennDoT, 2001). • Restrict resident access to the neighborhood (CCL, 2014). • Can shift traffic to parallel streets without TCMs (CCL, 2014).
Safety	• Can improve pedestrian safety by providing refuge areas and reducing crossing distances (PennDoT, 2001).
Other	• Can enhance visual environment when landscaped (PennDoT, 2001).

Table 21 – Expected impacts associated with raised median through intersection.

Traffic	• Reduce cut-through traffic. Volumes on the local streets may be reduced by up to 70% (PennDoT, 2001). • Can shift traffic to other locations where left turn opportunities remain (PennDoT, 2001). • Restrict resident access to the neighborhood (CCL, 2014). • Can affect emergency vehicle access and response (PennDoT, 2001).
Safety	• Improve intersection safety by eliminating conflicting movements (PennDoT, 2001).
Other	• Can enhance visual environment when landscaped (PennDoT, 2001).

Table 22 – Expected impacts associated with full closure.

Speed	• Speeds can be reduced, especially if the created dead-end street is less than 120 m in length (PennDoT, 2001).
Traffic	• Reduce cut-through traffic. Volumes may be reduced by 80% or even more (PennDoT, 2001). • Impede emergency service access, unless designed with a special crossable barrier (PennDoT, 2001); • Restrict access for neighborhood residents (CCL, 2014). • Can shift problems elsewhere in large neighborhoods, if strategic pattern of closures is appropriate (PennDoT, 2001).
Other	• Can enhance visual appearance when landscaped (PennDoT, 2001). • Result in loss of on-street parking and/or require the acquisition of property to provide a turnaround area of sufficient diameter (PennDoT, 2001).

2.10. Summary of advantages and disadvantages of TCMs

Advantages of Traffic Calming Measures

In summary, the implementation of traffic calming contributes to:

- Reduce vehicle speed;
- Reduce traffic volumes;
- Discourage through-traffic;
- Improve neighborhood safety especially for residents, pedestrians and cyclists;
- Promote social revalorization of public space;
- Improve travel and utilization conditions of public space;
- Promote local economic activity;
- Reduce conflicts between roadway users;
- Increase compliance with regulatory signs;
- Reduce traffic crash frequency and severity;
- Prevent crime by limiting motor vehicle access;
- Reduce environmental aggressions of motorized traffic, by reduction of traffic volume;
- Reduce emissions and noise, contributing to a better environment, by reduction of traffic volume and average speed;
- Landscape rehabilitation of urban space; and
- Reduce fuel consumption by increasing energy efficiency.

Disadvantages of Traffic Calming Measures

In summary, the disadvantages potentially created or caused by traffic calming measures:

- Increase in emergency vehicle response time;
- Difficulties to getting in and out of the neighborhoods on a daily basis;
- Result in expensive solutions (time and resources);
- Shifting or diverting traffic onto neighboring roadways;
- Increase maintenance time and costs;
- Add visually unattractive warning signs to a residential area;
- Reduce car parking space;
- Splinter neighborhood with strong ‘for and against’ traffic calming opinions; and
- Increase of pollutant emissions and noise.

Table 23 summarizes the studies where speed, exhaust emissions and/or fuel consumption were assessed, considering the implementation of traffic calming measures. It presents the authors, methodology adopted, approached of comparisons and the major results for each study.

Table 23 – Change results of speed, exhaust emissions and fuel consumption from studies concerning the implementation of traffic calming measures.

Author	Measure	Methodology	Approach of comparison	Results
Ahn & Rakha, (2009)	Traffic Circle	Second-by-second GPS field data were collected at three different sites with different traffic calming measures, used in combination with microscopic emission models to estimate the energy and environmental impact (CO_2, CO, NO_x and HC emissions) of a selection of TCM. The traffic circles, speed humps, stop signs and speed cushions were located on roads with a 40 km/h speed limit, while the speed bumps were at a road with a 25 km/h speed limit.	Untreated intersection vs. treated intersection	28% decrease in speed (39 km/h – 28 km/h) 34% increase in fuel consumption 35% increase in CO_2 20% increase in CO 56% increase in NO_x 31% increase in HC
	Speed Humps			30% decrease in speed (39 km/h – 27 km/h) 53% increase in fuel consumption 52% increase in CO_2 44% increase in CO 110% increase in NO_x 51% increase in HC
	Stop Sign			41% decrease in speed (39 km/h - 23 km/h) 114% increase in fuel consumption 112% increase in CO_2 145% increase in CO 264% increase in NO_x 125% increase in HC
	Speed Cushion		Original before vs. after	27% decrease in speed (46 km/h – 34 km/h) 48% increase in fuel consumption (0.008 – 0.012 l/100m) 48% increase in CO_2 (27.0 – 39.9 kg/100m) 47% increase in CO (157.6 – 232.3 kg/100m) 98% increase in NO_x (24.3 – 48.2 g/100m) 54% increase in HC (10.0 – 15.4 g/100m)
	Speed Bumps			17% decrease in speed (55 km/h to 48 km/h) 25% increase in fuel consumption (0.009 – 0.011 l/100m) 29% increase in CO_2 (28.7 – 37.0 kg/100m) 9% increase in CO (114.3 – 124.9 g/100m) 19% increase in NO_x (16.6 – 19.8 g/100m) 20% increase in HC (11.2 – 13.4 g/100m)
Lee et al., (2013)	Speed Humps	A field experiment using probe vehicles equipped with GPS devices was conducted to obtain vehicle trajectory data for use in more realistic simulations. A vehicle emissions model was used for the evaluation of environmental and public health impacts. The speed limit of the road was 50 km/h.	Between TCMs selected	- Lowest speed reduction, about 18%. Average speed was 40.78 and 41.51 km/h for scenarios 1 and 2; - Highest acceleration noise (1.09 m/s^2); - Lowest CO_2 and $PM_{2.5}$. They were 22.46 and 22.07 kg /100veh for CO_2 on scenario 1 and 2 respectively, and 0.93 and 0.90 g/100veh for $PM_{2.5}$ on scenario 1 and 2 respectively.
	Speed Table			- Average speed was 38.55 km/h (about 23%); - Acceleration noise was 1.02 m/s^2; - Average CO_2 and $PM_{2.5}$ were 22.64 kg/100veh and 1.02 g /100veh.
	Chicanes			-Highest speed reduction, about 37%. Average speed was 31.6 km/h; - Lowest acceleration noise (0.77 m/s^2); - Highest CO_2 and $PM_{2.5}$ emissions. They were 23.29 kg/100veh and 1.31 g /100veh.
Coelho et al., (2006)	Roundabout	The traffic and emission impacts of single lane roundabouts were quantified, based on experimental measurements of traffic and using the ''Vehicle Specific Power'' emission estimation methodology.	Different conflicting traffic flows and cruise speed conditions	-Conflicting traffic flow: 1 vph – 300 vph – 600 vph CO_2 90000 – 110000 – 210000 g/h CO 700 – 500 – 950 g/h NO_x 60 – 65 – 110 g/h HC 20 – 25 – 60 g/h -Cruise speed: 30 km/h – 60 km/h – 90 km/h CO_2 20000 – 30000 – 150000 g/h CO 1150 – 1500 – 2200 g/h NO_x 40 – 65 – 150 g/h HC 15 – 20 – 40 g/h (Approximated values. Taken from graphics)

Author	Measure	Methodology	Approach of comparison	Results
Ghafghazi & Hatzopoulou, (2014)	Speed Humps	The effects of isolated traffic calming measures at a corridor level and area-wide calming schemes are estimated with respect to traffic volumes, speeds, and emissions (CO_2, CO, and NO_x) using microscopic traffic simulation and emission modeling. A total of eight different traffic calming scenarios including isolated measures and network-wide measures were identified and simulated. The base case scenario represents a network-wide speed limit of 50 km/h.	Base case vs. scenario on network level evaluation	Total instantaneous air pollutant emissions and total VKT -Speed humps (area-wide): 1.1% increase in CO_2 – 2.83 ton (base case 2.80 ton) 1.7% decrease in CO – 49.51 kg (base case 50.35 kg) 1.4% increase in NO_x – 3.62 kg (base case 3.57 kg) VKT – 9733 -Speed humps (area-wide and lower speed limit): 1.4% increase in CO_2 – 2.84 ton 0.4% decrease in CO – 50.13 kg 1.1% decrease in NO_x – 3.53 kg VKT – 9683
	Speed Bumps			Total instantaneous air pollutant emissions and total VKT -Speed bumps (three individual corridors): 1.1% increase in CO_2 – 2.82, 2.84 and 2.85 ton 0.04% increase in CO – 50.45; 50.51 and 50.16 kg 0.8% increase in NO_x – 3.60; 3.62 and 3.61 kg VKT – 9690, 9744 and 9739 -Speed bumps (area-wide): 6.4% increase in CO_2 – 2.98 ton 1.6% increase in CO – 51.15 kg 5.9% increase in NO_x – 3.78 kg VKT – 9775 -Speed bumps (area-wide and lower speed limit): 7.9% increase in CO_2 – 3.02 ton 4.5% increase in CO – 52.63 kg 4.8% increase in NO_x – 3.74 kg VKT – 9691
	Speed Limits			Total instantaneous air pollutant emissions and total VKT -speed limit (area-wide): 1.4% increase in CO_2 – 2.84 ton 0.6% increase in CO – 50.66 kg 1.1% decrease in NO_x – 3.53 kg VKT – 9738
Boulter, (2001)	Curb Extensions	Study the impacts of multiple traffic calming measures on exhaust emissions. For each of the TCMs driving cycles to represent vehicles operation before and after their implementation were formulated. The emissions were measured from vehicles on a chassis dynamometer using the cycles.	Before vs. after	Speed reduction of 8 km/h 14% increase in CO_2 39% increase in CO 9% increase in NO_x 35% increase in HC
	Chicanes			Speed reduction of 11 km/h 13% increase in CO_2 126% increase in CO 10% increase in NO_x 72% increase in HC
	Speed Humps			Speed reduction of 16 km/h 32% increase in CO_2 40% increase in CO 22% increase in NO_x 48% increase in HC
	Speed Cushions			Speed reduction of 13-14 km/h 15-20% increase in CO_2 41-79% increase in CO 7-19% increase in NO_x 21-36% increase in HC
	Speed Tables			Speed reduction of 16 km/h 32% increase in CO_2 157% increase in CO 42% increase in NO_x 67% increase in HC

Author	Measure	Methodology	Approach of comparison	Results
	Traffic Circles			Speed reduction of 13 km/h 20% increase in CO_2 9% decrease in CO 17% increase in NO_x 23% increase in HC
	Raised Intersections			Speed reduction of 19 km/h 33% increase in CO_2 75% increase in CO 39% increase in NO_x 55% increase in HC
	Total with all			-Petrol non-catalyst: 20% increase in CO_2 (116 – 139 g/km) 34% increase in CO (13.9 – 18.5 g/km) 1% increase in NO_x (1.08 – 1.08 g/km) 50% increase in HC (1.52 – 2.28 g/km) -Petrol catalyst: 26% increase in CO_2 (132 – 167 g/km) 59% increase in CO (3.95 – 6.26 g/km) 8% increase in NO_x (0.09 – 0.09 g/km) 54% increase in HC (0.13 – 0.20 g/km) -Diesel: 26% increase in CO_2 (119 – 150 g/km) 39% increase in CO (0.61 – 0.84 g/km) 28% increase in NO_x (0.53 – 0.68 g/km) 48% increase in HC (0.22– 0.32 g/km) 30% increase in PM (0.10 – 0.13 g/km)
Höglund & Niittymäki, (1999)	Speed Humps	Study traffic calming measures with the aim of comparing the exhaust pollution (CO, NO_x, HC and particles) and fuel consumption The methodology used was traffic simulation and calculation of emissions associated with single vehicles' driving patterns. The emissions results were the total of a certain traffic flow in different times of the day.	Before vs. after	On semi-central street -Speed limit 50 km/h and peak hour: 26% decrease average speed (44.4 – 32.5 km/h) 19% increase in fuel consumption (39.65 – 47.18 l/h) 31% increase in CO emissions (4867.4 – 6418.7 g/h) 26% increase in NO_x emissions (533.0 – 672.1 g/h) 62% increase in HC emissions (827.9 – 1338.5 g/h) -Speed limit 50 km/h and middle traffic intensity: 31% decrease average speed (46.0 – 31.4 km/h) 4% increase in fuel consumption (19.62 – 20.53 l/h) 16% increase in CO emissions (2343.4 – 2735.2 g/h) 1% decrease in NO_x emissions (275.1 – 271.1 g/h) 45% increase in HC emissions (363.4 – 527.7 g/h) -Speed limit 50 km/h and low traffic intensity: 27% decrease average speed (44.8 – 32.3 km/h) 14% increase in fuel consumption (4.40 – 5.00 l/h) 31% increase in CO emissions (517.5 – 682.9 g/h) 18% increase in NO_x emissions (60.9 – 72.3 g/h) 76% increase in HC emissions (74.8 – 131.8 g/h) -Speed limit 30 km/h and peak hour: 1% decrease average speed (22.9 – 22.5 km/h) 3% increase in fuel consumption (54.57 – 56.18 l/h) 0.4% increase in CO emissions (6848.0 – 6878.7 g/h) 5% increase in NO_x emissions (400.4 – 420.9 g/h) 7% increase in HC emissions (1105.5 – 1184.7 g/h)

Author	Measure	Methodology	Approach of comparison	Results
Várhelyi, (2002)	Traffic Circles	The effects of traffic circles on emissions and fuel consumption were evaluated using the "car-following" method in a before/after study. The studies on changes in CO and NO_x emissions and fuel consumption were based on observations of the speed and acceleration of individual passenger vehicles.	Signalized intersection vs. TCM	28% decrease in fuel consumption (505.7 – 361.1 kg/per day) 29% decrease in CO (80.5 – 57.0 kg/per day) 21% decrease in NO_x (8.9 – 7.0 kg/per day)
			Yield regulated intersection vs. TCM	3% increase in fuel consumption (254.6 – 261.4 kg/per day) 6% increase in CO (35.1 – 37.0 kg/per day) 4% increase in NO_x (5.2 – 5.4 kg/per day)
Daham et al., (2005)	Speed Humps	A vehicle was fitted with a portable FTIR spectrometer, capable of measuring multiple components in real-time on the road. The baseline case study was an untreated road with a speed limit of 30 km/h.	Before vs. after	6% decrease in average speed (39.26 – 36.45 km/h) 35% in fuel consumption (79 g/km – 108 g/km) 90% increase in CO_2 (320 – 607 g/km) 117% increase in CO (2.49 – 5.51 g/km) 195% increase in NO_x (1.21 – 3.57 g/km) 148% increase in THC (0.14 – 0.34 g/km)

3. Methodology

This chapter covers the experimental design and techniques used for on-road data collection, including the equipment used and the methodology for analysis of the collected data. The major issues found during the development of the work are addressed.

3.1. Experimental design

A series of experimental on-road tests were designed around the City of Lisbon, taking into consideration the objectives of this work. Consequently, roads that allow an adequate evaluation of vehicle dynamics, energy and environmental impacts of traffic calming measures were selected.

3.1.1. Traffic Calming Measures considered and comparison plan

The experimental test design was carefully studied in order to allow for the comparison of the impacts of traffic calming measures in the case study of Lisbon. Therefore, some of the main variables considered to develop appropriate on-road tests were comparable conditions of:

- Speed limits;
- Topography;
- Construction and surroundings (site conditions); and
- Type of road and adjacent roads (local, collector or arterial roads).

When comparing traffic calming measures the traffic problems being addressed, such as speeding and cut-through traffic, were taken into account along with the variables mentioned before (PennDoT, 2001). The selection of traffic calming measures was based on all these previous conditions.

Consequently, comparison cases were created for the development of the experimental test plan. On one hand, a comparable road without any traffic calming measures was considered, which was used to assess the impacts of their implementation, in a hypothetical “before” approach. On the other hand, an “after” approach considering the measures already installed, with the selection of the specific equivalent street to evaluate the impacts of the traffic calming measure. As a result, each street with traffic calming measures had a comparison base.

To ensure a proper test plan and a fair assessment between different measures or between measures and a comparable road without measures, the variables considered should remain similar. For instance, comparison between intersection barriers and street closures is more adequate than with speed humps, since their typical use is to reduce unwanted through traffic, while the typical use of the speed humps is to slow vehicles down to a safe speed at or below the speed limit. The slope of the road, the type of road and the driving speed were the main variables involved in the choice of the comparison cases.

If the distance between traffic calming measures is not enough, the previous calming measures may influence driving behavior on the next measures (Lee, Joo, Oh, & Choi, 2013). To solve this issue, moments of deceleration after passing traffic calming measures must be ignored.

3.1.2. Locations

Lisbon Case Studies

The Municipality of Lisbon considers that road environment has an influence on the behavior of pedestrians and drivers, which is a relevant factor on road safety. Reducing speed has been a priority to the municipality authorities, since it is the most effective way to reduce the number of pedestrian accidents and their severity. It was essential to intervene in the road network of the city. Traffic calming measures are the best way to achieve these objectives and also have the advantage of reducing the cut-through traffic, considered to be faster and more dangerous (Equipa do Plano de Acessibilidade Pedonal, 2014).

Several areas had already suffered intervention when this thesis started, while others were planned to have TCMs implemented during and after this work. The areas in analysis were chosen after an in-depth study of the multiple options in the city of Lisbon. The study was based on information provided by the Lisbon Municipality that included the locations of the 30 km/h Zones implemented and the traffic calming measures constructed on them, along with other locations where TCMs were implemented in different contexts. Additionally, information on areas that were going to suffer interventions in the future was also provided; however, they were not implemented in time to be included and analyzed in this work. As part of the in-depth study, field trips to multiple areas were also conducted, in order to better evaluate local conditions and identify the TCMs that best allow for comparison and evaluation of the impacts that will be studied. This way, the TCMs were chosen according with their availability and adequateness in the city, with the purpose of covering a wide range of TCMs and fulfill the constraints regarding comparable conditions over a set of variables. The areas selected to carry the on-road tests were: Arco do Cego, Alvalade and Parque das Nações. The TCMs were chosen to allow the collection of representative samples, reflecting their influence on vehicle dynamics, fuel consumption and exhaust emissions impacts, according to their characteristics and local conditions.

The specific traffic calming measures and respective comparable road without intervention chosen were:

- TCM-A-1: Speed Table of Arco do Cego;
- TCM-A-2: Textured Pavement of Arco do Cego;
- TCM-A-3.3: Continuous Sidewalk of Arco do Cego (3rd intersection);
- TCM-A-3.4: Continuous Sidewalk of Arco do Cego (4th intersection);
- TCM-A-3.7: Continuous Sidewalk of Arco do Cego (7th intersection);
- TCM-B-1: Speed Tables of Alvalade;
- TCM-C-1: Speed Tables of Parque das Nações;
- TCM-C-4: Speed Humps of Parque das Nações;
- UR-A-(1,2): Untreated Road for Arco do Cego;
- UR-A-3.3: Untreated Intersection for Arco do Cego (3rd intersection);
- UR-A-3.4: Untreated Intersection for Arco do Cego (4th intersection);
- UR-A-3.7: Untreated Intersection for Arco do Cego (7th intersection);
- UR-C: Untreated Road for Parque das Nações;

These traffic calming measures and respective comparable road without intervention are briefly described next.

Arco do Cego Neighborhood

The Arco do Cego neighborhood located in the center of Lisbon, between Saldanha, Campo Pequeno, Av. da Republica and Praça de Londres, is characterized by housings with 2 or 3 floors and narrow streets with one-way lanes. The area was intervened and transformed into a 30 km/h Zone with several traffic calming measures. For this work, the selected measures a speed table, textured pavement and three continuous sidewalks, which originate different vehicle performances, as presented in the Figure 29.

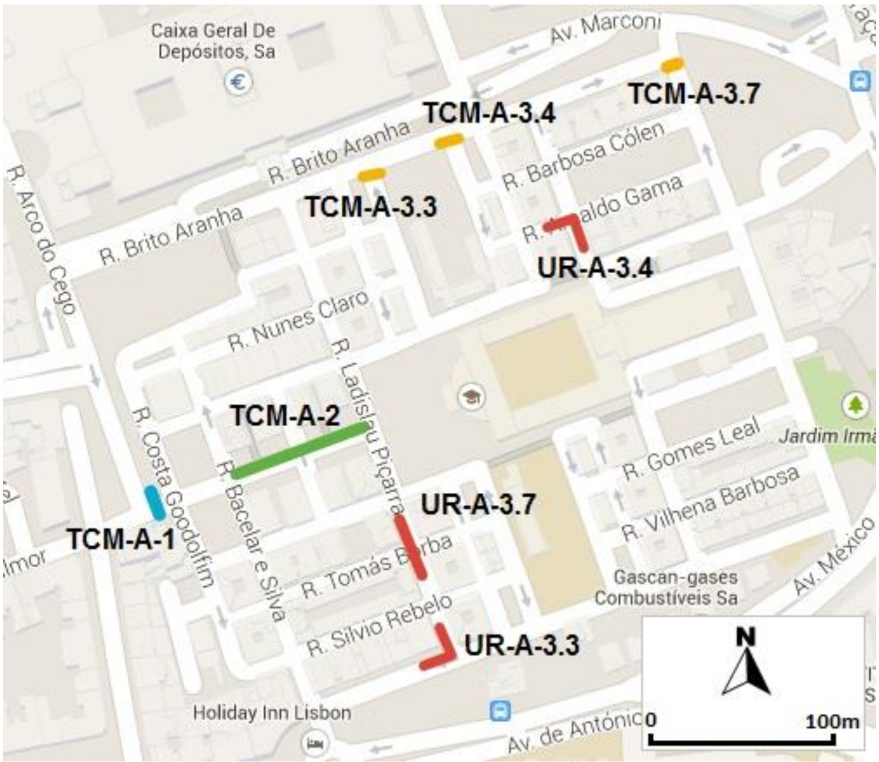


Figure 29 – Map of the Arco do Cego Neighborhood with the cases of study indicated. The red line represent the untreated sections, the blue the speed tables (TCM-A-1), the green the textured pavement (TCM-A-2) and the yellow the continuous sidewalk (TCM-A-3.3, TCM-A-3.4 and TCM-A-3.7) (adapted from Google Maps).

Speed Table (TCM-A-1) – The measure, built of asphaltic concrete, is used as a raised pedestrian crosswalk, similarly to other speed tables studied in this work. It is located at one of the entrances of the neighborhood on Avenida Visconde Valmor, as shown in the Figure 30.

Textured Pavement (TCM-A-2) – The road, built with concrete blocks, is raised to the height of the surrounding curb and has around 75 m in length. It is located on Avenida Magalhães Lima, which gives access to the Escola Secundária Dona Filipa de Lencastre. Figure 32 presents this measure.

Continuous Sidewalks – The measures are built in the same material as the sidewalk (Portuguese stone pavement) and are also used as a raised pedestrian crosswalk. They are located at the border of the neighborhood with connection to Rua Brito Aranha:

- TCM-A-3.3 – Third intersection with an exit on the neighborhood north side (from Campo Pequeno side). Intersection in the street Rua Stuart Carvalhais going uphill with a right turn;

- TCM-A-3.4 – Forth intersection with an entrance on the neighborhood north side. Right turn to the Rua José Sarmento with the road going downhill; and
- TCM-A-3.7 – Seventh intersection with an exit on the neighborhood north side. Interception in Rua Brás Pacheco going uphill, as presented on Figure 31.

Figure 30 – TCM-A-1: Speed Table of Arco do Cego.

Figure 31 – TCM-A-3.7: Continuous Sidewalks of Arco do Cego (7th intersection).

Figure 32 – TCM-A-2: Textured Pavements of Arco do Cego.

For each of the traffic calming measure an equivalent untreated road was selected, for “before” and “after” comparison purposes. The untreated road represents a “before” situation, without intervention, allowing for the evaluation of the intervention’s influence in the area. The comparison corridor for the speed table and textured pavements was a street outside of the Arco do Cego neighbourhood, because even though the area seemed to have comparable roads, data showed that the length of the blocks was too short and the deteriorated condition of the road pavement did not allow for a representative performance of the vehicle. The chosen street was Av. Sacadura Cabral, between Praça do Campo Pequeno and Avenida de Roma, as indicated in Figure 33. Even though Av. Sacadura Cabral has two directions, the lanes are separated by an area of car parking, creating narrow and individual lanes more suitable for comparison, as the Figure 34 demonstrate. The Av. Sacadura Cabral and the roads with speed table and textured pavement have identical road slope and road lane width, with vehicles parked on both sides. Speed limit from before the intervention was the same and the measurements were always performed under off-peak traffic conditions.

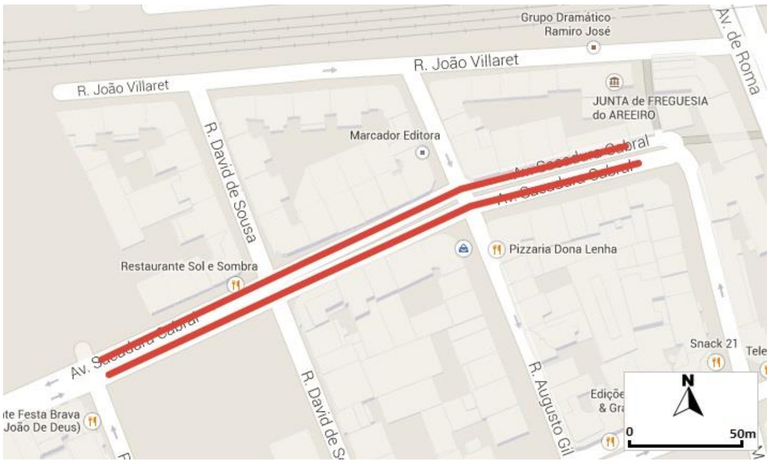


Figure 33 – Map indicating the two separated lanes of Av. Sacadura Cabral, UR-A-(1,2) (adapted from Google Maps).

Figure 34 – UR-A-(1,2): Untreated Road for Arco do Cego, on Av. Sacadura Cabral (adapted from Google Maps)

Three intersections in the Arco do Cego neighbourhood were selected to do the comparison with the continuous sidewalks:

- UR-A-3.3 - Intersection between the streets Rua Ladislau Piçarra and Rua Xavier Cordeiro, to compare with the third treated intersection on the neighborhood north side (TCM-A-3.3);
- UR-A-3.4 - Intersection between the streets Rua Arnaldo Gama and Rua Bernardo Pessoa, to compare with the forth treated intersection on the neighborhood north side (TCM-A-3.4); and
- UR-A-3.7 - Intersection between the streets Rua Ladislau Piçarra and Rua Tomás Borba, to compare with the seventh treated intersection on the neighborhood north side (TCM-A-3.7).

Each pair of comparison intersection (without TCMs) and intersection with continuous sidewalk has similar road slope characteristics and road width, with one lane and one direction.

Alvalade Neighbourhood

The Alvalade Sul/Poente neighbourhood, converted as well into a 30 km/h Zone, belongs to the central zone of Lisbon. It consists mainly of residential buildings with 3 to 4 floors, but also commercial spaces. The analysed street was the one-way lane going uphill in Rua António Patrício with two speed tables (TCM-B-1). The measures made of asphaltic concrete are separated by approximately 80 m. Figure 35 shows one of the speed tables studied.

Figure 35 – One of the Alvalade neighborhood speed tables, TCM-B-1.

Parque das Nações

The Via do Oriente near Parque das Nações is a street of about 1 km with two lanes in each direction, where the speed limit is 50 km/h. Throughout the route on both sides there are multiple speed humps and speed tables, separated roughly by 120 m, and made of asphaltic concrete, as the Figure 36 indicates. Located outside of the city center, it is a residential area with apartment buildings, commercial spaces and some still unconstructed lots. Two speed tables, also used as crosswalks (Figure 37), and five speed humps (Figure 38) were selected for study.

Figure 36 – Map indicating the measures in Via do Oriente. The blue lines represent the speed tables (TCM-C-1) and the purple lines the speed humps (TCM-C-4) (adapted from Google Maps).

Figure 37 – One of the speed tables on Parque das Nações road, TCM-C-1.

Figure 38 – One of the speed humps on Parque das Nações road, TCM-C-4.

The comparison road (without TCMs) for this site was the nearby Alameda dos Oceanos, presented in Figure 39. Both measures were compared with each other and quantification was performed. The Alameda dos Oceanos and the road with speed table and speed humps have identical road slope and road width with two lanes in each direction. Speed limit was the same and the measurements were always performed under off-peak traffic conditions. The roads selected in Parque das Nações have two lanes, unlike those selected in the Arco do Cego and Alvalade sites.

Figure 39 – UR-C: Untreated Road for Parque das Nações, on Alameda dos Oceanos (adapted from Google Maps).

Despite the best efforts, in collaboration with Lisbon Municipality, it has not possible to find roads in which the TCMs were not implemented, but were going to be in time to allow performing measurements before and after their construction. Thus it was only possible to study cases with equivalent untreated roads. The untreated roads used were carefully selected, and were the most appropriate found in the city of Lisbon. Their results were considered adequate to do the most realistic comparison possible. Nevertheless, it has to be noted that they are not the original roads without interventions, and they may contribute to less accurate results and therefore affect their validity, than a possible case with the original road. This can happen due to slight differences between the characteristics of the untreated road considered and the original road without the TCM.

3.1.3. Comparative Plan

For the purpose of this thesis, the comparison of the traffic calming measures with each other and with the roads without intervention was performed, according to the following plan:

- The corridors with measures were compared with an 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 were compared with each other.

Table 24 presents a schematic summary of the comparison cases developed for the comparative plan. Each line of the table is a comparison case.

Table 24 – Comparative plan summary.

<table>
<tr><th colspan="30">Comparison with Untreated road or Intersection</th></tr>
<tr><td colspan="15">TCM-A-1 Speed Table Arco do Cego
TCM-A-2: Textured Pavement of Arco do Cego</td><td colspan="15">UR-A-(1,2): Untreated road for Arco do Cego;</td></tr>
<tr><td colspan="15">TCM-A-3.3: Continuous Sidewalk of Arco do Cego (3rd intersection);</td><td colspan="15">UR-A-3.3: Untreated Intersection for Arco do Cego (3rd intersection);</td></tr>
<tr><td colspan="15">TCM-A-3.4: Continuous Sidewalk of Arco do Cego (4th intersection)</td><td colspan="15">UR-A-3.4: Untreated Intersection for Arco do Cego (4th intersection);</td></tr>
<tr><td colspan="15">TCM-A-3.7: Continuous Sidewalk of Arco do Cego (7th intersection)</td><td colspan="15">UR-A-3.7: Untreated Intersection for Arco do Cego (7th intersection);</td></tr>
<tr><td colspan="15">TCM-C-1: Speed Tables of Parque das Nações
TCM-C-4: Speed Humps of Parque das Nações</td><td colspan="15">UR-C: Untreated Road for Parque das Nações;</td></tr>
<tr><th colspan="30">Comparison within Arco do Cego Neighborhood</th></tr>
<tr><td colspan="6">TCM-A-1: Speed Table of Arco do Cego</td><td colspan="6">TCM-A-2: Textured Pavement of Arco do Cego</td><td colspan="6">TCM-A-3.3: Continuous Sidewalk of Arco do Cego (3rd intersection)</td><td colspan="6">TCM-A-3.4: Continuous Sidewalk of Arco do Cego (4th intersection)</td><td colspan="6">TCM-A-3.7: Continuous Sidewalk of Arco do Cego (7th intersection)</td></tr>
<tr><th colspan="30">Comparison within Parque da Nações Area</th></tr>
<tr><td colspan="15">TCM-C-1: Speed Tables of Parque das Nações</td><td colspan="15">TCM-C-4: Speed Humps of Parque das Nações</td></tr>
<tr><th colspan="30">Comparison between Speed Tables</th></tr>
<tr><td colspan="10">TCM-A-1: Speed Table of Arco do Cego</td><td colspan="10">TCM-B-1: Speed Tables of Alvalade</td><td colspan="10">TCM-C-1: Speed Tables of Parque das Nações</td></tr>
</table>

3.1.4. Measurements Plan

Selecting the sample in the right way and learning about its parameters is essential to provide reliable information. By increasing the sample size (in terms of monitored time for each measure) the amount of information collected increases, thus the question "How many measurements should be included in the sample?" must be considered, because sampling can become too expensive and too time consuming to perform.

In a statistical estimation problem, the accuracy of the estimate is measured by the margin of error or the width of the confidence interval, both of which have a specified reliability. Since both of these measures are a function of the sample size, specifying the reliability and accuracy allows for determining the necessary sample size.

If the standard deviation of the sampled population (σ) is unknown, it can be approximated by the sample standard deviation (s) when the sample size is large (n ≥ 30) (Mendenhall, Beaver, & Beaver, 2013). Using the equation below the sample size is obtained:

$$n = \left(\frac{z_{\alpha/2} \times s}{\varepsilon \times \bar{x}}\right)^2 \qquad \text{[Eq. 1]}$$

where,
s – Sample standard deviation;
ε – Margin error percentage;
$\bar{x}$ – Sample mean;
$z_{\alpha/2}$ – z-value corresponding to an area α/2 in the upper tail of a standard normal z distribution.

Table 25 – Values of $Z_{\alpha/2}$ (Mendenhall et al., 2013).

Confidence Level (1-α)	$Z_{\alpha/2}$
80%	1.28
95%	1.96

The calculation of the sample size was performed to obtain the number or crossings necessary to be performed, in order to achieve a certain statistic representatively. **Error! Not a valid bookmark self-reference.** shows the number of data seconds collected for each traffic calming measure, the corresponding number of crossings and the reached combination of confidence level and margin of error of each case study section.

To find the number of necessary measurements to achieve a representative sample, Equation 1 was used individually on multiple variables of each case study. Then, by identifying which variables were more relevant to the study, the choice of the sample size was based on those. The main variables for the purpose of this work were: tailpipe emitted gases (CO_2, CO and NO_x) and fuel consumption. CO always required a very high number of seconds measured, making it difficult to satisfy the necessary amount of crossings with the statistical confidence desired. As a result, it wasn't considered. Speed, rpm and calculated load were also studied and satisfied within the confidence level and margin of error chosen for the most relevant variables. In the end, the choice was based on the variable that required higher number of seconds, which in most cases was NO_x. The case studies with the sample that allowed for higher statistical representativeness were TCM-C-4 and also its comparative untreated road (UR-C). On the other hand, the sample of TCM-A-3.4 was the one with lower representativeness.

Table 26 – 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%.

3.2. Data Collection Methodology

The data was collected using a vehicle equipped with the adequate equipment to measure a number of variables necessary to achieve the objectives of the work. The monitoring of the trips was performed by three people: the driver, a person operating the computer and registering specific events during the trip and another person to assemble the equipment on the vehicle and ensure, in real-time, the proper behavior of the equipment installed.

Drivers can have different behaviors when crossing a TCMs, which leads to different patterns of vehicles operations and consequently influences the fuel consumption and exhaust emissions of the vehicle. Therefore, including multiple drivers in the on-road measurements can contribute to increase the validity of the data. However, in this work, the vehicle was driven just by one driver throughout the experimental plan measurements, as suggested by other studies such as Frey, Unal, & Chen (2002), Holmén, Robinson, Sentoff, & Montane (2010) and Duarte (2013), and due to time constraints. This question is addressed as future work.

Table 27 presents the more relevant details of the vehicle and its emissions and fuel consumption. This vehicle within the European M1 standards meets the Euro 4 emission limits with CO emissions of 0.284 g/km and NO_x of 0.245 g/km, along with 124 g/km of CO_2. The urban fuel consumption is 5.8 l/100km (VCA, 2015).

Table 27 – Main characteristics of the vehicle.(VCA, 2015)

Vehicle details	
Manufacturer	RENAULT
Model	Mégane Sport Tourer
Description	1.5 dCi 106
Engine capacity	1461
Transmission/gearbox	M6
Fuel type	Diesel
Emissions details	
CO_2 Emissions (g/km)	124
CO Emissions (g/km)	0.284
NO_x Emissions (g/km)	0.245
Fuel consumption details	
Urban (l/100km)	5.8

The portable laboratory used consists of an on-board vehicle monitoring device (named I2d) and a tailpipe gas analyzer. The gas analyzer was connected to a laptop, running a software specifically designed for the purpose. The on-board monitoring I2d device collects vehicle data in real-time that is transferred to a cloud service, later downloaded in an Excel file. The most important outputs of this combined monitoring system are engine data, vehicle dynamics, road topography, GPS location, fuel consumption and gas emissions. Some of these parameters are immediately available; others require various different variables to be calculated.

The source of the information and equipment from which outputs were obtained are described next. The main components of the portable laboratory are presented on Figure 40.

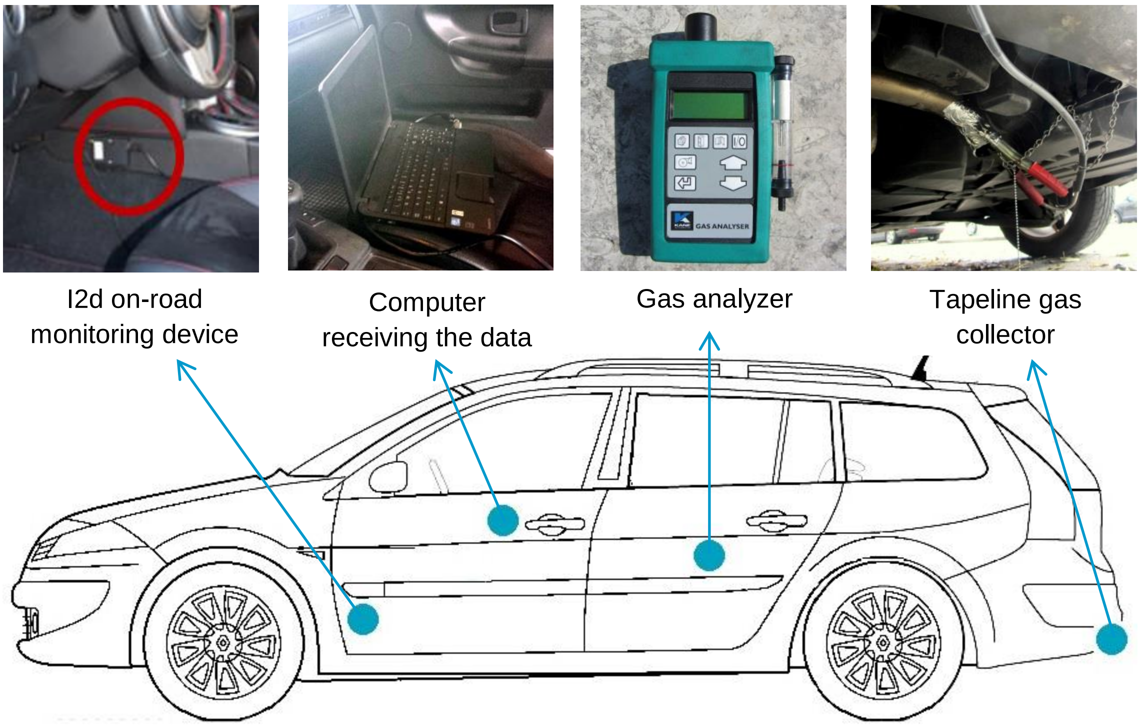


Figure 40 – Main components on the portable laboratory and their installation places.

3.2.1. Vehicle on-road Monitoring: I2d – Intelligence to drive

The I2d (intelligence to drive) device is an experimental tool used for vehicle on-road monitoring, as presented in Figure 41. The I2d device collects, measures and automatically transmits on a second-by-second basis driving data from the vehicle; including driving dynamics (speed and acceleration), engine data (engine load, rpm, mass or air flow, etc.) and road topography. With specific dedicated sensors such as GPS, barometric altimeter, tri-axial accelerometer and access to vehicle sensors via an OBD (On Board Diagnostics) port, the I2d provides a non-intrusive system that monitors all the main variables that characterize vehicle usage. (Baptista, Duarte, Gonçalves, & Rolim, 2014)

The OBD data communication port provides self-diagnostic functionalities, alerting for potential problems that can affect emission control systems. Since 1 January 2001 it became mandatory for light duty vehicles equipped with a positive-ignition engine and since 1 January 2004 for the registration of new vehicles equipped with a compression-ignition engine (Tsinoglou, Mellios, Xanthopoulos, Koltsakis, & Iakovou, 2005). The OBD interface can be used to obtain several operating parameters from the engine: rpm, calculated load, air flow and manifold air pressure. Accuracy is mainly related to the correct operation of vehicle sensors, such that errors and time delays of readings can occur due to malfunction of these sensors.

The GPS receiver provides information about positioning and speed along with the barometric altimeter and tri-axial accelerometer data. The relatively small time delay required to adjust to pressure variation (namely in inflexion points of the road) is the main source of errors on the barometric altimeter data. To solve this situation, an averaging and smoothing of the road grade was performed (Gonçalves, 2009; Duarte, 2013).

For the purpose of this work the most relevant variables acquired with the device were:

- Vehicle dynamics: distance travelled, speed and accelerations
- Engine operations: rpm, engine load, air flow; and
- Road topography and GPS location.

Figure 41 – The I2d (intelligence to drive) device (Baptista et al., 2014)

3.2.2. Gas analyzer

The tailpipe emissions were measured in a second-by-second basis with the Kane Auto 5-1 gas analyzer, which determines the concentrations of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). The analyzer is frequently calibrated and zeroing is done at each start and as requested during the measurements.

The gas analyzer has a significant response delay for each gas due to the sensors used and the length of the tube between the tailpipe probe and analyzer. This delay was considered constant independently of the engine load and rpm, and taken into consideration when synchronizing the data (Duarte, 2013).

The concentrations measured were permanently displayed on the analyzer, which was connected to a computer running the Lab-View software, allowing to verify whether the data was being sent correctly.

Table 28 – Main characteristics of the Kane Auto 5-1 gas analyzer (Keison Products, 2015).

Gas	Range	Resolution	Accuracy	Accuracy Volume
O_2	0-21%	0.01%	+-5%	+-0.1%
CO_2	0-16%	0.1%	+-5%	+-0.5%
CO	0-10%	0.01%	+-5%	+-0.06%
HC	0-5000ppm	1ppm	+-5%	+-12ppm
NO_x	0-5000ppm	1ppm	+-4%	0-4000ppm

Figure 42 – Gas analyzer.

Figure 43 – Connection of the gas collecting tube to the tailpipe.

Figure 44 – Placement of the gas collecting tube between the tailpipe and the gas analyzer in the vehicle.

3.3. Data Analysis Methodology

The collected data from the multiple equipments was exported to Excel spreadsheets. Initially, time synchronization was made, since the various data sources had different clock times. To solve this problem a “marking” procedure before each trip was necessary: at the beginning of the on-road measurement, with the vehicle stopped (but running), while writing a reference point with a mark on the Lab-View software collecting gas analyzer data, the driver pushed the throttle pedal simultaneously producing a reference point in the I2d data with speed and rpm. This procedure was also helpful to identify the time difference between I2d and gas analyzer data. There was also a delay on the data delivered by the gas analyzer due to the distance traveled by the gases in the tube between the tailpipe and the device, to correct this situation some bench tests were made. Additionally, tests relating the vehicle engine data (rpm and calculated load) with the emitted gases were performed to find the amount of seconds the two sets of data had in discrepancy. Each emitted gas had a unique time delay that was considered equal in all measurements.

Some of the variables could then be obtained directly, such as coordinates (latitude and longitude), speed, engine load, rpm, air flow, manifold air pressure (MAP), tri-axial accelerations, road grade. Others, as is 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. Acceleration is obtained from vehicle speed, and distance traveled in each case study section also is calculated from speed.

The GPS coordinates were particularly important in the work, since they were used to identify and isolate the studied sections and its traffic calming measures from all the information recorded during the trips. For each section the distance traveled was calculated and in the cases of the TCM sections portions of approximately 20 m before and after the measures was selected.

Vehicle Specific Power - VSP

It can become difficult to correlate specific diving events with emissions and compare the vehicle performance over different traffic calming measures as well as driving behaviors, due to the variability of driving conditions. Considering that there are several factors involved that characterize the vehicle behavior and its energy and environmental impacts, the VSP methodology was used to provide a simplification of the forces applied to the vehicle.

Vehicle Specific Power (VSP) captures the dependence of emissions on driving conditions and is a good predictor of transient high emissions. An important property of this parameter is that it is particularly suited from on-road measurements. VSP presents an estimate of the power per unit mass for specific driving conditions and can be calculated with good approximation from measurements of vehicle speed, acceleration, road grade and estimates of aerodynamic and rolling resistance (Jimenez-Palacios, 1999).

The equation used to calculate the VSP at each measured second was (Jimenez-Palacios, 1999):

$$VSP = v \cdot (1.1 \cdot a + g \cdot grade + 0.132) + 3.02 \cdot 10^{-4} \cdot v^3 \qquad \text{[Eq. 2]}$$

Where:

- v – Instantaneous speed (m/s);
- a – Acceleration (m/s^2);
- grade – Road Slope;
- g – Acceleration of gravity (9.8 m/s^2);
- 1.1 – Inertial mass;
- 0.132 – Rolling resistance term coefficient;
- 0.000302 – Aerodynamic drag term coefficient.

Pollutant Gases Emissions and Fuel Consumption

The measured gases needed to be converted into mass flow and the fuel consumption need to be calculated, both in grams per seconds. In order to do so, a series of calculations were necessary involving air mass flow (g/s) collected from the vehicle sensor and exhaust gas concentrations collected from the gas analyzer. Another required parameter was the composition of the fuel in terms of carbon and hydrogen, which in this case was diesel. The hydrocarbons (HC) emissions were not considered in this work, due to the very lower values associated with Diesel engines.

In Annex A the procedures used to calculate the mass emissions and fuel consumption are developed further.

With all the variables calculated, the traffic calming measure and untreated road sections were isolated for an independent analysis. Each untreated road sections were studied as a whole, while the sections with traffic calming measures were divided in three segments: the approach area (“Before”), the measure itself (“Measure”) and the exit area (“After”). A global analysis was also made (“Total”), as presented in Table 29. The different segments had several variables studied in order to evaluate the influence of the road intervention.

Table 29 – Scheme of how the information was analyzed.

	Before	Measure	After	Total
Variable	-	-	-	-

The minimum, maximum and average values of the speed, calculated load, rpm, acceleration, road grade and VSP were considered in the analysis, because they present a good representation of the vehicle dynamics and driving conditions.

Additionally, the average of fuel consumption and exhaust emissions, which are dependent on the previous variables, were calculated in l/100km and g/km respectively. The calculation of the average was performed by summing fuel or exhaust gases in grams per second and dividing it by the distance traveled in meters, as Eq. 3 demonstrates. Then to achieve the fuel consumption in l/100km was used the density of the diesel fuel (0.84 kg/l).

$$x = \frac{\sum v}{\sum d} \times 1000 \qquad \text{[Eq. 3]}$$

where,
x – Average of fuel consumption or exhaust gases on a required part of the scenario: before, measure, after or total (g/km);
d – Distance traveled (m);
v – Fuel consumption or pollutant gases (g/s).

The sum of the exhaust gases emitted and fuel consumed on each segment of the TCMs are also presented. The results are in grams once all TCMs have around 40 m, with an exception of the textured pavement (TCM-A-2) which has 110 m.

With the aim of accomplishing the Comparative Plan (Table 24) defined earlier, a comparison percentage of the different cases was developed for the final analysis, using the formula:

$$percent\ change = \frac{B-A}{A} \times 100 \qquad \text{[Eq. 4]}$$

where,
A – The comparative case study (TCM or UR) variable. The basis of comparison;
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.

In the case ‘Comparison with Untreated Road or Intersection’ each segment (Before, Measure, After and Total) of the TCMs section was individually compared to the respective untreated road section. While the in the cases of comparisons within Arco do Cego neighbourhood, within Parque da Nações area and between Speed Tables only the total values of variables were used.

4. Results

4.1. Results from on-road measurements

4.1.1. Vehicle dynamics

In order to evaluate the impact of traffic calming measures on exhaust emissions and fuel consumption, it was necessary to first characterize their influence on vehicle dynamics. This section addresses the variables related to the way the vehicle is used: speed, acceleration, engine speed and calculated load.

The evaluation of the variables on the TCMs is divided in four segments: the approach area ("Before"), the measure itself ("Measure"), the exit area ("After") and the "Total", aggregating the previous three segments. The results are in Table 30-Table 35, in which speed, acceleration, engine speed and calculated load parameters are presented for each TCM and its respective untreated road (UR). The impact on vehicle speed associated with the implementation of TCMs was calculated as a perceptual change between the speed found for each segment of the TCM sections and the respective untreated road.

Table 30 presents results of two TCMs in Arco do Cego and their correspondent untreated road for comparison. In both cases it is possible to observe the influence of the measure on the vehicle dynamics. In TCM-A-1 (speed tables), before the measure, a deceleration contributes to the lower speed while traveling on it, while at the exit area the speed increases with the acceleration. This pattern is also noticeable on the engine parameters, which have lower values before and higher after the speed table.

Table 30 – Parameters of driving dynamics and engine operation for TCM-A-1: Speed Table, TCM-A-2: Textured Pavement and UR-A-(1,2): Untreated Road of Arco do Cego scenarios.

	TCM-A-1				**TCM-A-2**				**UR-A-(1,2)**
	Before	**Measure**	**After**	**Total**	**Before**	**Measure**	**After**	**Total**	**Total**
Speed									
Maximum (km/h)	20	18	24	24	21	31	29	31	31
Average (km/h)	14	13	17	14	15	19	20	18	24
Change (%)	-45	-47	-31	-41	-40	-24	-17	-25	-
Acceleration									
Average (m/s^2)	-0.21	0.26	0.42	0.09	0.23	0.03	0.37	0.10	0.02
Engine Speed									
Average (rpm)	1028	1194	1360	1168	1206	1265	1362	1280	1433
Calculated Load									
Average (%)	4	12	16	10	15	12	24	14	10

TCM-A-2 (textured pavement) shows a different pattern, the lowest speeds were registered before the measure, where there is also positive acceleration. This situation may occur possibly due to the interference of an intersection in the corridor which leads to the decrease of speed and then acceleration. Although the "Measure" segment did not have the highest average speed, it was the one where the maximum value occurred, 31km/h. This situation is justified with a change in direction at the end of the street, when exiting the measure, that required a speed reduction contributing to a lower average. The reason why the higher speeds were on the textured pavement is that the road was in good conditions allowing the driver to feel comfortable, without constraints imposed by more deteriorated pavement. The average acceleration and calculated load present the lowest results in the textured pavement segment, indicating a smooth driving pattern. However as in the case of speed, the maximum and the minimum values are registered there.

In general, the TCM-A-2 has higher speeds compared to TCM-A-1, which would be expected since the speed tables are more effective at speed reduction, as other studies such Lee et al. (2013) have concluded. They are thought, however, to also have higher speed variation due to their vertical design which was not registered. This could be explained by the road characteristics, such as intersections, change of direction or the deteriorated road pavement.

Regarding the comparison with UR-A-(1,2) a higher total average speed and engine speed, with lower acceleration is observable. The measures are effective at reducing the average speed, by a percentage of change in vehicle speed of 41% in TCM-A-1 and 25% in TCM-A-2.

In the Arco do Cego neighborhood three continuous sidewalks were also studied separately, since they have different roads characteristics, such as road grade and traffic direction which consequently lead to different patterns of vehicle operations. The continuous sidewalks were analyzed separately and each one was compared with a different untreated intersection.

Table 31 shows the results of TCM-A-3.3 and its respective untreated intersection. This traffic calming measure is located at an intersection with the approach area on an uphill street. The lowest average speed was registered on the measure, as a consequence of the deceleration to reach the interception and the continuous sidewalk on it. The highest average speed occurred after the measure, as the vehicle accelerates to its regular operation on a road with well-maintained pavement. Together with the acceleration, the engine variables show the lowest values before and highest after. Although the average calculated load in the "Before" segment was considerably higher, than in other TCM sections, because of the uphill road traveled at low speeds.

Table 31 – Parameters of driving dynamics and engine operation for TCM-A-3.3: Continuous Sidewalks (3rd intersection) and UR-A-3.3: Untreated Intersection of Arco do Cego.

	TCM-A-3.3				UR-A-3.3
	Before	**Measure**	**After**	**Total**	**Total**
Speed					
Maximum (km/h)	19	15	25	25	23
Average (km/h)	12	7	18	12	15
Change (%)	-26	-53	17	-20	-
Acceleration					
Average (m/s^2)	-0.43	0.37	0.63	0.15	0.13
Engine Speed					
Average (rpm)	963	1016	1516	1155	1234
Calculated Load					
Average (%)	10	16	22	16	15

When comparing TCM-A-3.3 with UR-A-3.3 a 20% higher average speed is noticeable on the untreated intersection, meaning the intervention is slowing down the traffic. The average of the engine variables did not show significant differences.

According to Table 32, the results of TCM-A-3.4 (with a downhill slope during and after the measure) indicate that the lower speeds were registered on the measure. The highest average speeds on the TCM-A-3.4 occurred before the continuous sidewalk, where strong decelerations also occurred as the vehicle approached the measure. After the measure, the speed was not as high as before, even though it is a downhill road, possibly because the road condition did not allow for a comfortable drive. The lowest values of engine speed and calculated load were observed before the measure, with a slight increase on and after it, due to the power needed to overcome the measure and keep moving.

Table 32 – Parameters of driving dynamics and engine operation for TCM-A-3.4: Continuous Sidewalks (4th intersection) and UR-A-3.4: Untreated Intersection of Arco do Cego.

	TCM-A-3.4				UR-A-3.4
	Before	**Measure**	**After**	**Total**	**Total**
Speed					
Maximum (km/h)	24	16	16	24	17
Average (km/h)	14	9	14	13	12
Change (%)	16	-25	12	3	-
Acceleration					
Average (m/s^2)	-0.81	0.28	0.35	-0.17	-0.02
Engine Speed					
Average (rpm)	1023	895	946	965	990
Calculated Load					
Average (%)	1	6	9	5	4

The untreated road (UR-A-3.4) showed not to be the best corridor for comparison, since the road conditions did not allowed the best representation of a TCM-A-3.4 without intervention. The deteriorated asphalt and the abusive street parking limiting the space, slowed down the traffic and compromised the movement. However, it was not possible to find a more adequate intersection and the corridor initially chosen was kept. The untreated intersection showed lower average speeds and calculated load in addiction to higher average acceleration and engine speed than the TCM.

Table 33 presents the results of TCM-A-3.7 and the respective untreated intersection. This measure is located at an interception on a street with an uphill slope. The significant deceleration on the “Before” segment accompanied with the lowest average speed registered on the measure, was similar to the two previous TCM. The highest average speed occurred before the measure where the maximum value was registered. In the “After” segment, the average speed was lower due to an intersection at the end of the corridor that did not allow higher values to be reached. When looking at the calculated load, it is understandable that the lowest values occur before the measures, as the vehicle approaches it and slows down, while much higher values occur on and after the measure, since the vehicle needs more power to overcome the obstacle and move uphill.

In regards to UR-A-3.7, the total average speed was higher there than on the TCM, along with the engine variables' values. Considering the total length of the TCM, the average speed was reduced by 36% with the implementation of the continuous sidewalk showing that the measure is being effective on speed control. Similarly to previous measures presented from Arco do Cego, the speed was reduced from a value already under the speed limit. The speed limit on Arco do Cego is 30 km/h and the condition of the road along with the street characterizes did not allow higher speeds. In fact, the highest value registered was on the UR-A-(1,2), with 31km/h.

Table 33 – Parameters of driving dynamics and engine operation for TCM-A-3.7: Continuous Sidewalk (7th intersection) and UR-A-3.7: Untreated Intersection of Arco do Cego.

	TCM-A-3.7				UR-A-3.7
	Before	**Measure**	**After**	**Total**	**Total**
Speed					
Maximum (km/h)	20	15	16	20	28
Average (km/h)	14	9	13	12	18
Change (%)	-25	-54	-32	-36	-
Acceleration					
Average (m/s^2)	-0.77	0.22	0.22	-0.18	-0.23
Engine Speed					
Average (rpm)	1090	1086	1351	1160	1276
Calculated Load					
Average (%)	4	18	19	12	15

When looking at the analysis of all continuous sidewalks, the highest average speeds were found on TCM-A-3.4, since the overall condition of the road pavement before the measure and the road grade allowed for less constrained driving conditions.

Table 34 presents the results of the Alvalade speed tables, located on a street with an uphill slope. The lower speed values occurred on the measure, with a clear deceleration before it, like in previous TCMs. Similarly to the cases of Arco do Cego's speed table and the continuous sidewalk in TCM-A-3.3, the acceleration of 0.49 m/s^2 after the measures is considerably high, as the speed returns to its regular values.

Table 34 – Parameters of driving dynamics and engine operation of TCM-B-1: Speed Tables of Alvalade.

	TCM-B-1			
	Before	**Measure**	**After**	**Total**
Speed				
Maximum (km/h)	28	20	24	28
Average (km/h)	22	17	21	21
Acceleration				
Average (m/s^2)	-0.72	0.09	0.49	-0.10
Engine Speed				
Average (rpm)	1308	1102	1351	1271
Calculated Load				
Average (%)	0	13	27	13

In Table 35, the vehicle dynamics are presented for the speed tables (TCM-C-1), speed humps (TCM-C-4) and untreated road (UR-C) of Parque das Nações. The roads are wider (in comparison to Arco do Cego and Alvalade) with two lanes in both directions and a speed limit of 50 km/h. Regarding the average speed, in TCM-C-4 the lowest value occurred on the measure and the highest value after. Both TCMs presented a negative acceleration before the measure; even though on the TCM-C-4 the acceleration was the lowest, contributing to the slightly lower average speed on the measure. The speed humps have also the highest acceleration after the measure, indicating a less smooth driving pattern when comparing it to the TCM-C-1 (as Lee et al. (2013) had concluded) and to the others TCMs of this study.

The TCM-C-1 showed the lowest average speed before the measure and the highest after it, along with acceleration. In both cases the “After” segment of the measures presented greater values of average speed, accelerations and of engine variables. The “Total” results present the same average speed on the two TCMs.

Table 35 – Parameters of driving dynamics and engine operation of TCM-C-1: Speed Tables, TCM-C-4: Speed Humps and UR-C: Untreated Road of Parque das Nações.

	TCM-C-4				**TCM-C-1**				**UR-C**
	Before	**Measure**	**After**	**Total**	**Before**	**Measure**	**After**	**Total**	**Total**
Speed									
Maximum (km/h)	45	37	46	46	38	39	44	44	62
Average (km/h)	31	30	35	33	30	32	37	33	47
Change (%)	-34	-38	-26	-31	-37	-34	-22	-30	-
Acceleration									
Average (m/s^2)	-0.79	0.38	0.85	0.15	-0.44	0.77	0.84	0.28	0.00
Engine Speed									
Average (rpm)	1418	1385	1643	1526	1358	1457	1658	1503	1907
Calculated Load									
Average (%)	4	27	48	28	6	46	47	30	14

The UR-C registered higher values of average speed than the TCM as it was to be expected. It also shows higher engine speed but lower calculated load and acceleration, because of the higher speed and road condition which allowed a homogeneous driving performance without exceptional need for power. The implementation of traffic calming measures contributed to the almost equal reduction of average speed of 31% for speed humps and of 30% for speed tables, showing similar results as those from the Boulter (2001) study, which found an equal speed reduction for these measures.

When comparing the TCM of Parque das Nações with others on Arco do Cego and Alvalade, higher values of average speed, engine speed and calculated load are noticeable, as was expected from the characteristics of each zone. Figure 45 presents the average speed percentage of change (%) for all TCM analyzed with a correspondent untreated road, it is noticeable that TCM-A-1 is the one with the most influence on speed reduction, achieving a total of 41%. The lowest reduction occurred on TCM-A-3.3, with 20%. However, this TCM along with the TCM-A-3.7 were the ones with the lower total average speed values (12 km/h), which is normal since they are at an intersection.

With different results, all the traffic calming measures were effective at slowing down the traffic on the roads where they were built and on maintaining it under the speed limit defined there.

The maximum speed results indicated that all TCMs lead to second-by-second speed values under the speed limit, with the only exception being that of TCM-A-2 which slighty exceded it by 1 km/h. On average, the Arco do Cego TCMs contributed to a speed reduction of 6.3 km/h on the interviened roads, while the Parque nas Nações TCMs 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. Nevertheless, given the influence on speed all the measures contribute to an increase of both drivers' and pedestrian's safety.

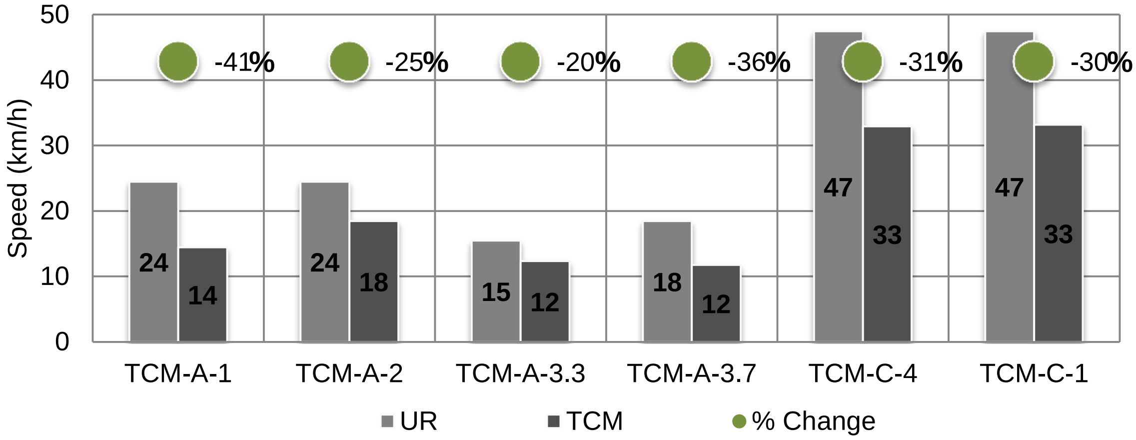


Figure 45 – Average speed (km/h) of the traffic calming measures (TCM) and respective untreated roads or intersection (UR); and average speed percentage of change (%) associated to each TCM. The green color on the circle indicates a reduction in speed the red indicates an increase.

4.1.2. Exhaust Emissions and Fuel consumption

This section analyzes the pollutant emissions generated in the combustion process of the vehicle and its fuel consumption. The local pollutants considered in this work are carbon monoxide (CO) and nitrogen oxides (NO_x) and as well as the global pollutant carbon dioxide (CO_2).

Exhaust emissions and fuel consumption

The comparison between the results associated with each TCM, in terms of exhaust emissions and fuel consumption, are presented next. The study is performed according to the comparison cases stipulated before. The evaluation of the variables on the TCMs is also presented in four segments: the approach area ("Before"), the measure itself ("Measure"), the exit area ("After") and the "Total" of all segments. The average concentration of exhaust emissions are presented in g/km, while fuel consumption is presented in l/100km. From these parameters the percentages of change (%) were calculated as in the previous section. The sum of exhaust emissions and fuel consumption on the four segments of the TCMs (in grams) were also accounted. This last calculation considers that all TCMs sections have approximately the same dimensions (TCMs sections have around 40 m, with the exception of the textured pavement (TCM-A-2) which has 110 m).

The analysis of CO emissions was not considered, due to lack of statistic validity. The number of tests required to achieve an acceptable statistical confidence was very high, thus impossible to satisfy. Nevertheless, results of CO emissions were presented to indicate the potential effects on CO emissions, but they should be observed with special caution.

Table 36 presents the results for the speed table and textured pavement sections, as well as those for the comparable untreated road on Av. Sacadura Cabral. The speed table (TCM-A-1) showed an increasing trend for exhaust emissions and fuel consumption from the “Before” to the “After” position, as CO_2 shows with an increase from 105 to 258 g/km. This situation is in line with the vehicle dynamic variables. Regarding the results between different segments of TCM-A-1 and UR-A-(1,2), it is observable that the untreated road presented less emissions and fuel consumption. With the speed tables there was a 107% total increase of fuel consumption and CO_2 emissions and a 198% total increase of NO_x.

Table 36 – Parameters of fuel consumption and exhaust emissions throughout measured paths in Arco do Cego. The results presents belong to TCM-A-1: Speed Table, TCM-A-2: Textured Pavement and UR-A-(1,2): Untreated Road.

	TCM-A-1				**TCM-A-2**				**UR-A-(1,2)**
	Before	**Measure**	**After**	**Total**	**Before**	**Measure**	**After**	**Total**	**Total**
Fuel									
g	0.4	0.6	1.2	2.2	0.7	4.3	1.4	6.5	1.6* / 4.1**
l/100km	3.9	8.2	10.6	7.9	10.9	5.9	10.1	6.9	3.8
%	3	114	178	107	186	54	164	80	-
CO_2									
g	1.3	1.8	3.7	7.2	2.3	13.9	4.4	20.6	5.1* / 13.1**
g/km	105	219	285	212	293	159	271	185	103
%	3	114	178	107	186	54	164	80	-
CO									
mg	1	1	5	7	0	0	4	4	17* / 45**
g/km	0.06	0.14	0.38	0.20	0.04	0.00	0.22	0.04	0.35
%	-83	-62	8	- 43	-90	-99	-38	-89	-
NO_x									
mg	1	2	5	8	3	17	6	26	4* / 11**
g/km	0.07	0.23	0.39	0.25	0.32	0.20	0.37	0.23	0.08
%	-21	178	368	198	279	135	339	175	-
VSP									
W/kg	-1.0	1.5	3.0	0.8	2.4	1.7	4.6	2.2	1.5

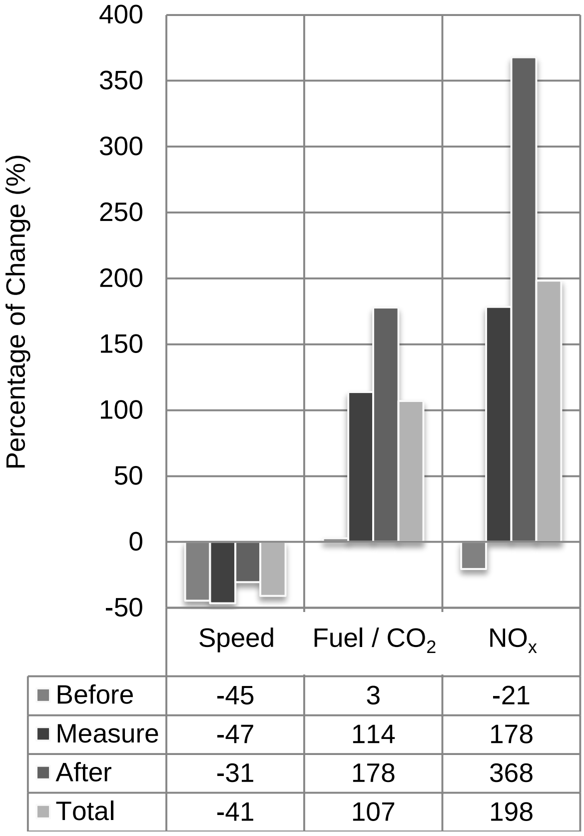
*Accumulated value in mg or g, according to the variable, for 40 m of the UR-A-(1,2), to be equivalent to TCM-A-1.

**Accumulated value in mg or g, according to the variable, for 110 m of the UR-A-(1,2), to be equivalent to TCM-A-2.

For TCM-A-2 (textured pavement) the lowest values of fuel consumption and CO_2 emissions occurred during the measure and the highest before (5.9 l/100km and 159 g/km on it and 10.9 l/100km and 293 g/km before it, respectively). NO_x emissions also showed the lowest value on the measure (136 g/km) and the highest (339 g/km) after. As expected the “Measure” segment of TCM-A-2 presented low energy and environmental impacts, due to smooth driving patterns without strong speed variation and not very low average speed on it.

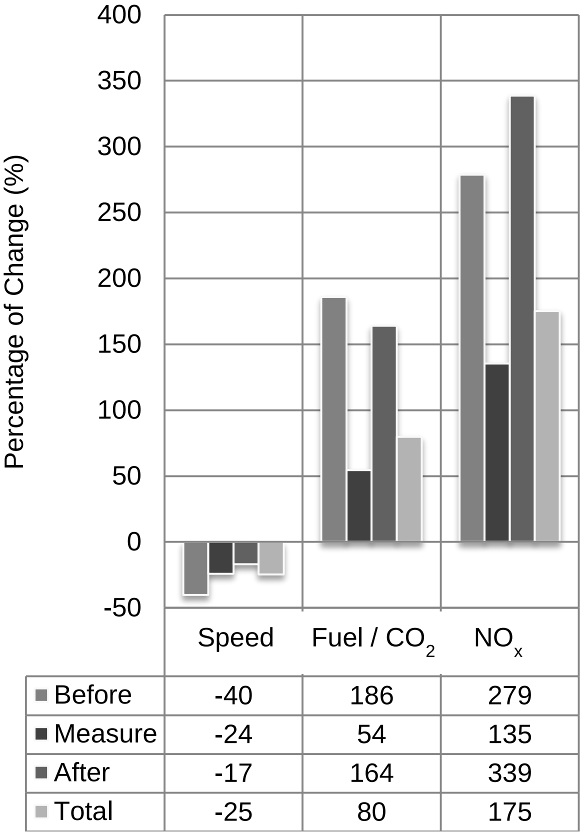
In general, the textured pavements had lower values of fuel consumption and exhaust emissions than the speed table, as shown later in Table 40 presenting the percentage of change between the Arco do Cego TCMs and its speed table, as comparison basis. The fuel consumption and CO_2 emissions are 13% lower and NO_x emissions 8% lower. However, as shown in Figure 46 and Figure 47, the approach area of the speed table clearly had less impact on emissions and consumption, due to road characteristics before the textured pavement, as explained earlier.

As in the case of the TCM-A-1, the comparison between the different segments of the textured pavement and UR-A-(1,2) indicate that the measure contributes to an increase on fuel consumption and CO_2 emissions by 80%, and the NO_x emissions by 175%. The results in grams confirm that the road without intervention (UR-A-(1,2)) has lower negative impacts than TCM-A-2, since the emitted gases and consumed fuel quantities on the "Total" segment were lower there.



	Speed	Fuel / CO_2	NO_x
■ Before	-45	3	-21
■ Measure	-47	114	178
■ After	-31	178	368
■ Total	-41	107	198

Figure 46 – Percentage of change (%) of speed, fuel consumption, CO_2 emissions and NO_x emissions on the TCM-A-1.



	Speed	Fuel / CO_2	NO_x
■ Before	-40	186	279
■ Measure	-24	54	135
■ After	-17	164	339
■ Total	-25	80	175

Figure 47 – Percentage of change (%) of speed, fuel consumption, CO_2 emissions and NO_x emissions on the TCM-A-2.

Table 37 presents the results for the continuous sidewalk TCM-A-3.3 and its untreated intersection. This traffic calming measure is located at an intersection and its approaching street has a positive road slope of 0.04. The fuel consumption and the CO_2 emissions are higher on the measure (16.9 l/100km and 453 g/km, respectively) and lower before it (8.9 l/100km and 238 g/km, respectively). The NO_x presents also the lowest values before the measure (0.21 g/km) and the higher after it (0.45 g/km). This behaviour is similar to VSP, which has its higher values after the measure, as shown for the engine variables. For fuel consumption and CO_2 emissions, impacts are worst on the measure, even though the higher values of dynamic variables and VSP occurred after, this can be explained by the differences of average speed on the TCM segments (7 km/h on and 18 km/h after).

Table 37 – Parameters of fuel consumption and exhaust emissions in Arco do Cego. The results presented belong to TCM-A-3.3: Continuous Sidewalks and UR-A-3.3: Untreated Intersection.

		TCM-A-3.3			**UR-A-3.3**
	Before	**Measure**	**After**	**Total**	**Total**
Fuel					
g	0.9	1.1	2.3	4.3	3.0
l/100km	8.9	16.9	14.2	13.0	10.5
%	-15	62	35	24	-
CO_2					
g	3.0	3.4	7.3	13.7	9.7
g/km	238	453	380	349	280
%	-15	62	35	24	-
CO					
mg	3	9	8	20	5
g/km	0.27	1.15	0.40	0.50	0.17
%	60	580	134	196	-
NO_x					
mg	3	3	9	14	11
g/km	0.21	0.41	0.45	0.37	0.32
%	-33	30	40	14	-
VSP					
w/kg	0.2	1.9	4.7	2.1	2.4

The TCM-A-3.3 consumed 24% more fuel, emitted 24% more CO_2 and 14% more NO_x. The main contributor to these increases was the “Measure” segment. The calculated accumulated mass in grams supports these results, once it always registered higher values on the intervened road. As an example the total fuel consumption is 4.3 g on TCM-A-3.3 and 3.0 g on UR-A-3.3.

The results presented in Table 38 concern the continuous sidewalk TCM-A-3.4 and its untreated intersection. This path has a downhill slope during and after the measure. Regarding CO_2 emissions and fuel consumption, the lowest values are registered before (14 g/km and 0.5 l/100km), while the higher are observed after the continuous sidewalk (126 g/km and 4.7 l/100km). NO_x also presents the lowest average value on the “Before” segment (0.01 g/km), while the highest are observed on the measure (0.07 g/km). When looking at the VSP, one can verify that the highest values are registered on and after the measure (0.6 w/kg on both) and the lowest before (-3.7 w/kg). Indeed the total average VSP was negative (-1.3 w/kg) as a result of the negative values before the measure.

The untreated intersection presented values not suitable for comparison, as explained earlier. It indicated higher emissions and fuel consumption, as well as lower speed, which can be observed in the Table 38.

Table 38 – Parameters of fuel consumption and exhaust emissions in Arco do Cego. The results presents belong to TCM-A-3.4: Continuous Sidewalks and UR-A-3.4: Untreated Intersection.

		TCM-A-3.4			**UR-A-3.4**
	Before	**Measure**	**After**	**Total**	**Total**
Fuel					
g	0.1	0.3	0.4	0.7	1.0
l/100km	0.5	4.1	4.7	2.8	3.5
%	-85	19	35	-21	-
CO_2					
g	0.2	0.8	1.3	2.3	3.3
g/km	14	111	126	74	93
%	-85	19	35	-21	-
CO					
mg	0	0	0	0	1
g/km	0.00	0.03	0.00	0.01	0.03
%	-100	7	-100	-74	-
NO_x					
mg	0	1	1	2	2
g/km	0.01	0.07	0.06	0.04	0.05
%	-80	26	17	-23	-
VSP					
w/kg	-3.7	0.6	0.6	-1.3	-0.7

Table 39 presents the results for the continuous sidewalk TCM-A-3.7 and its untreated intersection (UR-A-3.7). This measure is located at an interception on a street with an uphill slope. The higher average concentration of fuel consumption and exhaust emissions are registered after the continuous sidewalk and the lowest results are always before the measure. VSP is in line with the results from the variables mentioned before, along with calculated load and acceleration.

According to the percentage of change between the different segments of TCM-A-3.7 and UR-A-3.7, the untreated intersection registers a global higher fuel consumption and exhaust emissions. It uses 20% more fuel, and emits an additional 20% of CO_2 and 22% of NO_x. However, after the TCM-A-3.7 measure, an increase occurred on fuel consumption and CO_2 emissions (22% on both) and on NO_x emissions (21%). Moreover on the measure itself a slight 5% increase on fuel and CO_2 also occurred. Before the measure a strong decrease on the exhaust gases emitted and fuel consumed was registered, which compensated the influence of the continuous sidewalk, contributing to the overall decrease of their values. One can also verify through the quantity of these impacts, that the TCM had lower results than the untreated intersection, as observed for example on CO_2 with 4.8 g against 7.9 g.

Table 39 – Parameters of fuel consumption and exhaust emissions in Arco do Cego. The results presents belong to TCM-A-3.7: Continuous Sidewalk and UR-A-3.7: Untreated Intersection.

	TCM-A-3.7				UR-A-3.7
	Before	**Measure**	**After**	**Total**	**Total**
Fuel					
g	0.2	0.5	0.8	1.5	2.5
l/100km	2.5	10.4	12.0	7.8	9.8
%	-74	6	23	-20	0
CO_2					
g	0.6	1.8	2.5	4.8	7.9
g/km	67	277	322	209	262
%	-74	6	23	-20	0
CO					
mg	1	13	17	30	2
g/km	0.09	2.07	2.16	1.32	0.13
%	-28	1511	1583	925	0
NO_x					
mg	0	2	3	6	3
g/km	0.04	0.33	0.41	0.24	0.31
%	-87	7	33	-22	0
VSP					
w/kg	-1.6	1.8	2.4	0.6	1.8

Table 40 presents the percentage of change between the “Total” results of the textured pavement (TCM-A-2) and the continuous sidewalks (TCM-A-3.3, TCM-A-3.4 and TCM-A-3.7) with the “Total” results of the speed table (TCM-A-1) used as comparative basis, in order to do the comparison concerning the traffic calming measures in the Arco do Cego neighborhood. The results showed that TCM-A-3.3 present the highest impacts, while TCM-A-3.4 is the one with lower fuel consumption and exhaust emissions. These results are strongly related with road characteristics such as intersections associated, slope and pavement conditions, and not just with the traffic calming measure characteristics.

Table 40 – Percentage of change of the textured pavement (TCM-A-2) and the continuous sidewalks (TCM-A-3.3, TCM-A-3.4 and TCM-A-3.3) with the speed table (TCM-A-1) from Arco do Cego.

	TCM-A-2	TCM-A-3.3	TCM-A-3.4	TCM-A-3.7
Fuel				
%	-13	64	-65	-2
CO_2				
%	-13	64	-65	-2
CO				
%	-81	149	-96	552
NO_x				
%	-8	47	-84	-3
Speed				
%	26	-16	-12	-20

The results presented in Table 41 concern to the Alvalade speed tables (TCM-B-1), located on a street with an uphill slope. The lowest values of average concentration are registered before the measure, whereas the highest values occurred on the measure (9.3 l/100km of fuel consumption, 248 g/km of CO_2 emissions and 0.16 g/km of NO_x emissions). When looking at the VSP one can verify that it was also lower before and higher after the measure (5.4 W/kg). The energy and environmental impacts are worst on the measure, even though the higher values of VSP and vehicle dynamic variables occurred after; this can be explained by the highest average speed and acceleration on the “After” segment (and lower engine efficiency on the measure).

Table 41 – Parameters of fuel consumption and emitted pollutants throughout the measured paths in Alvalade. The results presents belong to TCM-B-1: Speed Tables.

	TCM-B-1			
	Before	**Measure**	**After**	**Total**
Fuel				
g	0.1	0.8	1.0	1.8
l/100km	0.7	9.3	7.5	5.5
CO_2				
g	0.3	2.4	3.1	5.7
g/km	20	248	200	148
CO				
mg	1	5	6	11
g/km	0.06	0.49	0.54	0.35
NO_x				
mg	1	1	1	3
g/km	0.07	0.16	0.10	0.10
VSP				
w/kg	-2.0	2.5	5.4	1.7

Table 42 presents the results for the speed tables (TCM-C-1), speed humps (TCM-C-4) and their respective untreated road (UR-C) on the Parque das Nações area. Both TCM-C-4 and TCM-C-1 had the lowest results of fuel consumption, gaseous emissions and VSP on the “Before” segment and the highest on the “After” segment. However, the results on TCM-C-1 are more homogeneous, as the acceleration pattern also was. As an example, at TCM-C-1 the variation of fuel consumption is between 2.4 l/100km and 4.4 l/100km, while at the TCM-C-4 is between 1.4 l/100km and 5.2 l/100km.

Using the calculated percentage of change between the different segments of TCM-C-4 and TCM-C-1 with respect to UR-C, it is noticeable that the “Total” results of the TCMs resulted in lower CO_2 emissions and fuel consumption and higher NO_x emissions than the untreated road selected. TCM-C-4 contributes to a total decrease of 3% on fuel consumption and CO_2 emissions, but a total increase of 345% on NO_x emissions. TCM-C-1 contributes to a total decrease of 6% on fuel consumption and CO_2 emissions, but a total increase of 263% on NO_x emissions. These decreases can be explained by the fact that, for the allowed speeds on the treated road, the influence of the measures on the engine efficiency, when the vehicle accelerates to its normal speed is balanced by the deceleration on the approach area. Even though after both TCMs an increase on fuel consumption and CO_2 emissions occurred (-30% at TCM-C-4 and -12% at TCM-C-1), it was not high enough to cause an overall increase. On the other hand, the NO_x emission present a strong increase, which occurred due to the high engine temperatures associated with the vehicle´s acceleration after and on the measure.

Table 42 – Parameters of fuel consumption and exhaust emissions in Parque das Nações. The results presents belong to TCM-C-1: Speed Tables, TCM-C-4: Speed Humps and UR-C: Untreated Road.

	TCM-C-4				TCM-C-1				UR-C
	Before	**Measure**	**After**	**Total**	**Before**	**Measure**	**After**	**Total**	**Total**
Fuel									
g	0.1	0.1	1.1	1.3	0.3	0.3	0.8	1.4	2.1
l/100km	1.4	2.5	5.2	3.8	2.4	3.8	4.4	3.7	4.0
%	-64	-37	30	-3	-39	-5	12	-6	0
CO_2									
g	0.4	0.4	3.4	4.2	1.0	2.6	4.4	6.7	1.0
g/km	39	66	138	103	65	101	119	100	106
%	-64	-37	30	-3	-39	-5	12	-6	-
CO									
mg	0	1	4	5	1	1	3	5	6
g/km	0.04	0.09	0.15	0.11	0.09	0.11	0.14	0.12	0.10
%	-62	-14	52	14	-10	9	40	19	-
NO_x									
mg	1	1	11	13	1	2	8	11	4
g/km	0.05	0.16	0.45	0.31	0.09	0.20	0.37	0.25	0.07
%	-22	132	548	345	25	192	428	263	-
VSP									
w/kg	-6.8	4.5	10.7	3.1	-2.9	9.3	11.6	5.0	2.6

The second column of Table 43 presents the percentage of change between TCM-C-4 and TCM-C-1 for the main variables, with TCM-C-1 used as comparison basis. TCM-C-1 showed less emissions and fuel consumption. The speed humps caused a 3% higher fuel consumption and CO_2 emissions and also a 23% higher NO_x emissions. Other studies such as Boulter (2001) and Lee et al. (2013) found contrary results, with speed tables causing higher emissions than speed humps.

Table 43, also presents on the third column the percentage of change between TCM-B-1 and TCM-A-1; and on the fourth column the percentage of change between TCM-C-1 and TCM-A-1 (using TCM-A-1 as comparison basis on both). The speed table from Arco do Cego neighborhood (TCM-A-1) is the one with higher CO_2 emission and fuel consumption. The speed tables of Parque das Nações (TCM-C-1) show the lowest values of CO_2 emissions and fuel consumption; however the highest results of NO_x occurred there. In Alvalade, TCM-B-1 contributed to the lowest NO_x emissions.

Table 43 – Percentage of change between TCM-C-4 and TCM-C-1 from Parque das Nações presented on the seconds column of the table. And percentage of change between TCM-B-1 and TCM-A-1 and also TCM-C-1 and TCM-A-1 to compare the performance of the speed tables, presented on the third and fourth columns, respectively.

	TCM-C-4 - TCM-C-1	TCM-B-1 - TCM-A-1	TCM-C-1 - TCM-A-1
Fuel			
%	3	-30	-53
CO_2			
%	3	-30	-53
CO			
%	-4	76	-41
NO_x			
%	23	-59	2
Speed			
%	-1	40	126

Figure 45 and Figure 48 to Figure 50 present summaries of the “Total” average speed, exhaust emissions and fuel consumption, as well as their percentage of change between each TCM and their comparative untreated roads. Of all cases, 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%). 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%.

The TCMs in Arco do Cego (30 km/h zone) registered the lowest average speeds, but the highest average on CO_2 emissions and fuel consumption (exception of TCM-A-3.4, due to the downhill road). As shown in other studies, lower average speed tend to generate more fuel consumption and emissions (Krzyzanowski et al., 2005; Ntziachristos & Samaras, 2000; Owen, 2005).

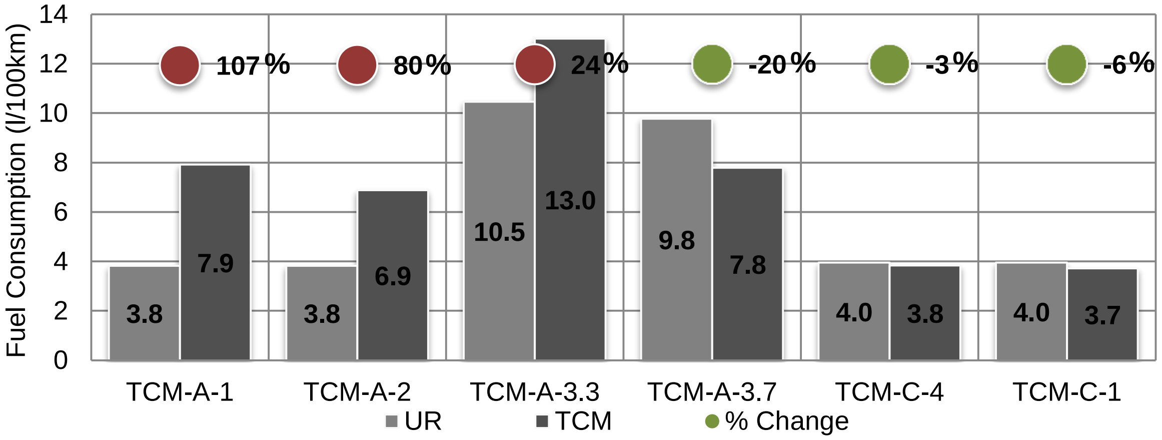


Figure 48 – Total average fuel consumption (l/100km) of the untreated roads or intersection (UR) and traffic calming measures (TCM); and percentage of change (%) for the total average fuel consumption associated with the implementation of each TCM. The green color on the circle indicates a reduction in fuel consumption and the red indicates an increase

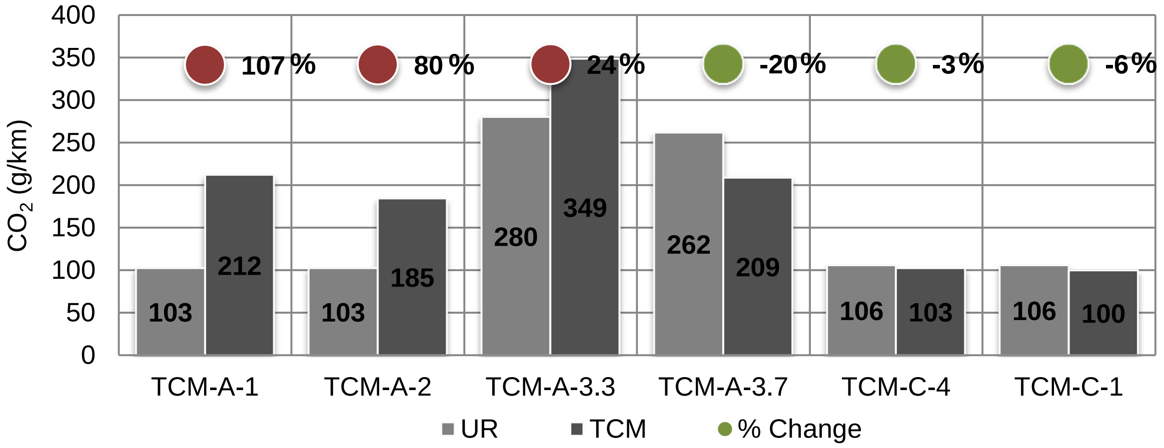


Figure 49 - Total average CO2 emissions (g/km) of the untreated roads or intersection (UR) and traffic calming measures (TCM); and percentage of change (%) for the total average CO_2 emissions associated with the implementation of each TCM. The green color on the circle indicates a reduction in CO_2 and the red indicates an increase.

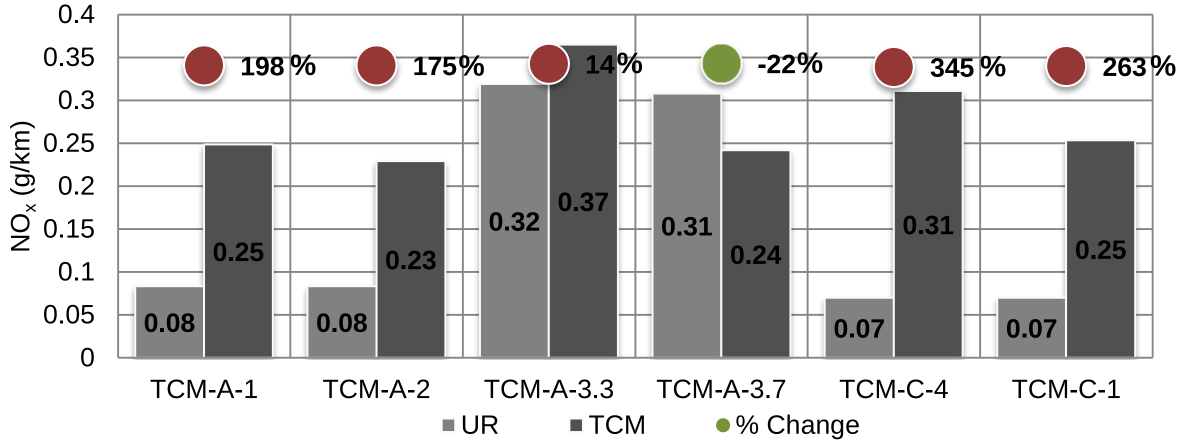


Figure 50 - Total average NOx emissions (g/km) of the untreated roads or intersection (UR) and traffic calming measures (TCM). And percentage of change (%) for the total average NO_x emissions associated with the implementation of each TCM. The green color on the circle indicates a reduction in NO_x and the red indicates an increase.

The untreated roads used in the Comparative Plan were carefully selected, and were the most appropriate found in the city of Lisbon. Their results were considered adquated to do the most realistic comparison possible (with the exception of the untreate road for TCM-A-3.4 which was not considered).

As mentioned before, these results are related with road characteristics such as intersections associated, slope, speed limit and pavement conditions, and not just with the traffic calming measure characteristics. However, they provide reliable information into the potential energy and environmental impacts of traffic calming measures, while indicating how differently road characteristis can influence TCM performance.

4.2. Traffic Calming Measures Assessment

This section assesses the traffic calming measures regarding a set of performance indicators based on their impacts. Due to the implications associated with TCMs, it is essential to identify which TCM performs best and creates an increase on traffic safety. The idea is to create a set of guidelines that can be used by local authorities when choosing the most appropriate measures to implement.

The considered performance indicators for the Traffic Calming Measures Assessment include three different areas of impacts:

Dynamic Data

- Maximum speed – The maximum speed does not exceed the local speed limit.
- Average Speed Reduction – The average speed was reduced.

Fuel Consumption and Exhaust Emissions Impacts

- Fuel Consumption – The average fuel consumption was reduced.
- CO_2 Emissions – The average CO_2 emissions were reduced.
- NO_x Emissions – The average NO_x emissions were reduced.

Safety

- Accident Reduction – The frequency of accidents was reduced.
- Probability of Death Reduction – The probability of death for pedestrians was reduced.

The 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.

Table 44 presents the results of road safety potentially obtained with each TCM, according to the accident reduction and the pedestrian probability of death reduction. 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 (inferior to 50 km/h). The accident reduction (%) was obtained using this relation and the absolute average 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 44 – Safety results according to the pedestrian probability of death and the accident reduction.

	Absolute Average Speed Reduction (km/h)	Accident Reduction (%)	Probability of Death Reduction (%)
TCM-A-1	10	37	3
TCM-A-2	6	22	2
TCM-A-3.3	3	11	1
TCM-A-3.7	6	22	1
TCM-C-4	14	52	54
TCM-C-1	14	52	54

Table 45 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. Three black circles indicate better performances, while one indicates the worse. Using the maximum and the minimum percentage of each performance indicator tercile groups were created. In Table 45 , 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.

The speed table (TCM-A-1) and the continuous sidewalk (TCM-A-3.7) of Arco do Cego neighborhood had the best performance on traffic data, especially on speed reduction. The speed tables (TCM-C-1) and speed humps (TCM-C-4) of Parque das Nações and along with continuous sidewalk (TCM-A-3.7) presented the best performance regarding fuel consumption and CO_2 emissions. On the other hand, while TCM-A-3.3 and TCM-A-3.7 showed the best results on NO_x emissions, Parque das Nações TCMs had the worst results. These results are in line with the previous analysis.

Regarding safety, Parque das Nações road with a speed limit of 50 km/h achieved the highest performance, with speed humps and speed tables. The results were based on an accident 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 Traffic Calming Measures Assessment developed can support local authorities during the process of selecting the most appropriate TCM to implement. The relative importance of the individual performance indicators may be defined by each local authority according to the existent circumstances and desired objectives.

Table 45 – Traffic Calming Measures Assessment based on performance indicator.

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

5. Conclusions

The purpose of this work was to quantify the impacts of traffic calming measures (TCMs) on vehicle dynamics, fuel consumption and exhaust emissions (CO_2, CO and NO_x) based on on-road measurements of a diesel vehicle (performed in a second-by-second basis). Data on driving dynamics (speed and acceleration), engine performance (engine load, engine speed, etc.), road topography, accelerometry and GPS information was collected from the vehicle using an I2d on-board monitoring device. Exhaust gas emissions were collected using a gas analyzer placed in the vehicle tailpipe, allowing to measure CO, CO_2, HC, O_2 and NO_x in a second-by-second basis. The measured concentration of the exhaust gases and engine data were used to calculate fuel consumption and exhaust mass flow emissions. The results of fuel consumption and exhaust gases were presented in l/100km and g/km, respectively. The Vehicle Specific Power (VSP) methodology was also used to assess the instantaneous power per vehicle unit mass, which present a high correlation with emissions. It was calculated to support the interpretation of the results, namely the fuel consumption and emissions.

The TCMs were selected according to their representativity on the city of Lisbon, and with the objective of comparing them. The TCMs chosen were speed tables, textured pavement and continuous sidewalk located on 30 km/h Zones, and speed tables and speed humps from a road with a 50 km/h speed limit. Each TCM was compared with an equivalent untreated road, and also with other TCMs from the same intervened area or of the same type.

From the collected GPS coordinates, the selected TCMs and untreated road sections were identified and isolated from the remaining information recorded during the trips. Each TCM section was divided in three segments: the approach area (“Before”), the measure itself (“Measure”) and the exit area (“After”). A global analysis was made (“Total”), for both TCM section and untreated roads. The different segments were studied in terms of speed, acceleration, engine speed, calculated load, fuel consumption, CO_2 emissions, CO emissions, and NO_x emissions, in order to evaluate the influence of the road intervention on the vehicle performance. Additionally, a traffic calming measures assessment was elaborated, concerning a set of performance indicators based on the impacts caused by each TCM.

The results obtained with this work aim at developing guidance for local authorities interested in implementing TCMs. The main conclusions and recommendations resulting from this work are:

Speed variations: TCMs highly influence vehicle dynamic performance. Speed variations occur as the vehicle travels through a TCM, typically with a deceleration before the measure and then acceleration on or after it. All the TCMs contributed to slow down the vehicle and keep it under the speed limit (except for textured pavement, exceeding by 1 km/h). They achieved reductions between 20% (15 to 12 km/h) on a continuous sidewalk (TCM-A-3.3) and 41% (24 to 14 km/h) on a speed table, both located on a 30 km/h zone. The highest absolute decrease was 14 km/h, caused by speed tables and speed humps on a road with a 50 km/h speed limit, corresponding to a speed reduction of about 30%.

Fuel consumption and CO_2 emissions: Vehicle fuel consumption and CO_2 emissions were also affected by the implementation of TCMs. Similarly to the speed variations, these variables decrease as the vehicle approach the measure (38% on average) and increase as the vehicle leaves it (56% on average). Moreover, the results indicate that the lower average speeds on 30 km/h zones led to an overall increase of fuel consumption and CO_2 emissions (except for continuous sidewalk TCM-A-3.7 which decreased them by 20%). 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 the other hand, the road with 50 km/h speed limit, where higher average speeds were allowed, presented decreases of 6% caused by the speed table and of 3% caused by the speed humps. On average, the 30 km/h zone contributed to an increase of 48% on fuel consumption and CO_2 emissions, while the 50 km/h speed limit road led to a decrease of 4%. 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 lower speeds.

Local pollutants emissions: NO_x emissions also showed to be affected by the implementation of TCMs. It decreases as the vehicle approach the measure (28% on average) and increases as the vehicle leaves it (283% on average). Additionally, 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. HC emissions were not considered in this work, due to the very low amounts associated with diesel engines. CO emissions were not evaluated due to lack of statistical confidence with the sample size acheived.

Comparison between TCMs: The speed table and textured pavement results for the 30 km/h zone showed that the absolute values of fuel consumption and exhaust emissions of the textured pavement were on average 11% lower, while the average speed was 26% higher, than the speed table. Additionally, from the road with a 50 km/h speed limit, the speed humps presented higher fuel consumption and exhaust emissions (13% on average) and slightly inferior average speeds (1%), indicating 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 speeds, when comparing with smother measures.

Safety performance: According to the Traffic Calming Measures Assessment section regarding the performance indicators, safety achieved the highest improvements on the speed humps and speed tables of the road with a 50 km/h speed limit. Accidents can be reduced by 52% and pedestrian probability of death during a collision can be reduced by 54%, due to the highest absolute speed reduction (km/h) caused by these TCMs. On the 30 km/h zone, the speed table was the one with the best results regarding the safety indicators, with the accident reduction of 37% and pedestrian probability of death during a collision reduced by 3%. This indicates that vertical deflection measures on a straight road have a greater impact on road safety, associated with the speed reductions. Nevertheless, the 30 km/h zones studied have overall higher safety conditions associated with their lower average speed.

Comparing with the literature review, the results of this work showed high sensibility to changes in road characteristics (such as speed limit and slope), as would be expected, since experimental tests with on-road measurements achieve more realistic vehicle operation, than simulations models or laboratory testing used in the reviewed work. In general, the speed variations results on the road with a 50 km/h speed limit were within the values found on other studies. However the results on 30 km/h zones achieved higher reductions than other studies of roads with the same speed limit. On the other hand, the fuel consumption and exhaust emissions presented higher impact on the 30 km/h zones. While on the road with a 50 km/h speed limit, fuel consumption and CO_2 emissions lead to lower impacts and the NO_x emissions to higher.

Greater speed reductions lead to greater improvements on safety conditions, but tend to result in higher exhaust emissions and fuel consumption. As a result, local authorities will need to adopt a balanced approach when developing a TCM project, especially in areas where air pollution is already a concern. Consequently, the potential benefits from a specific project on speed reduction and road safety increase need to be weighed against the possible adverse impacts on exhaust emissions and fuel consumption. Either way, the methodology developed can support local authorities during the process of selecting the most appropriate TCM to implement, according to the existent circumstances and desired objectives.

5.1. Future Work

This research work covers a number of traffic calming measure on different roads or intersection conditions. The on-road measurements to analyze the energy and emissions impacts can be improved with further researches. Thus, some suggestions for future work are addressed:

- Expand the on-road measurements to spark-ignition vehicles and also use a larger number of vehicles. Increase the number of drivers involved in the on-road measurements is other way to introduce higher diversity to the study, and improving its validity as well. Additionally, since drivers can have different driving behaviors, compare more aggressive drivers against calm ones would be interesting, in order to study how differently they behave upon a TCM and how different are the consequent impacts on vehicle dynamic, fuel consumption and exhaust emissions.
- Consider on-road measurements for particulate matter emissions, especially by compression-ignition vehicle.
- Add more types of traffic calming measures into the analysis. The city of Lisbon has implemented and will implement other types of TCMs, such as chicanes, raised median islands, curb extensions, roundabouts and raised intersections. It would be relevant to study their impacts on vehicle dynamic, fuel consumption and exhaust emissions. On the other hand, there are the same TCMs implemented in different road conditions, it would be interesting to study how different are the impacts associated with the new conditions. Another important approach is to find TCMs projects that are not yet implemented, in order to obtain more precise and realistic analyses of the road from before and after the implementation.
- Analyze the physiological response of the driver when crossing the TCMs. Driver physiological signals such as heart rate and force applied on the throttle pedal are possibly affected by the introduction of the TCMs. Studying the relation between these signals and the vehicles dynamics (acceleration and speed) would be essential to understand how the driver reacts according to the new situation. This suggestion was one of the initial objectives of the present thesis, but due to difficulties to synchronize and find a relation between the data collected from the driver and the vehicle, it was not possible to make a complete result analyses and obtain valid conclusions.
- Monitor the impacts on air quality of the TCMs using local measurements. In some situations it may be relevant to analyze the exposure of the pedestrians to the pollutants emitted by the vehicles into the street.
- Noise pollution is other type of environmental impacts frequently associated with the implementation of TCMs, which should also be considered in future studies.

The Municipality of Lisbon has been developing several strategies to promote and improve pedestrian accessibility. One of the tools developed was the *Traffic Calming Model* (EPAP, 2014a) containing technical specifications for planning, design and construction of traffic calming measures, with a view to reduce vehicle speed and the cut-through traffic in the city of Lisbon. The information gathered by the methodology developed in this thesis might contribute to the improvement of the *Traffic Calming Model*. Since, it provides information on road safety, speed reduction, along with pollutants emitted and fuel consumed according to different TCMs and road characteristics.

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Annex

A. Calculation of Mass Exhaust Emissions

The exhaust gases initially measured by the gas analyzer in dry concentrations (O_2 - %, CO_2 - %, CO - %, HC – ppm, and NO_x - ppm) are processed with the purpose of obtaining the mass emissions and consumption of the vehicle, using air mass flow (g/s) acquired directly from the I2d data.

The generic equation for combustion of the fuels analyzed is:

$$a\ (\alpha C + \beta H + \gamma O) + b\left(O_2 + \frac{79}{21}N_2\right) \rightarrow cCO_2 + dCO + eHC + fO_2 + gNO + hN_2 + iH_2O \quad (1)$$

Where a to i are the coefficients of the reaction; and α, β and γ are the molar fractions of C, H, and O from the fuel equivalent chemical formula.

Since, the gas analyzer removes water from the gases; the first step is to find the dry molar fractions of the combustion products from the concentrations of the measured exhaust gases (assuming perfect gas conditions).

$$x_{CO2}dry = [CO_2]/100 \quad (2)$$

$$x_{CO}dry = [CO]/100 \quad (3)$$

$$x_{HC}dry = [HC]/1000000 \quad (4)$$

$$x_{O2}dry = [O_2]/100 \quad (5)$$

$$x_{NO}dry = [NO]/1000000 \quad (6)$$

According to the fuel under analysis a correction from dry to wet molar fractions is prepared by considering the stoichiometric perfect combustion of the fuel, which in this case was diesel.

Table A 1 – Diesel fuel characteristics.

Fuel	**Composition**			**Correction for molar fraction x/x_{dry}**
	α	β	γ	
Diesel	10	18	0	0.878

Obtaining the coefficients *c* to *g* of equation 1:

$$c = x_{co2\ dry} \cdot x/x_{dry} \quad (7)$$

$$d = x_{co\ dry} \cdot x/x_{dry} \quad (8)$$

$$e = x_{HC\ dry} \cdot x/x_{dry} \quad (9)$$

$$f = x_{O2\ dry} \cdot x / x_{dry} \quad (10)$$

$$g = x_{NO\ dry} \cdot x / x_{dry} \quad (11)$$

With a carbon balance coefficient a is obtained:

$$a = (c + d + 6e)/\alpha \quad (12)$$

With a hydrogen balance coefficient i is obtained:

$$i = (a\beta - 14e)/2 \quad (13)$$

With an oxygen balance coefficient b is obtained:

$$b = (2c + d + 2f + g + i - a\gamma)/2 \quad (14)$$

And finally with a nitrogen balance coefficient h is obtained:

$$h = \left(2b \times \frac{79}{21} - g\right)/2 \quad (15)$$

Using the calculated coefficients of Equation (1), it is possible to achieve the mass basis of each component by multiplying the correspondent coefficient (a to h) by its molecular weight (Gonçalves, 2009).

B. Correlation study

Correlation tests between vehicle dynamic variables

A preliminary analysis on the vehicle dynamic and engine variables was performed through a correlation study, to better understand how these variables correlate together. As expected, the calculated VSP had a good correlation with acceleration and calculated load, 88% and 79% respectively. VSP showed lower correlation with road grade (19%) and speed (28%). The vehicle speed presented a good correlation with rpm (76%), and vehicle acceleration also demonstrated a fairly good correlation with the acceleration in the x axis, with an value of 70%. These results were expectable since most of those variables are dependent (or connected) to each another. On the other hand the variables without direct dependency showed a worse linear relationship, as was the case of speed and calculated load. However, both road grade and speed presented lower correlation with VSP, even though they are variables on which the VSP is directly dependent.

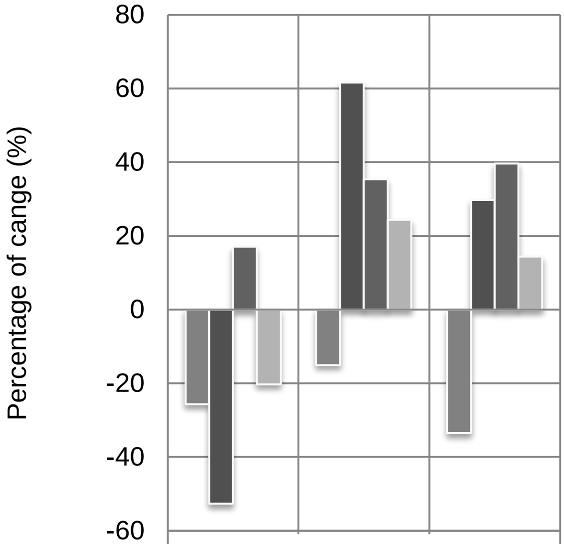
Correlation tests of vehicle dynamic variables with exhaust gases and fuel consumption

The analysis of exhaust emissions and fuel consumption and the interpretation of results are made in parallel with some vehicle dynamic variables. The vehicle dynamic variables were subjected to a correlation study with the environmental variables. CO_2 emissions and fuel consumption were best correlated whit VSP (63%), followed by acceleration (57%), engine speed (49%) and calculated load (49%). These results were expected, since all variables in some way influence fuel consumption and consequently the CO_2 emissions. NO_x showed higher correlation with calculated load (61%), followed by VSP (58%) and acceleration (51%), which can be explained by the higher engine load condition and speed variation, leading to higher temperatures on the engine and contributing to the formation of NO_x. The study also showed that CO had poor correlation with all variables considered (always inferior to 20%), probably associate with the insufficient statistic validity. Speed presented better correlation with fuel consumption and CO_2 (45% on both) than with NO_x (28%) and CO (3%).

Table A 2 - Results of the correlations performed in the preliminary analysis

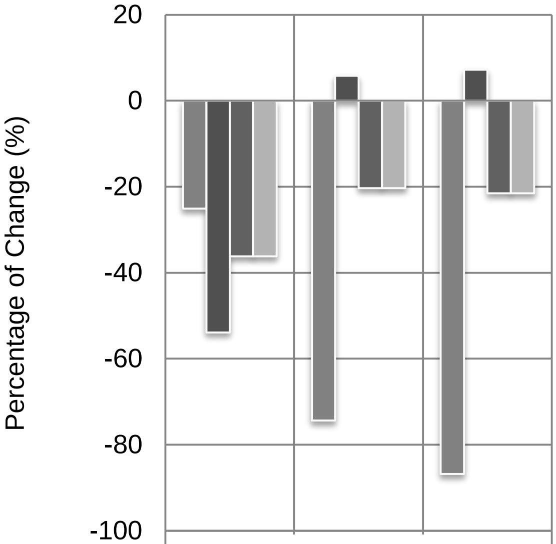
Speed (km/h) - Acceleration (m/s^2)	12%	Fuel Consumption (g/s) - CO (g/s)	12%
Speed (km/h) - Engine Speed (rpm)	76%	Fuel Consumption (g/s) - NO$_x$ (g/s)	58%
Speed (km/h) - Calculated Load (%)	26%	CO$_2$ (g/s) - Speed (km/h)	36%
Speed (km/h) - Road Grade	-10%	CO$_2$ (g/s) - Acceleration (m/s^2)	57%
Speed (km/h) - VSP (W/kg)	28%	CO$_2$ (g/s) - Calculated Load (%)	49%
VSP (w/kg) - Acceleration (m/s^2)	88%	CO$_2$ (g/s) - Engine Speed (rpm)	49%
VSP (w/kg) - Engine Speed (rpm)	33%	CO$_2$ (g/s) - VSP (w/kg)	63%
VSP (w/kg) - Calculated Load (%)	79%	CO (g/s) - Speed (km/h)	3%
VSP (w/kg) - Road Grade	19%	CO (g/s) - Acceleration (m/s^2)	12%
Acceleration (m/s^2) - Acceleration x (m/s^2)	70%	CO (g/s) - Calculated Load (%)	19%
Calculated Load (%) - Engine Speed (rpm)	19%	CO (g/s) - Engine Speed (rpm)	-2%
Fuel Consumption (g/s) - Speed (km/h)	36%	CO (g/s) - VSP (w/kg)	12%
Fuel Consumption (g/s) - Acceleration (m/s^2)	57%	NO$_x$ (g/s) - Speed (km/h)	22%
Fuel Consumption (g/s) - Calculated Load (%)	49%	NO$_x$ (g/s) - Acceleration (m/s^2)	51%
Fuel Consumption (g/s) - Engine Speed (rpm)	49%	NO$_x$ (g/s) - Calculated Load (%)	61%
Fuel Consumption (g/s) - VSP (w/kg)	63%	NO$_x$ (g/s) - Engine Speed (rpm)	22%
Fuel Consumption (g/s) - CO$_2$ (g/s)	100%	NO$_x$ (g/s) - VSP (W/kg)	58%

C. Graphs of percentage of change (%) of speed, fuel consumption, CO$_2$ emissions and NO$_x$ emissions on TCM-A-3.3, TCM-A-3.7, TCM-C-1 and TCM-C-4.



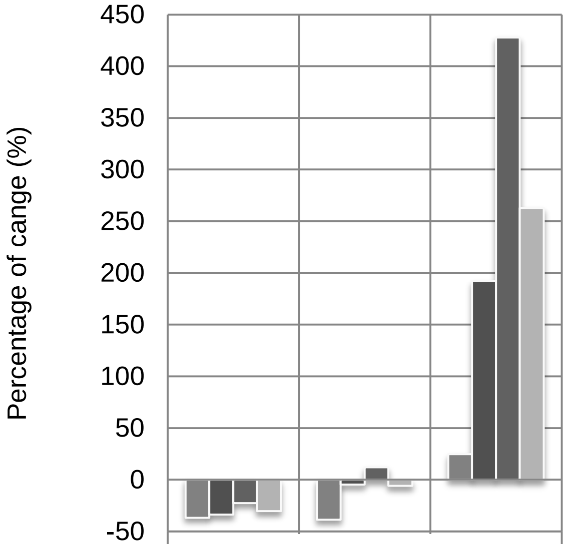
	Speed	Fuel / CO_2	NO_x
■ Before	-26	-15	-33
■ Measure	-53	62	30
■ After	17	35	40
■ Total	-20	24	14

Figure A 1 - TCM-A-3.3: Continuous Sidewalk of Arco do Cego (3rd intersection).



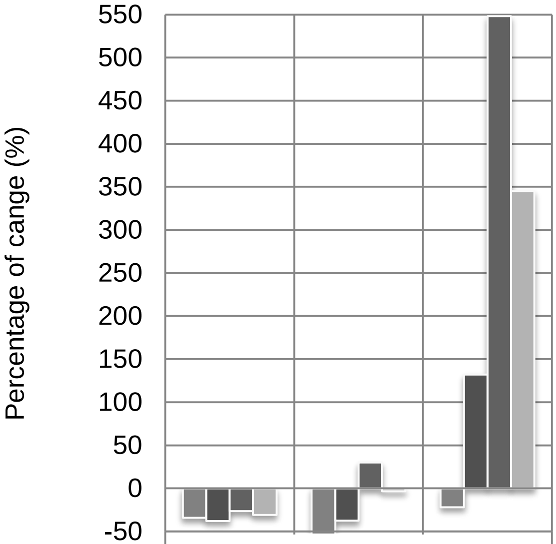
	Speed	Fuel / CO_2	NO_x
■ Before	-25	-74	-87
■ Measure	-54	6	7
■ After	-36	-20	-22
■ Total	-36	-20	-22

Figure A 2 - TCM-A-3.7: Continuous Sidewalk of Arco do Cego (7th intersection).



	Speed	Fuel / CO_2	NO_x
■ Before	-37	-39	25
■ Measure	-34	-5	192
■ After	-22	12	428
■ Total	-30	-6	263

Figure A 3 - TCM-C-1: Speed Tables of Parque das Nações.



	Speed	Fuel / CO_2	NO_x
■ Before	-34	-64	-22
■ Measure	-38	-37	132
■ After	-26	30	548
■ Total	-31	-3	345

Figure A 4 - TCM-C-4: Speed Humps of Parque das Nações.