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Temporal fluctuations in driving demand: The effect of traffic complexity on subjective measures of workload and driving performance

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ABSTRACT

Traffic density has been shown to be a factor of traffic complexity which influences driver workload. However, little research has systematically varied and examined how traffic density affects workload in dynamic traffic conditions. In this driving simulator study, the effects of two dynamically changing traffic complexity factors (Traffic Flow and Lane Change Presence) on workload were examined. These fluctuations in driving demand were then captured using a continuous subjective rating method and driving performance measures. The results indicate a linear upward trend in driver workload with increasing traffic flow, up to moderate traffic flow levels. The analysis also showed that driver workload increased when a lane change occurred in the drivers' forward field of view, with further increases in workload when that lane change occurred in close proximity. Both of these main effects were captured via subjective assessment and with driving performance parameters such as speed variation, mean time headway and variation in lateral position. Understanding how these traffic behaviours dynamically influence driver workload is beneficial in estimating and managing driver workload. The present study suggests possible ways of defining the level of workload associated with surrounding traffic complexity, which could help contribute to the design of an adaptive workload estimator.

1. Introduction

Driving a vehicle is a highly dynamic, safety critical task. Drivers are constantly exposed to a vast array of information and have to select what is relevant in order to make decisions and execute appropriate responses. These decisions are shaped by their expectations of the road, traffic scenarios and the conditions they encounter (Oppenheim et al., 2010; Oppenheim & Shinar, 2011). For safe driving, drivers have to perceive, identify and correctly interpret the relevant objects and elements in the current traffic situation. Drivers then construct and maintain a mental representation of the current situation which forms the basis of driver's decisions and actions (Endsley, 1995). Failure to process safety-relevant information may lead to errors. In dynamic changing traffic conditions, the task of driving fluctuates with the surrounding situation and the requirement to manoeuvre the vehicle appropriately. Task demand is defined as the demands of the process of achieving a specific and measurable goal using a prescribed method (Cacciabue & Carsten, 2010). Workload is the amount of information-processing resources used per time unit, to meet the level of performance required (Wickens & Hollands, 2000). Workload serves as an indication of the effect the task demand has on the driver as well as the driver state. In a dynamic traffic environment, the operator may occasionally experience periods of particularly high task demand and fluctuations in driver capabilities. From

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the human factors perspective of safe traffic and transport systems, the match between the driver's capabilities and the demands of the actual driving task determines the outcomes in terms of safer or less safe driving behaviour. This relationship has been modelled by Fuller (2000, 2005), as the task-capability interface model (TCI) of the driving process. Driving demand in dynamic conditions depends on the combination of environmental features, such as traffic complexity, other road users' behaviour, characteristics of the vehicle and its speed and position on the road. Driver capability is limited by personal competence (experience, age, attitude etc.) and shaped by momentary variations in driver states (such as fatigue, alcohol, time pressure). In the case when there is a mismatch between the task demand and the driver capabilities, the corresponding task difficulty which arises from the dynamic interaction between them, may be reflected in the changes in task performance.

With the interface between the driving demand and momentary driver capability being important for road traffic safety (Fastenmeier & Gstalter, 2007), the accurate modelling of driver workload is regarded as crucial in the context of driver assistance systems that aim to optimise drivers' workload. Automobile companies are developing intelligent systems such as workload managers to control in-vehicle communications based on the assessed workload of the driving situation. To date, research on workload manager systems had focused mainly on the distractions within the vehicle, such as studies on the effect in-vehicle warnings on driver workload (Hibberd, Jamson, & Carsten, 2013). However these systems have yet to consider external demands such as weather and traffic complexity in driver workload assessment. Research shows that traffic density affects driver workload; Brookhuis, De Vries, and De Waard (1991) reported that drivers' subjective mental effort was higher on a busy ring road compared to when driving on a quiet motorway. De Waard, Kruizinga, and Brookhuis (2008) showed that increased traffic density has been shown to increase workload and the probability that error will lead to accidents. Hao et al. (2007) found that driving performance did not worsen with increasing traffic, although mental workload (physiological and subjective assessment) increased and situation awareness worsened with increasing traffic. Schieβl (2008) also reported a significant effect of traffic density on strain or workload; measuring subjective strain continuously via a 15-point rating scale, she found it rose up to a medium traffic density, thereafter plateauing and remaining the same afterward, whereas physiological strain decreased. Although Schieβl (2008) argued that the continuous subjective rating measure was sensitive to the fluctuations in workload resulting from the surrounding traffic density, the analyses were computed based on a dataset which was rather limited ($n = 6$). Moreover, participants were instructed to give a new rating when they perceived a change in their subjective workload as opposed to being prompted at particular time points.

Changes in traffic demands can be sudden, urgent and unpredictable, such as a vehicle pulling-in from an adjacent lane. When such a critical situation occurs, driving task demand increases with the event occurring in the 'field of safe travel' (Gibson & Crooks, 1938). While some studies have reported that driving task demand increases when the absolute number of vehicles in the forward scene increases (Schweitzer & Green, 2007; Zhang, Smith, & Witt, 2009), it is unknown if the behaviour of the vehicles' lane changes such as their proximity and the direction of lane change affects driver workload.

Workload assessment has involved measurement of performance, subjective impressions of workload and physiological indicators (O'Donnell & Eggemeier, 1986). Sheridan (1980) suggests that operator ratings are the most direct indicators of workload. Subjective measures of mental workload are obtained from subjects' direct estimates of task difficulty and under repeated exposures to the same tasks, the reliability coefficients for subjective measures of mental workload using unidimensional ratings have been reported as high as or higher than 0.90 (Gopher & Browne, 1984). Since subjective measures are easy to obtain and excel in face validity as the measures depend directly on the subject's actual experience of workload (Gopher & Donchin, 1986), it is possible that subjective measures are more accurate in tapping into driver's current workload as compared to some objective measures. It is argued that physiological measures are able to provide information about mental workload that cannot easily be obtained from performance or subjective measures (Humphrey & Kramer, 1994). Heart rate for example, has the longest history of use in assessing operator workload and many studies have reported that heart rate variability measures are sensitive to variations in task demand. However, this rationale is not always supported as the body also responds physiologically to things other than mental workload. Physiological measures may therefore only capture certain elements and performance measures may not correspond to workload. Dissociations between the measures could also be resulted due to how the measures are taken. Therefore care should be taken to ensure that the measures utilised could provide explanations about the level of mental effort used. While there are not many studies use performance measures to evaluate workload, the studies that do make comparisons between the subjective and objective measures of workload often find dissociation (Yeh & Wickens, 1988). Although subjective measures are often collected at the end of a mission or task risking earlier experiences being forgotten, they are more sensitive to processes which require awareness (or attention) as they rely on subjects' conscious, perceived experienced with regard to the interaction between the operator and the system. Often, subjective experiences of overload take precedence when an operator is performing a task, even when objective measures do not indicate an overload (Moray et al., 1979). Therefore, regardless of the limitation of subjective measures, subjective workload represents the degree to which an individual experiences workload demands, and this experience itself has potential consequences for performance levels. Hence, subjective measures of workload are used in the present investigation to characterise how much mental effort is experienced in performing driving tasks in varying traffic conditions.

To further verify subjective measures of workload, driving performance such as longitudinal and lateral driving performance measures were also employed to examine whether driver's driving behaviour varied with changes in driving demand. Research has shown that mean gap from the lead vehicle (Schweitzer & Green, 2007; Green et al., 2011), time-to-collision (Kondoh, Yamamura, Kitazako, Kuge, & Boer, 2007; Wada, Doi, Tsuru, Isaji, & Kaneko, 2010), and variation of speed (Cacciabue, Re, & Macchi, 2007) are associated with the primary task demand relating to traffic. Although the aim of the study is to explore driver's temporal workload in response to changes in immediate traffic, understanding possible