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HAPTIC WARNING SIGNALS AT THE STEERING WHEEL: A LITERATURE SURVEY REGARDING LANE DEPARTURE WARNING SYSTEMS (Short Paper)

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ABSTRACT

Using the haptic modality to transfer information to the driver is recognized as a promising possibility in many in-vehicle applications. In the field of lane departure warning systems, several haptic warning signals were presented in the last years. The application of synthetic steering wheel torque or vibration informs the driver of an imminent lane departure. In this paper, an approach to classify the existing signals is provided. The examination of the literature reveals diversity in type and parameterization of the warning signals as well as methodical differences, complicating comparability. While the general effectiveness of haptic warning signals at the steering wheel could be proven, there still is room for improvement. Based on the findings, the authors derive hypotheses concerning requirements from a user’s point of view.

1. INTRODUCTION

Advanced driver assistance systems (ADAS) support drivers in the task of vehicle driving by sensing and processing information of the vehicle surrounding. These systems interact with the driver using the visual, the auditory or the haptic modality (e.g. [22]). While information transferred via the visual or auditory modality runs risk of being missed (due to driver inattentiveness, driver drowsiness, ambient noise etc., e.g. [6]), one main restriction of haptic information transfer is the required contact with the driver. After all drivers have to “feel” the information provided by the system. This limits the sources for in-vehicle application of haptic information transfer to the driver seat, the seat belt, the pedals and the steering wheel. Among these, the steering wheel is not only the primary actuator for vehicle lateral control but also the only actuator the driver is in constant contact with.

Based on the compatibility of the location of stimulus and response, most authors agree that haptic signals at the steering wheel should best provide information concerning vehicle lateral guidance (e.g. [14], [23]). This means that haptic signals at the steering wheel should be used to influence the drivers’ steering behavior. Numerous systems that try to influence the driver via haptic steering wheel signals were presented in the last years. They range from systems that continuously support the driver in semi autonomous lane guidance (e.g. [30]) to systems initiating a steering reaction or prohibiting a steering action of the driver, as in the case of an imminent lane departure or a possibly dangerous lane change manoeuvre, respectively (e.g. [4]).

This paper provides a survey of haptic signals at the steering wheel. A representative overview of these signals is achieved regarding studies of lane departure warning systems (LDWS) of the last 15 years. LDWS sense the position of the vehicle in the lane and warn the driver in case of an imminent lane departure. It is recommended by the Federal Motor Carrier Safety Administration that LDWS should issue a haptic or audible warning in case of an imminent lane departure [7]. The next part of this paper lists and classifies the existing signals. In the third part some general hints arising from the findings of the analyzed studies are given.

2. CLASSIFICATION

The examination of the existing literature on haptic lane departure warning signals at the steering wheel reveals two main groups. Signals based on additional torque, referred to as steering wheel torque signals (see fig.1 *left*) are included in the first group. An electric motor mounted at the steering column is generally used to generate additional torque that is perceivable at the steering wheel. Mechanical restrictions limit the dynamic range of steering wheel torque oscillations (i.e. torque applied subsequently in alternating directions) to less than 20 Hz. The direction of the oscillation corresponds to the direction of steering wheel rotation. If steering column and steering shaft are not decoupled, additional steering torque can cause both a rotational movement of the steering wheel and a deviation in the driven trajectory.

The second group includes haptic signals induced by motors with eccentric weights (i.e. vibration motors used in mobile phones), which are referred to as steering wheel vibration signals (see fig. 1 *right*). These motors are mounted directly into the steering wheel, and the vibrations can be applied at frequencies of up to 200 Hz. Furthermore, the vibration can be of any propagation and is not restricted to a specific vibration direction. It is imported to note that a steering wheel vibration will not lead to a rotation of the steering wheel without manual intervention by the driver.

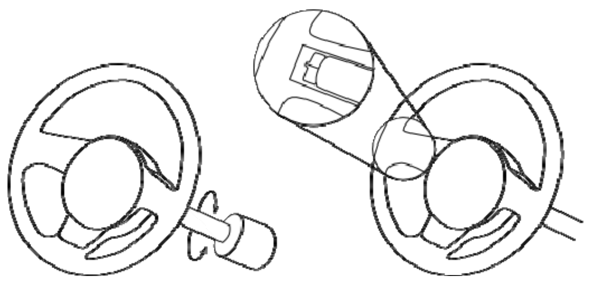

Figure 1. Schematic illustration of the differences between steering wheel torque (left) and steering wheel vibration signals (right)

2.1 Steering wheel torque signals

Steering torque jerk. By applying a steering torque jerk pointing towards the lane center, the driver is given the information about the appropriate steering reaction necessary to get back into the lane. Early studies focusing on truck applications were conducted by Ziegler et al. [32] (see also [2]). A more recent study in the field of truck applications is described by Montiglio et al. [16]. To compare the steering torque jerk signal with other (e.g. acoustic) warning signals, driving simulator studies were conducted by Tijerina et al. [31] and Kozak et al. [11]. Sato et al. [26], [27] as well as Mann and Popken [14] examine the concept of jerky steering torque in driving simulator studies and in real car studies. Pohl and Ekmark [21] describe a study on a test track where subjects are exposed to adjustable steering torque jerk warnings in the case of self induced lane departure events. Table 1 summarizes the parameters of the steering torque jerks applied in the studies (unfortunately, no parameters are stated by the authors in [1], [11], [26], [27] and [32]).

Table 1. Parameters of steering torque jerks

Study	Parameters
Mann & Popken [14]	1.5Nm, applied for 1s
Montiglio et al. [16]	Adjustable (< 3Nm, 4s)
Pohl & Ekmark [21]	Adjustable (e.g. 0.5Nm, 1s)
Tijerina et al. [31]	2Nm, 1.5s

Contrarious steering torque jerk: In the concept "ReflektAS" (see [12]), specific steering wheel torque jerks are applied in a manner causing reflexive steering reactions in the opposite direction. According to the authors, these reflexive reactions are elicited reliably and quickly.

(Symmetric) Steering wheel oscillation: When steering wheel torque of equal extent is applied subsequently in alternating direction, steering wheel oscillations are induced (fig. 2). These oscillations inform the driver about the necessity of a steering reaction without transferring information on direction. In the field of LDWS so far only studies in driving simulators are examining this type of signal. The first studies were conducted by Ziegler et al. [32], [2] and Rothe [25]. Tijerina et al. [31] investigate amongst others the influence of acoustic information provided in addition to steering wheel oscillation. Recent studies are particularly focusing on the comparison of steering wheel oscillation with other (haptic, visual or acoustic) warning signals, e.g. [29], [14], [18] and [19]. In table 2, the parameters of the symmetric steering wheel oscillations used in these studies are summarized (no parameters are stated in [2], [14] and [32]).

It has to be mentioned that steering wheel oscillations are commonly referred to as steering wheel vibrations (e.g. [14], [18], [19], [29], [31]), which is definitely not incorrect. The term "oscillation" is used in this paper to differentiate between signals induced by alternating torque (i.e. oscillations) and signals induced by vibration motors (i.e. vibrations). Other authors may however use the terms "vibration" and "oscillation" in a different way. For this reason, strong care has to be taken when comparing the findings of different studies.

Table 2. Parameters of steering wheel oscillation

Study	Parameters
Navarro et al. [18], [19]	±4° [1] , 5Hz
Rothe [25]	±0.4Nm, 20Hz
Suzuki & Jansson [29]	±1.5Nm, 5Hz
Tijerina et al. [31]	±1.5Nm, 10Hz, applied for 1s

1. Presumably the steering wheel angular rotation in the unfixed condition

Steering wheel oscillation with torque offset: These signals arise from the combination of a steady torque and symmetric oscillations at the steering wheel (see fig. 2). In this case, the zero position of the oscillation does not correspond to the zero position (i.e. upright position) of the steering wheel. Early studies examining the effect of steering wheel oscillation with offset on the driver were conducted by

Kopf [10] on a test track and by Rothe [25] in a simulator study. Motoyama et al. [17] describe a real road study. Two recent studies conducted by Navarro et al. as well as Navarro et al. and El Jaafari et al. are described in [18], [19] and [19], [20], [5] respectively. In addition, the concept of steering wheel oscillation with offset is compared to other warning signals in [29] and [11]. Table 3 summarizes the parameters used in the cited studies.

Table 3. Parameters of steering wheel oscillation with torque offset

Study	Parameters
Kopf [10]	±4Nm, 15Hz, 1.5Nm Offset
Kozak et al. [11]	±2Nm, 15Hz, no parameter stated for offset
Motoyama et al. [17]	<1.2Nm Offset (adaptive) applied for 1.5s; no parameters stated for oscillation
Navarro et al. [18], [19]	±4.6° [1], 3.3Hz, 1.4° Offset
Navarro et al. [19], [20], El Jaafari et al. [5]	±1.25Nm, 3.3Hz, 0.75Nm Offset
Rothe [25]	±0.4Nm, 20Hz, 0.5Nm Offset
Suzuki & Jansson [29]	±1Nm, 3Hz, 1Nm Offset

1. Presumably the steering wheel angular rotation in the unfixed condition

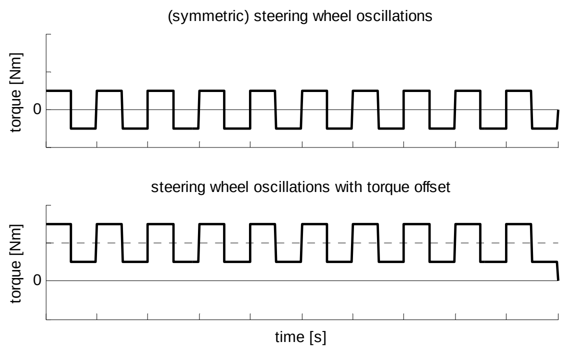

Figure 2. Schematic diagrams of symmetric steering wheel oscillation and steering wheel oscillation with torque offset.

2.2. Steering wheel vibration signals

Based on the authors' knowledge, there is no publicly available study investigating vibrations at the whole steering wheel as lane departure warning signals. However, Navarro et al. and El Jaafari et al. [19], [20], [5] apply vibrations at either the left or right half of a steering wheel (referred to as directional steering wheel vibrations) to warn the driver of an imminent lane departure. To realize the mechanical excitation, vibrators are mounted directly on the steering wheel.

Table 4 summarizes the existing studies on haptic lane departure warning signals at the steering wheel.

3. RESULTS

The studies listed in section 2 differ considerably in many aspects, e.g. type and parameterization of the warning signals (see tables 1 to 3), type of study (driving simulator, test track or real road study), sample size (from n=3 in [26] to n=64 in [31]) or provocation of lane departure events (varying from self induced steering towards the boundaries to lane departure due to micro sleep episodes). This considerably aggravates the comparability of the findings.

To determine the effectiveness of the warning signals, most studies evaluate effects in objective data such as reaction time to the warning (e.g. [2], [11], [14], [17], [18], [26], [29]), maximum lane excursion after the warning ([2], [11], [18], [20], [26], [29]) or time spent outside the lane [11]. While the objective data confirms the effectiveness of LDWS in general, the comparison of modality reveals diverse results, with advantages of the haptic over the acoustic modality in [14], [16], [17], [26], [27] and [29] and vice versa in [2]. This is not surprising considering the huge diversity of the studies as mentioned above.

As the haptic steering wheel warning signals investigated in the cited studies differ considerably in type and parameterization, it is hardly possible to summarize proven facts concerning "a haptic warning at the steering wheel". For this reason it is all the more important to "read between the lines" and to point out some general hints derived in these studies. These hints are discussed in this part.

Steering torque may remain unnoticed: Comparable to the risk of missing auditive information due to background noise, synthetically generated torque at the steering wheel interferes with "natural" torque, especially induced by the interaction of tyres and pavement. This impedes identification of the additional information based on steering wheel torque, thus increasing the rate of missed information. In [11], 32% of all steering torque warnings were missed. At the same time, 33% of all driver reactions were triggered by apparent torque warnings that did actually not exist. In contrast, steering wheel oscillations were recognized in more than 98%.

One possibility that may solve this problem is to overlay static torque jerks with alternating steering wheel oscillation as proposed in [10]. The oscillation emphasizes the synthetic torque information and facilitates its identification.

Table 4. Haptic lane departure warning signals at the steering wheel: studies and denotations
(in chronological order; denotations in italic type are translated from the german denotations)

Signal	Studies
Steering torque jerk	[1] [21] [26] [27] [31]: "torque"; [14]: *"steering torque"*; [16]: "active torque"; [11]: "steering wheel torque"
(Symmetric) Steering wheel oscillation	[1] [32]: "oscillating steering wheel"; [25]: *"shaking steering wheel"*; [31]: "vibrated steering wheel"; [29]: "steering vibration"; [14]: *"steering wheel vibration"*; [18] [19]: "vibratory warning"
Oscillation with torque offset	[10]: *"continuous torque + vibration"*; [25]: *"shaking steering wheel and torque"*; [17]: "vibration + torque"; [29]: "pulse-like steering torque"; [11]: "steering wheel vibration + torque"; [5] [18] [19] [20]: "motor priming"
Directional steering wheel vibration	[5] [19] [20]: "wheel vibratory warning"

Erroneous and reflexive reactions on steering torque jerks exist: Both Ziegler et al. [32] and Bishel et al. [2] report on erroneous reactions following warning by steering wheel torque jerks. Some drivers reacted on the torque jerk by turning the steering wheel in the opposite direction, thus acting against the torque instead of according to it.

This phenomenon was even more distinct when steering wheel torque and oscillation were combined. In [10], 7% of the information on direction transferred by the steering torque is misinterpreted, thus leading to a reaction in the opposite direction. This rate is even higher in [29], where 50% of all steering responses in the unpredicted condition (i.e. subjects were not aware of the meaning of the warning) opposed the direction of the torque. This rate decreased in the predicted condition, but not below 25%.

According to the authors in [29], the mental model of some subjects responsible for the reaction is inappropriate. For example, a steering wheel torque may correspond to the reaction of the car to a lateral disturbance, e.g. a wind gust, thus causing a corrective steering reaction opposing the warning torque. It should however be pointed out that it is not the mental model which is inappropriate but rather the haptic signal, as it triggers the "wrong" model.

While the erroneous reactions described above result from misinterpretations of the warning signal, the literature also reports on (desired) reflexive reactions on steering torque jerks. In [12], some subjects react on torque jerks with a reaction time of 60 to 70ms. According to the authors, these reaction times confirm that the torque jerks caused reflexes. Since reflexive reactions are automatic and can not be inhibited, the driver is overruled. The field of application of this signal should thus be limited to the case of emergency.

The amount of torque desired and accepted varies interindividually: When the synthetic torque applied at the steering wheel is too weak, its perceptibility decreases. Furthermore, a small torque range limits the range of interference of a system based on additional torque. On the other hand, strong torque is to be regarded critically not only in case of fault, but may also be perceived as being intrusive and disruptive.

The thresholds separating torque which is dimensioned in an appropriate manner from too weak and too strong torque are subject to interindividual variability. While 8 of 28 subjects in [21] asked for a higher amount of the applied steering torque (up to 150% of the nominal amount used by the authors), three subjects whished for a lower one (only 30% of the nominal value). Although these results do not allow for generalization, they show by trend that subjects desire and tolerate different amounts of steering wheel torque.

Haptic signals can transmit a meaning: As reported above, Suzuki and Jansson [29] assume inappropriate mental models to be responsible for erroneous reactions on steering wheel torque jerks. According to them, steering wheel torque is sometimes associated to lateral disturbances, thus causing unintended corrective steering reactions opposing the torque.

While this analogy to a known situation is rather hindering, desired analogies can appear in the case of steering wheel oscillation and vibration. These signals are sometimes associated with the rumble phenomenon created when the tyres hit profiled road markings or rumble strips milled into the pavement besides road markings. Thus the driver receives the reason for the warning (i.e. lane departure) along with the haptic warning signal. This analogy contributes to an enhancement in transparency and user acceptance consequently, thereby assisting in performing the correct steering reaction (see [5], [11], [19], [20]). The existence of this analogy is all the more astonishing given the fact that the rumble phenomenon described above is also (and perhaps primarily) perceived with the auditory modality. Hence acoustic lane departure warning signals (unimodal or as part of multimodal warnings) are often realized as acoustic rumble strip sound (e.g. [1], [8], [15], [19], [20], [24], [25], [32]).

Directional information seems to be preferred: Overlaying steering wheel torque with oscillation facilitates the perceptibility of the additional (static) torque, as mentioned above. Another reason for this combination is the addition of some “directional” content to the steering wheel oscillation, which by itself is non-directional and does not inform the driver about the direction of the desired steering reaction (e.g. [17]).

According to the survey conducted in [25], this lack of information on direction is the main fault of a symmetric steering wheel oscillation compared to an oscillation superimposed with static torque. Subjects also preferred warning signals with directional information to non-directional ones in the survey conducted in [31], which was rather clear-cut according to the authors.

Navarro et al. [19], [20] and El Jaafari et al. [5] try to transfer directional information with directional steering wheel vibrations. Two vibrators are mounted on the top half of the steering wheel (“10-to-2-position”) with the vibrating side indicating the direction of lane departure. This is comparable to the concept of directional driver seat vibrations already available as a lane departure warning signal in series production. Since the vibration excited on one side was also perceivable at the other side of the steering wheel and could hardly be distinguished by the subjects, it is mainly the missing information on direction that subjects criticize.

User acceptance is to be taken into consideration: On 1.000 km of car driving, a LDWS recognizes on average 50 to 80 imminent lane departure situations [3]. This rate is even higher for truck applications, partially due to their bigger dimensions. Drivers sometimes guide their vehicle to the lane border intentionally, e.g. when cutting corners. From this it is evident, that the absence of a warning (as in the case of vehicles without LDWS) does not necessarily result in a lane departure accident.

The subjective rating of the warning signal therefore becomes all the more important. Haptic warning signals generally benefit from their privacy, i.e. they are recognized only by the driver (e.g. [6], [10], [24]). As reported in [21], drivers accept some amount of nuisance warning for haptic signals which would not be accepted for audible warnings.

Albeit being applicable as a lane departure warning signal regarding the objective data in [19], [20] and [5], steering wheel oscillations with torque offset are least accepted by the drivers compared to other warning signals (acoustic warning, steering wheel vibration, seat vibration, etc.). Subjects characterized the signal as being intrusive, accompanied with the feeling of loss of control. Vibratory warnings on the other hand (both at the steering wheel and at the seat) were rated as being the best warning signals by most subjects (56%).

4. DISCUSSION

The application of synthetic haptic signals at the steering wheel can assist in inducing a steering reaction by the driver. Several signals and studies were presented in the last years in the field of LDWS, particularly signals based on superimposed torque at the steering wheel.

Based on more than 20 published studies in the last 15 years, most questions concerning the application of haptic lane departure warnings at the steering wheel are expected to be answered. First of all, a little consensus in the signal denotations can be observed, considerably aggravating the comparability of the findings of different authors. The usage of the term “steering wheel vibration” may particularly be mistakable, as this term is used both for signals based on alternating torque and vibrations induced by vibration motors. As a result, findings concerning driver reactions on steering wheel vibrations only allow for limited comparability. To make matters worse, some publications comprise only spare information. Results are often neither statistically documented nor critically discussed. As a matter of fact, the results listed in chapter 3 are to be considered as hypotheses requiring further investigation.

While the general effectiveness of haptic signals at the steering wheel in case of lane departure could be proven (e.g. with respect to reaction time), there still is some room for improvement. From a user’s point of view, a suitable warning signal should at least be clearly perceivable without being intrusive or disruptive. This is especially important when warnings are unnecessary in the driver’s opinion. The signal should furthermore transmit a meaning (“why did I get this warning?”) or at least not trigger the “wrong” mental model. Moreover, the signal should concretely recommend an action (“what exactly am I supposed to do now?”).

To remain with the application of LDWS, a signal combining an oscillation or vibration at the steering wheel (analogy to rumble phenomenon when leaving the road) with directional information seems to be reasonable. In the authors’ opinion, directional steering wheel vibrations are particularly capable of fulfilling the hypothesized requirements. While the single-sided vibrations were mostly felt on both hands in [5], [19] and [20], subjects were easily able to localize and name the vibrating side in a recent study [1]. This study addressed the question whether drivers intuitively steer away from directional steering wheel vibrations (as in the case of a lane departure warning) or toward the vibrations (as proposed in [9]).

Based on the results in [1], the application of directional steering wheel vibrations as lane departure warning signals could be proven. But still some questions remain open. Do drivers really associate steering wheel vibrations to the rumble phenomenon and to they really desire directional information? Future steps are now required to verify these hypotheses that were proposed based on the existing literature.

REFERENCES

[1] Beruscha, F., Wang, L., Augsburg, K., Wandke, H., *Do drivers steer toward or away from lateral directional vibrations at the steering wheel?* Proc. 2nd European Conference on Human Centred Design for Intelligent Transport Systems, 227-236, 2010.

[2] Bishel, R., Coleman, J., Lorenz, R., Mehring, S., *Lane Departure Warning for CVO in the USA*. SAE 982779, 1998.

[3] Breuer, J., *Sicherheitsprognose für neue Assistenzsysteme – Stand und Herausforderungen* (in German). Proc. 4. Darmstädter Kolloquium Mensch und Fahrzeug, 95-101, 2009.

[4] Campbell, J., Richard, C., Brown, J., McCallum, M., *Crash Warning System Interfaces*. Final Report DOT HS 810697, NHTSA, 2007.

[5] El Jaafari, M., Forzy, J., Navarro, J., Mars, F., Hoc, J., *User acceptance and effectiveness of warning and motor priming assistance devices in car driving.* Proc. European Conference on Human Centered Design for Intelligent Transport Systems, 311-320, 2008.

[6] Ho., C., Spence, C., Tan, H., *Warning signals go multisensory.* Proc. 11th International Conference on Human-Computer Interaction, 2005.

[7] Houser, A., Pierowicz, J., Fuglewicz, D., *Concept of Operations and Voluntary Operational Requirements for Lane Departure Warning Systems (LDWS) On-board Commercial Motor Vehicles.* Technical Report, FMCSA, 2005.

[8] Jenkins, D., Stanton, N., Walker, G., Young, M., *A New approach to Designing Lateral Collision Warning Systems.* International Journal of Vehicle Design, 45, 379-396, 2007.

[9] Kern, D., Marshall, P., Hornecker, E., Rogers, Y., Schmidt, A., *Enhancing Navigation Information with Tactile Output Embedded into the Steering Wheel*. Proc. 7th International Conference on Pervasive Computing, Springer, 42-58, 2009.

[10] Kopf, M., *Ein Beitrag zur modellbasierten, adaptiven Fahrerunterstützung für das Fahren auf deutschen Autobahnen* (in German). Fortschritt-Berichte, VDI-Reihe 12, 203, 1984.

[11] Kozak, K., Pohl, J., Birk, W., Greenberg, J., Artz, B., Blommer, M., Cathey, L., Curry, R., *Evaluation of lane departure warnings for drowsy drivers.* Proc. Human Factors and Ergonomics Society 50th Annual Meeting, 2006.

[12] Kullack, A., Ehrenpfordt, I., Lemmer, K., Eggert, F., *ReflektAS: lane departure prevention system based on behavioural control.* Proc. IET Intelligent Transport Systems, 2, 285-293, 2008.

[13] Kutila, M., *Methods for Machine Vision Based on Driver Monitoring Applications.* Tampere University of Technology, 2006.

[14] Mann, M., Popken, M., *Auslegung einer fahreroptimierten Mensch-Maschine Schnittstelle am Beispiel eines Querführungsassistenten* (in German). 5th Braunschweiger Symposium, 81-109, 2004.

[15] Marberger, C., Dangelmaier, M., Widlroither, H., Bekiaris, E., *User centred HMI development in the AWAKE-project*. IEEE International Conference on Systems, Man and Cybernetics, 2004.

[16] Montiglio, M., Martini, S., Murdocco, V., *Development of a lane keeping support system for heavy trucks.* 13th ITS World Congress, 2006.

[17] Motoyama, S., Ohta, T., Watanabe, T., Ito, Y., *Development of Lane Departure Warning System.* 7th ITS World Congress, 2000.

[18] Navarro, J., Mars, F., Hoc, J., Boisliveau, R., Vienne, F., *Evaluation of human-machine cooperation applied to lateral control in car driving.* Proc. 16th World Congress of the International Ergonomics Society, 4957-4962, 2006.

[19] Navarro, J., Mars, F., Hoc, J., *Lateral Control Support for Car Drivers: a Human-Machine Cooperation Approach.* Proc. European Conference on Cognitive Ergonomics, 2007.

[20] Navarro, J., Mars, F., Forzy, J., El Jaafari, M., Hoc, J., *Objective and subjective assessment of warning and motor priming assistance devices in car driving.* de Waard, D. (Ed.) “Human Factors for assistance and automation”, Shaker, 273-283, 2008.

[21] Pohl, J., Ekmark, J., *Development of a Haptic Intervention System for Unintended Lane Departure.* Proc. SAE World Congress, 2003-01-0282, 2003.

[22] Riener, A., *Sensor-Actuator Supported Implicit Interaction in Driver Assistance Systems.* Wiesbaden: Vieweg+Teubner, 2010.

[23] de Rosario, H., Louredo, M., Díaz, I., Soler, A., Gil., J. J., Solaz, J. S., Jornet, J., *Efficacy and feeling of a vibrotactile Frontal Collision Warning implemented in a haptic pedal.* Transportation Research Part F, 13(2), 80-91, 2009.

[24] Rossmeier, M., Grabsch, H.-P., Rimini-Döring, M., *Blind flight: Do auditory lane departure warnings attract attention or actually guide action?,* Proc. 11th Meeting of the International Conference on Auditory Display, 2005.

[25] Rothe, S., *Driver warning system – Sudden sleep warning system* (in German), VDI-Berichte Nr. 1188, 1995.

[26] Sato, K., Goto, T., Kubota, Y., Amano, A., Fukui, K., *A Study on a Lane Departure Warning System Using a Steering Torque as a Warning Signal.* Proc. Symposium on Advanced Vehicle Control, 1998.

[27] Sato, K., Kubota, Y., Amano, Y., *Development of Steering Assist System (STAR) for the Lane Departure Warning.* 7th ITS World Congress, 2000.

[28] Schumann, J., *On the use of discrete proprioceptive-tactile warning signals during manual control: the steering wheel as an active control device*. PhD thesis, Universität der Bundeswehr München, 1993.

[29] Suzuki, K., Jansson, H., *An analysis of driver’s steering behaviour during auditory or haptic warnings for the designing of lane departure warning system.* JSAE Review, 24, 65-70, 2003.

[30] Switkes, J.P., Rossetter, E.J., Coe, I.A. Gerdes, J.C., *Handwheel Force Feedback for Lanekeeping Assistance: Combined Dynamics and Stability*. Transactions of the ASME, 128, 532-542, 2006.

[31] Tijerina, L., Jackon, J. L., Pomerleau, D. A., Romano, R. A., Petersen, A. D., *Driving Simulator Test of Lane Departure Collision Avoidance Systems.* ITS America 6th Annual Meeting, 1996.

[32] Ziegler, W., Franke, U., Renner, G., Kühnle, A., *Computer Vision on the Road: A Lane Departure and Drowsy Driver Warning System.* SAE Mobility Technology Conference & Exhibit, 1995.