Fuel consumption and gas emissions of an automatic transmission vehicle following simple eco-driving instructions on urban roads

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Abstract

Following eco-driving instructions can reduce fuel consumption between 5 to 20% on urban roads with manual cars. The majority of Australian cars have an automatic transmission gear-box. It is therefore of interest to verify whether current eco-driving instructions are efficient for such vehicles. In this pilot study, participants (N=13) drove an instrumented vehicle (Toyota Camry 2007) with an automatic transmission. Fuel consumption of the participants was compared before and after they received simple eco-driving instructions. Participants drove the same vehicle on the same urban route under similar traffic conditions. We found that participants drove at similar speeds during their baseline and eco-friendly drives, and reduced the level of their accelerations and decelerations during eco-driving. Fuel consumption decreased for the complete drive by 7%, but not on the motorway and inclined sections of the study. Gas emissions were estimated with the VT-micro model, and emissions of the studied pollutants (CO_2, CO, NO_X and HC) were reduced, but no difference was observed for CO_2 on the motorway and inclined sections. The difference for the complete lap is 3% for CO_2. We have found evidence showing that simple eco-driving instructions are efficient in the case of automatic transmission in an urban environment, but towards the lowest values of the spectrum of fuel consumption reduction from the different eco-driving studies.

Keywords: Eco-driving, urban roads, driving performance.

1. Introduction

Transport accounts for nearly 27% of total CO_2 emissions from fossil fuel combustion. Transport is the second largest CO_2 emitting sector after electricity production [1]. Fuel combustion emits water and carbon dioxide (CO_2) exhaust gases (perfect combustion), carbon monoxide (CO), oxides of nitrogen (NO_X) and unburned hydrocarbons (HC). These emissions are pollutants whose emissions are controlled by government standards [2]. Vehicle emissions and energy consumption are largely influenced by driving style, particularly in terms of acceleration, choice of speed and idling time[3, 4]. Many countries have therefore promoted eco-driving as a key element of national strategies to reduce fuel consumption and CO_2 emissions.

Eco-driving consists of a variety of driving techniques (style) that save fuel and lower emissions. Eco-driving instructions in Europe, US and Japan have been shown to reduce fuel consumption between 5 and 20% on urban roads for combinations of manual and automatic transmission vehicles [5, 6, 7]. Eco-driving instructions is a cost-effective solution which can be implemented rapidly on a large scale, improving energy consumption and emissions without significant increase of travel time [8]. Eco-driving instructions vary considerably per country. Apart from Sweden, which has introduced a new law in 2007 to test eco-driving skill during a practical vehicle test, there is no international standard or benchmark on the optimal method to instruct and perform eco-driving. Eco-driving generally attempts to change drivers' behaviour through instructions or tips such as driving more smoothly by anticipating changes in the traffic, shifting gear sooner, operating the vehicle within an optimum revolution range, avoiding jerky braking/acceleration and avoiding traffic jams [9, 10]. European Union regulations already require eco-driving to be taught during training of novice drivers. Japan achieved its 2010 goal of reducing CO_2 emissions by 31 million tons below 2001 levels by encouraging drivers to use their vehicles more efficiently through eco-driving [1].

Traffic has increased in urban transport systems and driving pattern over a specified route varies to a great extent (e.g. road grade) [11]. In order to effectively reduce gas emissions it is necessary to change driver behaviour or style in a way such that eco-driving becomes the norm rather than the exception [12]. Research has shown that vehicle's emissions can be accurately estimated with models taking into account the speed and acceleration of the vehicle, such as the Comprehensive Modal Emissions Model (CMEM) and the VT-Micro Model [13]. The VT-Micro model has been shown to be above 90% accuracy [14]. Such models allow to assess the effects of driving style and hence can be used to evaluate the effects of eco-driving on emissions.

The claimed advantages of the eco-driving approach are that they can apply to vehicles of any age or size, they can take effect across the entire fleet of vehicles immediately at low cost (as opposed to being phased in), and that they can result in immediate savings to individuals from greater fuel efficiency, better safety and perhaps lower insurance rates [12]. One of the most popular eco-driving instructions for drivers operating vehicles with a manual gear box is to shift to the highest gear as soon as possible without lugging the engine. Such instructions reduce engine revolutions per minute (RPM) and consequently the fuel consumption. However, such instructions are very general and do not take into account driving conditions that could require different strategies. For instance, are such instructions relevant for urban driving, motorway and inclined road sections? As most passenger vehicles in Australia are equipped with an automatic transmission (also called automatic gear box), are such instructions adapted to automatic transmission vehicles? Drivers of automatic transmission vehicles are not aware of the gear they are driving in nor are they able to control gear shifts. Japan has conducted many trials to evaluate the effect of eco-driving instructions on fuel consumption in urban road. Shinpo's study [15] has shown positive eco-driving outcomes with a fleet of automatic and manual transmission vehicles, but without focusing on the transmission type. The Smart Drive study has established that almost 50% of fuel consumption in urban environments is spent on accelerating and decelerating, as illustrated in Figure 1 [16].

In France,St-Pierre and Andrieu[17] conducted a study which comprehensively characterised the immediate effects of eco-driving instructions on driver behaviour in a vehicle with manual transmission on semi-rural roads. Our study builds upon their findings and focuses on the effects of eco-driving instructions on driver's steady speed, acceleration and deceleration, in a vehicle with an automatic transmission and on urban roads. We use the simple advice for attaining eco-driving behaviours, as Andrieu and St-Pierre [9] showed that even though a complete eco-driving course provides higher benefits, differences are small. Our experiment will test the following two hypotheses:

- Simple eco-driving instructions improve fuel consumption of automatic passenger vehicle in an urban environment ;
- Simple eco-driving has positive effects on gas emissions when driving an automatic car in an urban environment.

This study comprises a within subject comparison of driving performance with and without eco-driving instructions using a medium size instrumented passenger vehicle featuring an automatic gear box travelling in an urban environment.

2. Method

2.1. Experimental Design

2.1.1. Instrumented Vehicle (Figure 2)

A medium size Toyota Camry Altise (2007) with automatic gear box was fitted with

- IBEO Laser scanner for leading vehicle detection.
- Vigil system (GPS receiver, accelerometer and cameras) for vehicle position, vehicle dynamics and to record the images of the road ahead and images inside the vehicle.
- NeoOBD On-board Diagnostic Device (OBD-II) for retrieving vehicle's RPM, speed, instantaneous fuel consumption and the percentage of throttle open.

All the above mentioned sensory data were recorded in a system using RTMaps software. The architecture of the in-vehicle system is illustrated in Figure 3.

2.1.2. Test track specification

The driving experiment was conducted in an urban environment at Kelvin Grove, Brisbane, Australia. The test track features a small portion of 2 lane motorway (3 km) and suburban single lane roads (2 km). Driving such a small distance allows us to control for driver's fatigue and habituation. Figure 4 illustrates the test track used for the experiment. Figure 4 (b) is a GPS point tracking of one of the participants. This image is also used to highlight the track's length. The track's length will be used to explain the beginning/end of the different road types (i.e. motorway, incline etc.) in the Procedure section. The map (GoogleMap) of the track is presented in Figure 4 (a). Specifications for the test track/circuit are given below

- A fixed start point and end point from where the test vehicle starts and stops respectively.
- Clearly visible marked lanes (two lanes). The length of the track was approximately 5,000 meters for encompassing different classifications of the road (motorway, suburbs, incline road etc.).

2.1.3. Traffic conditions

The experiment was designed for an urban environment without heavy traffic in which reaching the optimal speed of 80km/h for fuel consumption was unlikely. The time and location of the experiment were chosen to maximise free flow opportunities in most of the route.

2.2. Participant Recruitment

Participants were recruited via word of mouth within the Queensland University of Technology. In order to be eligible, participants were required to have a driver's licence issued within Australia, be younger than 60, have no medical conditions that affect their driving, be familiar with an automatic transmission, have driven a medium passenger car similar to the test vehicle and be an experienced driver (more than 5 years driving licence).

Participants for this study were 13 licensed car drivers, 9 males and 4 females, aged between 25 and 60 years.

2.3. Procedure

Upon their arrival, each driver was briefed about the itinerary, track geometry and the driving manoeuvres they would have to perform. Participants drove on a 5 km circuit around Kelvin Grove, which encompassed different road types (motorway, suburban roads) and significant variations in elevation. The suburban roads feature traffic lights and stop signs. Each participant drove three laps of the circuit, with a total duration of approximately 30 minutes per session. A research officer sat on the back seat to operate the equipments and to assist the participants if questions were asked. The first lap was a familiarisation drive. The second and third laps were randomly driven with or without any eco-driving instructions to eliminate a learning effect of the journey (counterbalanced). The eco-driving instructions were given just before the corresponding lap. The instructions were the following:

- Accelerate and brake smoothly
- Slow down and watch speed
- Anticipate the road ahead and avoid unnecessary abrupt braking
- Choose the appropriate speed
- Monitor RPM and avoid excessive RPM

Each participant's driving task was divided into three road sections corresponding to the road characteristic (i.e. motorway, incline and suburban). Every lap started and stopped at the positions identified as 'A' and 'C' in Figure 4. Each participant started from point 'A' as shown in Figure 4 and completed the lap (anticlockwise) in which the motorway section (speed limit 80km/h) started 800 meters from the starting point A. The motorway ended at 2,200 meters from the starting point. The section of road between 2,500 meters and ,3500 meters, from A, was a moderately inclined road (speed limit 60km/h). The ascending angle of inclination was measured to be 4 degrees. The rest of the roads were classified as suburban roads.

2.4. Data collection

The data related to the vehicle dynamics and obstacle positioning was recorded with the in-vehicle technology described in Figure 3. Data was collected from the sensors of the instrumented vehicle and the surrounding environment at varying frequencies. Data from the GPS was retrieved at 1Hz, vehicle dynamics (i.e. RPM, speed, throttle position) at 50Hz, cameras at 30Hz and laser scanner at 50Hz. The parameters that were successfully analysed from CAN-bus included RPM, speed, the percentage of throttle open and the mass air flow rate. We calculated the instantaneous fuel consumption using speed and air flow (throttle position) from CAN-bus readout. Lee et al. [18] demonstrated positive relationships between engine RPM, throttle position, and actual fuel consumption. The distance travelled per unit of fuel MPG can be obtained with the following formula (from Circuit Cellar), which includes conversion form miles per gallon (MPG) to kilometres per litre:

$$MPG = (14.7 * 6.17 * 4.54 * VSS * 0.621371) / (3,600 * MAF/100)$$

where 14.7 = grams of air to 1 gram of gasoline (ideal air/fuel ratio); 6.17 = pounds per gallon density of gasoline; 4.54 = grams per pound (conversion);VSS = vehicle speed in kilometres per hour; 0.621371 = miles per hour/kilometres per hour (conversion); 3,600 = seconds per hour (conversion); MAF = mass air flow rate in 100 grams per second; 100 = c MAF in grams per second (conversion).

2.5. Data Analysis

The characteristics of driving performance such as speed, RPM, throttle, fuel consumption with and without eco-driving instructions where compared within participants by Wilcoxon tests using the R statistical software version 2.11.1. Power analysis shows that 13 participants are required with such (one-tailed) tests to detect large size effects with a power β of .95 at $\alpha = .05$. We extracted and analysed the speed when there is no vehicle 30 meters in front of the test vehicle (free flow). The detection of vehicles in front was made with the IBEO laser scanner and confirmed manually by visualisation of the front camera footages.

2.5.1. Gears

We were not able to retrieve the gear level from the OBD-II. However, the gear selected is related to the speed and RPM. In vehicles with internal combustion engines, the output conversion between the engine and the drive wheels is achieved by the combined action of the assemblies of the power-train [19]. The power-train is characterised by a total power-train ratio i_A between engine speed RPM and the road wheel speed u as follows:

$$u = i_A.RPM$$

The resulting velocity/engine-speed diagram is therefore linear for each gear, with a different slope for each gear level. We were able to obtain the gear in which the vehicle was by recording data with the Toyota Camry at steady pace for various speeds. The ratio $^{RPM}/_{u}$ is characteristic of the gear, and the clustering was done by two different researchers, who analysed the RPM graphs and $^{RPM}/_{u}$ ratios to identify the gears of the vehicle.

2.5.2. Gas emissions

The VT-Micro emissions model was developed as a statistical model consisting of linear, quadratic and cubic combinations of speed and acceleration levels using chassis dynamo-meter data collected at the Oak Ridge National Laboratory (ORNL) and the Environmental Protection Agency (EPA) [13]. The VT-Micro models expresses the emissions of a gas $Emission_{gas}$ as a function 'of the speed u and the acceleration a of the vehicle as follows:

$$Emission_{gas}(u,a) = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3} L_{i,j}^{gas}.u^i.a^j} & \text{, if } a \geqslant 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3} M_{i,j}^{gas}.u^i.a^j} & \text{, if } a < 0 \end{cases}$$

where $L_{i,j}^{gas}$ and $M_{i,j}^{gas}$ are regression coefficients calibrated for the given gas and a given type of vehicle for positive and negative accelerations respectively. Such coefficients have been evaluated for the following gases: CO_2, CO, HC and NO_X [20]. We used the matrixL^{gas} and M^{gas} that were calibrated in that paper for the LDV3 category of vehicles, which is the category our Toyota Camry belongs to. This category was obtained by data mining techniques (CART) and is defined as light duty vehicles built after 1995, with an engine size lower than 3.2l and a mileage less than 83,653 km. This model is used in conjunction with boundary conditions in terms of speed and acceleration, in order to ensure realistic gas emissions estimates [14].

3. Results

The synchronisation software RTMaps was able to successfully record, synchronize and replay data from the sensors illustrated in Figure 3. Participants completed their drive on average in 435 seconds during the baseline. No statistical difference was observed for the eco-driving lap, with an average of 438 seconds. The average following distance clearance, as measured by the IBEO laser device during the experiment was approximately 28 meters. Therefore participants were generally able to drive in free flow traffic.

First we ensured that participants did follow the eco-driving instructions. We analysed first speed on both sections and for the overall lap. All participants complied to the posted speed limit. The mean speed before and after the eco-instructions for the complete lap, on the incline (4 degree) and on the motorway were very similar, as illustrated in Figure 5. Wilcoxon tests show that no statistical difference were observed for speed before and after instructions (p-value of .58, .78 and .60 for the complete lap, the motorway and incline sections respectively). Then we assessed the level of accelerations and decelerations. Accelerations for the complete lap decrease from 2.95 to 2.64 kph/s after eco-driving instructions ($p = .001$). Accelerations on the highway section were on average of 3.48 and 2.93 kph/s for the baseline and eco-driving respectively. This difference was statistically significant ($p < .001$). On the inclined section, no difference was observed (2.23 against 2.33 kph/s). Decelerations decreased for the complete drive after eco-driving instructions, from 2.42 to 2.13 kph/s ($p < .001$). For deceleration, no differences for deceleration were observed on the motorway and inclined sections. The average RPM (presented in Figure 6) was significantly higher after eco-driving instruction for the motorway ($p = .017$) with an increment from 1730 to 1913 revolutions per minute. No statically significant difference was observed for the incline section ($p = .30$). Analysis of the Positive Kinetic Energy (PKE) shows a reduction from .519 to .468 m/s^2 after eco-driving instructions ($p < .001$), showing a better anticipation of the traffic ahead. This analysis shows that participants have followed the posted speed limit and reduced both their accelerations and decelerations, anticipating traffic ahead, following partly the eco-driving instructions they received. They tried to improve the smoothness of their driving, while not reducing their travel time, and failed to reduce their RPM.

The instantaneous fuel consumption variation (pattern) with or without eco-driving instruction were similar within participants. For example, Figure 7 illustrates the instantaneous consumption (in mL/s) for a couple of participants as obtained from CAN-bus data. Red line corresponds to the consumption during the baseline drive while the green line represents consumption with eco-driving instructions. While some participants showed improvements after eco-driving instructions as for the left image of Figure 7, some did not show any improvements of even consumed more fuel (right of Figure 7). The fuel consumption for the complete lap, on the motorway and inclined sections is illustrated in Figure 8. While fuel consumption was slightly smaller on the motorway after eco-driving instructions (7.26 litres per 100 km instead of 8.37 litres per 100 km), Wilcoxon tests did not show any statistically significant decrement in fuel consumption ($p = .38$). On the incline section, average fuel consumption varied from 13.83 litres per 100 km before instructions to 11.35 litres per 100 km. This decrease of 17.9% of fuel consumption nevertheless failed to reach statistical significance ($p = .11$). For the complete drive, fuel conmsumption decreased from 11.47 to 10.64 litres per 100 km ($p = .048$), which corresponds to a 7.2% decrement during eco-driving.

Gears were identified by the following conditions on the $^{RPM}/_{u}$ ratio:

- 1^{st}gear is defined by a ratio between 45 and 53
- 2^{nd} gear: 33 to 42
- 3^{rd} gear: 26 to30
- 4^{th}gear: 19 to 23
- other values of the ratio are considered as transitions between gears.

The proportion of time spent in the four different gears of the vehicle were obtained and are presented in Figure 9 and Table 1 for the different driving sections and conditions. The baseline showed that on the motorway section, participants spent most of the time in the 4th gear (60%). Following eco-driving instructions resulted in a 21.3% reduction in time spent in the 4th gear ($p = .027$). For the incline section, the baseline showed that the 2d gear was the most used and that the 3d gear was used 17% of the time. After eco-driving instructions, the time spent in 3d gear decreased to 4% ($p = .076$) and the time spent in 2d gear increased by 15% ($p = .024$). For the complete lap, the time spent in the 4th gear decreased from 12.9% to 8.4% ($p = .026$). No other differences observed were statistically significant.

Gas emissions were estimated with the VT-Micro model from the speed and acceleration of the vehicle at each time. Table 2 presents the total emissions of CO_2, CO, HC and NO_X gases for the complete drive and the motorway and inclined sections. No differences were observed for the inclined section. For the motorway, CO_2 and NO_X emissions remained similar while emissions of other gases were reduced. Emissions of CO gas were reduced by 22.5% from .822g to .638g ($p < .001$); HC gas emissions were reduced by 18.2% from 33 mg to 27 mg ($p = .002$). While the fuel consumption did not decrease after eco-driving instructions on the motorway section, the decrement of CO and HC gas emission tends to show that the combustion was more efficient during eco-driving (i.e. the combustion was more complete). Unfortunately, no direct benefit was observed for CO_2 and NO_X emissions. For the complete lap, gas emissions were reduced for the four gas under investigation.CO_2emissions were reduced by 2.9% ($p = .033$) from 969.8 to 941.3g, CO emissions decreased by 9.9 % ($p = .001$) from 2.3 to 2.0g; HC gas emissions decreased from 96 to 89 mg ($p = .001$), which corresponds to a 7.3% decrement. Finally, NO_X emissions were reduced by 3.7% ($p = .033$), from 381 to 367 mg.

4. Limitations

As a pilot study, this experiment has several limitations. Firstly, we had a small sample size (N = 13) and sample type which might have impacts on its statistical validity. The gas emissions were obtained using a model that was not calibrated on our vehicle. Therefore the values obtained can only be used as a basic approximation of the effects on gas emissions of eco-driving instructions for automatic cars. Also, the psychological profile of the drivers were not controlled for (e.g. sensation seekers). Furthermore, a direct comparison between manual and automatic vehicles would have provided a more powerful evaluation of the effects of eco-driving with automatic cars. Despite these limitations this pilot study showed statistically significant change in the RPM, gears and gas emission variables when participants received eco-driving instructions.

5. Conclusions

Both hypotheses described in the introduction were confirmed. Eco-driving instructions for manual cars is expected to improve fuel consumption by 5 to 20% [5], we have shown that eco-driving instructions using a vehicle with an automatic gear box in an urban environment results in reduced fuel consumption of a magnitude close to the lower limit of what is observed with manual cars. The significant increase of RPM during eco-driving might have offset the theoretical fuel consumption gain from smoother accelerations. Simple eco-driving instructions failed to proved benefits on the inclined section of this study, suggesting that more comprehensive instructions should be provided to drivers for this particular task, particularly focusing on releasing the accelerator before passing crests and using momentum for the following hill by accelerating before reaching the bottom of the previous hill. Further analysis showed that the increase in engine RPM in eco-driving mode was a consequence of driving in lower gears for a much longer time, and a consequence of the smoother accelerations. These results suggest refining the gear chhanging points in automatic vehicles might be required for improving eco-driving efficiency. Furthner research is needed to assess whether such issue is widely found for a wide range of automatic vehicles, and to assess the potential improvements of eco-driving benefits with fine-tuning of gear shifting points. Benefits of eco-driving instructions in terms of gas emissions were also proven to be lower than expected. For the complete lap, all pollutants sudied were reduced, but only by 3% for CO_2. On the motorway section, we observed reduced emissions of approximately 20% for CO and HC, but not for CO_2 and NO_X. This is probably due to the reduced average acceleration during eco-driving. Future work should include detailed analyses of the environmental effects, and should also examine the effects of the eco-driving instructions (technology or education) on safety indices (e.g. following distances). Our analysis on the impacts of different urban road types on eco-driving behaviour will assist in designing comprehensive eco-driving strategies for urban contexts. These eco-driving strategies will have the ability to adapt to the changing environmental scenarios.

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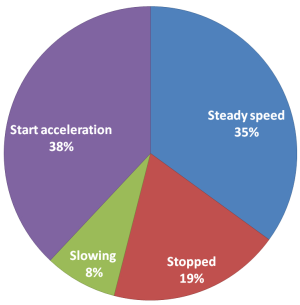


Figure 1: Fuel consumption pattern (adapted from Smart Drive, 2006)

Figure 2: Instrumented Toyota Camry vehicle with IBEO laser, GPS, OBD-II reader, accelerometer (Vigil) and video cameras

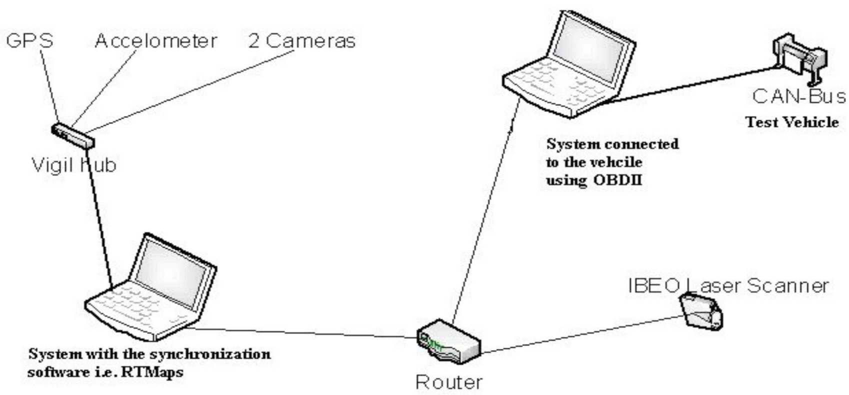
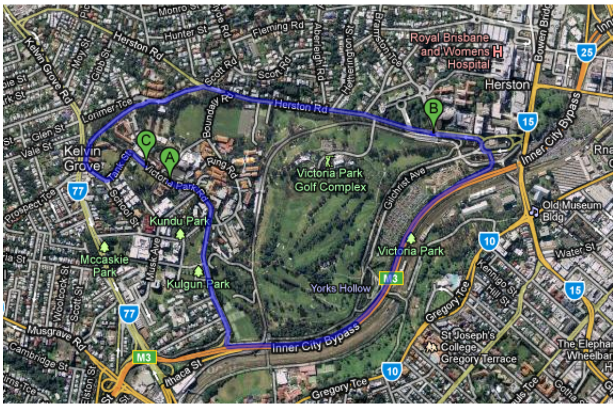


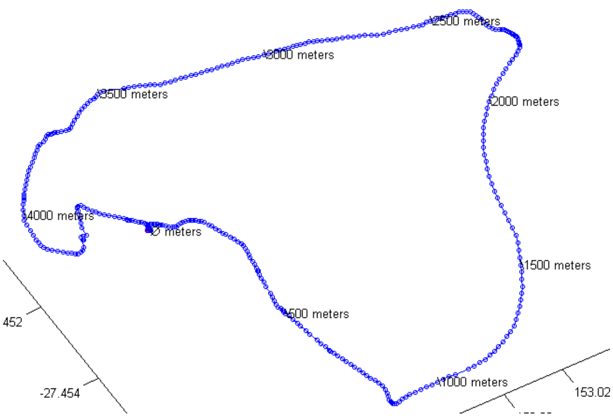
Figure 3: In-vehicle infrastructure for data collection

Figure 4

(a) Test Track (GoogleMap)



(b) The selected track's length in meters to identify the start/stop of different road segments



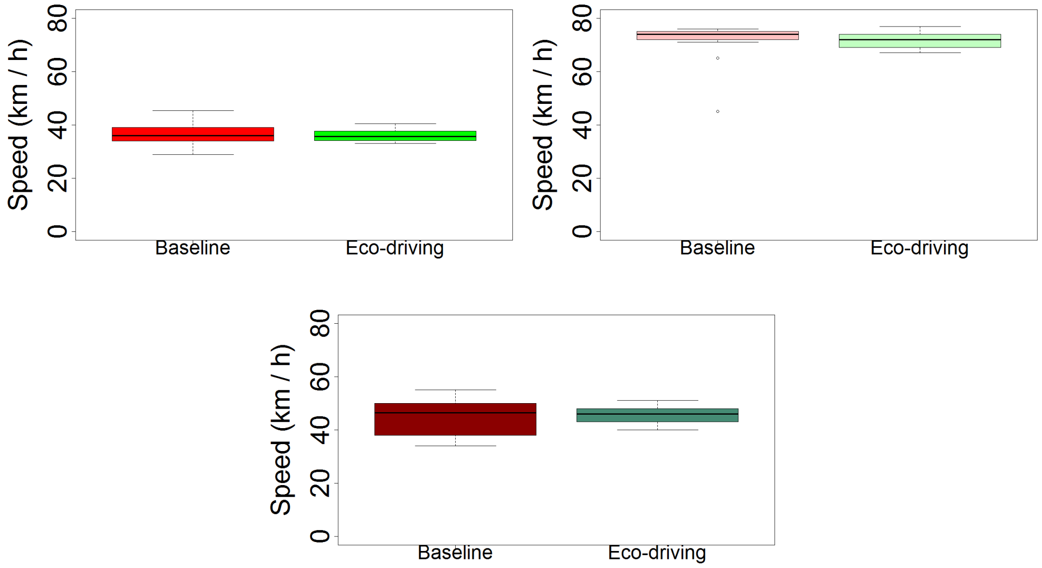


Figure 5: Average speed for the complete lap, the motorway section (light colours) and the 4 degree inclined section (dark colours) before and after eco-driving instructions

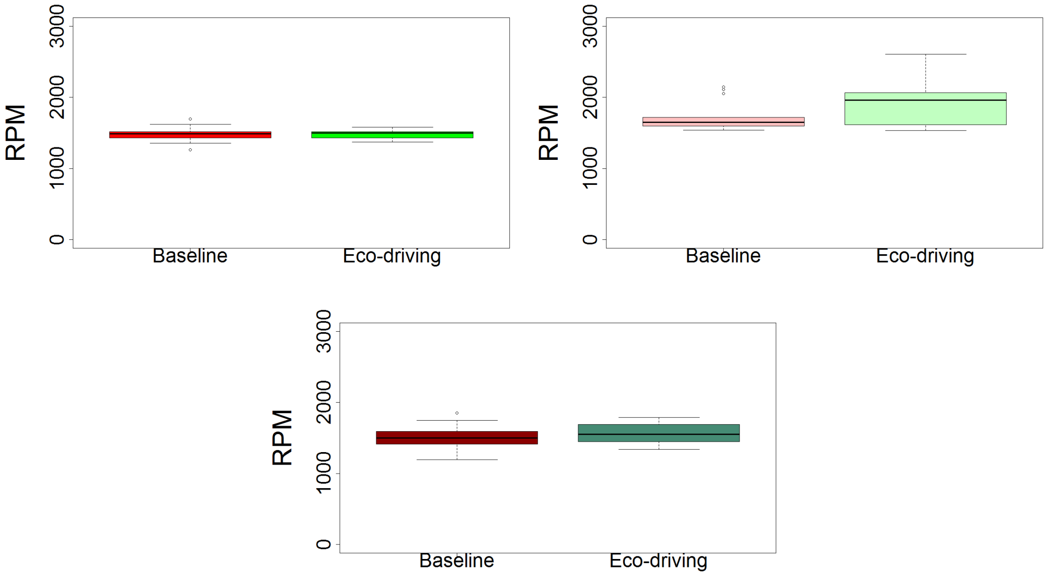


Figure 6: Average RPM for the complete lap, the motorway section (light colours) and the 4 degree inclined section (dark colours) before and after eco-driving instructions

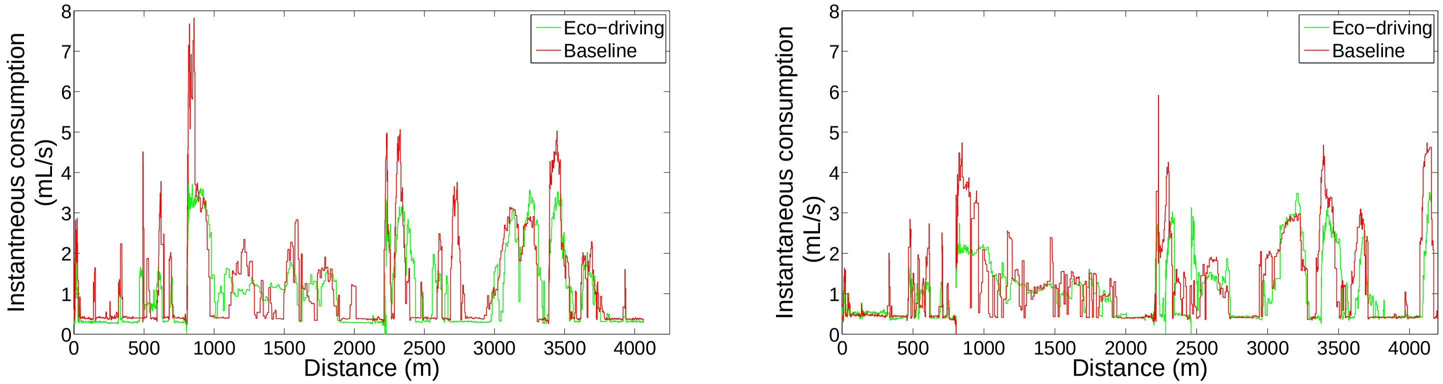


Figure 7: Example of instantaneous fuel consumption record for a couple of participants for the whole track

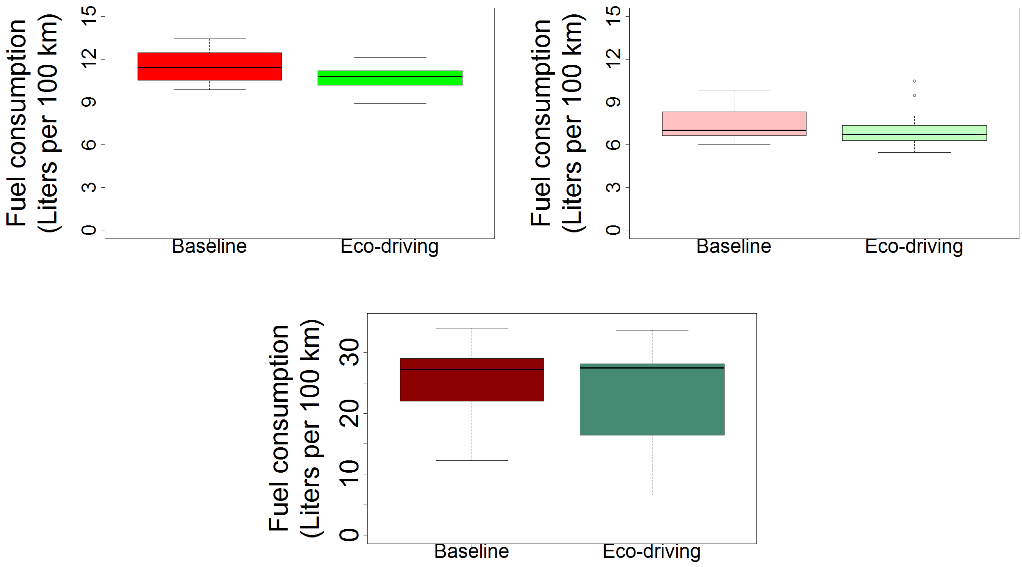


Figure 8: Instantaneous fuel consumption for the complete lap, the motorway section (light colours) and the 4 degree inclined section (dark colours) before and after eco-driving instructions

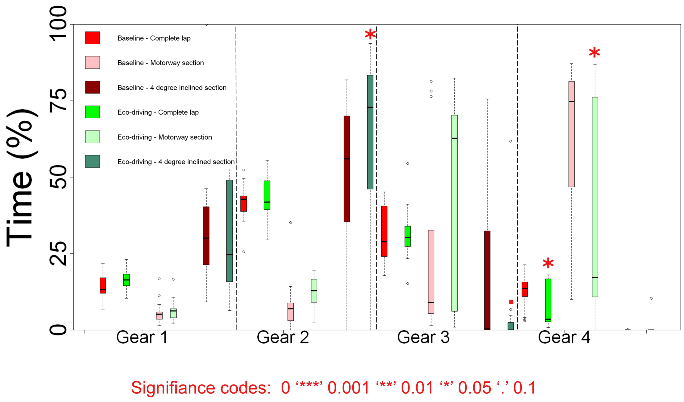


Figure 9: Percentage of time spent in each gears for the complete lap, the motorway section (light colours) and the 4 degree inclined section (dark colours)

Table 1: Time spent in the different gears (percentage)

	Complete lap			Motorway section			4 degree incline section		
	baseline	eco-driving	Δ^*	baseline	eco-driving	Δ^*	baseline	eco-driving	Δ^*
1st	14	16	-	6	7	-	35	30	-
2d	41	44	-	8	12	-	49	63	+**14%** (.024)
3d	32	32	-	25	42	-	16	6	-
4th	13	8	-**38%** (.027)	60	39	-**21%** (.027)	0	1	-

**statistically significant differences (p-value)*

Table 2: Gas emissions (in grams)

	Complete lap			Motorway section			4 degree incline section		
	baseline	eco-driving	Δ^*	baseline	eco-driving	Δ^*	baseline	eco-driving	Δ^*
CO_2	969.80	941.34	**-2.9%** (.033)	246.73	227.77	-	34.94	33.37	-
CO	2.264	2.040	**-9.9%** (.001)	0.822	0.638	**-22.4%** (<.001)	0.070	0.067	-
HC	0.096	0.089	**-7.3%** (.001)	0.033	0.027	**-18.2%** (.002)	0.0031	0.0029	-
NO_X	0.381	0.367	**-3.7%** (.033)	0.145	0.136	-	0.011	0.009	-

**statistically significant differences (p-value)*