Sustainable Effects of Simulator-Based Training on Eco-Driving

Cornelia Lüderitz, Maria Wirzberger, and Katja Karrer-Gauss

Abstract

Simulation-based driver training offers a promising way to teach ecological driving behavior under controlled, comparable conditions. In a study with 23 professional drivers, we tested the effectiveness of such training. The driving behavior of a training group in a simulated drive with and without instructions were compared. Ten weeks later, a repetition drive tested the long-term effect training. Driving data revealed reduced fuel consumption by ecological driving in both the guided and repetition drives. Driving time decreased significantly in the training and did not differ from driving time after 10 weeks. Results did not achieve significance for transfer to test drives in real traffic situations. This may be due to the small sample size and biased data as a result of unusual driving behavior. Finally, recent and promising approaches to support drivers in maintaining eco-driving styles beyond training situations are outlined.

Keywords

Simulator-based training • Eco-driving • Sustainability • Professional drivers

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B. Deml et al. (eds.), *Advances in Ergonomic Design of Systems, Products and Processes*, DOI 10.1007/978-3-662-48661-0_30

1 Introduction

Within the ongoing debate on environmentally friendly and resource-saving driving the issue of eco-driving training is becoming increasingly important, especially for large road transport companies, including from an economical point of view. A cost analysis by Wittenbrink [13] showed an increase in the proportion of fuel costs during long-distance transport. For example, in 2007 fuel already accounted for more than 25 % of the total costs. Fuel consumption can be reduced in various ways, including improving vehicle technology, optimizing traffic infrastructure, but also through driver training [12]. In particular, teaching drivers a fuel-conserving driving style has been examined in several studies [cf. 10, 11]. Some studies use purely theory-based training while others apply real test drives to demonstrate an green driving style. Eco-driving can be described as a more efficient driving performance involving the application of eco-driving skills and techniques not only to reduce fuel consumption but also greenhouse-gas emissions [2]. These techniques include both theoretical and practical components. Especially practical components can be easily taught by using simulators as an additional environment for exercising technical skills [8]. Usually, within such training, skills like correct acceleration and gear changing behaviour to reduce engine speed, optimum braking characteristics, and the benefit of coasting phases are communicated [2]. Simulators for training eco-driving represent an alternative medium that offers many advantages. Specific training situations can be designed to effectively teach the required behaviour and can be repeated under controlled conditions as often as necessary. During simulator training, exact behavioural parameters of each driver in terms of timing and brake or accelerator pedal actuations can be detected online, providing instantaneous feedback.

In the present study, a simulator-based training concept is tested for its effectiveness in eco-driving training to professional truck drivers. Training evaluation focuses on three main issues:

1. Potential of the training, which refers to the degree to which a driver is potentially able to improve performance. It will be investigated to what extent driving behavior might be changed towards an eco-driving style by training.
2. Sustainability of the training, focusing on long-term effects. It will be examined whether the training leads to a measurable and successful application of eco-driving behavior in the longer term, in this case after a time span of 10 weeks.
3. Transfer of the training content to unfamiliar driving situations. On this account, two questions are considered: Will the trained behavior be used by drivers on unfamiliar routes within the simulator? Does the training have effects on real life driving behavior in the daily work of truck drivers?

1.1 Hypothesis and Variables

To examine effectiveness of the training in terms of a green and cost-efficient driving style, various variables were assessed. According to previous studies, in which eco-driving trainings were evaluated on the basis of fuel consumption, the extent of fuel savings ranged from 7–27 % [e.g. 10, 11]. Hence, fuel consumption was taken as a key indicator for eco-driving performance, representing the overall potential and effectiveness of an eco-driving training concept. In addition, the time needed to complete the test drive was logged, since Thijssen et al. [12] report a significant increase in travel time after a training intervention for eco-driving, which would be a great disadvantage for truck companies, resulting in longer delivery times and thus additional costs. For this reason, the study also examined whether such a training intervention would increase travel time.

Acceleration performances of drivers were assessed by analyzing the profile of accelerator pedal usage, which is shown in Fig. 1 as triangles for trained and untrained drivers. There are three components of accelerator pedal activation indicating changes in terms of eco-driving style. The operating phase (a) reflects the overall time span of accelerator pedal usage, including acceleration phase (b), which describes the time participants need to accelerate to full depression of the accelerator pedal. The peak amplitude (c) was measured by coding the depression of the accelerator pedal from zero (no usage of acceleration pedal) to 255 (the maximum depression of pedal flooring the accelerator). It was assumed that with realization of an eco-driving style through training, operating phase as well as acceleration phase would be shorter, reflecting a more effective use of the accelerator pedal. In this context, a quicker acceleration performance together with a higher degree of pedal depression was expected. Hence, the peak amplitude should also increase. In this context, the absolute number of peaks for each drive was recorded. This should reveal information about the frequency of accelerator pedal use due to the smoothness of a participant's driving style. Trained participants would use the accelerator pedal less frequently in contrast to untrained drivers, resulting in a decreased number of peaks in accelerator activation.

Associated with acceleration performance, average speed was assessed as well as examined whether eco-driving training would lead to lower average speeds. Furthermore, coasting phases were measured. They were represented as time spans in which the vehicle was rolling and drivers neither used the accelerator pedal nor the breaks. It was hypothesized that trained drivers would use coasting phases to a greater extent than untrained drivers.

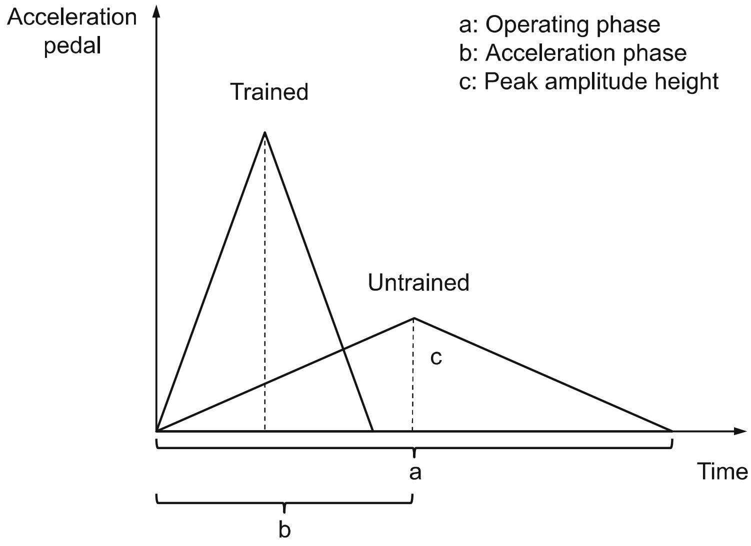

Fig. 1 Triangle profile of accelerator pedal activation to define acceleration performance variables

2 Methods

2.1 Participants

23 male truck drivers employed at a transport company participated in the study. 13 drivers ($M = 43.54$ years, $SD = 7.32$) completed the simulator-based training. The other 10 drivers ($M = 47.80$ years, $SD = 10.09$) served as a control group.

2.2 Simulation

Training evaluation was conducted using a "DriveSim mobile" simulator from SiFaT-Road Safety GmbH displayed in Figs. 2, 3 and 4. The air-conditioned, soundproof driver cabin conformed to a Mercedes-Benz Actros and included a shored motion system for simulating motor movements and braking. The driving scenario was back-projected onto a screen with 180° field of vision. Audible instructions from a male trainer were given promptly during the guided run regarding certain training events. The separate operator cabin displayed all driver views, a view to regulate the route, and dynamic displays showing the use of accelerator and braking pedal. The simulation emulated a four-wheeled goods vehicle with long wheelbase, drawbar trailer and a load of 32 barrels. The simulated route included urban traffic with crossroads and roundabouts as well as highways.

Fig. 2 Mobile truck simulator "DriveSim mobile" (SiFaT Road Safety GmbH)

Fig. 3 Trainer cabin of the mobile truck simulator (SiFaT Road Safety GmbH)

2.3 Procedure

As shown in Fig. 5, the inital training session was followed up by a validation run after an interval of 10 weeks.

Training sessions consisted of familiarization trial run and then two test drives, baseline (1) and guided drive (2). The main purpose was to demonstrate the potential of environmentally-motivated driving in terms of reduced fuel consumption after providing a short theoretical introduction, the previous driving behavior (baseline drive 1) was directly compared to a more environmentally aware driving style (guided drive 2) over the same route.

Fig. 4 Mercedes-Benz Actros driver cabin (SiFaT Road Safety GmbH)

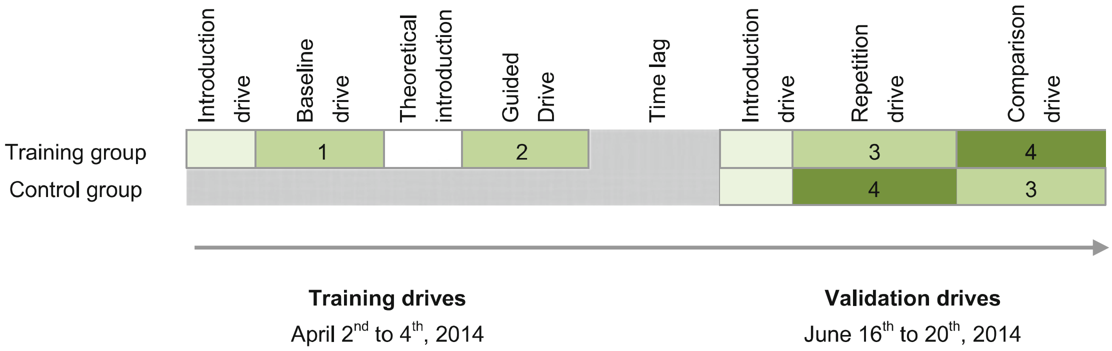

Fig. 5 Training and testing schedule

The follow-up validation drives aimed to examine long-term training effects. Trained drivers again completed the simulated route (repetition drive 3) to enable the comparison with their driving behavior from the baseline drive. At the same time, comparing repetition drive and guided drive, conducted within the training, provided information about how drivers exploit the fuel saving potential without instruction aid after a certain amount of time.

To avoid learning effects due to the repeated confrontation with the same route, another comparison between trained drivers and the control group of untrained drivers using a new route (comparison drive 4) was introduced. This made it possible to show the transfer of the acquired driving behavior to a new situation, containing elements similar to those from the previously completed route. In this way acquired knowledge was activated, but had to be applied to an unfamiliar route. Both routes were 8–10 km long.

To be able to assess the application of trained behavioral patterns in real-world traffic situations, fuel consumption from real driving data, was also inspected covering the time span from January to May 2014.

3 Results

3.1 Training Potential

Training potential was inspected in a within-subjects design, comparing fuel consumption within the baseline drive and guided drive by analyses of variance (ANOVAs). Travel time and fuel consumption were corrected with regard to a consistent starting point for each participant, i.e. the moment of first operation of the accelerator pedal. Means and standard deviations are displayed in Table 1. A significant effect for training potential was found, $F(1,12) = 23.404$, $p < .01$, with a lower fuel consumption in the guided drive. Travel time was examined in the same way, providing evidence for a significant effect in terms of shorter travel times in the guided drive compared to the baseline drive, $F(1,12) = 5.319$, $p < .05$. Considering the coasting phase revealed a significant effect for an increase in the amount of time within the guided drive, $F(1,12) = 67.122$, $p < .01$. Moreover, a significant effect for average speed arose in terms of higher average velocity in guided drive compared to baseline drive, $F(1,2) = 6.249$, $p < .05$.

Means and standard deviations of the acceleration performance variables are displayed in Table 2. ANOVAs revealed significant effects between baseline and guided drive for the number of peaks, $F(1,12) = 75.045$, $p < .01$, peak amplitude, $F(1,12) = 34.251$, $p < .01$, operating phase, $F(1,12) = 73.556$, $p < .01$ as well as acceleration phase, $F(1,12) = 48.400$, $p < .01$. The number of peaks in guided drive decreased in comparison to baseline drive, whereas the height of peak amplitude increased in the extent the accelerator pedal was depressed. Both

Table 1 Means and standard deviations of eco-driving variables within the training group on identical simulation tracks

	Fuel consumption (l/100 km)		Travel time (s)		Coasting phase (s)		Average speed (km/h)	
Track	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Baseline drive	30.18	2.67	570.92	25.85	59.15	39.01	45.76	2.07
Guided drive	25.64	1.00	555.62	18.16	191.62	39.01	46.80	1.78
Repetition drive	27.99	2.24	567.50	25.89	105.80	36.66	46.85	2.41

Table 2 Means and standard deviations for acceleration performance variables within the training group on identical simulation tracks

	Number of peaks		Peak amplitude (1-255)		Operating phase (s)		Acceleration phase (s)	
Track	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Baseline drive	66.78	9.58	164.81	12.20	430.46	43.49	272.46	27.52
Guided drive	38.62	9.64	190.00	16.30	299.78	46.67	208.08	17.48
Repetition drive	51.00	11.54	168.55	15.93	375.30	36.38	257.40	28.83

variables indicate a steady driving style, which was trained during the guided drive. The examination of the operation and acceleration phase revealed shorter durations for both phases in guided drive compared to baseline drive indicating a quicker accelerating performance of participants in guided drive in contrast to baseline drive.

3.2 Long-term Training Effects

To test long-term training effects, variances were analyzed in a within-subjects design to compare the results for the training group, both between baseline drive and repetition drive and between guided drive and repetition drive. Three participants of the training group did not complete the repetition drive. Therefore only ten datasets could be analyzed.

For fuel consumption there was a significant difference in the comparison between baseline and repetition drive, $F(1,9) = 7.766$, $p < .05$. Even after ten weeks fuel consumption remained at a lower level for trained participants, which can be attributed to the long-term training effect. However, fuel consumption was significantly lower in the guided drive compared to the repetition drive, $F(1,9) = 9.063$, $p < .05$. Likewise, there were significant effects on the coasting phase for baseline vs. repetition drive, $F(1,9) = 25.099$, $p < .01$, and the comparison between guided vs. repetition drive, $F(1,9) = 21.961$, $p < .01$. In the repetition drive, trained participants allowed the vehicle to coast longer than in the baseline drive, but not as much as in the guided drive, in which the coasting phase was longest. No significant long-term training effects could be shown for travel time (baseline vs. repetition drive: $F(1,9) = 0.029$, $p = .869$; guided vs. repetition drive: $F(1,9) = 1.855$, $p = .206$) or for average speed (baseline vs. repetition drive: $F(1,9) = 1.589$, $p = .239$; guided vs. repetition drive: $F(1,9) = 0.001$, $p = .976$).

Analyzing the results of acceleration performance variables, there were significant outcomes for the number of peaks in both comparisons (baseline vs. repetition drive: $F(1,9) = 22.257$, $p < .01$ and guided vs. repetition drive: $F(1,9) = 7.381$, $p < .05$). In the repetition drive, trained participants reached a lower number of accelerator pedal use compared to baseline drive; in comparison to guided drive, however, the number again increased significantly. For height of peak amplitude no significant effect could be found for baseline and repetition drive, $F(1,9) = 0.233$, $p = .641$, whereas the comparison between guided vs. repetition drive became significant, $F(1,9) = 13.109$, $p < .01$. Mean values for peak amplitude indicated a significant decrease in the extent of accelerator pedal depression in the repetition drive. In other words, in the repetition drive participants did not depress the accelerator pedal to the same intensity as in guided drive as shown in Fig. 6. The analysis of the operating phase revealed significant effects for both baseline vs. repetition drive, $F(1,9) = 55.981$, $p < .01$, and guided vs. repetition drive, F

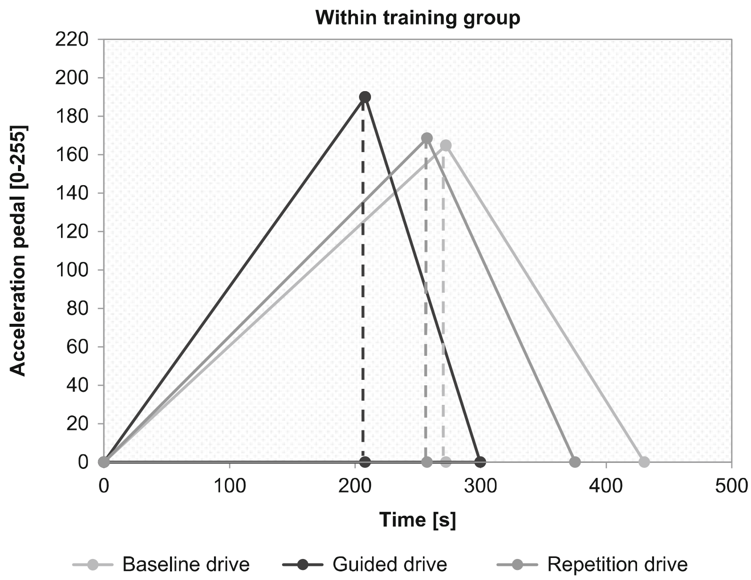

Fig. 6 Triangle diagram of acceleration performance variables displaying the potential and long-term effect of ecological training intervention

(1,9) = 13.854, $p < .01$. In the guided drive the duration of the operating phase in terms of acceleration activation was shorter in comparison to baseline drive. However, compared to the guided drive a significant increase was found in the repetition drive. The length of acceleration phase was only statistically significant for guided vs. repetition drive, $F(1,9) = 15.750$, $p < .01$, but not for baseline vs. repetition drive, $F(1,9) = 1.746$, $p = .219$. In the repetition drive, trained participants were not able to reduce the acceleration duration as in the guided drive. They roughly needed as much as time for acceleration as in baseline drive.

3.3 Transfer Effects

Transfer effects were assessed by comparing the results of the training group and the control group within comparison drive, displayed in Tables 3 and 4. Effects were tested by ANOVAs in a between-subjects design. The comparison of both groups yielded no significance for fuel consumption, $F(1,18) = 1.261$, $p = .276$, or travel time, $F(1,18) = 0.005$, $p = .943$. Although there was a tendency for longer coasting phase, shown by a higher mean value for training group, the difference was not significant, $F(1,18) = 1.727$, $p = .205$. Solely, average speed was significantly higher for training group compared to control group, $F(1,18) = 6.088$, $p < .05$.

For acceleration performance variables there were several significant differences in the number of peaks, $F(1,18) = 13.876$, $p < .01$, the peak amplitude, $F(1,18) = 16.967$, $p < .01$, and the operating phase as well, $F(1,18) = 15.229$, $p < .01$. The analysis of the acceleration phase did not reveal a significant effect for the comparison of control and training group, $F(1,18) = 0.019$, $p = .892$. Except for the acceleration phase, participants of the training group showed better acceleration performance compared to the control group in comparison drive, i.e. a shorter operation phase, less frequent use of accelerator pedal shown by fewer peaks as well as a higher degree of accelerator pedal depression, displayed in Fig. 7.

Table 3 Means and standard deviations for eco-driving variables in training and control groups

	Fuel consumption (l/100 km)		Travel time (s)		Coasting phase (s)		Average speed (km/h)	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Training group	32.95	1.77	524.00	28.83	70.10	26.10	40.62	2.37
Control group	31.71	3.01	523.00	64.13	57.60	14.96	37.44	3.31

Table 4 Means and standard deviations for acceleration performance variables in training and control groups

	Number of peaks		Peak amplitude (1-255)		Operating phase (s)		Acceleration phase (s)	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Training group	34.40	10.96	172.49	11.36	270.90	28.92	198.70	17.43
Control group	49.50	6.65	150.31	12.68	318.90	26.01	197.20	29.74

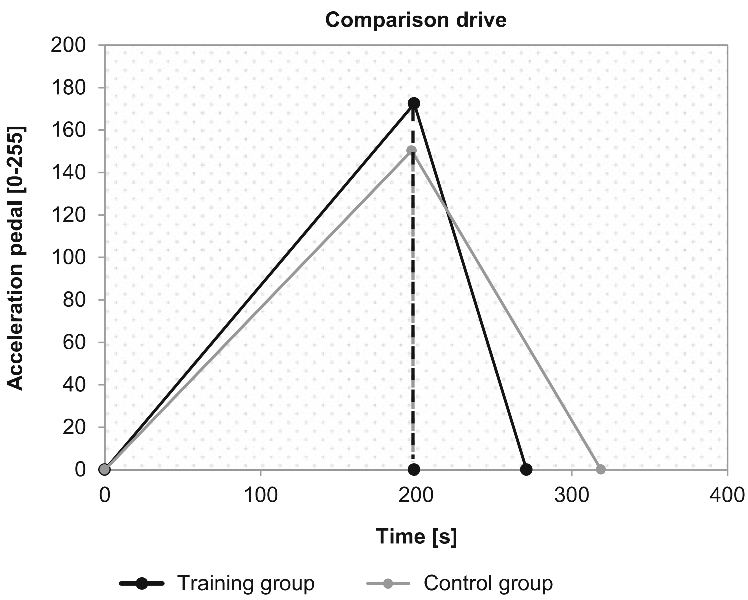

Fig. 7 Triangle diagram of acceleration performance variables displaying the transfer effect of ecological training intervention

Finally, driving behavior in real-world traffic situations was considered to provide evidence for transfer effects. For these purposes, fuel consumptions of the training group and control group were compared using available real driving data from January to May 2014, as shown in Table 5. Due to missing data, only nine datasets from each group could be analyzed. Data from both groups for March and April 2014 were tested by ANOVAs within a 2×2 mixed between-within-subjects design. There was a significant main effect for the factor time, $F(1,16) = 8.043$, $p < .05$, but not for group membership $F(1,16) = 0.000$, $p = 1.00$, i.e. fuel consumption declined after the training intervention, but not more than in the control group. A potential interaction effect did not achieve significance either, $F(1,16) = 0.371$, $p = .551$.

Table 5 Means and standard deviations of fuel consumption from real driving data

Group	Fuel consumption (l/100 km)									
	January		February		March		April		May	
	M	SD	M	SD	M	SD	M	SD	M	SD
Training group	32.7	1.19	31.62	2.44	31.99	1.43	29.79	3.89	31.44	1.92
Control group	32.5	2.15	30.83	2.57	31.60	2.51	30.18	2.12	31.24	2.11

4 Discussion

Even a single guided training session was able to demonstrate the potential and long-term effect of simulator-based training on driving behavior: Under instruction by a trainer, fuel consumption decreased by 16–21 %. This even exceeds other research findings which report up to 15 % fuel consumption decrease (as summarized in Camacho et al. [5]). In a repetition drive after a period of ten weeks fuel consumption was still reduced by about 8 %. Fuel savings were not obtained by longer driving times. On the contrary, driving time significantly decreased as well and remained below the level of the baseline drive in the repetition drive. Different to the results of Thijssen et al. [12], ecological driving training is not automatically prone to diminish the resulting benefit of reduced fuel consumption by means of increased travel times and in this vein associated with financial disadvantages. However, in their study, Thijssen and colleagues only refer to the training of skills concerning braking and coasting behavior and do not take into account the variety of other behavioral elements of an ecological driving style, such as behavioral patterns during an acceleration situation.

Considering acceleration performance in terms of the assumed long-term effects in this study, trainees could improve their acceleration behavior for several eco-driving techniques due to the simulator-based training intervention. Moreover, in comparison to an untrained control group, they deployed the learned skills on an unknown route, as indicated by significant transfer effects. Nevertheless, they did not accomplish the same acceleration performance as they were trained in the guided drive. In this case, one single guided training session might be not enough to practice and internalize the knowledge, skills and attitudes of ecological driving.

For fuel savings, the anticipated transfer effect could not be confirmed. Neither in the comparison drive nor in real traffic situations was significantly less fuel consumed by the trained group compared to the baseline drive or to the control group, respectively. However, factors such as weather and order situation could not be controlled for during the collection of real traffic driving data. Another potential influence on the results consists in motivational aspects. Saving costs due to reduced fuel consumption is primarily of interest for the company [12]. Promoting an environmental motivation to drivers thus plays an important role with respect to the further application of the acquired knowledge.

During the test drives some exceptional driving errors may have led to biases in the data, e.g. drivers failing to stop at a red traffic light. These aspects might confound comparisons between control and training group. General validity of results is limited as well by means of small sample size and drop outs due to simulator sickness.

5 Conclusions and Outlook

Receiving broad attention by politics and society, eco-driving comprises an often discussed topic. Besides technical and strategic variables like regular maintenance, appropriate loading, or route choice [1], the most effective way to decrease fuel consumption and erosion continues from the individual driver. By means of training, an environmentally friendly way of operating the vehicle should be communicated and internalized. However, the question arises, what exactly constitutes a desirable driving style. Traditionally, behavioral outcomes like reductions in fuel consumption or a more reasonable use of brakes or accelerator are regarded as indicators for a successful switch over to eco-driving. Nevertheless, to achieve long-term changes it is necessary to influence drivers' attitude as well via highlighting the individual environmental responsibility. In doing so, the critical goal consists in creating a solid environmental awareness that is—in the long term—able to contribute to climate protection and pollution reduction.

Moreover, although performance within the training situation is adequate in most studies, mainly based on the potential of simulator training to demonstrate drivers the direct effect of behavioral changes [8], training success seems to diminish over time and reveals a high variance between drivers [3]. To preserve constructive behavior even within real-world settings, a promising approach might involve assistance systems that remind drivers to constantly apply eco-driving [5, 6, 9]. While such strategies have definitely proven of value, the potential disadvantages have to be considered as well. Continuous feedback messages may put additional perceptual and cognitive demands on the driver. Recently, Jamson et al. [7] inspected the effect of either visual or haptic feedback on eco-driving in a simulator-based study. They reported visual feedback to be superior, but at the same time to significantly distract drivers' attention and increase their experienced workload. Haptic feedback, on the other hand, had less effects on performance, but in line with Birrell et al. [4] in this case no increase in subjective workload was reported.

With these results in mind, a less-is-more approach might be a wise solution to keep drivers focused on the key objective of safely reaching the destination. With increased environmental awareness, achieved by goal setting assistant systems, each driver would develop responsibility for protecting our environment, and therefore apply an environmentally friendly driving style to prevent harmful pollution.

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