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Test of HMI Alternatives for Driver Support to Keep Safe Speed and Safe Distance - A Simulator Study

Emeli Adell[1], András Várhelyi[*,1], Mario Dalla Fontana[2] and Laure Bruel[3]

[1]*Lund University, P.O. Box 118, SE-221 00 Lund, Sweden*

[2]*Università di Trento, Trento, Italy*

[3]*PSA Peugeot Citroën, Vélizy Villacoublay, Cédex, France*

Abstract: This paper describes a driving simulator trial to evaluate driver reactions to a number of alternative information/warning modes of a multi-modal system for the "safe speed and safe distance" concept. In 2006, eight Human Machine Interaction alternatives, consisting of a combination of visual, haptic and auditory modes were used alternatively to give information/warning to the driver on safe speed, safe distance and the prevailing speed limit. Thirty-four test drivers drove once without the SASPENCE system and twice with the system. The system did not affect the speed behaviour of the driver in either normal conditions or sharp curves. The average number of alarms was slightly larger when driving with the system. The haptic HMI alternative - the combination of force feedback in the accelerator pedal and vibration of the seat belt for speed warning and pulsation in the accelerator pedal for distance warning - gave the lowest proportion of time of being in an unsafe situation, and improved driver-reaction time most. This haptic alternative also resulted in the most positive driver ratings/experiences of the system. The visual alternatives used were positively rated by the drivers, but no clear differences between them could be found according to opinions. The auditory feedback was not appreciated by the drivers. All the drivers stated they would accept the SASPENCE system if the system was installed in their cars free of charge. The majority would accept a system that was both informative and advisory, while some of them also stated they would accept an intervening system.

Keywords: Driver support, safe speed, safe distance, HMI, driving simulator.

INTRODUCTION

The relationship between the speed level and the number and severity of accidents has been well established [1-3]. Moreover, too-short car-following distances contribute to a large proportion of road accidents, from 13% in Europe [4] to 28% in the USA [5] and 33% in Australia [6]. Information and Communication Technology offers the possibility of supporting the driver to maintain safe speed and safe distance to the vehicle ahead and thereby avoid accidents. A literature review of earlier research work [7] revealed that providing the driver with relevant and concise, but comprehensive, timely information is of paramount importance, allowing the driver sufficient time to understand and react to the situation. To support the driver in a critical situation, the design of HMI (Human-Machine-Interaction) is of major importance. Various modes (visual, auditory or haptic) are possible for supporting the driver in keeping safe speed and safe distance and there are several possible alternative HMI solutions for such a system. The decision on which solution to implement in the car should be based on (besides the HMI fulfilling all the necessary operational and functional requirements, ergonomics, standards and co-existence with other driver support systems) a scientific testing process.

*Address correspondence to this author at the Lund University, P.O. Box 118, SE-221 00 Lund, Sweden; Tel: +46 46 222 48 24; Fax: +46 46 12 32 72; E-mail: andras.varhelyi@tft.lth.se

Developing and testing of a system for the concept of "Safe Speed and Safe Distance" was carried out within the framework of SASPENCE, a subproject of the PReVENT integrated European project in 2006. The system aims to aid the driver in avoiding accident situations related to excessive speed or too small headway. The system is a driver support system - it suggests the proper speed for the given condition (road structure, traffic situation, frontal obstacles, etc.) for avoiding hazardous situations due to inappropriate speed or distance - but not a crash-warning system.

In a field experiment, exploring the effects of visual feedback on speeding [8], the display changed colour from green to amber whenever the speed limit was exceeded. When the speed limit was exceeded by more than 10% the colour changed to red with an additional auditory warning message "You are driving too fast, the local limit is …" and force-feedback was activated *via* the accelerator pedal. There was a reduction in speeding and speed variance and some drivers used the feedback to keep their speed within "limit to limit+10%" (amber). The display turned out to be the most acceptable system followed by haptic pedal feedback and auditory feedback.

In a series of simulator experiments [9-12], drivers were provided with visual and auditory messages when a speed violation was detected. The content of the message "You are driving too fast, the current speed limit is XX" was given by a female voice or text-projected on the simulator screen. Speeding decreased to the same extent with either modalities. The system was regarded as being positive in terms of usefulness, although satisfaction with the system was low among young drivers. Lahrmann *et al*. [13], testing a speed limit warning system, where the intervention consisted of a flashing red LED and a female voice saying, for example, "50, you are driving too fast", found positive effects on speed limit compliance.

May *et al*. [14] tested and compared visual distance warning to other HMI modes in a field experiment. Information on time headway (TH) was displayed to the driver in the form of a variable length bar, divided into three equal segments: top segment coloured red (indicating a TH of 0-1 s), middle coloured amber (1-2 s) and bottom segment coloured green (2 or more sec). When TH<1 second, a short, repeating, intermittent tone was emitted. The "bar-length" display was perceived as useful by the test drivers. Half of them found the tone distracting, but most agreed they would prefer some form of auditory feedback included in the system display. Dingus *et al*. [15] found that visual warnings were more effective than auditory warnings for improving car following behaviour. On the other hand, Janssen [16], in his review of earlier studies, reported that an auditory alarm kept drivers out of a critical "danger" zone most often when compared to a visual display or a force-feedback accelerator pedal. In a literature survey, Kuiken [17] also found that, given the already extensive demands on the driver's visual capacity, feedback should mainly be auditory (verbal) and tactile.

Groeger [18], testing a spoken warning message -"You are too close", when headway of 1 second or less was maintained for 0.5 seconds, concluded that the system was effective in encouraging drivers to adopt safer headways.

Experiments with haptic systems, such as the force-feedback accelerator pedal and the dead throttle (voluntary or mandatory), have demonstrated positive effects on speed behaviour in field trials [19-23] and in simulator studies [24-27].

Experiments with haptic feedback for short headway in a driving simulator showed that the force-feedback accelerator pedal with fixed duration force was clearly superior to the control situation with no driver support [28]. In a simulator study, Janssen and Nilsson [29] compared various driver interfaces with visual (red light), auditory or haptic (force-feedback accelerator pedal) for forward collision warning. All the modes reduced the incidence of very short headways, but only the force-feedback accelerator pedal was not associated with an increase in driving speed, an increase in acceleration and deceleration levels, or an increase in time spent in the left lane. Nilsson *et al*. [30], using a driving simulator, tested three collision avoidance systems, a constant force (30 N) of the accelerator pedal, a short vibration in the accelerator pedal (0.5 s at 10 Hz with amplitude of 20 N), and a vibrating accelerator pedal with automatic braking. The results indicated that the third system provided the most benefits, but drivers regarded it as the most intrusive and most disturbing. Kiefer *et al*. [31] tested a haptic alert for crash warning in the form of a brief brake pulse (about 600 ms), involving a brief vehicle jerk, with a peak deceleration of 0.24 g. Hoffman, *et al*. [32], in a simulator experiment, contrasted graded and imminent warning strategies with auditory and haptic warning modalities. Visual warnings were in the form of graded bars representing severity or an imminent collision icon, and paired with either an auditory warning or haptic warning, in the form of a vibrating seat. It was found that drivers preferred the graded or imminent haptic warning system to the auditory system. Tango and Bekiaris [33], testing a combined visual and auditory warning system for obstacles and dangerous situations, concluded that "two different levels of risk and provision of two levels of warning, one for cautionary and one for imminent risk" should be implemented. In an overview of previous research, Tijerina *et al*. [34] suggested that haptic displays (e.g., active accelerator pedal) and pulse-braking might be most appropriate for hazards that most likely require deceleration for their successful resolution.

These earlier studies proposed and tested a wide range of possible alternative HMI solutions for informing and warning the drivers of safe speed and distance to the vehicle ahead. Our study deals with the evaluation of driver reactions to a number of alternative information/warning modes of a multi modal system for the "Safe speed and safe distance" concept when driving in a driving simulator. The selection of the HMI alternatives was based on a pre-screening study of visual, auditory and haptic candidate alternatives [35].

AIM

This paper uses a driving simulator to evaluate the effects on driver behaviour and acceptance of the "Safe speed and safe distance" system. It also explores how different HMI alternatives for visual and haptic feedback influence the effects.

METHOD

The SASPENCE system

The SASPENCE system is an Advanced Driver Assistance System (ADAS) which assists the driver to drive at a safe speed (according to road and traffic conditions) and a safe distance to the vehicle ahead. The "Safe Speed and Safe Distance" function informs/warns the driver: a) when the car is too close to the front vehicle, b) when a collision is likely with an obstacle or vehicle due to a positive relative speed, c) when the speed is too high considering the road layout and d) when the car is exceeding the speed limit.

The system predicts the driver's behaviour and compares this with a reference manoeuvre based on traffic, weather, road layout, etc. [36]. When differences in driver behaviour and reference manoeuvre indicate danger, the SASPENCE system calculates an alarm level that corresponds to the risk of the situation and a warning is issued to the driver. There are two types of alarm levels: 1) Cautionary situation, related to excessive speed (e.g. for sharp curve or pedestrian crossing) or too short distance to the vehicle ahead, demanding increased alertness. 2) Imminent danger when an immediate action is required (e.g. a sharp curve approached too fast, or extremely short distance to the vehicle ahead). For a more detailed description of the system see [37, 38].

The HMI Alternatives

Visual, haptic and auditory modes were used to give information/warning to the drivers in the simulator trial.

Fig. (1). The two visual displays used, "v1" to the left and "v2" to the right.

Visual information/warnings were integrated on the dashboard of the simulator. The visual mode provided the driver with information/warning about the current speed limit (when the speed limit was exceeded), the recommended highest speed and the reason for the recommended highest speed. Two different displays were used for the recommended highest speed (see Fig. **1**). In the first visual alternative (v1) a red bar in the speedometer indicated the illegal speed zone and a yellow bar indicated further speed reduction recommended by the system. In the second visual alternative (v2) a sector in the speedometer indicated to what extent the driver needed to decrease his/her speed to comply with the recommended speed. A yellow sector indicated a cautionary warning and a red sector an imminent warning. When the driver's speed was below the recommended speed, a green sector between the SASPENCE minimum speed (30 km/h) and the driver's speed was displayed.

Table 1. The Haptic Warning Modes Tested in the Simulation Trial

Alt.	Safe Speed		Safe Distance	
	Cautionary Warning	**Imminent Danger Warning**	**Cautionary Warning**	**Imminent Danger Warning**
h1	Force Feedback in acc. pedal	High Pulsation in acc. pedal	Force Feedback in acc. pedal	High Pulsation in acc. pedal
h2	Pulsation in acc. pedal	High Pulsation in acc. pedal	Pulsation in acc. pedal	High Pulsation in acc. pedal
h3	Force feedback in acc. pedal + low seatbelt vibration	Force feedback in acc. pedal + high seatbelt vibration	Pulsation in acc. pedal	High Pulsation in acc. pedal
h4	Pulsation in acc. pedal	High Pulsation in acc. pedal	Low seatbelt vibration	High seatbelt vibration

Three types of haptic feedbacks were used: force feedback in the accelerator pedal, pulsation in the accelerator pedal and seatbelt vibration. The pulsation in the accelerator pedal and the seatbelt vibration were used with two different intensities. These three types were combined into four different haptic feedback alternatives (h1, h2, h3, h4) to give information/warning about safe speed and safe distance, see Table **1**.

The auditory mode was used for imminent danger from too short distance to the vehicle ahead. When the driver entered this situation a female voice said "Distance" (in French). If the driver did not increase the distance enough to exit the imminent danger warning, the message was repeated after one second of silence.

The four haptic feedback alternatives and the two visual display alternatives gave 8 HMI combinations to be tested, see Table **2**.

The Driving Simulator

The moving-base driving simulator SHERPA from PSA Peugeot Citroën – a semi-cabin of the Citroën C3 - was used in the tests [37].

Test Route and Scenarios

The test route consisted of motorway, rural roads and urban streets and included dangerous curves, pedestrian and railway crossings as well as critical weather conditions. Eight different scenarios where the driver could encounter the SASPENCE system were used during the test, see Table **3**. The test driver faced each scenario at least twice on each drive. The lengths of the circuits were between 27 and 32 km.

Table 2. The 8 HMI Combinations to be Tested

Number of HMI Combinations	Visual Alternative	Haptic Alternative	Auditory Warning
1	v1	h1	on
2	v2	h1	on
3	v1	h2	on
4	v2	h2	on
5	v1	h3	on
6	v2	h3	on
7	v1	h4	on
8	v2	h4	on

The Test Subjects

Thirty-four test drivers participated in the trial. They were recruited by the PSA research laboratory and were employees at the PSA research centre, but involved in activities other than ADAS. The age and gender of the participants can be seen in Table **4**.

Table 3. Scenarios Used During the Test Drives

Scenario Nr	Scenario Description	System Action
1	Normal driving, no obstacles appear	If speed limits are exceeded, visual warning is provided
2	Critical weather conditions (fog, ice, heavy rain, etc.), no obstacles appear	Information on safe speed is provided by visual and haptic warning
3	An obstacle appears ahead on the adjacent lane	No information or warnings are provided
4	An obstacle appears ahead on the ego-path without being dangerous	No information or warnings are provided
5	An obstacle appears ahead (the situation is potentially dangerous)	Warning is provided by visual and haptic channels. (Level 1)
6	An obstacle appears ahead suddenly (e.g. a cut-in vehicle)	Warning is provided by haptic and auditory channels. (Level 2)
7	An on-coming vehicle approaches on one-way road	Warning is provided by visual channel
8	The vehicle is approaching a particular site (railway and pedestrian crossing, etc.) at too high speed	Warning is provided by visual channel

Table 4. Age and Gender Distribution of Participants

	18-24	25-44	45+	Total
Men	5	20	5	30
Women	0	4	0	4
Total	5	24	5	34

Experimental Design

Each participant drove once without the SASPENCE system to allow registration of baseline driving data and twice with the system (rotated order of the subjects). When using the system the haptic feedback alternatives were rotated so that all the drivers used the two visual display alternatives and two of the four haptic modes, see Table **5**. The auditory mode was on in all the drives

Table 5. The Distribution of the Test Drives Over the Different HMI-Combinations

	Haptic 1	Haptic 2	Haptic 3	Haptic 4	Total
Visual 1	9	8	8	9	34
Visual 2	9	8	9	8	34
Total	18	16	17	17	68

Data Collection and Analysis

A large number of variables were logged at 20Hz during the test drives to study the behaviour of the driver (e.g. speed, acceleration, steering wheel angle) and to check the operation of the SASPENCE modules (e.g. recommended speed, alarm level, reason for alarm).

To understand the system's effect on driver behaviour, various parameters were analysed, such as driving speed, number of alarms, being in "unsafe state" and driver reaction time to warnings. The paired t-test was employed for analysing differences in mean driving speeds.

The distance to the car ahead would be an important variable to be analysed. Unfortunately, a software bug did not allow the alert to be conveyed to the driver when the headway was too short, and we were not able to analyse this variable.

Questionnaires were used to analyse the drivers' experiences of the SASPENCE system and the different HMI alternatives. Answers were elicited four times during the trial: before driving, after the baseline driving, after the first drive with one of the HMI alternatives and after the second drive with another HMI alternative. The questionnaires covered the following topics: experienced effects of the SASPENCE system, acceptance of the SASPENCE system and evaluation of the HMI alternatives. Most responses were elicited on continuous semantic bipolar scales, but unipolar continuous, ordinal and nominal scales were also used, as were open questions. When coding answers on continuous scales values from -5 to +5 (with 0 meaning neutral) were used for bipolar scales and from 0 to +10 for unipolar scales. A modified version of the method proposed by van der Laan *et al*. [39] was used to assess the drivers' opinions about the usefulness and satisfaction of the system and the different HMI alternatives. Originally, the questions were to be answered on a five graded bipolar scale, but a continuous scale was used instead. Workload assessment was made with a modified version of the raw task load index, RTLX [40]. The drivers stated their workload after baseline driving and after their first and second drive with the system. The change in workload when using the system was calculated as the difference between the assessments after baseline driving and after driving with the system.

The one-sample t-test was employed to assess statistical difference from the answer "neither" (neutral) in the analyses of test driver responses. In order to compare answers to different questions, t-tests were carried out. The Univariate analysis of variance, which was used to analyse the effects of the different HMI alternatives made it possible to evaluate how the different HMI alternatives and specific combinations thereof influenced the dependent variable. The driver id was used as a random factor in the analysis to control for the fact that not all drivers had driven all combinations. The model employed contained the haptic feedback, the visual feedback, the interaction between the haptic and the visual feedbacks and the driver id. The Pearson's Chi2-test was applied to study differences between groups with nominal variables. All the results are presented on a $p<0.10$ level of significance unless otherwise stated. The analysis of the open questions was through categorisation, and the analysis of opinions about the HMI alternatives or effects, depending on the HMI alternatives, included only drivers who were confronted with at least 5 warnings (speed and/or distance).

RESULTS

Driving Speed

Speed in Normal Conditions

The mean speeds and standard deviation of mean speeds in normal conditions on 13 sections are found in Table **6**. The mean speed when driving with the system was lower on 7 of the 13 sections studied, but the differences were not statistically significant ($p<0.05$) see Table **6**. The standard deviation of mean speeds was lower on 7 sections and higher on 6 sections when driving with the system.

Speed on Entering Curves

The mean speeds and standard deviation of mean speeds when entering sharp curves are shown in Table **7**. The mean speed when driving with the system was lower on 5 of the 9 sections, but the difference was statistically significant ($p<0.05$) on only one section. The standard deviation of mean speeds was lower on 6 of the 9 sections when driving with the system and higher on 3 sections, hence no difference in standard deviation could be established according to sign test.

Table 6. Mean Speeds and Standard Deviation of Mean Speeds in Normal Conditions when Driving with and without the SASPENCE System

Section Number	No. of Observations		Mean Speed (km/h)		Std. Dev. (km/h)		Difference in Mean Speed
	Without SASPENCE	With SASPENCE	Without SASPENCE	With SASPENCE	Without SASPENCE	With SASPENCE	
1	12	22	109.25	106.16	12.48	9.01	3.09
2	12	22	95.80	101.67	10.63	13.85	-5.87
3	12	22	89.47	82.24	19.24	19.47	7.23
4	12	22	133.26	132.72	14.03	11.17	0.55
5	10	21	84.77	89.07	15.62	16.88	-4.30
6	10	22	106.08	109.30	12.53	17.09	-3.22
7	10	22	95.73	97.51	14.87	15.79	-1.78
8	10	22	102.56	105.20	23.37	22.05	-2.64
9	10	21	101.69	97.33	21.66	18.88	4.36
10	10	23	121.64	125.11	7.29	12.83	-3.47
11	10	23	99.42	93.33	22.24	16.61	6.09
12	10	22	98.22	92.69	21.98	14.80	5.53
13	10	22	107.59	99.78	26.17	22.45	7.81

Table 7. Mean Speeds and Standard Deviation of Mean Speeds on Entering Sharp Curves when Driving with and without the SASPENCE System

Curve Radii (m)	No. of Observations		Mean Speed (km/h)		Std. Dev. (km/h		Difference in Mean Speed
	Without SASPENCE	With SASPENCE	Without SASPENCE	With SASPENCE	Without SASPENCE	With SASPENCE	
50	12	22	69.29	67.03	8.18	7.32	-2.26
100	12	22	80.3	77.86	9.95	9.30	-2.44
150	12	22	74.2	77.39	8.66	6.21	3.19
150	10	22	85.34	87.25	7.94	10.69	1.91
100	10	22	89.93	87.15	11.74	9.39	-2.78
50	10	21	73.28	67.63	6.67	7.69	-5.65
150	11	27	93.49	87.26	14.66	9.56	-6.23
100	11	26	86.26	87.17	8	10.16	0.91
50	10	27	70.82	76.82	9.75	19.84	6.00

Number of Alarms and Being in "Unsafe State"

One indication of hazardous driving behaviour is the number of times the driver caused an alarm to be raised. In Fig. (**2**), a scatter plot shows the influence of the specific HMI. The x-axis of the scatter plot shows the number of alarms detected by the system when driving without the HMI activated (SASPENCE off), while the y-axis shows the number of alarms with the HMI activated (SASPENCE on). A dot on the bisector means that the value does not differ between the two situations, a dot over the bisector means a greater value when feedback is activated and a dot under the bisector means that the presence of feedback from the system tends to lower the considered value. The average effect of the system is a slight increase in the number of alarms. The HMI alternative h1 gives the lowest increase, h3 a higher increase and h2 the highest.

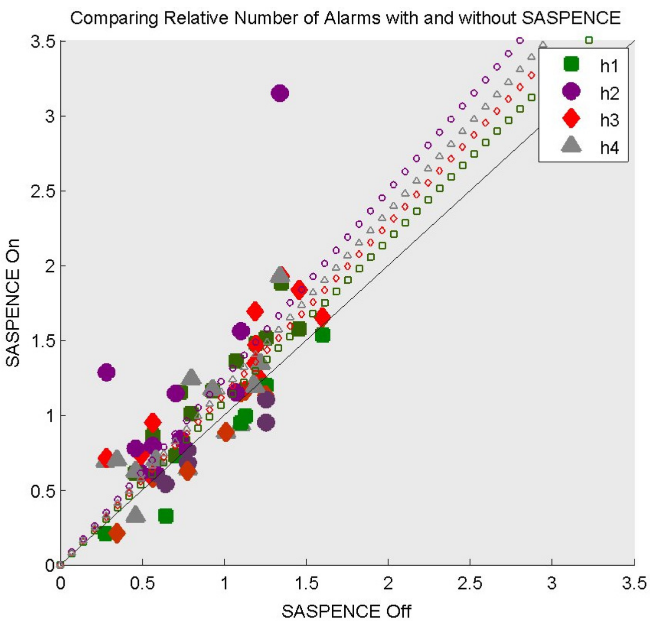

Fig. (2). Scatter plot of the number of alarms when driving with different haptic HMI alternatives.

Another indication of hazardous driving the time spent in unsafe situations, as proportion of total time. Alternative h3 gives a lower proportion of being in an unsafe state, while the other haptic displays tend to increase the time spent in unsafe state compared to driving without the system.

Driver Reaction Time

Fig. (**3**) shows the difference in the reactions of the driver to warnings by the different alternative HMIs. The time is shown on the x-axis (0 for alarm time) the median position of the throttle is shown (median with respect to all cases where the driver got an alarm) on the y-axis. It can be seen how the driver lowered his/her speed in a dangerous situation – but when the system is active the response was significantly quicker. The haptic alternative h3 caused the quickest response by the driver.

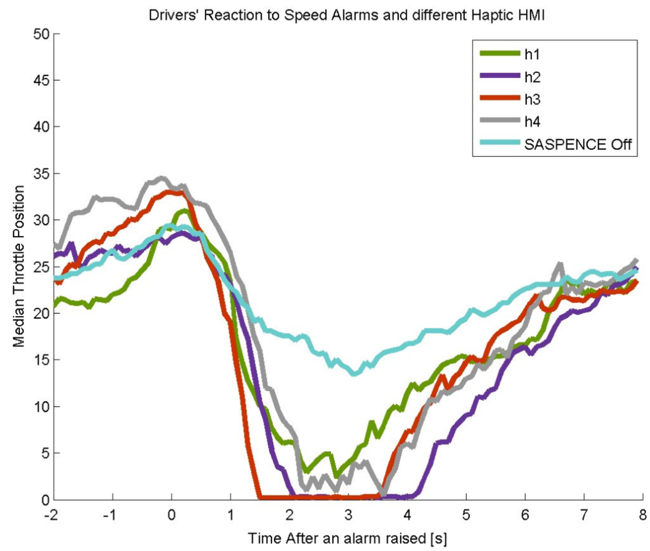

Fig. (3). Differences in reaction to warning by the different haptic alternatives.

TEST DRIVER'S OPINIONS ON THE SASPENCE SYSTEM

Acceptance

The drivers on average found the SASPENCE-functions "good" (see Fig. **4**). There were no statistically significant differences in opinions before and after using the system.

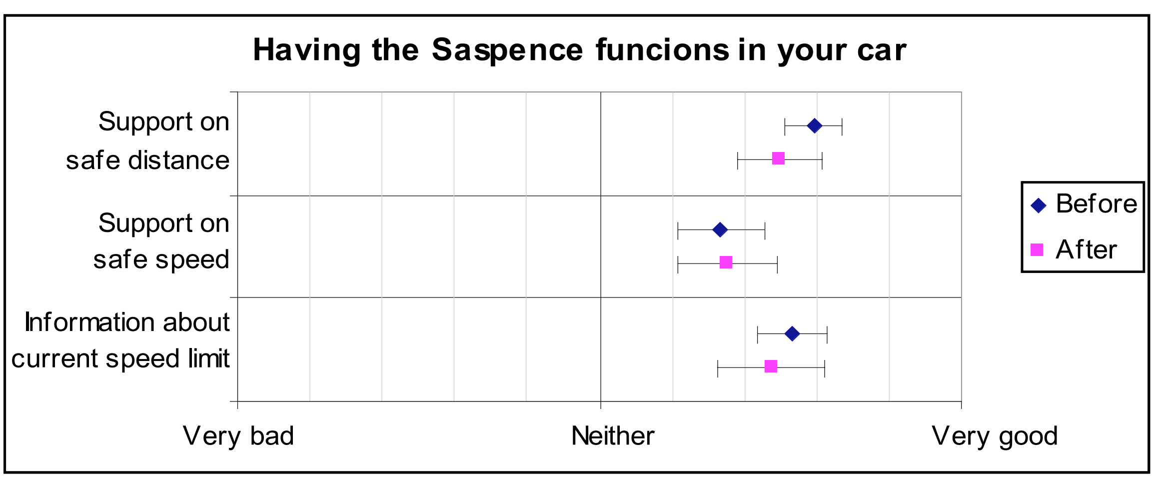

Fig. (4). The test drivers' opinion about having the SASPENCE-functions in their cars (mean and 90 percent confidence interval).

The support function for safe distance and speed limit information were on average rated as more desirable than the support on safe speed, although the difference between the support function for safe speed and speed limit information was not statistically significant after using the system. No statistically significant difference between opinions on support on safe distance and information about speed limits was found.

The benefits of using the system were, according to the test drivers, mostly related to increased traffic safety and reduced risk of getting speeding tickets (see Fig. **5**). After using the system the drivers thought that reduction of the risk of getting speeding tickets was less than they had thought before using the system. The benefits of reduced accident risk and reduced risk of getting speeding tickets were on average found to be larger than the benefit of more comfortable driving. Further, the increased comfort when driving was found to be a larger benefit than reduced fuel consumption. Reduced travel time was considered to be the least beneficial.

According to the "usefulness" and "satisfaction" assessment, in general, the system was perceived as "useful", "good", "effective", "assisting", "desirable" and "raising alertness". Compiling the comprehensive factors "usefulness" (including "useful", "good", "effective", "assisting" and "raising alertness") and "satisfactory" (including "pleasant", "nice", "likable" and "desirable") the system in general was believed to have a higher "usefulness" than "satisfaction".

The "usefulness" and "satisfaction" of the SASPENCE system were affected by the use of different haptic and visual alternatives (see Figs. **5**, **6**). Using the haptic feedback alternative h4 the SASPENCE system was found to be "annoying". Using the feedback alternative h2 resulted in positive ratings in all respects but "likable" and the feedback alternative h3 were rated positive in all respects except "pleasant" and "nice". Compiling the average score for "usefulness" and "satisfaction", all feedback alternatives resulted in a positive rating of the SASPENCE system for "usefulness" but only feedback alternatives h2 and h3 resulted in statistically significant positive scores for "satisfaction".

The visual feedback alternatives did not generally affect the drivers' opinion of the SASPENCE system (see Fig. **6**). However, the system was believed to "raise the alertness" more when using the visual feedback alternative v1 compared to using alternative v2 (mean difference: 0.9).

All the drivers stated they would accept the SASPENCE system if the system was installed in their cars free of charge. The majority (19 drivers) would accept a system that was both informative and advisory, while 9 drivers stated they would only accept it if it was informative and 6 drivers stated they would also accept an intervening system.

The willingness to pay for the SASPENCE system varied among the test drivers; from not paying at all (7 drivers) to paying between 500 and 750 €. Fourteen drivers were willing to pay up to 250 €, eleven drivers between 250 and 500 € and one driver between 500 and 750 €.

Concerning the individual HMI alternatives tested, for the safe speed support function the haptic feedback alternatives were in general assessed as "useful", "effective", "assisting" and "raising alertness" but also "unpleasant" and "annoying". The compiled scores showed that all haptic feedback alternatives were rated positively for the "usefulness" score while the feedback alternatives h3 and h4 were statistically significantly rated negatively on the "satisfactory" score (see Fig. **7**). The visual feedback for the safe speed support function was in general rated positively in all respects. No statistically significant differences among the visual feedback alternatives were found. The compiled scores of the visual feedback for the safe speed support function showed that both visual feedback alternatives were statistically significantly positively rated on the "satisfaction" score while only the alternative v1 was statistically significantly positively rated on the "usefulness" score (see Fig. **7**).

For safe distance warning, all the haptic feedback alternatives were considered to be "useful".

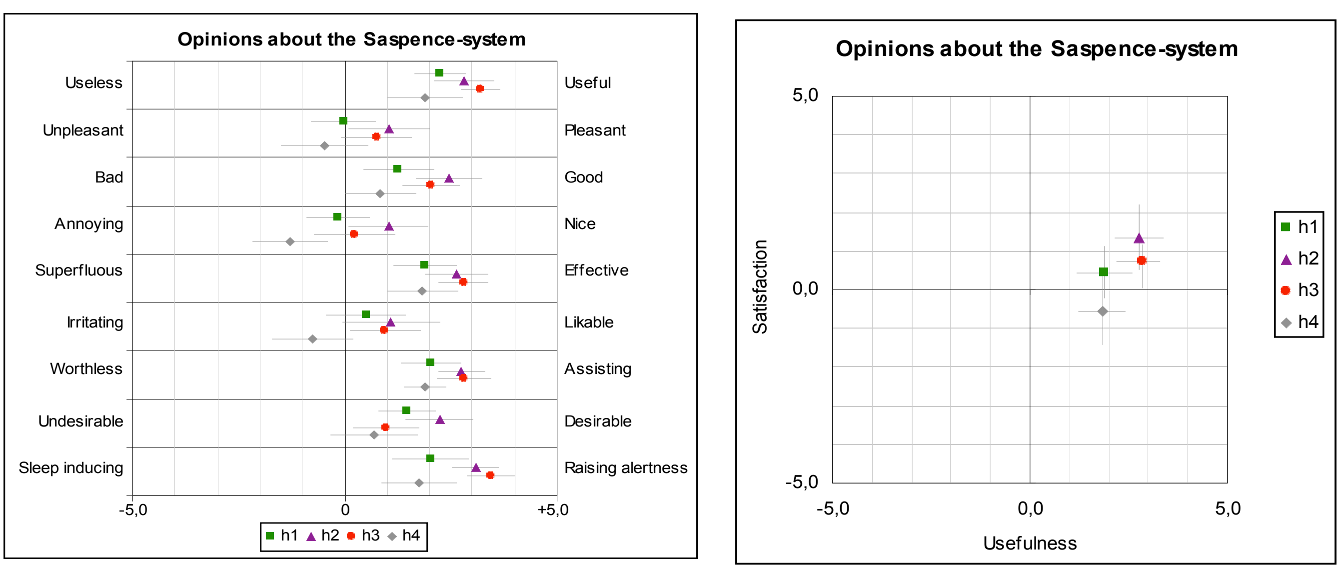

Fig. (5). Usefulness and satisfaction ratings of the SASPENCE system, depending on the haptic feedback alternatives used (90 percent confidence interval).

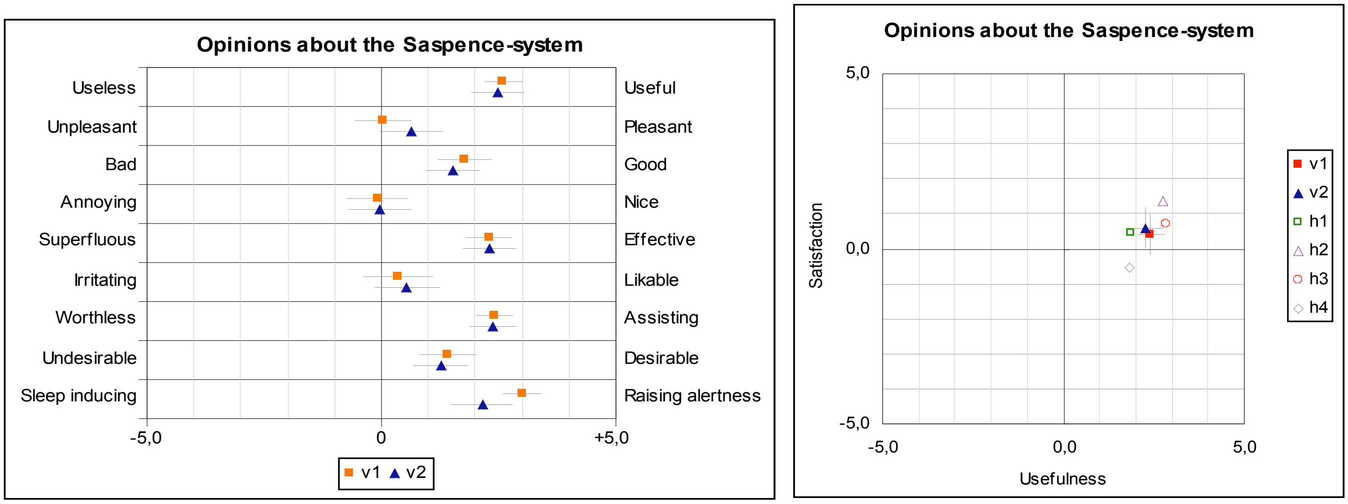

Fig. (6). Usefulness and satisfaction ratings of the SASPENCE system, depending on the visual feedback alternative used (mean and 90 percent confidence interval).

The compiled scores of the haptic feedback for safe distance warning showed that the feedback alternatives h1, h2 and h3 were statistically significantly positively rated on the "usefulness" score and that the alternative h4 was statistically significantly negatively rated on the "satisfactory" score (see Fig. **7**). The "satisfaction" score for alternative h1 was statistically significantly higher than the feedback for alternatives h3 and h4 and the score for alternative h2 was higher than for alternative h4. The visual feedback for the safe distance support function was in general rated positively in all aspects. The compiled score for the "usefulness" and "satisfaction" of the visual feedback for safe distance warning can be seen in Fig. (**7**).

The auditory feedback for safe distance support was rated neutral in general. The average scores were rated statistically significantly positive on the "usefulness" score, while no statistically significant effects could be shown for the "satisfaction score" (see Fig. **7**).

When choosing haptic feedback among the alternatives tested the most-liked feedback seemed to be the haptic feedback alternative h2 both for the safe speed and safe distance support functions. It was preferred by a majority of the drivers who tested this alternative. For the safe speed support function the haptic feedback alternatives h1 and h4 were preferred to feedback alternative h3, while no clear preference between the feedback alternatives h1 and h4 was found. For the safe distance warning function the haptic feedback alternative h1 was preferred to alternatives h3 and h4, and no clear preference between the alternatives h3 and h4 was found.

When choosing among the haptic feedback types (pulsating pedal, force-feedback pedal and vibrating seatbelt) providing warnings about appropriate speed, almost the same number of drivers chose the pulsating pedal and the force-feedback pedal (see Fig. **8**). For the safe distance support function, a majority preferred the force-feedback. The pref-

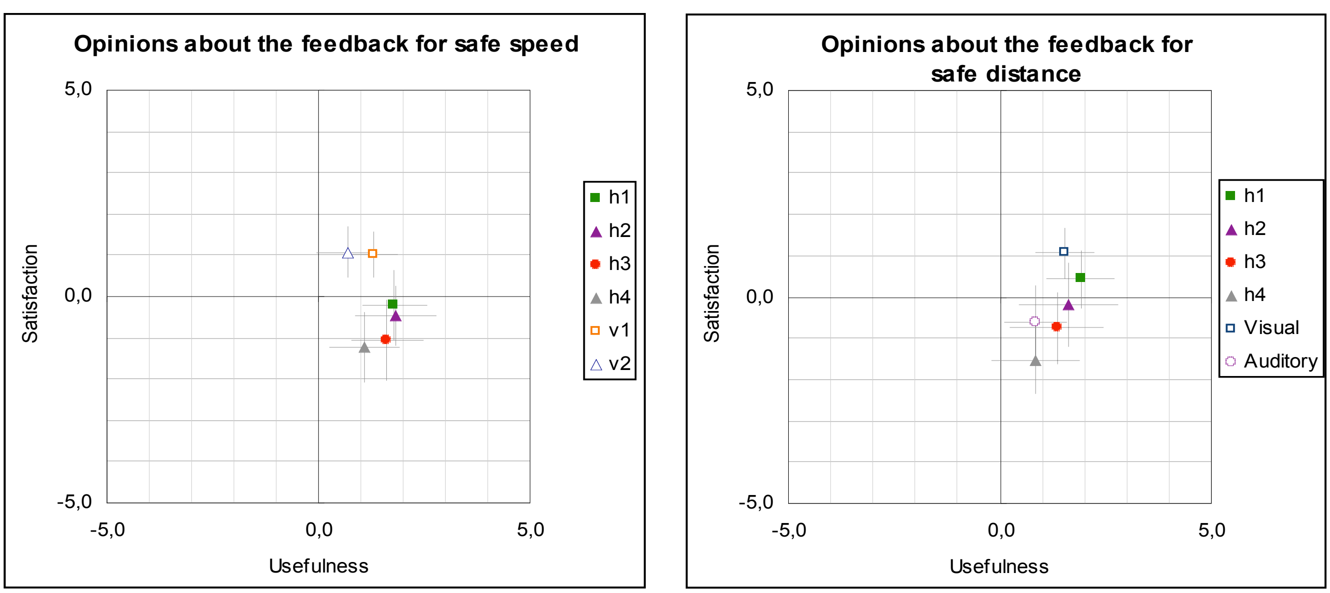

Fig. (7). The "usefulness" and "satisfaction" of the feedback alternatives concerning safe speed (left) and safe distance (right), (mean and 90 percent confidence interval).

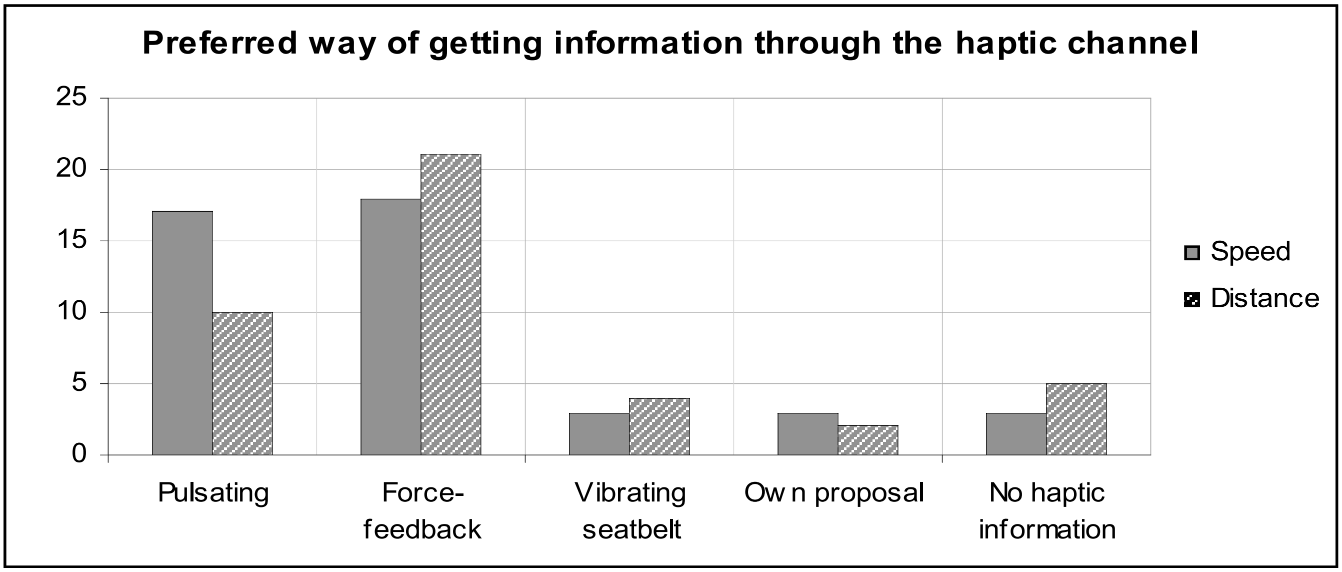

Fig. (8). Preferred way of getting information through the haptic channel (some drivers indicated equal preference for two principles, which is why the sum is more than 34).

erence for the vibrating seatbelt was lower. Three drivers put forward proposals for using different haptic systems for different types of warnings (no new haptic feedback alternatives were proposed by the test drivers).

If offered the option of the system in their cars, thirteen drivers wanted safe speed information continuously as long as they were in an unsafe state, ten drivers wanted the information in intervals and eight drivers just once. For distance warning, the preference was about equally distributed, "continuously" (11 drivers), in "intervals" (10 drivers) and "once" (10 drivers).

Fifteen drivers stated that they would like to have haptic feedback for speed limit warning. The most popular haptic feedback for this function was the force-feedback (8 drivers), while the pulsating pedal and the vibrating seatbelt were preferred by 3 and 2 drivers, respectively.

When choosing visual feedback for safe speed information, no clear preference could be found. Eleven drivers preferred the visual feedback alternative v1 and twelve preferred alternative v2 (no statistically significant differences between the two alternatives). Three drivers did not want any visual feedback for safe speed. Eight drivers proposed other alternatives.

When choosing visual feedback for safe distance warning the majority of the drivers (21) stated they would like the alternative used in the trial. Five drivers did not want any visual feedback about the safe distance. Seven drivers proposed other alternatives.

When choosing auditory feedback for safe distance warning, the majority of the drivers (19) did not want any auditory warning. Fourteen drivers stated they would like the auditory feedback they tested (spoken message: "distance") and two drivers stated other alternatives, both preferring a beep sound.

Emotional State

According to the test drivers, their emotional state was not generally affected by the system. However, there were tendencies indicating a decrease in driving enjoyment and an increase in "awareness". Although the emotional state in general was not affected by the system, the specific combination of HMI used had effects. When using the haptic feedback alternative h4, the drivers felt an increase in "irritation level" (compared to driving as "normal"), which was statistically significantly higher than when using the other three haptic feedback alternatives (mean differences between h4 and h1 0.9; h4 and h2 1.1; and h4 and h3 1.5). The same applied to the stress level (mean differences between h4 and h2 1.0; and h4 and h3 1.3). "Driving enjoyment" decreased in general, and the use of haptic feedback alternatives h1 and h3 did not result in a statistically significant decrease (see Fig. **9**). "Awareness" showed, in general, a tendency to increase when using the system, but this was not found to be statistically significant for the haptic feedback alternatives h1 and h3. When using the visual feedback alternative v1, the drivers felt a statistically significant increase in "the feeling of being in the way of other drivers".

Workload

The subjective workload was in general not affected by the use of the SASPENCE system. However, there was a tendency indicating an increase in "frustration level" (statistically significant when using the visual feedback alternative v2). Besides, a statistically significant increase in "physical demand" occurred when using the haptic feedback alternative h3 and an increase in effort when using the alternative h4 were found (see Fig. **10**). The "physical demand" when driving with the system was reported to be statistically significantly higher when using the feedback alternative h3 compared to the alternative h2. The system was also considered to result in higher "mental demand" and "physical

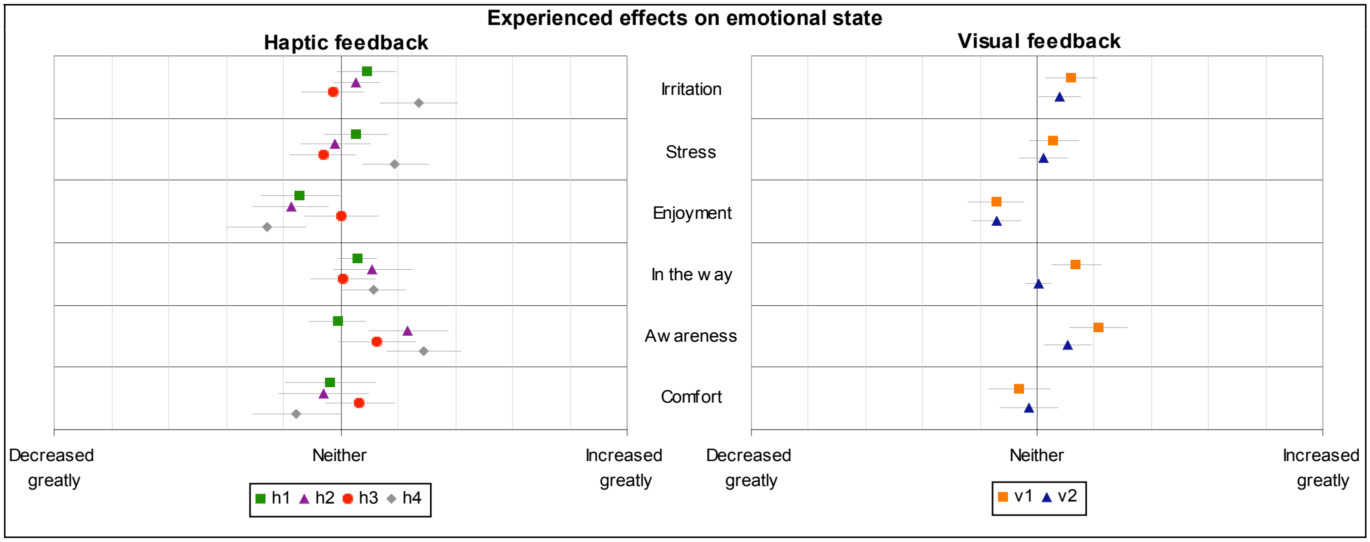

Fig. (9). Experienced effects on emotional state when driving with the different HMI alternatives of the SASPENCE system (mean and 90 percent confidence interval).

demand" when using the visual feedback alternative v2 compared to alternative v1.

DISCUSSION

The driving simulator experiments are a major step in the HMI design process of the SASPENCE system, since they provide information about the effects of the various HMI alternatives on driver behaviour and acceptance thereof.

The system did not affect the speed behaviour of the driver either in normal conditions or sharp curves. No statistically significant differences in mean speeds and standard deviation could be found. However, there was a tendency towards lower mean speeds and lower standard deviations when driving with the SASPENCE system. This tendency (although not statistically significant) points in the same direction as findings in earlier simulator experiments [9-12, 24-27] and field trials [8, 13, 19-23] where positive effects on speed behaviour were demonstrated.

The average number of alarms was slightly larger when driving with the system. The different haptic HMI alternatives caused different reactions. The HMI alternative h1 gave the lowest increase, h3 a higher increase and h2 the highest. This increase in the number of alarms might have been due to a novelty phenomenon and a wish from the driver to test the system: once he/she understands that this system works when there is short headway or high speed he/she might feel encouraged to go into hazardous situations. This effect could be due to delegation of responsibility.

The system improved driver-reaction time, which was indicated by the fact that the driver lowered his/her speed in a dangerous situation significantly quicker when the system was active. The haptic alternative h3 caused the quickest

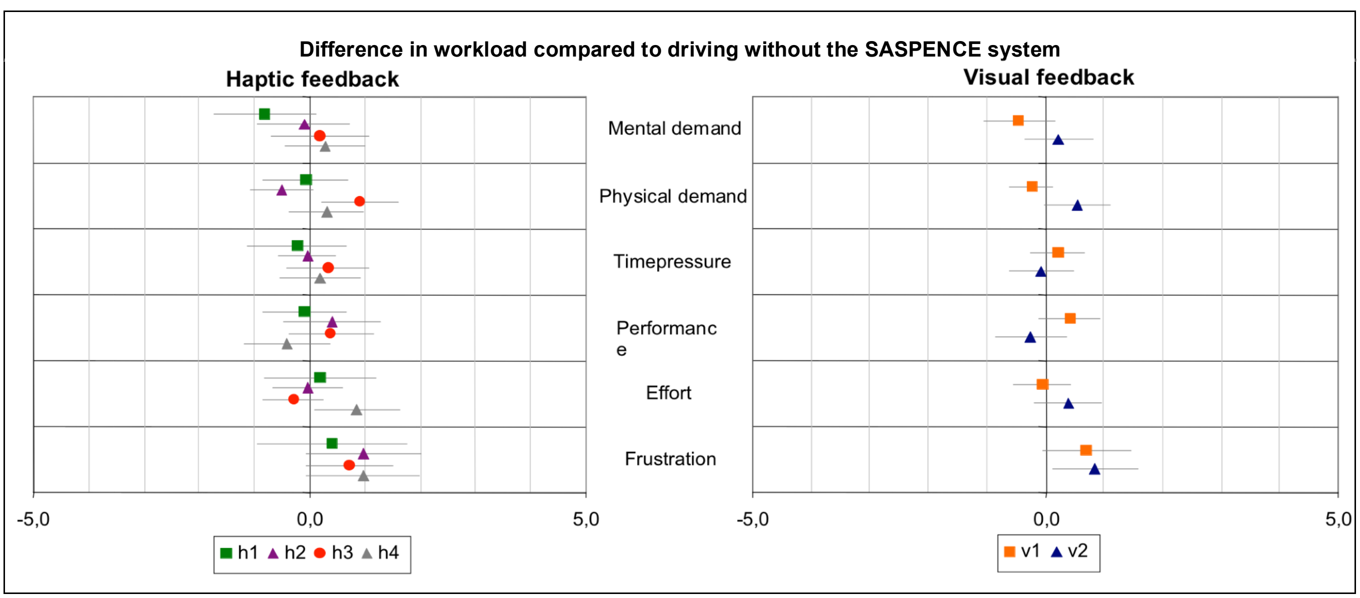

Fig. (10). Workload when driving with the different HMI alternatives of the SASPENCE system compared to driving without (mean and 90 percent confidence interval).

response. The HMI alternative h3 gave a lower proportion of the time spent in an unsafe state, while the other haptic displays tended to increase the time spent in an unsafe state compared to driving without the system.

The drivers' experiences showed that the SASPENCE-functions in general were rated as "good". The support function for safe distance and speed limit information were rated as more desirable than the support function for safe speed. The perceived benefits of using the system were mostly related to increased traffic safety and reduced risk of getting speeding tickets, although more comfortable driving could be a potential benefit from the system.

The system was considered to have a higher "usefulness" than "satisfaction". The most positive ratings of the SASPENCE system were given when the drivers used the HMI-alternatives h2 or h3, the worst with h4. All HMI-alternatives resulted in positive "usefulness" scores, while only the haptic alternatives h2 and h3 demonstrated positive "satisfaction" scores.

In general, the emotional state of the drivers was not affected by the SASPENCE system. However, different HMI-alternatives led to some differences in the assessment of the system. Using the haptic feedback h4, the drivers reported an increase in irritation and stress level and only alternative h3 seemed to leave the driving enjoyment unaffected, the other haptic alternatives were regarded as causing a decrease of driving enjoyment.

All the drivers stated they would accept the SASPENCE system if the system was installed in their cars free of charge. The majority would accept a system that was both informative and advisory, and some drivers would also accept an intervening system.

When evaluating the different HMI-alternatives used for appropriate speed, the results showed that all haptic feedbacks received positive ratings on the "usefulness" score and that the feedbacks h3 and h4 were rated negatively on the "satisfactory" score. The visual feedbacks both received positive satisfaction ratings and alternative v1 was also rated positively on the "usefulness" score.

The evaluation of HMI-alternatives for safe distance showed positive "usefulness" ratings for haptic alternatives h1, h2 and h3, while alternative h4 received negative ratings on the "satisfaction" score. The visual feedback used for safe distance received positive ratings on both the "usefulness" and "satisfaction" scores, while the auditory feedback only received a positive "usefulness" score.

The haptic feedback h2 was preferred by a majority of the drivers who tested this alternative, both for safe speed and safe distance. The least preferred haptic alternative seemed to be feedback h3 for safe speed and h3 and h4 for safe distance. For the visual feedback no clear preference was found for safe speed information, and the majority of the drivers accepted the visual information given for safe distance. Regarding the auditory warning for safe distance, the majority of the drivers did not want an auditory warning. That auditory feedback is less acceptable than, in particular, visual feedback is in line with earlier studies [8] showing that feedback through a display was most acceptable followed by haptic pedal feedback and auditory feedback. In this experiment, auditory feedback was only used for distance warning. This was based on findings from a related area, namely air transports, where aircraft pilots prefer an auditory warning if an immediate reaction is required (analogous to short distance to the car ahead on the road), but a visual warning when there is more time to react (analogous to speed choice on the road) [41].

The results show clearly that the combination of HMI-alternatives affected the drivers – otherwise the haptic HMI for speed h2 and h4, and for distance warning alternatives h2 and h3 would have received the same response from them. Further, the evaluation of the SASPENCE system showed that haptic alternative h3, followed by h2, resulted in the most positive evaluation of the system. However, when evaluating the HMI-alternatives per se, the most positive evaluation was given to h2 followed by h1. This highlights the importance of evaluating a system as a whole (with different HMI-alternatives) and not isolating the HMI-design from the use of the system. After all, the HMI serves to facilitate and enhance the use of the system and should not "live a life of its own".

The results also show clearly that the haptic alternatives used influenced the perception of the system more than the visual alternatives. This is not surprising, haptic feedback is generally seen as more intrusive than visual feedback and should therefore also influence the driver more. The vibrating seatbelt seemed to irritate a number of drivers whereas the active pedal seemed to be better accepted.

Based on the analysis of logged driving data it can be concluded that the most beneficial haptic display was alternative h3 (i.e. the combination of force feedback in the accelerator pedal and vibration in the seat belt for speed warning and pulsation in the accelerator pedal for distance warning). Based on the analysis of the drivers' experiences the haptic alternatives h3 and h2 (pulsation in the accelerator pedal for both safe speed and safe distance) resulted in the most positive ratings/experiences of the system. The explored visual information alternatives did not show any clear results and seemed to be less important to the drivers. Nevertheless, since the alternative v1 was received slightly more favourably, the recommendation is to proceed with this alternative, possibly with some modifications. The auditory feedback was not appreciated by the drivers. Since this modality may be omitted without negative consequences, it should be considered.

Hence, for further investigation of the safe speed and safe distance system in in-field studies in real traffic, the following combination of HMI solutions is recommended: haptic feedback through a combination of force feedback in the accelerator pedal, vibration in the seat belt for speed warning and pulsation in the accelerator pedal for distance warning; visual feedback in line with alternative 1 (possibly with some modifications) (see Fig. **1**); and no auditory feedback.

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