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Evaluation of Eco-Driving Training for Fuel Efficiency and Emissions Reduction According to Road Type

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Abstract: Eco-driving is becoming more widespread as individual car-use behaviour is a cost-effective way of improving vehicle fuel economy and reducing CO_2 emissions. The literature shows a wide range of efficiencies as a result of eco-driving, depending on route selection, traffic characteristic, road slope, and the specific impact evaluation method. This paper follows this line of research and assesses the impact of an eco-driving training programme on fuel savings and reduction of CO_2 emissions in a well-designed field trial, focusing on the specific impacts according to road type. The methodology includes a comprehensive trial on different types of road sections under various traffic conditions; a processed dataset using R codes to integrate, clean, and process all the information collected; and a systematic method to evaluate the overall and specific impacts of eco-driving. The final results show a general fuel saving after eco-driving training of up to an average of 6.3% regardless of fuel and road type. Driving performance, as represented by selected parameters (average and maximum RPM, average and maximum speed, aggressive acceleration/deceleration), changed significantly after the training. The highest fuel savings are achieved on major arterial road sections with a certain number of roundabouts and pedestrian crossings. This work contributes to an understanding of the key factors for eco-driving efficiency according to road type under real traffic conditions. It offers greater insights for policymakers in road transport planning and for drivers when applying eco-driving techniques.

Keywords: eco-driving; climate change; emissions; road type

1. Introduction

Recent decades have seen an ongoing debate on how and to what extent different policies and strategies mitigate the transport sector's impact on climate change. Dalkmann and Brannigan [1] proposed a framework to identify transport strategies capable of reducing carbon dioxide emissions from the transport sector on the demand side: the avoid-shift-improve-finance framework (ASIF2) paradigm. This determines different procedures that contribute to the goal of reducing the impact of transport on climate change in terms of CO_2 emissions, i.e. avoiding the need to travel, promoting a modal shift to sustainable transport modes, improving fuel efficiency, and financing sustainable urban development.

In 2017, the European Automobile Manufacturers' Association (ACEA) study [2] revealed that only 5.2% of the vehicles sold on the European market were electric, hybrid, or fuelled by natural gas. Despite a drop of 5.2% since 2016, the market for diesel and petrol vehicles still represents 46.3% and 48.5% of the European market, respectively, meaning that traditional fuels continue to play an important role in the road transport sector. A number of strategies and actions have been deployed to reduce Greenhouse Gas (GHG) emissions from the transport sector, including more stringent emission standards, improved vehicle technology, better fuel quality and renewable fuels, and the use of information and communication technologies (ICT) to improve transport efficiency [3]. However, the investments in these strategies are huge, and the implementations are usually complex and involve multiple stakeholders. Research has shown that the potential improvements in GHG reduction from advanced engine and vehicle technologies accounted for only 4–10% and 2–8%, respectively [4]. Meanwhile, eco-driving is becoming more widespread, as individual car-use behaviour is more cost-effective and could improve vehicle fuel economy and reduce CO_2 emissions by up to 45% [5].

At the operational level, eco-driving is defined as a strategy which primarily seeks to change driving habits by following easily typified rules, i.e., using vehicle inertia, accelerating and braking smoothly, maintaining a steady speed, shifting gears at low RPM, anticipating traffic, etc. [6,7]. Eco-driving can not only improve fuel efficiency but also reduce road accidents and noise as a result of drivers' calmer driving patterns [8].

The literature shows that the efficiency of eco-driving varies widely depending on the experimental design, the external circumstances, and the methods of impact evaluation [9]. The fuel savings before and after receiving eco-driving instruction in several field trials revealed that fuel reduction varies from 5% in the case of a single monitored vehicle [10] to 25% immediately after drivers were enrolled in a training course [9,11], and from 10% to −0.5% depending on the road type, i.e., highways or urban roads [12].

The recent work about eco-driving by Huang et al. [9] and Ng et al. [13] shows that drivers who practice eco-driving may prolong their travel time (about 7%) and consequently increase other pollutant emissions, such as CO (26%). A better understanding is required about the trade-off between fuel economy, pollutant emissions, and travel time under different road conditions. They also point out the lack of an effective experimental design to identify the key variables that impact fuel savings and emissions due to eco-driving performance.

This paper follows this line of research: it assesses the impact of an eco-driving training programme on fuel savings and CO_2 emissions through a comprehensive road trial focused on the specific impacts by road type (i.e., highway, urban arterial road, and local street). There are two aims associated with this objective. The first is to select proper routes to conduct the field trial, considering various road types under different traffic conditions; the second is to assess the impacts of eco-driving on fuel saving and emissions reduction by monitoring both internal (driving pattern variables) and external factors (road type and traffic characteristics). The field trial was carried out in Madrid, Spain, over one month and consisted of monitoring fuel consumption and other relevant variables (such as global positioning system (GPS) position, speed, revolutions per minute, and distance recorded) of two vehicles, one petrol-fuelled and one diesel-fuelled, along pre-established routes. We found that after the eco-driving training, 12 drivers reduced their fuel consumption by an average of 6.3%. Urban arterial roads are the best place to practice eco-driving, since this environment produced the highest fuel savings with no increase in travel time.

After introducing the research context and the objective, Section 2 of this paper contains a review of the literature on the concept of operational eco-driving and the results obtained in previous field tests. Section 3 focuses on the methodology used in this research, and includes a description of the field trial, the dataset, and the evaluation of the impact of eco-driving training. The results of the data analysis and the discussion are presented in Section 4. The article ends with the main findings and some policy recommendations.

2. Eco-Driving Training and Its Impact

Sivak and Schoettle [5] define eco-driving as referring to three different levels of decision-making: the vehicle choice and maintenance, the route choice, and the operational level, which depends on driving techniques. The main point of operational decision-making in eco-driving is that it is accessible to everyone. Eco-driving can also be practiced by all drivers in any vehicle, regardless of fuel type. Finally, the cost of eco-driving is very low: a 2006 study by the TNO (Netherlands Organisation for Applied Scientific Research) estimated that the cost to each institution interested in implementing eco-driving (through campaigns, courses, or others) would be only around €9 to reduce each ton of CO_2 [14].

The most commonly applied method for individual drivers to implement eco-driving consists of training programmes that teach drivers eco-driving knowledge (theoretical training) and skill (practical training). Table 1 presents a short summary of several analyses about fuel savings obtained in a relatively short period by applying eco-driving training programmes to drivers. It can be seen that the fuel savings obtained after attendance at training programmes are heterogeneous, from 0 to 25% depending on the design of the training programme and the individuals' performance (see Table 1).

Table 1. A summary of previous eco-driving training programmes.

Reference Number	Year of Publication	Road Type	Methodology	Fuel Consumption (fc)
[10]	1999	Mixed type	Results compared after instructions	−10.90%
[15]	2003	Mixed type	86 drivers; results compared after instructions	−8% with fc monitoring and −1.2% without
[16]	2007	15 km route	3 bus drivers	10–15%
[11]	2008	Mixed type	300 drivers; results compared after training	−25% short term, −10% long term
[17]	2011	City and highway	20 drivers; results compared after 2 weeks, receiving instant feedback	City −6%, Highway −1%
[18]	2012	70 km Mixed type	20 drivers; results compared before and after training	−11.3%
[19]	2013	Mixed type	After training; results compared after one month	−1.7 kg CO_2 emissions per day
[20]	2013	16 km urban road	54 drivers; results compared after 6 weeks	−6.80%
[21]	2015	Mixed type	116 drivers; pre-test, 30 min training, re-test	Less than −10%
[22]	2015	Mixed type	91 logistic drivers	No effect

The studies listed in Table 1 compare fuel consumption before and after eco-driving training through field trials under different road circumstances. The fuel savings are generally positive, except in the work of Schall et al. [22], who reported that purely theoretical training had no effect in either the short or long term, indicating the need for practical training elements. In regard to the impacts by road type, although most of these trials contain mixed road types (i.e., they include both highways and urban roads), they failed to address the specific effects of eco-driving training specialized for road type.

Borisboomsin et al. [17] reported that eco-driving performances were more effective under city conditions than highway conditions, but 40% of the drivers had already practiced eco-driving, which cannot reflect the true effect of an eco-driving training programme. The work of Andrieu and Saint-Pierre [18] shows that the average drop in fuel consumption after giving simple advice (12.5%) was slightly higher than after short-term training (11.3%). However, the road type and vehicles used for comparing the two methods (i.e., simple advice and training) were different, which means that the results cannot be comparable. A recent study carried out by 59 drivers in Canada [23] showed that short-term training reduces city and highway fuel consumption by 4.6% and 2.9%, respectively. The fuel saving for the city and the highway were not directly collected, but converted from the general fuel reduction by an official ratio of the actual fuel rate reported by manufacturers under city and highway conditions. Their real fuel savings under different road conditions remain unknown.

On-road experiments are significantly affected by certain traffic characteristics and the specific road type. Most of the previous studies involved field trials over short distances with simple or controlled traffic characteristics to avoid the influence of external factors [15,16,18,19]. The results of these experiments ignore the influence of real traffic, in which eco-driving drivers always find a mixture of different road types and traffic conditions. Moreover, the usual heterogeneity of the vehicle sample produced inferenced results, as vehicle typology is one of the main factors affecting fuel consumption. In order to fill these gaps in the research, this work tested eco-driving under real traffic and road characteristics to evaluate its efficiency when considering road type and traffic conditions. Moreover, to reduce as far as possible the influence of the vehicle over the average fuel consumption, only two vehicles were used.

3. Methodology

Figure 1 shows the three parts of the research framework: the field trial, the dataset, and the impact evaluation method.

The goal of the field trial was to collect the necessary data on both driving patterns and traffic before and after a training course. In this context, the trial was divided into two driving periods: Period 1 (pre-training) and Period 2 (post-training). Period 1 is classified as a "control" driving period that reflects the normal driving style of the individual participants without eco-driving elements; Period 2 is the driving period that combines the use of the eco-driving techniques that were learnt from the course and from on-road practice. The details of the selected routes, driver recruitment, and the training course are described in Section 3.1.

The dataset contains all the data recorded from the trial. Data from 1001 trips were downloaded, filtered, and processed using the R programming language. However, only 718 trips were finally included in the dataset due to the faulty registration of GPS, RPM, travel time, and fuel consumption. Each trip in the dataset is described by 128 variables relating to driving pattern and road condition. Details of the dataset are given in Section 3.2.

The impact evaluation indicates the changes that can be attributed to eco-driving training. It first assesses the overall effects on fuel savings and CO_2 emissions regardless of road type, and then focuses on the specific changes by four types of road. Section 3.3 describes 10 parameters related to fuel consumption, driving pattern, and traffic condition.

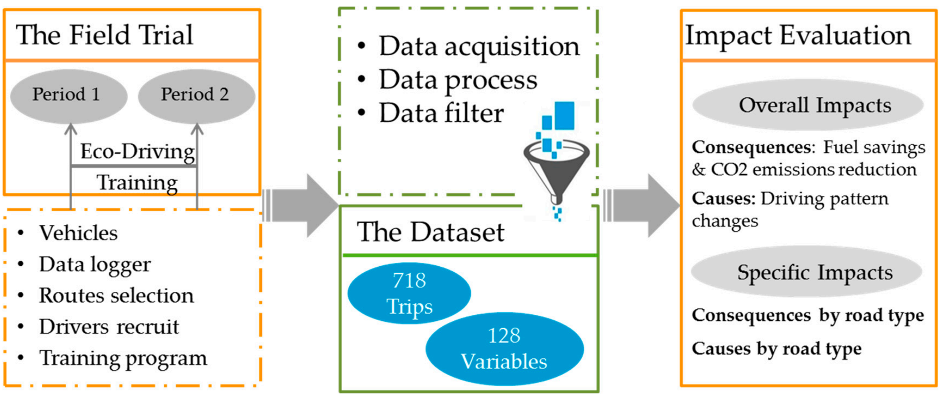


Figure 1. The research framework.

3.1. The Field Trial

The trial took place in April 2017 and May 2017 with two light-duty vehicles: a diesel-fuelled Opel Astra (Groupe PSA, Zaragoza, Spain) and a petrol-fuelled Fiat 500 (Fiat Automobiles S.p.A., Turin, Italy). The cars were rented from a local car-sharing company and are registered under Euro 5 standards; the vehicles can be classified as small (Fiat 500) and medium segment (Opel Astra), which corresponds to approximately 60% of the fleet in Spain [24]. The sample is therefore fairly representative of the composition of the Spanish fleet.

An on-board logging device (OBD-Key) (KBM Systems Ltd., London, UK) was installed in each vehicle to monitor key driving parameters during the two experimental periods. The measuring scheme using OBD-Key is given in Figure 2. A mobile APP called Torque installed in a pre-set up mobile phone was applied to collect trip data. A Torque user can freely select variables, such as average trip speed, trip distance, GPS latitude, GPS longitude, and litres per 100 kilometres, to observe each trip a vehicle makes. The instant data were recorded for each vehicle with a frequency of 1Hz, including GPS position, travel time, speed, and fuel consumption, and sent immediately from the vehicle's diagnostic port to a mobile phone via Bluetooth. The accuracy of the OBD-Key is acceptable; 83% of the trips' data was correctly recorded, although the instant fuel consumption was higher than the actual fuel consumption (verified by the fuelling record).

Figure 2. The trip data measuring scheme using OBD-key.

3.1.1. Route Selection

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 (Figure 3). 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 [25].

Following the road categories defined in [26], the itineraries cover the main road types with different functionalities, including highway, urban arterial road, urban collector road, and local road (see Table 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.

The experimental routes were selected based on three criteria: (i) the previous study in Madrid showed that eco-driving is less effective on urban roads with severe congestion [27], so less-congested suburban roads may be better for practicing eco-driving; (ii) we chose heterogeneous itineraries composed of different geometrical segmentations and traffic volumes to analyse the eco-driving effect under different conditions; and (iii) different routes but with the same origin and destination make it easier to monitor travel time and are more convenient for the drivers when changing shifts.

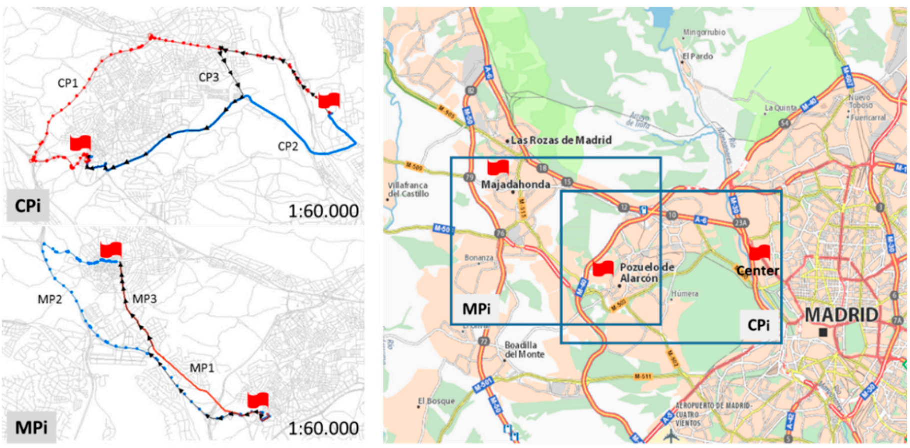


Figure 3. The location of the experiment routes.

Table 2. Information on the selected routes and road sectors in Madrid.

Route	*Road Type*	*Lanes*	*Speed Limit (km/h)*	*Distance (km)*	*Travel Time Range (min) **	*Average Daily Intensity ** 10^3*	*Average Slope (%) ****	
							Direction I	**Direction II**
CP1	Highway	2 × 2 to 4 × 4 lanes With high occupancy vehicle lane-HOV or barrier	80/120	15.2	18–35	77–133	−2.8~2.8	−2.5~2.9
	Local street	1 × 1 without barrier	50					
CP2	Highway	2 × 2 to 4 × 4 lanes With HOV lane or barrier	80/120	13.3	18–30	48–59	−3.6~3.0	−2.8~3.5
	Urban arterial road	2 × 2 separated by barrier. Parking both side	40					
	Local street	1×1 without barrier	50					
CP3	Highway	2 × 2 to 4 × 4 lanes With HOV lane or barrier	80/120	13.5	18–22	48–133	−3.2~3.2	−3.0~3.3
	Local street	1 × 1 without barrier	50					
MP1	Urban arterial road	2 × 2 separated by barrier	30/50	8.2	18–30	17	−3.0~3.0	−3.2~3.4
	Local street	1 × 1 without barrier	50					
MP2	Highway	2 × 2 or 3 × 3 separated by barrier	90/120	13.2	16–30	17–62	−2.6~2.9	−2.8~3.1
	Mayor arterial road	2 × 2 separated by barrier	30/50					
	Local street	1 × 1 without barrier	50					
MP3	Highway	2 × 2 separated by barrier	90	8.6	16–35	17–43	−3.2~3.1	−3.1~3.6
	Mayor arterial road	2 × 2 separated by barrier	30/50					
	Local street	1 × 1 without barrier	50					

* Travel time from non-peak to peak-hour (source Google Maps). ** Total volume of vehicle traffic of a road section for a year divided by 365 days (source Ministerio de Fomento, Mapa de Trafico 2016). ***The average slope is obtained from Google Geo based on selected routes.

3.1.2. Driver Selection, Scheduling, and Eco-Driving Training

Twelve drivers were recruited for the experiment for 1 month (see Table 3). Drivers were academic staff and students aged between 23 and 56; the sample was almost gender balanced, with seven men and five women. Most were young drivers with less driving experience; only four of them were more experienced with over 20 years' driving experience.

Table 3. Information on participating drivers.

Driver ID	Age (Years Old)	Gender	Driving Experience (Year)
1	25	Woman	7
2	24	Man	5
3	30	Man	11
4	24	Man	6
5	55	Woman	34
6	56	Woman	38
7	40	Man	21
8	42	Man	23
9	24	Man	6
10	23	Man	4
11	25	Woman	6
12	24	Woman	7
Average	33	-	14

During the experiment, six drivers were assigned to each vehicle each day to cover three driving shifts, in which two people took turns to drive (driver and assistant, changing every hour) and iteratively performed trips along the six selected routes. They drove 12 h a day (from 8 a.m. to 8 p.m.) to gather sufficient data under different traffic situations (free flowing, moderate traffic, and congestion) and weather conditions (rain, fog, etc.). The shifts were adjusted to cover peak times according to the mobility records [28]. An adequate data sample was thus obtained to distinguish between different traffic situations and type of road section, and to avoid alterations in driving style as a result of the weather conditions.

After Period 1, the 12 drivers received a six-hour eco-driving course on how to apply the techniques during Period 2. The training programme was taught by instructors from a local driving school, and included a theoretical class and operational practice with the same instructor. The main eco-tips were presented as driving techniques, including:

- 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;
- avoiding unnecessary weight;
- anticipating current traffic conditions;
- switching off the engine during stops of over 1 minute.

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.

3.2. The Dataset

The dataset contains 718 trips and covers an overall distance of 8014 km (4285 km in Period 1 and 3729 km in Period 2). One hundred and ninety-three (283) trips (28% of the total) were excluded due to faulty registration of GPS, RPM, travel time, and fuel consumption. The diesel-fuelled vehicle made a total of 349 trips during the trial, and the petrol-fuelled vehicle made 369. The significance of this study of the influence of different road environments on fuel consumption is supported by the over 100 trips carried out on each specific route. Each participant made an average of 60 trips; 32 in the first period and 28 in the second.

The descriptive statistics of each driver's profile and recorded trip were given by road sectors, which were obtained by splitting the initial dataset into 3153 data (Table 4). The dataset that was used to analyze the impact of eco-driving contained 128 variables for driving patterns (57 variables), road condition factors (10 variables), energy parameters (18 variables), and emissions (16 variables), according to the literature in this field [29–32].

The value related to fuel consumption was calculated based on the Vehicle Specific Power (VSP) 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 [33]. Informally, it represents the ratio between the power demand of the vehicle and its mass.

The value related to CO_2 emissions was converted from the value of fuel consumption using the emission factor extracted from the "Environmental Monitoring, Evaluation and Protection (EMEP)"/"European Environment Agency (EEA)" air pollutant emission inventory guidebook [34] for petrol and diesel light vehicles. A more detailed description of the VSP model and its conversion factors that were used in this study can be found in [33,35,36] and the Supplementary Material.

Table 4. Descriptive statistics of data per road sector.

Sets	Variables	Average	St.dev.	Min	Max
Drivers' profiles	*age*	31.7	11.7	23	56
	years of experience	13	11.3	4	38
Experiment on road n = 3153	*distance recorded (km)*	2.33	1.85	0.03	10.27
	travel time (s)	209	157	6	1533
	speed (km/h)	42.4	24.3	2.8	101.5
	fuel consumption (l/100 km)	5.71	1.06	3.98	12.66
	CO_2 emissions (g/km)	183.2	33.7	24.2	550.6
Period 1 (Pre-training) n = 1668	*distance recorded (km)*	2.36	1.87	0.03	10.27
	travel time (s)	207	163	6	1533
	speed (km/h)	43.1	25.0	3.3	101.5
	fuel consumption (l/100 km)	5.91	1.24	4.03	12.66
	CO_2 emissions (g/km)	189.4	34.6	69.2	550.6
Period 2 (Post-training) n = 1485	*distance recorded (km)*	2.30	1.83	0.09	6.88
	travel time (s)	210	150	15	1383
	speed (km/h)	41.6	23.4	2.8	94.9
	fuel consumption (l/100 km)	5.53	0.78	3.97	10.21
	CO_2 emissions (g/km(	177.4	33.1	24.2	480.2

3.3. The Impact Evaluation Method

Emissions and fuel consumption measurements in on-road traffic conditions provide valuable data for the driver while actually engaged in eco-driving. The evaluation of the impact of eco-driving focuses on changes in fuel consumption and CO_2 emissions between Period 2 (after eco-driving training) and Period 1 (before training) in two aspects.

We first checked the overall effects of the training programme in terms of the type of vehicles and drivers. Through a multiple regression analysis, we found that RPM (maximum), negative acceleration (especially average, and—to a lesser extent—standard deviation), and speed (maximum and average) are closely associated with a decrease in fuel consumption throughout the trip [37]. We, therefore, also included the changes in five variables plus aggressive acceleration in Section 4 to identify to what extent participants changed after the training programme.

Two variables related to traffic conditions (the percentage of stop time and the 95th percentile of recorded speed) were also analyzed in order to understand the influence of traffic on eco-driving efficiency. Table 5 presents an overview of the selected parameters, their units, and the corresponding abbreviations.

Table 5. A description of the selected parameters.

Parameter Type	*Description*	*Code*	*Unit*
Fuel consumption and emissions	Average fuel consumption	avg_FC	L/100 km
	Average CO_2 emissions	avg_CO_2	g/km
Driving-performance-related	Average RPM	avg_RPM	rpm
	Maximum RPM	max_RPM	rpm
	Average speed	avg_speed	km/h
	Maximum speed	max_speed	km/h
	% time with aggressive acceleration (more than 1.389 m/s^2)	avg_acc	%
	% time with sudden deceleration (less than −1.389m/s^2)	avg_dec	%
Traffic-intensity-related	percentage of stop time (0 km/h)	V_0%	%
	95th percentile of instant recorded speed	V95	km/h

We then extended the analysis by exploring the changes in the same variables based on specific road types and traffic characteristics in order to discriminate the best road conditions for practicing eco-driving. We considered four road types in terms of their functional and geometric characteristics and their speed limits (see Table 6). Access to highway and urban collectors was not considered in the analysis due to an insufficient amount of data.

Table 6. The road type categories.

Road Type	*Lanes and Barriers*	*Speed Limit (km/h)*	*Traffic Intensity (Vehicles/Day)*	*No. of Road Sectors in the Dataset*
Local street	1 or 1 × 1 without traffic barrier	30/50	<5000	1234
Major arterial road	2 × 2 separated by rigid barrier	50	15,000–20,000	330
Highway I (urban)	3 × 3 or 4 × 4 with rigid barriers	80/120	45,000–55,000	992
Highway II (national)	4 × 4 lanes separated by HOV lane	90/120	>100,000	243

On-road experiments are significantly affected by uncertainties in traffic characteristics, driver behaviours, and transient operations due to the different design of the experiment [9]. The second analysis seeks to capture the effects of road type and traffic characteristics by showing the specific changes and the changes in the drivers' performance on each road type to increase the understanding of how different road types can affect eco-driving efficiency.

4. Results

This section presents the impacts of eco-driving training on the two aspects. It first explores the overall impacts of eco-driving training regardless of road type, along with the changes in driving performance; then shows the specific impacts according to the four road section types to determine the best road type for practicing eco-driving. It should be underlined that, as this is a short-term experiment, traffic intensity varies day-to-day and hour-to-hour, which influences drivers´ performance and real fuel savings from eco-driving.

4.1. Overall Impacts of Eco-Driving Training

Table 7 presents the fuel savings and CO_2 reduction considering all of the data that were collected from the 3153 road sections. The results show the impact of eco-driving before and after training for the two vehicles and by fuel type.

Table 7. General impacts of eco-driving training.

Parameters \ Period	Period 1 (Pre-Training)		Period 2 (Post-Training)		Diff.
	Mean	**St.dev**	**Mean**	**St.dev**	
Total sample					
avg_FC (l/100 km)	5.91	1.24	5.53	0.78	−6.3%
avg_CO_2 (g/km)	189.4	34.6	177.4	33.1	−6.3%
Petrol vehicle					
avg_FC (l/100 km)	6.17	2.43	5.70	2.28	−7.6%
avg_CO_2 (g/km)	204.8	68.4	189.2	59.0	−7.6%
Diesel vehicle					
avg_FC (l/100 km)	5.61	2.52	5.35	2.18	−4.7%
avg_CO_2 (g/km)	172.6	76.5	164.6	72.2	−4.7%

The average reduction in instant fuel consumption that was achieved through eco-driving is 6.3%, which, due to their linear relation, leads to the same drop in CO_2 emissions (6.5%).

The discrepancy in the results from the FIAT 500 vehicle (petrol) compared to the Opel Astra (diesel) suggests a clear influence of vehicle and fuel type on fuel consumption and fuel savings. The literature confirms that vehicle selection is the most dominant contributor to fuel economy when compared to route choice and driving style; one vehicle can be up to nine times more fuel efficient than another [5]. To reduce this influence as far as possible, our study used two different vehicles that were powered by different fuels but with similar segmentation (small and medium), both registered under Euro 5 standards. However, better results were obtained with the petrol-fuelled car, achieving an average 7.6% reduction in average fuel consumption, compared to an average of 4.7% with the diesel vehicle.

We can also draw some general conclusions from the performance data for different driver profiles. As previously indicated, these refer only to our study. There was a certain heterogeneity among the participants in the experiment: five women aged between 24 and 56, and seven men aged 23–42. On average, men performed slightly better at eco-driving than women, achieving a 6% and 4% reduction in average fuel consumption, respectively, although the difference in sex does not appear to be representative. Our study also compared driving experience of less than 7 years with driving experience of over 20 years. While the reduction in average fuel consumption was quite similar, 5% and 4% respectively, drivers with less driving experience on average achieved a 5% lower instant fuel consumption than drivers with over 20 years' driving experience regardless of whether they adopted eco-driving or not.

Finally, it is important to underline that, as a car-use behaviour, eco-driving performs differently depending on the driver; considering different driver profiles, the savings in instant fuel consumption varied from 0 to 12%. Although all drivers involved in the experiment reduced their fuel consumption and CO_2 emissions, their driving behaviour changed positively after enrolling in the efficient driving course and adopted a smoother and calmer driving style. Table 8 shows the main changes in value in the parameters that were considered in our study between the first and second driving period.

With regard to specific driving performances, substantial changes can be seen in driving behaviour in Period 2. Drivers significantly reduced their maximum and average RPM (23% and 15%, respectively), and made far fewer aggressive accelerations (33%) and decelerations (44%). Although the average speed reduction is not significant—from 43 km/h to 42 km/h—drivers lowered their maximum speed by 8%. As proof of correct eco-driving performance, we obtained a greater reduction in the 95th percentile of speed (7%), which is also representative of the free-flow condition. In fact, while average speed can be strongly affected by traffic characteristics, the reduction in maximum speed and its 95th percentile is more representative of correct driving behaviour, as this is one of the most important eco-tips.

Table 8. Changes in driving-performance-related parameters.

Parameters \ Period	Period 1 (Pre-Training)		Period 2 (Post-Training)		Diff.
	Mean	St.dev	Mean	St.dev	
avg_rpm (rpm)	1773	422	1510	365	−14.8%
max_rpm (rpm)	2850	503	2209	428	−22.5%
avg_speed (km/h)	43.1	25.0	41.6	23.4	−3.5%
max_speed (km/h)	69.1	25.0	63.8	24.0	−7.7%
avg_acc (%)	6.50	4.61	4.33	3.24	−33.4%
avg_dec (%)	5.69	4.60	3.21	2.70	−43.5%
V95 (km/h)	65.6	25.0	60.7	23.8	−7%
V_0% (%)	6.4%	11%	5.2%	10%	−18.9%

4.2. Impacts of Eco-Driving by Road Type

Figure 4 shows a comparison of the average fuel consumption changes between Period 1 and Period 2 for the four road types. The fuel reduction that was achieved through eco-driving performance varies by road type. Higher fuel savings and emissions reduction are observed along major arterial sectors (8% fuel savings). Drivers have higher fuel consumption on highways than on local streets as a result of higher speeds. When drivers have less control of the vehicle, they make frequent speed and gear changes to adapt to the prevailing traffic conditions, which explains the greater standard deviation in the instant fuel consumption recorded along highway road sectors (in both Period 1 and Period 2).

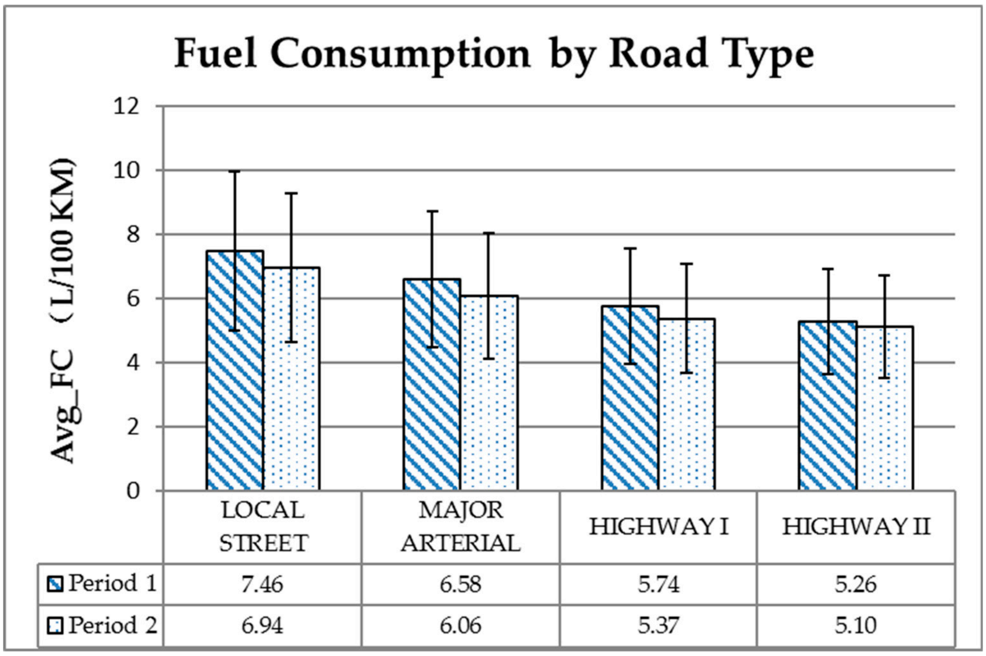
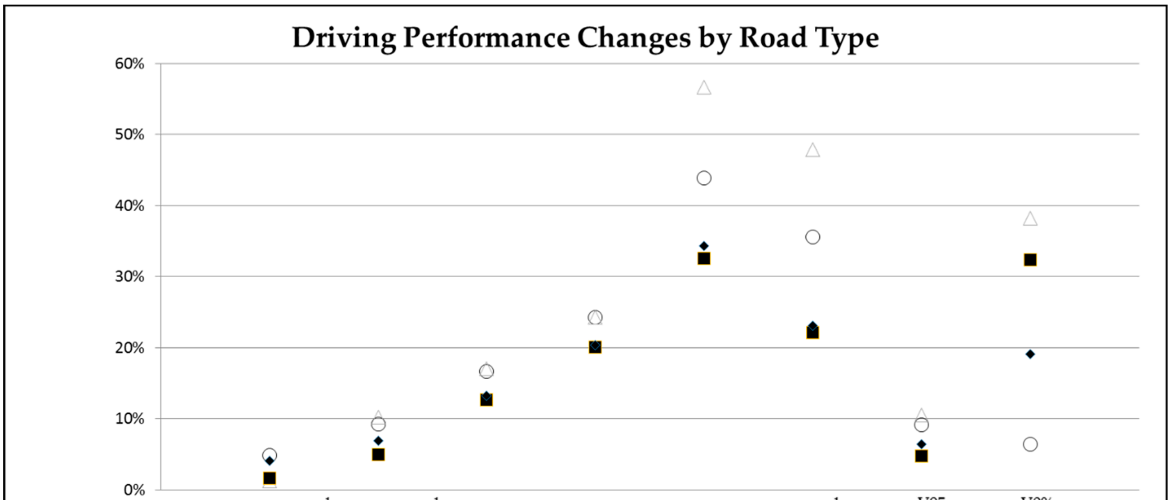


Figure 4. The Fuel Consumption by road type before and after training.

The variations in fuel savings between the four road types can be explained by the changes in the driving performance parameters. Figure 5 compares the two experimental driving periods and shows the behavioural changes that were achieved, which answers the question of the extent to which different road characteristics influence fuel savings due to eco-driving.



	avg_speed	max_speed	avg_rpm	max_rpm	avg_acc	avg_dec	V95	V0%
○ LOCAL STREET	4.9%	9.2%	16.7%	24.3%	43.9%	35.6%	9.2%	6.4%
△ MAJOR ARTERIAL	1.2%	10.3%	17.1%	24.3%	56.7%	47.9%	10.6%	38.2%
■ HIGHWAY I	1.6%	4.9%	12.7%	20.1%	32.5%	22.2%	4.8%	32.4%
◆ HIGHWAY II	4.0%	6.9%	13.2%	20.4%	34.3%	23.1%	6.4%	19.1%

Figure 5. Changes in driving-performance-related parameters by road type.

With regard to changes in driving performance, we observed a positive effect of eco-driving training on drivers' habitual behaviours along all road types. The most notable changes are related to acceleration and deceleration: most of the drivers considerably reduced sudden acceleration and deceleration on all road types (an average reduction of 40% and 32%, respectively). Although the reduction in acceleration/deceleration is significant on highways, Figure 5 shows that this value is two times lower than the one that was achieved along local streets and major arterial roads, perhaps because of the higher traffic density that was encountered along highways during the second driving period.

The RPM parameters (both average and maximum) and speed (both average and maximum) are also significantly lower (from 13% to 24% depending on road type); a steadier speed was maintained during the driving period where eco-driving was used. V_0% is much lower along the two types of highways, and a similar decrease is observed in V95 for all four road types during Period 2.

The results show that eco-driving performs best on major arterial roads than on other road types, which coincides with the results for fuel savings. It should be noted that the major arterial road in the selected routes has speed limits of less than 50 km/h and has a number of roundabouts, intersections, and pedestrian crossings.

The difference between the eco-driving patterns that was registered along Highway I and Highway II reveals that high speed limits not only affect fuel consumption, but also the potential savings that could be achieved through efficient driving techniques. It was observed that drivers have more difficulty in modifying their driving behavior to eco-driving under conditions of high speed.

In addition to the four road types, a 26% fuel reduction was also achieved along the urban collector road, which has a length of 800 m. While the average slope on the other four road types is almost null, at near 0%, on the urban collector road the average slope was ±3%. In this case, we conclude that roads with a greater average slope not only produce a greater instant fuel consumption [37], but, more importantly, are another ideal type of road on which to practice eco-driving.

5. Conclusions and Policy Recommendations

5.1. Main Findings

The aim of this paper is achieved by analyzing eco-driving efficiency through a well-designed field trial involving an eco-driving training programme. An innovative evaluation method was designed to assess the impacts on fuel savings, considering both internal and external factors. The main findings from these results are the following:

- A short-term eco-driving training course has significant effects on changing drivers' habitual driving performance. The general savings in fuel consumption due to the application of eco-driving is up to 6.3% regardless of fuel type and road type. However, this study only focused on the immediate effects of eco-driving training; so, it cannot guarantee that the same effects would remain long-term, since drivers may turn back to their ingrained driving habits. This is also the major challenge for eco-driving technology, as mentioned in the previous studies [9,14,17,38,39].
- The driving performance parameters that were considered in the study (average and maximum RPM, average and maximum speed, aggressive acceleration/deceleration) changed significantly after the training. Drivers were observed to modify their driving behaviour and drive more smoothly, accelerate/decelerate less aggressively, and avoid unnecessary stops during the trip.
- The field trial involving different road sectors shows various outcomes in terms of fuel savings and changes in driving patterns. The highest fuel savings were achieved on major arterial roads (8%) with a number of roundabouts and pedestrian crossings. Drivers have more difficulty in applying eco-driving techniques on highways with high traffic intensity. When traffic conditions are favorable, eco-driving is more successful on itineraries that are characterized by lower speed limits and with several roundabouts and give ways; on highways and high-speed roads, free-flow conditions can encourage an increase in cruising speed, which translates into higher instant fuel consumption.

5.2. Policy Recommendations

This article aims to contribute to transport planning by serving as a work that extends our understanding of eco-driving efficiency; it offers a broader view for both policymakers and drivers applying eco-driving techniques.

This study confirms that drivers can apply eco-driving techniques along urban roads that are crossed by roundabouts and pedestrian crossings to reduce the fuel consumption that is required for sudden acceleration/deceleration [40]. One recommendation for transport planners is to implement a "green wave" of coordinated traffic lights along corridors with intensive traffic flows in order to ensure a constant speed (and reduce sudden accelerations/decelerations) and to relieve roundabouts of major flows and permit eco-driving.

Our data show that eco-driving efficiency is strongly dependent on external causes that often cannot be controlled. Due to their almost null cost of implementation, eco-driving techniques produce highly favourable results in all cases. However, as fuel consumption is so heavily affected by external factors, it is necessary to improve and act on road transport planning.

One major strength of this study is the amount of data that was analyzed. Data were analyzed on the influence of an efficient driving course on eco-driving performances in urban and extra-urban contexts; data were also recorded by monitoring two vehicles that were powered by different fuel types and driven by different drivers along different itineraries at different times of day.

Based on our positive results, this study underlines the public need to create greater awareness of the role played by drivers in limiting their vehicle emissions under different traffic conditions. In some circumstances, eco-driving can significantly reduce fuel consumption, so its social and financial value could be promoted and included in driving lessons. Another recommendation to raise awareness of its value is to promote in-car equipment for measuring fuel consumption so the driver receives instant feedback.

This work also shows that a simple low-cost eco-driving course could improve drivers' performance in terms of fuel economy and driving style. Governments thus can put similar programmes in place in driving licence courses and have some expectation of success.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/11/3891/s1, Vehicle Specific Power (VSP) model. Table S1 VSP mode and corresponding power requirements and Table S2 Instantaneous Fuel consumption regarding to VSP mode.

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