DUBAI
ITS World Congress
16-20 September 2024
Mobility Driven by ITS

30th ITS World Congress, Dubai, UAE, 16-20 September 2024

Paper ID #

Investigation of the Impact of Eco-driving on Fuel Consumption Using Smartphone Data

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Abstract

This study conducted a six-month naturalistic driving experiment with 15 participants to analyze the impact of eco-driving on fuel consumption using data collected via the OSeven smartphone application. In the first four months, participants drove as they normally would, followed by two months of eco-driving. Preliminary analysis using R Studio showed a reduction of harsh accelerations and harsh braking by 3.79% and 27.42%, respectively, and 8.14% in fuel consumption. Log-normal regression models developed to study the relationship between driving behavior and fuel consumption indicated that smoother driving styles, characterized by gentle acceleration and deceleration, are associated with lower fuel consumption. Other factors, including the vehicle's age and driver's adherence to speed limits, also influenced fuel efficiency. The study provides valuable insights into promoting eco-driving practices, suggesting future research directions to explore the nuanced effects of different driving behaviors on fuel consumption.

Keywords: Eco-driving, Fuel Consumption, Naturalistic Driving, Smartphone

Introduction

The modern era is marked by continuous advancements in technology and economics. Road transportation plays a crucial role in daily life, significantly enhancing living standards. Currently, the transport sector is confronted with numerous challenges, including the need to offer safe, cost-effective, rapid, comfortable, and eco-friendly modes of transportation.

Climate change is now considered a major phenomenon for every country, and globally, as it has significant environmental, social and economic impacts. The transport sector is responsible for producing the largest volume of greenhouse gases, estimated at about 30% of anthropogenic emissions (Xu et al., 2018). In order to reduce the environmental footprint of driving, new technologies have been developed in vehicles, such as catalytic converters, alternative fuels and improvements in engine efficiency (Manzie et al., 2007). Congestion pricing is also implemented in many countries and the use of public transport is encouraged (Simeonova et al., 2021; Basagaña et al., 2018). In recent decades, a new eco-driving behavior known as eco-driving has been adopted by many countries.

Literature Review

Eco-driving, a concept not uniformly defined across countries, emphasizes energy-saving driving practices. These practices focus on reducing fuel consumption, lowering gas emissions, and enhancing road safety (Ho et al., 2015; Fafoutellis et al., 2021). This multidimensional concept relies on various factors, including driver behavior, route choice, and decisions impacting fuel consumption, such as fuel quality, air-conditioning usage, vehicle maintenance, and peak hour driving (Fafoutellis et al., 2021). Applicable to vehicles of any age or size, eco-driving is beneficial for individual drivers and vehicle fleets.

Key aspects of eco-driving involve smooth acceleration, timely braking, adhering to speed limits, and harmonizing speed with other vehicles. It's also viewed as a decision-making process, encompassing pre- and post-vehicle purchase choices. These decisions are categorized into strategic, tactical, and operational (Sivak and Schoettle, 2012), and positively impact the environment, traffic, and road safety (Fafoutellis et al., 2021). Economically, drivers benefit from reduced fuel consumption, maintenance costs, and road accidents (Caban et al., 2019; Barić et al., 2013). Additionally, eco-driving promotes social responsibility through conservative driving, reduced stress, and enhanced comfort for both drivers and passengers (Barić et al., 2013). Its effectiveness is observable from day one in any vehicle, whether individually owned or part of a fleet (Barkenbus, 2010), offering broad applicability in various road conditions (Caban et al., 2019).

Shivak and Schoettle (2012) define eco-driving as a decision-making process influencing a vehicle's fuel consumption and emissions both before and after purchase. Strategic decisions involve vehicle selection and maintenance, considering factors like fuel consumption and engine size. Regular maintenance, including engine tune-ups, tire pressure checks, and appropriate oil grade usage, can significantly improve fuel efficiency (EPA, 2022). Tactical decisions relate to route selection and additional vehicle weight. Route choice depends on road type, gradient, and congestion, while unnecessary weight and external attachments can substantially increase fuel consumption (EPA, 2022).

Research indicates eco-driving's considerable impact on road safety. Safe driving necessitates choices about individual and collective behavior on the road. These choices include adherence to speed limits, vehicle control, and compliance with road safety regulations (Knapp et al., 2003; Vershuur et al., 2008). Lowering speeds can reduce the likelihood and severity of accidents, while consistent speed maintenance, avoiding sudden starts and stops, and using the highest gear on highways are integral to both safe and eco-friendly driving (The Alliance of Automobile Manufacturers, 2010; Beusen et al., 2009). However, certain practices beneficial for eco-driving might have negative implications under specific traffic conditions.

Therefore, based on the aforementioned, the purpose of this study is to investigate the impact of eco-driving on fuel consumption, using data collected from smartphones.

Methodology

Data Collection

In order to fulfill the above objective, a naturalistic driving experiment was conducted in which 15 drivers participated in real-life conditions for a period of six (6) months (end of November - beginning of May 2023). The data of the experiment was collected from drivers' smartphones. The experiment consisted of two phases, the first lasting four (4) months and the second two (2) months. In the first stage, drivers were asked to drive with their usual behavior (November - February), while in the second stage (March - May) they were asked to drive with ecological behavior. For this process, an innovative data collection system was implemented through the personalized recording of the driver's behavior in real time using smartphone sensors through the OSeven (www.oseven.io) smartphone application. Data collected from the application has been utilised in earlier research papers which also feature additional details regarding the application (Kontaxi et al., 2021; Ziakopoulos et al., 2023).

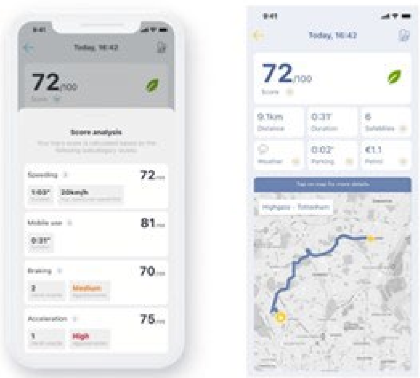

Fig. 1. Screenshot from the OSeven smartphone application

The research continued with the completion of the fuel consumption recording table by the users themselves throughout the experiment and questionnaires, on the basis of which the necessary data were collected, specifically the general driving data, the habits towards eco-driving and the demographic data of each driver.

Statistical Analysis

Linear regression models are utilized when the dependent variable is continuous and follows a normal distribution, such as fuel consumption, which is the dependent variable in the current study.

Log-normal regression enables the development of a model that correlates two or more variables, maintaining a linear relationship between the dependent and independent variables. In this regression, the coefficients of the variables are equivalent to those in linear regression, derived through regression analysis based on the least squares principle. Log-normal regression operates under the premise that the dataset contains only non-negative values, the natural logarithm of the independent variable adheres to a normal distribution, and the arithmetic mean is relatively large. The mathematical formula representing this method is as follows:

$$\log(y_i) = \beta_o + \beta_1 \cdot x_{1i} + \beta_2 \cdot x_{2i} + \cdots + \beta_v \cdot x_{vi} + \varepsilon_i \quad (1)$$

Results and Discussion

Descriptive Statistics

Here are some key charts produced using the statistical analysis software R Studio. These charts represent a preliminary analysis, aiding in a deeper understanding of the results. For example, Figure 2 shows a 3.79% reduction in the number of harsh accelerations, indicating that drivers are smoothing out their speed changes. On interurban roads, harsh accelerations decreased by 5.61%. In urban areas, there's an observed increase in incidents, while on motorways, the rate remains relatively stable. Furthermore, there's a significant reduction in harsh braking incidents, by 27.42%, which is evident in both interurban and urban road networks.

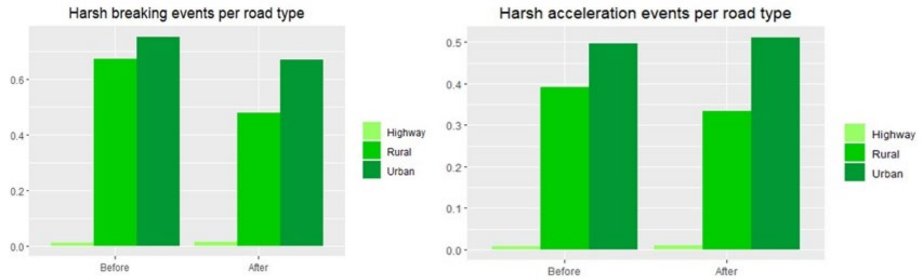

Fig. 2. Harsh events per road type before (normal driving) and after (eco-driving)

By enhancing drivers' behavior, fuel consumption was reduced by an average of 8.14%. Had there been a further reduction in the number of sudden accelerations and driving speeds, this decrease in fuel consumption could have been even more substantial. Notably, the most significant reduction observed among drivers was 39.09%.

On another note, adopting a more eco-friendly driving style led to a decrease in sudden braking incidents. Drivers managed to reduce abrupt stops and braking by maintaining appropriate distances between vehicles, particularly on interurban and urban roads. As drivers' behaviors improve, there is a corresponding decrease in average acceleration. Aggressive drivers, characterized by high initial acceleration and a tendency to drive at high engine speeds, contrast sharply with more moderate and cautious drivers. The latter group avoids sudden starts and accelerations, refraining from full-throttle driving and varying their speed smoothly.

It's evident that eco-driving can lead to improvements in fuel consumption, even in a fleet primarily composed of older, manually operated vehicles. Young drivers, in particular, can implement eco-driving effectively, underscoring the importance of educating drivers with less experience about these techniques.

Lognormal Regression Models

This section presents the findings of the statistical analysis regarding the impact of eco-driving on fuel consumption, which is the dependent variable. One overall model and two separate (before-after) models were developed. In Table 1 the overall model is presented.

Table 1. Overall Model

Parameters	**Estimate**	**p-value**	**Odds Ratio**
(Intercept)	9.214	<0.001	-
dec_avg	-2.027	<0.001	0.132
acc_avg	-2.827	<0.001	0.059
harsh_acc_per_km	5.794	<0.001	328.324
duration_stops_avg	-0.021	0.005	0.979
before_after	-0.116	<0.001	0.890
veh_date	0.141	0.006	1.151
age	-0.231	<0.001	0.794
dr_exp	0.113	0.054	1.120
quest_resp_speed	-0.207	<0.001	0.813
R^2	0.9835		

The variables included in the model are defined below:

- dec_avg: Average deceleration (km/h/s)
- acc_avg: Average acceleration (km/h/s)
- harsh_acc_per_km: Number of harsh acceleration events occurred per km
- duration_stops_avg: Average duration of stops (s)
- before_after: Bivariate categorical variable that takes the values 0 and 1, (0 for before and 1 for after). Before: normal driving, After: eco-driving
- veh_date: Vehicle construction date
- age: Drivers age
- dr_exp: Years of driving experience
- quest_resp_speed: Drivers self-declaration whether they respect speed limits

The overall model displayed in Table 1 outlines the statistical findings regarding the impact of eco-driving on fuel consumption, serving as the dependent variable in the analysis. Each parameter in the model has a significant p-value (below 0.001), demonstrating the statistical importance of each variable, except for the driving experience (dr_exp), which has a p-value of 0.054. Both average deceleration (dec_avg) and acceleration (acc_avg) negatively impact fuel consumption, with odds ratios of 0.132 and 0.059 respectively, indicating that smoother driving styles that avoid rapid acceleration and deceleration are associated with lower fuel consumption. The variable harsh_acc_per_km, representing the number of harsh acceleration events per kilometer, exhibits a positive coefficient (5.794) and a large odds ratio of 328.324, suggesting that frequent harsh accelerations significantly increase fuel consumption.

Other noteworthy variables include duration_stops_avg, before_after, veh_date, age, and quest_resp_speed. The average duration of stops (duration_stops_avg) and the before-after variable (indicating periods of normal and eco-driving) both negatively influence fuel consumption. Interestingly, the model shows that older vehicles (as indicated by veh_date) tend to consume more fuel, as do drivers who are older (age). Finally, drivers who self-report respecting speed limits (quest_resp_speed) are associated with lower fuel consumption, underlining the importance of adherence to speed limits for efficient fuel use. Each of these variables provides valuable insights into the different factors influencing fuel consumption during driving, offering a comprehensive understanding for promoting eco-driving practices.

Table 2. Before Phase (baseline) and After Phase (eco-driving) Model

	Before phase model			After phase model		
Parameters	**Estimate**	**p-value**	**Odds Ratio**	**Estimate**	**p-value**	**Odds Ratio**
(Intercept)	-336.8	<0.001	0.000	-191.6	0.015	0.000
harsh_brk	-0.233	0.063	0.792	0.08	0.319	1.083
dec_avg	-0.636	0.286	0.529	0.648	0.089	1.912
duration	-0.001	0.037	0.999	0.001	0.029	1.001
lisence_date	0.167	<0.001	1.182	0.096	0.015	1.101
daily_trip_dist	0.014	0.005	1.014	-0.007	0.052	0.993
vehicle_cc	0.001	0.007	1.001	0.001	0.011	1.001
R^2	0.7243			0.5899		

The variables included in the model are defined below:

- dec_avg: Average deceleration (km/h/s)
- harsh_brk: Number of harsh breaking events occurred (absolute value)
- duration: Total duration of the journey (s)
- lisence_date: Date of drivers driving lisence
- daily_trip_dist: Daily driving distance according to drivers (km)
- vehicle_cc: Vehicle cubism (cc)

The models for the Before and After Phases illustrate differential impacts of various driving parameters on fuel consumption. he average deceleration (dec_avg) shows an interesting shift, moving from a negative coefficient in the Before Phase (-0.636, p=0.286) to a positive one in the After Phase (0.648, p=0.089), indicating a possible increase in fuel consumption with smoother deceleration post the implementation of eco-driving practices. Moreover, the duration of the journey consistently influences fuel consumption in both phases, albeit minimally, with a slight increase in the odds ratio from the Before to the After Phase. License date (lisence_date) and vehicle cubic centimeters (vehicle_cc) positively correlate with fuel consumption in both models, though with reduced coefficient values in the After Phase. Notably, the daily driving distance (daily_trip_dist) switches from a positive relationship with fuel consumption in the Before Phase to a negative one in the After Phase, suggesting that longer daily trips might be associated with decreased fuel consumption following the adoption of eco-driving practices, with this change approaching statistical significance (p=0.052 in the After Phase).

Conclusions

Consequently, by altering user behavior, a significant reduction in fuel consumption of 8.14% was achieved. Drivers who aimed for a more eco-conscious approach noticed a direct correlation between their driving habits and fuel usage. Specifically, the study conclusively shows that eco-driving practices markedly affect fuel consumption. This is evident from the observed decrease in harsh accelerations and decelerations in the descriptive statistics. The overall regression model corroborates these observations, indicating that variables like average deceleration and acceleration (dec_avg and acc_avg) negatively impact fuel consumption. This suggests that smoother driving styles are more fuel-efficient.

Moreover, the comparative analysis of the Before and After Phase models unveils interesting trends. For example, smoother deceleration post-eco-driving implementation appears to slightly increase fuel consumption, indicating a complex interaction between driving smoothness and fuel efficiency. Additionally, it was found that older vehicles and drivers tend to have higher fuel consumption, but adhering to speed limits correlates with reduced fuel usage. This comprehensive analysis of factors affecting fuel consumption provides valuable insights, laying a groundwork for effectively promoting eco-driving to enhance fuel efficiency and sustainable driving.

The evolution of technology also plays a role, enabling drivers to monitor their ecological impact during or after their journey through dedicated apps. Aggressive, non-ecological driving behaviors can be recorded, and drivers can receive advice and suggestions for improvement. Moreover, implementing incentives like discounts on traffic charges based on eco-friendly driving habits could be crucial. Additionally, car insurance companies might offer lower premiums to cautious drivers with no road accidents. Such policies could financially motivate drivers to adopt safer, more efficient driving practices, thereby reducing accidents, fuel consumption, and air pollution.

Future research should further investigate the intricate relationship between eco-driving practices and fuel consumption. A longitudinal study monitoring driver adaptation to eco-driving over time could provide deeper insights into the long-term efficacy and potential habituation effects of these practices. Additionally, exploring the role of technology-based interventions and real-time feedback in promoting and maintaining eco-driving behaviors is important. This could lead to the development of more advanced, personalized eco-driving training and support tools.

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