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Effect of road geometry on driver fatigue in monotonous environments: A simulator study

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ABSTRACT

Driver fatigue, induced by task monotony can increase the risk of road accidents. Highways are usually designed with few geometric changes so that high-speed traveling would be possible. Such conditions when combined with repetitive and stimulus-free environments, create a monotonous driving experience that can lead to mind wandering and task disengagement, and subsequently affect driver's performance. This paper focuses on the relationship between road geometry and driver's vigilance level in monotonous environments. Therefore a driving simulator experiment with three different scenarios, which were originated from three existing highways in rural areas of Iran, with low, moderate, and high levels of geometric variety was developed. Participants drove for 45 min in each scenario and their steering wheel movements (SWM), standard deviation of steering wheel movements (SDSWM), and lane positioning ability (indexed by the area between trajectory and road's centerline (ABTC)) was analyzed. The results indicated a significant effect of road design on lane positioning ($P < .001$). The mean value of total ABTCs showed 11.3 and 20.6 percent of performance improvement for scenarios with moderate and high geometric variety respectively. Also, a significant effect of time on task was observed on SWM and SDSWM ($P < .001$). However, the deterioration rate was considerably lower in scenarios with higher geometric variety. This work can help to develop more efficient monotony countermeasures with regards to road's geometric design characteristics. It also provides useful information for more optimized road designs in such environments from driver's mental workload perspective.

1. Introduction

Since the first motor vehicle accident that is said to have happened in London at 1896, road traffic crashes have taken lives of approximately 40 million people (Shen et al., 2015) and still, more than one million people die in car accidents worldwide every year (WHO, 2015). According to World Health Organization's report, Iran with the average of 34.1 casualties per 100,000 population, is one of the five countries with the worst record of road accidents (Violence, Prevention, & Organization, 2013). Due to Iran's geographical characteristics, a significant number of its rural roads are located in arid or semi-arid flat areas which represent few visual stimuli for drivers. Also, many of these roads are designed for high-speed driving (maximum speed of 120 km/h), with little amount of geometric variety. Therefore a highly predictable and

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monotonous driving experience is created, which can lead to boredom and trigger dangerous risk-taking behaviors (Steinberger, Schroeter, & Watling, 2017). Moreover, such conditions generate a physiological and psychological state that can exacerbate driver fatigue (May & Baldwin, 2009). While possible road safety countermeasures like the implementation of roadside stimuli or rest places may be beneficial, some questions arise in association with the amount and frequency of such countermeasures. Does driver fatigue occur with a similar rate in different road designs? What is the relationship between road geometry and driver fatigue? Is the application of more complex road designs an effective method to hinder driver's vigilance decrement in monotonous environments? This study tries to answer such questions through a driving simulator experiment.

Driver fatigue is known as one of the major factors leading to road accidents. Studies show that up to 20 percent of traffic crashes are due to fatigued driving (Brown, 1997; Maycock, 1995; Zhang, Yau, Zhang, & Li, 2016). Fatigue can result in physical and mental disorders, which are detrimental to attention, recall, reaction time, hand-eye coordination and vigilance (Jiang, Ling, Feng, Wang, & Shao, 2017). Dinges states that vigilance decrement is the most robust effect of fatigue and sleepiness (Dinges, 1995). Vigilance decrement may lead to observable changes in driving performance, such as an impaired capacity to maintain speed and remain in a lane and also increased time and errors in decision making (Jiang et al., 2017). Fatigue-related accidents are more prevalent in rural highways. Fell and Black estimate that sleepiness is responsible for 30 percent of fatal crashes on country roads (Fell & Black, 1997). McCartt et al. reported that 40 percent of sleep-related accidents occur on highways or expressways (McCartt, Ribner, Pack, & Hammer, 1996).

Fatigue is a multi-dimensional phenomenon, and it has been difficult for researchers to precisely define it. The terms of fatigue, sleepiness, and drowsiness have usually been used as synonyms in posterior literature. Fatigue is a general term which relates to both physiological and psychological process (Thiffault and Bergeron, 2003). May and Baldwin classified driver fatigue based on its causal factors into two subgroups of sleep-related fatigue and task-related fatigue (May and Baldwin, 2009). Also, task-related fatigue can be generated by active or passive fatigue (May and Baldwin, 2009).

Sleep-related fatigue comprises various performance decrements due to circadian rhythm, sleep deprivation or sleep disorders. For example number of sleep-related accidents increase in the early morning (2–6 AM) and late evening (2–4 PM) (May and Baldwin, 2009; Pack et al., 1995). These hours overlap with most people's low point of arousal in their circadian rhythm (Körber, Cingel, Zimmermann, & Bengler, 2015).

Task-related fatigue is caused by mental overload or underload (May and Baldwin, 2009). Active fatigue is the most common and more studied aspect of task-related fatigue. Resource theory explains that active fatigue is created by depletion of the cognitive resources necessary for the maintenance of performance in tasks with high cognitive demand (Helton and Russell, 2012). Due to the complex nature of driving and its constant need for recognition, assessment, and prioritization of surrounding stimulants, it usually demands a high amount of mental resources. Examples of such conditions are driving in urban areas, intersections, roads with high traffic, and prolonged driving.

Passive fatigue, on the other hand, is originated from monotony, highly repetitive and predictable stimulants, and autonomous systems (Körber et al., 2015). Because of the improvements made in infrastructure design alongside with vehicle safety advancements and application of driver assistant systems (ABS brakes, cruise control, GPS maps, etc.) the driving task has been oversimplified. Therefore new types of accidents have been generated due to boredom and inattention of driver (Larue, Rakotonirainy, & Pettitt, 2010). Under-load theories such as mindlessness theory state that monotony and boredom of vigilance tasks lead to task disengagement and mind wandering with task-unrelated thoughts in a way that attentional resources are drawn away and attentional lapses occur (Helton and Russell, 2012; Yanko and Spalek, 2014).

A relation between task demand and task performance has been described by Meister (1976). He proposed a model with 3 performance regions of A, B, and C. later de Waard added a D region (D for deactivation) to the left end of this model to describe monotonous tasks and underload situations, with regards to Yerks-Dodson law Fig. 1 (De Waard, 1996).

Region A which is described as high and stable performance is splitted up into three parts. In the middle part, region A2, the operator can easily cope with task demands and performance remains at a stable and high level. With increased task demands in region A3, a computational effort is exerted to help information processing and keeping performance at a high level (task-related effort). With increasing task demands, performance deteriorates in region B. In region C, extreme levels of

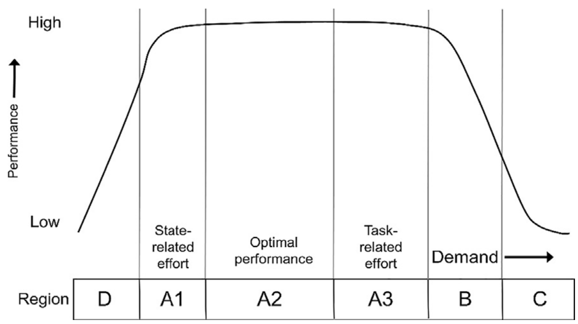

Fig. 1. The relation between task demand and performance (De Waard, 1996).