Towards Hybrid Driver State Monitoring: Review, Future Perspectives and the Role of Consumer Electronics*

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Abstract— **The purpose of this paper is to bring together multiple literature sources which present innovative methodologies for the assessment of driver state, driving context and performance by means of technology within a vehicle and consumer electronic devices. It also provides an overview of ongoing research and trends in the area of driver state monitoring. As part of this review a model of a hybrid driver state monitoring system is proposed. The model incorporates technology within a vehicle and multiple brought-in devices for enhanced validity and reliability of recorded data. Additionally, the model draws upon requirement of data fusion in order to generate unified driver state indicator(-s) that could be used to modify in-vehicle information and safety systems hence, make them driver state adaptable. Such modification could help to reach optimal driving performance in a particular driving situation. To conclude, we discuss the advantages of integrating hybrid driver state monitoring system into a vehicle and suggest future areas of research.**

I. INTRODUCTION

According to NHTSA [1], up to 94% of all observed accidents have occurred due to presence of human error i.e., a car crash critical reason attributed to a driver. These errors are complex and often cannot be described by a single impact factor e.g., lack of attention or incorrect control. However, there is generally a major critical reason in every human error related road accident, which is sometimes influenced by a pre-crash event and associated factors. The driver-related critical reasons can be classified into the following types: (i) recognition error e.g., distraction and inattention, (ii) decision error e.g., aggressive driving behavior, (iii) performance error e.g., overcompensation, and (iv) non-performance error e.g., mental fatigue [1]. Thus, it is important to track this multitude of driver-attributed critical reasons in order to pre-determine a high risk of an accident and try to eliminate it by means of in-vehicle safety and information systems. In the early 90's, advances in sensor technology and increase of computational capability turned the research community into investigation of innovative approaches of driving impairments mitigation. New research streams emerged aiming to measure driving performance, context, and driver behavior. Modern Advanced Driver Assistance Systems (ADAS) e.g., parking assist and adaptive cruise control, became very robust in interpreting vehicle state and context; this has significantly enhanced vehicle's awareness of a driving situation. However, the majority of these systems do not address common cause of abnormal driving behavior, that is constantly changing drivers' state. Impaired mental and physical state makes a driver prone to errors and could lead to dangerous driving [2]–[4]. On-board tracking and analysis of drivers' state (in synchronization with driving context and performance) could help to estimate and mitigate the risk of incorrect vehicle control prior to its actual occurrence, which subsequently has a potential to reduce the number of human error related road accidents. Such feature is often referred to as Driver State Monitoring (DSM) system. Frost & Sullivan [5] have forecasted that the variations of DSM is expected to become a standard passenger car feature by 2025.

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II. DRIVER STATE MONITORING

In the course of the last two decades the human factors research community has been working toward implementation of a DSM system. In early 90's, the concept was discussed in the publication by De Waard & Brookhuis [6] as part of Dedicated Road Infrastructure for Vehicle Safety in Europe (DRIVE) initiative. Authors have foreseen a demand for such system and referred to it as a Driver Status Monitoring device. They concluded that it is important to keep track of driver's state to allow detection of short-term driving performance deviations from its ideal state. Today, the concept has significantly evolved. The experimental and commercial implementations often consist of multiple devices that contribute to the goal of valid and reliable evaluation of drivers' state, and, to some extent, are capable of estimating up to four driver state constructs: (i) cognitive distraction, (ii) mental workload, (iii) mental fatigue, and (iv) emotions (see TABLE I). These driver state constructs were found to influence driving performance both positively and negatively [2]–[4], [7]–[12]. Some of those were found to impair driving, for example high level of mental fatigue was found to be responsible for up to 20-30% of road fatalities [13]. High level of mental workload might lead to negative stress and may cause driving performance impairments and distraction from the primary task of driving [3], [14]. In contrast, low level of mental workload might lead to degraded vigilance and cause mental fatigue [15]. Mental workload was also proven to be a good indicator in estimating driver's mental capacity [16]. According to Ranney et al. [17], distraction is a critical factor in up to 25% of all observed road accidents. Emotions, and anger in particular, were found to degrade driving performance [18].

Happiness, on the other hand, could be beneficial to driving [19]. Clearly, the evidence shows that until a human remains in full or partial control of a vehicle, drivers' state is an important aspect of driving and cannot be neglected due to its critical influence.

In recent years, few attempts were made to understand and balance state of a driver through variety of objective and subjective methods in order to mitigate an effect of human error on road safety. Some researchers expressed the importance of introducing different elements of DSM to complement existing ADAS and In-Vehicle Information Systems (IVIS). However, there is no direct agreement in the literature upon what driver state extraction methods must be primarily included in an efficient DSM system. Among these methods, the subjective measures are fundamentally not suitable for commercial DSM, because they are generally measured before or after a driving activity by means of self-reporting therefore, cannot provide driver state reference for real-time systems. Today, human factors researchers explore various objective methods to measure driver state constructs that were proven to correspond to certain physiological phenomena, such as heart, brain, electro dermal, and eyelid activity. For example, Paxion et al. [20] concluded that the most sensitive measure to mental workload seems to be the electrical heart activity i.e., Electrocardiogram (ECG). The generally accepted method of deriving mental fatigue level is eye blink pattern analysis, commonly referred to as PERCOS, that is proportion of time the eye remain 80-100% closed [21]. Brain [22] and heart [10] activity were also found to be a good indicator of fatigued driving. Some physiological phenomena were found to be viable measures for two or more driver state constructs. For example, electrical heart activity and blood pressure can be used to objectively measure levels of mental workload [16], stress [9], and mental fatigue [23]. Eyelid activity tracking was used to estimate level of mental fatigue [21] and detect visually distracted driving [24].

TABLE I. Driver State Constructs.

Driver state construct	**Definition**
Cognitive distraction	"*any activity that diverts a driver's attention away from the task of driving*" [17, p. 1]
Mental workload	"*the specification of the amount of information processing capacity that is used for task performance*" [16, p. 15]
Mental fatigue	*"a functional state, which grades in one direction into sleep, and in the other direction into a relaxed, restful condition, both of which are likely to reduce attention and alertness."* [10, p. 175]
Emotions	*"a complex pattern of changes, including physiological arousal, feelings, cognitive processes, and behavioral reactions, made in response to a situation perceived to be personally significant."* [25]

Indeed, the driver state is truly multidimensional. However, its evaluation by means of physiology could be obscured due to intrapersonal nature of physiological indicators e.g., heart rate patterns may vary between individuals due to differences in age or gender. It requires comprehensive sensory network in order to reliably trail and interpret multitude of constantly changing physiological phenomena. Due to presence of complex interrelationships between driver state constructs and their indicators it is important to keep track of as many physiological phenomena as possible to promote valid and reliable interpretation, because none of the individual physiological indicators can guarantee full correlation with underlying driver state construct. Additionally, physiological measurements are prone to errors and artefacts hence, cannot guarantee full reliability. Therefore, a DSM system must account for it by including alternative methods of capturing those indicators. For example, heart rate sensors could be embedded into a vehicle's seat or a seatbelt and alternatively, same measurements could be captured though a wearable device attached to driver's body. However, this will require extensive computing capabilities to deal with fusion of alternative data sources. Frost & Sullivan [5] declares three real-time data sources that a DSM system may be linked to, these are (i) built-in (embedded) sensors, (ii) brought-in (peripheral integration) devices, such as smartphones and wearables, and (iii) cloud-enabled (broadcast) information transmitted from external databases. For the purpose of this paper, a system that incorporates data from multiple sources can be referred to as hybrid DSM system.

Dong et al. [11], in the review of driver inattention monitoring systems, have indicated the need for a hybrid system that is capable of combining driver state metrics with driving performance (e.g., vehicle speed, acceleration, and steering wheel angle), as well as driving context (e.g., the road type, weather conditions, and traffic density). Hybrid evaluation is believed to provide more reliable and valid solution in estimating drivers' state. Barua [26] backs the suggested approach in her thesis. The author accentuates that the approach of considering one aspect of features is not completely reliable and therefore, the recognition could be more accurate when a system combines multiple sources of information about the driver.

III. Trends in Driver State Monitoring

Significant amount of research into DSM was conducted as part of European Union (EU) funded projects [27] i.e., DETER [28], SAVE [29], SENSATION [30], and DESERVE [31]. DETER project investigated the relationship between driving performance and driver impairment. SAVE project looked into potential solutions to mitigate driving impairments by analyzing driver state, driving performance and contextual data. Several data fusion methods were applied to generate seven criteria in order to determine if appropriate warning needs to be issued or vehicle emergency handling needs to be initiated. The Integrated Monitoring Unit (IMU) was developed and patented as part of this project. SENSATION project was aiming to explore wide range of sensor technologies to allow real-time and cost-effective human physiological state monitoring in relation to fatigue and stress. DESERVE project structure included eight subprojects, one of which was aiming to develop and integrate a DSM application to complement ADAS. The sensory network consisting of camera, physiological sensors and eyelid motion module was used in order to estimate driver distraction and drowsiness. The projects discussed above have presented some elements of DSM, but did not manifest system design recommendations.

A. Automakers' adoption of DSM

Several car manufacturers have also contributed to the development of DSM. In 2006 Toyota presented its first version of driver monitoring system [32]. The system was able to determine the direction of the driver's face and included eye activity feature extraction through front-facing camera. The company emphasized the importance of such system, it claimed that the critical safety warnings can be issued to the driver earlier than it would be possible without such system. The press-release stated that "*the development of driver-condition evaluation technologies is vital to improving overall vehicle safety performance, as driver condition is seen as a key factor in traffic safety*."

Ford has been actively collaborating with MIT's New England University Transportation Center to understand the correlation between stressors and driving performance and identify technological advancements that both mitigate stress and create a more enjoyable experience. Collaboration resulted in creation of in-vehicle stress tracker based on heart activity measurements [33]. A later version of the system combined data from a driver i.e., heart rate, sweat data, temperature, and breathing patterns, with data from a car, including acceleration patterns, steering adjustments, and braking [34]. The prototype consisted of multiple sensors embedded into the seatbelt and steering wheel.

Volvo and VTT Technical Research Centre of Finland have also developed a method for monitoring driver status though front-facing camera [35]. The method is based on an assessment of the driver's eye direction and behavior. The project was in the research stage from 2004 to 2008 and the system is now commercially available in the new Volvo XC90.

Mitsubishi Electric has developed a machine-learning technology that detects cognitive distraction in drivers [36]. The system combines driving performance e.g., steering wheel angle, physiological indicators e.g., heart rate, and head position to determine current drive state and compare it to the "appropriate" driver state predicted by machine learning. If a distraction is detected, the relevant alerts are presented to the driver. Company has stated that technologies for detecting cognitively and visually distracted driving are expected to be sold commercially from around 2019 or beyond.

BMW has developed a DSM system incorporating wide range of sensors to acquire information from three sources: a vehicle, environment, and a driver [37]. In their experimental setup a vehicle was fitted with driver-facing camera for head position and point of gaze extraction. The driving performance metrics were also collected though Controller Area Network (CAN) i.e., acceleration and speed. The company discussed an importance of adopting machine learning e.g., Neural Networks and Support Vector Machine, for better drivers' intention prediction. The setup was aiming to complement Lane Departure Warning System (LDWS), making it adaptable to contextual, performance, and driver state metrics e.g., LDWS is set to higher awareness level if a driver is known to be fatigued. The company highlights current limitations of modern ADAS and IVIS, that is absence of driver information [38]. It believes the driver state evaluation could shape truly intelligent in-vehicle safety and information systems.

Jaguar Land Rover (JLR) is also exploring innovative ways to measuring driver's state [39]. The company has presented its projects under "Sixth Sense" research initiative. One of these is "Mind Sense" project, which aims to derive driver's concentration level by keeping track of brain activity; if the system detects fatigued driving it will initiate pedal or steering wheel vibration in order to bring driver's concentration level back into optimal state. JLR has also equipped its Jaguar XJ test vehicle with Driver Wellness Monitoring seats for research purpose. The seats are embedded with sensors which keep track of heart and respiration emitted vibrations and derive driver's stress level. The company is planning to link driver state metrics with in-car ADAS in order to mitigate distracted and stressful driving i.e., automatically change in-car ambient lighting, audio settings, and climate control.

B. Smartphone-based sensing

Engelbrecht et al. [40] categorized applications of smartphone-based sensing into four major types, that is (i) traffic information (i.e., location of other vehicles or pedestrians), (ii) vehicle information (i.e., vehicle heath telematics), (iii) environmental information (i.e., road and weather condition), and (iv) driving performance (i.e., acceleration, braking and etc.). Smartphone based systems usually employ embedded sensors e.g., accelerometer, gyroscope, magnetometer, and GPS, to derive behavioral and contextual driving information. Smartphone embedded cameras could be also used to assess drivers' state. For example, mobile software solution offered by Affectiva Inc. [41] allow human emotional state detection though facial expression analysis.

Johnson & Trivedi [42] have presented completely mobile way to detect and recognize driving events and driving style. The system employs smartphone's sensors in aggressive and non-aggressive driving detection. The system actively detects and records events that characterize driving style, thereby increasing the awareness of potentially-aggressive actions. The authors claim that their mobile system is capable of detecting vehicle movements with similar data quality to a vehicle-provided telematics. However, the system did not incorporate IVIS or ADAS links, therefore it is incapable to counteract aggressive driving.

Lee & Chung [43] have developed a smartphone based DSM system using a data fusion approach to combine eye features, physiological indicators, and driving performance metrics. The Fuzzy Bayesian Network (FBN) was adopted to estimate driver's state (vigilance) index in the scale from zero to hundred percent. When 75% index was detected, a fake phone call was initiated in order to alert the driver about potentially dangerous driving state. The chosen mitigation method is prone to false alarms and could result is distracted driving. The system can be improved by enabled link with ADAS and IVIS. This could promote the substitution of smartphone based alert with some adaptable auditory, visual or haptic feedback emitted by IVIS.

C. *Wearable devices*

Katsis et al. [44] have presented a real-time wearable system for remote car racing drivers' emotional state estimation. The system consists of three subsystems: (i) wearable part i.e., specially designed Electromyography (EMG) sensors embedded in subject's fireproof mask, a respiration belt, ECG sensor placed on subject's chest, and Electro Dermal Activity (EDA) monitor placed on left hand, (ii) data acquisition and wireless communication subsystem, and (iii) centralized subsystem, which stores all acquired data and performs statistical analysis for driver's state estimation. The state is classified into high stress, low stress and valence i.e., dysphoria and euphoria. Experiments revealed that emotions do not always correlate with specific driving events; subjects may experience different emotional patterns during the same events, depending on their personalities. Unfortunately, the system did not incorporate a method for unfavorable emotion mitigation. Also, the custom built sensory mask is not a feasible solution in the context of passenger vehicle therefore, unlikely that this method would be accepted by passenger car drivers.

Healey & Picard [9] have developed a stress tracking system, which consists of a network of wearable sensors that do not interfere with the driver's perception of the road. The authors managed to derive stress using five-minute intervals of ECG and EDA. They conclude that these two indicators provided the highest overall correlations with driver stress level and suggest that the first sensors that must be integrated into a car should be skin conductance and heart rate sensors. They also emphasize that these measures could be used in future intelligent transportation systems to improve safety and to manage IVIS cooperatively with the driver.

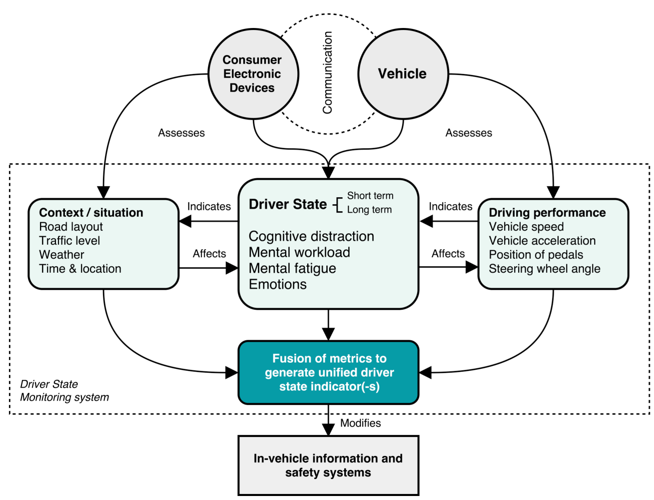
Lin et al. [45] have presented a wearable sensor module equipped with Photoplethysmography (PPG), which is the method of deriving heart rate from measurements of blood volume fluctuations. The module transmits captured data to the smartphone it is synchronized to. The analysis of data is performed on the smartphone, where the heart rate detection algorithm is implemented. In the case of abnormal heart rate the smartphone application is programmed to use the sound and vibration alerts to warn the driver. The results suggest that the system is able to monitor heart rate without any substantial artefacts in the driving context. The method may enable the physiology assessment outside of driving activities thus, provide a vehicle with long-term driver state evaluation.

Rigas et al. [12] have developed a methodology for detecting drivers' stress, fatigue, and predicting driving performance. The system combines multiple data sources i.e., (i) physiological indicators, including ECG, EDA, and respiration, (ii) video recording of driver's face, and (iii) environmental measures. Every data stream is run though feature extraction mechanism and then combined in the feature selection module. Next, classification is performed by means of Support Vector Machines (SVM). The authors conclude by demonstrating the impact of fatigue on driving performance and emphasize that the method they have presented can contribute to early detection of driving impairment.

IV. THE MODEL

In this section a model of hybrid DSM system, which combines the potential requirements for adequate system design, is envisioned (see Figure 1). The model accounts for major DSM trends and promotes a realistic design that could be implemented using currently available technology. The model relies on a dynamic relationship between system constructs i.e., driver's state, driving performance and context (Figure 1), which addresses the need of hybrid DSM for more sophisticated interpretation of driver's state. The DSM could be further improved by dividing driver state into two categories, that is long-term and short-term [46]. Long-term state is usually influenced by longstanding fatigue or mental workload, whereas short-term state is usually influenced by temporary impairments i.e., interim cognitive distraction, mental workload, fatigue, and elicitation of various emotions. For example, work-related stress may affect driving performance in the long period of time, whereas short-term stress may be caused by some unexpected road event and then promptly dissipate. Both cases may be equitably important and must be accounted for.

Figure 1. Hybrid Driver State Monitoring System Diagram.



The model also identifies potential data sources i.e., actual vehicle (built-in sensors) and CEDs (brought-in devices) with emphasis on reliable connection between CEDs and a vehicle. Based on previous discussion, the system should incorporate technology within a vehicle and multiple brought-in devices for enhanced validity and reliability of recorded data. Additionally, the model draws upon requirement of data fusion in order to generate unified indicator(-s) of driver's state that could be used to modify in-vehicle information and safety systems. Such modification could help to bring driver's state and driving performance back into an optimal condition in a particular situation. The system could also track the direct influence of a driving situation on driver's state and, hence, try to estimate the severity of any particular event. Driver state could also serve as an indication for some specific driving context e.g., individual physiological patterns could be detected during night time driving or during high traffic density situations.

The successful implementation of proposed DSM design model is believed to have a significant environmental and social impact. A hybrid DSM system could potentially enhance road safety by reducing possibility of road incidents that mostly happen due to human error. Also, it has consistently been shown that an impaired driver state influences driving performance, which might lead to inferior fuel economy. A vehicle user might also experience some tangible benefits of such DSM system. It could be used to innovate human-machine interfaces (HMIs), making them more affective and non-intrusive. The customer value could be generated by improving convenience of particular IVIS. These could become driver state dependent and present only relevant feedback to a driver. Hence, offer enjoyable driving experience.

V. Discussion and Conclusions

The abundance of evidence suggested that road safety could benefit from introduction of sophisticated DSM system. Automakers, however, do not rush to innovate existing ADAS and IVIS by means of DSM. Some attempts have been made to integrate some elements of it into existing vehicles, mostly, consisting of image based processing devices for visual distraction and fatigue level estimation. The reluctance may be caused by high integration cost of new technology into a vehicle. Nevertheless, research community continues to innovate DSM. There is an emerging field of research which aims to adopt advances in smartphones and wearable sensory technology for DSM purposes. This ties well into the scope of a hybrid system, which advocates in the favor of comprehensive sensory network for enhanced validity and reliability of data. Furthermore, CEDs may accelerate integration of DSM into the vehicles and eliminate the need for in-vehicle integrated sensors to capture driver physiology.

A. DSM to complement existing ADAS and IVIS

ADAS systems usually act in a linear manner, that is it adopts the same method to mitigate an inappropriate control every time. Similarly, IVIS generally inform a driver in a linear manner too e.g., always issue a visual signal when a vehicle is detected in a blind spot or issue an auditory signal when collision danger is present. The linear approach has a potential to cause the task overload or distraction by providing feedback or control mitigation at inappropriate times, or at times when the driver is engaged in corrective action. Without the mechanism of detecting driver state, current ADAS and IVIS are unable to vary its methods accordingly. Perhaps, future ADAS could become driver state dependent, that is vary safety alertness level depending on the individual driver. This could help to eliminate, sometimes, unnecessary active safety system intrusions e.g., issue a lane departure warning when the driver is fully aware of a situation. IVIS could also become driver state dependent, and only issue non-critical warnings when a driver is known to be capable of processing that information. Also, if a car is aware of driver's attentiveness level, IVIS could vary its methods of presenting non-critical cues e.g., radio, incoming calls or navigation commands. Similarly, the critical cues could be issued in the most efficient way and the time it takes for the driver to react can be evaluated. Finally, the IVIS could become adaptable to driver's presentation preferences thus, provide truly non-invasive driving experience.

B. DSM and autonomous driving

Rapid ADAS development will eventually result in implementation of full vehicle autonomy [47]. It is forecasted to reach its commercial state and penetrate 9% of automotive market by 2035 [48]. Full driving automation has the potential to entirely eliminate the effect of human errors in the context of driving thus, oust the need of DSM system as a tool to counteract unfavorable driver behavior. This is certainly a legitimate statement, but there will be manual driven vehicles for many years, mostly, fitted with semi-autonomous features that require sophisticated techniques for short-notice manual control take over with a predetermined length of time [49]. Therefore, a DSM system could promote a time-efficient transition of control. Dr. Wolfgang Epple, JLR's Director of Research and Technology has spoken in support of DSM technologies in the context of autonomous driving [39], "… our research team is looking at the potential for a range of driver monitoring technologies to give the car enough information to support this decision [manual control take over]. If the car detects severe health issues, or simply how alert the driver is, then the car could take steps to ensure the driver is focused enough on the driving task to take over."

C. Future Research

Before DSM systems can be integrated into a commercial vehicle there is abundance of issues that have to be solved first, ranging from innovations in hardware and software, required for reliable driver state tracking and processing, to human factors implications of such integration e.g., acceptance of DSM. Therefore, future research should focus on the following areas: (i) sensory network integration into a vehicle in a flexible way as well as communication of multiple sensors in the context of DSM, (ii) implementation of DSM cloud data collection module to support driver state aware infrastructure, (iii) innovations in brought-in data acquisition methods in the scope of particular driver state constructs, (iv) fusion of DSM metrics, and (v) integration of driver state into vehicles' assistance systems i.e., modification of ADAS and IVIS based on DSM outputs.

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