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Subliminal vibro-tactile based notification of CO2 economy while driving

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ABSTRACT

A general reduction of carbon dioxide emissions is an important topic currently discussed by both society and government – lower allowed emission values would strongly affect automotive manufacturers as road transport produces, for example, about one fifth of the CO_2 emissions in the European Union. But that's not all, also the individual driver could be affected from regulatory mechanisms as it is feasible, not least due to the broad availability of wireless and information technology in cars, to demand the assembly of a "personal carbon dioxide profile" including all the emissions accumulating from operating vehicles, traveling by plane, and even from using public transport, and in succession to charge a person based on its effective CO_2 consumption. One problem arising in this field is that an individual usually is not aware about his/her CO_2 consumption, neither about which means of transportation produces what amount of carbon dioxide (what is the personal fraction of CO_2 for a large plane with 250 passengers traveling $5,000km$?), nor how exactly to drive a vehicle economic or wasting with respect to CO_2 emission or what the difference between these two extreme values (in terms of cost) is. To counteract the issue of driving economy, which is the only the driver can directly control, we propose a inattentive operating vibro-tactile notification system integrated into the car (safety belt or seating), helping the driver in his/her (i) subjective CO_2 valuation and (ii) reduction of CO_2 emissions while driving.

Results from real driving experiments have shown that drivers tend to drive more economic with regard to carbon dioxide emission when perceiving tactile feedback about their current driving efficiency compared to baseline tests without technology assistance.

Categories and Subject Descriptors

H [**Information Systems**]: H.5 Information Interfaces and Presentation—*H.5.2 User Interfaces*; H [**Information Systems**]: H.1 Models and Principles—*H.1.2 User-Machine Systems*; B [**Hardware**]: B.4 Input/Output and Data Communications—*B.4.2 Input/Output Devices*

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Keywords

Subliminal driver notification, Ambient intelligence, CO_2 efficient driving, Vibro-tactile information, Safety belt interface, Tactile driver seat, Assistive technology

1. INTRODUCTION

The trend for fuel-saving vehicles, and with that the meet of lower exhaust emission standards, can be observed in automotive exhibitions all over the world. The new releases of almost all big car manufacturers, presented for instance at the Frankfurt trade fair (IAA) in 2009, revealed that the central focus of interest was directed – for trade visitors, policy makers, press, and normal guests – to the display stands of midget and small cars with low fuel consumption. The market launch of this new generation of so-called "green cars" is not only running costs driven, but to a greater extent determined by societal and governmental demand for fuel efficiency, which directly translates into lower CO_2 emissions. The European Commission, for instance, has enacted a regulation for new cars sold in the EU-27 to reach the $120g\ CO_2/km$ target on average emissions by 2012 (IP/07/155, February 7, 2007), a reduction of around 25% from 2007 levels. The main reason for this regulation is that the improvements in vehicle technology over recent years have not been enough to neutralize the effect of increases in traffic and car size (while the EU-25 reduced overall emissions of greenhouse gases by almost 5% between 1990 and 2004, CO_2 emissions from road transport rose by 26%) [10].

Fuel efficient driving would also save carbon dioxide output (direct correlation of measures), thus supporting the requested goal (Saito [29] has already shown that driving economically is a feasible approach to reduce CO_2 emissions). A stronger personal constraint to submit to this attempt could be demanded when compiling and charging the individual based on his/her aggregated CO_2 wastage. A system determining the CO_2 emissions from the personal car use is imaginable similar to a system proposed by Coroama [6] as the "Smart Tachograph" and calculating a personal insurance rate on a driven kilometer basis. Nevertheless, almost no driver is aware about the carbon dioxide emissions produced by his/her car (this ignorance has also been reinforced in the post-experiment questionnaire completed by each subject) while most of them can assess the fuel consumption in liters per 100 kilometer. This is somehow surprising as it is mandatory for car manufacturers in Europe since more than 10 years to release both vehicle fuel consumption and CO_2 emission information for new cars [12].

Displays Supporting Economic Driving

The current generation of cars provide some indication of fuel consumption, either as (*i*) green (efficient driving) or red (wasting fuel/energy) lamp, (*ii*) analog fuel consumption meter like a common speed indicator, (*iii*) digital value representing the mean fuel consumption per $100km$ or since last refill or (*iv*) as an arrow guiding the driver to change up or down in order to reduce fuel consumption [17]. In general, these notification types provide not a very detailed indication of CO_2 efficiency. The greater problem, however, is, that the driving process is highly visual [25] and fuel consumption indication systems also are highly visual and it is evidenced that too much (visual) information at the same time can lead to distractions by overstraining a driver's cognitive capabilities. There is a considerable body of scientific evidence that driver distraction is a major problem in terms of road safety [36, p. 20]. From an evaluation of more than 250,000 crash records, Wierwille and Tijerina [38] reported that driver distraction based on problems with visual allocation and/or workload accounts for a significant proportion of road accidents.

Unemployed Information Reception Capacity

For drivers operating a vehicle today it is common to carry out multiple tasks and activities, and to interact with several devices and/or applications simultaneously, and all in addition to the main activity of driving. For the automotive domain it is agreed [18], [27, p. 9] to classify the entirety of activities into the three task classes (*i*) primary tasks (driving related, e. g. braking, changing gears, checking the distance to cars ahead), (*ii*) secondary tasks (car status functions, e. g. adjusting the navigation system, using safety systems), and (*iii*) tertiary tasks (comfort and communication, e. g. infotainment and entertainment functions such as operating car stereo, checking E-mails, web browsing).

Independent from a later assignment to one of these three categories, a successful transmission of additional information, followed by correct user perception of the same, could only be guaranteed on utilizing unused capacity. Thereby, the modalities vision, hearing, touch, or other channels could be employed; as the former three accounts for almost 99% of human's information processing capacity [41], others will be left out in our further considerations. Additionally, it has to be revealed that the amount of "free space" is dynamically changing and dependent from the current driving situation – there is no guarantee for free capacity at all. Since there is no guarantee, the potential need of a certain capacity for delivering information on CO_2 efficiency without cognitive overload must be ensured in another way, e. g. by using subliminal/subconscious information transmission.

Sensory modality selection criteria. In principle, any of the (three) available sensory modalities could be used for delivering information, for example on CO_2 efficiency, to the driver. Supplementary to the information on *visual displays* provided above, it has to be taken into account that with the emergence of head-up displays (HUD) a viable alternative for information delivery was created [39], [4]. It is evidenced that information presentation via a head-up display results in reduced workload and decreased response times [23]. (Since drivers can receive information without taking their eyes off the road, distraction is estimated to decrease as the driver is still primarily focused on the traffic scene, not, e. g., the dashboard instruments.) Unfortunately, the optical system that projects the information is complicated and its light efficiency is currently low (usage of HUD projectors in clear sun light is therefore a big issue) [1].

The adaptation of the *audio channel* in the car is supposed to be sophisticated, e. g. due to several sound sources appearing at the same time (environmental noise, motor sound, voice instructions from navigation systems, "beeps" from a park distance control system, etc.). Furthermore, sound based feedback can quickly become annoying when disturbing other auditory activities like music or conversations [32, p. 131]. Past experience has also shown that drivers do not like to receive driving instructions from a voice command system [40] and that speech modalities in native or known languages have very high saliency – the latter might distract a driver's attention from the traffic in situations where attention to the traffic has top priority [2].

To overcome shortcomings associated with the use of the visual and auditory interfaces, *vibro-tactile interfaces* in cars have recently been introduced [30], [27, p. 62], [19], and are accredited to affect a driver's cognitive workload to a lesser degree compared to traditional channels of feedback [35]. [5] experimented with tactile signals for blind spot warning to compensate for sensory overload during driving – their results showed that the vibro-tactile feedback improved drivers' performance (e. g. for secondary tasks) over that attained by using the rear view mirror alone. The CAR2CAR consortium also suggested to apply haptic feedback for collision warnings, traffic optimization, access control, etc. [14].

In some vehicles such systems are already in production for several years; automobile manufacturer Citroen has been integrating a lane departure warning (LDW) system based on vibro-tactile notifications via the car seat since 2004 [21], [24, p. 34], Audi's recent collision warning system provided in the premium class informs the driver in case of collision risks with a warning jolt produced by the brake system[1], and BMW's LDW system alerts the driver to potential lane departure by providing tactile warnings through (binary) vibrations in the steering wheel[2].

Our research interest reported in this work is inferred from the before mentioned restrictions on the one, and follows latest achievements in vehicular technology on the other hand.

Outline. The rest of this paper is structured as follows. The next section discusses the general problem of indicating fuel consumption to the driver, defines some of the terms as used in this work, and declares in detail the research hypotheses followed in this work. Section 3 describes the setup of the experiment including the agreements made for the different control parameters and closes with a detailed insight into the execution of the field study. Section 4 evaluates recorded data and discusses the results. Furthermore, it includes an evaluation and interpretation of the post-experimental interview conducted on all test participants. Finally, section 5 concludes and summarizes the paper.

2. RESEARCH HYPOTHESES

Despite many cars (e. g. the Toyota Prius[3]) have a built-in feature showing current fuel consumption (which is is di-

[1] `http://www.audiworld.com/news/05/frankfurt/q7/content4.shtml`, retrieved Sept. 5, 2010.
[2] `http://mobileye.com/sites/mobileye.com/files/SVDO.ME.LDW.pdf`, retrieved Sept. 5, 2010.
[3] `http://www.toyota.com/prius-hybrid`, retrieved August 27, 2010.

rectly correlated to $C0_2$ emission) on a visual display, and there are also add-on devices showing fuel economy in real-time (e. g. ScanGauge II [20] or HKS' CAMP2 engine monitoring system [15]), drivers are in general not aware about their actual manner (efficiency) of driving. The reason for that is that these displays cannot be read due to (*i*) more important driving related information to be tracked, and (*ii*) the information carrier (green or red light bulbs, small-sized LCD displays, etc.) often prevents inattentive perception.

On this account, we propose a vibro-tactile feedback system integrated into the car seat (either in the safety belt or the seating), and notifying the driver in a subtle, subliminal way about his/her current CO_2 efficiency.

Definition of Terms

The aim pursued in this work was to deliver these notifications without demanding a driver's attention or "active awareness", thus ensuring a full information perception even in the case that there is no capacity left for transmitting accessorily information in a traditional way. Following earlier considerations by Egermann [8]("*..characterized by perception without awareness*"), Rosen [28] ("*..tendency to be influenced by stimuli presented below the level of conscious awareness*") or Merikle [22] ("*..situations in which unnoticed stimuli are perceived*") the term "subliminal perception" would be the best for describing this approach. In general, subliminal perception can be understood as stimuli that might be (*i*) inaudible to the conscious mind but hearable and interpretable to the subconscious mind, (*ii*) images transmitted so quick that they are perceived only subconsciously, or (*iii*) pressures or vibration patterns not sensible by our conscious psyche, but noticeable subconsciously. More precise, we have focused our experiments presented and discussed in this work on the latter option – subliminal notification using vibration patterns. (The somatic senses, in particular the sense of touch, operate all-over the body at all times, and integrating our experience of the outer world with that of ourselves [7].)

Though the terms "subliminal" and "subconscious" have a different meaning in cognition science (subliminal refers to a communication that is not intended to be understood consciously, but to influence thoughts, feelings, and/or behavior at the subconscious level and subconscious refers to processes that take place in the human mind of which we are not totally aware) they are used within this work in a interchangeable way, as both are, for the purpose of this work, similar enough, referring to the same basic effect namely *perception beneath the level of perception* or *not strong enough to be recognized explicitly*.

In this respect, we hypothesize that

(H.i) Subconscious (subliminal) notification of actual CO_2 efficiency using a vibro-tactile display installed into the car would help the driver to improve his/her subjective valuation of CO_2 (or fuel) efficiency, and in succession, to drive more economic.

(H.ii) The achieved result is independent from the selected setting (tactors either in the safety belt or the seating) when using two similar designed systems (Figure 1).

(H.iii) Different road segments or driving situations, such as driving intra-urban or on a motorway, or stucking in a traffic jam, can be derived from the run of the CO_2 emission curve as indicated in Figure 3.

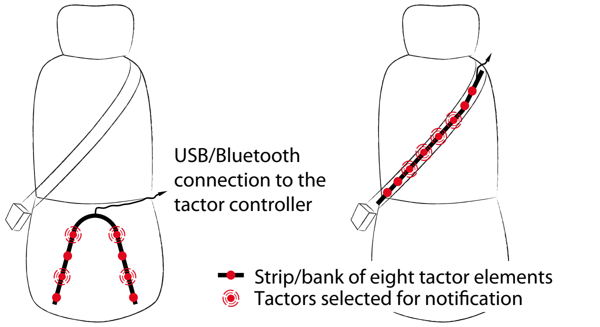

Figure 1: Sketch of the two applied settings (i) vibro-tactile seat and (ii) tactile safety belt.

At least ***(H.i)*** could be attributed good prospects, as it was reported, e. g. in [29], that decreasing CO_2 emissions can be achieved when accelerating the vehicle more moderate, thus requiring less "driving energy". Furthermore, they analyzed the history of engine rpm and load on the engine map while driving economical (defined by shifting-up at lower engine speeds and using higher load) and found out, that the engine operated more often in the range with highest thermal efficiency, which resulted in CO_2 emissions reduction. These findings were confirmed by the US Federal government, as they stated that the way you drive (aggressive vs. sensible) can affect fuel economy by up to 33%[4].

3. EXPERIMENTAL DESIGN

To prove our hypotheses we have developed a vibro-tactile stimulation system subtle notifying the driver about his/her current CO_2 emission compared to the mean value as specified in the cars' registration certificate.

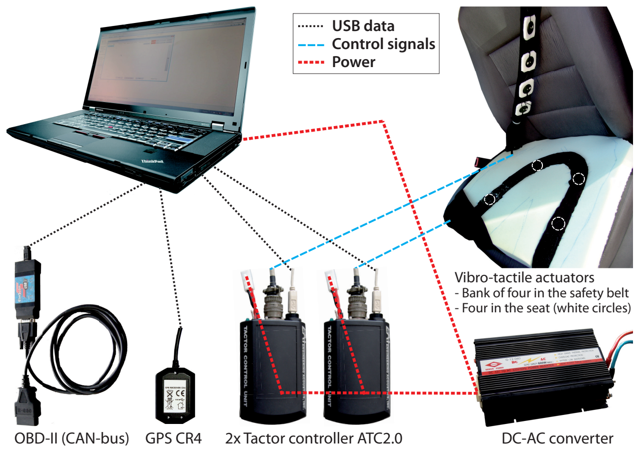

Figure 2: Overview of the hardware setting as utilized for the experimental studies. Both tactile interfaces kept installed all the time and independent from the setting actually activated in a test run.

The system is built up from (*i*) a sensing part for gathering vehicle specific data from the CAN-bus (ElmScan5 USB ELM327 OBD-II interface) as well as vehicle position data (CR4 GPS receiver), (*ii*) the developed processing software

[4] `http://www.fueleconomy.gov/feg/driveHabits.shtml`, retrieved August 25, 2010.

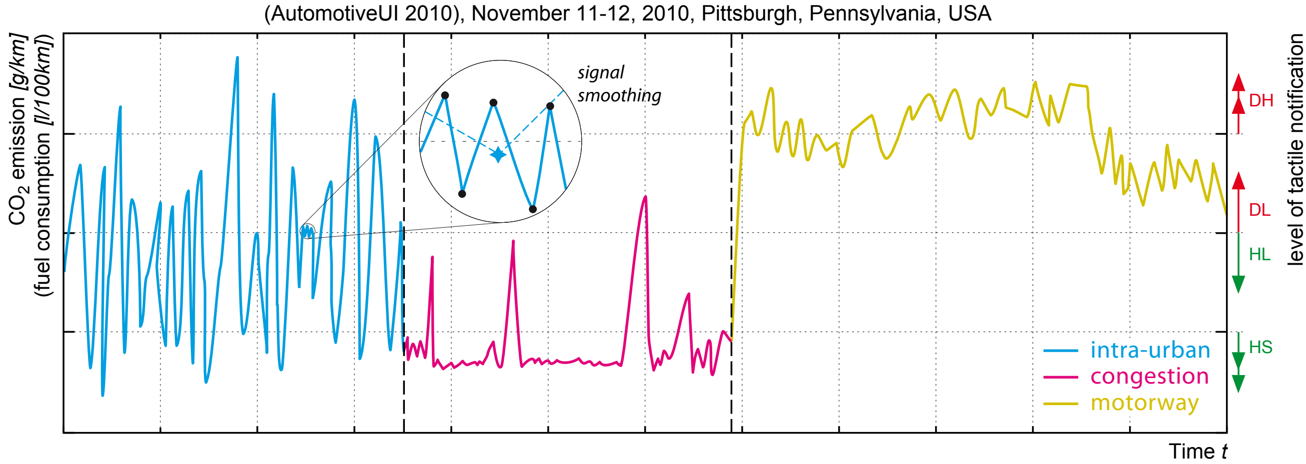

Figure 3: CO_2 emission (fuel consumption) while driving through different road segments (intra-urban with lots of gear shifting, congestion with stop-and-go traffic, motorway driven at rather constant speed).

(C#) running on a standard notebook computer, and (*iii*) the actuator subsystem for providing vibro-tactile feedback to the driver (two similar 8-channel tactor controller units ATC2.0 from EAI with connected C-2 actuators).

Missing standards. Unfortunately, todays application of tactile feedback in vehicles is adversely affected by the circumstance of still missing standards; contrariwise, a standardization of requirements for tactile signals for other domains has been passed years ago, e. g. EN 61310-1[11]. (This norm specifies requirements for visual, acoustic and tactile methods of indicating safety-related information at the human-machine interface. It specifies (i) warning signals intended for use in the indication of hazardous situations and (ii) ways of coding visual, acoustic and tactile signals for indicators and actuators to facilitate the safe use and monitoring of the machinery.) Standards defining general conditions of vibro-tactile driver stimulation would definitely lead to a broader application of tactile notification systems in cars, and the availability of (cheaper) components and assemblies to experience with new fields of utilization.

For this reason we determined the tactile patterns experimentally and based on our previous knowledge on tactile interfaces.

3.1 Estimation of CO2 Emission

Vehicle specific data are obtained in real-time from the CAN-bus using a OBD-II interface. Unfortunately, the utilized device does not provide a variable for determining the CO_2 emission directly. But as carbon dioxide (CO_2) is directly related to the fuel consumption it could be easily calculated. As CO_2 emission and fuel consumption are associated linearly one to the other, we use these two terms in the remainder of the paper in a interchangeable way when speaking from the effect of economically efficient driving.

In elaborate preparatory driving studies we have tested and optimized the algorithm finally used for tactile feedback, trimming the calculation function along the parameters (*i*) engine rpm (shown as x-axis in Figure 4) and (*ii*) pressure values obtained from (*a*) the mass air flow (MAF) sensor as well as with (*b*) the much more stable values from the throttle pedal position (range 0–100%) – as the latter is regarded as a coarse approximation of the former (y-axis). The experimentally determined static regions of different fuel consumption levels as indicated in the fuel consumption map (Figure 4) and used for selecting the different tactile stimulation patterns, can be described using quadratic regressions parametrized according to equations (1) to (3).

$$\text{QR1: } 2.0153 \times 10^{-5} \cdot x^2 - 0.0822 \cdot x + 114.5 \quad (1)$$

$$\text{QR2: } 4.5222 \times 10^{-5} \cdot x^2 - 0.1703 \cdot x + 214.0 \quad (2)$$

$$\text{QR3: } 8.8356 \times 10^{-5} \cdot x^2 - 0.3016 \cdot x + 350.1 \quad (3)$$

To increase system stability, particularly against outliers and during gear switching operations, the mean of the last three obtained fuel consumption values was used for feedback calculation. Although a low level of effective pressure (or a throttle pedal floored only to a small degree) corresponds to high fuel consumption, the region below a pressure of $2bar$ (or 20% of throttle pedal position) has been left out from vibro-tactile stimulation in order to avoid negative feedback, punishment or even driver confusion when driving at walking speed or on waiting times at traffic lights.

3.2 Human Factors

A important predetermination fixed before assembling the two variants of the feedback system was to use a similar setting with regard to (*i*) the number of tactors and (*ii*) their activation in order to ensure comparability.

Tactor Placement: Discrimination Threshold

The placement or distance of the vibro-tactile elements follows the values derived from the Weinstein Enhanced Sensory Test (WEST) conducted in 1968 [37], [16, p. 315]). After Weinstein, the minimal separation between two points needed to perceive them as separate (=*two-point threshold*) is 32–34mm on the chest (belly) and 41–43mm on the back. According to a recent study published by van Nes *et al.* [34] and conducted on a large scale, there is a significant age-dependent increase in the two point discrimination values while no significant gender difference was found. The latter corresponds to the measures of Weinstein [37] whereupon the two point touch threshold is almost the same for males and females. Following this result, the proposed tactile feedback systems could be used universally across males and females of all age groups when considering threshold distances clearly distinguishable also by the older.

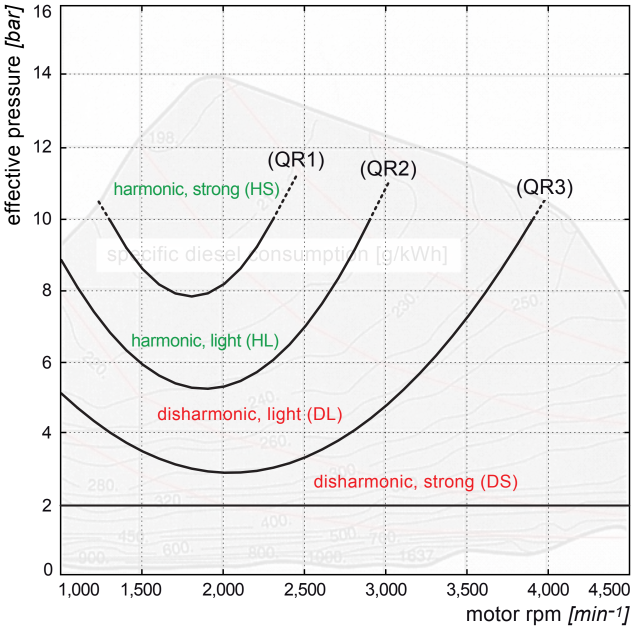

Figure 4: Quadratic regressions to distinguish between regions of different fuel (CO2) consumption. The underlying fuel consumption map corresponds to the car engine used in the experimental studies.

Considering the two point touch thresholds applicable for the seating ($43mm$), up to eleven tactor elements (4) could be embedded per dimension for optimal, non-redundant information transmission. On the other hand, the safety belt with its small width of about $50mm$ together with the discrimination threshold of $34mm$ would only allow a bank of tactile elements to be integrated (5). The contact length of the safety belt on the chest (from shoulder over chest to belly) is person dependent and in the area of 500–600mm; therefore a maximum number of about $500mm/34mm \approx 14$ tactors could be integrated (and discriminated). However, in preliminary studies we identified that the integration of a large number of tactors into the safety belt was felt unpleasant by most of our subjects and furthermore makes the same rather inflexible.

Following the predeterminations that tactile feedback should be perceived subconsciously, we found in an educated guess that the system to be integrated into the safety belt should be build up from not more than 8 actuators. Ensuring ease of installation we only used four tactors (in both seat and safety belt) in the applied setting – this low number poses no problems as all tactors are activated simultaneously and showing exactly the same information all the time (see Figure 1).

$$\frac{500mm \text{ [seat width]}}{43mm \text{ [threshold distance]}} = 11.63 \text{ [tactors]} \quad (4)$$

$$\frac{50mm \text{ [safety belt width]}}{34mm \text{ [threshold distance]}} = 1.47 \text{ [tactors]} \quad (5)$$

Mechanoreceptors and Stimulation Frequency

Humans can detect vibrations over a rather wide frequency range, from about $1Hz$ to $1,000Hz$ [27, p. 91], but they are not equally sensitive to frequencies over the whole range [16, p. 314]. Tactile perception in the human skin results from the added perception values of four types of mechanoreceptors, overlapping in their perception range [13], [27, p. 51]. Each of the mechanoreceptive systems consists of a receptor and an afferent neuron determining characteristics such as frequency range or adaptation rate.

For the application of vibration feedback in the here projected aim we suppose a vibro-tactile display to innervate that type of mechanoreceptor that (in order of importance) (i) adapt very quickly as it used in a real-time setting, (ii) is highly sensitive to vibrations as it is embedded in the seat cushion and has to override both attenuation from the foam material and vibrations induced from the vehicle motor or the roadbed, (iii) allows for point-like stimulation (high spatial resolution) as vibration elements are only, according to the two-point touch threshold, a few centimeters apart, and (iv) facilitates both stimulation with comfortable (*harmonic*) and annoying (*disharmonic*) vibrations to implement gratification and punishment strategies.

From (i) follows the application of Meissner or Pacinian corpuscles, requirement (ii) ranks Pacinian corpuscles first (highest vibration sensitivity in the range 50–220Hz), according to (iii) Merkel discs should be used, followed by Meissner and Pacinian corpuscles, the last requirement (iv) would only be fulfilled with Pacinian corpuscles as they mediate threshold for vibrations above $50Hz$ (vibrations at about $50Hz$ are used for releasing spasm of muscles and massage[5], and thus should be felt comfortable by any person; below around $15Hz$ vibrations are very light and can often be not detected and (unfeasible) slowly adapting responsiveness was revealed for such stimuli [33]). Pacinian corpuscles are the most suitable type of mechanoreceptor to fulfill the needs of the present experimental setting.

Tactile notification patterns. The current CO_2 emission level is, as described before, derived from the vehicle-specific measurements (OBD interface), the underlying fuel consumption map, and the quadratic regression functions. Vibro-tactile output for innervating Pacinian corpuscles is given, based on the determined level of CO_2 emission, as one of the patterns (6)–(9). The frequency of $50Hz$ for the harmonic feedback follows the thoughts above, the frequency attitude for disharmonic driver stimulation was determined experimentally where it turned out that a superimposition of the frequencies 137 and $145Hz$ (these values corresponds to basic data packets to be sent to the tactor controller) creates uncomfortable vibrations in a intensity like the harmonic ones). All the patterns were designed with respect to similar vibration strength to avoid “active adaptation” of a person’s driving behavior to get, for example, the *gentle* harmonic feedback instead of a *strong* disharmonic one.

$$\text{HS: } 50Hz, 500ms \text{ (on)}, 7,500ms \text{ (pause)} \quad (6)$$

$$\text{HL: } 50Hz, 500ms \text{ (on)}, 5,000ms \text{ (pause)} \quad (7)$$

$$\text{DL: } 137 + 145Hz, 500ms \text{ (on)}, 5,000ms \text{ (pause)} \quad (8)$$

$$\text{DS: } 137 + 145Hz, 500ms \text{ (on)}, 2,500ms \text{ (pause)} \quad (9)$$

3.3 Field Test

To prove our hypotheses of different CO_2 emissions while driving with and without assistive technology, real driving tests were conducted. The field study was carried out in

[5] http://www.energeta.ch/produkte/produkt_vibration_plate.htm, retrieved June 12, 2010.

Figure 5: Hardware setting as used for the experimental studies. The vibro-tactile seat and safety belt interface with protective covers partly opened (1) and all closed (2), test person sitting in the car with both types of interfaces attached (3), tactile controller and data processing notebook in the back seat (4).

May/June 2010 with 13 participants, all men with a valid driving license in the age range 22 to 29 years with on average $5,000$ to $15,000$ kilometers traveled per year (one person generally uses public transportation, and thus drives a car for less than $5,000km/year$, another one uses his car for more than $15,000km/year$). As it was already expected in an early stage of experiment design that tests will be conducted in real traffic, with other road users maybe affecting test participants in different ways, it was very important to ensure similar traffic conditions (volume of traffic, etc.) as good as possible. Taken this into account, we agreed to process the experiments on two consecutive Saturdays from 9AM to 6PM each.

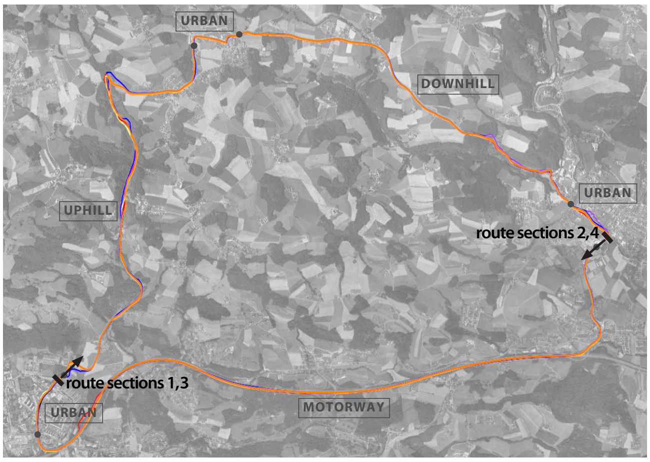

Figure 6: Circuit driven in the experiments with annotated regions. Colored, overlayed curves represent GPS tracks for several test persons.

Test persons were selected in order to exclude (*i*) age dependency for the perception of vibration stimuli (as stated above), and (*ii*) gender dependency for evidenced reaction time differences between female and male [27, pp. 228] as well as to ensure similar tactile perception of all actuators embedded into the safety belt. (The latter could be guaranteed if the safety belt lies flat on chest and belly, which actually would not be the case when having female drivers.) All test persons were students – not a single one was with our department – and received a 10 Euro petrol voucher as compensation for their effort of about 1 1/2 hours (net driving time of 43m:52s±02m:33s). Each test participant had to drive two rounds on a circuit course under real conditions and without a break in-between. The short briefing before departure addressed the following issues (*i*) the route to be driven (by help of a Google map printout; a navigation system has not been used), (*ii*) the possible appearance of vibrations via one of the two interfaces (no additional information was given, neither to the purpose of the interface nor to the meaning of vibrations), and (*iii*) the instruction to drive as natural as possible. Giving this information, drivers were not aware of the addressed research question.

Data evaluation later revealed to remove data sets from three attendees due to missing (recording of two data sets was interrupted for a while) or noisy (GPS trace for one test run was useless due to a covered GPS receiver) data so that the final analysis was conducted using records from ten test persons (five for the seat, five for the safety belt interface).

Route Specification

The route (see Figure 6) with a length of $24km$ was selected in order to cover as many as possible different road and driving conditions (rural road as well as urban area with $50km/h$ and $70km/h$ limits, highway with a maximum speed of $100km/h$, and motorway section with $130km/h$ speed limit) and segments to be driven with varying motor load (higher revolution speed and motor power uphill, constant motor load in urban and even sections, higher revolution plus motor brake downhill). The circuit, driven twice per test person, was further divided into two almost equal subsections, thus yielding in a total of four subsections. Each of these sections was driven once with, and the second time without technology assistance (=baseline) while the type of interface, seat or safety belt, was retained unchanged per test driver. The assignment of variation was made, according to Table 2, quasi-random before departure to ensure similar distribution over the small number of test persons.

For further improvement of the comparability of test results the following restriction has been taken into account at the time of experiment conduction. Both vibro-tactile feedback systems were installed in the car all the time; however, in order to reduce environmental factors to a minimum, vibro-tactile notifications were given – without test participants knowledge – only using one interface per day (vibration seat on the first, tactile safety belt on the second).

INPUT (OBD-II, GPS)						OUTPUT (ATC2)	
Engine rpm $[r/min]$	Vehicle Speed $[km/h]$	Air Flow Rate $[g/s]$	Throttle Position [0..100%]	Timestamp *date/time*	GPS Position *NMEA (WGS84)*	Fuel Consumption *[calculated]*	Tactile Pattern see Fig.3
2,666	118	44.10	16.5	Sat Jun 05 2010 11:26:35	$GPRMC,092635..	19.23	DS
2,645	117	26.50	15.3	Sat Jun 05 2010 11:26:36	$GPRMC,092636..	19.30	DS
2,629	116	30.20	18.4	Sat Jun 05 2010 11:26:37	$GPRMC,092637..	19.26	DS
...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
1,025	52	17.98	32.9	Sat Jun 05 2010 11:44:22	$GPRMC,094422..	4.03	HL

Table 1: Vehicle specific characteristics as scanned and processed in real time to generate tactile output corresponding to the current fuel consumption level.

Table 1 gives an overview of recorded and processed vehicle specific parameters (scanned in real time using a Elm-Scan5 USB ELM327 OBD-II interface and a CR4 GPS receiver) as well as the calculated fuel consumption rate and the generated tactile output (four tactile elements per system, each driven by a EAI ATC2.0 controller).

Tactile Setting	S1	S2	S3(=S1)	S4(=S2)
Seat Interface	VTS	VTS	–	–
Seat Interface	VTS	–	–	VTS
Seat Interface	–	VTS	VTS	–
Seat Interface	–	–	VTS	VTS
Safety Belt	VTS	VTS	–	–
Safety Belt	VTS	–	–	VTS
Safety Belt	–	VTS	VTS	–
Safety Belt	–	–	VTS	VTS

Table 2: All possible variation patterns for two rounds of driving and tactor activation in the two tactile settings (VTS... vibro-tactile stimulation).

4. EVALUATION AND DISCUSSION

The vehicle actually used for all of the experiments was an Audi A6 Avant, 1.9TDi with a engine performance of $81kW$. According to the car type certificate, the fuel consumption is on average (for mixed traffic) $6.5l/100km$. The actual consumption calculated for the conducted studies is given, for the entire experiment without preparatory studies (full refill before and after the experiments), in equation (10). A verification of the fuel consumption rate as derived from the scanned CAN bus data resulted in a quite similar value.

$$\frac{29.71l \cdot 100km}{464.20km} = 6.401l/100km \tag{10}$$

Compared to the mean value of $6.401l/100km$, the average fuel consumption for the different sub-experiments is $6.31l/100km$ for the baseline fraction and $6.22l/100km$ (98.6%) for vibro-tactile notification on fuel economy using the seat interface (day one), and $6.81l/100km$ for the baseline segment with $6.26l/100km$ (91.9%) when using the tactor elements in the safety belt (day two)(Figure 7, left image). The entire experiment was, as stated above, conducted on two Saturdays to ensure similar volume of traffic. All experiments using the seat interface were processed on the first day while experiments with the safety belt interface were conducted on the second day. This should guarantee comparability of segments driven with and without application of ambient technology, at least per interface type.

The large difference in the mean fuel consumption for the two baseline segments (which was expected to be constant) most likely results from changed environmental conditions. On the first day it was dry with scattered showers and outside temperatures in the range of 18 °C, while it was sunny and hot with temperatures near 30 °C on the second day. The air conditioning system of the car was turned off most the time on the first day but was heavily used on the second day (at least in the afternoon), and causing additional fuel consumption of up to 0.45–$0.62l/100km$ [31], [3, p. 64]. It cannot be substantiated whether or not a deactivated ACC would have caused an additional reduction of fuel consumption in case of stimulation via the safety belt on day two.

Fuel efficiency for the vibro-tactile seat interface. Assuming a normal distributed population and, for the general case, an unknown standard deviation s_d, we can apply bivariate, inductive data analysis using the (two-sided) Student's t-test [26] for verifying data sets against the null hypothesis H_0: "the mean of the two control samples X, Y is equal" (alternative hypothesis H_1: "the mean of the two control samples is different"). Sample X (n=5) corresponds to the aggregated CO_2 emission values for the vibro-tactile seat interface (system active); sample Y (n=5) corresponds to CO_2 values for the deactivated seat interface (baseline). According to the result gained in equation (12) ($\bar{d} = -0.09$, $s_d = 0.472$, $t = -0.4263$), the null hypothesis (assistive technology is without any effect) cannot be declined (5% level of significance). The unidirectional alternative hypothesis that subliminal vibro-tactile feedback reduces the amount of CO_2 emission is also not significant (at least not due to the small sample size of $n = 5$).

$$t_{(1-\alpha;n-1)} = t_{(0.95;4)} = 2.776 \tag{11}$$

$$|t| < t_{0.95;4} \Rightarrow 0.426 < 2.776 \tag{12}$$

Efficient driving initiated by the vibrating safety belt. The results for subliminal notification via the safety belt are quite different. X and Y samples as well as the stated null and alternative hypotheses are similar to the former case (seat interface), but now tested for the tactile interface embedded into the safety belt. The mean deviation of measurement values calculates to $\bar{d} = -0.55$, standard deviation follows to $s_d = 0.47$, and finally $t = -4.841$.

$$t_{(1-\alpha;n-1)} = t_{(0.99;4)} = 4.604 \tag{13}$$

$$|t| > t_{0.99;4} \Rightarrow 4.841 > 4.604 \tag{14}$$

From (14) follows that H_0 ("expected values of CO_2 emission with and without vibro-tactile feedback in the safety belt are equal") can be declined to a level of significance of

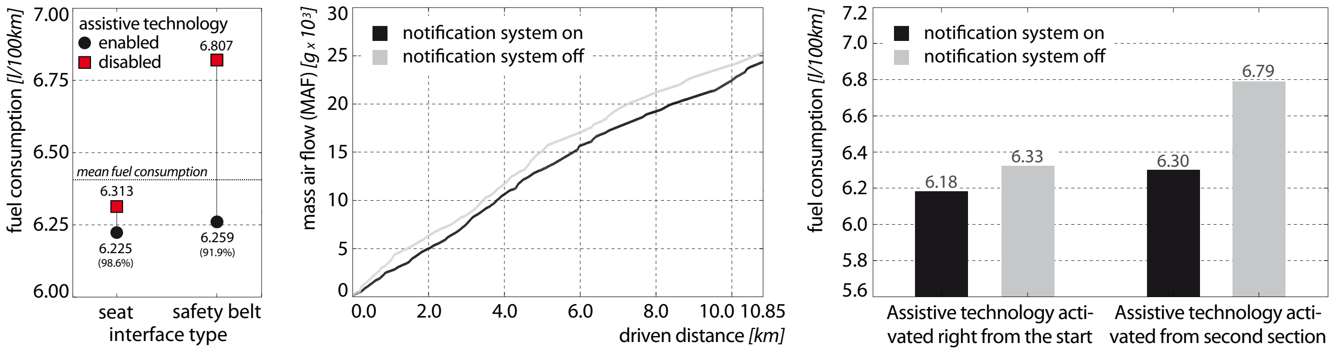

Figure 7: Differences in fuel consumption with and without assistive technology (left). Mass air flow (MAF) as an indicator for fuel consumption in relation to the driven distance (one driver, section one, safety belt interface) (center). Both lower variance and fuel consumption can be observed for early tactile feedback compared to an initially drive without assistive technology (right).

$\alpha = 0.01$. Furthermore, it follows that the unidirectional alternative H_1 ("subliminal notification reduces CO_2 emission") is significant.

Influence on Feedback Patterns and Placement Options

Harmonic versus disharmonic feedback. The two types of feedback patterns (gratification, punishment) have been established according to findings from related work and our own preparatory studies, and modified to met our requirements. Test drivers were not affected by the tactile feedback (neither by harmonic nor by disharmonic vibrations) as all of them assured in the post-experiment interview, therefore it can be assumed that they did not (actively) tried to alter their driving behavior e. g. to get the harmonic feedback or avoid punishment. Furthermore, we have found no evidence that a behavior change would have been caused due to the fact that the disharmonic feedback was stronger (according to the knowledge that people will drive slower if their car starts to rattle strongly, e. g. on increasing speed).

So far we have also no experience what the described tactile feedback (if any) would cause on longer runs. Questions like "*is the harmonic pattern still pleasant when experienced for several hours?*" or "*is disharmonic feedback ignored after some time of experience, e.g. due to a decreased perception threshold*" have still to be answered in further studies.

Different perception for seat and safety belt interface. According to the results as presented above the seat interface has less impact on CO_2 emission savings compared to the safety belt interface. Several reasons can be envisaged to account for this. From our own experience gained in the preparatory studies as well as from statements given by the test participants we discovered that vibrations delivered via the tactile interface in the seating tend to wear out rather quickly, while the tactors in the safety belt were clearly noticeable all time long. One reason for that could be the integration of tactors into the foam mat placed on top of the seat (see Figure 5) which attenuates vibrations so that they were felt not very strong even with maximum vibration amplitude. Another reason is the high susceptibility to other vibrations coming up from roadbed or the engine, and potentially having much higher vibration maxima. This effect is anticipated on the second interface mounted on the safety belt as this is placed orthogonal to the emerging vibrations.

Influence on the driving sequence. Figure 7 (right image) shows that the fuel consumption is lower for route sections driven with assistive technology compared to that driven without (dark gray against light gray). But the driving sequence also posed, different than expected, a distinction in the fuel consumption on route segment basis. It is lower when the technology was activated in the first segment (section 1, 3) compared to the tests were the tactile feedback system was activated in the second segments (sections 2, 4). Both trial groups were equal-sized; however, no empirical evidence has been achieved for this result.

Post-experiment Questionnaire

After each experiment test drivers were asked in open discussions about their assessment on driving economy as well as on their thoughts about fuel conserving driving. None of the test persons indicated the experimental setting as annoying or distracting and 100% stated that they were not impaired from the modified safety belt or the foam mat placed onto the seat pan. Two persons perceived no vibrations at all (consciously), another five explicitly stated that they have noticed vibration patterns (two persons on the seat, the rest via the safety belt) but without having any idea about their meaning. Of particular interest are the results obtained from the evaluation of the following questions.

Question 1: "In order to drive CO_2 emission efficient, at which engine rpm's would you change up/down?" (given the motor rotation speed ($1,900rpm$) for maximum engine torque of the car used in the experiments)
(*Answers: two values, one for changing up, the second for changing down*)

Question 2: "Which driving behavior is the most efficient to drive away from standstill (e. g. on a traffic light controlled crossing)?"
(*Answers: One or more cross marks at option A, B, C, or D as detailed in Figure 8*)

Question 3: "To what extent would you floor the throttle pedal in order to accelerate fuel or CO_2 efficient?"
(*Answer: Cross mark either at* 25%, 50%, 75%, *or* 100%)

The evaluation of the questionnaires (see Figure 8) produced the following results. *Question 1.* The variation for both changing up and down is with $1,000rpm$ rather high, allowing for the conclusion that test drivers' are not aware about

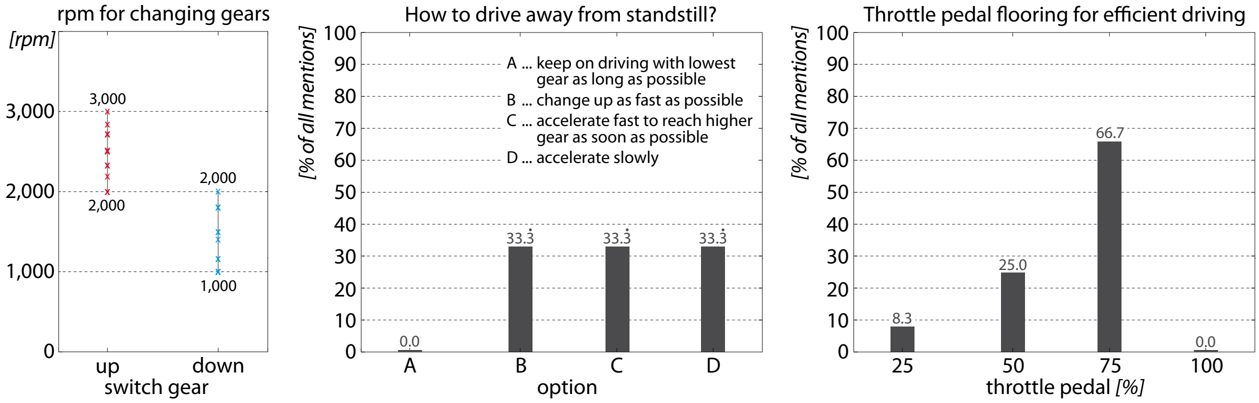

Figure 8: Evaluation of questions 1–3 from the post-experiment questionnaire (from left to right).

economic driving or at least have no idea on how to relate motor rpm with CO_2 emission. *Question 2.* Drivers' actually do not know which driving characteristic is CO_2 efficient (accelerate slow or fast, change up early or late); however, all the drivers suppose that driving with lower gears, which directly translates into higher motor rpm, is not the most efficient steering behavior. *Question 3.* The result (67% for flooring the pedal to an extent of 75% with no vote for 100%) gives a significant indication that participants believe that accelerating with maximum fuel injection would not be as efficient as speeding up with medium to high fuel injection with regard to fuel consumption or CO_2 emission (which, in fact, is not correct as, e. g., derivable from the fuel consumption map).

5. CONCLUSION

We have conducted real driving experiments with thirteen voluntary drivers to assess the applicability of ambient intelligence for subliminal (subconscious) driver notification on CO_2 efficient driving. Initial results, compiled from 464 driven kilometers, have revealed that the application of assistive technology for notifying the driver subliminally on the current carbon dioxide emission has the potential to reduce CO_2 emission by about 8%. Therewith, *H.i* can be accepted. The comparision of two types of vibro-tactile interfaces, one embedded into the seat, the second attached to the safety belt, showed that both types achieved fuel savings with higher possible savings obtained with the safety belt interface, which implicates a rejection of *H.ii*. One reason for this difference could be the higher sensitivity of the seat to superimposed vibrations evoked from the engine or roadbed [9] compared to the safety belt. With respect to *H.iii* we cannot – at this time – provide a statement whether or not to accept/reject the hypothesis because of too few kilometers driven (although the route was set to contain a multitude of different road segments).

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6. REFERENCES

[1] ArticlesBase. Advantages and Disadvantages of a "Head-up Display". online, article ID 132752, April 17, 2007. `www.articlesbase.com/technology-articles/`.

[2] N. O. Bernsen. Natural human-human-system interaction, 2001.

[3] H.-H. Braess and U. Seiffert, editors. *Vieweg Handbuch Kraftfahrzeugtechnik*. ATZ/MTZ-Fachbuch. Vieweg+Teubner Research, 5th edition, 2007. ISBN: 978-3-8348-0222-4.

[4] V. Charissis, S. Papanastasiou, and G. Vlachos. Interface development for early notification warning system: Full windshield head-up display case study. *Human-Computer Interaction. Interacting in Various Application Domains*, pages 683–692, 2009.

[5] A.-M. Corley. The Danger-Sensing Driver's Seat. *IEEE Spectrum*, 47(7):10–11(2), July 2010.

[6] V. Coroama. The Smart Tachograph – Individual Accounting of Traffic Costs and its Implications. In *Proceedings of Pervasive 2006*, pages 135–152, Dublin, Ireland, May 2006.

[7] R. Driscoll. *By the Light of the Body: Touch in the Visual Arts*, chapter 9: The Sense of Connection, page 12. in preparation, 2010. `http://www.rosalyndriscoll.com/downloads/chapter9_sense_of_connection.pdf`, retrieved August 28, 2010.

[8] H. Egermann, R. Kopiez, and C. Reuter. Is there an effect of subliminal messages in music on choice behavior? *Journal of Articles in Support of the Null Hypothesis*, 4(2), 2006.

[9] J. B. F. V. Erp. Vibro-Tactile Information Presentation in Automobiles. In *Proceedings of EuroHaptics 2001*, pages 99–104, TNO Human Factors, Department of Skilled Behaviour, P.O. Box 23, 3769 ZG Soesterberg, The Netherlands, 2001.

[10] European Commission. Commission plans legislative framework to ensure the EU meets its target for cutting CO2 emissions from cars. online, February 7, 2007. IP/07/155.

[11] European Committee for Standardization (CEN). EN 61310-1:2008 (Safety of machinery – Indication, marking and actuation – Part 1: Requirements for visual, auditory and tactile signals), 2008.

[12] European Communities. Directive 1999/94/EC relating to the availability of consumer information on fuel economy and CO2 emissions in respect of the marketing of new passenger cars. Official Journal of the European Community L 12/16, January 18, 2000. http://eur-lex.europa.eu/LexUriServ/site/en/oj/2000/l_012/l_01220000118en00160023.pdf, retrieved June 17, 2010.

[13] G. Fryer. *Distinguishing Characteristics of Thoracic Medial Paraspinal Structures Determined as Abnormal by Palpation*. PhD thesis, Victoria University, School Of Health Science, Faculty of Health, Engineering and Science, February 2007.

[14] Heyms et al. CAR 2 CAR Communication Consortium Manifesto: Overview of the C2C-CC System, Version 1.1. Technical report, August 28, 2007.

[15] HKS. Computerized Automobile Multi Player (CAMP2). online, retrieved August 25, 2010. http://www.hksusa.com/info/?id=3474.

[16] Jeremy M. Wolfe et al. *Sensation and Perception*. Sinauer Associates, Inc., 2nd edition, October 17 2008. ISBN: 978-0-87893-953-4.

[17] D. Kern, P. Holleis, and A. Schmidt. Reducing fuel consumption by providing in-situ feedback on the impact of current driving. In *Adjunct Proceedings of Ubicomp 2008, Seoul, Korea*, pages 18–19, 2008.

[18] D. Kern and A. Schmidt. Design space for driver-based automotive user interfaces. In *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '09)*, pages 3–10. ACM, 2009.

[19] J. Lee, H. Kim, Ryu, J., and J. Woo. Preliminary User Studies on Tactile Interface for Telematics Services. *IEEE Intelligent Transportation Systems Conference (ITSC 2007)*, pages 929–933, September 30 – October 3, 2007. ISBN: 978-1-4244-1396-6.

[20] Linear Logic LLC. ScanGauge II Automotive Computer. online, retrieved August 25, 2010. http://www.scangauge.com/.

[21] J. McCormick. Crash Avoidance Goes High-Tech. *Automotive Industries*, 184(11):36–39, November 2004.

[22] P. Merikle. *Encyclopedia of Psychology*, volume 7, chapter Subliminal Perception, pages 497–499. Ox, 2000.

[23] K. Nakamura, J. Inada, M. Kakizaki, T. Fujikawa, S. Kasiwada, H. Ando, and N. Kawahara. Windshield Display for Safe and Comfortable Driving. *SAE World Congress on Intelligent Vehicle Initiative (IVI) Technology 2005, Advanced Controls and Navigation Systems*, 2005.

[24] J. Noren. Warning systems design in a glass cockpit environment. Liu-iei-tek-a–08/00335–se, Department for Management and Engineering, University of Linköping, January 2008.

[25] B. Peacock and W. Karwowski, editors. *Automotive ergnomics*. Taylor and Francis, London, 1993. ISBN: 0748400052.

[26] G. Reiter and W. G. Matthäus. *Marktforschung und Datenanalyse mit EXCEL*. Oldenbourg Wissenschaftsverlag GmbH, 2000. ISBN: 3-486-25394-8.

[27] A. Riener. *Sensor-Actuator Supported Implicit Interaction in Driver Assistance Systems*. Vieweg+Teubner Research, Wiesbaden, Germany, 1st (January 14, 2010) edition, January 2010. ISBN-13: 978-3-8348-0963-6.

[28] D. L. Rosen and S. N. Singh. An investigation of subliminal embed effect on multiple measures of advertising effectiveness. *Psychology and Marketing*, 9(2):157–173, 1992.

[29] A. Saito, S. Ueki, Y. Nagatomi, N. Sawazu, and Y. Takada. Analysis of CO2 Reduction Mechanism by Eco-Driving with Light Duty Diesel Freight Vehicle in Real Traffic Conditions. In *Proceedings of SAE World Congress & Exhibition, Detroit, MI, USA*, April 2008.

[30] C. Tan, F. Delbressine, and M. Rauterberg. Vehicle seat design: state of the art and recent development. In *In Proceedings of World Engineering Congress (WEC07), Penang, Malaysia*, page 10, August 2007.

[31] Technik und Umwelt, Emmen. Klimaanlage im Auto – Luxus oder Sicherheit. Technical Report 3124, Touring Club Suisse, July 2005. pp. 3.

[32] M. Toennis, V. Broy, and G. Klinker. A Survey of Challenges Related to the Design of 3D User Interfaces for Car Drivers. In *Proceedings of the 3D User Interfaces (3DUI'06)*, pages 127–134, Washington, DC, USA, 2006. IEEE Computer Society.

[33] S. Toma and Y. Nakajima. Response characteristics of cutaneous mechanoreceptors to vibratory stimuli in human glabrous skin. *Neuroscience Letters*, 195(1):61–63, 1995.

[34] S. van Nes, C. Faber, R. Hamers, O. Harschnitz, M. Bakkers, M. Hermans, R. Meijer, P. van Doorn, and I. Merkies. Revising two-point discrimination assessment in normal aging and in patients with polyneuropathies. *Journal of Neurology, Neurosurgery & Psychiatry*, 79(7):832–834, 2008.

[35] A. Varhelyi. Speed management via in-car devices: effects, implications, perspectives. *Transportation*, 29(3):237–252, August 2002.

[36] B. Wallace. External-to-Vehicle Driver Distraction. Research report, Scottish Executive, Human Factors Analysts Ltd. (HFAL), August 1993. last modified March 31, 2006.

[37] S. Weinstein. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. Kenshalo, editor, *The skin senses*, pages 195–218, Springfield, IL, 1968.

[38] W. W. Wierwille and L. Tijerina. *Vision in Vehicles*, volume V, chapter An analysis of driving accident narratives as a means of determining problems caused by in-vehicle visual allocation and visual workload, pages 79–86. Elsevier Science B.V., 1996.

[39] M. Wittmann, M. Kiss, P. Gugg, A. Steffen, M. Fink, E. Pöppel, and H. Kamiya. Effects of display position of a visual in-vehicle task on simulated driving. *Applied Ergonomics*, 37(2):187–199, 2006.

[40] M. Wolf, A. Weimerskirch, and T. Wollinger. State of the art: Embedding security in vehicles. *EURASIP Journal on Embedded Systems*, 2007:16, 2007. Article ID 74706.

[41] M. Zimmermann. *Human physiology*, chapter The nervous system in the context of information theory, pages 166–173. Springer-Verlag Berlin, Germany, 2nd edition, 1989.