Transportation Research Part D 36 (2015) 86–95

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Economic-environmental analysis of traffic-calming devices

Aron Jazcilevich [a,*], José María Mares Vázquez [a], Pablo López Ramírez [b], Irma Rosas Pérez [a]

[a] Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Mexico
[b] Centro de Investigación en Geografía y Geomática, Consejo Nacional de Ciencia y Tecnología, Mexico

ARTICLE INFO

Article history:
Available online 13 March 2015

Keywords:
Emissions
Traffic
Bumps

ABSTRACT

A set of indicators are proposed to determine the effect of traffic-calming devices on the environment and economy. They are based on vehicular emissions and energy consumption and are used to evaluate the viability and positioning of traffic-calming devices. First, a time window is defined on which the influence of a traffic-calming device can be determined providing a convenient frame of reference. Second, a concept of local cruising conditions is defined in order to have a basis of comparison between cases "with" and "without" traffic calming devices. The emissions considered were: HC, NOx, CO, PM_{10}, and CO_2. From the latter fuel consumption was estimated. Valuation of speed bumps on a secondary road in Mexico City was obtained as an example application of the proposed methodology.

Introduction

Emissions and energy costs due to vehicular travel have significant effects on the economy, environment, and urban planning. In this context the role of traffic-calming devices such as speed cushions, bumps, humps, and stop signs, has been questioned: Is there a conflict between the environment and traffic safety prevention? This discussion includes urban centers in developed and underdeveloped countries (Höglund and Niittymäki, 1999; Madjadoumbaye et al., 2012; Lee et al., 2013; Daham et al., 2005; Bellefleur, 2012).

Despite the importance of this problem, there is no consensus on the effects of these devices in terms of vehicle emissions. According to experiments by Daham et al. (2005), traffic-calming devices increased CO, NOx, and CO_2 emissions by 117%, 195%, and 90%, respectively, whereas Höglund and Niittymäki (1999) found that the increase in CO emissions ranged from 391% to 1551% and that the increase in NOx emissions ranged from −4% to +139%. Comparison studies by Daham et al. (2005) with comprehensive studies performed by Bellefleur and Gagnon (2011), show large discrepancies in the emission depending on the contaminant. Table 14, p. 44 in this reference shows that emission CO increases due to calming devices were between 7% to 71%, CO_2 increased between 7% to 19%, while reductions in NOx ranged from −60% to −38%. The disparity of these results may arise due to the different methodologies used in each study: emissions are dependent not only on vehicle kinetics and the technology but also on the cycle chosen and driver behavior during the experiment. This situation makes it difficult to achieve repeatable conditions.

This study proposes measurable and repeatable indicators to determine the effect of traffic-calming devices on the environment, energy consumption, and economy. Arguments are thus provided for an objective discussion to determine the effects of traffic calming devices with greater certainty. Our indicators are based on "real life" driving conditions that can

* Corresponding author.
E-mail address: jazcilev@unam.mx (A. Jazcilevich).

http://dx.doi.org/10.1016/j.trd.2015.02.010
1361-9209/

be used to evaluate the viability and positioning of traffic-calming devices. First a time window is defined in which the influence of a traffic-calming device can be determined, providing a convenient frame of reference for energy and emission considerations. Second, the concept of local cruising conditions is defined in order to have a basis of comparison between cases “with” and “without” traffic calming devices. The following emissions were considered: HC, NOx, CO, PM_{10}, and CO_2. The latter is used to obtain the fuel consumption rate via stoichiometry, from which energy-economic indicators can be obtained.

Using our methodology in conjunction with local data on vehicle flow and activity, the monetary costs and emissions of a specific traffic-calming device in Mexico City are determined. The proposed indicators lead to important conclusions upon which recommendations are made.

Material and methods

A set of definitions of quantifiable indicators is presented which will be used to environmentally and economically evaluate traffic-calming devices. All of this material was made operational in MATLAB® programs. First we analyze a typical speed vs. time profile due solely to the presence of a traffic-calming device and not due to interactions with other vehicles. The distinctive characteristics of this profile are then exploited to define a time interval to determine a convenient time and space frame of reference for the proposed indicators.

Characteristic speed and time window of a traffic-calming device: direct case

The following are the phases of the characteristic speed variation induced by a traffic-calming device: (a) a maximum approach speed that monotonically decreases and leads to (b) a minimum speed followed by (c) a recovery phase with positive acceleration until a new maximum speed is reached. These phases are shown in Fig. 1. The time window t_w is the time it takes for these phases to occur. This situation is characteristic when speed changes are due to the presence of a traffic-calming device and not due to interactions with other vehicles. It takes place during light traffic conditions and no queue is formed behind the calming device.

To obtain Fig. 1, a total of 49 passes were made through traffic-calming devices under light traffic conditions using different car technologies and weights. Distances and speeds were recorded every second using a global positioning system (GPS). It was observed that the range of value of t_w in seconds varies as function of vehicle’s power to weight ratio: for “light” vehicles the range was (17, 29), for a modern bus (26, 30), and for underpowered vehicles (30, 48). Nevertheless, as Fig. 1 shows, the characteristic phases can be discerned. This normalized graph was obtained rescaling data of each pass by dividing the time and velocity axis by corresponding maximum values and averaging all rescaled graphs.

As shown in Fig. 1, the maximum recovery speed tends to be higher than the maximum approach speed. In addition, the absolute values of the accelerations in the recovery phase are of greater magnitude than the decelerations in the approach phase. This phenomenon can be explained through the logic used in transit models, which indicates that as distances between vehicles become larger, vehicles increase their speeds (see Treiber et al., 2000). This situation occurs immediately after passing a traffic-calming device. The phases of this direct case, which are easy to distinguish, allows for the definition of time window t_w. This will be used in the following sections.

Under light traffic conditions the change in the speed of a vehicle is due only to the presence of the traffic-calming device. Thus the profile of the characteristic phases, as shown in Fig. 1, is essentially maintained. Instances of this phenomenon can be observed in traffic data collected by other authors, as in Lee et al., 2013, Fig. 2, p. 70 where in 6 of 15 passes over calming devices the proposed characteristic phases can be recognized. This situation was not fulfilled by the other passes possibly because of interaction with traffic during the approach or recovery stage, a case not considered here.

Induced work and power for the direct case

In the following discussion row arrays will be identified by italic bold and scalars by italic non-bold letters. If the time window t_w is divided into intervals Δt_w [s], the direct induced specific work w_w, or work per unit mass [J kg^{-1}], is defined by the array dot product:

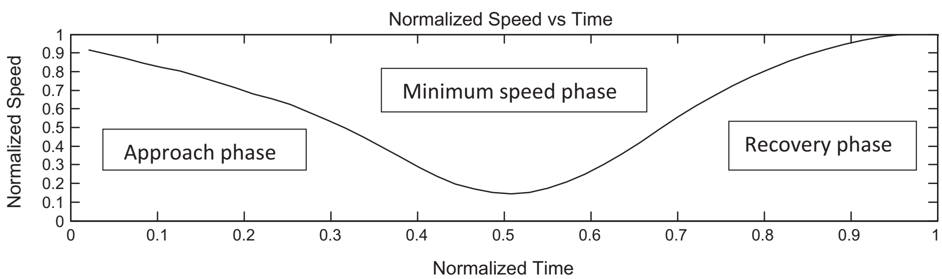

Fig. 1. Normalized time window that contains the approach, minimum, and recovery speed phases for 49 passes on a bump under light traffic conditions.

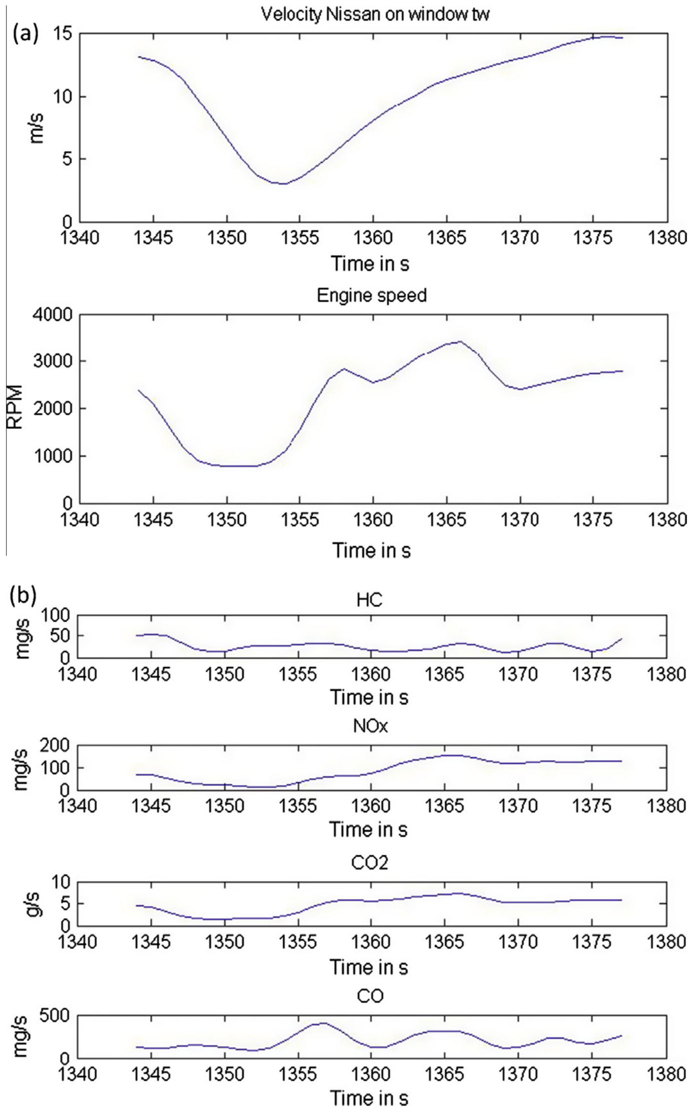

Fig. 2. Example of measurements while on t_w. On panel (a) vehicle velocity and motor speed in RPM, which indicates that the cruising speed at the end of t_w is reached after changes in the transmission gears have occurred; the engine works under lower stress than during the recovery phase. On panel (b) corresponding HC, NOx, CO_2 and CO emissions.

$$w_w(t_w) = \boldsymbol{a}_w \cdot \boldsymbol{d}_w = \sum_{i=1}^{i=N-1} a_{wi} * d_{wi}, \tag{1}$$

where $\boldsymbol{a}_w = (a_{w1}, a_{w2}, \ldots, a_{wN-1})$ and $\boldsymbol{d}_w = (d_{w1}, d_{w2}, \ldots, d_{wN-1})$ are the row arrays whose elements contain accelerations magnitudes in [ms^{-2}] and corresponding distances [m] incurred in each time step Δt_w, respectively. Therefore if $t_w = \sum_{i=1}^{i=N} \Delta t_w$ [s], the number of elements in $\boldsymbol{a}_w$ and $\boldsymbol{d}_w$ will be $N - 1$. The elements on array $\boldsymbol{a_w}$ are dependent on road data gathered for each vehicle, i.e., a bus will tend to have lower acceleration magnitudes than a lighter vehicle. The value of w_w (t_w) is then the specific work spent by traversing through the calming device. It can be obtained as a mean of several repetitions under similar traffic conditions and vehicles.

In the following, vehicular mass will be taken into account. Therefore, a fleet should be grouped in k classes according to weight.

To obtain the work W_k [J] incurred by a vehicle class k passing through the calming device, w_w is multiplied by the mass $m_k(\Delta T)$ [kg] of corresponding vehicle class passing during time interval ΔT. The time interval ΔT is the desired integration time. Then W_k is obtained by:

$$W_k(\Delta T) = m_k w_w = m_k \sum_{i=1}^{i=N-1} a_{wi} * d_{wi} \tag{2}$$

The values of m_k change for different ΔT's since it depends on the number of cars (flow) and the composition of fleet passing through as a function of time. The value of W_k includes the negative work resulting from transforming energy into heat from braking (or electricity in the case of regenerative brakes) and the positive work used by the engine to drive the vehicle and reach the recovery speed. Since W_k is sensitive to vehicle activity and flow it is a useful indicator representing the energy effect over the time to traverse the zone of influence of the calming device.

The power P_k for vehicle class k induced by the traffic-calming device in [kW] is defined as:

$$P_k(\Delta T) = m_k \left(\sum_{i=1}^{i=N-1} a_{wi} * d_{wi} \right) \Delta t_w^{-1} = m_k{}^* w_w{}^* \Delta t_w^{-1}. \tag{3}$$

The total work $W(\Delta T)$ and power $P(\Delta T)$ induced by calming device is obtained by summing over k, i.e. all vehicle classes.

These indicators can be linked to energy costs if we know the energy price per kW. It can be deduced from these definitions that the proposed indicators do not account for the energy due to friction or wind resistance.

Direct emissions induced by a traffic-calming device

Using vehicle tailpipe emissions data for a vehicle class k, an emission array $\boldsymbol{e}_{ck} = (e_{ck1}, e_{ck2}, \ldots e_{ck\,N-1})$ is formed. The units are [mg s^{-1}]. The components are registered every Δt_w when passing through t_w. The sub-index c stands for a chemical compound of interest such as CO and HC. The emissions are obtained in the field using a portable emission monitor or in a laboratory with a dynamometer. The emitted mass M_{ck} [mg] of a compound c and vehicle class k within the time window t_w is obtained via the product:

$$M_{ck}(t_w) = \Delta t_w \sum_{i=1}^{i=N-1} e_{cki}. \tag{4}$$

The direct emissions $E_{ck}(\Delta T)$ [g] of a car fleet or category k due to the presence of a traffic calming device are calculated by multiplying $M_{ck}(t_w)$ by the number vehicles of class k passing through the calming device in a specified time interval ΔT. It represents the mass of compound c emitted by a given amount of vehicles due to a calming device passing through during ΔT. The total direct emissions $E_c(\Delta T)$ for a compound c due to a calming device, is obtained by summing E_{ck} over k.

Based on the direct CO_2 emissions, i.e. E_{CO2}, the fuel consumption induced by the traffic calming device can be calculated using a stoichiometric relationship. The molecule used for the stoichiometry and the factors used to convert the CO_2 emissions in mg s^{-1} to fuel liters are listed in Table 1. Also shown there is the fuel costs used in this study.

Case without calming device: speed and local cruising conditions

To measure the effect of a traffic-calming device, is necessary to compare the results with a case in which the device "does not exist". This case was constructed as follows:

(a) The local cruising speed v_c is defined as the speed achieved at the end of window t_w. As exemplified in Fig. 2, the recorded RPMs (revolutions per minute) exerted within t_w indicate that when v_c is reached, changes in the transmission gear have already occurred. Therefore, we consider that at that moment, the operation regime of the engine approximates cruising conditions.
(b) The distance d_w, obtained for the case "with calming device" and including the characteristic speed phases, is now traveled at constant speed v_c with the corresponding emissions exerted to achieve it.

Naturally, the time to travel distance dw is different in the presence of the calming device than when traveling that same distance at a constant speed v_c; in the latter case, the time will be shorter given that v_c is a maximum velocity within the t_w window, as mentioned in Section 'Characteristic speed and time window of a traffic-calming device: direct case'.

A set of proposed *parameters such as* d_w, t_w, v_c, W, w_w, P and E_c is obtained to build statistical data to acquire a basis for comparison. Two cases are evaluated: one with the presence of a traffic-calming device where the described characteristic

Table 1
Stoichiometric factors to convert from g s^{-1} of CO_2 to liters of fuel and price per liter in the U.S., which were obtained from the EIA (Energy Information Administration), 2014.

	Gasoline (C_8H_{18})	Diesel ($C_{12}H_{23}$)	LP Gas (C_3H_8)
Stoichiometric factor	4.76×10^{-4}	3.65×10^{-4}	6.00×10^{-4}
Price per L (USD)	0.93	1.03	1.03

speed phases occur, and the case "without" the traffic-calming device in which a constant speed v_c is used to traverse d_w. As mentioned, the emissions used in this case correspond to the ones exerted when a stable v_c is reached. The distance d_w is the one obtained when the calming device is present. Because v_c is constant, the accelerations for the "without calming device case" are zero, since friction forces are not considered here.

Net emissions estimation

To obtain net emissions due to the presence of a calming device, a subtraction of the E_c's "with" and "without" calming devices scenarios is performed, thus obtaining net emissions for each *c*. By doing so, any additive experimental bias is canceled, or at least reduced, since both cases share information. After all, v_c and its corresponding emissions are taken from data while in t_w. Therefore, the difference between minimum and maximum values (range) of net emissions per vehicle type tends to be smaller than the corresponding emissions of the "with" and "without" cases. An example of this, using CO_2 emissions of the case study presented later, is shown in Fig. 3. This fact allows using the mean of the net emissions per vehicle type as a robust parameter.

Implicit is the fact that the net estimation is obtained supposing that vehicular flux with and without cases remains the same. The proposed methodology does not evaluate the effect of calming device on traffic flow, but only the effects of a calming device on emissions and energy while maintaining same vehicular flux.

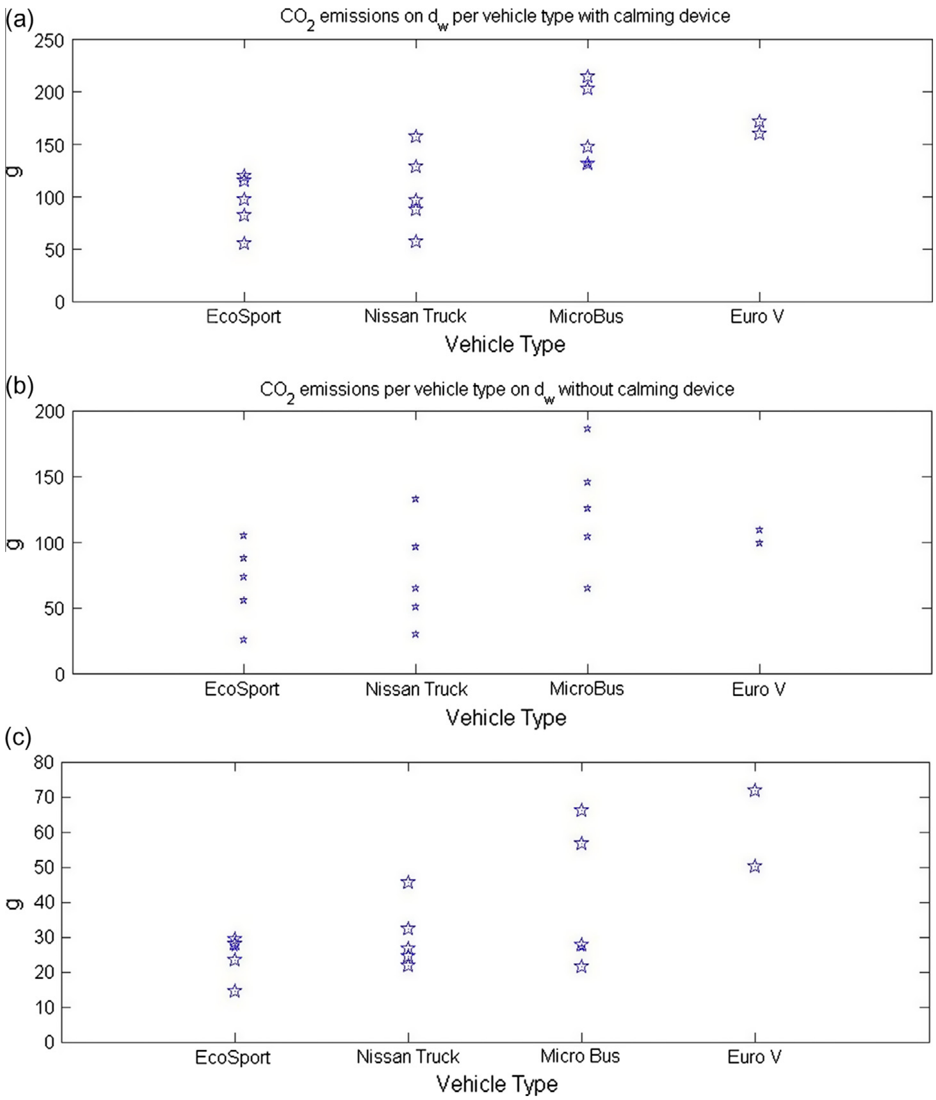

Fig. 3. Mass of CO_2 in *g* emitted per pass per vehicle type. On (a) with calming device, in (b) without calming device (using v_c), in (c) the net emission. Ranges are reduced in the latter case.

Site specific evaluations

To evaluate a specific calming device, net emissions estimations and power indicators such as W_k, P_k, E_{ck}, are related to local vehicular flux (number of vehicles per unit of time) and activity (fleet composition varying with time). To accomplish this, the flux of a fleet category or vehicle type k is obtained by multiplying its activity percentage with general flux data. This flux is then multiplied by the net emissions and power indicators corresponding to that type. The results are net emissions and power indicators as a function of time due to the calming device for a fleet category. If this is done for all vehicle categories, its sum will result in the evaluation of the calming device.

The time resolution of the evaluation will be the same as of the flux and activity data. For example, if activity and flux are provided in the order of minutes, the evaluation is possible for every hour, or $\Delta T = 3600$ s. If traffic patterns changes are important, day of the week can be specified. For example days can be classified as weekend or weekdays, as will be done in the following case study.

Case study: A bump traffic-calming device in Mexico City

The case study used bumps as the traffic-calming devices located on a secondary road in Mexico City. The road considered in the study is used by private cars, medium (microbuses) and heavy public transport vehicles (diesel) as well as freight trucks (diesel and gasoline). The described methodology was applied to evaluate these devices in terms of emissions, energy consumption, and economic benefits.

Selection of vehicles and technologies

Four vehicles were selected to perform passes on the traffic-calming devices to be evaluated. Fig. 4 shows photographs of the vehicles. Relevant characteristics of vehicles are described in Table 2. These vehicles are representative of different weights and technologies of the vehicular fleet of Mexico City and of the type of cars passing over the calming device to be analyzed. They form four k vehicle categories. With the exception of the DINA-Euro V, all these vehicles are widely available in the Mexican market. The microbus is a typical public transport vehicle in the city and does not use modern electronic fuel injection system nor catalytic emission filters.

Obtaining the emissions data

The HC, NOx, CO, CO_2, and PM_{10} (in the case of diesel) emissions were obtained every second using an Axion portable emission monitor (PEM), which was built by Global MRV, with an integrated GPS (Global MRV, 2014). Ballast was used for the Euro V bus, which is equivalent to 70% of its capacity. The microbus was loaded with 960 kgf, the NISSAN-Pickup truck carried 4 passengers (a total of approximately 280 kgf) and the private automobile (EcosSport) carried two passengers weighing altogether 150 kgf approximately.

The location of the devices used for this evaluation is shown in Fig. 5. From the 49 passes used to obtain Fig. 1, a subset of 24 corresponded to the bumps of interest. From this subset, seventeen were selected based on being able to distinguish the characteristic speed phases. The discarded cases showed interaction with traffic ahead or before reaching the approach stage. Data of passes run on the bumps for each vehicle are described in Table 3.

Net E_c emission and percent variation of with and without bump cases are shown. Units are in [mg] or [g] because the emissions per second are multiplied by the time it takes to travel the window d_w. It is worth noting that gas emissions generated by the microbus are the highest when compared with that of the other vehicle types. However, the greatest net emissions ,i.e. largest difference between the emissions due to the presence of the traffic calming device and those corresponding to travel at the local cruising speed was found for PM_{10} for the diesel technology (DINA), with a 670% increase. Similarly, for gasoline technologies Nissan-Pickup, Ford Eco-Sport, CO emissions exhibited significant increases. NOx emissions exhibited a dissimilar behavior because for the microbus and the Eco-Sport, the presence of the traffic-calming devices reduced these emissions only by about 3%. For the case of HC, in general, the traffic-calming devices increased the emissions significantly, with the exception of the Nissan-Pickup, for which there were reductions of only 5%. The largest change in CO_2 emissions was found for the DINA bus due to its greater weight.

(a) (b) (c) (d)

Fig. 4. (a) Dina-Euro V Bus, (b) Microbus, (c) Nissan Pickup truck and (d) Ford Eco-Sport.

Table 2
Vehicle characteristics used in the field experiments.

Make-model	Year	Fuel	Engine displacement (L)	Transmission	Cylinders	GVW [tons]	Passenger mass [kgf]	Technology
Nissan Pickup	2008	Gasoline	2.4	5-speed manual	4	2.55	280	Tier I
DINA	2012	Diesel	8.9	5-speed automatic with retardants	6	20.3	1,224.5	Euro V
Microbus	2010	LP Gas	5.7	4-speed manual	8	5	960	Carburetor
Ford Eco-Sport	2004	Gasoline	2.0	5-speed manual	4	2.55	150	Tier I

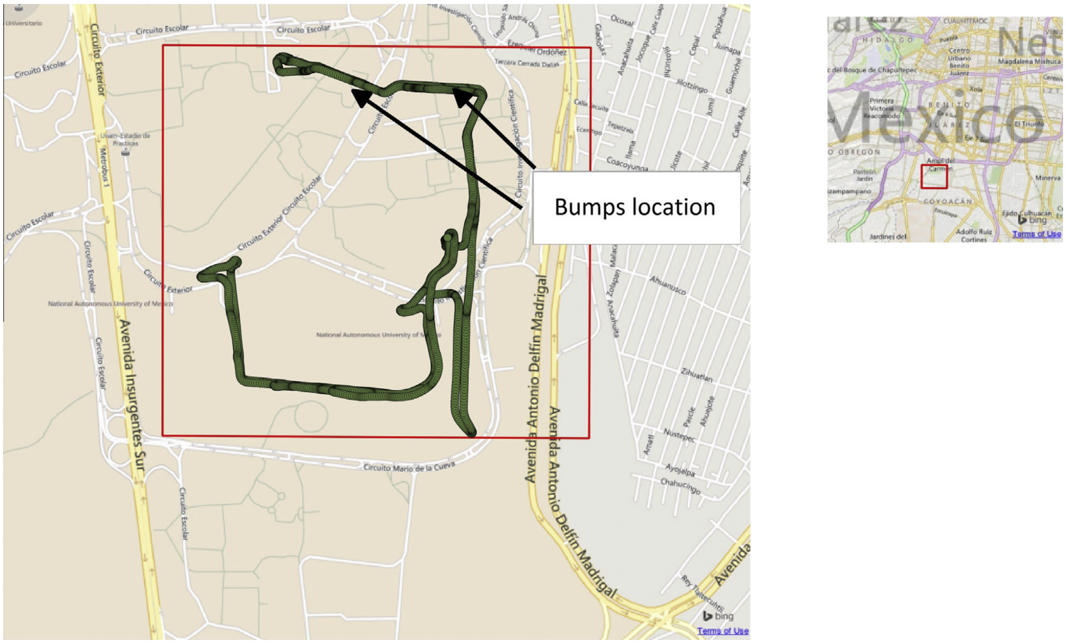

Fig. 5. Location of traffic-calming devices (bumps) on a secondary street in Mexico City used for the case study.

Table 3
Net emissions E_{ck} per vehicle: (with traffic-calming device) – (without traffic-calming device) and percent variation: ((with traffic-calming device) – (without traffic-calming device)/(without traffic-calming device)) × 100.

Vehicle	HC [mg] (%)	NOx [mg] (%)	CO [mg] (%)	CO_2 [g] (%)	PM_{10} [mg] (%)
Nissan Pickup (Runs over bump: 5)	1182 – 1220 = –37 (–3)	1583 – 1287 = 296 (23)	5151 – 2986 = 2986 (100)	105 – 75 = 30 (40)	–
DINA Euro V (Runs over bump: 2)	368 – 259 = 109 (42)	826 – 789 = 37 (4.6)	582 – 428 = 154 (36)	165 – 106 = 61 (58)	3.54 – 0.46 = 3.08 (670)
Microbus (Runs over bump: 5)	7259 – 5144 = 2114 (41)	1579 – 1664 = –84 (–5)	24,760 – 20,540 = 4220 (20)	165 – 104 = 39 (31)	–
Ford Eco-Sport (Runs over bump: 5)	424 – 310 = 114 (37)	236 – 273 = –36 (–13)	1585 – 672 = 913 (135)	94 – 69 = 24 (35)	–

To compare emissions and energy use due to the presence of these specific traffic-calming devices and corresponding local cruising conditions, i.e., the “no bump case”, the definitions provided in Section ‘Material and methods’ were used.

Vehicle activity and flow

Vehicular flow was determined using traffic measurements obtained in the area being studied in September of 2010. Activity was obtained by observing videos on a Wednesday and a Thursday between 11:00 and 12:00 LST. Since activity

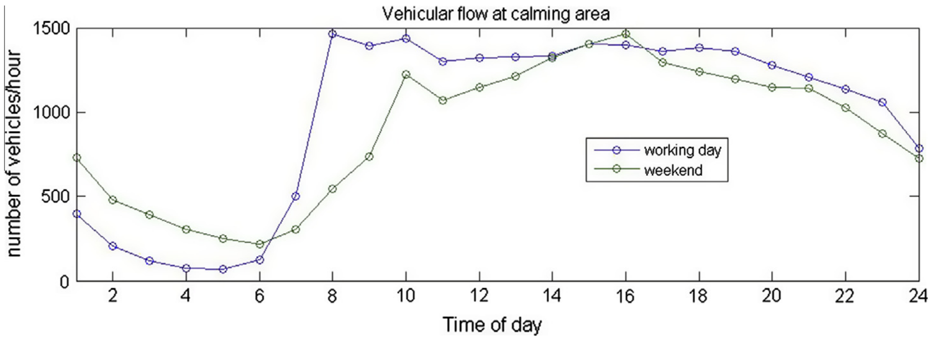

Fig. 6. Vehicle flow (number of vehicles per hour) during weekdays (Monday to Friday) and weekends.

was observed to be similar on all days, for simplicity it was assumed to be constant. Therefore, the vehicle activities for the different technologies were as follows: Ford Eco-Sport, 85%; Nissan Pickup, 5%; microbus, 5%; and DINA Euro V, 5%.

Fig. 6 shows the hourly vehicle flow on the study road. Flow is differentiated from weekends and weekdays (Monday through Friday). The peak hourly flows are similar for both, although they occur at different times: during the weekdays, the maximum occurs at 7:00 LST, and during weekends it occurs at 16:00 LST. Night traffic during the weekend is higher than that during the weekdays in the study area.

Energy-environmental evaluation

Based on the methodology described in Section 'Material and methods' in conjunction with the data on vehicle flow and activity from Section 'Vehicle activity and flow', the following results on emissions and energy-economic expenditures due to the direct influence of traffic-calming devices in the study area were obtained.

Using data of Table 3, vehicle flow and activity for 313 weekdays and 104 weekend days, Table 4 was obtained. It shows the direct annual net emissions (E_c) for HC, NOx, CO, CO_2 and PM_{10} in [kg year^{-1}] considering same activity and vehicular flow of with and without cases.

Table 5 shows the results on fuel efficiency and consumption due to the traffic calming devices and those incurred at cruising speeds inside d_w. It also shows the specific power w_w due to the traffic-calming devices, as defined in Section 'Induced work and power for the direct case'. It can be observed that the fuel efficiency is reduced by the presence of the traffic-calming devices, and as a result, consumption increases. The greatest net fuel consumption increase due to the bumps occurred for the DINA EURO V due to its greater weight. Taking into account that its activity is 5%, its yearly net consumption is disproportionate. This is shown in Fig. 7 where the net CO_2 yearly contribution of each vehicle type ($E_{CO2\ k}$) on calming area is presented. The specific power is higher for the Eco-Sport due to the speed at which it was driven.

From the consumption results, a conservative rule can be established: for a private automobile the net fuel consumption is 10 mL. Fig. 8 shows the power P induced by the traffic-calming device according to the definition in Section 'Induced work

Table 4
Net annual emissions considering the flow and activity in Fig. 3.

HC [kg year^{-1}]	NOx [kg year^{-1}]	CO [kg year^{-1}]	CO_2 [kg year^{-1}]	PM_{10} [kg year^{-1}]
9934.0	773.9	16324.0	719280.0	12.84

Table 5
Fuel efficiency [km L^{-1}] and consumption [L] averages due to the traffic-calming devices per vehicle per pass: (with traffic-calming device) – (without traffic-calming device) and percent variation, ((with traffic-calming device) – (without traffic-calming device)/(without traffic-calming device)) × 100. The last column lists the averages of specific power w_w in Watts per gram [Wg^{-1}] induced by the traffic-calming device.

Vehicle	km L^{-1} (%)	L (%)	W g^{-1}
Nissan Pickup	4.10 – 6.21 = –2.11 (–34)	0.035 – 0.05 = .014 (28)	8.41
DINA	3.34 – 5.34 = –2.00 (–37)	0.06 – 0.038 = 0.22 (58)	5.59
Microbus	2.24 – 3.11 = –0.87 (–28)	0.099 – 0.075 = 0.024 (32)	5.25
Ford Eco-Sport	4.00 – 5.50 = –1.50 (–27)	0.045 – 0.030 = 0.012 (40)	9.62

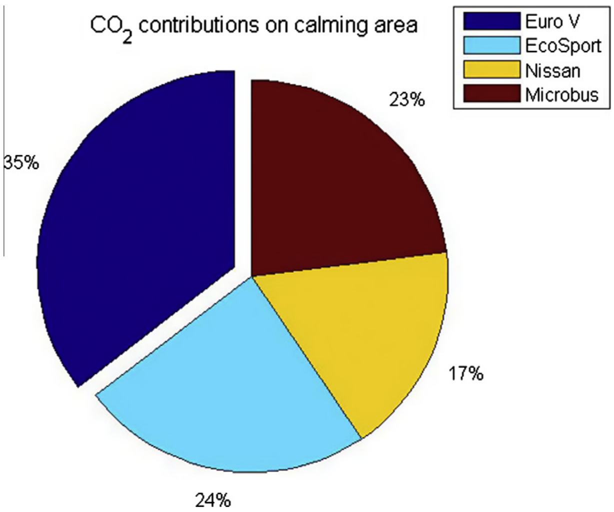

Fig. 7. Percentage of yearly net CO_2 ($E_{CO2\ k}$) contributions per vehicle on evaluated bump.

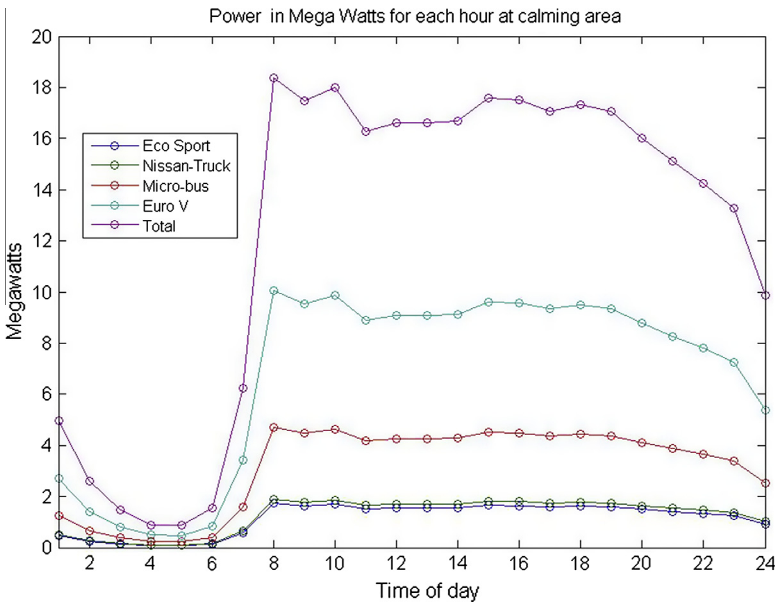

Fig. 8. Net power in Megawatts induced by the traffic-calming device considering vehicle flow and activity (fleet composition).

and power for the direct case'. The power was calculated by taking into account the mass of each vehicle type and the flow shown in Fig. 6. These data were obtained from the measurements described in Section 'Vehicle activity and flow'. The induced power P can be comparatively used to determine the (direct) effect on vehicle transit of the traffic-calming device.

Table 6 calculates the monetary fuel benefit per day and year of not having the traffic calming device. It is determined using the consumption for each vehicle type calculated in Table 5 and the price per liter of gasoline, diesel, and LP in the

Table 6
Energy benefit valuation.

Daily benefit (USD)		Annual benefit (USD)		
Weekday	Weekends	Weekdays	Weekends	Total
926.70	848.80	241686.00	130592.00	372278.00

U.S. from Table 1. A total of 365 days were used including 104 weekend days. This is another indicator that can be comparatively used to determine the effect of traffic-calming devices.

Conclusions

The results of the case study using the proposed environmental-energy indicators demonstrate that the use of traffic-calming devices on roads with a high vehicle flow causes the following:

- Increased emissions, particularly PM_{10} from diesel vehicles.
- Extraordinary costs due to energy consumption.

It was determined that energy consumption is especially aggravated by heavy transport. For a private TIER 1 automobile, the increase in fuel consumption due to traffic-calming devices is approximately 10 mL. It was also found that the more modern the vehicle technology, the lower the emissions and fuel consumption relative to its weight and power due to the bumps. These experiments indicate that the microbus exhibits emissions and fuel consumption disproportionate to its weight and power due to the bump.

Due to the vehicle flow of the case study, the energy-economic benefit was about 370 thousand USD per year. If we consider that the construction cost of a pedestrian bridge accessible for handicapped users and pedestrian-cyclists is approximately 250 thousand USD, its construction to avoid traffic-calming devices in that location can be economically justified in one year, while preserving pedestrian safety. Other measures, such as intelligent traffic lights, could also be considered and resulting emissions can be compared with the provided methodology.

In addition to inducing emissions, particularly PM_{10} from diesel vehicles, the presence of traffic calming devices on high-flow roads result in substantial private expenditures in fuel and vehicle maintenance, hindering investments in clean technology. This is against what urban policies should strive for. Traffic calming devices in these roads are therefore in contradiction with urban policies focused on improving the environment.

This study showed that there is no conflict between safety and the environment, as suggested in the introduction: the energy benefit of not having traffic-calming devices in high-flow roads justifies the construction of urban infrastructure as long as it offers safety and comfort to pedestrians while avoiding exposure to emissions when traveling near traffic calming devices.

Future work will focus on the following objectives: enlarging the population for a more complete statistical analysis, application of the proposed methodology to different type of calming devices and vehicle technologies, and expanding the scope to the indirect case, i.e., to evaluate the emissions and energy costs due to the presence of calming devices considering their role in forming traffic queues.

Acknowledgements

To Secretaría de Ciencia y Tecnología e Innovación del Distrito Federal, SECITI GDF 2051101. To Pablo Álvarez Sánchez and Roberto Galicia Morales for their help during field tests.

References

Bellefleur, O., 2012. Urban Traffic Calming and Air Quality: Effects and Implications for Practice. National Collaborating Centre, Institut National se Santé Publique, Quebec. http://www.ncchpp.ca/docs/AirQuality_TrafficCalming_En.pdf.

Bellefleur, O., Gagnon, F., 2011. Urban Traffic Calming and Health. National Collaborating Centre for Health Public Policy, Quebec.

Daham, B., Andrews, G.E., Li, H., Partridge, M., Bell, M.C., Tate, J., 2005. Quantifying the Effects of Traffic Calming on Emissions Using on-Road Measurements. SAE Technical Paper 2005-01-1620.

Global MRV, 2104. http://globalmrv.com/ (accessed June 2014).

Höglund, P.G., Niittymäki, J., 1999. Estimating Vehicle Emissions and Air Pollution Related to Driving Patterns and Traffic Calming. Submitted Paper for the Conference Urban Transport Systems, Lund, Sweden, V. 7.

Lee, Gunwoo, Joo, Shinyee, Cheol, Oh, Choi, Keechoo, 2013. An evaluation framework for traffic calming devices in residential areas. Transp. Res. Part D 25, 68–76.

Madjadoumbaye, J., Fokwa, D., Tchemou, G., Ngopnang, R.B.P.B., Tchewou, T.T.T., 2012. Critical analysis of speed bumps: case study of the Triangle Yaoundé-Douala Bafoussam-Yaoundé highway in Cameroon. Int. J. Emerg. Technol. Adv. Eng. 2 (6), 457–463.

Treiber, M., Hennecke, A., Helbing, D., 2000. Congested traffic states in empirical observations and microscopic simulations. Phys. Rev. E 62 (2), 1805–1824.