Ecodriving Performances of Human Drivers in a Virtual and Realistic World∗

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Abstract—In this study, results of an ecodriving challenge that took place during the Paris Motor Show in 2014 are presented. The principle of this challenge was to drive a simulated passenger car as far as possible with a limited quantity of energy (15 cL). The experimental setup, constituted of the SiVIC software, an Oculus Rift Helmet and a fuel consumption model, is also detailed. 1211 trips of visitors were validated during the 17 days of the event. Results showed that high acceleration without kickdown is desirable and that constant speed can lead to significant reduction in energy consumption. Next work will concentrate on improving the simulation and the scenario to increase the immersion realism and the ecodriving behavior sensitivity.

I. INTRODUCTION

Research interest in Eco-driving is growing due to its potential to reduce fuel consumption, CO2 and particles emission [2], [3], [4]. A wide range of eco-driving strategies have been proposed by traffic psychologists, engineers and traffic simulation researchers [6], [12], [14]. Despite its popularity, there is poor and inconsistent research evidence regarding the effects of different type of eco-driving instructions on fuel consumption. Eco-driving instructions are very context sensitive and have different performance in different situations. Rakotonirainy et al, [17], demonstrated that standard instructions do not provide the expected 20% fuel consumption reduction on an automatic car in an urban environment. Then, several methods are used to generate optimal commands instead of the driver [7], [9], [10], [11]. These algorithms, relying on optimization procedures, are then devoted to ecological driver assistance systems or automated driving vehicles. However, optimization procedures often lack of human factors and tend to be unacceptable for human drivers or passengers. For instance, practised accelerations and jerks are not sufficiently taken into account and the vehicle passengers feel discomfort. Several researchers have already dealt with the subject of efficient driving technics [8], [5] but none of this study had precisely defined the acceleration and speed profiles resulting in the minimum fuel use. In this paper, we propose to use a specific driving simulator to better understand how drivers successfully reduce energy consumption. Conclusions of this study can then be used as guidelines for designing new optimization procedures for optimal commands of passenger cars. More important, this study presents a method that can be used to validate ecodriving technics in various driving conditions. This paper has two main original parts. On the first hand, it proposes an original method of gathering data from a driving simulator during a major international car event in Paris. On the second hand, the simulator itself is a combination of several innovative elements such as a true immersion using a Head Mounted Display (HMD), a simplified but precise fuel use modeling and simulation software to link them all. All these contributions have been tuned with on-road measurements to improve reality of the scenarios. The here presented application is focused on the optimization of the covered distance by a driver with a limited amount of fuel. This scenario is done with a real car and a real driver immersed in a 3D virtual modeling of the real Satory test track. The results obtained from this simple eco-driving scenario have allowed to validate our architecture’s capabilities. In the remainder of this paper, methodology is presented in section 2. Then, the global experimental setup with SiVIC, RTMaps, the fuel consumption model, the hardware and finally the interconnection between these platforms to obtain our desired eco-driving prototyping environment is described in section 3. Section 4 is dedicated to the presentation of Results while section 5 presents the discussion. Finally, we will conclude and present some perspectives in section 6.

II. METHODOLOGY

As the objective of this paper is to better understand how drivers efficiently reduce energy use while driving, it has been decided to collect a wide dataset of speed profiles. In this case, simulation is often a cost effective and reproducible solution. The idea was to design a simple driving simulator and to use it during the Paris Motor Show 2014. This event, gathering more than one million visitors every year, was a good opportunity to reach our objectives.

However, this event raised several challenges. Firstly, an efficient driving simulator was needed in a limited space. It has then be decided to use an Oculus Rift Helmet as main display in order to increase the simulation realism. Secondly, it was required to attract a lot of visitors that were coming to see vehicles and not simulators. In order to attract them, a challenge has been designed. Its principle was for each driver to drive as far as possible with a limited quantity of fuel in the tank. The five best ecodrivers would receive a gift in the end of the event.

Before each trial, the driver received the instruction to go as far as possible without leaving the road. Due to relative low resolution of the helmet, an instructor had to stay on the driver side to warn him about upcoming sharp curves.

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The selected simulated scenario was specifically designed to study acceleration and speed impact on energy use. Therefore, there was no possibility for the participants to change gears. The simulated vehicle is a Renault Clio 3 petrol engine with automatic transmission. Furthermore, there was only one car in the simulation.

Finally, collected data are analyzed using a multi-objective optimization point of view in order to generate guidelines for this kind of algorithms. Here, it is assumed that if optimization algorithms are inspired by human drivers, they will be more acceptable when inserted in automated vehicles or driving assistance systems.

III. EXPERIMENTAL SETUP

The experimental setup is constituted of a driving seat, a steering wheel and pedals simulating the driving environment of a passenger car. They have been especially selected so that they can be easily moved to exposition centers and quickly collect data. The Oculus Rift Helmet and infrared camera (for absolute positioning) has been used as main display. The software linking these elements to the virtual world is SiVIC that is detailed in subsection III.A and the fuel consumption model used is detailed in section III.B. A picture of this hardware setup is shown in figure 1. The seat is able to receive visitors from 1.30 m to 2.0 m. The helmet is very easy to adapt to any head from independently of the user’s age even if the helmet is not convenient for young children under 8 years old.

A. SiVIC platform

SiVIC platform [15], [16] was designed to enhance the process of developing and evaluating ADAS. This platform enables the simulation of multi-frequencies sensors embedded in static or dynamic devices, equipments and vehicles commonly used in ADAS scenarios. The SiVIC platform is a very efficient tool to develop, prototype and evaluate high level ADAS, including distributed applications. SiVIC can be easily interconnected with several external platforms such as RTMaps (Intempora) or Matlab (Mathwork). This interconnection interface is efficient and useful to perform a great number of developments in both SiL (Software in the Loop) and HiL (Hardware in the Loop) approaches. Once the application is evaluated in virtual condition and validated in simulation, it can be integrated and tested into real embedded hardware architecture (on vehicle) further towards the end of the development cycle.

Currently, the SiVIC platform is mainly useful for sensor modeling and ADAS prototyping. In this specific application of the proposal of an eco-driving platform, 2 main technical tasks are necessary. The first one is to develop a car consumption sensor and the second one is to build a dedicated module for 3D immersion. The first task is presented in the next subsection. For the second task, an HMD has been used to reproduce the human perception functionality. Actually, when a human looks at an object in front of him, he naturally sees the volume because his two eyes (spaced of 64 mm on average) receive two almost similar points of view of the object. Then, the brain combines these two images into only one. The same point, located on the left image, moves slightly on the right image. This distance, called parallax, produces the sensation of stereoscopic depth. This phenomenon is reproduced by generating two images of the scene with a corresponding offset in order to reproduce the parallax (see figure 3). The two images are merged in one image that is sent to the HMD which displays it on a screen located in front of the driver eyes.

Depending on the orientation of the driver’s head provided by an inertial sensor integrated into the HMD, the simulator...
computes the position and the orientation of the view for each eye. Actually, in order to enslave the both environment view to the centre of the camera base (like on the human head), a positionable object is used. The orientation and translation coming from the HMD control this positionable object. In this stereoscopic modeling, the frequency and the parallax can be adjusted in order to optimize the visual comfort and the rendering for the real driver. A counters and gauges overlay mechanism was added to take into account the display of infinite indicators like the tank level, a speedometer, the curvilinear distance covered by the vehicle and fuel consumption.

B. Fuel consumption model

The main challenge with a fuel consumption model dedicated to eco-driving simulations is that it has to be efficient (low time consumption and accurate enough). But it also has to be tunable enough to represent a wide set of vehicles. The basic hypothesis of this model is that the engine efficiency ratio is a polynomial function of the vehicle speed. This is consistent with an automatic gearbox vehicle but the model is still efficient for manual gearbox vehicles even if engine speed is not directly taken into account. The theoretical consumed energy, \( E_{\text{theo}} \), in a time step \( dt \) can be evaluated by the following formulae:

\[
dE_{\text{theo}} = \left( \frac{1}{2} \mu_{\text{air}} SC_x v_{\alpha}^2 + C_r r m g + m p + m a_{\alpha} \right) v_{\alpha} dt,
\]

where \( \mu_{\text{air}} = 1.2 \text{ kg.m}^{-3} \) is the density of the air, \( S \text{ (m)}^2 \) is the end face, \( C_x \) is the longitudinal drag coefficient, \( C_r r = 0.015 \) is the coefficient of rolling resistance, \( m \text{ (kg)} \) is the vehicle mass, \( g = 9.81 \text{ m.s}^{-2} \) is the standard gravity, \( p \text{ (%)} \) is the road grade, \( a_{\alpha} \text{ (m.s}^{-2}) \) is the \( \alpha \text{ vehicle acceleration} \) and \( dt \text{ (s)} \) the time step.

Then, an efficiency ratio has been applied to take into account the energy lost in the combustion process and transmission. This ratio has been built on real experiments from Wang et al. [13] where the fuel consumption has been measured at different speeds. This method has the disadvantage not to take into account the engine speed. However, as it could be seen further in this paper, precision is still high enough compared to other modelings [1].

\[
\eta = \frac{E_{\text{theo}}}{E_{\text{meas}}} = 10^5 \times \frac{\frac{1}{2} \mu_{\text{air}} SC_x v_{\alpha}^2 + C_r r m g + m p}{f(v_{\alpha})e_{\text{carb}}\rho_{\text{carb}}},
\]

where \( E_{\text{theo}} \) is the theoretical energy consumed if the vehicle was the one tested by Wang et al., \( E_{\text{meas}} \) the measured energy consumed by the test vehicle, \( f(v_{\alpha}) = 0.05 v_{\alpha}^2 - 1.8 v_{\alpha} + 21 \) is a function identified on the works of Wang et al [13]. giving the fuel consumption in liters per hundred kilometers versus the vehicle speed, \( e_{\text{carb}} = 42.5 \times 10^6 \text{ J.kg}^{-1} \) is the energy density of fuel and \( \rho_{\text{carb}} = 0.76 \text{ kg.L}^{-1} \) is the fuel density.

The computed efficiency ratio can be seen in figure 4. This efficiency curve has a typical shape with an optimal efficiency about 50 kph. Under this speed, the engine is less efficient and it spends more time consuming for the same distance traveled. Above this speed, resistive forces increase rapidly. This fuel consumption model has been validated on 650 km database gathering 42 drives (21 drivers driving twice) on a 15 km open road. An resulting example is given on figure 5. It can be noticed that the modeled and experimental instantaneous fuel use are very similar and that experimental and simulated cumulated fuel use are superimposed. In this case, the final cumulated fuel use prediction error was of 0.5%. Global results showed that the model has a 4% error margin on cumulated fuel use that is the same level as very detailed fuel consumption models but it requires less parameters and less computations.

C. Key figures

During the 17 days of the event, more than 1900 people tried the ecodriving simulator (more than 100 per day for a 5 minutes simulation). Within those 1900 trips, 1211 trips have been accepted for analysis while the others were either stopped before the end, log was not started or started after the beginning or data were impossible to use (permanent run-off road). Finally, more than 3400 km have been travelled by using more than 193 liters of fuel.

IV. RESULTS

Results showed that the best driver reached 3800 m with 0.15 L that is approximately 3.9 L/100 km. As explained

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\text{Fig. 4. Fuel consumption model efficiency ratio}
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\[
\text{Fig. 5. Fuel consumption on a specific trip}
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in the methodology section, data have been analyzed with a multi-objective optimization point of view. The idea was to consider all trips as multidimensional solutions of an optimization procedure. To each trip is associated a total travel time and an average fuel use in L/100km. Then, the concept of dominating solutions has been used to extract the most interesting solutions. Actually, a solution A is dominating a solution B if the A travel time is lower than the B travel time AND if the A fuel use is lower than the B fuel use. Finally, while plotting these dominating solutions on figure 6, it can be seen that they constitute an envelop, called the Pareto frontier. On the Pareto frontier there is no solution dominating another one that is also on the Pareto frontier. It is theoretically not possible to find a solution on the left side of the Pareto frontier. A clear example of non optimal solution is for trips at 250 seconds: One consumed 5 L/100 km while another consumed 14 L/100 km. Here, a great amount of energy could be saved by ecodriving without losing time. On this figure, it can also be seen that some of the dominant solutions are consuming a lot of energy (35 L/100km). These trips are clearly not interesting for ecodriving but they show that even with a high consumption, a trip can be considered efficient (in the Pareto optimality definition) because it was very short. Also, drivers do not want to spend too much time on the road. Each driver has his own way of balancing travel time and energy use and this can be extracted from these data. Most of drivers were between 150 and 350 seconds of travel time.

Then, by analyzing the best speed profile, it appears, on figure 7, that speed was almost constant at 50 kph although some oscillations persist. That is due to the impossibility for a standard human driver to stabilize the speed. Then, it could be assumed that an automated car could reach better performances. It has also been noticed that the first acceleration was strong but not the strongest. It can not be concluded that a high acceleration is less energy consuming than a low acceleration because of the long constant speed phase that makes the total energy use less sensitive to the acceleration phase. The red plots show all dominants solutions. It can be seen that most of the red trajectories were at stabilized speed between 50 and 60 kph. Some of the participants had a very strong acceleration at the beginning, reaching the maximum speed allowed in the simulation (90 kph). About 1200 m, speeds suddenly decrease due to the presence of very sharp curve. At this step, some drivers already had consumed all their fuel.

V. DISCUSSIONS

This paper has addressed the following topics:

A. Speed profile analysis

As the main objective of the paper was the understand the impact of speed and acceleration on energy use, figure 8 shows in details all acceleration profiles. It can be noticed that initial acceleration from the best individual it not the strongest nor the weakest. This acceleration (about 1.7 m.s\(^{-2}\)) has been followed by an almost steady and near-zero acceleration. This rather strong acceleration tend to prove that an optimal acceleration exists in specific conditions. Of course, this acceleration is highly dependent on the distance between the start and the end point (for instance, from one junction to another). Compare to the other acceleration profiles, the best one shows that near-zero acceleration is the key to lower fuel use when road is free of any obstacle.

Figure 9 shows the average fuel use against the traveled distance. At the beginning, this average is necessarily high due to the initial acceleration. An important point is that the best individual has not the best average in the beginning of the trip. It becomes one of the best only after 400 meters. This could mean that the level of acceleration is optimal only for trips greater than 400 meters. For shorter trips, the optimal level of acceleration may differ. Another concern is about the energy use of non dominant individuals. It can be noticed that all trips with a low energy use in the beginning are not optimal ones. That means that acceleration should not be under 0.5 m.s\(^{-2}\) (see figure 8).
However it was also a challenge for developers to increase the SiVIC performances to be able to generate two HD pictures for 3D rendering. Furthermore, in spite of our safety procedure, some participants felt the simulator sickness. This is impossible to avoid but it could be attenuated by improving the simulation.

- Original ecodriving challenge: A challenge has been proposed to attract a wide audience of drivers. In this sense, it was a success. However the scenario was still too simple to apprehend all particularities of human drivers while accelerating and cruising. These results need to be extended to more complex scenarios with several vehicle and more interaction with the infrastructure (traffic lights, roundabouts, speed limits, ...).

- Collection of a wide dataset: Collecting 1211 trips in 17 days during the Paris Motor Show is probably a high score and proves the efficiency of the method. However, the sample can still be discussed as visitors are mainly interested in sport cars. A complete questionnaire on drivers could help to analyze data.

- Fuel consumption modeling: Within this simulator, a simplified but accurate fuel consumption model has been used. It has proven to be accurate enough to be used in numerical simulation. Nevertheless, it has not been validated on other categories of vehicle than the one tested in this study.

Results of this study may help car manufacturers and suppliers to develop more efficient ADAS (Advanced Driver Assistance Systems) by adapting the system behavior to the driver expectations. It could also be a guidance for driving trainers during the initial training or specific ecodriving trainings.

VI. CONCLUSIONS

In this article, a methodology to collect a wide range of data from ecodriving simulations has been presented. These data has then been analyzed to understand how driver assistance systems and automated cars could benefit from simulations. Results showed that high acceleration could be interesting to reduce energy use. Cruising at steady speed has also shown promising results. In future works, the driving simulator fidelity will be enhanced by increasing the pictures resolution and frequency and results will be compared to theoretically optimal speed profiles. The ecodriving scenario will also be improved to be more realistic and data analysis will be deepened to quantify all results.

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