

Developing Eco-Driving Strategies Considering City Characteristics

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1. Introduction

One of the challenges of the developed societies is to foster low carbon mobility models, looking at social equity and fair distribution of wealth criteria. It is, in short, the challenge of sustainability. For this reason, sustainable mobility means ensuring that our transport systems respond to economic, social and environmental needs, minimizing their negative repercussions (Government of Spain, 2010).

In 2017, the transport sector contribution to EU-28 greenhouse gas emissions was 28.5 % of total. Emissions from transport in 2016 were 26 % above 1990 levels despite a decline between 2008 and 2013 (EEA, 2018a). Emissions need to fall by around two thirds by 2050, compared with 1990 levels, in order to meet the long-term 60 % greenhouse gas emission reduction target as set out in the 2011 Transport White Paper (EC, 2011). Achieving the 2030 targets will require new and expanded policies and approaches to energy efficiency in the Member States that can keep their energy consumption in check (EEA, 2018b).

Countries may act in several key areas in order to reduce transport sector GHG emissions. A comprehensive transport-sector GHG reduction strategy should at least address the following four areas:

- 1) Reducing the demand for transport: control of land uses to avoid car dependency, increasing load factors and balancing modes in mobility patterns.
- 2) Mode share: measures facilitating less GHG intensive modes such as public transport and non-motorised modes.
- 3) Fuel choice: measures aiming to use of technologies for alternative fuels and new energy sources different than petrol.
- 4) Fuel efficiency: foster efficient technologies for vehicles and traffic management, traffic congestion abatement measures and eco-driving (OECD, 2008).

In this context, eco-driving emerges as an operational decision of drivers to maximize fuel efficiency and, consequently, reduce GHG emissions (Sivak and Schoettle, 2012). The literature shows that the efficiency of eco-driving varies widely depending on the external circumstances and learning methods (Huang et al., 2018). The reduction of CO₂ emissions before and after receiving eco-driving instruction in several field trials varies from 10% to 0.5% depending on the road type, i.e., highways or urban roads (Alam and McNabola, 2014). Traffic flows and road slope as external factors have direct influence on eco-driving efficiency (Wang and Boggio-Marzet, 2018). Therefore, eco-drivers should adopt specific strategies according to different cities context and distinct road conditions and traffic volumes.

Most of the investigations done so far focus on measuring very specific impact of particular type of cars and rad. But the results from this specific case study approach are very difficult to generalize and transfer to other urban contexts.

This paper presents a research aiming to compare the impacts produced by adopting eco-driving in different cities, type of vehicles, road segments and drivers features. It intends to deepen understanding of the influence of city size and driving characteristics on the effectiveness of eco-driving. Therefore, the aim of the research is to compare the general changes in fuel consumption, CO₂ emissions and driving patterns in terms of city and road type in order to develop specific eco-driving strategies.

The field trials have been conducted in two Spanish cities (Madrid and Caceres), which in the central and the west part of the Country. 24 drivers of both gender, with different year of driving experience, drove two different fuel type of vehicles- gasoline and diesel- along roads of different characteristics at various time periods during one month. During the experiment, drivers attended an eco-driving course. Thus, it enables to compare the impacts of eco-driving before and after the training for two cities.

After this introductory section, Section 2 presents the methodology for testing the impacts of eco-driving in both cities Madrid and Caceres. Section 3 analyses the results and compares them with previous studies. The final part includes the main conclusions and possible policy recommendations based on these results.

2. Methodology

In order to develop specific eco-driving strategies considering cities' characteristics, this paper evaluates eco-driving short-term impacts of a training programme on fuel savings and reduction of CO₂ emissions in two different cities. The methodological framework is shown in Figure 1.

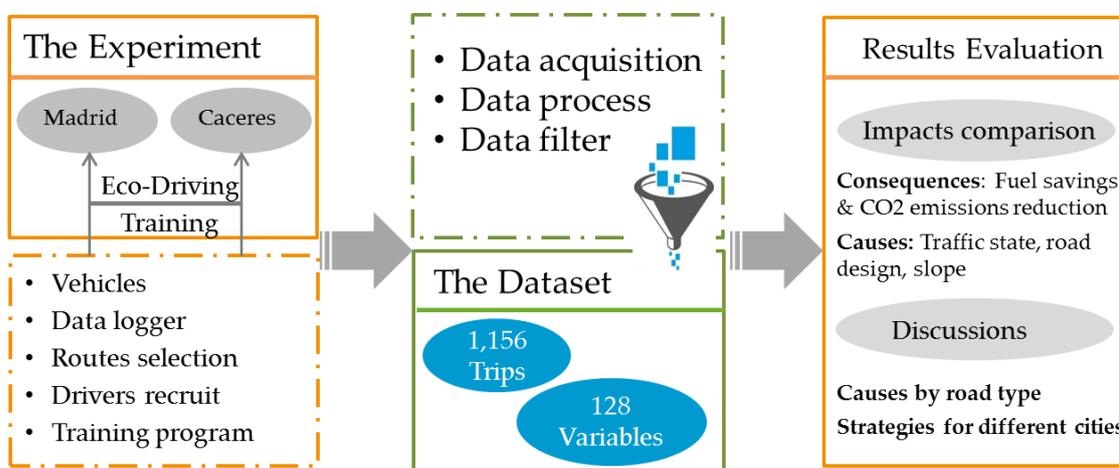


Figure 1: Research Framework.

The research is based in real life experiments, and the methodology consists of three steps: data acquisition, dataset creation through data processing and filtering, analysis of results by evaluating impacts before and after eco-driving training.

Firstly, two eco-driving case studies were carried out in parallel in two Spanish cities (Madrid and Caceres). Madrid is the capital city of Spain and has a population of 6.5 million inhabitants and a land area of 8,030 km², while Caceres is a relatively small city with 95,000 inhabitants covering an area of 30 km². As a consequence, the cities have very different road characteristics and traffic flows. The experiment consisted of 4 field trials, two in each city, two without and two with eco-driving. 24 drivers were performing the trials following pre-established routes composed by different road sections, according to infrastructure capacity and traffic conditions. The trial took place in April-May 2017 with two vehicles: a diesel-fuelled Opel Astra and a petrol-fuelled Fiat 500. The test was first performed with drivers driving normally along pre-established itineraries. Then, after drivers attended an eco-driving training, a second set of car-runs following the same itineraries of the first driving period.

Data were recorded second by second through an on-board logging device (OBD-Key) (KBM Systems Ltd., London, UK), preinstalled in each vehicle. Through this, we have been able to know the instantaneous value of GPS position of the vehicles and instantaneous values of several driving patterns during the whole test (i.e. instantaneous speed, acceleration, deceleration, engine speed.). Once collected all data recorded, the VSP-Vehicle specific power model has been applied to estimate the instantaneous fuel consumption of each vehicle (more details in part 2.4). Then, data have been processed and statistical values of them have been calculated through the software R. Through the same software and Google Geo, we were able to split each itinerary

covered, into road sectors with homogeneous road section. In this terms, we could later perform the analysis of results depending on road type (Table 1, Table 3)

Thus, after the data cleaning and the data process, the sample is composed by 1,156 trips, corresponding to 8,140 km (5,959 km in period 1 and 5,232 km in period 2), each one characterized second by second by 128 different variables.

Finally, the results evaluation has been focused on the impact of eco-driving in terms of changes in fuel consumption and CO₂ emissions between Period 2 (after eco-driving training) and Period 1 (before training). Results are presented in the next section 3.

Ten different routes were selected -six for Madrid and four for Caceres- to cover different traffic and infrastructure conditions: moderate or steep slopes and congested or fluid traffic flows. The image below, shows the location of the field trials in both cities of Madrid and Caceres.

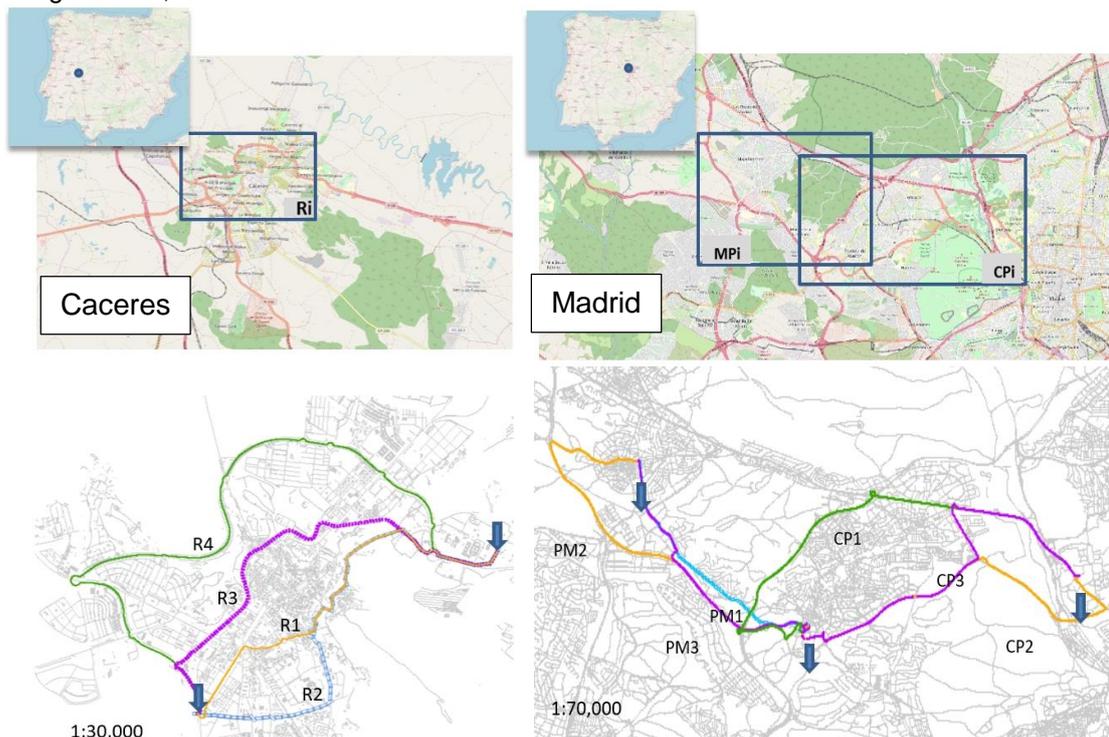


Figure 2: Monitored itineraries in the data collection campaign in Madrid and Caceres.

Roads with common characteristics are used both in Madrid and Caceres for the sake of comparative analysis. They correspond to three different road typologies: *local street*, *urban collector* and *major arterial*. The results obtained for these types of routes serve to compare the efficiency of eco-driving in both cities. Table 1 includes the main characteristics of these roads.

Table 1: Information on the common circulation routes in both cities

Road Type	Lanes	Speed Limit (km/h)
Local street	1 x 1	50
Urban collector	2 x 2 separated by barrier. Parking both sides	30/50
Major arterial	2 x 2 separated by barrier	50/80

2.1 Case study of Caceres

The city of Caceres is quite small and can be crossed from side by side in less than 15 min. Four alternative routes with different Level of Service (LOS) (U.S. Department of Transportation, 2013) were chosen to cross the city following itineraries with different characteristics and traffic volumes. They can be ordered in terms of their increasing LOS (from lowest to highest), as follows:

Route 1 (local road) runs along urban streets and passes right through the heart of Caceres city centre. It is 6.1 km long, and its travel time is around 15 min. This route has a dual carriageway with a median. Speed is limited to 50 km/h. It is regulated by traffic lights and suffers some congestion problems at peak hours.

Route 2 (urban collector road) is 6.7 km long and its travel time is about 14 min. It is one of the most important avenues in Caceres as it provides access to the bus station, conference centre, sports arena, mortuary, and hospital, leading to some traffic delays. It also has a dual carriageway with a median, but due to its urban character, the speed limit is 50 km/h and 30 km/h in several sections.

Route 3 (perimeter road) is the old bypass road, which is already integrated in the urban network. It also has a two-lane dual carriageway and a median or is demarcated by a continuous double line. The speed limit is 50 km/h. It has a length of 6.7 km and a travel time of about 13 min. It has almost no congestion.

Route 4 (Major arterial road) follows the outer city bypass. It has a length of 10.3 km and can be travelled in about 12 min. It is the longest and quickest route. It runs through the north of the city with a two-lane dual carriageway with a median. Intersections are in the form of roundabouts and pedestrian crossings regulated by traffic lights. Speed limits vary between 80 km/h and 40 km/h. Traffic is usually fluid all day.

2.2 Madrid Case Study

Two itineraries, located in the Northwest of Madrid with different road sections and alignments, were selected to guarantee a variety of driving performances and traffic characteristics in the sample. The two itineraries have a moderate slope and connect the Madrid city centre with two municipalities in the Madrid Region (Pozuelo and Majadahonda), where 92% of daily trips are made by car (Wang and Monzon, 2016).

The itineraries cover the main road types with different functionalities, including highway, major arterial road, urban collector road, and local road. With reference to the image above, (Fig. 2), itinerary CPi (Centre to Pozuelo, both directions) contains three parallel routes (i.e., CP1, CP2, and CP3) consisting of mixed highways with different levels of service. Itinerary MPi (Majadahonda to Pozuelo, both directions) also has three routes (i.e., MP1, MP2, and MP3) that combine highway with typical urban arterial roads to the suburbs, and contain several roundabouts and pedestrian crossings.

2.3 Driver Selection, Scheduling, and Eco-Driving Training

Twenty-four drivers (twelve in each city) of different sex were recruited in a wide range of ages (Mean = 30.15) and driving experience (Mean = 10.30). All of them participated in an eco-driving training in the middle of the experiment, so they could deploy these techniques during the second driving period and we could compare the results obtained with the first one.

An analysis of key performance indicators (KPI) was used to assess drivers' performance before and after the course, its relation with fuel consumption, and the ways to incentivize better performance for top decision managers.

During the driving test, six people were assigned to each vehicle, with two people taking turns to drive (driver and assistant, changing every hour) who iteratively performed trips along the selected routes. Each couple of drivers covered a driving shift and drove 4 hours a day; each day there were three different driving shift. Thus, each vehicle has been driven 12 h a day to obtain enough

data on the different traffic situations (free circulation, moderate traffic, and congestion) and weather conditions (rain, fog, etc.).

2.4 Fuel consumption and emissions calculation

The value related to fuel consumption was calculated based on the VSP-Vehicle Specific Power model, which is a convenient single measure that represents road load on a vehicle, being an accredited methodology to characterize vehicles and driving profiles using real-world data (Coelho et al., 2009). Informally, it represents the ratio between the power demand of the vehicle and its mass. Knowing the instantaneous speed, acceleration and road slope, this model provides the instantaneous power demand of the vehicle according to the following formula, developed by Jimenez-Palacio in 1999.

$$\text{VSP} \left[\frac{\text{W}}{\text{kg}} \right] = \frac{\text{Power}}{\text{Mass}} = \frac{\frac{d}{dt} (E_{\text{kinetic}} + E_{\text{potential}}) + F_{\text{rolling}} * v - F_{\text{aerodynamic}} * v}{m} =$$

$$= v(1.1 * a + 9.81 * \text{grade} + 0.132) + 3.02 * 10^{-4} * v$$

in which: E_{kinetic} is the kinetic energy; $E_{\text{potential}}$ is the potential energy; F_{rolling} is the rolling resistance force; $F_{\text{aerodynamic}}$ is the aerodynamic resistance force; v is the instantaneous speed (m/s); m is the mass (kg); a is the acceleration (m/s²); grade is the road grade (m/m).

Then, each second of driving has been associated to a VSP mode, each one related to a certain value of fuel consumption, according to Faria et al. (2017) it's possible to correlate every mode with fuel consumption and emissions by using the following table (Faria et al., 2017).

The value related to CO₂ emissions was converted from the value of fuel consumption using the emission factor (equal to 3.169 for both diesel and gasoline) extracted from the "Air Pollutant Emission Inventory Guidebook 2016" (EEA, 2016) for petrol and diesel light vehicles.

2.5 Impacts comparison method

The evaluation of the impact of eco-driving focuses on changes in fuel consumption and CO₂ emissions between Period 2 (after eco-driving training) and Period 1 (before training).

Effects of the training programme in terms of the type of vehicles, drivers and road type in both cities are firstly checked. Through a multiple regression analysis (Coloma et al., 2018), we concluded that, RPM, negative and positive acceleration and speed are closely associated with the fuel consumption throughout the trip. An additional variable related to traffic conditions (95th percentile of recorded speed) is also analysed in order to understand the influence of traffic on eco-driving efficiency. Table 2 presents an overview of the selected parameters, their units, and the corresponding abbreviations

Table 2: Description of the parameters selected for measuring eco-driving impacts

Parameter Type	Description	Code	Unit
Fuel consumption and emissions	Average fuel consumption	avg_fc	l/s
	Average CO ₂ emissions	avg_CO ₂	g/km
Driving performance	Average speed	avg_speed	km/h
	Average RPM	avg_rpm	rpm
	time with acceleration more than 0.83 m/s ^s	Pacc_3	s
	time with deceleration less than -0.83 m/s ^s	Pdec_3	s
traffic intensity	95 th percentile of instant recorded speed	V ₉₅	km/h

The analysis is extended then by exploring the changes in the value of the parameters in the different scenarios: specific road types with similar characteristics in both cities. These results will show the influence of the size of a city on the efficiency of eco-driving, considering not only the savings in fuel consumption and CO₂ emissions, but also the changes achieved in the driving behaviour through eco-driving.

3. Analysis of Results

This section presents the impacts of eco-driving training. First it explores the overall impacts of eco-driving training regardless the city, along with the changes in driving performance. Then, it shows the specific impacts according to the three road types selected in Madrid and Caceres to investigate the combined influence of city size and eco-driving in the different situations of the test trials.

The performance features of the driving tests in both cities aggregated are shown in Table 3, along with the experimental statistics of distances driven by route and each vehicle.

Table 3: km-driven per vehicle, road type and test period.

Road type	Non eco-driving (period 1) (trips/km)				Eco-driving (period 2) (trips/km)			
	Astra (diesel)	Fiat (gasoline)	Total trips	Total km	Astra (diesel)	Fiat (gasoline)	Total trips	Total km
Local street	467	539	1006	1035	499	480	979	985
Urban collector	114	168	282	394	126	150	276	395
Major arterial	212	241	453	1,208	241	225	439	1,096

3.1 Overall Impacts of Eco-Driving (after training course)

Figure 3 shows the reduction (%) of the different driving parameters analysed due to eco-driving in the three types of road common to the cities of Madrid and Caceres.

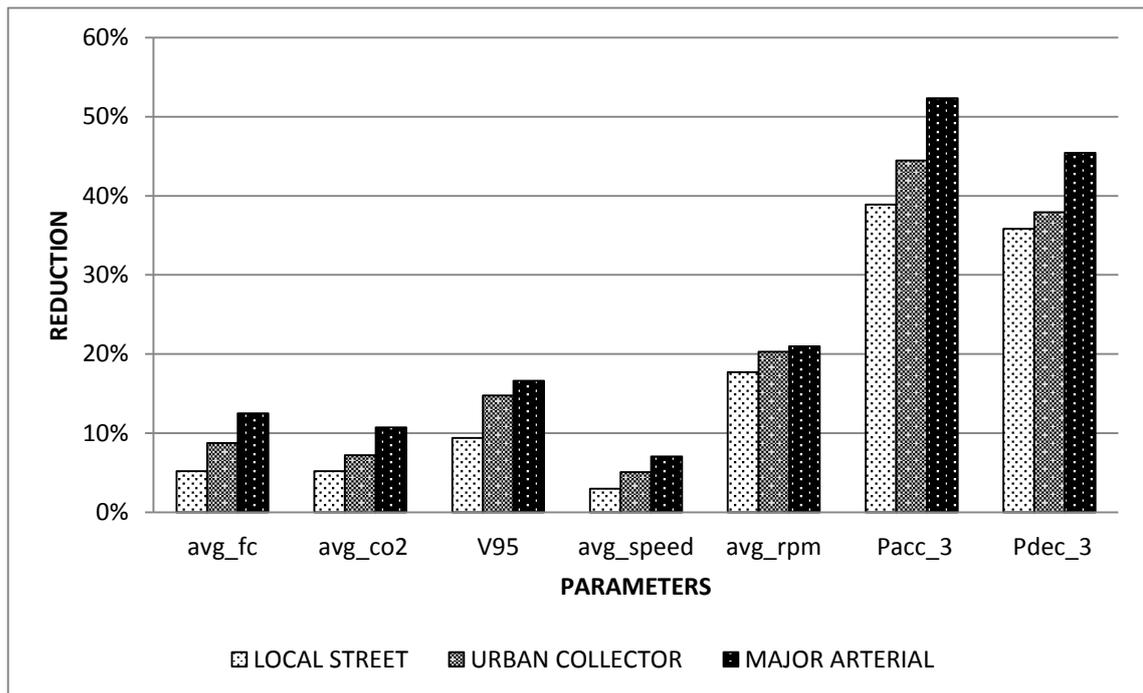


Figure 3: Eco-driving impact on traffic and emissions parameters

Fuel consumption and CO₂ emissions are always reduced with the eco-driving, with higher savings on the roads with the highest LOS (major arterial) and lower on the lower level (local street). The savings values are between 5% and 12%, being consistent with other studies values (Johansson, 1999; Andrieu and Saint Pierre, 2012).

The eco-driving produces important reductions in all the driving parameters analyzed in this research. The greatest savings are again linked to the best level of service, being "major arterial" which provides the most reduction value and "local street" the least.

Accelerations and decelerations are the parameters that produce the greatest reductions in their values (36-52%) while the average speeds are those that reduce their value less with the eco-driving (3-7%).

3.2 Impacts of Eco-driving according to city and road type.

3.2.1 Fuel Consumption and emissions

Figures 4 and 5 show the reduction in fuel consumption and CO₂ emissions produced by eco-driving in the two cities and for the three types of roads studied.

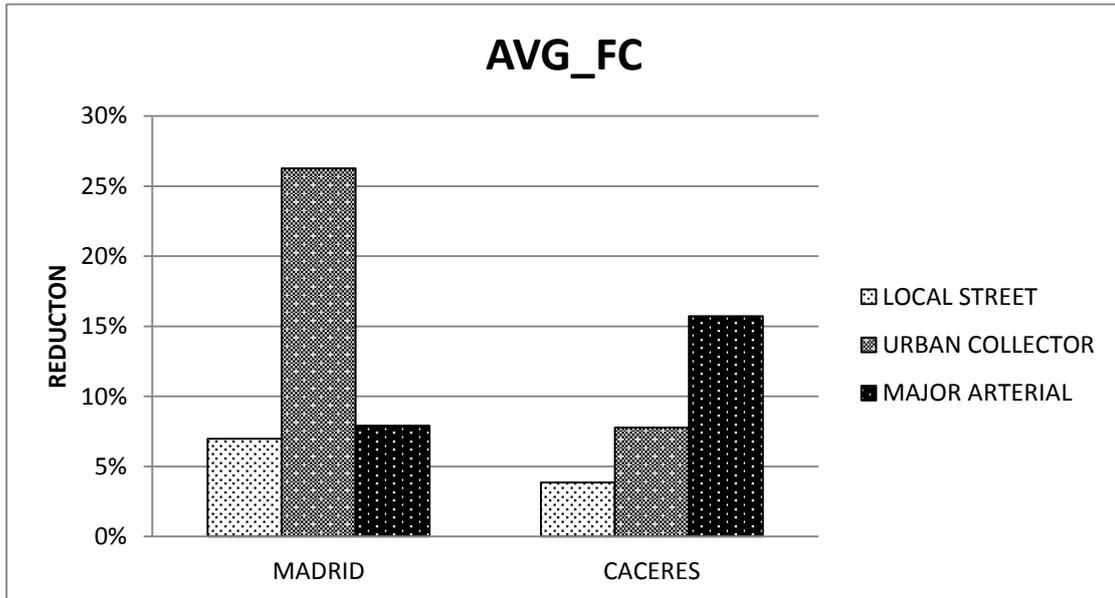


Figure 4: Average fuel consumption.

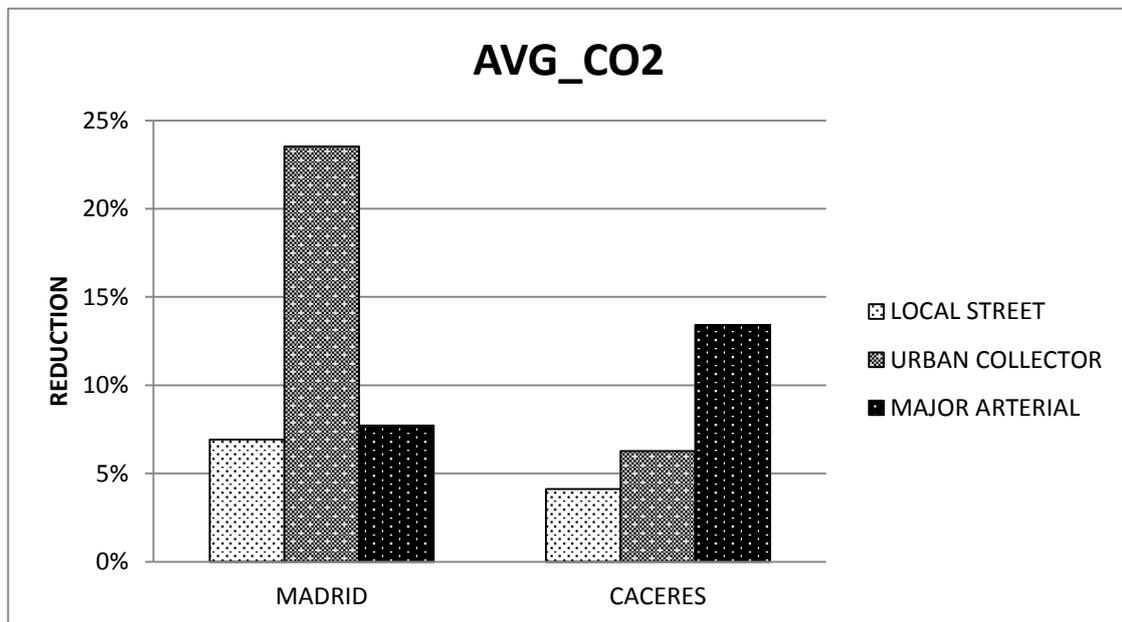


Figure 5: Average CO₂ emissions.

Caceres shows reductions in consumption and CO₂ emissions for all road types, increasing the savings with the LOS. In Madrid the result is more dispersed. Local street produces less savings, comparing with urban collector and major arterial. As known, in Madrid these type of streets is frequently congested, this suggests that eco-driving is not effective in traffic jams (congestion). This type of negative effects on saturated roads have been obtained in other studies carried out

in Madrid (García-Castro and Monzon, 2014). On the other hand, the effect of duplicating a lane of circulation (urban collectors) is very favourable in fuel consumption and CO₂ emissions for the urban collector, also observing a positive effect in the major arterial.

3.2.2 Impact on driving performance

Figures 6, 7, 8 and 9 show respectively, the reduction that the eco-driving produces on the parameters average speed, average rpm, accelerations and decelerations, which are the parameters with the greatest influence on fuel consumption.

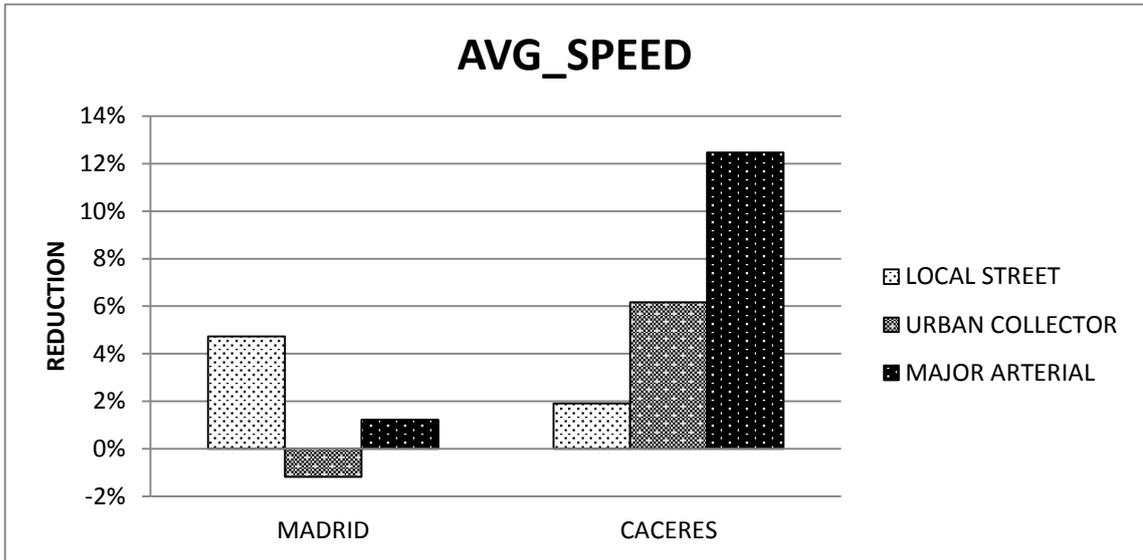


Figure 6: Changes on average speed.

The eco-driving reduces the average speed of circulation in general in all types of road. These values are much higher in the Caceres roads than Madrid, since they suffer to a lesser extent, the effects of traffic congestion.

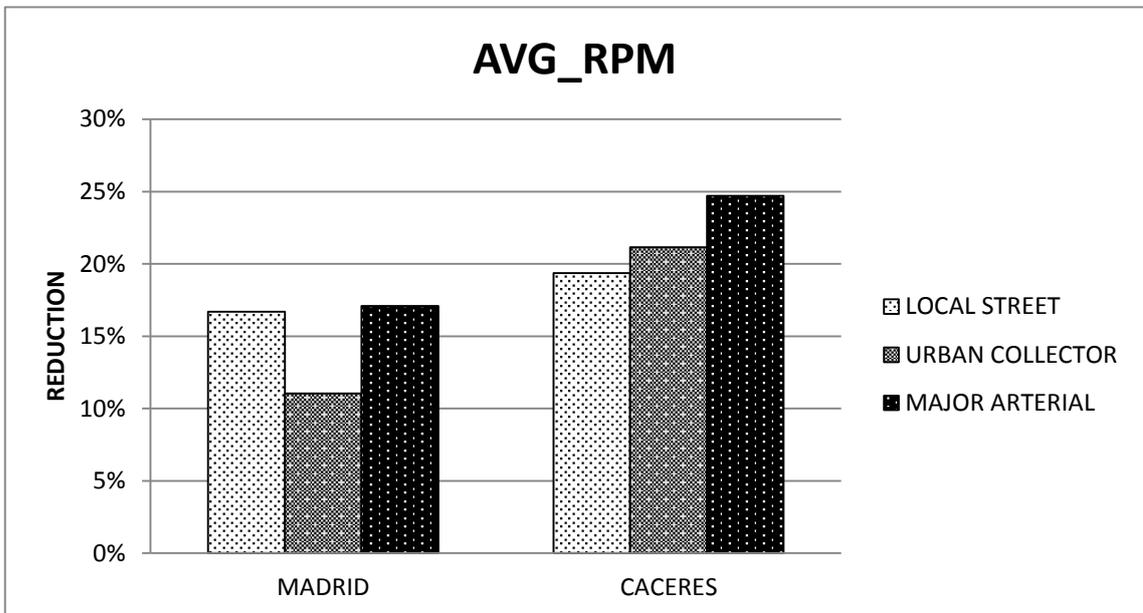


Figure 7: Changes on average RPM.

RPMs are reduced in both cities and for all types of roads with eco-driving. The reduction is also greater in the less congested city

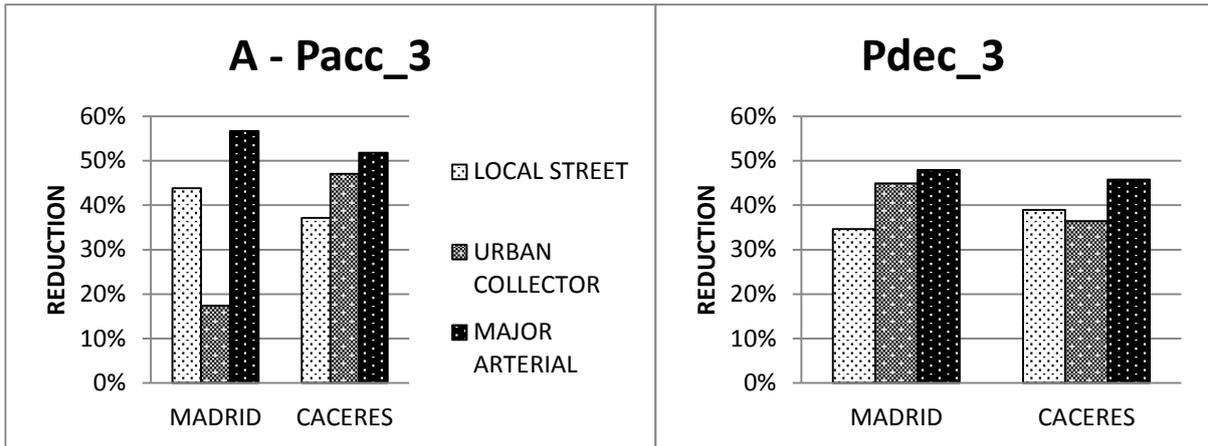


Figure 3: Reduction of time in accelerations and deceleration higher than 0.83 m/s².

Eco-driving produces smoother driving that is reflected with the accelerations and decelerations that take place. In all type of road and for both cities, important reductions are produced with the savings being proportional to the LOS.

3.2.3 Impacts on traffic intensity

Figure 9 shows the reductions produced in the V₉₅ with the eco-driving.

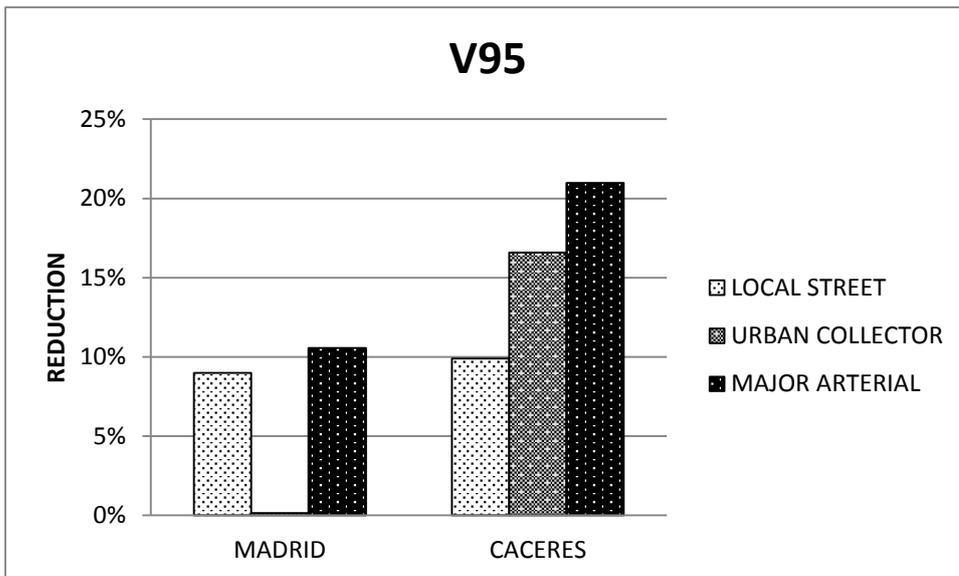


Figure 4: Speed reduction for V₉₅.

A generalized reduction of the V₉₅ speed is observed for both cities, which increases with the LOS, except for urban collector that in Madrid remains constant. In our research, for each type of homogeneous road section, the 95^o percentile of the speed distribution is assumed as free flow speed characterizing the sector. Thus, results indicate that eco-driving reduces traffic speeds, being greater these reductions in the roads with higher level of service.

4. Conclusions and Policy Recommendations

4.1 Main findings

This research studies the effects of eco-driving on fuel consumption, CO₂ emissions and driving parameters in two very different cities of Spain, Madrid and Caceres.

The results obtained show that eco-driving techniques are very effective in reducing fuel consumption and CO₂ emissions, both in large congested cities and in small cities. The savings values achieved in both cities are in a range of 5% and 12%. This efficiency grows with the road LOS and decreases with the size of the city, being the small cities not congested, the most effective in the application of these techniques. On low LOS roads, which are usually congested, the efficiency of eco-driving decreases and can even produce more congestion and increase fuel consumption.

The effectiveness of eco-driving in a large and congested city like Madrid is different. Eco-driving techniques have been found to be inefficient on local streets with one lane. However, these same roads, when the lane is duplicated (urban collector), improve the reduction of consumption and emissions. Finally, the effects of saving fuel on higher LOS roads (major arterial), are similar to those obtained in a small city such as Caceres.

4.2 Policy recommendations

For small and non-congested cities like the city of Caceres, it is recommended to apply the eco-driving techniques in any type of road, being more efficient the savings of fuel consumption and CO₂ emissions in roads with higher LOS.

For large cities like Madrid, it is recommended to duplicate lanes whenever it's possible, since this measure improves the LOS of the road and the efficiency in the application of eco-driving techniques. As in small cities, also in Madrid the major arterials result to be the perfect roads to perform eco-driving.

Therefore, Public Administration should encourage the use of these techniques and train the drivers from the driving schools.

4.3 Future developments

In future investigations it would be advisable to measure if the results of this study could vary when the number of eco-drivers increase. The benefits of one single eco-driver appear to be relevant for both type of cities. However, it is dubious how the impacts could change with high percentage of cars making eco-driving in the three type of road sections and city categories. If the traffic density could change as to have impact on the emissions, and which one.

Acknowledgements

This work was supported in part by the national R & D programme (Ministerio de Economía y Competitividad) under the Eco-Traffic Project "Medición y Modelización de Eco-Driving táctico y operacional". Ref TRA2016-76485-R. The authors also acknowledge the collaboration of the City of Caceres in the data collection process

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