S. Azzi
RENAULT, Technical Centre for Simulation, Avenue du Golf – 78288 Guyancourt, France;
Arts et Métiers ParisTech, Le2i, CNRS, Institut Image, Rue Thomas Dumorey – 71100 Chalon sur Saône, France

G. Reymond
RENAULT, Technical Centre for Simulation, Avenue du Golf – 78288 Guyancourt, France

F. Mérienne
Arts et Métiers ParisTech, Le2i, CNRS, Institut Image, Rue Thomas Dumorey – 71100 Chalon sur Saône, France

A. Kemeny
RENAULT, Technical Centre for Simulation, Avenue du Golf – 78288 Guyancourt, France;
Arts et Métiers ParisTech, Le2i, CNRS, Institut Image, Rue Thomas Dumorey – 71100 Chalon sur Saône, France

Eco-Driving Performance Assessment With in-Car Visual and Haptic Feedback Assistance

In this experiment, 28 participants completed an urban driving task in a highly immersive driving simulator at Renault's Technical Centre for Simulation. This simulator provides a 150 deg field of view in a fully instrumented cockpit. Two different eco-driving assistance devices were added: a visual display on the midconsole and a force feedback system on the gas pedal, in order to apply an additionnal reaction torque on drivers' foot. 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. This experiment has three main goals: I. Assess the contribution of verbal instructions to eco-driving performance; II. Quantify the additional contribution generated by two eco-driving assistance systems (visual and haptic); III. Measure drivers' acceptance of haptic eco-driving assistance system. Basic eco-driving instructions, such as changing gears under 2000 Rpm, yield 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 the haptic feedback provides the same ecoperformance 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. [DOI: 10.1115/1.3622753]

Keywords: Eco-driving, active gas pedal, in-car assistance, haptic feedback, driving simulator

Introduction

Context. Since the early 70s, the European Union has been controlling the polluting emissions of its vehicles by setting more and more drastic ecologic standards [1]. From the early 90s, the development of the collective consciousness for ecology, associated with 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 sensory 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 its consumption display system, Honda has developed in 2009 a speedometer with changing colors, depending on drivers' ecoperformance [2]. Car simulators provide an effective mean to study the impact of such visual information systems on driving attention and performance [3,4]. 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 [5]. Moreover, lane keeping and distance keeping to followed car, with the help of peripheral vision, appears to be impaired when watching a visual display on the speedometer. This impairment grows when the display is on the midconsole [6]. A quantitative performance assessment of the display indicates that the vertical eccentricity compared to the line of sight of the road, has a greater detrimental effect than the horizontal distance [7].

Haptic Assistance Feedback. Haptic stimulation through gas pedal is another way to provide feedback information on ecoperformance. One of the strengths of the human haptic system, as compared with the visual system, is the fast information transmission to the brain [8]. Continental has developed an accelerator force feedback pedal AFFP [9], which vibrates to inform drivers on optimal gear-shifting instant. Nissan proposes since 2009 an ECO Pedal [10] 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 the visual assistance. Significant decreases of mean and variation of speed, as well as polluting emissions, are observed [11]. Haptic feedback pedal acceptance is positively rated by drivers, but they do not show enough willingness to use it daily, nor to pay for it [12].

In-car following applications, haptic feedback pedal systems give information on intervehicular 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 intervehicle distance and braking reaction time [13,14]. It also induces an increase of visual detection performance by reducing driver's workload, in particular, because subjects apparently apply a basic strategy of maintaining a constant effort against the gas pedal when driving [15].

Objectives. 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

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Fig. 1 Principle of Renault eco-driving model

assistances. Finally, we test whether drivers feel at ease at a first use 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 Comprehensive Automobile Research and Development (CARDS) [16] at the Technical Center for Simulation of Renault. This simulator, is composed of a modular cockpit, completely instrumented, providing to the driver all the equipments and interactions existing in a real car (Fig. 1). It is based on the SCANER2 [17] simulation software package, developed by Renault, which is a real-time distributed application, providing a large set of functionalities for driving research fields. The front view is provided by three projectors delivering a 150 deg horizontal field of view image. The visual absolute validity of the simulator is enhanced by our large field of view, which allows a correct estimation of longitudinal speed by visual cues [18].

For experimental needs, the simulator has been enriched with two eco-driving assistance devices: A visual interface positioned on top of the central console provides visual information on $F_{additional}$ value through a progress bar; 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.

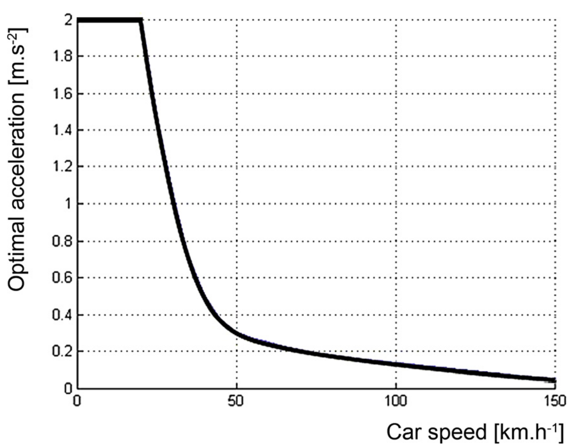

Fig. 2 Picture of the CARDS simulator, with midconsole assistance display

A Renault proprietary eco-driving model (Fig. 2) compares in real time the longitudinal acceleration of the drive 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 are over the optimal value, a normalized counter-acting force $F_{additional}$, proportional to the gas pedal position X_{pedal}, is opposed to drivers' foot (Fig. 1). Gas pedal force was equal to 35N when Acc_veh reached twice Acc_opt.

$F_{additional}$ is calculated as follows:

Acc_veh = Vehicle acceleration
Acc_opt = Optimal acceleration
ΔAcc = Overacceleration based on our model
X_{pedal} = Pedal position
$\Delta\text{Acc} = \text{Acc\_veh} - \text{Acc\_opt}$
$F_{additional} = K.\ X_{pedal}\ .\ (\Delta\text{Acc}/\text{Acc\_opt})$
With K = Pedal stiffness factor

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.

Participants. Twenty eight 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 four distinct groups of seven 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. The fourth group is the reference group (S_n), no assistance was provided, and 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 min 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 were 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.

Table 1 Results of the ANOVA planned comparison analysis

	Total polluting emissions	Std (X_{pedal})	Mean (ΔAcc)
All subjects ($T1_{ref}$ versus $T2_{eco\text{-}behavior}$)	$F(1.88) = 19{,}87$; $p < 0.001$	$F(1.88) = 25{,}85$; $p < 0.001$	$F(1.88) = 23{,}15$; $p < 0.001$
S_v group (T2 + T4 versus T3)	NS	NS	NS
S_h group (T2 + T4 versus T3)	NS	$F(1.88) = 12{,}84$; $p < 0.001$	$F(1.88) = 6{,}62$; $p < 0.05$
Svh group (T2 + T4 versus 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 versus 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 versus 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 versus S_{vh})	$F(1.88) = 7{,}51$; $p < 0.01$	$F(1.88) = 7{,}55$; $p < 0.01$	$F(1.88) = 7{,}86$; $p < 0.005$

Results

We performed an analysis of variance (ANOVA) planned comparison with $\alpha = 0{,}05$ on these parameters (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 $T2_{eco\text{-}behavior}$ and $T4_{eco\text{-}behavior}$) to assisted runs $T3_{eco\text{-}assistance}$ (T2 and T4 serve to cancel the bias due to learning effects of low engine speed driving across the three last trials), visual assistance does not lead to significant improvements for any of the parameters of interest. In the haptically assisted group, total polluting emissions are the only result, which is not significantly improved. In visual-haptic group, all the recorded parameters are significantly reduced.

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 chose 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 with 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 EcoPerformance

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 (Fig. 3(*a*)). Mean overpass of optimal acceleration, significantly decreases (Fig. 3(*b*)), 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 5–7% of total polluting emissions, in addition to the decrease observed when following verbal instructions to drive at low engine speed (Fig. 4(*a*)). This result is consistent with the performance announced for the Continental's accelerator force feedback pedal [9], or the Nissan's eco pedal [10]. However, there is

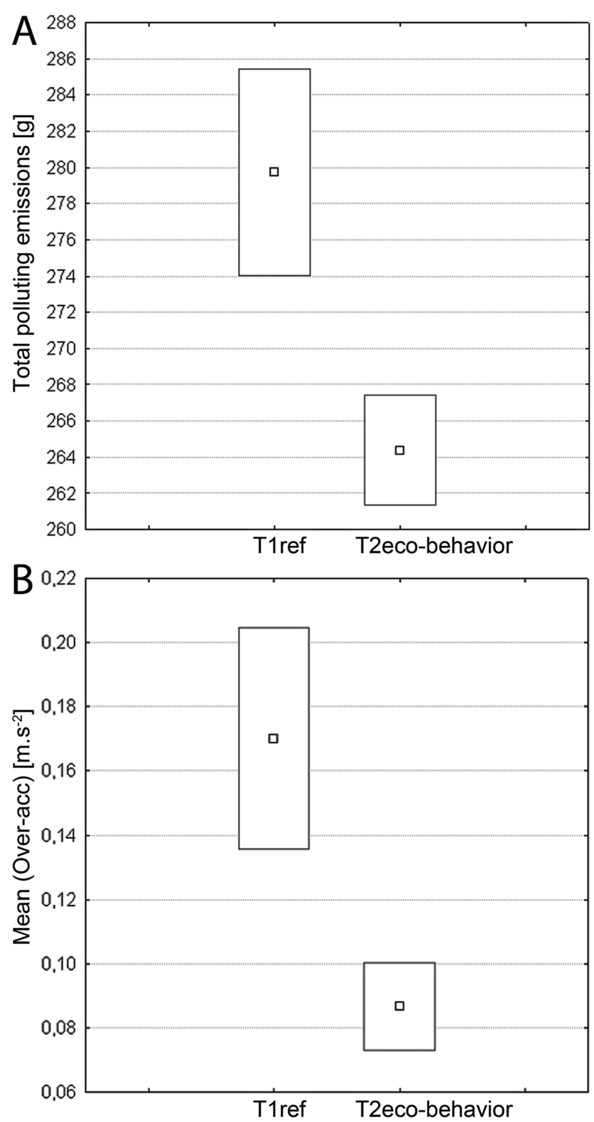

Fig. 3 Plot by trials, among all subjects, of total polluting emissions (*a*); and mean over-acceleration compared with optimal (*b*)

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 (Fig. 4(*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 position, in assisted trials, compared to low engine speed verbally instructed trial, without active assistance. In the visual group, this decrease is not significant (Fig. 5(*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.

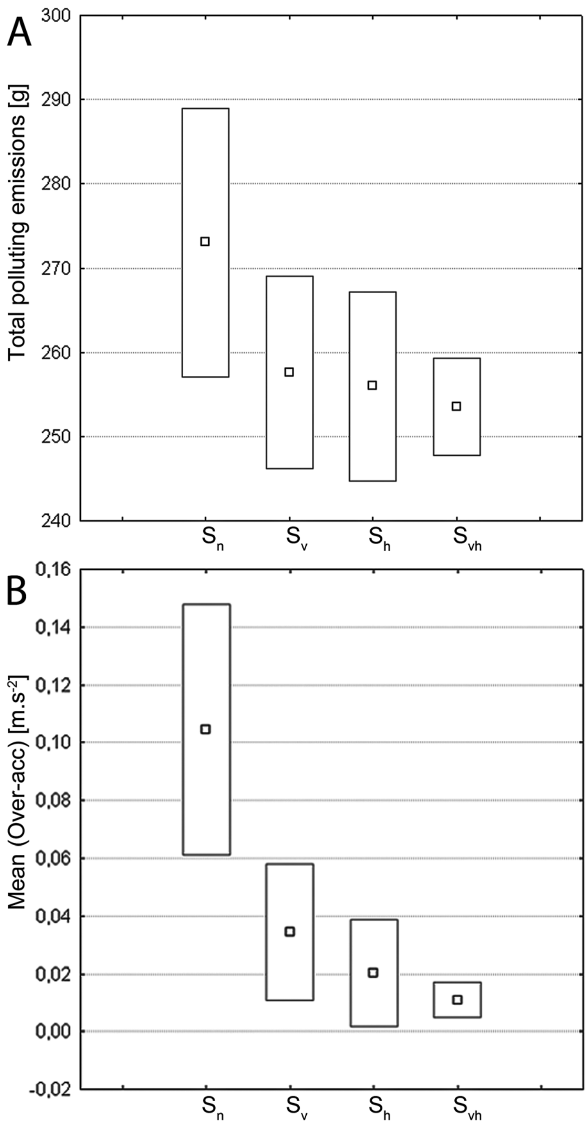

Fig. 4 Plot by groups of T3$_{\text{eco-assistance}}$ trials for total polluting emissions (*a*); and mean of overacceleration (*b*)

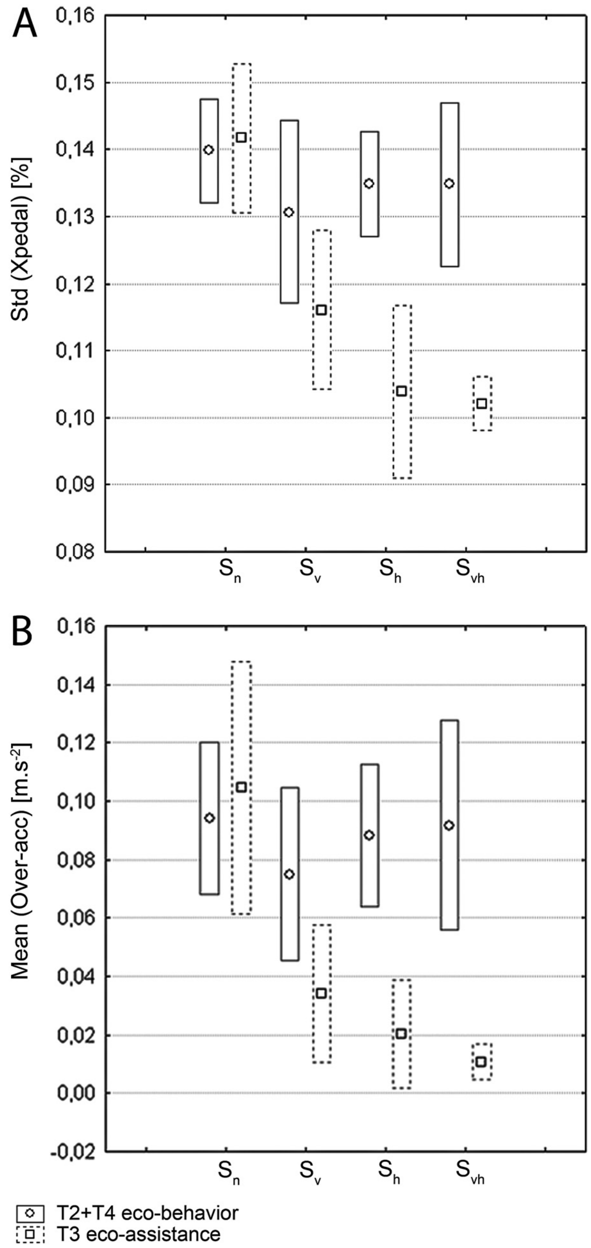

Fig. 5 Plot of verbally instructed trials and assisted trials for each group for standard deviation of pedal position (*a*); and mean of overacceleration (*b*)

Drivers are able to make fast modifications of their foot response, 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 [19]. In our force task experiment, the feedback stimulation provided by the haptic pedal was inhibitory [20], 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 [21]. We know, furthermore, that the foot and the hand have the same degree of differentiation in haptic modality [22]. 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. This ability allows fast detections of force feedback variations perceived by drivers' foot, and thus induces fast response to this haptic stimulation by releasing gas pedal. This property of haptic perception could explain the good results in terms of over-acceleration minimization in presence of haptic assistance pedal.

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 (Fig. 5(*b*)). Drivers show better self ecoperformance 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 when visual perception is impaired, for instance, in a visual-haptic size detection task [23,24]. In our study, this impairment on the reliability of visual assistance perception could be a consequence of the competitive visual workload induced by the driving task. In that case, visual perception performance tends to decrease when car traffic complexity increases, since a reduction of the performance in driver's visual detection and discrimination is observed [25]. As well, one could assume that increasing number of curves on the track could lower visual perception ability.

Conclusion

This study confirms the efficiency of basic eco-driving behaviors, such as gear-shifting under 2000 rpm, on the amount of 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 has 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 the lack of car traffic. Further studies should analyze the impact of the curviness of the road, as well as the impact of car traffic complexity 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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