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Eco-Driving Effects Depending On The Travelled Road. Correlation Between Fuel Consumption Parameters

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Abstract

Eco-driving has been shown to be a very efficient driving technique to reduce consumption and CO_2 emissions into the atmosphere. This paper investigates firstly, depending on the road type of each route studied and its level of service, how eco-driving affects the fundamental driving parameters through a field test in Caceres. Secondly, presents two steps of analysis regarding the ¨effectiveness¨ of eco-driving. The first step is to conduct a factorial analysis in order to underline the theoretical parameters related to fuel consumption and road conditions. On the second step, the effect of experimental condition like traffic state, road slope is examined and ordered by means of regression analysis.
The first part of the research concludes that maximum speed is always lower in any road type when driving in eco mode. The eco-driving, therefore, helps to limit the excesses of speed in these types of roads. Average rpm is always lower in eco mode than non-eco. As the level of service is lower, the average rpm decreases are also reduced. Negative accelerations are lower in eco mode than non eco. This produces a more comfortable driving and a lower fuel consumption.
The second part of the research revealed a strong and significant relationship between independent variables and fuel consumption. The analysis of beta standardized coefficients shows that the fuel consumption is strongly affected by the road slope. Besides, more congestion and more RPM were associated with an increase in fuel consumption. Conversely, less negative acceleration, more speed is associated with a decrease in fuel consumption along the trip in urban area.

Keywords: eco-driving; climate change; emissions; traffic performance

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1. Introduction

Greenhouse gas (GHG) emissions and overconsumption of energy resources pose a global problem in terms of both their causes and consequences (Ramanathan and Ferg, 2009). The transportation sector is one of the largest emitters of GHG (Emberger, 2015), despite advances in the field of engine technology and improvements in fuel quality. This sector accounted for 25.6% of global energy consumption in 2015, and transportation energy use is expected to increase by 1.1% every year until 2040 (EIA, 2017).

Public authorities have different ways of achieving environmental objectives: promoting social changes in mobility patterns to achieve greater use of cleaner modes, improving vehicle technology and fuel (Bottiglione et al., 2014), reducing the number of motorized journeys through demand management (Li et al., 2016), and using information and communication technologies (ICT) to improve transport efficiency (Lin and Nguyen, 2016).

However, these objectives can only be achieved with the contribution of the consumer. Some policies need to be accepted by the public, while others depend directly on the mode of driving and on travel decisions. These measures include efficient driving or eco‑driving, which has major potential for individual fuel savings, e.g., Xia et al. (2013) developed an eco‑driving velocity planning methodology, showing individual vehicle fuel consumption and CO_2 reductions of around 10‑15% depending on corridor parameters (including traffic volume and speed), and on the other hand, Ahn and Rakha (2008) achieved significant improvements to energy and air quality (6–7% fuel and CO_2 savings) when drivers utilize a slower route although they incur additional travel time.

The Spanish Energy Saving and Efficiency Action Plan 2011–2020 (IDAE, 2011) considers the efficient driving of private cars to be a key measure for achieving energy savings over the next few years. Specifically, by 2020 this practice is expected to produce significant energy savings in Spain of 493 ktoe (5.5% of the total estimated savings for the entire transportation sector) and to avoid emissions for a value of 1703 kt2. In order to achieve its objectives, the plan lays down some clear guidelines to encourage the rational use of transport modes and to promote demand management policies for route optimization and efficient driving.

Real‑life automotive research done in EU context has identified the potential of driving styles for reducing consumption and CO_2 emissions (Fiat, 2010). It also highlights the need to provide real‑time data to use the infrastructures in the most efficient way possible. There are many devices and technologies available for travel planning but whose potential has not yet been quantified to enable a more efficient use of transport infrastructures (including eco‑driving and eco‑ routing).

In this context, efficient driving aimed at reducing fuel consumption by modifying driver behaviour has increased in importance since the 1990s. However, this simple definition includes many concepts and strategic actions, depending on the level of decision‑making considered (Sivak and Schoettle, 2012):

- Strategic decisions: vehicle selection and maintenance.
- Operational decisions: driving style geared to maintaining a constant speed, smooth acceleration, etc.
- Tactical decisions: route selection and vehicle load.

Since driving pattern varies to great extent over specified road conditions in urban transport system, it differs the impacts of eco-driving on fuel savings. Thus this research aims to analyze according to the descriptive characteristics of the road (local street, urban collector, minor arterial and major arterial) the variation of the different fundamental parameters of driving (maximum speed, average speed, average rpm, average deceleration time) driving in eco-driving mode in a small city like Caceres, Spain. In the second part a factorial analysis and regression analysis are made to determine and rank the explanatory variables regarding the ¨effectiveness¨ of eco-driving.

The greatest potential for eco‑driving policies appears to be in areas where traffic levels are not very heavy, and yet most studies have analysed the impact of eco‑driving in large cities suffering chronic congestion problems. To fill this gap, we set out to study the effects of eco‑driving in a small city, where traffic flow is not conditioned by peak hours or congestion, in relation to driver’s profile and perception through a post-trip survey.

2. Methodology

In order to achieve the aim of this research, a field trial of eco‐driving were tested under real traffic conditions, in a campaign conducted to collect data on different road types (urban roads and access roads to the city) under different traffic conditions in a small city such as Caceres (less than 100,000 inhabitants). The field test phases were as follows:

1. A data campaign was organized to collect data on driver behaviour following routes along different types of city roads under distinct traffic conditions. Four itineraries were selected with different levels of service (LOS). Level of Service is a quality measure describing operational conditions within a traffic stream; these conditions affect to speed and travel time, freedom to maneuver, traffic interruptions, and comfort and convenience. The test was first performed with drivers driving normally, and then a second set of car runs was recorded after they had taken an eco‐driving course, following the same routes and at the same times of day (reference).
2. Individual driving variations produced by eco‐driving were recorded using an OBD‐key (KBM Systems Ltd, London, United Kingdom) installed on board (see Section 2.5), the corresponding CO2 emissions savings were estimated also.
3. Drivers were surveyed to capture changes in their way of driving and perceptions before and after they were trained in eco‐driving techniques.

2.1. Case Study: City of Caceres, Spain

The city of Caceres is located in western Spain and has a population of 95,000 inhabitants in an area of 30 km². It is a historic city with a high density of monuments and a unique medieval urban layout and was named a World Heritage site by the UNESCO in 1986 (UNESCO, 2017). The city today has succeeded in maintaining a moderate and constant economic growth (Caceres has had a GDP growth of 4.5% in 2015, 3.1% in 2016, and a population reduction of 323 inhabitants in the year 2017), despite a slight decline in its population, as has occurred in other similar cities and which is to a large extent due to the current economic crisis.

The city of Caceres needs to implement measures to encourage further use of public transport and pedestrian mobility to make it even more sustainable. Although policies for environmental protection and emission reduction have already been applied in the historic town centre, which is mostly restricted to pedestrians, they need to be extended to the more car‐dependent surrounding areas to achieve sustainability targets for the whole city.

2.2. Selecting Routes to Represent Different Road Types and Traffic Conditions

The city of Caceres is quite small and can be crossed from side by side in less than 15 min.

Four test routes were selected with the same origin and destination. They all start from the train station located in the western part of the city and end at the School of Technology (University of Extremadura) in the eastern part.

For each of these routes, different types of roads have been set according to the number of lanes in each direction, the existence or not of parking space, their maximum speed and the city's crossing area. Classified from lowest to highest level of service (US Department of Transportation, 2013), we have the following classification of the roads for each route:

1. Local Street. This road goes through the interior of the city, its carriageway may have one or two lanes in each direction with median and normally one-sided parking. Its driving speed is limited to 50 km/h.
2. Urban collector. Road that surrounds the city crossing the neuralgic points of the city. Its carriageway has two lanes for each direction with median and parking on both sides. Its driving speed is limited to 30 km/h.
3. Minor arterial. This road goes through the outskirts of the city. Its carriageway has two lanes for each direction and has no parking space. Its driving speed is limited to 50 km/h.
4. Major collector. Road that is outside the city and surrounds it. Its carriageway has two lanes for each direction and it is separated by a median. Traffic is regulated by traffic lights and roundabouts. Its driving speed is limited in a range of 40-80 km/h.

2.3. Driver Selection, Eco-Driving Training, and Assignment

Twelve drivers of different sexes were recruited in a wide range of ages and driving types, comprising eight men and four women aged between 21 and 44, in a fairly representative sample of the driving population in the city of Caceres. The 2016 directory of the general traffic management (DGT, 2016a) indicates that the range between 25 - 44 years exceeds 51% of the census. In addition, the distribution of male/female drivers is 62% and 38%, respectively. The 12 drivers received an eco - driving course so they could deploy these techniques during the second driving week and compare the results with the first week's driving.

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 four selected routes. They drove 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.).

The driving turns were adjusted to cover peak hours according to the mobility records for Caceres. The following driving turns were selected:

- 1st period. Morning peak: 7:30–11:30 am
- 2nd period. Lunchtime: 12:00–4:00 pm
- 3rd period. Evening peak: 4:30–8:30 pm

The first test was done from May 2 to May 5, 2017, and the second the following week, from May 9 to May 12, after taking the eco - driving training course.

2.4. Experimental Car Data Collection

Caceres has a fleet of 48,554 passenger cars (approximately one vehicle for every two people), of which 60% are diesel and 40% gasoline. Two different cars were used for the data campaign, an Opel Astra 1600 cc diesel and a Fiat 500 1200 cc gasoline. These vehicles correspond to the small (Fiat 500) and medium (Opel Astra) car segments, which represent approximately 75% of the fleet in Caceres (DGT, 2016b). The sample is therefore quite representative of the Caceres fleet composition. Driving was done following the experimental car method in order to reproduce the average driver behaviour.

2.5. Measured Variables

Data was collected using an OBD - key (OBDKEY, 2017) installed on board to obtain and store the parameters that define driving profiles. The geographical location of the vehicle was recorded at all times.

The following parameters were collected before and after the drivers took the eco - driving training course:

1. GPS position (longitude and latitude) and distance travelled (km);
2. Travel time (h);
3. Instantaneous speed (km/h);
4. Fuel consumption (l);
5. Number of stops, rpm, acceleration, and deceleration (m/s2).

These data are necessary to measure the variation in speeds, accelerations and emissions produced by eco - driving at the individual level.

3. Results

3.1. Study of the driving parameters by road type.

3.1.1 Average speed and maximum speed

The variation of the average speed and maximum speed in the different types of roads for the four routes has been studied. The results show that the maximum speed is always lower in any road type when driving in eco mode (figure 1). The highest decrease in maximum speed occurs in the major arterial (19.11%) since it is a road that surrounds the city with speed limited to 80 km/h and drivers usually exceed this limit driving in non eco mode. The eco-driving, therefore, helps to limit the excesses of speed in these types of roads.

The smallest decrease in maximum speed occurs in the urban collector (6.41%), since this type of road has its speed limited to 30 km/h as it passes through the strategic points of the city, such as hospitals, sports centers, schools and the City Council, for road safety, has recently proceeded to limit the speed in this type of roads.

In local street (12.81% decrease) and minor arterial (decrease of 17.37%), eco driving also controls those maximum driving speeds, which is a very positive effect to consider in road safety policies.

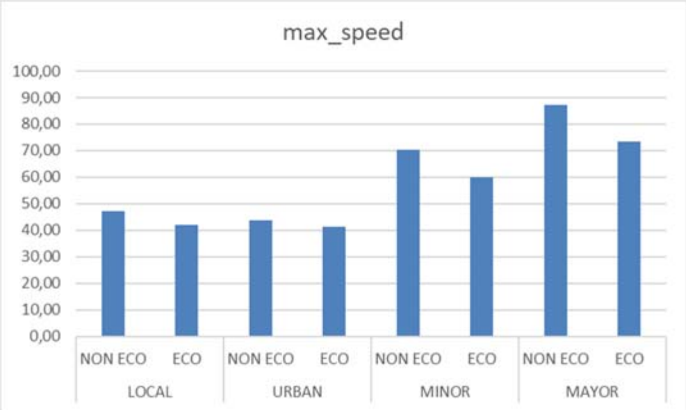

Fig. 1. Analysis of the maximum driving speed (km/h) in the different types of roads with eco and non eco-driving.

3.1.2 Study of the rpm

The analysis of the revolutions per minute of the vehicle shows that the average rpm is always lower in eco mode than non-eco (figure 2). The greatest reductions occur in the major artery (30%). As the level of service is lower, the average rpm decreases are also reduced, with values of 25% in minor arterial, 21.76% in local street and 8.32% in urban collector. It can be concluded that as the level of service of the road increases, the vehicle's rpm decreases in greater percentage between eco and non eco-driving.

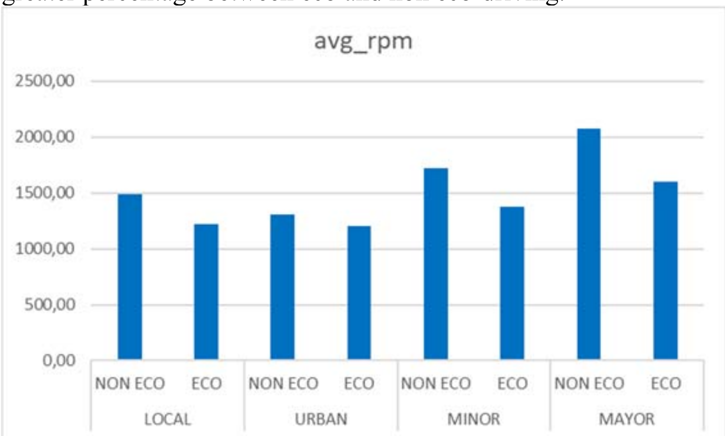

Fig. 2. Analysis of the maximum revolutions per minute with eco and non eco-driving in the different types of roads.

3.1.3 Study of negative accelerations

In all road types the average decelerations are lower in eco mode than non-eco. This means that eco-driving is a much smoother ride, in which decelerations (braking) are always reduced. This produces a more comfortable driving and a lower fuel consumption.

The most significant decrease in negative accelerations is in the major arterial, where they are reduced by 61%. In the minor arterial it is reduced 33%, in the urban collector 25% and in the local street 23%. This decelerations decrease among different road types corresponds to the decrease in maximum speeds in each of the roads.

3.2. Factorial analysis and regression analysis.

This section presents two steps of analysis regarding the ¨effectiveness¨ of eco-driving. The first step is to conduct a factorial analysis in order to underline the theoretical parameters related to fuel consumption and road conditions. On the second step, the effect of experimental condition like traffic state, road slope is examined and ordered by means of regression analysis.

3.2.1 Factorial analysis

Table 1 presents the association of parameters and defines three components (or say factors), explaining a variance of 80% of recorded trips from the field test. This result is used to identify main exploratory factors in driving context. The first components achieved through the factorial analysis is called inefficient driving behavior which is main defined by deceleration rate (avg_acc_neg), variability (sd_acc_neg), maximum speed (max_speed), percentage of speed over 70 km per hour (perc_spd_70), average RPM (avg_rpm) and average speed (avg_speed). This definition is coincided with eco-driving rules that were summarized in many previous studies (Barkenbus, 2010; Dogan et al., 2011; Ecowill, 2013 and Stromberg et al., 2015). The second component named eco-driving under congestion is explained by lower percentage of speed over 70 km per hour (perc_spd_70), lower average RPM, longer stop time per km under 5km/h (st_t_aux_5_per_km), more number of stops (Nstop_aux_5_per_km), less average speed, longer travel time and finally higher fuel consumption per kilometer. The last component strongly associates to more slope grade and higher fuel consumption. Multicollinearity of underlying factor analysis was previously checked (Bartlett test: Sig = 0.00; MSA = 0.766), and varimax rotation was used to find the factors.

Table 1. Results of the factorial analysis.

Variable	Factor Inefficient driving behaviour	Eco driving under congestion	Road gradeability
ave_acc_neg	-0.933		
sd_acc_neg	0.878		
max_speed	0.848		
perc_spd_70	0.741	-0.480	
max_rpm	0.723		
avg_rpm	0.708	-0.436	
st_t_aux_5_per_km		0.932	
Nstop_aux_5_per_km		0.911	
avg_speed	0.445	-0.823	
duration_recorded		0.774	
avg_slp			0.949
AVG_FC_KM		0.413	0.874

3.2.2 Regression analysis.

Using the 9 parameters were addressed in the factorial analysis, a multiple regression was conducted to examine the effect on fuel consumption in order to rank the hierarchical structure among driving pattern factors and road environment factors.

The summary and the corresponding coefficients of the multiple regressions are given in table 2 and 3 respectively. The analysis revealed a strong and significant relationship between independent variables and fuel consumption ($F = 232.102$, $p < .001$, $R^2 = .830$). As can be seen in Table 3, the analysis of beta standardized coefficients shows that the fuel consumption is strongly affected by the road slope (avg_slp). Besides, more congestion (stop time and number of stops) and more RPM (maximum) were associated with an increase in fuel consumption. Conversely, less negative acceleration (especially average and to a larger extent, standard deviation), more speed (maximum and average) are associated with a decrease in fuel consumption along the trip in urban area. Number of stops per kilometer, other parameters of congestion (p=.07 and 20), and RPM (max, p = .20) were not significant variables.

Table 2. Summary of the regression model.

Summary of the Regression Model						
Model	R	R square	R square adjustajustado	Estimate standard error	Change statistics R square change	F change
1	0.911b	0.830	0.826	0.882	0.830	232.102

Table 3. Regression on fuel consumption.

Coefficients					
Model		Non-standardized coefficients		Standardized coefficients	
		B	Standard error	Beta	t
1	(Constant)	7.381**	0.388		19.007
	max_speed	-.030**	0.005	-0.225	-6.309
	avg_speed	-.051**	0.010	-0.245	-4.930
	avg_slp	61.522**	1.858	0.708	33.109
	avg_rpm	0.001**	0.000	0.169	4.104
	max_rpm	0.000	0.000	0.079	2.340
	sd_acc_neg	-4.229**	1.008	-0.223	-4.196
	Nstop_aux_5_per_km	0.338*	0.124	0.107	2.729
	st_t_aux_5_per_km	0.013	0.006	0.094	2.341
	ave_acc_neg	-5.163**	0.922	-0.342	-5.602

4. Conclusions

This research is completed by analyzing the eco-driving impacts according to the descriptive characteristics of the road. Through the factorial analysis and multiple regressions, we address the key explanatory variables on fuel consumption; thereby confirming the results in 3.1 on driving pattern changes.

Regarding the changes on driving pattern after adopt eco-driving, this research concludes that maximum speed is always lower in any road type when driving in eco mode. The eco-driving, therefore, helps to limit the excesses of speed in these types of roads.

Difference between average speeds are not as significant as those of the maximum driving speeds for eco and non-eco mode and the different types of road studied. Average rpm is always lower in eco mode than non-eco. As the level of service is lower, the average rpm decreases are also reduced.

Negative accelerations are lower in eco mode than non eco. This means that eco-driving is a much smoother ride, in which decelerations (braking) are always reduced. This produces a more comfortable driving and a lower fuel consumption. This decelerations decrease is linked to the decrease in maximum speeds in each of the roads.

The second part of the research revealed a strong and significant relationship between independent variables and fuel consumption. The analysis of beta standardized coefficients shows that the fuel consumption is strongly affected by the road slope. Besides, more congestion and more RPM were associated with an increase in fuel consumption. Conversely, less negative acceleration, more speed is associated with a decrease in fuel consumption along the trip in urban area.

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