Preventing Driving Accidents via Detection of Driver-induced Steering Oscillations

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Abstract: We propose an approach of classifying the driver-induced steering oscillation of a simulated car driven by a cognitively distracted human driver. The inadequate cognitive engagement of the driver would result in delayed steering response of the latter. Applying the control theory for the driver-car system, we hypothesize that such a delayed response would result in an oscillating trajectory of the car. To verify our hypothesis, we experimented with the following two driving conditions: (i) attentive (normal) driving and, (ii) distracted (inattentive) driving. The distraction of the driver in the latter case is caused by texting on mobile phone while driving. The first condition corresponds to the cognitively adequate driving with non-delayed steering response, while the second one accounts for the delayed response due to the required additional cognitive engagement of the driver while performing the primary task of driving. In order to classify each of these two cases, we propose an approach of analysing the power spectrum of the lateral acceleration of the car. The experimental results suggest that magnitude of the power spectrum of normal, driving (without delay in steering response) could be well distinguished from driving with delayed steering response in most cases of the human drivers. The difference in the power spectra is due to the subtle, yet identifiable steering oscillations caused by the delays of response of the cognitively distracted drivers. The proposed approach of detecting steering oscillations as early signs of unsafe driving could ultimately facilitate the development of devices that would warn the (distracted) driver well before a traffic accident might eventually occur.

1. Introduction

The innovations in embedded devices in transportation systems has revolutionised the world. These advancements have added both luxury and convenience by transforming limited space of a vehicle into a kind of mobile office. The advanced technologies in today's vehicles, such as lane detection, adaptive cruise control, navigation systems, wireless network connectivity, and real-time systems providing information about the traffic, road-conditions, weather, location-dependant points of interests (fuel stations, parking areas, restaurants, sightseeing spots, etc.), news, etc. are gradually becoming a standard for many of modern automobiles. With over 1 billion vehicles around the world [1], integrating these devices and technologies might well result in developing of intelligent transportation systems that could save our valuable time and tedious efforts. However, using these technologies while driving might prove to be a significant source of distraction for the driver, which, in turn might ultimately result in increase of the number of traffic accidents caused by driver's inadequate or slow response to urgent hazardous traffic situations [2].

Driver inattention is a prominent factor of traffic hazards. Most often, distraction is seen as a main reason for such inattention [3]. Distraction happens when driver shift their attention from the primary task of driving to secondary or even tertiary (unrelated to the driving) tasks [4]. The distraction of the driver could be categorised in the following four main types [5][6]: (i) *visual* distraction, occurring when driver looks away from the current road situation (e.g. looking at the map of navigation system, air-conditioner settings, etc.), (ii) *cognitive* distraction, occurring when driver take off their concentration from driving to some other task (e.g., daydreaming), (iii) *physical* or biomechanical distraction, induced because of biomechanical requirement of a driver to operate the secondary task, (e.g. operating the navigation system, air-conditioner, CD player, etc.), and (iv) *auditory* distraction, triggered by auditory signals from the external sources (e.g. in-vehicle conversation with passengers, hands-free conversation via mobile phone, etc.). Different types of distraction could be induced by different, independent sources and, therefore, multiple types of distractions could occur simultaneously. In a case of texting while driving, all of the above-mentioned distractions (visual, cognitive, physical, and auditory) might occur simultaneously. First, when message is received in a cell phone, driver might receive an auditory signal, which results in a corresponding auditory distraction. Then, driver looks away from the current road situation in order to check the contents of the received message, which implies a visual distraction. Driver becomes cognitively distracted when trying to comprehending the received message, and when thinking about the eventual response the message. Finally, driver types a reply to the message, which results in biomechanical distraction. Therefore, texting while driving could be considered as quite dangerous case of inattention because it is usually associated with all types of distraction of the driver. In our work, we consider primarily the visual and cognitive aspects of the distraction caused by texting while driving.

Since, even the mere switch of attention - implying a cognitive multitasking (as in texting and driving) that the human usually does not excels at - leads to the disruption of the cognitive engagement dedicated to the primary task of driving. In such situations, the degree of attention dedicated to driving becomes considerably lower than that actually needed by the existing traffic situation. Such disruption of cognitive engagement is often viewed as inadequate cognitive load of the driver. We consider the following two cases of inadequate cognitive load while driving:

Cognitive *underload*: usually, while driving in non-demanding conditions, e.g., through a low-traffic expressway in a relaxed environment, the required cognitive load of driver is much lower than the actual mental capabilities of the latter. The situation might be additionally aggravated by various driving aids that either (i) take a part of the driving burden off the driver (e.g., adaptive cruise control) or (ii) exaggerate the sense of safety (e.g. anti-locking brake system, electronic stability program, inadvertent lane change warning system, etc.). Moreover, due to several human-related factors (e.g., day-dreaming [7], micro-sleep, etc.), the cognitive engagement of the driver may decrease even further. In such circumstances, it might be too difficult for the driver to reallocate quickly the dormant cognitive resources in order to match the suddenly increased demands of driving.

Cognitive *overload*: typically, while driving through a busy traffic or unregulated junctions, the cognitive engagement required by the current traffic environment might surpass the actual cognitive abilities of the drivers. A cognitive overload might temporarily occur when the driver that suffers a temporal cognitive underload faces an urgent hazardous traffic situation, as we elaborated above. In addition, a longer-term cognitive overload might be observed in elderly drivers as the cognitive abilities – to various extend – decline with age. Moreover, because of slowing-down of cognitive processing in elderly, even the moderately fast traffic events might appear as too fast to be perceived and judged in a real-time. As a result, the most common type of accidents caused by the cognitive overload of drivers is the "looked-but-failed-to-see" at busy intersections [8].

The identification of these two cases of inadequate cognitive load of a driver is essential for the prevention of the traffic accidents. The basic way of detecting such a cognitive load could be by analysing the delay of response (DoR) of a driver. DoR could be estimated through the direct measurement of the delay of pressing of pedals (either brake or accelerator) in suddenly arisen hazardous situations. However, such an approach would suffer for the following two drawbacks:

- First, the way the drivers press pedals is a trait that depends on (i) the personality of the driver, (ii) condition of the car and (iii) condition of the road [9]. Indeed, some drivers prefer a sporty driving with faster accelerations and faster decelerations in any conditions. Their brake points are late, and the braking is stronger. In addition, according to the risk homeostasis theory [10], drivers of the cars equipped with high-grip tires and advanced driving aids such as anti-locking brake system and electronic stability program, would brake late even in slippery (e.g., rainy, snowy, or icy) road conditions.
- Second, in extreme hazardous situations, inferring the inadequate cognitive load by measuring DoR would be next to meaningless. Indeed, in case of detected anomalies in the obtained value of DoR, it would be too late to activate any real-time accident-preventing functionality (alerting the driver, or even - automated braking).

Hence, we assume that there is a need for a different approach for the detection of DoR way before any dangerous situation might occur. Such an approach would facilitate a potentially crash-preventive early warning to the (cognitively inadequate) driver.

In our previous research, we explored some of the most fundamental aspects of such an approach. Initially, we used genetic programming to evolve an artificial driving agent that models the steering behaviour of human driver. The evolved driving agent perfectly steers the realistically simulated car in The Open-source Racing Car Simulator (TORCS) with an instant (non-latent) steering response both on straights and in corners. In addition, we verified our hypothesis that, the delay that we explicitly introduced in the steering response of driving agent resulted in well-expressed driver-induced steering oscillations [11][12]. This hypothesis was inspired by the possible application of the control theory on the agent-car system. The driving agent was consistent with the servo-control model of steering behaviour of human drivers. This model considers driver as an error-correcting entity in a purely reactive feedback-control system. The driver constantly attempts – via appropriate steering inputs – to minimize the perceived errors in the position and orientation of the car. What we could not know however, was whether the hypothesis that DoR causes steering oscillations would be valid for the human driver too.

In another work, we assumed that the approach of detecting the steering oscillations in two most general driving situations (driving on straight and in cornering) would require a mechanism for reliable identification of these situations. We assumed that such an identification should be reliable and should not depend (i) the particular human driver who drives the (simulated) car and (ii) whether the driver suffers from implicitly induced (by texting on mobile phone while driving) DoR or not. Indeed, as the experimental results suggested, the pattern of the lateral acceleration of the car controlled by driver *with* DoR on the *straight* to a significant extend mimics the pattern of the *cornering* car even when driven by *instantly* responding driver. We proposed an approach, based on digital filtering of the signal of lateral acceleration of the car, for identifying these driving situations [13].

In this research, we consider an approach of recognizing the steering oscillations caused by inadequate cognitive load (and the resulting DoR) of human driver irrespective of both (i) the driving situation and (ii) the particular human driver who currently controls the simulated car. The *objective* of our work is to explore the feasibility of applying the power spectrum analysis of the signal of lateral acceleration of the car for the identification of the driver-induced steering oscillations. We are especially interested in investigating the maximum values of the power spectrum(PS) at the point when driver induce steering oscillation (during inattentive driving)and compare it with the maximum values of PS during normal driving (attentive driving) so that it could be used to prevent such accidents.

The remaining of the article is organized as follows. Section 2 elaborates the proposed approach of identification of driver-induced oscillations. Section 3 presents the experimental results. Section 4 draws a conclusion and highlights on our future work.

2. Proposed Approach

2.1. The Simulated Car

Our approach relies on a car (and its environment) realistically simulated in TORCS. The idea of using a software prototype rather than experimenting on a real car is motivated by the fact that the former is a crash-safe, and there is no risk of jeopardising a human life or a property. In addition, being a widely used car simulator over the years, TORCS features a well-developed physics engine that faithfully models the underlying dynamics of the car. Moreover, because it is free of charge and open-source, we could modify its code according to the needs of our research [14]. The simulated car and its basic features (consistent with our previous work [11][12][13]) are illustrated in Figure 1.

Model	CLK DTM
Length, m	4.76
Width, m	1.96
Height, m	1.17
Mass, kg	1050
Front/rear weight repartition	0.5 / 0.5
Height of centre of gravity, m	0.25
Drivetrain	front engine, rear wheels drive

Fig.1. *The simulated car (left) and its main features (right)*

2.2. The Driver

Our previous experiments [9][10] were conducted on a simulated car that was driven by (an artificial) driving agent. The steering function of the driving agent was evolved via genetic programming. The approach of using the driving agent as a computational model of the human driver (instead of real human driver) was an important intermediate step in our research. It allowed us to introduce explicitly different values of DoR (e.g. 100ms, 200ms, 400ms, etc.) in decision-making functionality of the agent, and to investigate the corresponding changes in the steering behaviour of the car. Conversely, explicit introduction of specific, precise values of DoR would be impossible in eventual experiments with a real human as driver [9][10]. Moreover, even if we could observe the oscillating behaviour of the car driven by human with delayed steering response, the actual DoR of the human that caused the eventually observed oscillations would have been unknown to us.

In the current work, we allow a real human driver to control the simulated car. In order to investigate the general effect of eventual DoR (due to inadequate cognitive load) on the steering behaviour of the simulated car, we requested the human driver to drive the car with a constant speed of 51 km/h in the following two general driving conditions: (i) driving in a straight, and (ii) cornering. Moreover, in order to guarantee that the cognitive engagement of the drivers is shared only between steering (primary task) and texting (secondary task), we freed the drivers from any unnecessary cognitive burden that would have been required to maintain the desired speed of the car. We implemented a simulated cruise control that automatically accelerates the car to 51 km/h (14 m/s) and maintains this speed through the entire experiment.

Further, on each of these two driving conditions we consider two cases of cognitive load: (i) a normal load when the driver could focus completely on the primary task of driving (attentive driving), and (ii) a case with cognitive overload caused by texting on mobile phone while driving (inattentive driving). As mentioned previously, texting while driving is extensively studied, and it is recognized as both (i) an effective and (ii) most often seen form of driver distraction [15] [16]. Therefore, we conducted our experiments on texting while driving in order to provoke the naturally occurring DoR in the human driver. We requested 10 subjects to drive the simulated car in the above-mentioned driving conditions.

2.3. Methodology

The detection of steering oscillations as early symptoms of inadequate cognitive load of drivers is crucial because it would allow us to warn the drivers about their cognitive inadequacy (possibly, due to distractions, tiredness, micro-sleep, etc.) well before a sudden potentially hazardous traffic situation occurs. In our work, we propose an approach of measuring the magnitude of the PS (spectrum density) of the lateral acceleration of the car. The proposed approach features three phases: first, we collected the raw signal – time series of lateral acceleration of a simulated car, driven by human driving in the following two situations: (i) inattentive driving (driving while texting) and (ii) attentive driving (normal driving). In the second phase, we apply Fourier transformation on the time series of lateral acceleration in order to obtain its spectrum. Finally, in the third phase, we calculate the power spectrum (PS) of the transformed signal.

In order to model the eventual real-time implementation of the proposed approach, we initiate the Fourier transformation on the data in a window (buffer) of the first 100 samples (corresponding to the first 2 s of data) of the signal. Then, we calculate the value of PS in the frequency range between 1 Hz and 50 Hz of the obtained spectra of the initial 2 s of data, and associate this PS value with the time instant $t_{initial}+2s$. Then, we proceeded by repeatedly (i) sliding the window of 100 samples by one frame (corresponding to the sampling interval of 20 ms), (ii) performing Fourier transformation, and (iii) calculating the PS until we reach the last 100 samples of the acquired time series. We use Fourier transformation and the PS because we anticipate that the driver-induced oscillations will introduce specific changes to the amplitudes of the relevant frequencies of oscillations. These frequencies would depend on the hysteresis and delays in the steering system of the car, speed of the car (in our case, constant, equal to 51km/h), and DoR of the driver. We also postulate that the spectrum of oscillation frequencies would not overlap significantly with the (higher) frequencies of the noise caused by either (i) the inevitable mechanical plays in the steering system of the car and (ii) irregularities of the tires and the road. In addition, we think that the spectral pattern of oscillations due to DoR would differ from the pattern of the lateral acceleration in normal cornering, and that such a difference would be grasped by the proposed approach.

Alternatively, we could use much simpler methods such as the deviation of lane position to infer the inadequate cognitive load of a vehicle. However, such an approach would face several challenges. First, there are no such sensors that could reliably determine the position of the car on any road and in any driving condition (night, day, snow, rain, etc.). In addition, even if we assume that reliable sensors that detect the margins of the lane for different conditions and lane position do exist, we would be unable to detect reliably the inattentive driving from deviation of the lane position. Indeed, a fully attentive driver might deliberately ”wave” across the lane in cornering (entering from outside, moving to the inside at the apex, and exiting from the outside), may circumnavigate obstacle, rough road, bicyclist, or, simply, may not mind driving slightly off the middle of the lane. We believe that it would be difficult to discriminate these cases of attentive driving from oscillations caused by DoR of the driver without an appropriate spectral (frequency-related) analysis of the relevant parameters (deviation from centreline, steering angle, lateral acceleration, etc.) of the moving car. Moreover, the proposed approach of using lateral acceleration implies that we might merely require an accelerometer (which is already available as a component of navigation systems, airbags control systems, electronic stability programs of the modern cars) as a sensing device.

3. Experimental Results

As we briefly mentioned in Subsection 2.1, we conducted our experiments in TORCS environment on a MS Windows based PC with attached steering wheel and pedals. We asked 10 subjects to drive the car at 51 km/h (kept constant by simulated cruise control) in the two familiar driving conditions: (i) driving on a straight section of road, (ii) driving on a corner. Experiments were conducted in two successive days. In the first day, drivers were familiarized with TORCS and controls of the car, and were given enough time to adapt to the specifics of driving in the simulated environment. Because of the significant body of research suggesting that the sleep is vital for learning (including learning how to drive a simulated car) and helps in memory consolidation [17], we conducted the actual experiments on the following day.

Further, for each of the two driving conditions we consider two cases of cognitive load as mentioned in previous sections: (i) normal load when the driver could focus completely on driving (attentive driving) and, (ii) cognitive overload caused by texting on mobile phone while driving (inattentive driving). In the second case, we requested each of these drivers to respond to a text message (that was sent to the messaging application running on their mobile phone) while driving. The texting was intended to induce inadequate cognitive engagement and the corresponding DoR in their primary task of driving. We registered the raw signal (with sampling interval of 20ms) of the lateral oscillation of the car driven by all subjects in all driving conditions. Then we used the raw data to perform an offline analysis of the power spectra for all 10 cases. Figures 2a and 2b illustrate the typical forms of the raw signal of lateral acceleration of both attentive and inattentive driving on straight (Figure 2a) and curve (Figure 2b) section of the road, respectively. The corresponding values of the PS are illustrated in Figures 3a and 3b.

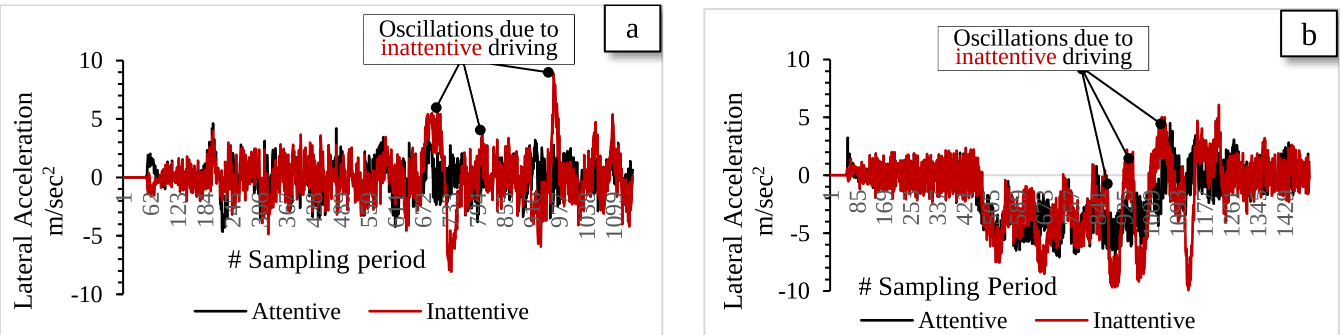

Fig.2, *Typical dynamics of lateral acceleration on straight (a) and curve (b) section of the road.*

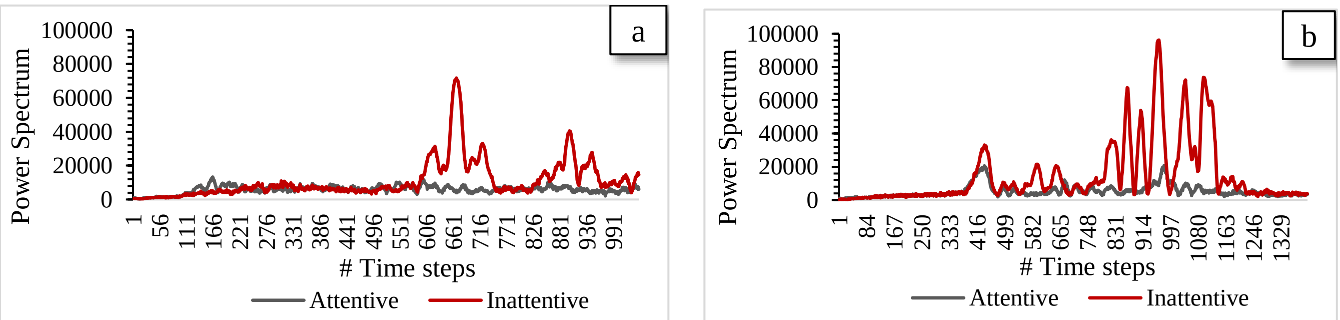

Fig.3, *Typical dynamics of PS on straight (a) and curve (b) section of the road.*

3.1. Effects of the Delay of Driver's Response on Steering Behaviour and its Detection

As Figures 2a and 2b illustrate, the lateral acceleration for inattentive driving (and resulting DoR) due to texting while driving in both driving conditions (i.e. driving on a straight and on cornering) feature subtle, yet distinguishable oscillations. No such oscillations could be observed in the case of normal (attentive) driving. The corresponding PS of the lateral acceleration of inattentive driving is higher than that of attentive driving (Figures 3a and 3b).

As we mentioned before, we assume that steering oscillations are the result of cognitive overload caused by both visual and non-visual distractions of texting while driving. Alternatively, we can also consider the idea that these oscillations could have resulted from the disruption of visual feedback only while texting, rather than due to inadequate cognitive load. However, we speculate that the oscillations are not a mere result of drivers taking their eyes off the road. Even without a timely visual feed, the attentive driver is involved in an extensive mental workload – such as planning the trajectory of the car, anticipating the parameters pertinent to the state of the car (speed, position, orientation, distance to the obstacles, distance to the corner ahead, etc.), and calculating the rates of these parameters. This mental workload, when unimpaired, easily compensates for the brief disruptions in the visual feed. Indeed, the situations when driver briefly looks at the mirrors, dashboard indicators, map of the navigation system, etc. are viewed as rather routine and do not result in steering oscillations. Therefore, we assume that the oscillations occur also because of the cognitive impairment that compromises the ability of the driver to accomplish the above-mentioned workload. In the near future, we are planning extensive experiments that could verify whether taking the eyes off the road could be manifested in driver-induced oscillations. Nevertheless, even if we acknowledge that according to the experimental results, driver-induced steering oscillations are caused by mere visual distraction, we assume that this facts could not be used as an argument against the necessity of their automated detection.

On the other hand, some studies [18] have revealed that instead of resulting in steering oscillations, lane-following ability of the driver would rather improve during cognitive overload. However, in these studies, only auditory stimuli have often been considered as a cause of cognitive overload. Consequently, the degree of impairment (and the corresponding DoR) might be lower than in texting while driving. Moreover, such a seemingly anomalous improvement of driver abilities during cognitive overload could be explained by the risk homoeostasis theory [10], which argues that human drivers often alter their behaviour in order to keep a certain preferred level of subjective perceived risk. Hence, the improved driving under cognitive overload could be seen as a compensatory behaviour to the elevated risk associated with perceiving auditory stimuli while driving. Conversely, texting and driving could cause all four forms of distraction (visual, cognitive, auditory, and biomechanical) with a cumulative effect that can well surpass the compensatory abilities of drivers.

Figure 4 illustrates the maximum value of PS of lateral acceleration during attentive and inattentive driving of all 10 drivers on straight (Figure 4a) and corner (Figure 4b) section of the road, respectively. As shown in the figure, considering a fixed, single threshold (shown as dotted horizontal line), would result in correct recognition of oscillatory steering behaviour of the car in 80% to 90% of the drivers. These results also indicate that different drivers indeed experience different level of steering oscillation resulting in varying PS. Considering the driving as a subjective activity that depends on drivers we have to acknowledge the fact that a single average value of the threshold that could be successfully applied to all drivers might be non-existent [19]. In our future work, we are planning to investigate various mechanisms that would enable us to apply thresholding that is variable, and adapting dynamically to individual driving styles and changing driving conditions.

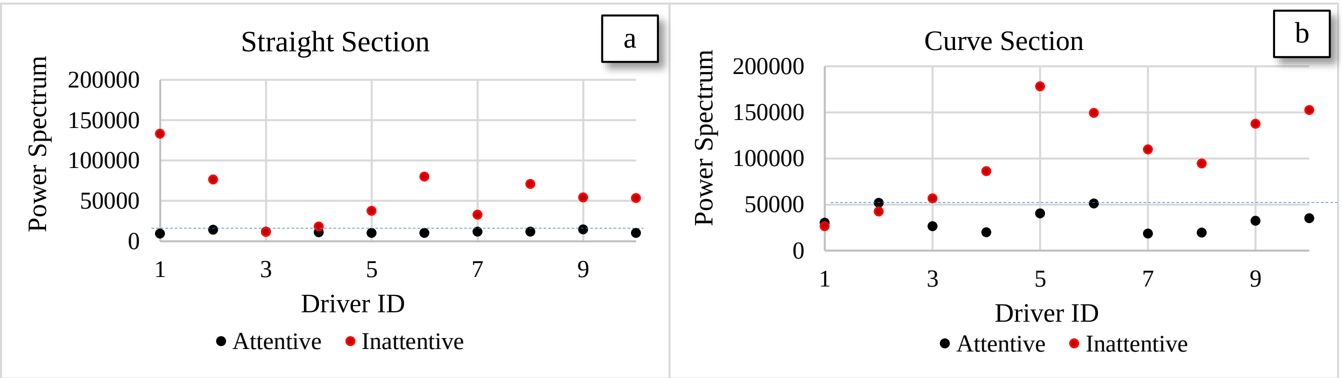

Fig.4, *Maximum value of power spectrum of attentive driving and inattentive driving on straight (a) and curve (b) sections of the road*

4. Conclusion

We investigated an approach of detecting driver-induced steering oscillation of a simulated car driven by a cognitively inadequate human driver. The inadequate cognitive engagement of the driver is associated with DoR, which, in turn, according to the control theory applied to the system driver-car, results in an oscillating steering behaviour of the car. In order to identify the inadequate cognitive load by resulting steering oscillations, we propose an approach of analysing the power spectrum of the lateral acceleration of the car. The experimental results suggest that the magnitude of the power spectrum could be used to classify the oscillating steering behaviour of the simulated car driven by at least 80% of the tested drivers.

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