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Analysis of autonomic indexes on driver's workload to assess the effect of visual ADAS on user experience and driving performance in different driving conditions

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ABSTRACT

Advanced driver assistance systems (ADASs) allow information provision through visual, auditory, and haptic signals to achieve multi-dimensional goals of mobility. However, processing information from ADAS requires operating expenses of mental workload that drivers incur from their limited attentional resources. The change in driving condition can modulate driver's workload and potentially impair driver's interaction with ADAS. This paper shows how the measure of cardiac activity (heart rate and the indexes of autonomic nervous system) could discriminate the influence of different driving conditions on driver's workload associated with attentional resources engaged while driving with ADAS. Fourteen drivers performed a car following task with visual ADAS in a simulated driving. Driver's workload was manipulated in two driving conditions: one in monotonous condition (constant speed); and another in more active condition (variable speed). Results showed that driver's workload was similarly affected, but the amount of attentional resources allocation was slightly distinct between both conditions. The analysis of main effect of time demonstrated that drivers' workload increased over time without the alterations in autonomic indexes regardless of driving condition. However, the main effect of driving condition produced a higher level of sympathetic activation on variable speed driving compared to driving with constant speed. Variable speed driving requires more adjustment of steering wheel movement to maintain lane-keeping performance, which led to higher level of task involvement and increased task engagement. The proposed measures appear promising to help designing new adaptive working modalities for ADAS on the account of variation in driving condition.

INTRODUCTION

The rapid improvement of Advanced Driver Assistance Systems (ADASs) and the growing number of their implementations in vehicles have increased, to some extent, road safety and have resulted in better mobility [1, 2]. Generally, types of ADAS could be distinguished into four broad categories [3]: (1) systems that give information to support driving activity such as road navigation and information about traffic conditions, commonly known as intelligent vehicle information system (IVIS), (2) systems that support driver by giving warning/feedback to reduce driver's errors or mistakes (e.g. collision warning system, lane departure warning), (3) systems that partially take over driving task but still requires driver intervention to resume the control in certain condition (e.g. Adaptive Cruise Control (ACC), Intelligent Speed Adaptation (ISA)), and (4) systems that fully overtake driving task without driver role to control the vehicle (e.g. self-driving car). Recently, demands in the type of ADAS that supplements driver with information and feedback for the purpose to influence driver behavior toward safe and eco-driving have emerged [4-6]. This type of system operates by giving continuous and real-time feedback to advice driver in adopting 'smart' driving (i.e. both safe and eco-friendly). Although, the objectives to achieve safer and more efficient fuel consumption could be arguably achieved by other type of ADAS such as automated driving system, ADAS advisor is considered more superior, concerning the maintenance of driver situational awareness and enhancement of driving skill over the time, thereby avoiding the issue of automation effects [7].

However, the increasing number of traffic volume has made the road traffic even more complex and potentially demand drivers' attention more steadily. This situation could impose more challenges to the design of such advisory system as its implementation could introduce distractions and excessive workload, which are contributing factors to road accident. In a previous study, the increase of traffic demand was found to have influence on task-performance in dual-task driving [8]. Different traffic conditions produced variation in driver workload during dual-task driving which resulted in a slower reaction time in response to the demand of secondary task in higher traffic demand as opposed to lower traffic demand. From this finding, it could be suggested that workload induced by ADAS interaction should match with the fluctuation of road demand as to ease up driver in attending primary driving task. One way to achieve this implementation is to adjust the working parameter of ADAS (e.g. headway distance) to accommodate the uptake of higher driver attentional resource in higher workload condition as demonstrated by [9]. Considering this aspect in ADAS design would better facilitate drivers to manage their attentions to safety critical situations or/and improve their abilities to meet the wider range of traffic demand. Thus, design and development of ADAS that promote optimal cooperation with driver in different driving condition is a vital element for the realization of traffic road safety. This present study focused on the issues related to the design of ADAS that presents continuous and real-time feedback (hereafter, referred ADAS advisor) aiming to help drivers in achieving the performance goals (i.e. safety and eco-friendly).

Safety Assessment of ADAS Design

The problem in the design of ADAS advisor has been mainly concentrated to the design of Human-Machine Interface (HMI). The key issue focuses on designing the interaction between driver and assistance system concerning the communication of driver's information. This concern arises due to the provision of information to the driver could either produce excessive workload or increase the likelihood of diverting driver's attention away from the traffic. Some attempts have been done for identifying the problem in the HMI design for ADAS and its implication on driving performance and road safety.

In the last decade, a comprehensive study was conducted under the framework of European project HASTE with the objective to investigate the effect of visual/cognitive IVIS task load on driving [10]. The primary finding of this study demonstrated that the additional task imposed by in-vehicle device has distinct impacts on driving performance and visual behavior between visual and cognitive demands. This study also pointed out different strategies adopted by drivers to maintain an acceptable level of performance (i.e. lane keeping) in face of different types of task demand. The additional task, which requires visual time-shared with a driving task, leads driver to reduce the speed and/or to apply large steering corrections. Conversely, the task with cognitive loads lead the driver's eye movements concentrated on the road center and it turns out improving the lane-keeping performance. The conclusion of this study suggests the inclusion of event detection measure in order to capture safety related impact of cognitive and visual task loads, which are compensated by driver behaviors.

In [11] the authors investigated the effect of cognitive demand induced by a surrogate in-vehicle system on event detection. The results of this study proved that the influence of cognitive distraction as a side effect of in-vehicle system had a little impact on the response to a braking lead vehicle. However, the differences in event detection between driving with or without in-vehicle system were apparent considering driver ability to detect the bicyclist along the side of the road. The reaction time to respond to the bicyclist increased during dual-task driving, and the increase in reaction time was also observed as the duration of interaction increased from the first to the subsequent minutes.

Apart from cognitive distraction, the risk of accident was also thought intuitively to increase as the driver look away more often from the roadway to interact with in-vehicle technologies and become momentarily unaware about road condition. To establish a direct relationship between driver behavior and risk accident, the study conducted in United States [12], which uses the data of 100-car naturalistic driving, inferred that while short glances away for the purpose of scanning road environment are safe and actually improve safety, the glance duration of eyes-off-road more than 2 seconds for any purpose increases near-crash/crash risk at least two times of normal driving. Based on this reference, reducing the complexity and the length of task required by a device which limit the interaction in a single short glance away may minimize the increased risk associated with distraction. Recently, the study [13], which assessed the effect of IVISs on driver visual behavior, found that the use of navigation system requiring visual time shared with driving task increases the percentages of eyes-off-road time of 14.3% as compared to 6.7% of baseline condition. While, the assessment of visual attention on driving advisory device showed that drivers spent on average of 4.3% of their time looking at the system. Nevertheless, the impact on safety is minimal due to both glances durations, for both in-vehicle devices that were more than 2 seconds were very few, and the average glance durations were well below two seconds in duration, 0.76 seconds for navigation system and 0.43 seconds for driving advisory device.

The assessment of affective/emotional states in addition to visual and cognitive workload to improve the usability of in-vehicle devices has also been studied [14]. In their study, a multimodal data processing of physiological data was proposed to infer the emotional states of the driver for predicting user satisfaction as well as the computation of task performance as indicator of cognitive workload. The implementations of physiological and behavioral computing thus allow the objective identification of usability issues of in-vehicle device in real-time without altering the task performance of the driver, and thereby allowing continuous detection of driving condition that could interfere with the operation of in-vehicle device.

Based on the conclusions of these studies, it can be stated that driving task is mental resources demanding and increasing visual/cognitive load would increase the risk of being exposed in critical situation. The assessment of visual/cognitive demand is necessary to evaluate potential distraction and overload following the use of in-vehicle system. This is especially important for the type of ADAS that gives complementary information and feedback, intended to optimize driver execution to meet road demand. Safety assessment is necessary to evaluate whether this innovative technology could support driving task without a hidden cost that can compromise driver safety. The review from the previous studies suggest that the key point for safe implementation is that ADAS should be designed in a way that it does not take more visual/cognitive resources beyond that are required for primary driving task. In other words, the impact of task load induced by ADAS should be able to facilitate driving task without bringing detrimental effect to safety by degrading driving performance in critical situation.

In order to obtain more insight on how additional task demand from ADAS may have an influence on driving performance, it is worth considering the model of task performance and mental workload as a function of task demand [15]. In Fig. 1., task performance and mental workload consisted of six regions in which the optimal region (A2) is where the operator can easily manage the task requirement with the optimum level of performance. Two regions (A1 and A3) where the optimal region (A2) lies in between are the regions where the task performance remains stable in response to change in task demand, either higher or lower, at the cost of effort exerted. Task-related effort is related to the increased task demand, whereas state-related effort refers to the decrease in task demand. Other two regions (D and B) are the regions next to each effort-related region where effort is no longer possible and hence performance declines.

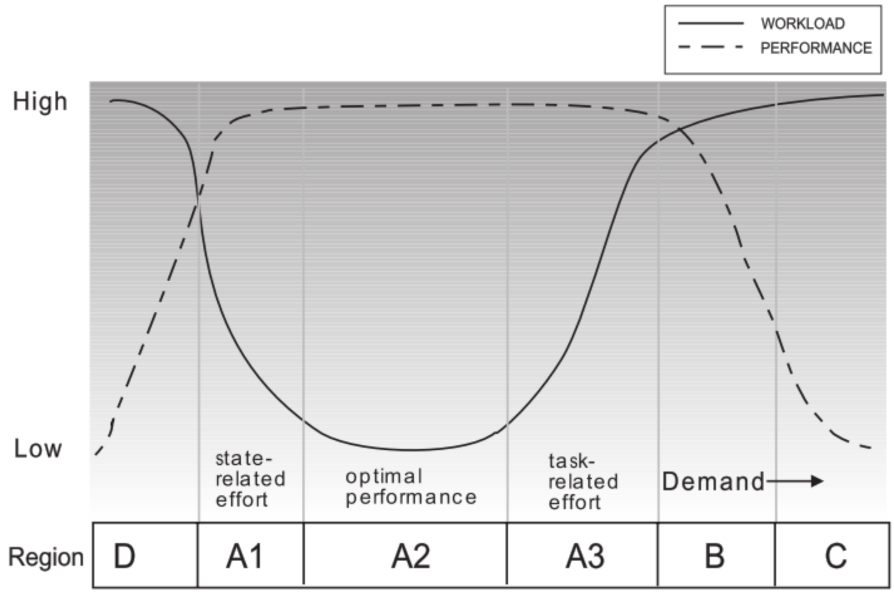

Fig. 1. The variation of workload and performance in six regions, the figure is taken directly from the source [14]

The last region (C) is associated with minimum level of performance where the operator is overloaded. While the regions where performance degrades (D and B) must be prevented, ADAS designer should always target driver's mental workload at optimal performance (A2) and avoiding critical regions or effort related (A1 and A3) even though task performance could still be maintained to a certain degree, by increasing effort. For this purpose, the design of ADAS that promotes optimal performance in dual-task driving with ADAS and the method to detect the increased effort while driving with ADAS on the account of dynamic environment are necessary to achieve this objective.

Driver's Mental Workload While Driving with ADAS

In the previous section, distinction is made between task demand and mental workload [15]. Task demand has been viewed as external and independent of the individual. The demand itself is made up of sub-tasks with certain performance levels that have to be met by every individual for accomplishing the task. In relation to driving task demand, the author [16] proposes the hierarchical model that posits car driving as a multi-task activity, consisting of processes at a minimum of three hierarchical levels: strategic, tactical, and operational. This model views that activities from each level interact dynamically, from higher level of general road trip planning (strategic), via obstacle avoidance (tactical) to lower level of immediate vehicle control (operational). These series of processes constitute driving task demand that are imposed on driver in which certain level of performance on each hierarchical level is required for achieving safe mobility. Thus, the complexity of task depends on the context of the task itself. For instance, high-congested traffic increases driving task complexity as the number of activities in each level increases.

On the other hand, mental workload is the level of difficulty experienced in response to the task demand which dependent on individual. Mental workload reflects the expenses of limited attentional resources available to perform the task at certain level of performance. According to [17], the allocation of attentional resources to achieve task performance depends on the type of task demand. Rasmussen's performance model divided three level of task performance based on cognitive demand;

knowledge-based, rule-based, and skill-based. Task that is never encountered before would require high attentional resources allocation to achieve the performance goal (knowledge-based performance). While task that involves the application of learned rules requires partial attentional resource allocation (rule-based). Finally, task that requires minimum/no attentional resources are automated (skill-based performance). Further, the hierarchical model of driving task [16] and performance model [17] has been related by [18] to distinguish the differences of experienced load (mental workload) as person-specific capabilities that differ between individuals. For example, novice driver tends to experience higher mental workload as compared to experienced driver. However, as a driver becomes more experienced, most of the control actions will be based on the learned rules and skill-based which lead to a decrease in experienced workload.

Although, driving capabilities become the fundamental factor that affect the amount of cognitive processing while driving, the variation of mental workload experienced by driver can still be modulated by traffic conditions and driving conditions. Excessive demand could occur at each sub-task, and hence, the introduction of ADAS should not only be facilitating driver to perform driving task but also relieving driver from trying harder to maintain task performance.

The demand of the driving task could also be seen as goal-directed activity as depicted in COCOM/ECOM hierarchical control model [19]. This model differs slightly from the hierarchical model of driving task proposed by [16], which consists of four levels control from higher to lower level; targeting, monitoring, regulating, and tracking. *Targeting* refers to the general goal of driving task. *Monitoring* refers to the regular observation of vehicle and traffic information. *Regulating* involves the task to continuously maintain the desired safety margin. *Tracking* refers to dynamic control of speed and directions. Unlike the former model, this model has put forward that each level of task as goal-directed activity, in which the control of one level could undermine or enhance the control of other levels. In terms of the proposed model, ADAS could be characterized based on the goal(s) they are intended to support.

For instance, in-vehicle system that assists eco-driving might at least provide support on regulating and tracking layer (i.e. helping driver to maintain proper speed and pedal’s position). In the case of eco-driving device is being used, inappropriate design could give rise to excessive workload during high demanding situation which is potential to position driver to operate near the threshold of his convenience. Additional task demand from ADAS, besides workload increment as a result of driver’s interaction with more demanding traffic condition (e.g. transition from rural to urban area), could increase the level of difficulty for maintaining dual-task performance. In this situation, driver would have choices to either exert more effort to maintain the current performance with ADAS or to reduce the task demand required by ADAS (driving without ADAS) in order to remain comfortably in vehicle control (i.e. avoiding the interference with *monitoring* and *regulating* layers). In the case when effort is exerted, the author in [20] argues that effort mechanism could take place not only when the operator spends more energy in response to an increase in task complexity (computational effort) but also during the situation when the operator’s state diminishes from the required state (compensatory effort). For example, facing unstimulating or monotonous task would trigger compensatory effort to keep up with the performance goal. Both efforts have been shown to manifest in increases in mental workload [15, 20]. The model COCOM/ECOM complements the concept of limited workload capacity and together gives a more complete understanding on driver’s strategies to negotiate the change in task demand based on workload experienced while driving with ADAS.

Therefore, the performance gain obtained when driving with ADAS advisor could also possess pitfalls related to the increment in mental workload as a result of continuous changing of driving demand. When the task demand is escalated due to an encounter of increasing complexity of traffic demand, drivers may choose to deactivate the system instead of exerting effort in order to focus on the primary driving demand. In contrast, under low traffic demand, it is probable that drivers may perform additional secondary task (i.e. having phone conversation) to remain wakeful in attending to ADAS. From this point of view, the consequence of effortful interaction with ADAS under certain circumstances could some extent affect user acceptance toward the system. While, in a more extreme view, the absence of effort due to inadequate of processing resources at a cost of divided attention might lead to adverse impact of driver safety (i.e. fail to comply with critical information requested by ADAS).

Purpose of the Study

The assessment of ADAS advisor to improve vehicle control was often targeted at the cost associated with driver-ADAS interaction in terms of additional demands imposed to the driver. Common assumption that is held in defining optimal design of such assistance system beside perceived benefits, has often focused on how this critical information delivered to the drivers in a clear and unobtrusive ways [3]. There are at least two considerations usually required to ensure effective utilization of ADAS advisor by the driver. Firstly, the performance goal set by ADAS should not be too strictly high as it could add more workload to the drivers and interfere with primary driving task. Secondly, the presentation of information should not introduce distractions and excessive workload as to allow drivers to use this information at their conveniences to influence their decision making in driving.

However, these requirements are insufficient due to driver’s task engagement can be modulated by dynamic change of driving environment. Numerous studies have shown that drivers’ mental workload can easily vary with respect to driving environment [21, 22]. For instance, monotonous driving environment (e.g. highway and rural area) that requires a little number of information processing could potentially reduce driver’s alertness and place drivers into passive mode. This situation may raise several concerns if driver chose to use ADAS that particularly gives continuous feedback to support driver in underload situation. For example, one of the issues would be if the driver would need to try harder to keep up with safety instruction provided by ADAS in underload condition due to a reduction in driving task engagement. Other questions that follow could be whether or not the change in effort could be detected, and eventually whether or not this situation could be avoided.

The present study focused on state-related effort, which was modulated by the change in driving condition. This study was carried out based on the experimental setup in the previous study [23] in which an experiment was designed to test the car-following ADAS that presented continuous feedback through visual interface for assisting drivers to maintain the safe headway distance to a leading vehicle. The impact of dual-task performance on driver’s mental workload while driving with ADAS was evaluated in two different working modalities: one in a monotonous condition (constant speed); and another in a more active condition (variable speed). In the current study, driver’s mental workload was assessed in relation to subjective assessment of workload and fatigue as well as driving performance to evaluate possible impacts on user acceptance and driver safety. Some specific research questions addressed by current study were: (1) can continuous interaction with ADAS advisor impose increment in mental workload in monotonous situation? (2) can the change in mental workload quantitatively be measured?, and (3) can this situation be compensated by the design of ADAS itself?.

METHODOLOGY

Procedure

Fourteen healthy participants who held a driver's license with a minimum of three years driver's experience volunteered for the experiment. All participants were graduate and post-graduate students and consisted of one female and thirteen males with the mean age of 25.9 year-old (SD = 4.4) and drove regularly at least three hours weekly.

Each participant was required to perform a car-following task in two driving trials that differed in speed regulation, i.e. constant speed and variable speed, while the order of the test was counterbalanced. Before the experiment began, the participant was instructed to relax for three-minutes, sitting in the driver's seat while being equipped with physiological sensors for recording physiological activities under rest period. After that, they took five minutes driving familiarization scenario to become familiar with the control of driving simulator and virtual driving environment before the experimental session. They were also given ten-minutes adaptation scenario and were instructed to practice two driving tasks that they were about to do in the driving tests. The adaptation scenario was a continuous shortened-version of two driving scenarios (five minutes each) that represent experimental sessions, and was designed to minimize any novelty or learning effect that might be experienced by the participant during the driving test. After driving adaptation, the instruction about the driving task was repeated and each participant performed two driving tasks that lasted for 30 minutes where each task was separated with five-minutes rest period. Physiological data were also recorded throughout the driving sessions. During the rest period, they filled out fatigue and workload questionnaires. Participants was also informed before that he/she could request to stop the experiment in case of uncomfortable feeling experienced during the driving session without any problem. In the conclusion of the experiment, participants were asked in an informal interview about their driving experience as to which they thought and felt during both driving trials.

Driving Task

This study attempted to investigate driver's mental workload variation while driving with ADAS in different condition under monotonous environment. Driving environment was designed within rural area, composed of only straight road. Roadside along the drive was green environment with trees, grass, and mountains. The environment also consisted very light traffic with oncoming vehicle at every twenty seconds of driving. This situation was designed to create monotonous impression that constituted repetitive and predictable visual perception. Two car-following conditions in assisted driving were administered:

1. Car following with constant speed. The subject was required to follow the lead vehicle that travelled with constant speed at 40 km/h. The road was marked with a single white solid line and subject was instructed to stay

behind the lead vehicle until throughout the drive. This condition was used as a control group.

2. Car following with variable speed. This condition was similar with previous one except the lead vehicle changed the speed to 40 km/h or 60 km/h at every 30-s interval. The subject needed to adjust their speed accordingly to catch up with the lead vehicle.

Driving tasks also included the necessity to maintain the vehicle's position at the center of the lane for both driving tests without any external assistance. Nevertheless, for the control of headway distance, subjects drove with the aid of visual assistance system that displayed the visual signals that they needed to respect throughout the drive to keep the safe distance. The visual assistance system was designed as head-up display positioned at the bottom left of the windshield for right-hand traffic as shown in Fig. 2. The system used time headway as a safety indicator and indicated three colors (red-green-red) that was used, as in [24] to signify the headway as too close (< 1.8 s), appropriate distance ($1.8 < t < 2.5$ s), and too far (> 2.5 s) from lead vehicle. Subject was instructed to keep the appropriate distance by referring to the green signal (middle bar) during the entire driving sessions. This way of representation enabled the driver to easily perceive the safe distance from the lead vehicle as to keep relatively constant safe distance.

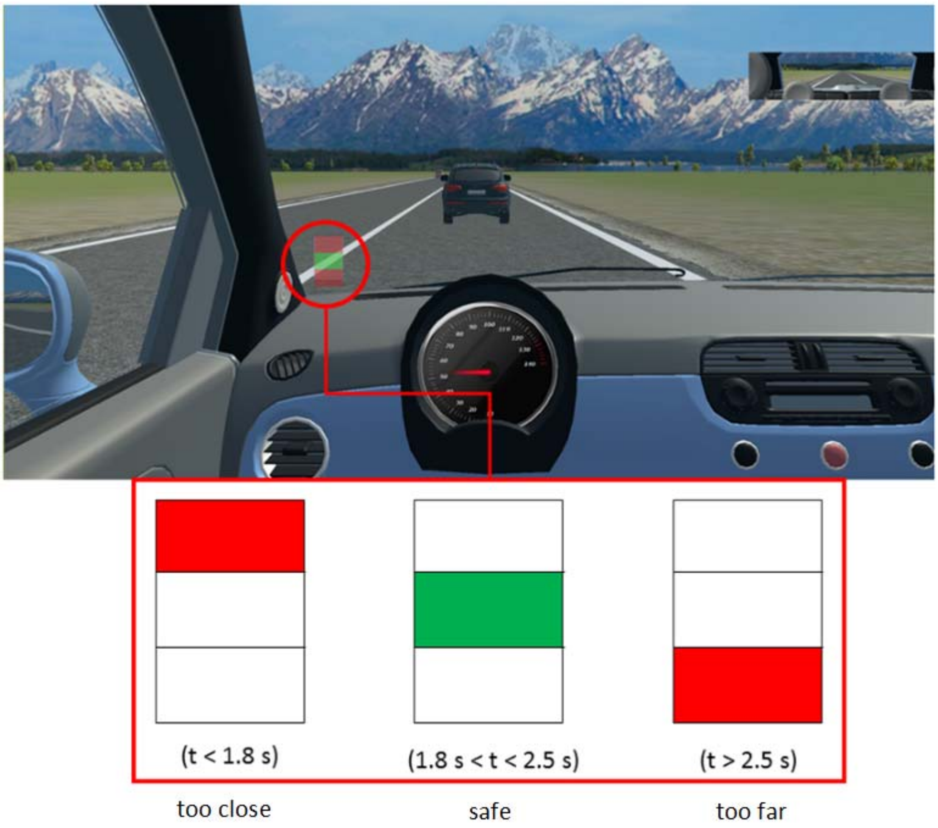

Fig. 2. The design of ADAS that guides driver to maintain safe headway distance through visual interface based on time headway

Tools and data measures

A fixed-based driving simulator was used to simulate a monotonous driving experience for assessing the influence of monotony on the driver's state, and consequently, its impact on the interaction with ADAS. Driving simulator comprised a set of vehicle control such as a steering wheel with force feedback, gear shifter with automatic transmission, and brake and gas pedals. The sound of engine and surrounding traffic were spatialized by using a 5.1 surround sound system with a subwoofer.

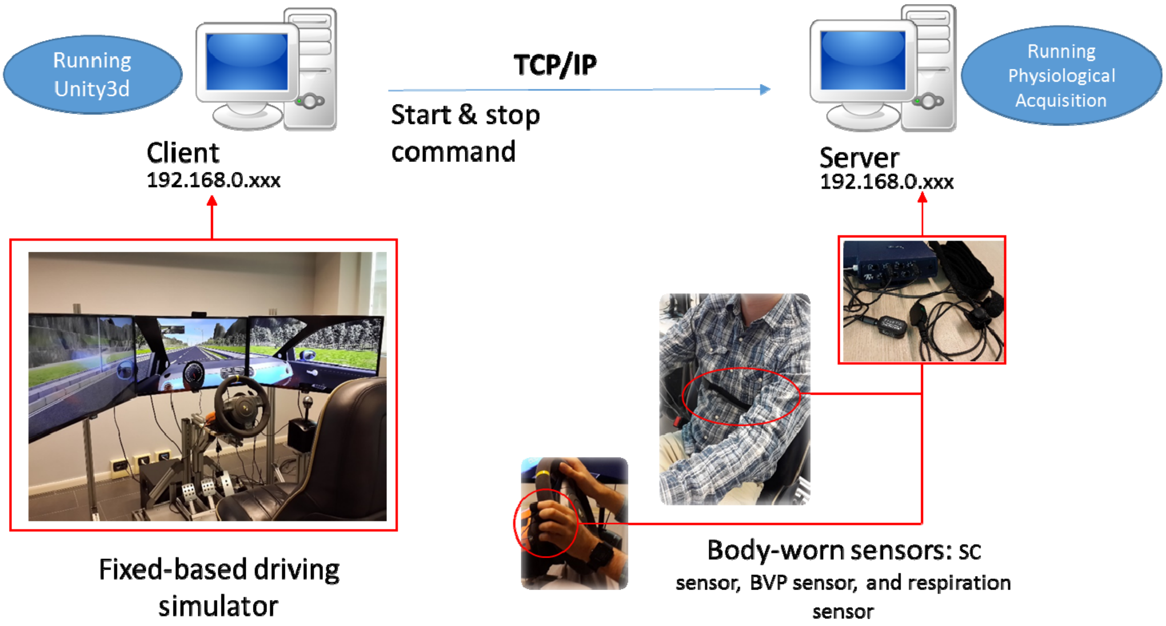

Fig. 3. System architecture of driving simulator and physiological sensors setup

The driving scene was displayed in three-screens providing 36 degrees and 165 degrees on vertical and horizontal field of view respectively. Virtual driving environment was built on the Unity game engine [25]. This engine was also used to interface between vehicle controls and multi-modality displays (visual, auditory, and haptic feedback) of virtual driving experience in simulator system. The driving simulator was equipped with the commercial physiological sensor Biograph Infinity system from Thought Technology [26] to record skin conductance, respiration rate, and blood volume pressure (BVP) for identifying driver’s state. The physiological data acquisition runs in a server computer, and communicated with Unity software running in a client computer through TCP/IP as depicted in Fig. 3. This network allowed the synchronization of start and stop data record across multiple data acquisition. Consequently, physiological data could be analyzed easily in comparison with vehicle data (e.g. speed, acceleration, lateral position, steering angle, etc.) and driving scene that were recorded at 50 Hz and 30 frame/sec respectively based on our current system implementation.

Physiological Measures

Physiological responses from cardiac system were investigated to assess the change in mental workload demand for two driving contexts. Among the other physiological measures, mean heart rate has been established to be a sensitive indicator to the change in mental workload [27]. However, the measure of heart rate alone in response to increased task difficulty can be limited in terms of diagnosticity of resource allocation [28]. This is particularly due to cardiac activity is controlled by the combination of two branches of autonomic nervous system (ANS), namely sympathetic nervous system (SNS) and parasympathetic nervous system (PNS). Thus, the amount of mental workload experienced in response to the change in task difficulty was determined by the product of sympathetic and parasympathetic activations. According to the literature, the analysis of sympathetic and parasympathetic activities in autonomic space [29] could distinguish different cognitive operations that contribute to the change in mental workload in dual-task setting [30-33].

The concept of autonomic space determines the relationship between SNS and PNS in which three different types of activity could be elicited: uncoupled, reciprocal, and co-activity. Uncoupled activity represents the increase of activity in one branch while activity in the other remains unchanged. Reciprocal activity occurs when there is an increase of activity in one branch followed by a decrease activity of the other branch. Co-activity describes the relation when there is either increased or decreased activation in both branches. The representation of sympathetic and parasympathetic in autonomic space defines the mode of autonomic control of cardiac activity [29].

Furthermore, the mode of autonomic control identifies processing efforts underlying the change in mental workload in human-task interaction. Based on a previous study in automotive field [31], performing a driving task that mainly relied on perceptual/manual processing would elicit uncoupled parasympathetic inhibition mode that is reflected by a decrease in parasympathetic activity without the significant activation in sympathetic activity from resting state. While, adding a side task to the driving that incurs central processing demand (i.e. working memory or mental arithmetic task) would stimulate sympathetic activity that in turn would elicit reciprocally coupled sympathetic activation and parasympathetic inhibition mode of control in autonomic space. In addition, it has also been shown that the increased demand of central processing resources induced by the need to switching attention in manual tracking task while driving would trigger uncoupled sympathetic activation [33].

In this current study, the mean heart rate was used as mental workload indicator to measure and detect the change in effort over time while driving with ADAS in different driving context (see Fig. 4). The autonomic indexes were incorporated to the analysis of mental workload to determine the influence of autonomic mode of control elicited by ADAS. Autonomic indexes were plotted in a 2D autonomic space to show the autonomic mode of control elicited for different tasks over the time (see Fig. 5). Sympathetic activity as indexed by BVA was plotted on *x-axis* and parasympathetic activity as indexed by HF-HRV on *y-axis*. The vector in autonomic space was standardized values that were obtained from the mean difference of the baseline value (the origin) divided by its standard deviation for both BVA and HF-HRV across driving condition and time. From the origin coordinates (0, 0), the change toward the negative value in *x-axis* indicates the increase in sympathetic activation from resting baseline. While, the negative value in *y-axis* indicates the increase in parasympathetic inhibition from resting baseline.

Physiological data were obtained from blood volume pressure (BVP) sensor that was placed on the middle finger of subject’s left hand and recorded at sampling rates of 2048/s. Two important features from the BVP raw data such as blood volume amplitude (BVA) and inter beat interval (IBI) were analyzed and extracted using algorithm from BioGraph Infiniti software. BVA has been investigated as widening or contraction of blood vessels that are controlled by autonomic nervous system (ANS). Previous studies have shown that the contractions of microvessels of the finger that is due to the increases activation of sympathetic tone was found to cause a decline in BVA [34, 35]. This feature was then used as an index of sympathetic activity. Furthermore, the IBI data that was derived from BVP signal could be further elaborated in frequency component to derive cardiac vagal tone in high frequency range between 0.15 Hz and 0.4 Hz, namely high frequency of heart rate variability (HF-HRV), which represents the contribution of parasympathetic nervous system to cardiac regulation [36, 37]. Therefore, HF-HRV was used as an index for parasympathetic activity.

Data reduction for BVA followed the same procedure as in [35]. BVA data were visually checked with respect to the BVP raw data and were excluded from the statistical analysis when the artifacts were more than 20%. For the IBI data, ARTiiFACT software [38] was used to correct the artifacts and to process heart rate variability (HRV) parameters. The initial process of artifact correction was done by automatic artifact detection module followed by a visual checked of the BVP raw data. In order to keep the temporal relationship between data points and prevent data distortion in HRV frequency components, each data that was considered as artifact was substituted with interpolated data using cubic spline function. The result of artifact-free dataset was then analyzed with ARTiiFACT software to calculate HRV in time domain and produce the parameter of mean heart rate, and in frequency domain (0.15 Hz – 0.4 Hz) to obtain HF-HRV.

Driving performance measures

Driving performance such as standard deviation of lateral position (SDLP), standard deviation of steering wheel angle (SDSWM), and mean amplitude of steering wheel movement (SWM) were recorded and extracted from driving simulator. SDLP was used as the index for lane-keeping performance, while SDSWM and mean amplitude of SWM were considered as indexes for steering wheel management.

Subjective measures

Subjective perceived workload was measured using the NASA-TLX [39] administered after each driving trial. Participant rated a workload score from 0 to 100 on how much workload in terms of six components (mental, physical, temporal, performance, effort, and frustration) that they had experienced during assisted driving. In addition, self-perceived fatigue was also recorded in a post-drive using Swedish Occupational Fatigue Inventory (SOFI-20) [40] that consist of 20 Likert-type scale questions related to five dimensions of fatigue (lack of energy, physical discomfort, physical exertion, lack of motivation, and sleepiness).

Data Analyses

The impact of ADAS advisor on driver's mental workload was assessed in two working modalities induced by different driving conditions; following the lead vehicle that run with constant speed and variable speed. To assess the change in workload during the drives and variation over the time, driving duration for each condition was subdivided into two-time blocks where the first-time block (Time 1) was the first five minutes of driving, while the second-time block (Time 2) represented the last five minutes of driving. Statistical analysis of variance (ANOVA) was performed to determine the effect of within-subject factors, 2 (working modalities: constant speed, variable speed) X 2 (time: Time 1, Time 2) on physiological measures and driving performance indexes. Two sets of analyses were performed on physiological data. The first was to test statistical significant differences of all physiological responses from resting baseline for different tasks over time. The second was to test statistical significant effect of ADAS working modalities (constant, variable speed) and time (Time 1, Time 2) for all physiological indexes. Reactivity scores of physiological indexes were calculated and used as data input to statistical model to determine the effects of ADAS working modalities and time. Following the analysis of physiological data, the statistical analysis of behavior data was examined to test the statistical significant influence of ADAS working modalities (constant, variable speed) and time (Time 1, Time 2) as to determine the influence of driver’s mental workload on driving performance. Finally, analysis of multivariate ANOVA was performed to test statistical significant effect of ADAS working modalities on overall scores of self-perceived workload and fatigue as well as different effect of ADAS on each dimension of perceived workload and fatigue. Further, the analysis of univariate ANOVA was carried out to test statistical significant effect of different ADAS working modalities on each dimension of perceived workload and fatigue. An alpha value of .05 was selected to determine significance for all statistical tests. In the case when Mauchly test returned significant results in univariate repeated measures ANOVA, Greenhouse-Geisser estimates of sphericity was used [41, 42].

RESULTS

Physiological Measures

The impact of different ADAS working modalities on physiological measures (mean heart rate, HF-HRV, and BVA) was examined initially in comparison with the resting baseline. For statistical data analysis, natural log (ln) transformation was applied to the measure of HF-HRV (ms^2) to normalize its distribution that tends to be positively skewed [43].

The change in mean heart rate from resting baseline for each ADAS working modality in each time block was computed. Fig. 4. shows a lower level of mean heart rate as compared to the baseline condition in Time 1 regardless of ADAS working modality. However, as the driving period continued to the second-time block, the increase in heart rate was observed to approaching the baseline condition in both groups.

Data were analyzed with one-way repeated-measures ANOVA to examine if the change of mean heart rate from resting baseline was statistically significant. The analysis showed that there was no significant within-participant differences on mean heart rate, $F(1.932, 25.155) = 3.149$, $p = 0.062$, partial $\eta^2 = 0.195$ between resting baseline and driving sessions for both ADAS working modalities for both time blocks.

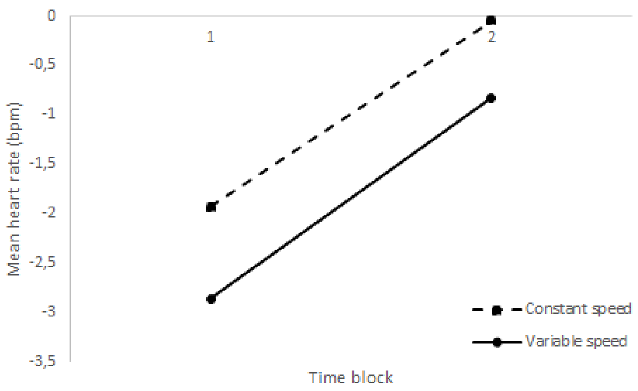

Fig. 4. The changes in mean heart rate from the resting baseline in the first- and second-time blocks for different working modalities

Following the analysis of mean heart rate, autonomic indexes were visited to see whether there were differences in attentional resources processing between resting baseline and driving tasks. Separate one-way repeated measures ANOVA were performed on HF-HRV as an index of parasympathetic activity as well as BVA as an index of sympathetic activity. The analysis of a one-way repeated measure ANOVA showed that dual-task driving elicited statistically significant changes in HF-HRV from resting baseline, $F(4, 52) = 11.849$, $p < 0.0005$, $\eta^2 = 0.477$, whereas no statistical significant changes were found in BVA, $F(1.553, 20.190) = 1.848$, $p = 0.188$, $\eta^2 = 0.124$.

More specifically, a simple contrast with Bonferroni adjustment (preserving the alpha value of 0.05 by dividing it with the number of comparisons [42, 44]) showed that HF-HRV magnitude during dual-task performance were statistically significant suppressed from resting baseline for both ADAS working modalities in both Time 1 and

Time2. For constant speed in the Time 1, $F(1, 13) = 22.735$, $p < 0.0005$, $\eta^2 = 0.636$, and Time 2, $F(1, 13) = 24.376$, $p < 0.0005$, $\eta^2 = 0.652$. For variable speed in Time 1, $F(1, 13) = 16.917$, $p < 0.005$, $\eta^2 = 0.565$, and Time 2, $F(1, 13) = 22.200$, $p < 0.0005$, $\eta^2 = 0.631$. Data were presented in Table 1.

From the analysis of autonomic indexes in autonomic space, these results showed that drivers elicited uncoupled parasympathetic inhibition over the time regardless of ADAS working modalities. Furthermore, a two-way repeated-measures ANOVA was run to test the main effect of different ADAS working modalities and time on the reactivity scores of physiological responses (mean heart rate, respiration period, HF-HRV, and BVA) and the interaction between independent variables. The result found statistically significant main effect of time on the increased of mean heart rate from Time 1 to Time 2, $F(1, 13) = 18.725$, $p < 0.005$, $\eta^2= 0.590$, regardless of different ADAS working modalities, $F(1, 13) = 1.226$, $p = 0.28$, $\eta^2 = 0.086$.

On the other hand, the analysis on autonomic mode of control in autonomic space showed that drivers appeared to elicit distinct pattern of uncoupled parasympathetic inhibition mode of control in different working modalities as shown in Fig. 5.

Table 1. Mean and standard deviation for physiological responses for constant and variable speeds in the first and second time blocks

	Constant speed				*Variable speed*			
	time block 1		*time block 2*		*time block 1*		*time block 2*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Heart rate (bpm)	-1.931	3.583	-0.046	4.661	-2.866	4.952	-0.828	5.410
HF-HRV* [ln(ms^2)]	-0.795	0.624	-0.879	0.666	-0.797	0.725	-0.707	0.562
BVA (arbitrary unit)	0.418	4.432	0.501	3.845	-1.095	3.201	-1.085	3.698

*** statistical test: $p < 0.05$**

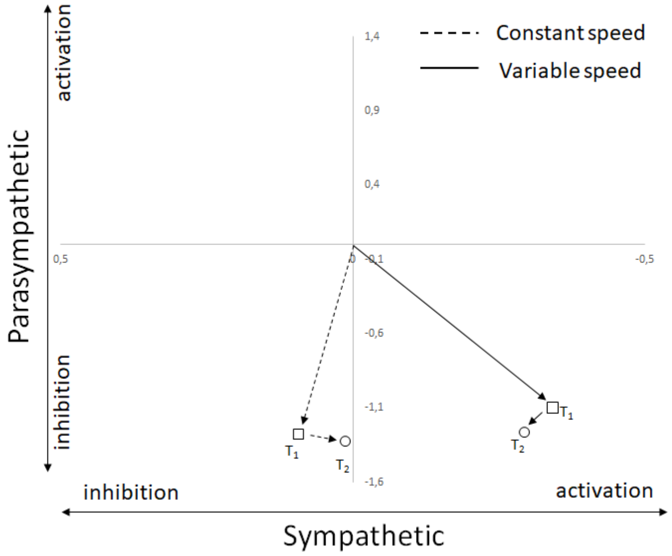

Fig. 5. Cardiac control for two working modalities; constant speed (dashed line) and variable speed (solid line) over the time (T_1 to T_2) in autonomic space

HF-HRV was observed to decrease in both speed conditions during the Time 1 and remained slightly constant in the Time 2. On the other hand, the result of simulated driving showed that driver's interaction with ADAS in variable speed condition produced a trend toward sympathetic activation as indexed by a larger decrease in BVA from resting baseline, whereas a shift in the direction of sympathetic withdrawal was observed when the speed was kept constant. Similar with parasympathetic control, the change in sympathetic control between Time 1 and Time 2 appeared to be slightly stable regardless of speed conditions. Statistical analysis showed the main effect of working modality was statistically significant different on BVA, $F(1,12) = 10.191$, $p < 0.01$, $\eta^2 = 0.459$, regardless of time, $F(1, 13) = 0.335$, $p = 0.573$, $\eta^2 = 0.025$, but not on HF-HRV, $F(1,12) = 0.669$, $p = 0.429$, $\eta^2 = 0.053$, irrespective of driving periods, HF-HRV, $F(1, 13) = 0.001$, $p = 0.977$, $\eta^2 = 0.0005$.

Behavioral Measures

A two-way repeated-measures ANOVA was run to examine the effect of ADAS working modalities and time as to provide comparable analysis within the same aggregate between physiological data and behavior measures on SDLP, SDSWM, and mean amplitude of SWM.

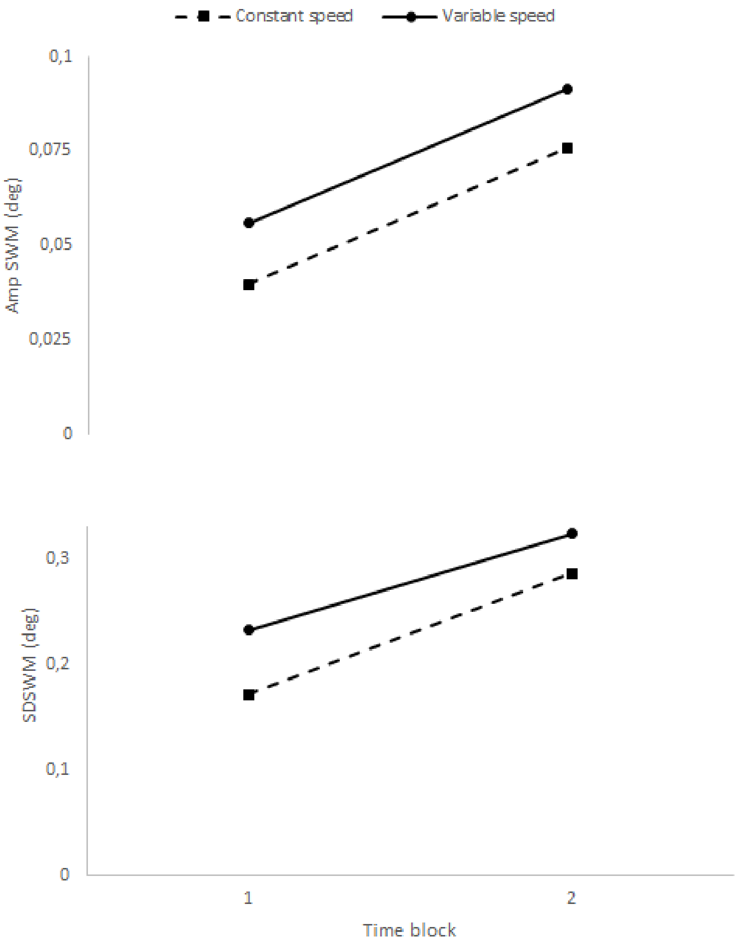

Fig. 6. Steering wheel management performances, as indexed by amplitude of steering wheel movement (SWM) and standard deviation of steering wheel movement (SDSWM) between two working modalities over the time

The result of the analysis found a statistical significant main effect of ADAS working modality on the mean amplitude of steering wheel movement, $F(1,13) = 21.841$, $p < 0.0005$, partial $\eta^2 = 0.627$, but not on others measure such as steering wheel angle variability, F(1,13) = 3.431, p = 0.087, partial η^2 = 0.09, and lane-keeping variability as indexed by SDLP, F(1,13) = 0.387, p = 0.545, partial η^2 = 0.029. The results may suggest that the difference in lateral control performance between driving with different speed conditions was apparent in steering wheel management and was more sensitive in the mean amplitude of steering wheel movement. Drivers exhibited a larger magnitude of mean steering wheel movement when driving with variable speed than with constant speed as shown in Fig. 6. This finding also showed that drivers appeared to be more active in steering wheel handling when the speed was varied to maintain the same level of lane-keeping performance when the speed was kept constant.

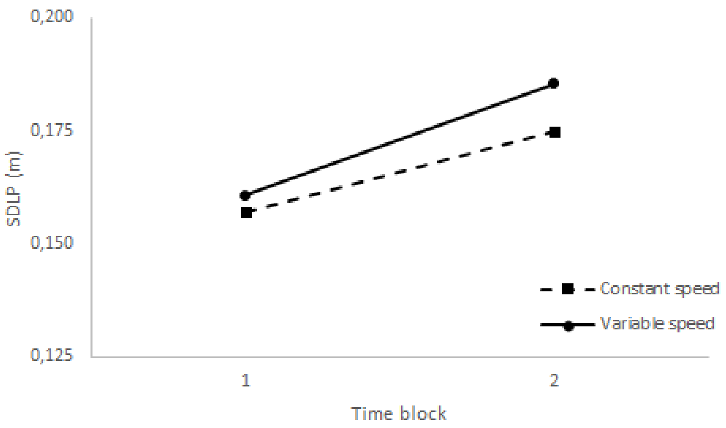

Fig. 7. Lane-keeping variability performance, as indexed by standard deviation of lateral position (SDLP) for both working modalities over the time

Furthermore, a significant main effect of time was obtained for mean amplitude of steering wheel movement, F(1,13) = 7.615, $p < 0.05$, partial η^2 = 0.369, and steering wheel angle variability, F(1,13) = 8.559, $p < 0.05$, partial η^2 = 0.397, and a tendency toward significant on lane-keeping variability, F(1,13) = 4.337, p = 0.058, partial η^2 = 0.250. The change in performance on mean amplitude of SWM, SDSWM, and SDLP were found to increase between the first- and the second-time block as shown in Fig. 6 and Fig. 7. The effect of time dependent decrements in lateral control characterize driver's reduction in vigilance which was attributable to the need to sustain attention in monotonous driving task for an extended period of time [21, 22].

Subjective Measures

In the overall sample, driving with variable speed (M = 36, SD = 16.366) was considered to induce higher overall workload, as assessed by NASA-TLX than driving with constant speed (M = 33.321, SD = 14.652). On the other hand, driving with variable speed (M = 1.086, SD = 0.737) was rated less in perceived fatigue, as assessed by SOFI-20 than when driving with constant speed (M = 1.200, SD = 0.749). A two-way repeated-measures MANOVA was run to examine the main effect of different working modalities of ADAS and a combined of different rating components in perceived workload (mental, physical, temporal, performance, effort, frustration).

For participant's workload assessment using NASA-TLX, the result of analysis did not show any significant main effect of working modalities, F(1, 13) = 1.438, p = 0.252,

$\eta^2 = 0.1$, but the analysis of main effect of workload components was significant $F(2.623, 34.097) = 3.295$, $p < 0.05$, $\eta^2 = 0.202$. Of all NASA-TLX workload components, temporal demand was rated to be the least contributive to the overall workload, (12.36 %), while the component of effort was rated to be the highest demanding (20.05 %) when driving with ADAS. Post-hoc test using Bonferroni correction for multiple comparisons determined no statistically significant difference between workload components except for temporal and effort ($p < 0.05$).

Furthermore, the univariate analysis was run to test the difference of working modality in each component of perceived workload in NASA-TLX. The result revealed that drivers who varied the speed during assisted driving reported a statistically significant higher degree in temporal component, $F(1, 13) = 6.582$, $p < 0.05$, $\eta^2 = 0.336$, as compared to the condition when they kept the speed constant.

The same analysis on working modalities and subjective assessment of fatigue dimension (lack of energy, physical exertion, physical discomfort, lack of motivation, and sleepiness) were carried out. A two-way repeated measures MANOVA showed no significant main effect of working modalities, $F(1, 13) = 1.208$, $p = 0.293$, $\eta^2 = 0.085$, but the analysis demonstrated a significant effect of fatigue dimensions, $F(4, 52) = 4.026$, $p < 0.005$, $\eta^2 = 0.236$. The result of self-perceived fatigue indicated that the score of physical exertion was the lowest (6.87 %), followed by lack of energy (21.25 %), lack of motivation (21.71 %), and sleepiness (21.88 %), while physical discomfort (28.281%) being the greatest contribution to the overall score of perceived fatigue. Post-hoc test using Bonferroni correction for multiple comparisons determined that there was a statistically significant difference between the rating of physical exertion and lack of energy ($p = 0.026$), lack of motivation ($p = 0.028$), and physical discomfort ($p = 0.028$). This result may suggest that drivers made less physical effort in vehicle control or being more passive following the use of ADAS which resulted in drivers feeling lack of energy, lack of motivation, and physically discomfort.

Further, a univariate analysis was performed to determine the significance difference on each dimension of perceived fatigue between two working modalities. The result showed a statistical significant higher rating in lack of motivation dimension in constant speed as opposed to variable speed, $F(1, 13) = 6.566$, $p < 0.05$, partial $\eta^2 = 0.336$.

DISCUSSION

Previous research in the automotive field has shown the analysis of autonomic indexes is more informative than single physiological measures in discriminating the change in attentional source and demand from resting baseline to single-task driving and from single- to dual-task driving [31]. Although, the present study did not analyze the difference of task demand between single- and dual-task driving, we discovered that drivers elicited the change in autonomic indexes from resting baseline that indicates the presence of information processing during dual-task driving which was not pronounced in traditional workload index such as mean heart rate. Our current finding showed that simulated driving in dual-task setting with ADAS elicited uncoupled parasympathetic inhibition (i.e. a decrease in parasympathetic activation from resting baseline) regardless working modality. Uncoupled parasympathetic inhibition is commonly interpreted as the engagement of driver’s attention on perceptual/manual processing demands [30]. This autonomic mode of control elicited by drivers when driving with ADAS was expected as driving demand in this current study was relatively low, monotonous, and unstimulating. Besides, the interaction with ADAS also mainly involved visual-manual tracking task that requires drivers to adjust accelerator and brake pedals to keep the headway distance with the lead vehicle. The involvement of visual task (i.e. visually assess the distance to lead vehicle and signals from ADAS) and manual task (i.e. controlling pedals) explains the observed autonomic mode of control.

Following the result from behavioral measures, the observed degradation of dual-task performance with corresponding physiological state might indicate the detrimental effect of parasympathetic inhibition mode of control on performance over the time. Drivers tended to show more variability in lane-keeping performance and greater steering wheel variation in the second-time block as opposed to the first-time block. Concerning the change in performance, it was also observed that time effect induced an increment in mental workload as indexed by an increase in mean heart rate. Nevertheless, the analysis of first-time block to second-time block when driving with ADAS generated neither significant increment in sympathetic activation nor parasympathetic inhibition for both working modalities. This autonomic pattern may suggest that drivers were trying to maintain their engagement during dual-task performance despite receiving unstimulating information flow. Considering the evolution of autonomic control mode that remained unchanged over time, performance degradation could be attributed to the decrease in driver's state (vigilance) due to monotonous stimulation [21, 22].

In addition, declines in alertness due to continuous exposure to unstimulating flow of information leads to a reduction of brain activation which is likely to result in underload effect such as boredom [45, 46]. In particular, previous studies have also shown that boredom impaired individual's ability in error detection of sustained-attention, and hence, exhibited a decline in performance over time [47]. Possible interpretation to the increase of mean heart during monotonous driving in the current study could be found in the study of psychophysiological mechanism of boredom [48]. The authors suggested that performing a task that is too easy with monotonous external simulation will lead to a subjective state of boredom. In such condition, maintaining attention on task demand for an extended period of time will require extra allocated energy, as manifested by increased autonomic arousal. In their study, the signature of autonomic arousal as indexed by mean heart rate was significantly higher when attending boring task as compared to the interesting task. The author [48] argues that this focusing energy is required to oppose the seeking for stimulus that is not available from the current task demand.

The analysis of time effect between first- and second-time blocks might suggest that drivers' feelings of boredom were apparent following prolonged interaction with

ADAS. Drivers exhibited a higher mean heart rate accompanied by a decrease in driving performance over the time as they continued the interaction with ADAS in monotonous driving environment. The experience of boredom was also confirmed by participants from the post-drive interviews in which the first impression of driving sessions was described verbally as boring and unmeaningful. Thus, the increment in mean heart rate found in this study might not be indicative of increased cognitive workload associated with the change in task difficulty, rather, it can be attributed to the increased effort (compensatory effort) applied to maintain the safe headway distance set by ADAS. While, it has been shown in other study that the increased effort (computational effort) in response to the increase in task difficulty experienced by drivers gave rise to increases in mean heart rate and autonomic indexes when performance remain unaffected [31].

Therefore, our result clearly shows the possibility of using the analysis of autonomic mode of control to detect the excessive workload associated with different cognitive processes that could undermine driver’s interaction with ADAS in different driving conditions. The analysis of autonomic mode of control could complement the measure of heart rate to differentiate types of effort expanded by driver to protect the performance. Through the current study, it could be anticipated that uncoupled parasympathetic inhibition elicited during assisted driving would be vulnerable to time-on-task. This is particularly important to be considered for development of ADAS that primarily uses visual interface to communicate information such as driver’s error (e.g. eco-driving information, car-following support) in which drivers have to refer continuously to the information provided by ADAS. Although, ADAS has been properly planned in conveying the message within the safety threshold with the least interference with the primary driving task, there is still a certain situation where driver's state could diminish and affects the efficiency of driver-ADAS cooperation. Thus, the issue in designing optimal visual assistance system is not simply reducing visual demand to minimize driver's distraction or complexity of the system, but it also deals with attentional resources engaged during assisted driving that can be modulated by the change in driving condition. Previous literature supports the current finding that uncoupled parasympathetic inhibition characterizes a task that requires sustained-attention [49], which may not be well responded by human operator in a prolonged duration. In the context of assisted driving, our present finding showed that such autonomic mode of control operated in underload situation (e.g. monotonous highway or urban area) may give rise to boredom, degrading performance, and influencing subsequent driver acceptance to ADAS.

Furthermore, the present study also found that the assessment of driver's mental workload in assisted driving using autonomic control was functional to discriminate the impact of different driving conditions on drivers' attentional resource allocation. Although, no significant central processing demand from baseline was required by the drivers to perform driving task with ADAS, the amount of sympathetic activation was significantly higher in variable speed when compared to constant speed. This difference was manifested as constant speed driving tended to produce sympathetic withdrawal whereas variable speed driving showed a tendency to generate sympathetic activation. Consequently, operating vehicle with ADAS between two driving conditions led to a shift in cognitive demand which was associated with more central processing resource allocation was needed in face of more active driving task than the passive one. The effect of the change in cognitive demand was also evidenced by driving performance measure concerning steering wheel management. It was observed that the mean amplitude of steering wheel movement in variable speed was significantly higher than the condition in constant speed, while there was no different in the quality of lane-keeping performance in both speed conditions. This result might suggest that driving in more active condition demands more steering wheel adjustment. The need of greater adjustment implies more judgement of drivers was required to keep the same level of lane-keeping performance. Besides, subjective assessment of workload via NASA-TLX also confirmed that dual-task difficulty concerning temporal demand was heightened when drivers had to interact with ADAS in active condition than monotonous condition.

With respect to the subjective assessment of fatigue (SOFI-20) in both driving context, interaction with ADAS in a more active driving situation was self-perceived as more favorable to meet road demand as opposed to driving in a passive situation. Despite being more demanding, allowing drivers to be more actively involved in assessing the distance with ADAS produced a relatively higher degree of engagement (i.e. lower lack of motivation), whereas limiting driver’s task in underload situation following the use of ADAS led to lower motivation level that resulted being more monotonous and tedious. This finding might suggest that changing working modality of ADAS in favor of driver's workload could help to avoid poor user experience during monotonous situation. The analysis of autonomic mode of control permits the identification of different cognitive operations that contribute to workload impairment and decrement in driver's attention. Therefore, through the analysis of autonomic mode of control, it seems realistic to proceed in a noninvasive way the recognition of underlying workload that enables the assessment in which condition, working modality of ADAS could be adjusted to be cognitively suitable and to further enhance driver's interaction with ADAS [50].

An important limitation of the current study was the absence of ADAS working modality that trigger a significant amount of sympathetic activation. Although, driving with ADAS in variable speed condition elicited higher level of sympathetic activity compared to constant speed, the sympathetic change from resting baseline was insufficient. The lack of sympathetic activation might explain the ineffectiveness of this working modality to attenuate the increment in mental workload over the time during monotonous driving. Further study should include ADAS working modality could trigger a sufficient amount of sympathetic activation, and thus, it would permit the evaluation whether the modification of ADAS working modality that stimulate the change of autonomic mode of control is functional for the optimization of driver-ADAS interaction in the context of the current study. Nevertheless, current study has provided insight that different working modalities of ADAS that elicited similar autonomic mode of control had the same influence on driver alertness and detrimental effect on performance over the time. Thus, the question related to whether the effortful interaction with ADAS in monotonous condition could be counteracted by the design of ADAS itself remains hypothetical. In the case of underload driving that could lead drivers to boredom or fatigue, it might be worth considering the suggestion to adopt gamification concepts into ADAS design to make safe driving more pleasurable and stimulating in face of monotonous condition [51, 52].

CONCLUSION

ADAS plays an important role in optimizing drivers' attentional resource allocation and improve their abilities to attend to driving demand for achieving safe and pleasant mobility. The way toward this ideal will require the knowledge on how to properly present information/feedback to the drivers in a timely-manner while taking into account the limitation of human cognition in response to the request elicited by ADAS. The detection of different cognitive processes induced by ADAS with respect to different driving conditions and the evaluation of their detrimental effects appear to be critical for successful integration of ADAS with human driver. In particular, the analysis of autonomic mode of control in the current study presented the potential for identifying the underlying cognitive processes while driving with ADAS, and thereby allowing the recognition of ADAS feedback that could interfere or enhance primary driving task. The outcome of this study demonstrated the liability of the autonomic mode of control (i.e. uncoupled parasympathetic inhibition) elicited by visual-assistance system in monotonous environment and its possible effect on reduced user acceptance and driver safety. The combination of autonomic indexes and heart rate in the present study also provides a way to interpretate types of effort that are computational- or compensatory-related as they have safety implication in ADAS design that need to be addressed differently. The assessment of mental workload and associated effort as the result of driver interaction with ADAS and traffic demand could help to design the adaptive ADAS working modality for the purpose to maintain optimum level of performance. Further study is required to address problems in ADAS design especially in relation to accommodate the variation of mental workload experienced by the drivers. Possible technique that presents pleasurable and engaging stimuli through gamification seems promising to be incorporated in ADAS design for reducing the effect of monotonous driving, and hence, reducing the effort required to maintain interaction with ADAS.

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