Eco-driving performance assessment with in-car visual and haptic feedback assistance

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Abstract – *In this experiment, 28 participants completed an urban driving task in the CARDS simulator at Renault's Technical Centre for Simulation. This simulator, based on the SCANeR2© software package, provides a 150° field of view in a fully instrumented cockpit. Two different eco-driving assistance devices were added: a 7 inches display on the mid-console, and a force feedback system on the gas pedal. The feedback information was computed by comparing the car's instant acceleration with an optimal acceleration level based on a proprietary consumption model of a Renault diesel engine. Basic eco-driving behaviors, like gear-shifting under 2000 Rpm, allows significant decrease of polluting emissions. Assisting drivers with visual, haptic, or visual-haptic on-board devices, in addition to low engine speed verbal instructions, lead to supplementary significant savings of polluting emissions. There is no significant difference between assistance feedback type; suggesting that haptic feedback provides the same eco-performance as visual feedback. In particular, subjects show good adaptation to the haptic feedback pedal at first utilization of the system. They apparently relied more on haptic modality to achieve the eco-driving task, when they used both visual and haptic assistance.*

Résumé - *Dans cette expérimentation, 28 participants accomplissent une tâche de conduite dans le simulateur CARDS du Centre Technique de Simulation de Renault. Ce simulateur, équipé du logiciel de simulation SCANeR2©, délivre un angle de vue de 150° dans un cockpit entièrement instrumenté. Deux interfaces d'assistance à l'éco-conduite complètent le dispositif expérimental : un écran de 7 pouces sur la console centrale et un dispositif appliquant un retour d'effort à la pédale d'accélérateur. Le retour d'information est calculé en comparant l'accélération instantanée du véhicule à un niveau d'accélération optimal, d'après un modèle de consommation de moteur diesel Renault. La pratique de l'éco-*

conduite, comme le changement de rapport sous les 2000 Rpm, permet de réduire significativement les émissions polluantes. L'assistance des conducteurs avec des systèmes d'aide visuel, haptique ou visuo-haptique, permet une réduction supplémentaire significative des émissions polluantes. Aucune différence significative n'a été constatée entre les différents modes d'assistance ; ce qui laisse penser que l'assistance haptique engendre la même éco-performance que l'assistance visuelle. En particulier, les sujets font preuve d'une adaptation satisfaisante à la pédale haptique lors d'une première utilisation du système. Ils accordent apparemment plus de confiance à la modalité haptique pour accomplir leur tâche d'éco-conduite en présence d'une assistance visuo-haptique.

Introduction

Context

Since the early seventies, the European Union has been controlling the polluting emissions of its vehicles by setting more and more drastic ecologic standards. From the early nineties, the development of the collective consciousness for ecology, associated to continuous fuel price increase urges countries to set up sustainable development plans for their vehicle market. In addition to the rules fixed to carmakers, actions have been led to sensitize car holders to eco-driving practicing. In particular, recently, eco-driving has been largely promoted by public organizations. Another way to provide help in eco-driving is to use an on-board assistance system with information on driving eco-efficiency. Feedback may be carried through various perceptive modalities: visual, auditory or haptic.

Visual assistance feedback

Nowadays, most of the cars are equipped with a digital information display of instant consumption. In order to enhance the visual salience of their consumption aid system, Honda has developed in 2009 a speedometer with changing colors, depending on drivers' instantaneous eco-performance [Honda]. However, drivers' visual attention is mainly focused on the road. By submitting driving participants to other visual on-board detection tasks, it is suggested that visual stimulus detection performance deteriorates, while reaction delay remains unaffected [Recarte & al, 2003]. Moreover, lane keeping and keeping distance to followed car, with the help of peripheral vision, appears to be impaired when watching a visual display on the speedometer, which is otherwise inefficient when the visual display is on the mid-console [Summala & al, 1998].

Haptic assistance feedback

Haptic stimulation through gas pedal is another way to provide feedback information on eco-performance. Continental has developed an accelerator force feedback pedal AFFP© [Continental], which vibrates to inform drivers on optimal gear-shifting time. Nissan proposes since 2009 an ECO Pedal© [Nissan] to provide force feedback information on optimal pedal position, depending on engine state. Both announce fuel savings of between 5 and 10%. Haptic feedback pedal has already been studied in long-term and large field studies for speed limitation requirements. In this particular application, haptic appears to be more efficient than visual assistance. Significant decreases of mean and variation of speed, as well as polluting emissions are observed [Várhelyi & al, 2004]. Haptic feedback pedal acceptance is positively rated by drivers, but there is no willingness to pay for it [Adell & al, 2008].

In car following applications, haptic feedback pedal systems give information on inter-vehicular distance by modifying the gas pedal stiffness proportionally to the distance separating subject to forward car. This system allows significant decrease of standard deviation of inter-vehicle distance and braking reaction time [Kuge & al, 2005; Mulder & al, 2008].

Problematic

In this study, we aim at evaluating the efficiency of basic eco-driving instructions for polluting emissions reduction. We also try to assess and compare the additional improvements brought by the visual, haptic and coupled visual-haptic eco-driving assistances. Finally, we test whether drivers feel at ease at a first utilization of the force feedback pedal, which intuitively could appear as very intrusive in the control of the car.

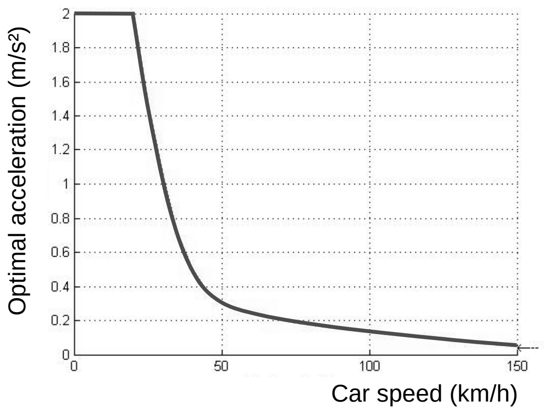
Method

Experimental device

This experiment has been conducted on the dynamic driving simulator CARDS at the Technical Center for Simulation of Renault. This simulator based on the SCANeR2© simulation software is composed of a modular cockpit, completely instrumented, providing to the driver all the equipments and interactions existing in a real car. The front view is provided by 3 projectors delivering a 150° horizontal field of view image.

For experimental needs, the simulator has been enriched with two eco-driving assistance devices: a visual interface positioned in front of the central console with a progression bar, provides a visual information on $F_{additional}$ value; and a gas pedal coupled with an actuator stimulates haptically driver's foot by superposing $F_{additional}$ to the initial pedal torque. These two devices provide exactly the same information to drivers through different modalities.

A Renault's proprietary eco-driving model (see Fig 1) compares in real time the longitudinal acceleration of the driven vehicle (Acc_veh) to an optimal acceleration level, depending on car speed (Acc_opt). This model does not take in account the engine revolution speed. When the drivers' acceleration is over the optimal acceleration, a normalized counter-acting force ($F_{additional}$), proportional to the gas pedal position (X_{pedal}), is opposed to drivers' foot (see Fig 1). Gas pedal force was equal to 35N when (Acc_veh) reached twice (Acc_opt).



Acc_veh = Vehicle acceleration
Acc_opt = Optimal acceleration
ΔAcc = Over-acceleration
X_{pedal} = Pedal position

ΔAcc = Acc_veh – Acc_opt
$F_{additional} = K \,.\, X_{pedal} \,.\, (\Delta Acc / Acc\_opt)$
With K = Pedal stiffness factor

Figure 1. Schematics of Renault's proprietary eco-driving model (left); and calculation of $F_{additional}$ (right)

Protocol

Task description

The experimental task consists in driving through an urban environment, along a predefined route. No car traffic is present, to facilitate control task repeatability and compare more efficiently eco-driving performances between experimental conditions.

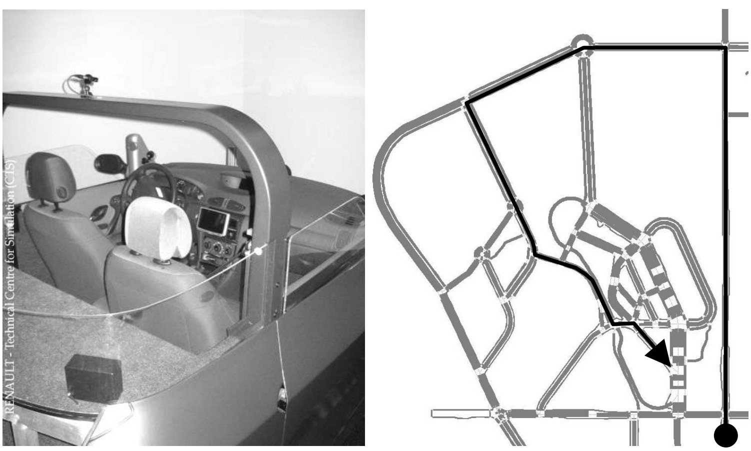


Figure 2. Picture of the CARDS simulator, with mid-console assistance display (left); experimental database with predefined route (right)

Participants

28 subjects aged between 25 and 45 took part in the experiment (7 females and 21 males). All drivers were in possession of a valid driving license. Participants were split into 4 distinct groups of 7 subjects. Three groups were

given assistance feedback at third trial: the visual group (S_v) had a visual assistance display; the haptic group (S_h), was assisted with the haptic pedal; and the visual-haptic group (S_{vh}), had both visual and haptic assistance. Fourth group is the reference group (S_n), no assistance was provided, drivers had to accomplish the verbally instructed condition.

Conditions

Initially, participants had to follow a training session, during which, drivers were asked to accomplish two practice runs in order to get used to drive comfortably with the CARDS simulator and to memorize the experimental task path. Participants in assisted groups drove 1 minute more to understand the functioning of the assistance system to use. After practicing, all participants confirmed that they felt at ease with the whole experimental device.

Participants drove the same route four times in different conditions: ($T1_{ref}$) Normal driving without instructions nor assistance; ($T2_{eco\text{-}behavior}$) Driving with the verbal instruction not to exceed 2000 Rpm; ($T3_{eco\text{-}assistance}$) Same as condition 2 with the support of an assistance feedback; ($T4_{eco\text{-}behavior}$) A repetition of trial (T2).

Data recordings

The following objective data was recorded for each subject:

- Total polluting emissions, calculated on the base of a Renault proprietary model of fuel consumption of a Megane diesel car.
- $Std(X_{pedal})$, the standard deviation of gas pedal position, calculated on the whole trajectory for each run.
- Mean(ΔAcc), the mean of over-acceleration, resulting from the difference between (Acc_veh), the instantaneous longitudinal acceleration of the car, and (Acc_opt), the optimal acceleration depending on car speed, given by the Renault proprietary eco-driving rule.

Results

We performed an ANOVA planned comparison with $\alpha = 0{,}05$ on these parameters (see Table 1).

A comparison between $T1_{ref}$ and $T2_{eco\text{-}behavior}$ was computed among all subjects. A significant decrease was observed on our parameters of interest.

A between group comparison on assisted trial $T3_{eco\text{-}assistance}$ was computed, to evaluate the benefit of each assistance, compared to the reference unassisted group (S_n), with verbal instruction to drive at low engine speed. Assistance systems induced a significant decrease. However, there were no significant effects of the type of assistance feedback.

By comparing, into each assisted group, verbally instructed runs (mean of $T2_{eco\text{-}behavior}$ + $T4_{eco\text{-}behavior}$) to assisted runs $T3_{eco\text{-}assistance}$ (T2 and T4 serves to cancel the bias due to learning effects of low engine speed driving across the three last trials), visual assistance do not lead to significant improvements for any of the parameters of interest. In the haptically assisted group, total polluting emissions is the only result which is not significantly improved. In visual-haptic group, all the recorded parameters are significantly reduced.

Table 1. Results of the ANOVA planned comparison analysis

	Total polluting emissions	**Std (X_{pedal})**	**Mean (ΔAcc)**
All subjects ($T1_{ref}$ vs $T2_{eco\text{-}behavior}$)	$F(1.88) = 19{,}87$; $p < 0.001$	$F(1.88) = 25{,}85$; $p < 0.001$	$F(1.88) = 23{,}15$; $p < 0.001$
S_v group (T2 + T4 vs T3)	NS	NS	NS
S_h group (T2 + T4 vs T3)	NS	$F(1.88) = 12{,}84$; $p < 0.001$	$F(1.88) = 6{,}62$; $p < 0.05$
S_{vh} group (T2 + T4 vs T3)	$F(1.88) = 4{,}32$; $p < 0.05$	$F(1.88) = 14{,}23$; $p < 0.001$	$F(1.88) = 9{,}38$; $p < 0.005$
$T3_{eco\text{-}assistance}$ trials (S_n vs S_v)	$F(1.88) = 4{,}69$; $p < 0.05$	$F(1.88) = 5{,}45$; $p < 0.05$	$F(1.88) = 4{,}42$; $p < 0.05$
$T3_{eco\text{-}assistance}$ trials (S_n vs S_h)	$F(1.88) = 5{,}74$; $p < 0.05$	$F(1.88) = 5{,}68$; $p < 0.05$	$F(1.88) = 6{,}35$; $p < 0.05$
$T3_{eco\text{-}assistance}$ trials (S_n vs S_{vh})	$F(1.88) = 7{,}51$; $p < 0.01$	$F(1.88) = 7{,}55$; $p < 0.01$	$F(1.88) = 7{,}86$; $p < 0.005$

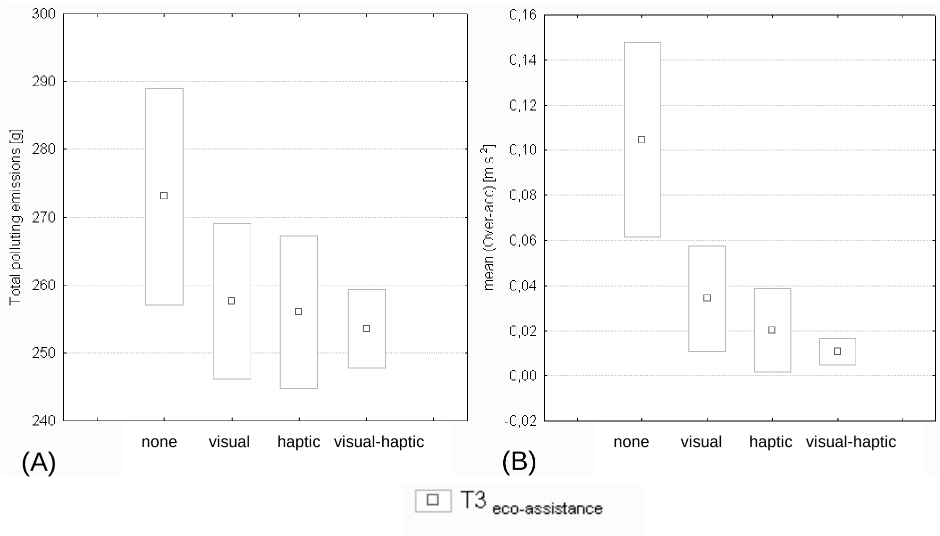


Figure 3. Plot by groups of total polluting emissions on T3 eco-assistance trial for (A) total polluting emissions and (B) mean of over-acceleration

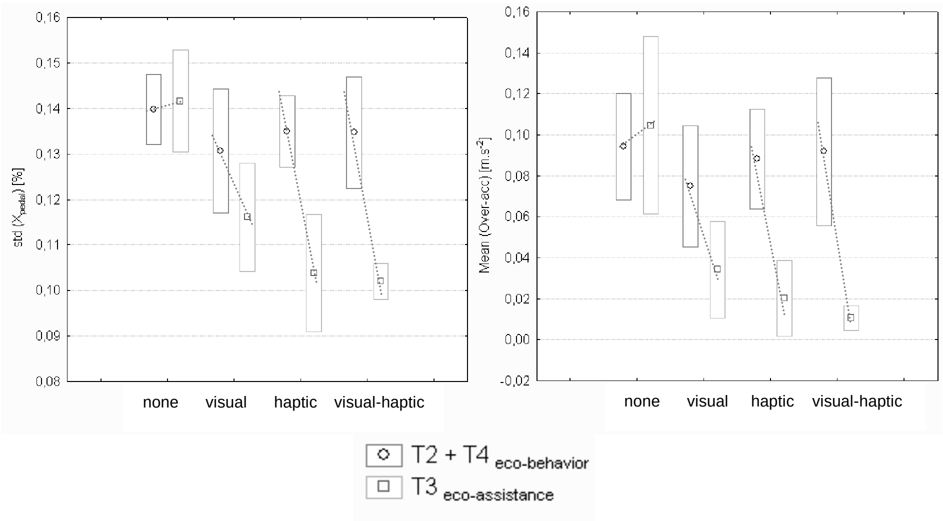


Figure 4. Plot of (A) standard deviation of pedal position; and (B) mean of over-acceleration, for verbally instructed trials and assisted trials for each group

Discussion

This study is a first step to demonstrate the efficiency of a haptic feedback gas pedal on eco-driving, and the ability of drivers to adapt at first use of such an information feedback system. We choose to immerse drivers in a simulated driving context, without traffic to allow performance comparisons between experimental conditions. This choice may give preferential treatment to the visual assistance condition compared to ecological driving condition, because the visual perception of car traffic competes with the visual attention allocated to watching the visual assistance display.

Contribution of verbal instructions to eco-performance

In this experiment, adopting eco-driving behavior, by limiting engine speed at 2000 Rpm, constitutes a first significant step to reduce total polluting emissions by 5%, compared to driving sessions without instructions. Mean overpass of optimal acceleration, significantly decreases, suggesting that a correlation exists between our optimal acceleration model and eco-driving requirements.

Additional contribution generated by eco-driving assistances

The three assisted conditions provide significant decreases by 5 to 7% of total polluting emissions (see Fig 3 (A)). This result is consistent with the performance announced for the Continental's accelerator force feedback pedal, or the Nissan's eco pedal. However, there is no significant effect of the type of assistance feedback. This suggests that, haptic stimulation can be as efficient as visual stimulation, in terms of assisted eco-driving performance. Moreover, in presence of assistance feedback, drivers' over-acceleration level also significantly decrease (see Fig 3 (B)), suggesting that optimizing over-acceleration allows additional polluting emissions improvement, compared to engine speed optimization.

Drivers' reaction when first using the haptic pedal assistance

Even if haptic devices are newer than visual displays for eco-driving assistance, drivers show a good adaptation to haptic signal modulations. In the groups assisted haptically (haptic and visual-haptic conditions), we notice a significant decrease of the standard deviation of the accelerator pedal in assisted trials, compared to low engine speed verbally instructed trial, without active assistance. In the visual group, this decrease is not significant (see Fig 4 (A)). One could think that pedal stability is enhanced by opposing a counterforce to the foot, which helps guiding it to the position recommended by the system. This result shows a better efficiency of the force feedback pedal on foot stability, for a first usage of the haptic pedal system.

Drivers are able to make fast modifications of their foot admittance, depending on the specificity of the task they are performing. By measuring muscular activity of the leg pressing a car pedal, during "force tasks" (minimize effort variations) and "position task" (resist to perturbations), it appears that drivers use antagonist muscles of the leg to accomplish the various use modes imposed by an active car pedal [Abbink & al, 2004]. In our "force task" experiment, the feedback stimulation provided by the haptic pedal was inhibitory [Mugge & al, 2009], since participants were asked to cancel additional force feedback when it appeared, by releasing accelerator pedal.

This ability to modify the biomechanical admittance has also been highlighted for upper limbs with a steering wheel handling task. Drivers are able to control the trajectory of their car with different steering wheel force feedback strategies, whether they are linear or not, which implies a strong sensorimotor plasticity and a large capacity of quasi-instantaneous adaptation to haptic disturbances [Toffin & al, 2003]. We know furthermore, that the foot and the hand have the same degree of differentiation in haptic modality [Hajnal & al, 2007]. In spite of their neuronal and anatomic differences, the upper and lower limbs seem to have the same perceptive performance in terms of force discrimination ability.

Visual-haptic merging

When drivers have both visual and haptic assistance for a first use, the decrease in over-acceleration is significant. This decrease is also significant in haptic modality, but not with visual feedback (see Fig 4 (B)). Drivers show better self eco-performance improvement when, at least, haptic feedback is available, in comparison to visual assistance alone: this suggests that haptic is more suited for that particular double task (driving and following the eco-driving indications). This result is otherwise coherent with the higher reliance accorded by participants to the haptic modality, for instance in a visual-haptic size detection task [Ernst & al, 2002].

Conclusion

This study confirms the efficiency of basic eco-driving behaviors, like gear-shifting under 2000Rpm, on the generated polluting emissions for diesel engines. Adding eco-driving assistances (visual or haptic) allows additional reduction of polluting emissions, but no effect of the type of assistance feedback have been noticed in our experiment. With haptic and visual-haptic assistance, we also observe significant reductions of control activity, measured by standard deviation of gas pedal position, which demonstrates the ease of use of haptic feedback pedal for a first utilization of the system. Moreover, drivers apparently rely more on haptic modality when using both visual and haptic assistance. In this experiment, visual assistance may have an advantage in comparison to ecological driving conditions, because of lack of car traffic. Further studies should analyze the impact of car traffic on the efficiency of visual and haptic assistance, but also drivers' adaptation to haptic feedback pedal in critical situations, when drivers need to accelerate, despite of the increased rigidity of the pedal.

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