A Physiology-based Driver Readiness Estimation Model for Tuning ISO 26262 Controllability

Moses Mariajoseph*, Barbara Gallina†, Marco Carli* and Daniele Bibbo*
**Department of Engineering, Roma Tre University*, Rome, Italy,
moses.mariajoseph@uniroma3.it, marco.carli@uniroma3.it, daniele.bibbo@uniroma3.it
†*School of Innovation, Design and Engineering, Mälardalen University*, Västerås, Sweden, barbara.gallina@mdh.se

***Abstract*—When a hazardous situation approaches, the semi-autonomous vehicle opts for the driver as a fallback solution, unaware of the driver's readiness. During such a situation, autonomy misuse can occur when a driver becomes over-reliant on autonomous driving. For handling the hazardous event, controllability is paramount. We postulate that semi-autonomous vehicles decline their consideration in understanding the drivers' focus on the vehicle and the road. To examine the drivers' focus on the vehicle and the road we uphold that the vehicle must initiate exploring the drivers' situation awareness for the readiness, which could feasibly tune the ISO 26262 controllability. In this paper, we propose a physiology-based driver situation awareness for the readiness model through the driver's stress and drowsiness estimation. In addition, we boost the situation awareness for the readiness of the driver by enabling frequent interaction between the driver and the vehicle managing system.**

***Index Terms*—ISO 26262, controllability; situation awareness for the readiness; physiological signals; interaction.**

I. Introduction

In the recently revised taxonomy and definitions for terms related to on-road motor vehicle automated driving systems, which perform part or all of the dynamic driving task (DDT) on a sustained basis, SAE defines six levels of automation[1]. In level three, the driving automation system performs the entire DDT. However, a DDT fallback-ready user is expected to take over the DDT when a DDT performance-relevant system failure (i.e., hazardous event) occurs or when the driving automation system is about to leave its operational design domain (ODD). As clearly stated, the user is expected to be receptive and able to resume DDT performance when alerted to the need to do so, and contribute to mitigate the risk. Due to the current absence of published standards specifically conceived for self-driving vehicles, ISO 26262 remains the unique reference. ISO 26262 [2] is a functional safety standard targeting safety-relevant automotive electrical and electronic systems. It recommends the adoption of safety life-cycles. The top-level safety life-cycle activities consist in the definition of the system to be developed, identification and categorization of hazards, and on the corresponding risk assessment procedures, known as HARA. Once hazards are identified, they are categorized by assigning the automotive-specific safety level, i.e., an ASIL (Automotive Safety Integrity Level) value. The ASIL can assume one out of five values, ranging from negligible QM and from lower level A to higher level D. The level D represents a hazard that may lead to catastrophic consequences [3]. The value of the ASIL depends on the estimate of exposure, controllability and severity of the hazardous events combined with the operational situation. Once hazards are categorized, safety requirements aimed at reducing risk are elicited as well as traced throughout the traditional steps (i.e., specification, design, implementation, etc.). In more detail, the ISO 26262-related controllability refers to the assessment of the likelihood that, when subject to a hazardous event, the driver of the vehicle is able to avoid accidents [4]. According to ISO 26262-part 9, the ASIL D, highest safety requirement, can only be achieved if less than 90% of the average drivers are able to handle the occurred hazard [3]. Thus, the SAE above-mentioned expected readiness implies a high level of controllability. Despite the fact that SAE-Level-3 demands the complete attention of the driver to ensure the safety task, many tests show that drivers fail in maintaining the focus on the vehicle and the road while the automated driving system performs all of the dynamic driving task [5]. The automated driving system may alert the driver about an impending hazardous event before the vehicle reaches a potentially hazardous situation. As an example, if the preceding vehicle pushes the brake, the automated driving system may request for the driver's attention to push the brake pedal according to the situation demand. However, if the situation does not provide enough time for the driver to act accordingly or if the driver is inattentive (due to over-reliance on automation [6]), an accident might occur.

Monkhouse et al. [4], states that the driver is an important part of the control loop thus requiring that the driver must be fully aware of his/her surrounding environment. For improved understanding of the driving environment, the driver must have good situation awareness for *readiness*. The term readiness refers to the fastest ability of the driver to get engaged in the driving task from the Non Driving Related Task (NDRT) such as radio volume adjustment, speaking over mobile etc. [7]. According to [8], for achieving situation awareness, the driver has to go through three stages hierarchically: perception of elements in the current situation, comprehension of the current situation and projection of future status.

The driver collects the information about his/her current situation environment through perception elements (such as visual, haptic, and acoustic sense) and saves them in the sensory memory. These elements are highly dependent upon the driver physical and physiological states. For instance, if the driver is tired or depressed his/her physical and physiological states might be low [9]. The driver behaviour depends upon the type of task (skill based, rule based or knowledge based) [10]. During this process, the driver gets back to his/her work memory to select the proper action (such as activating the head-body system, hand-arm system, or foot-leg system). Before exploiting a driver as fall back solution, it is crucial for the vehicle management system to understand the driver situation awareness for the readiness: a possible method is based on estimating stress/drowsiness from drivers physiological parameters [11], and the response time of the driver in the driver-to-vehicle interaction [12].

Human physiological function such as heart rate, sweat glands, etc., are controlled by the central nervous systems which can be broadly classified into Somatic Nervous System and Autonomic Nervous Systems (ANS). The ANS involves involuntary body regulations which could be further classified as Sympathetic Nervous System (SNS) and Parasympathetic Nervous System (PNS). SNS helps to prepare the body for intense physical activity (e.g., fight) while PNS relaxes the body by slowing down high energetic functions (e.g., rest and digest) [13]. Increase of SNS leads to stress, while increase of PNS leads to drowsiness. These variations may be detected from physiological parameters [14]. To improve the controllability over the SAE-Level-3, the main contribution of this paper is to estimate the situation awareness for the readiness of the driver through his/her physiological functions, using practically feasible non-invasive medical devices. Similarly, through frequent interaction between the driver and the SAE-Level-3 managing system, we improve the situational awareness for the readiness of the driver. In addition, the SAE-Level-3 managing system evaluates the reaction time of the driver to understand the drivers' situation awareness level for the readiness.

The rest of the paper is organized as follows. In Section 2, we discuss related work, in Section 3, we introduce our proposed model, while our preliminary experiment and the results are discussed in Section 4. Finally in Section 5 the conclusions are drawn.

II. Related Work

The study of driver situation awareness, obtained through physiological functions, can be used for estimating drowsiness or stress induced while driving, or, more in general, the user Quality of Experience [15]. Electroencephalography (EEG) [16] or facial expression detection [17] have been exploited for reliable stress/drowsiness estimation. However, as can be easily imagined, those techniques are of difficult implementation (i.e., the use of an EEG device in the driver's head may cause a restless state). To cope with this issue, indirect measure methodologies have been proposed. For example, ANS activity can be estimated from the heart rate variability indicator (HRV) obtained from the Electrocardiogram (ECG). Vincente et al. [18] proposes drowsiness episodes estimator by analyzing each minute drivers ECG data. Results show that HRV is modified during stress/drowsy state. The HRV helps in identifying the status of a person, but the results used to be hypothetical (as shown in Figure 1). To increase the estimation accuracy, other signals should be considered.

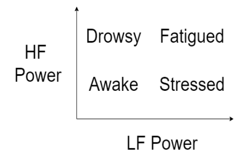

Fig. 1. Hypothetical situation as function of LF and HF power of HRV [18].

ANS activity could also be estimated by exploiting skin conductance. Christopoulos et al. [19] introduced the basic aspects of Galvanic Skin Response (GSR) methodology and explain the behavioral significance of the signal, especially in connection with the emotional experience. Rajasekaran et al. [20] show that a stressful situation may cause an increase of the user respiration rate, thus increasing the subglottal pressure during speech, which is known to increase the fundamental frequency during voiced section.

III. Proposed Model

For identifying the situation awareness for the readiness of the driver, the proposed model is based on four interconnected blocks (as shown in Fig. 2).

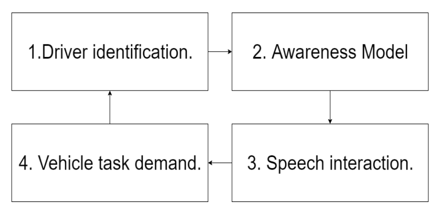

Fig. 2. Proposed model

A. Driver identification

The estimation of stress and drowsiness levels of a person requires the comparison of the collected information with respect to a normal status. Therefore, it is necessary to enroll the user before the driving session. Once stored in a database, the system could automatically retrieve this information after having identified the current user (i.e., by person identification protocols). This information could be stored in the car, or in a cloud-based scenario, could be shared in a reliable way to the control center by means of wireless protocols[21].

B. Awareness model

Stress and drowsiness conditions are estimated from the driver physiological signals [13] and used as input to both the driver and the SAE-Level-3 automation system, thus enabling feeding the SAE-Level-3 automation system with realist information to estimate and tune the controllability, instead of using statistically collected data based on lower levels automation

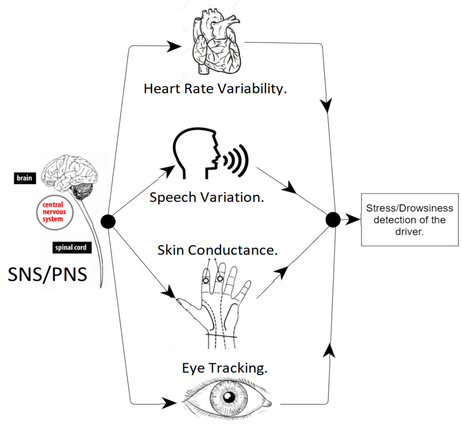

Fig. 3. Stress/drowsiness detection form drivers physiological signals.

systems (i.e., (SAE-Level-0-2). As mentioned earlier, a change in physiological parameters may be considered as indication of increased stress condition (increased heart rate, speech frequency, and skin conductance) or drowsiness (decreased heart rate, speech frequency, and skin conductance). The proposed awareness model exploits non-invasive biomedical devices:

- ECG sensors for HRV analysis. HRV is a commonly used technique for stress and drowsiness detection [13]. The analysis of HRV can be done in both spatial and spectral domain [13].
- GSR for detecting skin conductance. GSR is a bio-marker of SNS activation [19] and is considered one of the most sensitive and valid markers of emotional arousal. During high levels of emotional arousal, sweat secretion is intensely activated. It can be measured using a GSR sensor placed on hands or feet.
- Microphone for recording the speech signal of the driver. The recorded audio signal is used for driver identification and for analyzing modification in the speech. The effect of stress in relation to speech has been investigated over the past decades. Due to the higher involvement of SNS, the contraction of cricothyroid muscles causes high tension, so thyroarytenoid muscle becomes relatively lower causes variation of speech production [20].
- Eye tracker for analyzing the eye motion [22]. To this aim, the eye gaze pattern, the blink frequency, and pupil size may be collected and analyzed. The pupillometric measures change according to cognitive load and emotional processes [23]. In this preliminary work, the eye features collected by eye trackers have not to be considered.

C. Speech interaction

In the next generation of smart cars, it is likely that interaction between the driver and the vehicle managing system will also be obtained by exploiting speech. In the proposed model, we use audio information for analysing speech variation and for evaluating the reaction time of the driver. By analysing the driver speech signals an estimation about the stress/ drowsiness may be obtained.

In general, to achieve higher driver situation awareness for the driver's readiness, it is more crucial to have less NDRT for the driver. This could be obtained by frequent speech interaction between the driver and the vehicle managing system. The driver situational awareness dsa is obtained from the driver's current physiological state C_{state} and the driver skill C_{skill} [9].

$$dsa \approx C_{state}.C_{skill} - NDRT \quad (1)$$

D. Vehicle task demand

This block explains the required amount of effort that the SAE-Level-3 automation system must give through the driver or itself in a specific situation [9]. Different situations require different task demand. For example, having to drive, all of a sudden, a SAE-Level-3 automation system on a rainy night is more demanding than in a sunny day. In general, road conditions, visibility, etc., have a big impact on the driving and control system. As previously mentioned, the driver belongs to the control loop being considered as a fall back solution [4]. Through the awareness model, the vehicle holds sufficient information about the drivers' current physiological status. We believe that the information extracted by the collected signals are highly correlated to ANS, thus resulting in a precise estimation of the stress and the drowsiness of the driver.

Let us assume that the SAE-Level-3 automation system is additionally supported with our proposed model; three main situations may occur:

S1 The driver is stressed or drowsy.
S2 The driver is in a normal physiological condition with poor situation awareness level for the readiness.
S3 The driver is in a normal physiological condition with good situation awareness level for the readiness.

In S1 the vehicle managing system should alert the driver and request the driver to stop the vehicle. In the worst situation the system should stop the vehicle and dial the emergency contact. In S2, an audio interaction between the vehicle managing system and the driver is recommended. Based on the length of the reply delay, a warning sound is suggested for improving the situational awareness of the driver. During S3, in case of take-over-request by the vehicle, the drivers' readiness is high to master the situation. We postulate that adding an awareness model and speech interaction technique in SAE-Level-3 automation systems helps in estimating and improving the drivers' situation awareness for the readiness, through which better controllability is achieved.

IV. Preliminary Experiment and the Results

A. Experiment

The goal of the experiment was to estimate the stress/ drowsiness induced in a person subject to a challenging situation. To simulate such a situation, we asked subjects to perform

TABLE I

POWER OF HRV

SUB/ TIME	Nor mal	1^{st} min	2^{nd} min	3^{rd} min	4^{th} min	5^{th} min	6^{th} min	7^{th} min	8^{th} min	9^{th} min	10^{th} min	11^{th} min	12^{th} min
SUB 1	7.78	L	L	L	L	H	L	L	L	H	H	H	H
SUB 2	18.0	L	L	L	L	L	L	L	L	L	L	L	L
SUB 3	8.28	H	L	L	L	H	L	H	L	H	H	L	L
SUB 4	2.05	H	L	L	L	L	H	H	H	H	H	H	H
SUB 5	0.46	N	N	H	N	H	H	H	H	H	H	H	H
SUB 6	16.5	L	L	L	L	L	H	L	L	L	L	L	H
SUB 7	4.57	L	L	L	L	L	L	H	H	H	L	H	H
SUB 8	2.99	H	L	N	H	H	L	N	H	L	H	H	H
SUB 9	31.0	L	L	L	L	H	L	L	L	H	H	H	L
SUB 10	1.89	H	L	H	H	H	H	H	H	H	H	H	H
SUB 11	3.98	H	H	L	H	N	L	L	H	H	H	H	N
SUB 12	1.60	H	H	H	H	H	H	H	H	H	H	H	H

TABLE II

MEAN VALUES OF NORMALIZED SPATIAL DOMAIN SKIN CONDUCTANCE

SUB/ TIME	Nor mal	1^{st} min	2^{nd} min	3^{rd} min	4^{th} min	5^{th} min	6^{th} min	7^{th} min	8^{th} min	9^{th} min	10^{th} min	11^{th} min	12^{th} min
SUB 1	0.08	H	H	H	H	H	H	H	H	H	H	H	H
SUB 2	0.45	L	L	L	L	N	H	L	L	L	L	L	L
SUB 3	0.09	H	N	L	H	N	N	L	N	N	N	N	L
SUB 4	0.55	L	L	L	L	H	H	L	L	L	N	N	H
SUB 5	0.47	L	L	L	L	L	H	H	H	H	H	H	H
SUB 6	0.48	N	L	L	L	N	H	L	L	L	L	L	L
SUB 7	0.21	H	L	N	H	H	H	H	H	H	H	H	H
SUB 8	0.38	N	L	L	H	H	N	N	N	L	L	L	L
SUB 9	0.15	N	L	H	H	H	H	H	H	H	H	H	H
SUB 10	0.29	H	L	L	L	L	H	N	H	N	N	H	N
SUB 11	0.43	N	L	L	L	L	H	N	H	N	N	H	N
SUB 12	0.16	N	L	L	N	L	H	H	H	H	H	H	H

the Stroop [24], [25] and the arithmetic tests. The Stroop effect is a well known demonstration of cognitive interference where a delay in the reaction time of a task occurs due to a mismatch in stimuli. The arithmetic calculus, even if simple, can cause stress in the user. We use these two stimuli for reproducing a controlled challenging scenario to detect variations in the physiological functions of a person. The test was conducted for 12 healthy volunteers aged between 22 to 27. ECG and GSR signals were collected using the Arduino-Uno board by placing the electrodes on the fingers and on the chest. Speech signals were recorded through a microphone. A Labview interface was designed for Stroop and arithmetic tests [24], [25]. Volunteers were requested to start with the Stroop test and switch to the arithmetic test. Being subject to the time limitations for each task in the test made the volunteer to reach a restless state. In the Stroop test some words, represents the name of a colour, were shown to the volunteer. The words were written in a colored form. The volunteer was asked to name the color of each word, independently from the meaning of the word. In the first part of the test the name and the color were congruent (e.g., the word ”red” was displayed in red) while in the second

TABLE III

VOCAL FOLD P-VALUE (NEUTRAL VS EACH MINUTE)

SUB/ TIME	1^{st} min	2^{nd} min	3^{rd} min	4^{th} min	5^{th} min	6^{th} min	7^{th} min	8^{th} min	9^{th} min	10^{th} min	11^{th} min	12^{th} min
SUB 1	0	-	-	-	0	1	-	1	1	1	1	-
SUB 2	0	-	-	-	0	1	-	1	1	0	-	-
SUB 3	1	-	-	1	-	1	1	1	1	1	1	1
SUB 4	-	-	-	0	-	0	0	-	0	0	0	0
SUB 5	1	-	-	1	1	1	0	1	-	0	0	-
SUB 6	0	-	-	-	0	0	0	0	0	0	0	0
SUB 7	-	-	-	-	0	1	1	-	0	0	0	0
SUB 8	0	-	-	-	0	0	1	0	0	0	0	-
SUB 9	-	-	-	-	0	0	-	0	0	0	0	0
SUB 10	1	-	-	-	1	0	0	1	1	1	1	1
SUB 11	-	-	-	0	0	0	0	0	0	0	0	0
SUB 12	1	-	-	-	-	0	0	-	0	0	0	0

part the name and the color were not congruent (e.g., the word ”red” was displayed in green). While the number of words was increased slide by slide the font size was maintained the same for all the tests. In addition, the time transition between consecutive pages was fixed for further inducing stress in the volunteers. In each transition between consecutive Stroop pages, the arithmetic test (a two-digits integer addition) was proposed to the volunteer. The time length for each arithmetic test was 4 seconds. The Stroop-arithmetic-Stroop alternation was repeated until the end of the experiment. The period of the experiment was almost 12 minutes. Before starting the experiment, physiological signals were acquired in order to set the 'normal physiological function' (i.e., the ground-truth).

The SNS or PNS involvement can be estimated from the ECG tacogram: in general, SNS can be recognized in the Low Frequency (LF) sub-band (i.e., [0.04 - 0.15 Hz]) and PNS in the High Frequency (HF) one (i.e., [0.15 - 0.4 Hz]) [26]. In Table 1, the HRV power was computed as ratio between LF power and HF power, and is reported for each subject with the 1 minute rate. The second column represents the HRV power obtained in rest condition (called Normal in the following). During the experiment, the value of HRV power varies from the Normal one. In Table 1, an increase of HRV power with respect to its Normal value is reported as High (H), a decrease is reported as Low (L), if no sensitive variation is present, it is depicted as Normal (N). Table 2 reports the average values per subject of the normalized spatial domain skin conductance. Also in this case, the second columns represents the rest value. Also in this case, an increase in normalized spatial domain skin conductance is reported as High (H), a decrease is mentioned as Low (L), and for no variation it is mentioned as Normal (N). The analysis of the speech signal was performed by using the inverse filtration technique thus resulting in the removal of the vocal track and lip radiation from the opening and closing waveform of the vocal fold [26]. Vocal folds are tissue folds, located in the larynx, used for producing the sounds for speech. As earlier mentioned, stressed syllables are produced with greater vocal effort, so when the volunteer makes a greater vocal effort, the amplitude of higher frequency components increases more than lower frequency ones. In order to measure the relative distribution of spectral energy from lower to a higher frequency, the spectral tilt was adopted. In the performed experiment, as reported in Table 3, for each subject a statistical (Wilcoxon rank-sum test [27]) comparison was performed: 5 seconds normal non-parametric probability density plot with respect to 5 seconds varied non-parametric probability density plot, obtained during the experiment, were considered. The individual difference of the distribution is statistically significant if the P-value $\leq$0.10, which means during that situation the volunteer might be either stress or drowsy. In Table 3, few rows are left blank (-) due to the fact that according to our experiment design the volunteers' speech signals were not periodic. Similarly, when the subject vocal fold P-value founds below the threshold of $\leq$0.10, it is mentioned a "1", and if over the threshold a "0" is reported.

B. Result Discussion

Our hypothesis is that HRV is a good indicator for estimating the subject status-variation. If the HRV power is H then the subject might be under stress, similarly, if it is L it could be drowsy. By using this information as a trigger, it can be noticed in Table 1, that most of subjects show a possible stress or drowsy condition from 6^{th} to 12^{th} minute of the experiment. The HRV seems to be stable to indicate a stress condition for all the demanding phases of the experiment. Moreover, the subjects need time to recover from these conditions as it is assessed by the indicators in the recovery phase. The given time is shorter with respect to the needed one. While considering the Table 2, it can be noticed that the results are not stable after the 6^{th} minute of the experiment. This may be due to higher sweating of the finger. The GSR data can be apparently considered as a good predictor of the stress/ drowsy condition since the provided information are coherent for all the subject at the beginning of the demanding phase of the test. However, due to the instability of the sensor used, in the following phases, the information provided is not stable since the sweating condition can change in different ways for every subject. In Table 3, subjects 4, 6, 9 and 11 are considered outliers. If we consider both HRV and Vocal fold, we can notice that subjects (other than outliers) start facing the stress / drowsy situation from the 6^{th} to 12^{th} of the experiment, thus confirming the effectiveness of this objective assessment methodology.

V. Conclusions

In this contribution, a driver readiness estimation model has been presented. It is based on the estimation of the driver's stress and drowsiness performed with non-invasive sensors. Electrocardiogram, galvanic skin response, speech, have been identified as possible features able to estimate the driver situation awareness for the readiness. Based on these features, a more realistic tuning of the ISO 26262-related controllability value would be possible. A preliminary experiment has been performed. The results are promising and push us to further investigation.

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