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Multivariate analysis of fuel consumption related to eco-driving: Interaction of driving patterns and external factors

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A R T I C L E I N F O

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A B S T R A C T

Eco-driving, as individual car-use behavior, is a cost-effective way of improving fuel efficiency, reducing CO_2 emissions and other air pollutants like NO_x. This paper aims to expand the knowledge on the short-term impacts of eco-driving by developing an analytical model of the key factors that explain fuel consumption and eco-driving, and to examine their relations in greater depth. Additionally, this paper analyses the effects on drivers' stress levels after eco-driving.

An eco-driving field trial is applied to collect real data of 1156 trips, using two vehicles and 24 drivers (42% Female; Age, M = 30.15; Years of driving experience, M = 10.30) in two Spanish cities with different road characteristics. A sequential method involving factor analysis, regression analysis and path analysis is used to analyze the sample.

The results confirm that eco-driving is strongly affected by driving behavior like deceleration rate, RPM and speed, also showing that external factors as congestion and road slope have a direct influence on fuel consumption. The results also reveal that perceived stress levels vary among drivers, but there is not significant change when drivers eco driving.

1. Introduction

Eco-driving is emerging as an operational decision by drivers that can maximize fuel efficiency and consequently reduce global Greenhouse Gas (GHG) emissions and other air pollutants like NOx (Sivak and Schoettle, 2012). A recent work of Huang et al. (2018) reported that further research on eco-driving should focus on key variables with significant effects on fuel savings. Previous works in evaluating eco-driving impacts usually omit the influence of real traffic condition like congestion, road type, city size or slope. Both internal factors (like speed, acceleration) and external factors (like congestion and road slope) may lead to a possible failure in fuel savings during eco-driving. To the best of our knowledge, there are no studies in the literature that analyze key factors for fuel consumption and eco-driving, controlling external factors (Ericsson 2001; Brundell-Freij and Ericsson, 2005; Vogt, et al., 2015; Lois et al., 2018; Alam and McNabola, 2014).

To this end, the present study aims to expand the knowledge on the short-term impacts of eco-driving by developing an analytical model of the key factors that explain fuel consumption and eco-driving, and to examine their relations in greater depth. More specifically, it uses a sequential method to firstly identify the explanatory variables in relation to fuel consumption and eco-driving, and then examines the interrelations through path analysis. Moreover, this paper is also analyzing the complementary effects on drivers' stress levels before and after eco-driving.

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The following section outlines the previous studies on eco-driving and its impacts in relation to driving pattern, congestion, road slope and drivers' stress levels, and identifies the research objectives. Section 3 presents the material and methods of the study, including data collection and data analysis. Section 4 develops the results by applying the sequential method. Section 4 interprets the results and discusses on the main findings. The final section presents the conclusions, research limitations and future research lines.

2. Literature review

2.1. Eco-driving and its impacts

The concept of eco-driving refers to a set of rules that differ from the normal driving and includes calm driving, avoiding unnecessary stops, anticipating, and eliminating excessive idling (Barkenbus, 2010). Eco-driving is an initiative that can improve fuel efficiency and reduce road accidents and noise as a result of the drivers' calm driving (Huang et al., 2018).

Previous studies using field trials show that eco-driving has the potential to reduce fuel consumption by an average of 5%, but its effects among trials are quite different (Zarkadoula et al., 2007; Barkenbus, 2010; Boriboonsomsin et al., 2011; Sivak and Schoettle, 2012).

Boriboonsomsin et al. (2011) found only 6% fuel savings by applying eco-driving on city streets and 1% on highways with 20 drivers tested in Southern California. A similar trial in South Korea revealed different outcomes, with no significant improvement in fuel consumption after activating eco-driving (Lee et al., 2010). Lee's work determined that drivers' mental demand, effort and stress levels are the main factors affecting the results after adopting eco-driving. Smit et al. (2010) developed a field test with 24 drivers and six types of vehicles under urban and rural traffic conditions, showing that fuel consumption and emissions vary from a reduction of up to around 10% to a slight increase of around 0.5%. Specific road conditions appear to produce significant differences in eco-driving outcomes. However, the findings are somewhat confusing for users seeking to practice eco-driving in real life (Wang and Boggio-Marzet, 2018).

In order to identify the key factors influencing fuel consumption and eco-driving, Zhou et al. (2016) reported six groups of factors, namely driving, weather, vehicle, roadway, traffic and drivers' characteristics in relation to fuel consumption, but they did not investigate the relationship among the factors. The work of Saboohi and Farzaneh (2009) shows that traffic delays caused by congestion, traffic lights and giving way lead to excessive fuel consumption. Moreover, down-up slopes also have a strong influence on driving patterns and can double fuel consumption when the road grade is over 4% (Boriboonsomsin and Barth, 2009).

Experiments in real traffic are significantly affected by certain traffic condition and road state. Most of the previous studies conducted field trials over shorter distances with simple or controlled traffic condition (only free flow) to avoid the influence of external factors (Johansson, 2003; Zarkadoula et al., 2007; Boriboonsomsin et al., 2011; Andrieu and Saint Pierre, 2012; Rutty et al., 2013). The results then misestimate the real impacts of eco-driving, overlook the influence of real traffic, in which drivers always find a mixture of different road types and traffic conditions.

In order to fill these gaps, a field trial combining all the important explanatory factors affecting fuel consumption, including human-factor driving patterns in relation to eco-driving (Section 2.2) and external factors such as road type, gradient and traffic congestion (Section 2.3) is required.

2.2. Driving patterns influenced by eco-driving

Driving pattern in general is defined as the speed profile of vehicles, here it gives a broader concept, including other parts of driving behavior, such as acceleration and deceleration. Field trials have been conducted in a number of studies by giving participants advice on eco-driving, such as planning ahead to avoid unnecessary stops (Johansson, 2003; ECOWILL, 2013; Young et al., 2011), accelerating gently (Barkenbus, 2010; Dogan et al., 2011; Strömberg et al., 2015), reducing deceleration rates (Young et al., 2011; Andrieu and Saint Pierre, 2012), minimizing the use of low gears (Ericsson, 2001), increasing the use of high gears (Ericsson, 2001; Wåhlberg, 2007; Birrell et al., 2014), maintaining a steady speed (Johansson, 2003; El-Shawarby et al., 2005; Ho et al., 2015), and avoiding idling (Onoda, 2009).

The results of the field trials show that 6–18% of eco-drivers reduced their speed and accelerations/decelerations, 9–20% lowered their engine speed, and 5–14% minimize the number of stops –often resulting in increased acceleration–, while practicing eco-driving in real traffic (Evans, 1979; Barkenbus, 2010; Young et al., 2011; Ho et al., 2015; Sanguinetti et al., 2017).

Eco-driving as a broad and variable technique is still poorly understood due to its distinct behaviors under different road conditions. A behavioral approach to defining and classifying eco-driving should be based first and foremost on behavioral functions (Sanguinetti, et al., 2017). In this context, Ericsson (2001) devised nine independent driving pattern parameters (i.e., stop factor, acceleration, moderate speed rate, energy speed, etc.) with considerable effects on emissions and fuel consumption using factor and regression analysis. However, her study did not consider eco-driving neither the factors like road condition, which requiring further studies on it.

2.3. External factors and fuel consumption

Here we consider the effects of traffic condition and road alignment on fuel consumption, which do not depend on driverś behavior but have synergies with eco-driving. Brundell-Freij and Ericsson (2005) showed that fuel consumption is largely influenced by traffic delay, which refers road congestion and stops necessitated by traffic lights and street functions. The characteristics of traffic and street configurations have a cumulative effect on fuel consumption and exhaust emissions (Nesamani et al., 2007), and increases in traffic volumes (i.e. congestion) and stopping time significantly raise vehicle fuel consumption and emissions. As reported by Ericsson (2001), driving at speeds of below 2 km/h (that is, stopped) on urban roads significantly increases fuel consumption and CO2 emissions.

Energy consumption and emissions depend not only on driving patterns and congestion, but also on other physical features such as road slope, weather conditions and loaded weight. Only a few studies consider road slope when simulating the impacts of eco-driving. Kamal et al. (2011) found that eco-driving required around 9% less fuel than other driving styles on hilly roads. The study by Boriboonsomsin and Barth (2009) concluded that vehicle fuel economy is approximately 15% to 20% higher on flat routes than on hilly routes. These achievements in fuel saving underline the credibility of this type of ecological driving based on predictions of road shape.

Most previous eco-driving trials were conducted during off-peak hours with no traffic congestion, and covered a determined route without considering road terrain, thus overlooking the effect of these two important factors. They therefore do not report the combined effects of congestion and road gradient on eco-driving.

2.4. Psychological issues in eco-driving: Stress experience

Different drivers have a different perception and understanding of the advice given. Although their driving decisions have been widely studied in terms of traffic safety (Kanellaidis et al., 1995; Iversen and Rundmo, 2004; Oltedal and Rundmo, 2006), there is very little evidence of drivers' psychological response to eco-driving. For instance, Jansson (2011) reported on the differences between eco- and non-eco-drivers as influenced by norms, attitudes, novelty-seeking and how innovation attributes are perceived. A recent study by Barla et al. (2017) showed that the effects of eco-driving are highly heterogeneous among individuals, with standard deviations of about 5%.

Nègre and Delhomme (2017) highlighted the existence of different mental models for eco-driving and differences in adopting eco-driving behaviors, including basic behaviors such as acceleration, braking, steady speed, and advanced behaviors such as gearshift management and longer inter-vehicle distance. They concluded that "only a few relationships were established between eco-driving self-perceptions and self-regulation, so more investigations must be conducted in this area". Daily congestion could affect stress levels, which vary with age, driving experience and driving conditions, and depend on drivers' overall perception of driving as a stressful activity (Gulian et al., 1990). Mesken et al. (2007) show that stress/anxiety is the most frequent emotion when driving, followed by anger and joy. Negative emotions are related to other drivers being perceived as "guilty" (of violating traffic regulations), situations of interrupted progress (slowness, traffic jams) or traffic situations that threaten the driver's safety (possible accidents, collisions). We therefore believe it is also important to look at the changes in drivers' stress levels (before and after eco-driving training).

3. Research objectives

To the best of our knowledge after reviewing the existing literature, there is little research on the combined impact of external factors and eco-driving. Previous works have focused only on the direct fuel reduction by applying eco-driving on different types of roads, or through different training programs. Despite its limitations, this work aims to assess the impacts of eco-driving while also considering other relevant variables such as city size, traffic congestion and road slope. The investigation is based on a field trial to study driving pattern factors that influence fuel savings of eco-driving.

The aims of the present work were threefold. The first was to identify the explanatory variables related to driving patterns and other road environmental predictors of fuel consumption (Ericsson, 2001; Brundell-Freij and Ericsson, 2005; Lois et al., 2018). The second aim was to examine the interrelations between these key variables and fuel consumption. Finally, the paper also sought to determine whether eco-driving influences stress levels by surveying drivers before and after an eco-driving training program.

4. Material and methods

In order to achieve the objectives of the paper, this section includes two aspects: (1) data collection, a well-designed field trial that covers both internal and external factors which have potential influence on fuel consumption and eco-driving, and (2) data analysis methods, a sequential data analysis method to identify the key factors and their interrelation.

Fig. 1 shows the framework of the research regarding to the two aspects. Part 3.1 presents the data collection process, which was a field trial conducted in two cities of Spain and the details of the campaign. The data collection campaign was to collect real data on driving patterns, traffic states and several psychological variables before and after drivers received an eco-driving training program. The trial was tested on various road segments with different traffic intensities and characteristics.

Part 3.2 introduces the data analysis method firstly via a descriptive analysis to generate the image of the whole sample after integrating, cleaning and filtering all raw data. The final sample was analyzed by applying a series of statistical tools (Fig. 1). Then the multivariate analysis as well as its results is given in Section 4.

4.1. Data collection

- Route selection

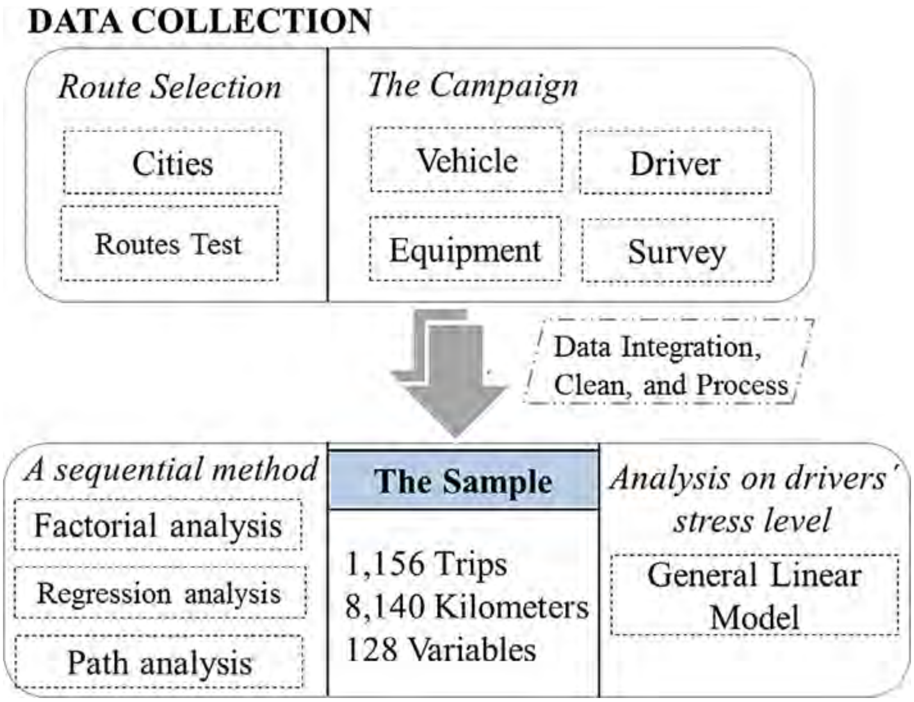

Fig. 1. Research framework.

The data collected in two Spanish cities: Madrid and Caceres. We sought to collect a sample with a broad array of traffic conditions and infrastructures, because these structural elements undoubtedly affect people's behavior and mobility, including their cultural difference. These two cities were selected to guarantee a variety of driving patterns and traffic conditions in the sample collected. The Madrid Metropolitan Area has a population of 6.5 million inhabitants and covers an area of 8030 km^2. Private car shares 53% of daily mobility in the metropolitan ring where the field trial conducted (Wang and Monzón, 2016).

Caceres is a relatively small city with 95,000 inhabitants and an area of 30 km^2 with hilly layout. 55% of daily trips take place within the city using car mode. Pedestrian trips account for one third of all mobility, while public transport is used for only 10%.

The route selection was designed after a prior study: Garcia and Monzońs work (Garcia-Castro and Monzon, 2014), which is from the same research group, evaluated the impacts of eco-driving on some adjacent urban streets and inner ring road of Madrid. To avoid repetition on same type of roads, the routes in this work were selected mainly in the suburb within high car modal sharing.

The routes chosen for the eco-driving field trial in Madrid were located in the northwest, a wealthy area with moderate slopes and the highest car ownership in the city (see Fig. 2). The six routes connect the city center with two municipalities –Pozuelo and Majadahonda– where 92% of daily trips are made by car (Wang and Monzón, 2016). The routes cover the main road types with different functionalities, including motorways and arterial, collector and local roads (see Table 1). Routes CP_i (Centre to Pozuelo) are mainly motorways but have different traffic intensities. Routes MP_i (Majadahonda to Pozuelo) are a mix of motorway and the typical arterial roads to urban suburbs, with a layout of roundabouts and pedestrian crossings.

Caceres is composed of a protected pedestrianized historic center and a series of urban districts. The dominant transport mode in Caceres is the car, which accounts for 55% of all movements within the city. Considering the city's size and hilly layout, four routes with the same origin and destination (University campus to Train station) were selected to test the impact of eco-driving (Fig. 2). The four routes are all in different road categories but have a similar traffic intensity. Travel times seldom vary, which means there is little congestion (Coloma et al., 2017). Caceres is also a hilly city with an average 6.8% slope on the routes selected (Table 1).

The routes were selected based on three criteria: (i) including the main road types characterized by different functionalities both in big and mid-size cities; (ii) choosing heterogeneous itineraries composed by different geometrical segmentations and traffic volumes; and (iii) different routes but with the same origin and destination make it easier to monitor travel time and more convenient for the drivers when changing shifts.

The selected routes provide the chance enable us capturing the effect of the experimental conditions, while controlling the influence of congestion and road slope on different types of roads as external factors (Table 1).

- Data collection campaign

The method to evaluate the impact of eco-driving on fuel consumption was to analyze the results of the parameters recorded in two driving periods (13 working days each). Period 1 was a "control" driving period without eco-driving, reflecting the normal driving style of each individual. All drivers then followed an official eco-driving training course. Period 2 involved putting the eco-

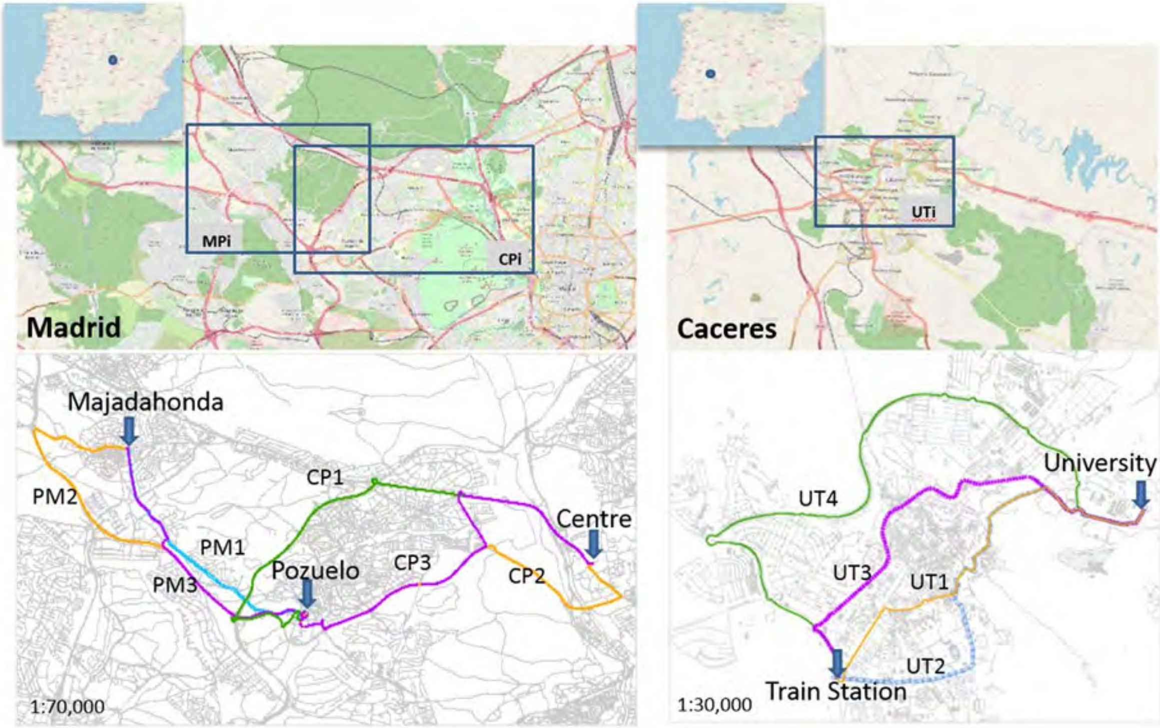

Fig. 2. Location of the field trial in Madrid and Caceres.

Table 1
Description of the routes in Madrid and Caceres.

City	Route name	Road type	Distance (km)	*Travel time range (min) Off-peak to peak hour	** Average daily intensity10*3	***Average slope (%)
Madrid	CP1	Motorway	15.2	18–35	77–133	2.8
	CP2	Motorway + Collector	13.3	18–30	48–59	3.3
	CP3	Motorway + Collector	13.5	18–22	48–133	3.2
	MP1	Urban arterial	8.2	18–30	17	3.1
	MP2	Motorway + Urban arterial	13.2	16–30	17–62	3.0
	MP3	Highway + Urban arterial	8.6	16–35	17–43	3.2
Caceres	UT 1	Local road	6.1	14–20	5–10	7.0
	UT 2	Collector	6.7	12–16	5	6.9
	UT 3	Urban arterial	6.7	12–18	5–7	6.7
	UT 4	Motorway	10.3	12–16	5–10	5.9

* Travel time from non-peak to peak-hour (source Google Maps).
** Total volume of vehicle traffic of a road segment for a year divided by 365 days (source Ministry of development of Spain, Traffic Map 2016).
*** The average slope is obtained from Google Geo using based on selected routes.

driving techniques learnt on the course into practice.

The campaign lasted from April 2017 to May 2017 in Madrid and Caceres. In order to reduce as far as possible the influence of the vehicle over the average fuel consumption, only two vehicles were used. One petrol-engine vehicle (FIAT 500) and one diesel-engine vehicle (Opel Astra) were instrumented for the driving test. Both cars were equipped with an on-board device (OBD) and mobile phone to record the data on driving patterns, engine parameters, travel time, distance and the geographical position on the road. The instant fuel consumption of the two vehicles was also recorded using OBD and validated by the refueling records. The data were collected in a data logger and sampled at 1 Hz. The road slope was obtained through Google Geo according to instantaneous GPS coordinates.

24 drivers were engaged from among university staff and students to take part in the two driving periods. The participants were aged between 21 and 50 years old (M = 30.15) with average 10.30 years driving experience, including 14 males and 10 females. The driving schedule covered 12 h per day (from 8 am to 8 pm), considering both peak and off-peak hours. Every experimental day was divided into three driving shifts (four hours each), in each shift two people (driver and co-pilot) covered the selected routes iteratively. Each driver every time accompanied by a co-pilot who aims to help the driver to write down the information about the trip.

The driver every day drove accurately two hours and exchanged his position with the co-pilot. After each driving shift, driver and co-pilot were changed with other couple of drivers.

The data collected from both vehicles continuously for 12 h a day, which allowed us to obtain a sample of enough data for different traffic conditions and avoided alterations in driving styles. At the end of each shift, participants were also asked to complete a survey on traffic conditions (i.e., weather, congestion and accidents) and on their perceived stress while eco-driving.

All 24 participants took a professional eco-driving training course (six hours in total) between the two driving periods on how to apply the techniques to reduce fuel consumption. The training program was given by the same instructor from the local driving school in each city. All 24 participants were divided into six groups (four people each) and joined the eco-driving course with the instructor in three consecutive working days. Each group of participants firstly drove in a determined route with 15 km accompanying with the instructor (two hours for 4 people). Then they were given a theoretical class of eco-driving (two hours) by the instructor. After that, each group of participants joined another operational practice in which each driver practice eco-driving on the same route accompanying with the same instructor for 15 min each (two hours for 4 participants). The instructor gave specific suggestions of eco-driving based on their current driving behaviors.

The main tips participants received include reducing and maintaining a steady speed; reducing unnecessary accelerations; using higher gears and changing up to higher gears as rapidly as possible; rolling the vehicle with the gear engaged and without accelerating on the approach to an intersection or pedestrian crossings; anticipating current traffic conditions; and switching off the engine during stops of over 1 min. The eco-driving tips received from the training course are consistent with the "Golden Rules of eco-driving" that generated in the project ECOWILL (2013). An analysis of key performance indicators (KPI), including number of gear changes, average speed, instantaneous fuel consumption, etc., were used to assess the drivers' performance during their training. Finally, 24 drivers achieved an average 10% fuel savings at the end of the practice course. (The fuel consumption was measured manually recorded from the dashboard of the vehicle in the training course).

The data recorded during each trip were downloaded, cleaned and processed using the R programming language. The final sample contains 1156 trips for both Madrid and Caceres, covering a global amount of 8140 km (5959 km in Period 1 and 5232 km in Period 2). 425 trips (27% of the total) were excluded due to missing information on GPS, RPM, travel time, or fuel consumption.

The diesel vehicle made a total of 570 trips during the trial, while the petrol vehicle made 586 trips. Over one hundred trips were made on each test route to ensure the significance of the study of the influence of different road environments on fuel consumption. Each driver made 53 trips on average: 28 in Period 1 and 25 in Period 2.

4.2. Data analysis

- The sample

The sample contained 128 variables relating to trip information (17 variables), driving patterns (57 variables), road characteristics (10 variables), energy parameters (18 variables), and emissions (16 variables). In order to analyze the impacts of eco-driving, we selected twelve variables according to previous studies in the field (Ericsson, 2001; Smit et al., 2010; Greenwood et al., 2007; Beusen et al., 2009) and an explanatory correlation analysis.

The variables represent general driving pattern (average/maximum RPM, average/standard deviation deceleration, average/maximum speed, rapid speed), traffic characteristics (trip duration, number of stops and stope time), road grade (average slope) and fuel consumption. Their mean value and standard deviations are given in Table 2.

- A sequential method

We analyzed the results as a function of the theoretical predictors of fuel consumption by conducting a regression analysis to order each predictor in terms of importance, after checking the possible underlying driving situations in the sample through factor analysis.

We examined the effect of including the experimental condition and its influence on consumption in general terms, in addition to

Table 2
Means and standard deviations of main variables.

Variables	Ms	SDs
RPM (average)	1593.23	316.20
RPM (maximum)	3010.93	633.81
Negative acceleration (m/s^2, average)	−0.42	0.11
Negative acceleration (m/s^2, SD)	0.41	0.09
Speed (km/h, maximum)	87.34	17.95
Speed (km/h, average)	38.77	12.06
Speed (% above 70 km/h)	17.84	17.95
Trip duration (second)	950.22	257.71
Number of stops/km	7.29	5.14
Stop time second/km	12.22	13.52
Slope (%, average)	0.08	1.52
Fuel consumption (litre/100 km)	6.23	1.69

Table 3
Results of the factor analysis.

Variables	Factor			
	Free-flow driving	Inefficient driving behavior	Congestion situations	Hilliness
Speed (% above 70 km/h)	0.92			
Speed (average)	0.87		−0.38	
Speed (maximum)	0.84			
RPM (average)	0.72	0.38		
Negative acceleration (average)		−0.93		
Negative acceleration (SD)		0.91		
RPM (maximum)		0.66		
Trip duration			0.87	
Number of stops/km.	−0.52		0.67	
Stop time/km	−0.55		0.63	
Slope (average)				0.93
Fuel consumption (average /km.)	−0.40			0.76

[*] Values below 0.3 are not reported.

its interrelation with the rest of the variables in the consumption model, by means of path analysis.

- Complementary analysis on diveŕ stress

Furthermore, the drivers completed a brief questionnaire to measure the main emotions they experienced on a series of randomly selected routes (28% of the total), in which they reported their level of stress (using a 1 to 7-point Likert-type scale) and other variables (such as weather, accidents, etc.) not used in the present study. The items on the questionnaire were designed based on the works of Betella and Verschure (2016) and Russell (1980).

We also conducted a GLM (General Linear Model) univariate procedure to test possible differences in stress according to the responses of the participants in the eco-driving experiment.

5. Results

5.1. Driving context and characteristics as the main predictors of fuel consumption

Fuel consumption depends on the driving style and the road and traffic context in each road segment. An exploratory factor analysis was done to identify the main underlying factors related to driving elements, grouping the variables with high factor loadings. Table 3 shows the association of variables and defines four factors which explain a variance of 81.7% of the trip variables. The first factor concerns "*free-flow driving*" conditions, defined by higher speed and lower fuel consumption. The second factor, "*inefficient driving behavior*", is mainly defined by more deceleration situations (average), variability (high deceleration SD) and excessive engine RPM. The other two factors aggregate external variables beyond the driver's control. The third factor corresponds to "*congestion"* circumstances, while the fourth is strongly associated to "hilly road" sections and high fuel consumption. The multicollinearity of the underlying factor analysis was previously checked (Bartlett test: Sig = 0.00; MSA = 0.71), and varimax rotation was used to determine the factors.

A multiple regression method was used to examine the impact on consumption of variables associated with driving patterns, or external variables such as congestion or hilliness (i.e. road slope). The analysis revealed a strong and significant relationship between independent variables and fuel consumption ($F = 287.31$, $p < .001$, $R^2 = 0.702$). As can be seen in Table 4, the analysis of beta

Table 4
Regression on fuel consumption.

Variables	Bs	SEs	ts	βs
Speed (maximum)	−0.019**	0.00	−0.019	−0.20
Speed (average)	−0.028**	0.00	−0.028	−0.20
Slope (average)	61.38**	1.87	61.38	0.55
RPM (average)	0.00	0.00	0.00	0.03
RPM (maximum)	0.00**	0.00	0.00	0.11
Negative acceleration (SD)	−2.37*	0.78	−2.37	−0.12
Number of stops/km.	0.14	0.08	0.14	0.05
Stop time/km	0.02**	0.00	0.02	0.22
Negative acceleration (average)	−3.71**	0.61	−3.71	−0.25

* $p < .01$.
** $p < .001$.

Table 5
− Differences in fuel consumption with eco−driving according to vehicle type and city.

	n	Ms (litre/100 km)	Dif.	SDs	ps
Total sample					
Normal driving	608	6.44		1.71	
Eco-driving	548	5.99	−6.89%	1.65	0.87
Petrol vehicle					
Normal driving	296	6.01		1.25	
Eco-driving	274	5.78	−9.26%	1.31	0.16
Diesel vehicle					
Normal driving	312	6.84		1.93	
Eco-driving	274	6.21	−3.86%	1.87	0.32
City: Caceres					
Normal driving	229	6.25		2.03	
Eco-driving	210	5.70	−8.63%	2.20	0.65
City: Madrid					
Normal driving	379	6.56		1.26	
Eco-driving	338	6.18	−5.82%	0.75	0.22

standardized coefficients shows that higher slopes (*average*), more congestion (*stop time per kilometer*) and more RPM (*maximum*) were associated with an increase in fuel consumption. Conversely, less negative acceleration (especially *average* and to a lesser extent, *standard deviation*), and higher speed (*maximum* and *average*) are associated with a decrease in fuel consumption. Number of stops per kilometer, which is another way of measuring congestion ($p = .08$) and RPM (*average*, $p = .29$) were not significant variables.

5.2. Eco-driving effect on consumption: General results

The comparison of fuel consumption after adopting eco-driving (period 2, after the driver training course) with prior normal driving conditions (period 1) reveals almost 7% less consumption. These differences vary more widely when comparing types of vehicles and cities, as shown in Table 5.

The general fuel saving (liters per 100 km) when eco-driving is significant due to the changes in driving patterns. Participants exhibited explicit changes in their driving behavior. We observed 16% lower RPM on average, 4% lower average speed, 37% lower acceleration and 46% less deceleration. Particularly, drivers achieved higher fuel savings with the petrol vehicle in Caceres where itineraries have higher road slopes. The differences in fuel savings are hypothetically due to the combined influence of driving patterns and the traffic conditions during the test. This hypothesis is tested in part 4.3. The difference in fuel savings was analyzed by road type and traffic state and was included in the previous publication (Wang and Boggio-Marzet, 2018).

5.3. Including external factors in the fuel consumption model

To directly test the hypothesis that eco-driving behavior reduces fuel consumption after controlling the influence of co-variables such as congestion and road slope, we conducted path analyses with the observed variables using the maximum likelihood estimation method with the AMOS 24 program. This model also considered that the influence of driving on consumption is mediated by its effect on the RPM, decelerations and speed of the vehicle. The indicators were selected from Table 3, choosing those with a greater effect on consumption. We examined the fit of the model by using the root-mean-square error of approximation (RMSEA) and tested incremental model fit with the comparative fit index (CFI). We used the standard of acceptable fit RMSEA ≤ 0.10, and CFI ≥ 0.90 (Weston and Gore, 2006). The overall model fit was satisfactory (RMSEA = 0.057; CFI = 0.98).

Fig. 3 shows the estimated standardized path coefficients ($p < .001$). The results indicate a strong and positive effect of eco-driving on negative acceleration average and a negative effect on RPM (maximum), variables that sequentially influence the reduction in fuel consumption. In contrast, eco-driving decreases vehicle speed (maximum). It is worth noting that eco-driving has a greater influence on the internal factors: practitioners' driving patterns.

The covariables included in the model have the strongest direct effect on fuel consumption: congestion (as time stopped per km), as a flexible external factor, and slope (average) considered as a fixed external component. On the other hand, the model shows that congestion also has an indirect effect on fuel consumption by reducing the incidence of deceleration. Finally, regarding the determination coefficients, the model explained 31% of the variance in RPM (maximum), 21% of negative acceleration (average), 24% of speed (maximum) and 67% of average fuel consumption.

5.4. Psychological correlates of eco-driving: Changes in stress levels

A univariate GLM analysis was done to examine differences in the assessment of perceived stress levels by drivers in period 1 (normal driving) versus period 2 (eco-driving). This psychological variable was collected in 326 of the 1156 trips, as explained in the method section. *Trip duration* and *congestion* (stop time per kilometer) were also included in the analysis as possible factors

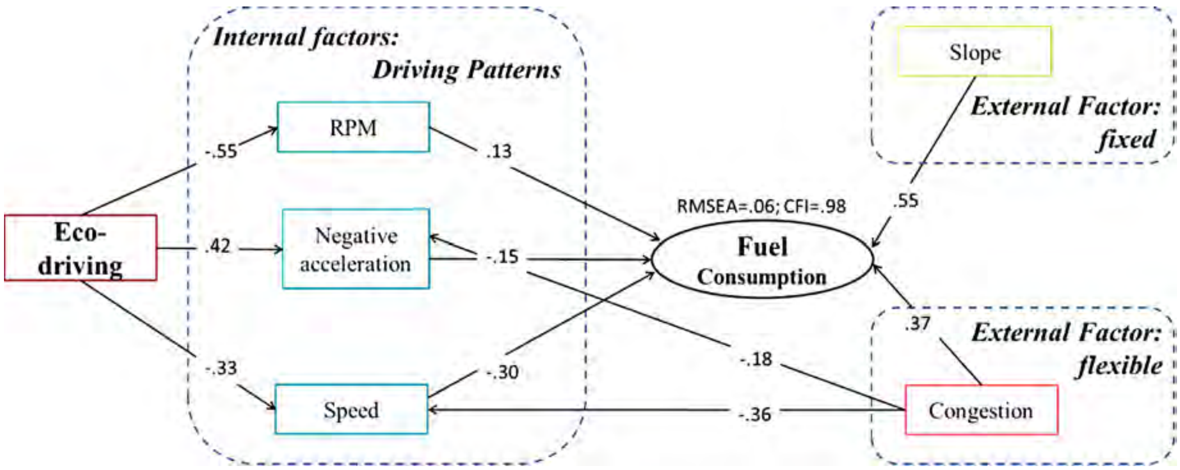

Fig. 3. Path analysis model related to fuel consumption, including both internal and external factors.

influencing stress levels, considered as covariables.

As can be seen in Table 6, the GLM analysis reveals a major significant effect for the driver (F (1.21) = 5.31, p < .0001) and the interaction between the driver and the eco-driving condition (F (1.21) = 4.06, p < .0001). It is worth noting that neither eco-driving, congestion or trip duration influence stress levels.

Overall, the results show low stress level scores among the participants in both periods, with an average score of 2.14 during *normal* driving (range 1 to 7, SD = 1.41,) and 2.11 (SD = 1.40) in the *eco-driving* condition, considering that the theoretical mean of the scale is 4 points. Secondly, it was verified that eight of the 22 drivers *reduced* their stress levels in the eco-driving condition versus normal driving, nine drivers experience no change, while in only five cases the stress levels *rose* slightly.

6. Discussions

The main findings of the paper are following:

1. We have identified four factors (i.e., free-flow driving, inefficient driving behavior, congestion situation and hilliness) that explained the main common driving environment through exploratory factor analysis. Free-flow refers to driving at higher speed and lower fuel consumption; inefficient driving behavior (non-eco-driving) involves excessive RPM and more deceleration; the congestion situation is explained by longer travel time, more stops and longer stop time, and hilly road segments are associated to higher fuel consumption.
2. Seven variables were found to explain 70% of fuel consumption in the field trial by means of a multiple regression analysis. They are average/maximum speed, maximum RPM, average road slope, average/SD negative deceleration, and congestion. Less deceleration, lower maximum speed and RPM are all similar in nature to the eco-driving rules stipulated in previous research (Young et al., 2011; Andrieu and Saint Pierre, 2012). The main change in eco-driving behavior is the reduction in maximum speed rather than in average speed, which involves avoiding aggressive driving.
3. The fitted path model showed that learning eco-driving skills influences substantially on driving patterns (RPM, speed and negative acceleration) and confirmed that congestion and road slope are direct predictors of fuel consumption (Nesamani et al., 2007; Boriboonsomsin and Barth, 2009). Reducing average speed in congested traffic situations is not efficient for achieving fuel savings. Eco-driving was found to achieve higher fuel savings in a free-flow condition.
4. The consequences of the stress caused by driving circumstances on compliance with eco-driving may be underestimated in our experiment resulting it was carried out by contracted drivers. Since the participants were not rewarded or punished to change/not change their driving patter to eco-driving, the stress level did not show significant changes before and after applying eco-driving. Nègre and Delhomme (2017) mentioned that interaction with other users' behaviors, road infrastructures (e.g., intersections),

Table 6
Level of stress experienced during the trip. Univariate GLM.

Predictors	Sum of squares	dfs	R^2s	Fs	ps
Eco-driving	0.00	1	0.00	0.00	0.95
Driver	155.34	21	7.39	5.31	0.00
Eco-driving* driver	85.41	21	4.06	2.92	0.00
Congestion	0.25	1	0.25	0.186	0.66
Trip duration	3.87	1	3.87	2.78	0.09

and/or temporary or chronic time pressure can generate emotional states such as anger (e.g., when the car behind you is tailgating), thereby leading to negative effects on compliance with eco-driving rules. Perceived stress levels vary among participants. It was observed that eco-driving has a different effect on the participants' stress levels; most report less stress when eco-driving, while only five of the 22 drivers increased their stress during the eco-driving experiment. Future research should explore whether aggressive driving styles (i.e. "macho driving"; Steg, Vlek, and Slotegraaf, 2001) or the pressure to get to work on time could have a negative impact on eco-driving behavior.

This research also underlines the need to enhance car drivers' awareness of limiting the impact of their emissions under boundary conditions. In some circumstances, eco-driving can significantly reduce fuel consumption; its social and financial value could be promoted and included in driving lessons, and it could be useful to promote in-car equipment to measure fuel consumption to raise awareness of its importance.

The path analysis proves that the external factor like road slope plays a key role in fuel consumption. Less fuel-using and emissions can benefit from better design and constructed roads with small gradient. Besides, a more efficient traffic network (meaning less congestion) through well-coordinated application of *carrot* and *stick* transport policies can reduce overall fuel consumption as well as GHG emissions as it is addressed via the finding between congestion and fuel consumption.

7. Conclusions

The field trial conducted in two cities with different road characteristics provides a suitable case for expanding the knowledge of the benefits of eco-driving through a training program. In this paper, we show that modelling the factors correlated to fuel consumption with external factors (such as traffic congestion and road slope) contributes to a better understanding of the most important aspects of fuel saving.

An important contribution of this study concerns the amount of data obtained from real traffic conditions. This work analyzed the effects of an efficient driving course on eco-driving performances by monitoring data recorded before and after the training along different itineraries, in vehicles with different power trains at different hours of the day by different drivers in an urban and extra-urban context.

One of the main limitations of the current work is that the field trial is done with a relatively small number of participants who were mostly contracted to take part in the experiment. Only non-automatic fuel vehicles were tested in the study. Future lines of interest in the same research could replicate the experiment with more eco-driving practitioners, more types of vehicle and include drivers' profiles as another control variable in the analysis. The influence of road characteristics – e.g., number of lanes, level of service, speed limit and traffic intensity– are other potential impacts on eco-driving efficiency (Brundell-Freij and Ericsson, 2005).

Despite these limitations, this work demonstrates the importance of the key factors identified in terms of driving patterns. Based on the positive results of fuel reduction, this study provides the evidence to the public to create greater awareness of the role played by drivers in limiting their vehicle emissions.

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Author contributions

David Lois conducted the statistical and multivariate analysis and wrote the manuscript; Yang Wang conducted the research and was responsible to collect, process the data, as well as wrote the manuscript; Alessandra Bioggio-Marzet collected and processed the data of the field trial; Andrés Monzón designed and coordinated the project, reviewed the manuscript and proposed changes and improvements to its structure.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2019.05.001.

References

Alam, M.S., McNabola, A., 2014. A critical review and assessment of eco-driving policy & technology: benefits & limitations. Transp. Policy 35, 42–49.
Andrieu, C., Saint Pierre, G., 2012. Comparing effects of eco-driving training and simple advices on driving behaviour. Procedia-Soc. Behav. Sci. 54, 211–220.
Barkenbus, Jack N., 2010. Eco-driving: an overlooked climate change initiative. Energy Policy 38 (2), 762–769.
Barla, P., Gilbert-Gonthier, M., Castro, M., Miranda-Moreno, L., 2017. Eco-driving training and fuel consumption: impact, heterogeneity and sustainability. Energy Econ. 62, 187–194.
Betella, A., Verschure, P.F., 2016. The affective slider: A digital self-assessment scale for the measurement of human emotions. PloS one 11 (2).
Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijsbers, M., Panis, L.I., 2009. Using on-board logging devices to study the longer-term impact of an eco-

driving course. Transport. Res. D: Transp. Environ. 14 (7), 514–520.
Birrell, S., Taylor, J., McGordon, A., Son, J., Jennings, P., 2014. Analysis of three independent real-world driving studies: a data driven and expert analysis approach to determining parameters affecting fuel economy. Transport. Res. D: Transp. Environ. 33, 74–86.
Boriboonsomsin, K., Barth, M., 2009. Impacts of road grade on fuel consumption and carbon dioxide emissions evidenced by use of advanced navigation systems. Transp. Res. Rec. 2009, 21–30.
Boriboonsomsin, K., Vu, A., Barth, M., 2011. Eco-Driving: Pilot Evaluation of Driving Behavior Changes Among us Drivers. University of California Transportation Center, UC Berkeley.
Brundell-Freij, K., Ericsson, E., 2005. Influence of street characteristics, driver category and car performance on urban driving patterns. Transport. Res. D: Transp. Environ. 10 (3), 213–229.
Coloma, J.F., García, M., Wang, Y., Monzón, A., 2017. Green eco-driving effects in non-congested cities. Sustainability 10 (1), 28.
Dogan, E., Steg, L., Delhomme, P., 2011. The influence of multiple goals on driving behaviour: the case of safety, time saving, and fuel saving. Accid. Anal. Prev. 43 (5), 1635–1643.
Ecowill, 2013. The golden rules of eco-driving. Accessed 01/07/2017. http://www.ecodrive.org/en/what_is_eco-driving-/the_golden_rules_of_eco-driving/.
El-shawarby, I., Ahn, K., Rakha, H., 2005. Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions. Transport. Res. D: Transp. Environ. 10 (1), 13–30.
Ericsson, E., 2001. Independent driving pattern factors and their influence on fuel-use and exhaust emission factors. Transport. Res. D: Transp. Environ. 6 (5), 325–345.
Evans, L., 1979. Driver behaviour effects on fuel consumption in urban driving. Hum. Factors 21 (4), 389–398.
Garcia-Castro, A., Monzon, A., 2014. Using floating car data to analyse the effects of ITS measures and eco-driving. Sensors 14 (11), 21358–21374.
Greenwood, I., Dunn, R., Raine, R., 2007. Estimating the effects of traffic congestion on fuel consumption and vehicle emissions based on acceleration noise. J. Transp. Eng. 133 (2), 96–104.
Gulian, E., Glendon, A.I., Matthews, G., Davies, D.R., Debney, L.M., 1990. The stress of driving: a diary study. Work Stress 4 (1), 7–16.
Ho, S.H., Wong, Y.D., Chang, V.W.C., 2015. What can eco-driving do for sustainable road transport? Perspectives from a city (Singapore) eco-driving programme. Sustain. Cities Soc. 14, 82–88.
Huang, Y., Ng, E.C., Zhou, J.L., Surawski, N.C., Chan, E.F., Hong, G., 2018. Eco-driving technology for sustainable road transport: a review. Renew. Sustain. Energy Rev. 93, 596–609.
Iversen, Rundmo, 2004. Attitudes towards traffic safety, driving behaviour and accident involvement among the Norwegian public. Ergonomics 47 (5), 555–572.
Johansson, H., 2003. Impact of eco driving on emissions. Transport and air pollution. Proceedings from the 12th Symposium, Avignon, France.
Jansson, J., 2011. Consumer eco-innovation adoption: assessing attitudinal factors and perceived product characteristics. Bus. Strat. Environ. 20 (3), 192–210.
Kamal, M.A.S., Mukai, M., Murata, J., Kawabe, T., 2011. Ecological vehicle control on roads with up-down slopes. IEEE Trans. Intell. Transp. Syst. 12 (3), 783–794.
Kanellaidis, G., Golias, J., Zarifopoulos, K., 1995. A survey of drivers' attitudes toward speed limit violations. J. Saf. Res. 26 (1), 31–40.
Lee, H., Lee, W., Lim, Y., 2010. The effect of eco-driving system towards sustainable driving behavior. CHI'10 Extended Abstracts on Human Factors in Computing Systems, pp. 4255–4260.
Lois, D., Monzón, A., Hernández, S., 2018. Analysis of satisfaction factors at urban transport interchanges: measuring travellers' attitudes to information, security and waiting. Transp. Policy 67, 49–56.
Mesken, J., Hagenzieker, M.P., Rothengatter, T., de Waard, D., 2007. Frequency, determinants and consequences of different drivers' emotions: an on-the-road study using self-reports (observed) behaviour, and physiology. Transp. Res. Part F 10, 437–492.
Nègre, J., Delhomme, P., 2017. Drivers' self-perceptions about being an eco-driver according to their concern for the environment, beliefs on eco-driving, and driving behavior. Transport. Res. A: Policy Pract. 105, 95–105.
Nesamani, K.S., Chu, L., McNally, M.G., Jayakrishnan, R., 2007. Estimation of vehicular emissions by capturing traffic variations. Atmos. Environ. 41 (14), 2996–3008.
Oltedal, Rundmo, 2006. The effects of personality and gender on risky driving behaviour and accident involvement. Saf. Sci 44 (7), 621–628.
Onoda, T., 2009. IEA policies – G8 recommendations and an afterwards. Energy Policy 37 (10), 3823–3831.
Russell, J.A., 1980. A circumplex model of affect. J. Pers. Soc. Psychol. 39 (6), 1161.
Rutty, M., Matthews, L., Andrey, J., Del Matto, T., 2013. Eco-driver training within the City of Calgary's municipal fleet: monitoring the impact. Transp. Res. Part D Transp. Environ. 24, 44–51.
Saboohi, Y., Farzaneh, H., 2009. Model for developing an eco-driving strategy of a passenger vehicle based on the least fuel consumption. Appl. Energy 86 (10), 1925–1932.
Sanguinetti, A., Kurani, K., Davies, J., 2017. The many reasons your mileage may vary: toward a unifying typology of eco-driving behaviors. Transport. Res. D: Transp. Environ. 52, 73–84.
Smit, R., Rose, G., Symmons, M., 2010. Assessing the impacts of eco driving on fuel consumption and emissions for the Australian situation. In: Proceedings of the 33rd Australasian Transport Research Forum (ATRF), Canberra, ACT, Australia.
Sivak, M., Schoettle, B., 2012. Eco-driving: strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy. Transp. Policy 22, 96–99.
Steg, L., Vlek, C., Slotegraaf, G., 2001. Instrumental-reasoned and symbolic-affective motives for using a motor car. Transport. Res. F: Traffic Psychol. Behav. 4 (3), 151–169.
Strömberg, H., Karlsson, I.M., Rexfelt, O., 2015. Eco-driving: Drivers' understanding of the concept and implications for future interventions. Transp. Policy 39, 48–54.
Vogt, R., Wang, H.Zh., Gregor, B., Bettinardi, A., 2015. Potential changes to travel behaviors & patterns: a fuzzy cognitive map modelling approach. J. Transport. 42 (6), 967–984.
Wang, Y., Monzón, A., 2016. Economic crisis and its influences on the interaction between land use and transport in Madrid Region. Transp. Res. Procedia 18, 100–107.
Wang, Y., Boggio-Marzet, A., 2018. Evaluation of eco-driving training for fuel efficiency and emissions reduction according to road type. Sustainability 10 (11), 3891.
Wåhlberg, A.E., 2007. Long-term effects of training in economical driving: fuel consumption, accidents, driver acceleration behaviour and technical feedback. Int. J. Ind. Ergon. 37 (4), 333–343.
Young, M.S., Birrell, S.A., Stanton, N.A., 2011. Safe driving in a green world: a review of driver performance benchmarks and technologies to support 'smart' driving. Appl. Ergon. 42 (4), 533–539.
Zarkadoula, M., Zoidis, G., Tritopoulou, E., 2007. Training urban bus drivers to promote smart driving: a note on a Greek eco-driving pilot program. Transport. Res. D: Transp. Environ. 12 (6), 449–451.
Zhou, M., Jin, H., Wang, W., 2016. A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing. Transport. Res. D: Transp. Environ. 49, 203–218.