BENEFITS OF TACTILE WARNING AND ALERTING OF THE DRIVER THROUGH AN ACTIVE SEAT BELT SYSTEM

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Abstract

Research Question/Objective: Strengthening human ability to perform the driving task in emergency situations is a key ambition of vehicle design. This work aims to further improve driver reaction time by utilizing the tactile sensory channel in multi-modal warning concepts. A specific emphasis of the work is the evaluation of unique characteristics of tactile warning through an active seat belt system in contrast to other modalities.

Methods and Data Sources: Two complementary user studies were conducted by two independent research facilities with two dynamic driving simulators. With 87 participants in total there was the aim for statistical relevance of the measurements. The setup included alternative driver warning concepts for both drivers, during manual and assisted driving, and drivers engaged in another task during conditional driving automation. The tactile warning by the active seat belt system consisted of a series of retract pulses on low force levels. The assumption is that drivers will benefit from a high exclusivity of the modality in comparison to a tactile seat, steering wheel or pedal.

Results: In a first setup (manual driving, undistracted), the replacement of the acoustic/auditory warning by a tactile warning, when combined with a visual signal, resulted in an improvement of reaction time of 250 milliseconds for brake initiation. In a second setup (AD SAE Level 3) the driver took over vehicle control 1.0 second earlier with a combination of auditory, tactile and visual warning compared to a warning without vibrotactile alerting.

Discussion: Until now, only a few studies existed aimed to evaluate a tactile warning provided by a seat belt system. The work may support, within the limitations of these studies, the initial assumption that a seat belt system providing vibrotactile stimuli to the torso – specifically chest and shoulder – shows some unique benefits. The exclusivity of the sensory channel and a low interference with other signals in the vehicle lead to high degrees of detectability, discriminability, and intelligibility.

Limitations and outlook: Is the use of a tactile warning always positive, or what are effects of training or habituation? A differentiated semantic design of such tactile stimuli, the incorporation in escalating and multi-modal warning concepts, and the combination with a holistic occupant monitoring are seen as levers for improvement and subjects of further investigations.

Conclusion: This research has found that tactile warning of the driver, through an active seat belt system, can contribute significantly to improved warning effectiveness and can help to improve the driver's ability to react in vehicles equipped with Advanced Driver Assistance Systems (ADAS) and Automated Driving Systems (ADS). Functions like take-over request (TOR) or forward collision warning (FCW) may benefit by more robust alerting of the driver as part of the emergency warning procedure.

INTRODUCTION

Why is there an investigation of tactile warning and alerting through an Active Seat Belt system?

The ability for the vehicle to communicate to the driver and other passengers is one of the most active fields of automotive developments and a key lever for current brand differentiation.

In the context of occupant safety, the design of the vehicle's human machine interface (HMI) aims to contribute to safer driving by an enablement of the driver to fulfill the dynamic driving task. Well-performing HMI systems reduce unnecessary distraction and adapt to specific situations or driving modes. In-vehicle HMI systems help to build trust with other in-vehicle systems and raise the acceptance of safety features through relevant warnings and alerts [1]. On the other hand, HMI functionalities may cause distraction from the driving task by using infotainment features or through confusion of the driver by poor warning and alerting experiences.

With higher levels of driving automation, expectations to functionalities of the HMI raise as well, because the driver still needs to be involved and needs to interact with the vehicle in most cases. The presence of visual and auditory modalities across all levels of importance and urgency is developing. ADAS (ADS up to SAE Level 2) systems *help* to control the vehicle but don't cover the whole operational range. With ADS SAE Level 2 and below, drivers have the driving responsibility and therefore need to know such system limits, need to be aware of them in every moment of assisted driving and are to be prepared to *contribute* to vehicle control or *take it over*. ADAS systems require '*cooperative*' vehicle operation – driver *and* vehicle together. For flawless vehicle operation drivers need to perfectly anticipate and perceive the (limited) actions of the vehicle function and complete it with their own *contribution* – a complex operation requiring additional 'brain power'.

An ADS SAE Level 3 (AD L3) with conditional driving automation also has system limits. However, during an active AD L3 drivers do not contribute to the vehicle control. When reaching the system limit, a TOR will be sent to the driver. After a verified take-over process, the conditional driving automation ends, and the ride will be continued by manual control. This leads to an '*alternating*' vehicle control: either the vehicle function *or* the driver. During conditional driving automation drivers do not need any 'brain power' regarding vehicle control. However, in case of the automation system reaching its limits, they need to be prepared for a takeover process. Both *cooperative* and *alternating* vehicle operations challenge drivers with processes beyond unassisted driving in close interaction between human and machine. Thus, ADS functions are to be based on an effective communication. HMIs and warnings – as a crucial part of the communication between vehicle and driver – are safety relevant building blocks in today's vehicle design. HMI functionalities of ADS are subject to technical standards or regulations, and they are addressed by safety performance protocols of consumer rating organizations.

Amongst others tactile warning is being applied for vehicle safety systems – i.e., a force feedback of brake pedals when Electronic Stability Control (ESC) is in action or a vibrating steering wheel in the case of a Lane Departure Warning (LDW). In newer applications, vibrotactile features of the seat are used to provide driver warnings as well as for LDW but also for Park Distance Control (PDC) or other ADS functions.

TERMS

> **Tactile/Haptic**: Here, the term *tactile* describes the investigated solutions in a clearer way than only *haptic*, which is defined as *active* exploration of objects or surfaces
>
> **Automated driving systems (ADS)**: For ADS or Advanced Driver Assist Systems (ADAS) SAE J3016 [2] differentiates the six levels of driving automation. ADS interface with the in-vehicle infotainment (*IVI*) or in-car entertainment (*ICE*) to perform human machine communication
>
> **Alerting and Warning** are essential ADS features. *Alerting* can be defined as the notification or perception of an approaching danger. According to Ayres et al. [3] *warning* can be defined as 'any information that has the potential to change behavior and prevent accidents'
>
> **Warning Concept**: In this paper a *warning concept* is understood as HMI solution that first alerts drivers and second transmits warning information by using appropriate human sensory channels. Thus, as an example one warning concept could be '*auditory alerting*' combined with '*visual warning information*' and will be abbreviated in this text as '*A-V*'

BASIC PRINCIPLES

This work aims to contribute to the ongoing investigations of improved performance of the warning and alerting by an in-vehicle HMI. This paper outlines investigations if and how the tactile modality can support and improve the performance (effectiveness) of driver warnings. The specific context is safety-relevant communication and the utilization of tactile warning for ADS functions and related traffic scenarios.

Vehicle warnings are generated as an initiating process step for safe vehicle operation by the driver targeting a safe state in the vehicle. The situations in which warnings are to be processed by drivers are influenced by human factors.

Situations causing an emergency warning

Warnings are required in situations where the occurred or predicted problem is of safety-relevant importance and urgency. *Importance* describes the *relevance* for driving and safety, while *urgency* describes the *need* for action under the aspect of time. Driver *warnings* are rooted in both, importance and urgency, as e.g., in a forward collision warning (*FCW*). The situation is relevant for driving and safety (importance) and needs immediate driver action (urgency).

Driver mental state of mind and the need for alerting

Drivers are expected to always be prepared for every situation. However, drivers might be in a mental state affecting their 'readiness' to appropriately react on an emergency in a traffic situation. They might be *drowsy* instead of *wide awake*, *indifferent* instead of *attentive*, or *busy with a non-driving task (distracted)* instead of *focused on driving*. An inappropriate mental state may cause a dangerous traffic situation needing a warning, but also needs an *appropriate alerting* designed to *arouse* the driver.

What is emergency warning? A closer look to the process of warning and alerting

A detailed look to the warning and alerting procedure is shown by *Figure 1* and the discussion of three elementary steps is important for the design of an efficient emergency warning:

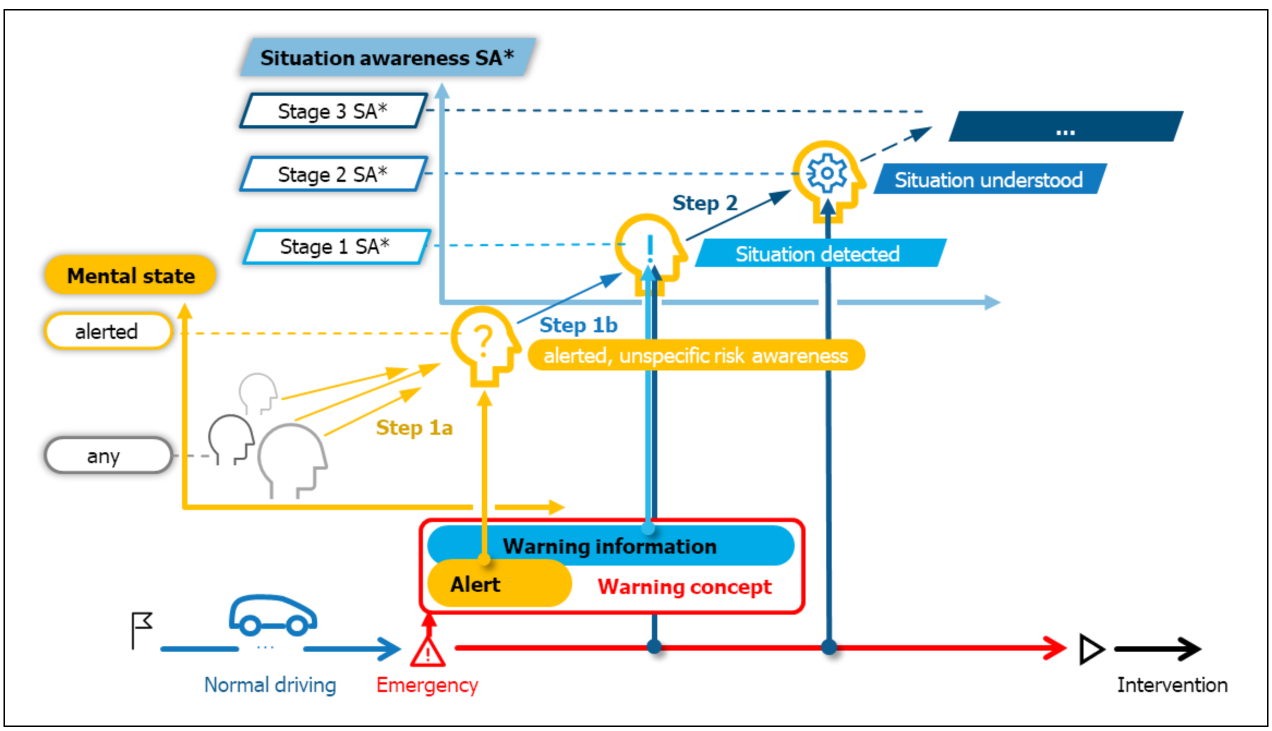


***Figure 1** Detailed steps of the warning and alerting process prior to intervention*
** with reference to Endsley's situation awareness (SA) concept* ***[4]***

Alerted/alarmed: Since drivers might be in mental states affecting cognition processes an alerting process is required as a first step (*Figure 1*, *'Step 1a'*) to ensure the following:

- an *aroused state* (awake, attentive, and focused) to enable processing of new information,
- an *unspecific risk awareness*, i.e., the perception that there is *any* safety-relevant situation needing his immediate intervention. With this perception the driver is *alerted/alarmed* – still not knowing the details of the emergency.

Situation Detected: In a following step (*Figure 1*, *'Step 1b'*) the alerted driver must detect the *specific threatening character* of the situation. For example, the driver detects that the vehicle ahead brakes suddenly.

Endsley [4] proposed a three-stage model of situation awareness (SA) with a 'Stage 1 SA' to *perceive* the situation, a 'Stage 2 SA' to *comprehend* and a 'Stage 3 SA' to *project* the situation into the future. The 'Steps 1a' and '1b' described in *Figure 1* are a closer look into Endsley's 'Stage 1 SA' resulting in the situation detection.

Situation understood: In 'Stage 2 SA' of Endsley's three-stage model the driver *comprehends* the significance and meaning of warning and situation. For example, the drivers understand that they need to brake immediately to avoid a collision (*Figure 1*, '*Step 2*').

The *stimulus* for 'Step1a' in *Figure 1* to create an *unspecific risk awareness* is labeled as an '*alert*' or '*alarm*' in this paper, depending on the level of *'criticality'* in the current situation. This stimulus does not need complex informational content. Its only purpose is to arouse the driver and to create an unspecific risk awareness. Therefore, main requirements are to be salient, short, and simple. An alarm tone in the event of an emergency is a good example. It shall be *salient* to penetrate the consciousness of a person and to be *noticed*. It also should be *crisp* and *simple* to be *quick*.

Creating *unspecific awareness* is not only a preparational step for *warnings* but used for other information transfers as well. Mobile devices, for example, create a notification sound accompanied with an incoming message. Some vehicles generate a soft gong sound, this causes the driver to look up more information on the instrument cluster or central display, e.g., in this case the fuel tank is at the reserve limit. Hence, a preparational signal to give notice of available information is an established *HMI concept* not only used in vehicles and not only for warnings.

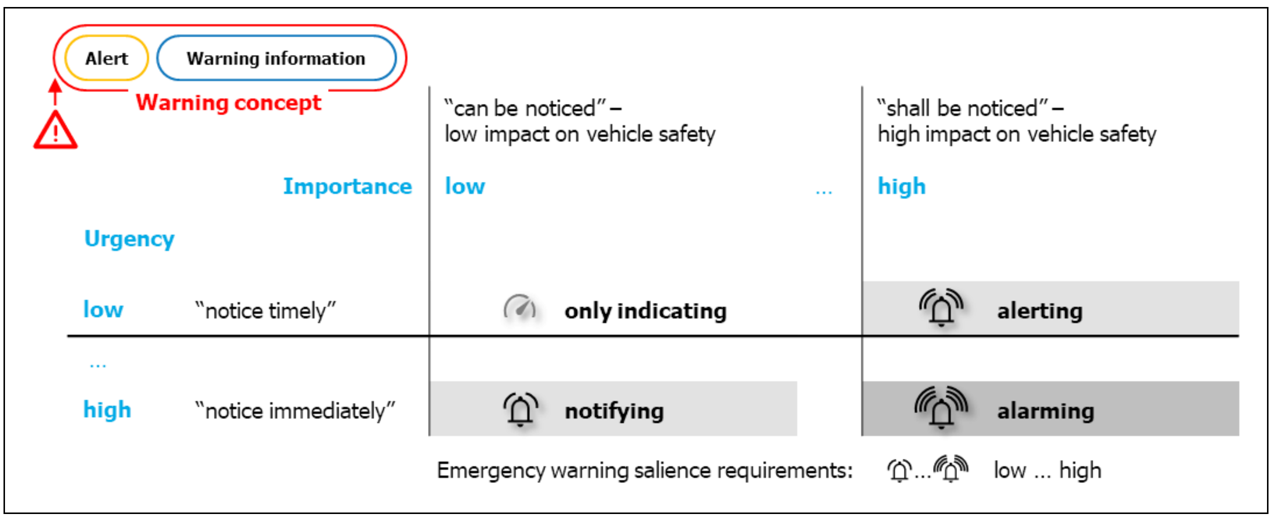


***Figure 2** Criticality of an emergency warning and salience requirements of alarming stimulus*

Therefore, when applying this concept in vehicles for *warnings* the related alerts/alarms must differentiate from notifications with less critical information. The stimulus for alerting or alarming must be *salient* but does not need to be pleasant or comfortable. Furthermore, since there are situations of different *criticalities*, it might be desirable to differentiate between lower and higher criticalities.

Figure 2 shows a proposal for alerting stimuli with a salience adapted to the criticality of the situation, as a preparational step to enable an ensured and efficient processing of warning information.

The criticality is driven by importance and urgency of a situation while '*importance*' describes the *relevance* for driving and safety and '*urgency*' describes the need for action under the aspect of time. Both, importance and urgency, might be low or high, by this creating a two-by-two matrix with different criticality levels as shown in *Figure 2*. If a situation is of low importance and low urgency a notification is not needed. In the case of a personal or general information as e.g., the exterior temperature '*notification*' – as a pleasant form of an alert – might be appropriate. In driving and safety relevant situations a salient alert would be justified and in case of a life-threatening situation an alarm is the strongest and most effective form of an alert that is required.

Aroused drivers are *prepared* for the following *cognitive* 'Step 1b' to *detect* the dangerous situation. As indicated in *Figure 1* there are two options to detect details of the emergency:

- by directly looking into the related direction (*Figure 1*, *red arrow*),
- or first, spotting the warning information (*Figure 1*, *blue arrow*) and then looking into the direction of the related critical situation (*Figure 1*, *red arrow*)

The first way – also described as 'bottom up' processing – may be faster since there are no additional cognitive processes being involved but requires that the driver immediately looks in the direction of the problem. The second way – 'top down' – needs processing time to redirect the gaze to the instrument cluster, detect the related warning information, understand the meaning of the symbol, redirect the gaze to the related dangerous situation and then detect it.

Which processing path is being used, strongly depends on the nature of the alerting stimuli and warning information received. Alerts of high salience are likely to trigger bottom-up processes whereas information enriched with expectancies and value are likely to trigger top-down processes [5].

In case of an *unspecific alerting stimulus* the driver is expected to direct his gaze in the driving direction allowing for the detection of critical situations as e.g., imminent forward collision or lane departure situations. In cases of *specific* emergencies *out of* the normal viewing area. E.g., a vehicle is in the blind spot, and it might be beneficial to alert the driver with a *specific* stimulus guiding his attention/gaze into the relevant direction. The flashing light of a Blind Spot Detection (*BSD*) system in the exterior mirror draws the driver's gaze to the side facilitating the driver to notice the vehicle nearby. An *alerting stimulus* works *intuitively* when the driver's attention is guided to the related critical situation and the driver can detect it. In this case additional *warning information* might not be necessary and the speed of situation detection is high.

However, drivers need further assistance in case they don't recognize the threatening situation immediately. Therefore, *specific threat warning information* helps show what might happen, e.g., a forward collision – but hopefully is not needed. Therefore, for fast and effective situation detection, the warning design should *explain* the character of the critical situation, e.g., an imminent forward collision. Warning information – usually visual symbols – should be clear and simple for rapid understanding.

However, alarms are limited to unique events with both, highest importance, and highest urgency, and are assumed to be very seldom. Therefore, training effects cannot be presupposed for alarms by this emphasizing the requirement for being intuitive.

Warning design requires sensory channel selection for both, alerting and informing, to create an effective (multi-) modal concept. The visual, auditory, and tactile modalities or any combination of them are eligible options. But to better understand the potentials of these options it needs a closer look into the nature of the three sensory channels.

MODALITIES FOR WARNING AND ALERTING

What are distinguishing characteristics of the relevant modalities?

Warning systems in today's vehicles mostly address those human modalities known for their high resolution and relevance for the driving task, hence, the visual and auditory modality. *Figure 3* outlines a qualitative assessment of the three modalities visual, auditory, and tactile in the context of this work.

The **visual sense** is switchable 'on/off' by the eyes, perceives the half space in gaze direction while recognition of detailed structures with complex informational content is restricted to a small area around the visual center. The visual sense has its limits to *alert/alarm* drivers, since drivers might not look in the direction of the alerting/alarming signal or have their eyes closed for a moment. However, *warning information* can be relayed very well, and contents can be displayed simultaneously. A reading process of several content elements usually follows a sequential order – influenced by their salience values.

Furthermore, the visual sense is known for its dominance in the field of sensorimotor transformations in tool use. Driving a car meets the definition of a sensorimotor transformation as driving is being guided by the information perceived from the outside. In other words, information sensed by the different human modalities (*visual*, *auditory*, *haptic/tactile/kinesthetic*, *vestibular*, etc.) are being cognitively processed and transformed into an event file with certain features [6] which is relevant for the motor action to be performed.

In sensorimotor transformations, the visual modality is known for its dominance in terms of guiding motor actions which is supported by various experiments in the field of tool use [7], [8].

In contrast, the **auditory sense** is always 'switched on'. It is not directed and can receive either simple or complex information sequentially. It is also highly involved in the driving task and therefore this modality is permanently exposed to a broad variety of stimuli. While visual messages still can be looked up a moment later, vocal warning information is transient and is lost when not captured instantaneously.

While driving a car, the driver is confronted with stimuli originating from infotainment, further passengers, environment and from ADS – all of them competing in the prevailing noisy situation. These stimuli need to be either filtered out or further processed and selected by the human processing system regarding their relevance, which in turn underlies a certain limitation of capacities [9]. The merely cognitive process is highly demanding and exhausting as it has the potential to bind a high level of cognitive resources, especially when the message is not simple (e.g., '1 bit') but complex, of lower salience or takes longer (word or sentence).

Therefore, the auditory sense works for *alerts* with *simple* and *salient* stimuli and in fact is used frequently for this purpose. Complex information can be transmitted as well but competes with noisy backgrounds, needs cognitive resources, a certain time for transmission and is to be understood immediately during transmission.

From the nature of sound and auditory sense it follows that acoustic information will be received not only by the driver but all other occupants in the interior as well. This could be a negative attribute for user acceptance and might lead to switched off ADS systems.

Tactile sensing by mechanoreceptors is distributed across the entire human body. It requires physical contact, the tactile sense is always 'switched on', its eligibility for transmission of complex information is very poor and the signals are transient (to be captured when sent, otherwise lost). Tactile signals can be transmitted in a discrete way without disturbing other passengers.

	Indicative characteristics of modalities for automotive applications					
	Direction of signal *Transmission characteristics of signal*	**Transience of signal** *Availability of signal over time*	**Effort for reception** *Recipient senses with or without additional effort*	**Suitable for alarming** *Ability to raise or redirect attention of recipient*	**Message content** *Ability to transmit low or also rich information*	***Warning concept*** *Main purpose for an emergency warning concept*
Modality						
visual	unidirectional	depends	with effort (gaze)	lower	low ... complex	*Warning information*
auditory	omnidirectional	only during transmission	no additional effort	higher	low ... complex	*Alerting*
tactile	dedicated body parts	only during transmission	no additional effort	higher	low	

***Figure 3** Modalities of automotive applications and characteristics*

What makes Active Seat Belts unique compared to other means of tactile warning?

The conclusion from above is that tactile stimuli are effective to arouse driver's attention in case of critical situations. This work aims to investigate, how tactile warnings provided by an Active Seat Belt system can help raise the performance of driver warning in safety-critical situations.

Figure 4 indicates the key differences between the Active Seat Belt and other tactile options like seat-integrated and steering wheel-integrated tactile actuators, and vibrating pedals.

As the impact of those factors is minor on the seat belt there is a potential roadblock due to missing norms for the fastening of seat belts. Still, certain regions do not mandate the use of seat belts and therefore seat belts cannot be utilized for tactile warning.

Wickens et.al [5] outlined factors that determine the *noticing probability* of visible events. Applying the findings to the tactile modality it can be derived that a high noticing probability can be achieved when first a stimulus is tangible by the mechanoreceptors e.g., by contact and second the tactile stimulus shows high *salience*, meaning the ability for easy discrimination from other competing signals, or ‘background’ noise, coming from the environment.

Seat, seat belt, steering wheel and pedals are potential interfaces to the driver, see *Figure 6*. In vehicles with ADS systems and higher levels of driving automation the physical contact between the driver and the pedals or the steering wheel is not present. Therefore, warnings related to safety-critical emergencies or ADS functions provided by these actuators would not be recognizable in certain situations. Also, an increased variation of an occupant’s posture may impact the steady contact to these tactile actuators.

Factors / Tactile Actuators	**Influence by signal noise on sensory channel** Ideally, the tactile sensory channel is free other noise or overlays introduced from the environment, which may influence perceptibility and appearance		**Influence on physical contact between vibrotactile actuator and occupant** The physical contact between driver/passenger and the tactile actuator depends on his status, behavior or the given driving situation		
	Road Conditions	**Vehicle Dynamics**	**Driving Automation**	**Occupant Posture**	**Belted Status Impact**
Active Seat Belt	minor	minor	no	minor	potential roadblock
Vibrating Steering Wheel	high/moderate	high	roadblock when hands-off	high	minor
Vibrating Seat	very high	high	moderate	high	minor
Vibrating Pedal	moderate	high	roadblock	high	minor

Figure 4 Assessment of alternative tactile actuators within the automotive interior

As discussed above, the second condition for a high noticing probability is high salience. The signal must be recognized and separated from this superimposed background. Seat surface and backrest are interfacing with the human body and take the largest share of the body weight. The interaction of body weight, seat surface, backrest and human body creates local compressive forces constantly stimulating certain areas of the body. Driving accelerations and vibrations emerging from the road surface are transmitted to the mechanoreceptors of those areas. They build a tactile ‘background’ noise when an additional tactile signal for warning and alerting is added to that interface.

In contrast, seat belt systems are designed to provide the highest possible wearing comfort and minimal perceptibility. A transmission of forces and vibrations from the vehicle chassis to the driver is hardly possible since there is just a slight contact between driver/occupant and the flexible seat belt. Without tactile noise background this channel transmits the tactile signals exclusively. Hence, a high noticing probability and fast perception is expected making the seat belt-based tactile modality unique.

As discussed above, driver warning at first needs a ‘Step 1a’ initiated by an alert/alarm generating an (unspecific) risk awareness. For this the driver is to be aroused, mental state to be raised to an *awake* and *attentive* state with a focus on driving. Both the auditory and the tactile modality fulfill the requirements for a stimulus to alert/alarm drivers and can be understood as *alternatives* for alerting and alarming while the visual modality fits best for providing more detailed information.

Finally, it would be desirable to generate the tactile stimulus with components already existing in the car. Active Seat Belt systems for reversible seat belt pretensioning are widely used in today's vehicles and allow the generation of tactile stimuli simply by adding the function by software change.

	Receivability Tactile actuator and driver body (receptor) have physical contact	**Noticeability** Noticeability of alert through the tactile stimulus ('Step 1a', see *Figure 1*) estimated for ADS functions Level ≥ 1
Active Seat Belt	given across all ADS modes (if belted)	++
Vibrating Steering Wheel	not given in hands-off situations (if lateral controlled by ADS)	-
Vibrating Seat	ensured, however variations due to passenger posture	+
Vibrating Pedal	only given if feet have contact with pedals (manual driving only)	-

***Figure 5** Utilization of alternative tactile actuators for warning concepts of ADS functions*

How is tactile warning adding to the other Active Seat Belt use cases?

Since its first application two decades ago, Active Seat Belts are widely used across automotive brands, vehicle segments and regions. Usually, seat belts are part of the Passive Safety domain. The initial purpose of Active Seat Belts was improved effectiveness of the occupant safety system by adding proactive seat belt pretensioning in emergency situations. Today, Active Seat Belts enable use cases of further domains like ADS/ADAS, HMI and passenger ergonomics/comfort for a superior user experience.

Active Seat Belt key functions

Active Seat Belts are equipped with an additional mechatronic drive unit to a apply a broad range of force to the seat belt. In contrast, standard seat belt pretensioners are equipped with a pyrotechnic pretensioning unit that is only intended to operate once during single crash event. Active Seat Belts serve passengers and the driver along multiple driving phases:

- Driver Warning and Notification – A *TOR* or an emergency warning of an ADS/ADAS (e.g., *FCW*) can trigger a vibrotactile pulse by Active Seat Belts being part of a multimodal warning or notification scenario
- ADS/ADAS Maneuver – Interventions in longitudinal (e.g., Autonomous Emergency Braking, *AEB*) and lateral (e.g., Autonomous Emergency Steering, *AES*) directions may impact the occupant position. Active Seat Belts may help to stabilize the occupant towards the nominal position
- Passenger Ergonomics – For buckling up and during normal driving, passengers experience a high freedom of movement as Active Seat Belts can enable a reduced seat belt retraction force
- Driving Experience – If the driver and the passengers intend to experience a dynamic and agile driving experience Active Seat Belts help stabilize the torso and mimic the experience of a 4-point belt system
- Belt Slack Removal – Shortly after the start of driving Active Seat Belts aim for a tight fit to improve the effectiveness of the seat belts in the event of a crash. It also contributes to a habit for buckling up and positive experience of the vehicle's safety systems
- Emergency prior to a potential crash event – Occupant in-position: Reversible pre-pretensioning of the seat belt in severe driving conditions to ensure that the driver is in a nominal position using strong, reversible pre-pretensioning of the seat belt prior to a likely crash event

Design aspects of vibrotactile warning with Active Seat Belts

The extended functionality makes Active Seat Belts relevant for the ADAS/ADS warning system and the vehicle HMI/UI. A salient tactile stimulus by an Active Seat Belt system can be created by an initial explicit pre-tensioning followed by a phase of consecutive pulls or vibration (see *Figure 6*). The vibrotactile pulse to the driver is customizable for different types of notifications, confirmations of operations or warnings. This allows variations depending on type of notification or warning, priority, occupant/ driver state, responsiveness of occupant/driver, context and driving situation. Frequency, force level, amplitude and duration are adjustment parameters. Cascading warning concepts or escalation strategies with a higher level of responsiveness are possible.

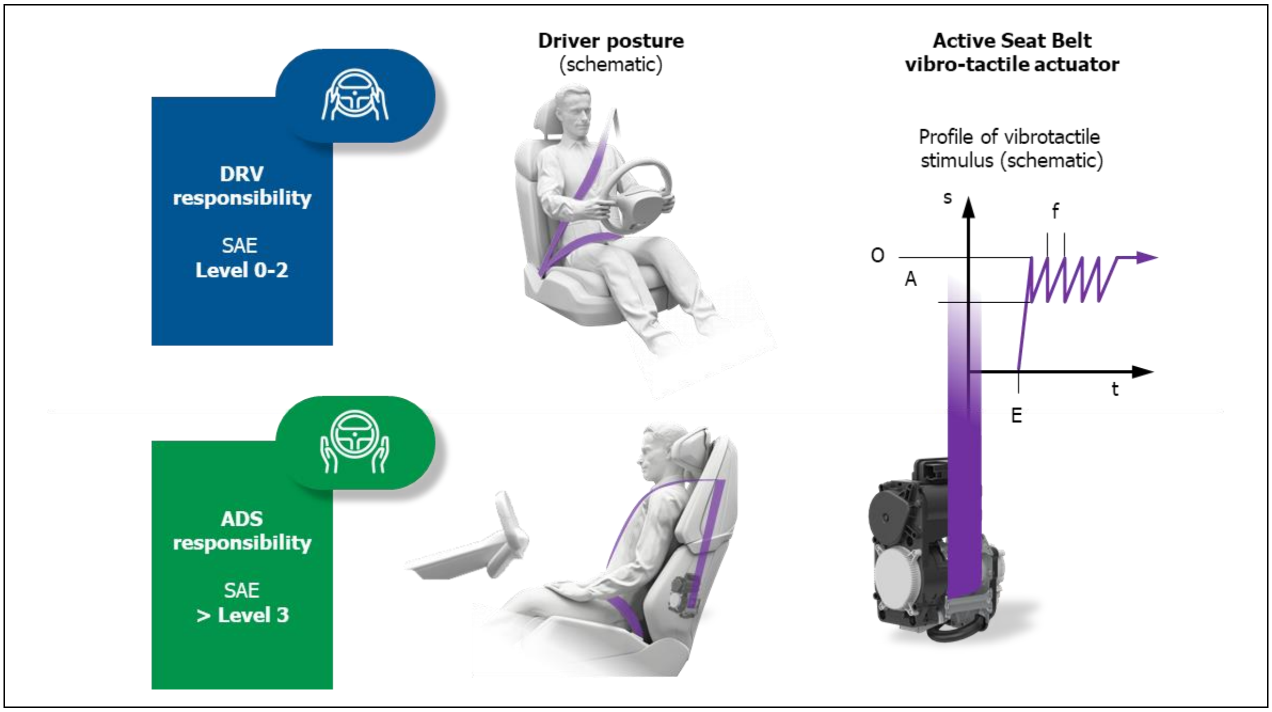


Figure 6 Vibro-tactile warning provided by an Active Seat Belt system

Application of vibrotactile warning for ADS/ADAS functions

Today, the Euro NCAP protocol considers tactile/haptic warning as an option for a multimodal warning in case of driver distraction (short/long distraction, phone usage) and driver fatigue (drowsiness, microsleep, sleep) [10]. The ADAS Performance Testing Program of U.S. NCAP by NHTSA considers tactile/haptic warning also as an option for multimodal warning concepts for different ADAS functions, e.g., Lane Departure Warning (*LDW*). The current protocol mentions tactile/haptic alerts through steering wheel or seat vibrations to alert the driver.

Previous research

Research on the impact of alternative bi- or multi-modal cues and the influence workload shows that tactile stimuli result in a more effective warning compared to the visual and/or auditory cues, especially when a certain workload must be processed [11], [12]. In general, multi-modal redundant warning concepts show faster reaction times in both situations – easy and complex – compared to a warning concept with a single cue [13], [14], [15].

Further research on automotive use cases shows that the tactile stimulus can facilitate the response to a visual information when monitoring the traffic, especially when tactile information as a spatial (location-specific) warning signal can be synchronized with the visual information [16], [17], [18].

A relevant benefit of the tactile cue for warning concepts is the robustness and noticeability under various conditions. It seems to be more difficult to miss a tactile stimulus compared to visual or auditory information [19].

The application of tactile stimuli in Automotive applications for ADS functions had been assessed for different tactile actuators like steering wheel [20], brake and accelerator pedals [21], [22], or seat [23], [24], [25], [26]. See also the survey of Petermeijer et.al [27] on driver support systems with tactile warning concepts.

The use of the seat belt system to transmit vibrotactile stimuli to the driver had been investigated already in the past [28], [29]. Alternative solutions for the tactile actuator had been investigated for certain ADS functions, e.g., tactile seat belt vs. vibrating steering wheel [30]. However, it can be assumed that the detailed technical solution for the vibrotactile stimulus is different to the Active Seat Belt with vibrotactile feature used for the studies of this work.

RESEARCH QUESTIONS AND METHODOLOGY

The nature of the tactile modality, as part of a warning concept by an ADS system and especially the use of Active Seat Belt systems as the tactile actuator, have not yet been sufficiently investigated and therefore are in the scope of these investigations.

The tactile modality is considered as an option for multi-modal warning concepts of ADS in case of emergencies. Multiple combinations of modalities and specific configurations of stimuli – also along an escalation path – are possible. The performance of tactile warnings should be investigated across different driving automation levels in a controlled environment and across a significant number of users. This leads to the following research questions:

Research question 1

What, if any, are the advantages of a tactile stimulus for warning concepts of ADS systems?

For safety-relevant emergencies, the most relevant parameter is *reaction time* of the user. In the focus of this work are warning concepts related to ADS functions for different levels of driving automation. In a first test setup, the driver's reaction time should be measured after the occurrence of an emergency. Reaction time is the time from the beginning of an event (i.e., cut-in vehicle begins to leave its own lane) to the measurable reaction of the driver (i.e., time until brake is pressed). In a second test setup the reaction time of a driver will be measured in a TOR during conditional driving automation of an ADS. See below for a more detailed description of the selected test scenarios.

Research question 2

Which conclusions can be derived from user studies regarding further aspects of efficient warnings?

To better understand the impact on warning concepts by an ADS system, further data was collected during the series of tests with altered warning concept modality combinations.

Decision quality was evaluated when comparing the multi-modal warning concepts. In the first user study the driver could choose between braking and evasive steering. In the second user study driving parameters like speed or lateral offset were measured to compare the impact of the specific warning concept on drivers' perception of the situation or reaction.

Other evaluation aspects are related to the specific alerting or information function within a warning concept. How does a tactile stimulus compare to the auditory stimulus to arouse the driver within the first part of the warning process (impact initial mental state of mind)? What is the influence of the driver's mental load during the emergency warning? How robust are the different warning concepts in different types of emergencies or different mental states of mind?

Research question 3

How do the users respond to tactile stimulus being part of ADS warning concepts?

Today, drivers are familiar with visual and auditory modalities applied for warning concepts and may have experienced a few applications of tactile/haptic modalities during emergency warnings. However, the seat belt is currently not known for tactile warning capabilities by consumers. Therefore, personal user feedback was collected through structured interviews during and after the simulated test drives.

Research question 4

How does an Active Seat Belt system with tactile features compare to other tactile actuator options?

The user interface increasingly needs to respond to diverging conditions and requirements of ADS driving automation levels. As a tactile actuator typically requires physical contact to the human body, options are limited. The findings of the user studies should be utilized to discuss tactile stimuli provided by an Active Seat Belt system with other options of tactile actuators.

Design of test series

It is the ambition of this work to assess the impact of vibrotactile stimulus as part of multi-modal warning concepts across a broad range of driving conditions, and different conditions of the drivers during driving with or without the presence of driving automation.

Therefore, the design of the user studies and the selection of the specific test series configurations should cover both conditions and driving modes (see *Figure 7*):

- first: the driver is responsible for the driving task: SAE Level 0 to 2
- second: ADS is responsible for the dynamic driving task: especially SAE Level 3

With the driver being responsible for the driving task and the driver being in an alert (attentive) mental state of mind, the most challenging environment for the comparison of alternative multi-modal warning concepts was selected. This condition can be considered as the nominal state for SAE Level 0 to 2.

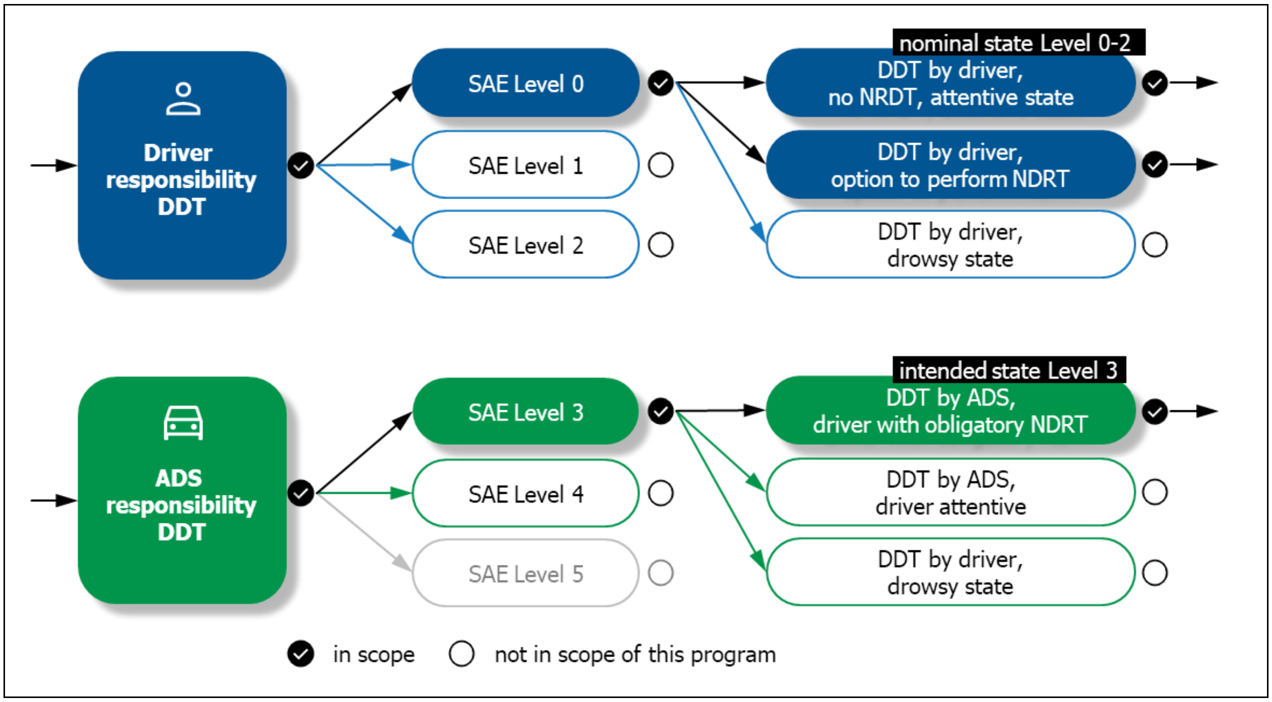


Figure 7   Proband study program

Due to the nature of vibrotactile alerting, compared to an auditory cue, the impact on the performance of the warning concepts might be even higher in situations with a driver being not attentive or distracted especially during partial driving automation (SAE Level 2) with longitudinal and lateral vehicle motion control.

For driving scenarios with responsibility of the dynamic driving task transferred to the vehicle's ADS, an emergency resulting in a take-over request was selected to compare alternative multi-modal warning concepts. Here, the driver will be occupied with non-driving related tasks as the intended use case during conditional driving automation. In real driving situations, the driver might be listening to music, watching videos, or having conversations with other passengers. Otherwise, drivers might require a recovery phase or are in a less attentive state. Haptic signals may be advantageous in these situations for alerting the driver compared to other cues.

The two studies were designed following alternative approaches. In the first study, the sample size was divided in three groups so that one participant received one type of warning concept. Here, the aim was to avoid potential training effects due to repeated test situations. The second study followed a repeated measurement design. All participants received all three warning concepts with the different configurations of alerting stimuli and warning information. Here, the aim was to assess the statistical significance of the different variation parameters (warning concept, emergencies, sequence/learning effect) across the entire sample size.

USER STUDY TACTILE WARNING DURING DRIVING WITHOUT DRIVING AUTOMATION

A first user study on benefits of tactile warning through an Active Seat Belt system had been carried out by RWTH Aachen University, Institute for Automotive Engineering (ika) and fka GmbH, Aachen. The driving simulator test series, comparing three variations of warnings, were conducted in the ika's high fidelity driving simulator. Here, test scenarios focused on emergencies during a driving scenario without driving automation (SAE Level 0).

Method and procedure

The dynamic driving simulator at ika is utilized for the assessment of driver assistance systems, future steering and control concepts, and the analysis of driver behaviour (see *Figure 8*). The dome's diameter is 7.0 m and the field of view is 360° x 45°. The driving scenarios were created using the driving simulation software Virtual Test Drive by Vires. A mock-up of a BMW i3 served as the test vehicle.

The user study was carried out over six days of testing during the period between November 23 and 30, 2019. Participants started off by completing a socio-demographic questionnaire and then were introduced to the driving simulator. In a short familiarization drive participants were able to get accustomed to the simulator.

***Figure 8** Test setup for user studies with 'No Driving Automation' (SAE Level 0) scenario*

Following the familiarization drive, participants were asked to maintain a target speed of 120 km/h, causing them to be in the left of two lanes, passing slower traffic on the right. For an illustration of the test scenario see *Figure 9*. Each participant experienced two test scenarios in random order, which were designed identically, but differed in the demand put on the driver due to the presence or the absence of a non-driving related task (NDRT).

Participants drove on the left lane of a two-lane highway at a target speed of v = 120 km/h, passing slower traffic on the right. Suddenly a vehicle from the right lane, moving with a speed of v = 100 km/h, cuts in front of the test vehicle (time-to-collision TTC = 5 seconds). After 0.8 seconds the cut-in vehicle contacts the lane and the multi-modal warning of the driver takes place ($TTC_{warn} \approx 4.2$ seconds) according to the experimental conditions. The only correct reaction of the driver, to handle the situation, was braking as the highway is equipped with crash barriers and therefore swerving is not an option.

After experiencing the situation, participants were asked to stop in the emergency lane and participate in a short question and answer session. The participants were then again instructed to proceed driving and maintain a speed of 120 km/h. Before participants experienced the described test situation a second time, a dummy event followed aimed at the prevention of learning effects. The dummy event consisted of driving through a construction site with a (uncritical) braking event with a preceding vehicle. After experiencing the cut-in event a second time, the questioning was repeated.

During one of two test drives, participants were instructed to carry out a non-driving related task (NDRT) as quickly and accurately as possible. The chosen task was the *Surrogate Reference Task* (*SuRT*) introduced by Mattes et.al [31], which is an artificial motor-visual task that allows distraction of the drivers under controlled conditions.

Multimodal warning system and stimuli

Participants were presented one of the three multimodal collision warning systems considered in the study. Today, requirements for the design of warning concepts already exist and mostly consider auditory alerts combined with visual information. To assess the impact of the tactile stimulus it replaced the auditory cue in one configuration and was added as a second alerting cue. The design of the stimulus modalities was identical across the combinations:

- *Acoustic and visual (A-V)*: A standard acoustic stimulus using a standard warning tone ('beep') and a visual sign ('hands-on-wheel' with a 'general caution' symbol) was presented in a heads-up display
- *Tactile, and visual (T-V)*: A vibrotactile stimulus by the Active Seat Belt replacing the acoustic stimulus was combined with a visual sign ('hands-on-wheel' with a 'general caution' symbol) presented in the heads-up display of the car
- *Acoustic, tactile, and visual (A/T-V)*: Three modalities as combination of acoustic, tactile, and visual stimulus for the take-over request

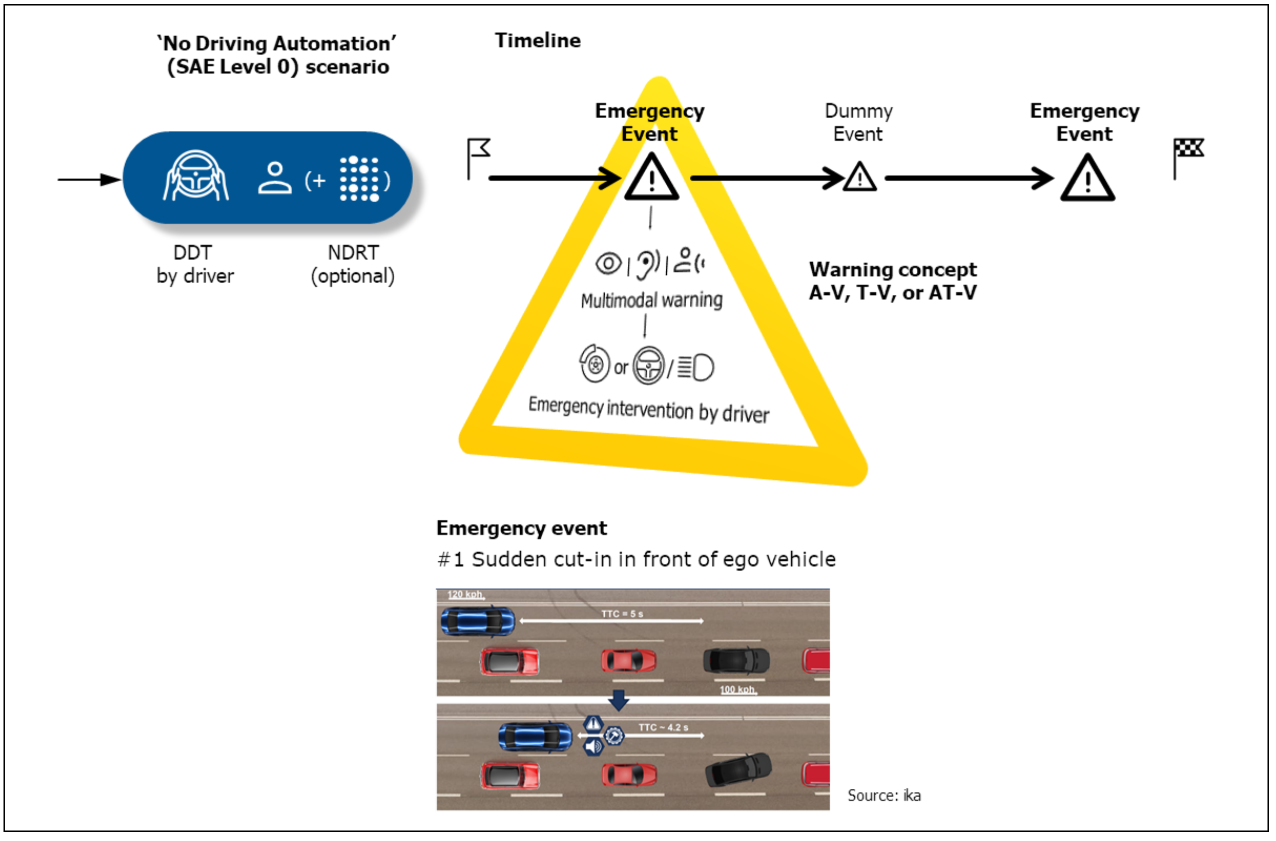


Figure 9 Characteristics of test scenario without driving automation (SAE Level 0)

Sample

A total of *N* = 42 drivers (17 female, 25 male) participated in the study. The participants' mean age was *M* = 40.5 years, ranging from 20 to 66 years (*SD* = 14.6). On average, the drivers had a driving experience of 22.6 (M = 20). The average annual mileage as a driver was *M* = 15,295 km (*SD* = 15,418 km).

Subjects were asked about their practical experience with driver assistance systems. 31% reported using a Cruise Control System (*CCS*) on a regular basis and 36% used it at least several times before. The regular use of Dynamic Cruise Control (DCC) and of a Lane Keep Assistant (LKA) was reported by 5% and 10% of the drivers.

Results

Objective data

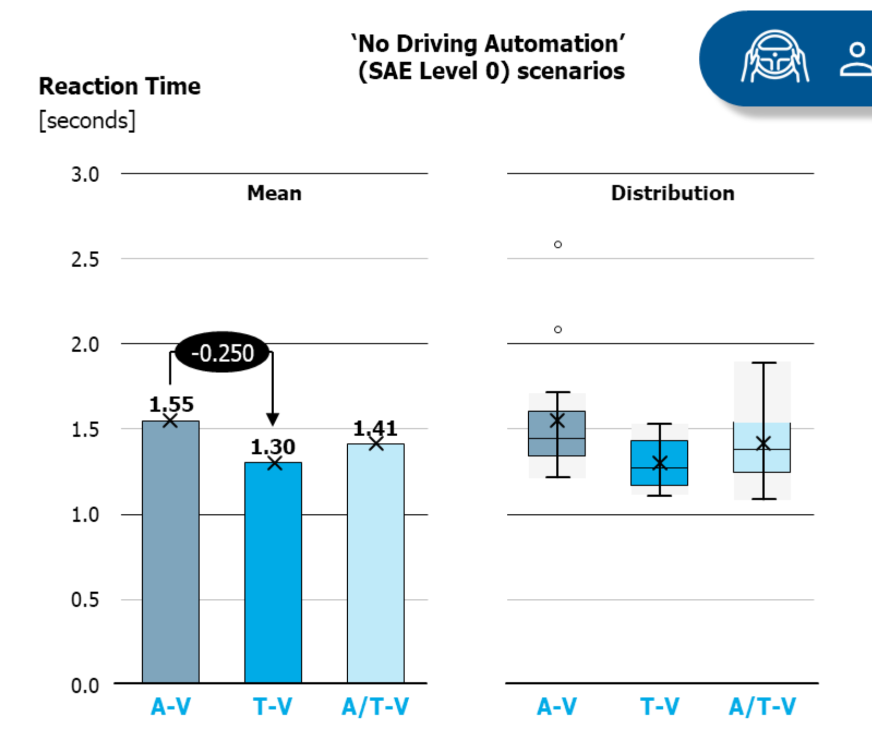
Measures: To describe the driver's response to the critical situation and, accordingly, the warning concepts, the *reaction time* was of particular interest. In the simulated emergency this was the time from the beginning of the event (cut-in vehicle begins to leave its own lane) to a measurable reaction of the driver, i.e., brake pedal deployed.

As braking is considered the only correct response, the time until the brake is applied (brake time) is of particular importance. To investigate the effect of a tactile or acoustic cue, each in combination with visual information, brake times when using the acoustic-visual and tactile-visual warning strategies were compared.

The data was analysed using the statistics software IBM SPSS Statistics, Version 27. Abbreviations in all tables are to be understood as follows: *SS* = total sample size, *N* = analysed samples, *M* = mean, *SD* = standard deviation. Inferential statistical analysis was carried out by means of one-way ANalysis Of VAriance (*ANOVA*).

Data suggests that the response time is shorter when using the tactile-visual system variation rather than using the acoustic visual system variation ($F_{1,26} = 5.275$, $p = 0.03$, $\eta^2 = .169$). Please see *Figure 10* for the results.

In addition, it was investigated whether the addition of a tactile cue to a system variation consisting of an acoustic stimulus with visual information (A/T-V) adds further value in terms of the warning effect (operationalized here via braking time). Although the mean braking time for the acoustic-tactile-visual system variation appears to be descriptively shorter compared to the acoustic-visual system variation, inferential analysis shows no significant differences.



	A-V	T-V	A/T-V
SS	15	15	15
N	14	14	14
Mean	1.55	1.30	1.41
SD	0.37	0.15	0.25
	A-V	T-V	A/T-V

***Figure 10** Reaction time for alternative warning concepts A-V, T-V and A/T-V after emergencies / SAE Level 0 scenarios*

Subjective data

Following the critical driving scenario, subjective data was collected by means of a questionnaire.

Questionnaires: The response of the participants to the different warning strategies was examined on a subjective level regarding the *cognitive demand*, the *perceived efficiency* of the warning effect, as well as with regard to *acceptance values* and *usability criteria*. A selection of the instruments and items used is described below.

Cognitive demand of the participants during the tests was assessed by a 5-staged response scale from ‘not demanding at all’ (‘-2’) to ‘very demanding’ (‘+2’).

Perceived efficiency was assessed by means of two Likert scales referring to the support provided for choosing the right reaction (‘The warning system helped me to react *correctly*’) and to the resolution of a fast response (‘The warning system helped me to react *quickly*’). A 5-staged response scale was used for both items from ‘do not agree at all (‘-2’) to fully agree (‘+2’).

The Van der Laan Acceptance Scale [32] was used to assess *system acceptance* by applying the two scales usefulness and effective satisfaction. Both scales are collected by means of nine items in total. Each item consists of an opposite pair of adjectives and the participants must indicate how far the adjectives apply (score reaches from -2 to +2) to the experienced system.

The *cognitive demand* in the situation does not seem to be influenced by the variation of modalities in the warning strategies. In both system variations acoustic-visual (A-V) and tactile-visual (T-V) users rated the cognitive demand almost identically on the 5-staged rating scale ranging from -2 (*‘not demanding at all’*) to +2 (*‘very demanding’*) (A-V: $M = 0.36$, $SD = 0.88$; T-V: $M = 0.38$, $SD = 0.82$). Also, within the experimental condition with the system variation including all three modalities the demand in the situation does not appear changed ($M = 0.46$, $SD = 1.12$).

Regarding the *subjectively perceived efficiency* of the system variations there seems to be a slight tendency towards the tactile-visual (T-V) option on a descriptive level. On average, participants who have experienced the tactile-visual (T-V) system are slightly more likely to agree with the statement that the warning system helps them to react correctly than participants who have experienced the acoustic-visual (A-V) option on the 5-staged rating scale from -2 (*‘do not agree at all’*) to +2 (*‘fully agree’*) (A-V: $M = -0.08$, $SD = 0.88$; T-V: $M = 0.46$, $SD = 0.89$; A/T-V: $M = 0.23$, $SD = 1.41$). Still, there is no clear (dis)agreement with the statement for either of the three options for multimodal warning. The same applies to the agreement with the statement that the respective warning strategy helps reaction time. Within the context of no clear (dis)agreement, on a descriptive level it appears highest for the tactile-visual system (A-V: $M = 0.00$, $SD = 0.92$; T-V: $M = 0.62$, $SD = 0.88$; A/T-V: $M = 0.15$, $SD = 1.20$).

System acceptance ratings collected via Van der Laan Acceptance Scale [32] were very similar for all three options with a slight benefit on a descriptive level for the system tactile-visual (T-V) regarding the factor *usefulness*. Please see *Figure 11* for results.

	Acoustic-visual A-V		Tactile-visual T-V		Acoustic-tactile-visual A/T-V	
	Usefulness	Satisfaction	Usefulness	Satisfaction	Usefulness	Satisfaction
N	13*	12	13	13	12*	12*
Mean	0.41	0.5	0.95	0.48	0.66	0.55
SD	0.98	0.83	0.65	0.71	0.91	0.80

Note: * = mean n in the case of missing values in single items

Figure 11 System acceptance ratings collected via Van der Laan Acceptance Scale

Further questionnaire responses indicate that the tactile warning cue is rarely not perceived (T-V alert: $n = 2$, A/T-V alert: n = 3). The visual warning cue is the most frequently not perceived across all system variations (A-V alert: $n = 6$; A-V alert: $n = 6$).

USER STUDY TACTILE WARNING DURING CONDITIONAL DRIVING AUTOMATION

A second user study on the assessment of tactile warning through an Active Seat Belt system had been carried out with the focus on the take-over request (TOR) during conditional driving automation.

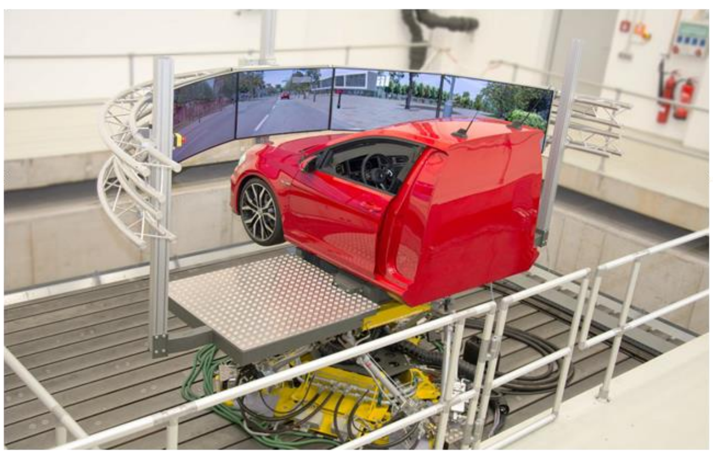
Thus, a driving simulator study was conducted by the Department of Engineering and Traffic Psychology of TU Braunschweig in the dynamic driving simulator of the NFF (Niedersächsisches Forschungszentrum Fahrzeugtechnik; Automotive Research Centre Niedersachsen) comparing three types of warning signals in order to evaluate the benefits of haptic signals for take-over requests in automated driving at SAE Level 3.

At SAE Level 3, the car driver becomes a passenger for part of the journey and may engage in other activities like reading, using the smartphone or laptop, watching videos etc. However, the SAE Level 3 system has limits where the driver has to take over. About 10 to 15 seconds before these limits are reached, the driver is warned and requested to take over control of the car (TOR). At that moment, acoustic and visual warnings are used to issue this TOR. However, when the driver listens to loud music or videos, this warning may take some time to perceive and react to. Additionally, there may be other signals or warnings which may prevent the driver from understanding that this current warning is a take-over request. Haptic signals may be advantageous in this situation.

Method and procedure

The study was conducted in the dynamic driving simulator at the NFF (see *Figure 12*). The front part of a car is situated on a moving platform. Six screens are used to present the scenery. The platform including the car and the screens are moved to simulate a realistic driving feeling including the typical forces on the driver within a vehicle.

Conditional Driving Automation (SAE Level 3) scenarios



Source: Technische Universität Braunschweig, Niedersächsisches Forschungszentrum Fahrzeugtechnik

Figure 12 Test setup for user studies with '<u>Conditional Driving Automation</u>' (SAE Level 3) scenario

On a simulated, two-lane highway, drivers started handing over the driving task and continued in a conditional driving automation mode (SAE Level 3). During the simulated rides, three different emergencies were presented to the users resulting in a take-over-request:

- The first emergency scenario consisted of a TOR due to missing lane markings on the road ahead (see *Figure 13*, *#1*). About 10 seconds before the vehicle reached that location, the TOR was given. After take-over, the driver manually controlled the vehicle through this stretch of the road until the markings reappeared and the automation could take over again.

- In the second emergency scenario, a crash had happened and one of the crashed cars was partially blocking the right lane (see *Figure 13*, *#2*). A police car was present at the right shoulder and a hazard triangle had been placed on the road. Here, the drivers had to take over, had to change the lane and then had to pass the crash before re-engaging the conditional driving automation mode.
- The third emergency scenario was suddenly starting heavy rain (see *Figure 13*, *#3*) with the vehicle requesting the driver to take over due to limitations of environmental sensing under these circumstances. Later, the drivers re-engaged the conditional driving automation mode.

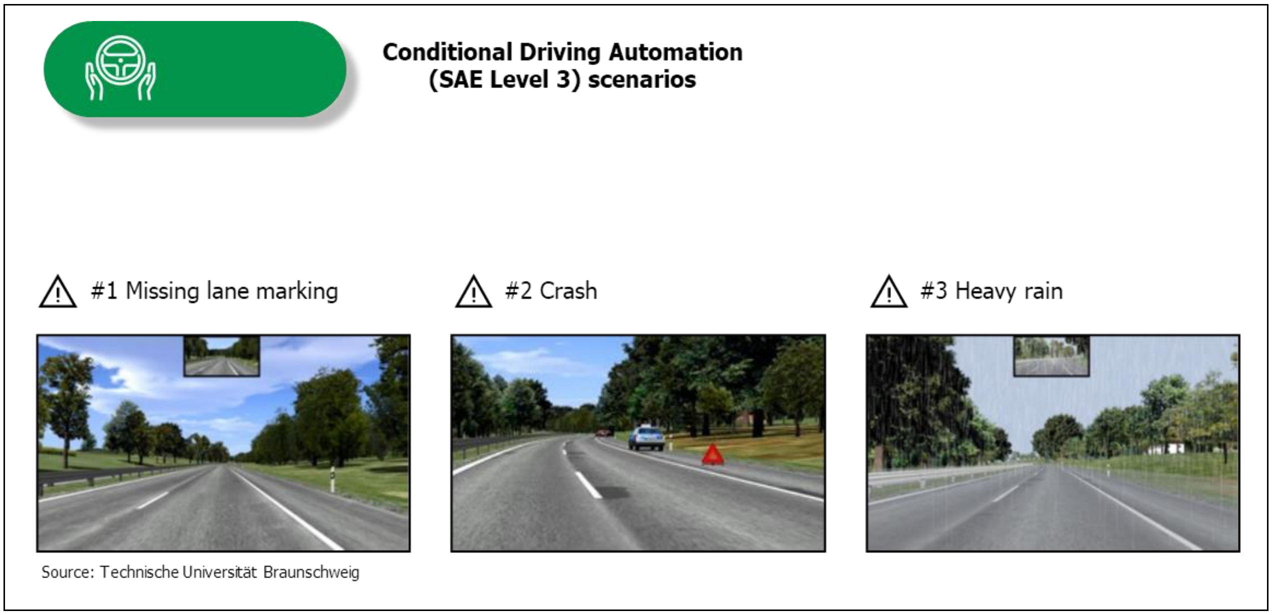


Figure 13 Emergencies resulting in a take-over-request

Each driver experienced one type of take-over request in these three situations as one trip. Three different types of take-over requests were compared by having each driver do three trips. The order of the three situations was different in each of the three trips. Moreover, the order of the three types of take-over requests was also varied in three different groups of drivers in order to control for time effects. The three kinds of take-over requests were the following:

- A standard acoustic and visual request, using a standard warning tone (‘beep’) and a symbol in the head-up display (A-V – acoustic-visual) which was shown in a simulated head-up display.
- A tactile and visual request, replacing the warning tone with a jerking movement of the seat belt (T-V – tactile-visual)
- A combined tactile, acoustic and visual take-over request thus adding a haptic signal to the standard acoustic-visual take-over request (A/T-V – acoustic-tactile-visual)

The vibrotactile stimulus was at a frequency of 9 Hz at a force level of approximately 50 N. This configuration was chosen based on previous experiences aiming for a salient but acceptable stimulus.

After receiving this take-over request, the driver could turn back to manual driving by simply braking or by using the headlight flasher.

During the trip, take-over times and driving behavior after taking over were recorded. After each trip, drivers were questioned with regard to usability and subjective acceptance of the system. At the end of the study, each driver was asked to select the kind of feedback that he or she would like most to have.

45 drivers (15 females and 30 males) were recruited from the subject pool of the NFF ranging from 20 to 73 years of age in order to have a heterogeneous sample with regard to age and sex. The mean age was 37 years (sd = 15 years). On average, the drivers had obtained their driving license 19 years ago. About half of the sample drove less than 9,000 km per year but there was also one driver going more than 50,000 km per year. Subjects were asked about

their attitude towards driving assistance system (without qualifying this further) and about 75% of them had a positive or very positive attitude. About 70% reported being very interested in new technologies. Thus, the sample was a wide mix of different drivers, however, with a somewhat positive bias towards new technologies and driver assistance systems.

Results

Driving behavior

The most relevant parameter is take-over time. This was measured from the start of the take-over signal to the time-point of deactivating the automation. As the experimental design was a repeated measurements design, loss of data due to technical problems in even one situation led to exclusion of the subject. Data from 34 drivers was fully complete and used for the analyses of driving behavior. For the analysis, a 3x3 (type of situation x type of warning) repeated measures ANOVA was conducted.

For take-over time, a significant main effect was found for type of warning ($F_{2,66} = 9.7$, $p = 0.000$), no effect of the driving situation ($F_{2,66} = 0.1$, $p = 0.863$) and no interaction ($F_{4,132} = 0.1$, $p = 0.988$). Thus, independent of the driving situation, there was a clear effect of the type of warning, which is shown in *Figure 14 (left)*. Take-over time with the typical acoustic-visual warning was on average 5.4 seconds. Replacing the acoustic warning with the haptic warning, take-over time was reduced to 4.6 seconds, thus 0.8 seconds faster with the haptic as compared to the acoustic warning. Adding the haptic component to the acoustic-visual warning resulted in the fastest take-over time of 4.4 seconds, thus one second gain by the additional haptic signal.

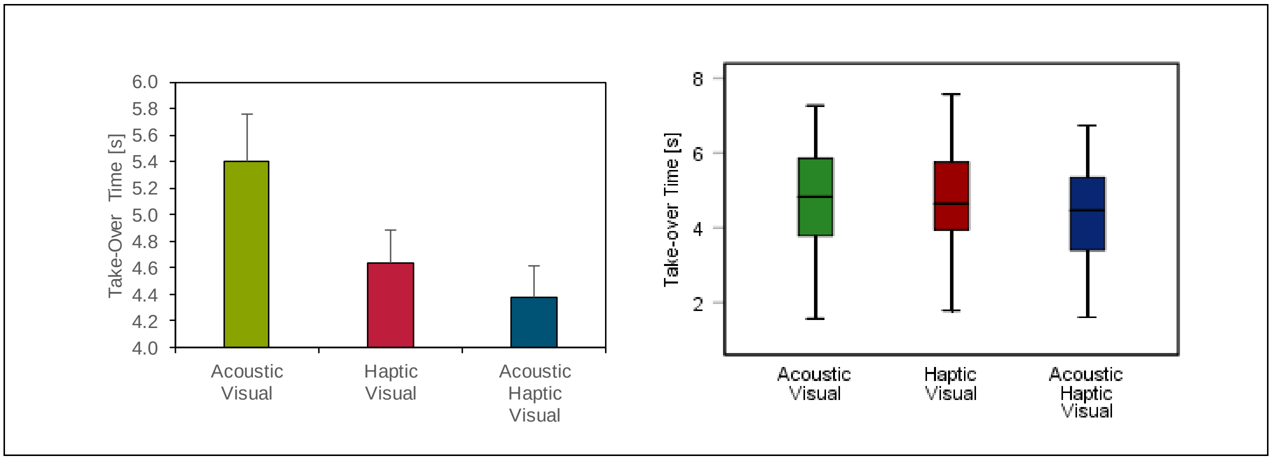


***Figure 14** Average take-over time in seconds for the different warning signals. The left gives mean and standard error. At the right, the same data are given as boxplots showing the distribution of the take-over times*

Figure 14 (right) shows the same data as boxplots. In every condition, there is a large variation of take-over times reflecting the individual take-over behavior of the drivers, ranging from 1.6 to 7.6 seconds as averaged for each driver over the three driving situations with each warning signal. On an individual level, comparing individual take-over times with the haptic warning instead of the acoustic warning, 66% of the take-over times in the different situations were shorter with the haptic warning. With the haptic warning added to the acoustic-visual warning, 75% of all take-over situations benefited from this additional component with a faster take-over time.

With regard to the driving behavior after taking over manual control of the car, the maximum speed when driving manually was taken as an indication of adaptation to the situation as having a lower maximum speed indicates a better adaptation to the take-over situation with going more slowly being more careful. For maximum speed, there was a main effect for type of warning ($F_{2,66} = 24.9$, $p = 0.000$) and a main effect of the driving situation ($F_{2,66} = 21.8$, $p = 0.000$) but also an interaction ($F_{4,132} = 10.6$, $p = 0.000$).

First of all, the adaptation of speed depends on the criticality of the situation after take-over with the smallest reduction in speed at the missing lane markings, followed by the crash and then heavy rain. The amount of adaptation is clearly different for the three warning types. The least adaptation is shown with an acoustic-visual warning. The tactile-visual warning increases the reduction in speed with the crash and the heavy rain. Adding the tactile warning to the acoustic-visual warning leads to the strongest adaptation, especially when heavy rain occurred.

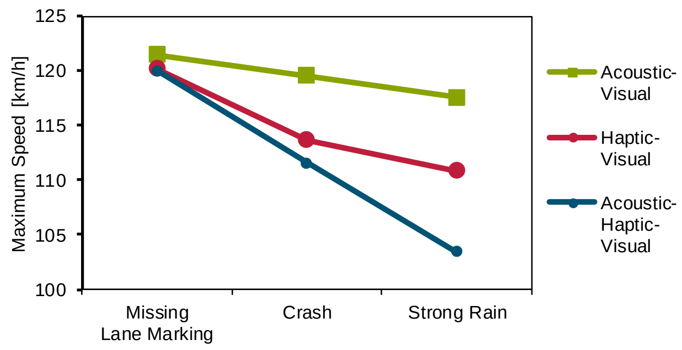


Figure 15   Maximum speed in the three take-over situations with the three different warning signals

With regard to lateral control of the car, the standard deviation of the lane position was computed (SDLP). For this parameter, there was neither a main effect for type of warning ($F_{2,66} = 0.7$, $p = 0.492$) nor an interaction ($F_{4,132} = 0.6$, $p = 0.656$), but only a main effect of the driving situation ($F_{2,66} = 3.7$, $p = 0.000$). The SDLP is largest in the crash situation. This is due to the lane changes which had to be done to avoid colliding with the crashed car. Otherwise, the three different warning signals did not influence the lateral control of the car.

Subjective evaluation

After each trip drivers were asked to evaluate - depending on the warning signal condition - the visual warning symbol (included in every warning type), the acoustic warning (in the acoustic-visual and acoustic-tactile-visual condition) and the tactile warning (in the tactile-visual and acoustic-tactile-visual condition) separately with regard to the signal being clear, urgent and annoying. A repeated measures ANOVA was conducted for each of these questions (data from 43 drivers). The warning components did not differ with regard to being clear ($F_{2,84} = 1.5$, $p = 0.227$) or being annoying ($F_{2,84} = 1.4$, $p = 0.251$), but in being urgent ($F_{2,84} = 6.6$, $p = 0.002$).

All components were equally clear (between the category 'somewhat clear' and 'clear' and medium annoying. The visual symbol was rated less urgent than the tone and the tactile vibration. However, all three were within the category 'urgent'.

With regard to the design of the tactile component, all ratings lie in the middle to positive range of the scales. The vibration is not really pleasant but also not unpleasant. It can very well be noticed, is not too weak but also not too strong. Time-point and duration are good to very good.

When directly asking afterward, which component of the system was most helpful, 69% of the drivers indicated the tactile vibration, 49% the tone and 13% the visual symbol in the head-up display (drivers could also indicate two or even three components).

Finally, drivers were asked which combination they would buy if they ever bought a car with SAE Level 3 automation. The typical acoustic-visual HMI would be bought by 22% of the drivers. 29% would prefer the tactile-visual system and 42% the acoustic-tactile-visual warning system. 7% would like an acoustic-tactile system (which was not included in the study).

SUMMARY OF MAIN RESULTS FROM BOTH STUDIES

The warning concept with *acoustic alerting* and *visual information* (‘A-V’) was used as a reference configuration for both studies (manual driving and conditional driving automation) as it is the usual warning concept for critical driving situations in vehicles today. The efficiency of the warning concept was measured by comparing the driver’s reaction time between the reference warning concept (‘A-V’) and two alternatives – one with *additional tactile* alerting (‘A/T-V’) and the other one with *tactile alerting* replacing the *acoustic cue* (‘T-V’).

In the first test setup ‘**manual driving**’ undistracted drivers (as the nominal driver condition) had been exposed to a sudden situation requiring them to brake.

- Measures: The reaction time with the tactile alert (‘T-V’) was **reduced by 250 ms** (mean) in comparison to the reference warning concept (‘A-V’).
- Calculated safety effect: The impact of this faster reaction time is a reduction of a stopping distance of 6.6 m for a vehicle at a speed of 100 kph. According to a report on real world accident data and the impact analysis of active safety technologies [33] this reduction of reaction time may result in 27.5% avoided collisions.

	‘No Driving Automation’ (SAE Level 0) scenarios				Conditional Driving Automation (SAE Level 3) scenarios		
	Measures		Calculated safety effect		Measures		Calculated safety effect
Warning concepts	Reaction time emergency scenarios (mean)	Difference **reaction time** compared to ref. warning concept (A-V)	**Stopping distance** reduction from 100 kph (calculated)	**Collisions avoidance** potential (calculated) [33]	Reaction time Take over request (TOR) (mean)	Difference **reaction time** compared to ref. warning concept (A-V)	**Stopping distance** reduction from 100 kph (calculated)
Acoustic-visual (A / V)	1,55 s	reference	reference	reference	5,4 s	reference	reference
Tactile-visual (T / V)	*(1,41 s)*	*measures statistically not significant*			4,4 s	**-1 s** (-18%)	**-28 m** (18,5%)
Acoustic-tactile-visual (A, T / V)	1,3 s	**-250 ms** (-16%)	**-6,6 m** (-17%)	**-27,5 %**	4,65 s	**-750 ms** (-14%)	**-21 m** (14%)

Use of modalities for the warning concepts: Alert | Warning information

Figure 16 Summary of measures and calculated safety effects between warning concepts

The reaction time with an additional tactile alert (‘A/T-V’) was reduced by 140 ms, but the difference was not significant. Mental overload during the demanding emergency situation combined with a redundant alerting (acoustic and tactile) and the additional visual information could be a reason for this result. Such effect has been detected before [14] but may need to be investigated in further studies.

In the second test setup ‘**conditional driving automation**’ drivers were focused on a non-driving-related task (NDRT) when different emergency situations occurred. They had to react with a take-over request (*TOR*).

- Measures: The reaction time after the warning with the tactile alert (‘T-V’) was **reduced by 750 ms** in comparison to the reference warning concept (‘A-V’). The reaction time with additional tactile alert (‘A/T-V’) was reduced by **1.0 second**.
- Safety effect: For the ‘T-V’ warning the safety effect of this faster reaction time is a reduction of a driven distance at 100 kph by 21 m compared to the ‘A-V’ warning. The safety effect of the faster reaction time of the ‘A/T-V’ warning is a reduced stopping distance of 28 m for a vehicle at a speed of 100 kph.

Here, the addition of a second alerting stimulus resulted in an additional improvement of the reaction time and the related safety effects. An explanation could be that the mental load of drivers in the automated driving mode (but with NDRT) might be lower as the mental load of drivers in a demanding emergency. And a lower mental load could allow for better processing of the 'A/T-V' warning concept using three sensory channels simultaneously.

LIMITATIONS

First, some limitations are rooted in the study design. Both studies have been implemented with dynamic drive simulators and with 87 users in total: 42 (manual driving) and 45 (AD Level 3). However, due to the variations of test parameters as described above in the chapter *Methodologies*, analyzable sample data sets are based on 14 (manual driving) and 34 (AD Level 3) users. The specific implementation of the tactile and auditory alerting stimuli and visual information may have a further influence on the measurements. Each vehicle's HMI system may have differing characteristics, and therefore influence the individual performance of warning and alerting in emergency situations. For example, tactile alerting stimuli could be realized by seat vibration and visual warning information could be displayed in a head-up display.

Second, the *driving scenarios* had been limited to *highways*. Users had a main task, either DDT or an NDRT, were *not distracted from this task.* In addition, required sensory channels were *not* loaded with *additional* noise. Further studies could help to extend the range of driving scenarios and environmental influences.

Third, the *dynamic simulator-based* study results should be compared to investigations of *real-world driving* studies with natural conditions or events influencing the emergency situations. However, the authors are aware of comparable investigations based on real-world driving that already support the findings of this work.

Fourth, the *mental states (awake, attentive, focused)* of the users have not been varied during the simulations. A detailed analysis of the influence of the mental states on the effectiveness of warning concepts would be desirable. Additionally, users might perceive their participation during the study as a *test situation* and study data might be influenced by this.

Fifth, *warning concepts* are part of the human machine communication. The *concept* found in this paper *'alert and inform'* with its multimodal options as e.g. 'A-V', 'T-V' or 'A/T-V' can be expanded to non-critical situations leading to the concept variant '*notify and inform*'. This should be the subject of further investigations. Further concept options as e.g., 'alert only' (e.g., 'T- ') or 'inform only' (e.g. ' - V') or any other have not been investigated and could be subject of further work to better understand how to support human alerting and perception (situation awareness) with technologies available in vehicles.

Sixth, since warning is just a crucial step to achieve safe driving, it would be desirable to investigate the effectiveness of warnings also in the context of the whole process chain. In this study vehicle control parameters after the warnings have been measured, also to measure whether the reaction of the warning was correct or leading to undesired reactions (not reported here in detail) but detailed investigations of vehicle control and threat control performance in different driving and threat scenarios would be desirable to allow an assessment of how intuitive various warning concepts are in different threatening situations.

Seventh, the intent of this study was to employ prototypical examples of the concepts ('A-V', 'T-V' and 'A/T-V') to provide a general comparison of driver response to each. Therefore, the conclusions provided in this section emphasize general principles and relative effectiveness of general concepts rather than detailed design specifications.

CONCLUSION

This work answers the four research questions (see *Research Questions and Methodology*) in the following way:

1: Advantages of a tactile stimulus for a warning concept of an ADS system
The work presented in this paper found that the *replacement* of the *auditory alerting stimulus by a tactile seat belt alert* in warning concepts with additional visual warning information can significantly contribute to an improved effectiveness of driver warnings. Furthermore, the study data shows that an *additional tactile alerting stimulus* by an Active Seat Belt in a common warning concept with auditory alerting and visual warning information may improve reaction time and effectiveness of driver warning – depending on the selected driving mode and related workload level of the drivers.

2: Conclusions regarding further aspects of efficient warning
The results also *suggest* that during *demanding driving situations*, as e.g., manual driving in dense traffic, *single alerts* with visual warning information can be more effective than *complex* warning concepts with *dual alerts* (acoustic with tactile) and visual information.

3: User feedback to tactile stimulus
Tactile alerting stimuli are well accepted by the study participants in both driving modes, manual driving and automated driving as well. The positive perception includes the usefulness and the preference to buy a vehicle with this feature.

4: Comparison of tactile stimulus of an Active Seat Belt vs. other options of tactile actuators
Active Seat Belt with a vibrotactile alert feature can help to improve the driver's ability to react faster than with alternative multi-modal warning and alerting scenarios during manual driving and in driving scenarios with conditional driving automation (SAE Level 3).

The vibrotactile alerting through an Active Seat Belt system is unique compared to other means of alerting (e.g., seat, steering wheel, pedal) as it is free of signal noise and therefore easy to identify by the users. Especially significant warning and alerting scenarios for ADS functions, e.g., Forward Collision Warning (FCW), Take-over requests (TOR), may also benefit from the Active Seat Belt.

The study provides a clear recommendation for tactile alerting provided by an Active seat Belt for ADS functions like FCW or TOR and should be considered for future HMI systems.

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- ZF Group, ZF Automotive GmbH, Germany with a focus on the system function, the tactile Active Seat Belt system, and the coordination of the user studies
- RWTH Aachen University, Institute for Automotive Engineering (ika) together with fka GmbH, Aachen Germany with a focus on the implementation of the user study 'Tactile Warning during driving without driving automation'
- Technische Universität Braunschweig, Institute of Psychology, Engineering and Traffic Psychology Germany with a focus on the implementation of the user study 'Tactile Warning during Conditional Driving Automation'

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