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Effects of driver task-related fatigue on driving performance

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Abstract

In this study, passive task-related fatigue effects on highway driving were analyzed by means of driving simulator experiments. Ten drivers were asked to drive in various environments in the morning (9:00-11:00 a.m.) and early afternoon (1:00-3:00 p.m.). Mean of Absolute Steering Error and Standard Deviation of Lateral Position, calculated on sub-intervals of 4 minutes, were analysed as response variables. The results confirmed the negative influence of the duration of driving tasks and circadian effects on driving performance, increasing the likelihood of “near misses” and accidents.

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Keywords: Driving Simulator; Fatigue; Monotony.

1. Introduction

There is converging evidence from analysis of road safety statistics that driver fatigue is a contributing factor in many accidents and that every year about 20% of total accidents are related to sleepiness (MacLean, Davies, & Thiele, 2003). According to the sub-categorization of the fatigue concept of May and Baldwin (2009), this paper examines the passive task-related (TR) effects of highway driving. The main aim of the study is to evaluate the separate relative importance of each effect in the fatigued state.

The analysis is based on results from driving simulator experiments (conducted at the Transportation Laboratory, University of Padova), widely adopted in recent years for this kind of study. The aim of the research is better comprehension of driving fatigue phenomena, which can affect methods and/or equipment intended to reduce the risk of accidents and to enhance driving safety.

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The paper is organized as follows: Section 2 gives a brief description of previous works concerning driving fatigue. Section 3 describes the laboratory experimental design and Section 4 deals with case-study analysis. Concluding remarks and future developments are presented in Section 5.

2. Theoretical background

The analysis presented here is based on the study by May and Baldwin (2009), who proposed a sub-categorization for fatigue based on its causal factors (Figure 1), i.e., making a distinction between sleep-related (SR) and task-related (TR) fatigue.

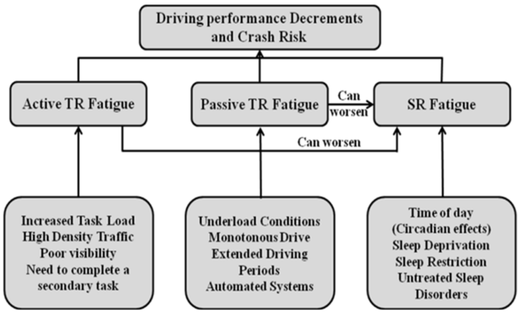

Fig. 1. A model of fatigue. Source: (May & Baldwin, 2009)

SR decrements in driving performance are related to the circadian rhythm (i.e., time of day), sleep disorders, and sleep deprivation or restriction. The body's natural circadian rhythm controls sleep/wake alternation during the day, including a loss of attentiveness in the early afternoon, when people are sleepier. Decrements in driving performance as effects of the circadian rhythm have been examined in previous driving simulator studies (e.g., Lenné, Triggs, & Redman, 1997) and may be correlated to the increased numbers of sleep-related car accidents observed at the peaks of sleep needs (Pack, Pack, Rogman, Cucchiara, Dinges, & Schwab, 1995) in the early morning (2–6 a.m.) and early afternoon (2-4 p.m.). Similarly, sleep deprivation or restriction causes impaired driving performance (Akersted et al., 2010).

Instead, TR fatigue depends on driving conditions (Figure 1): active and passive task-related fatigue may arise according to the combination of driving task and driving environment. Active TR fatigue is related to overload (high-demand) driving conditions [(Gimeno, Cerezuela, & Montanes, 2006); (Desmond & Hancock, 2001)], which include driving in high traffic density, poor visibility, or being required to perform an auxiliary secondary task in addition to driving, e.g., cell-phone conversations, in-car passenger conversations, auditory tips from navigation systems, or auditory alerts from driver warning systems. Passive TR fatigue is associated with underload driving conditions, which include driving in monotonous environments for extended periods of time, or partially/completely automated driving tasks (Gimeno, Cerezuela, & Montanes, 2006).

In fatigue studies, the use of driving simulators has been widely adopted in recent years [(Ting, Hwang, Doong, & Jeng, 2008); (Philip et al., 2005), (Thiffault & Bergeron, 2003)], in view of the opportunity of analysing hazardous driving conditions in a safe environment, to control effects induced by subjects' characteristics, and to measure changes in driving performance accurately. However, May and Baldwin (2009) argued that, in most studies, the experiments confused different causes of fatigue, focusing, for example, on circadian rhythm effects (SR-Fatigue) during highway driving performance (TR-Fatigue).

As a consequence of these remarks, in this paper we focus on analysis of passive task-related (TR) effects of highway driving in monotonous environments, studying the temporal evolution of performance indicators, with particular attention to clear definition of fatigue effects. This paper is the second part of a more comprehensive analysis of fatigue phenomena, the first results of which were reported in a previous paper (Rossi, Gastaldi, & Gecchele, 2011).

3. Methodology – Case Study

A driving simulator was used to obtain reliable observations of drivers' behavior [Rossi, Gastaldi, Gecchele, & Meneguzzer, 2012); (Rossi, Gastaldi, Meneguzzer, & Gecchele, 2011), (Bella, 2008a), (Bella, 2008b), (Bittner, Simsek, Levison, & Campbell, 2002), (Godley, Triggs, & Fildes, 2002), (Klee, Bauer, Radwan, & Al-Deek, 1999), (Kaptein, Theeuwes, & van der Horst, 1996), (Blana, 1996), (Staplin, 1995)] and to achieve the experimental control necessary to collect information about driving fatigue.

3.1. Apparatus

Experiments were conducted with the fixed-base driving simulator of the University of Padova, produced by STSoftware®. The simulation system includes a realistic cockpit equipped with a Dolby Surround® sound system, three networked computers, and five high-definition screens. This configuration can produce realistic virtual views of the road network and the surrounding environment.

3.2. Participants

The drivers were ten university students, with the following characteristics:

- absence of previous experience of a driving simulator;
- at least 3 years of driving experience;
- annual average driven distance of at least 3000 km.

Table 1 lists the test drivers' characteristics.

Table 1. Test drivers' characteristics: age and driving experience.

	Mean	Standard Deviation	Range
Age	25.3	0.9	24-27
Years of driving	6.6	0.7	6-8
Km driven per year	6350	2539	3000-10000

3.3. Driving Simulator Experiment Design

In the design phase, two road environment scenarios were built in virtual reality. They had the same road circuit and differed in type of environment: in the Monotonous Environment (ME), pairs of trees were regularly placed on both sides of the road and further rows of trees closed the line of vision at the horizon; in the Varied Environment (VE), buildings and vertical signs were added on both sides of the road (Figure 2).

The road circuit was 100 km long, composed of two straight stretches 25.0 km long and two 10.0 km long, connected by three circular curves (radius 3.18 km). The circuit had two driving lanes (width 3.6 m) and a hard shoulder (width 3.6 m) with a virtual bank which created a tendency to deviate to the right, requiring drivers to make compensatory steering corrections. Participants were asked to drive in the center of the right-hand lane, as they would normally do in a natural setting, keeping a safe speed (choosing a speed suited to their normal driving style).

(a) Varied Environment (a) Monotonous Environment

Fig. 2. Driving scenarios adopted for the experiments: (a) Varied Environment, (b) Monotonous Environment.

In both scenarios, visibility was good (daytime, good weather), disturbance effects were absent (no wind or traffic) and temperature was controlled. Each experiment was divided into four phases:

1. driving task on a rural road (10 minutes' training), to become familiar with the simulator driving;
2. rest (5 minutes);
3. interview, for information on participants' status (levels of fatigue and alertness);
4. driving task on the circuit (40 minutes);
5. interview, for information on participants' status (levels of fatigue and alertness), driving task and driving style (driving habits).

The experimental design was specifically intended to consider the relative importance of both monotony (Monotonous vs. Varied environments) and daytime (morning conditions, 9:00-11:00 a.m., vs. early afternoon conditions, 1:00-3:00 p.m.). For this reason, each driver was asked to drive in four experimental conditions:

1. Varied Environment in the Morning (VEM);
2. Varied Environment in the Afternoon (VEA);
3. Monotonous Environment in the Morning (MEM);
4. Monotonous Environment in the Afternoon (MEA).

Thus, the various causes of fatigue were clearly distinguished, following the comments of May and Baldwin (2009). The order of the four experiments was randomly counterbalanced among participants.

3.4. Response Variables

Using driving simulators allowed us to make high-frequency (10 Hz) recordings of the parameters describing drivers' behavior, such as position, speed, vehicle acceleration, and many cabin parameters. For the purposes of this study, Absolute Steering Error and Lateral Position were considered representative of driving performance. Absolute Steering Error [°] is the absolute difference between Steering movements made by drivers and the ideal Steering movements required to drive in the center of the right-hand lane; Lateral Position [m] is the position of the vehicle measured from the right-hand side of the right-hand driving lane.

As reported by Brookhuis and De Waard (1993), vehicle parameters and steering movements in particular (Brown, 1997) can be used to develop monitoring devices, given cross-validation with physiological measures commonly adopted in fatigue studies (e.g., Liu, Hosking, & Lenné, 2009). In this paper, driving sessions (each lasting 40 minutes) were subdivided into ten sub-intervals each lasting 4 minutes and, for each interval, the means and standard deviations of the output variables were calculated. Lastly, Mean of Absolute Steering Error (Mean.Steer.Error) and Standard Deviation of Lateral Position (SD.Lat.Pos) were chosen as response variables.

In addition to these vehicle-based measures, the Stanford Sleepiness Scale (SSS) was completed by drivers before and after the task. The SSS contains a 7-point Likert-type scale, ranging from 1 for "very alert" to 7 for "very sleepy", and was used to measure changes in drivers' alertness during the experiment (Hoddes, Zarcone, Smythe, Philips, & Dement, 1973).

3.5. Data cleaning

The dataset used here included the values of response variables (Mean.Steer.Error, and SD.Lat.Pos.) for 4-minute sub-intervals. Analysis was conducted on 5 sub-intervals (8', 12', 20', 28', 32'), because non-significant data were cleaned according to the following criteria:

- elimination of sub-intervals with data recorded in curve segments (16', 24', 36', 40'). The choice to consider only data recorded in the straight segments of the circuit was made to isolate drivers' fatigue better in the most hazardous condition, as noted by Nelson (1997).
- elimination of the first sub-interval (4'). At the beginning of the task, drivers need one or two minutes to reach the desired highway speed, and the first sub-interval was therefore eliminated, so that only data representing stable highway driving conditions were analysed.

3.6. Data treatment

Following previous studies of fatigue [(Ting, Hwang, Doong, & Jeng, 2008); (Philip et al., 2005), (Thiffault & Bergeron, 2003)], a separate analysis of variance (ANOVA) for repeated measures was performed on each response variable (SD.Lat.Pos., Mean.Steer.Error) to evaluate the influence of task duration, circadian rhythm, and monotony of environment. In cases of violation of sphericity assumptions (Mauchly Test), the Greenhouse-Geisser correction was adopted to calculate F-ratios. The responses given by drivers to SSS ratings were compared by a non-parametric matched paired test.

4. Results

4.1. Subjective Sleepiness Evaluation

Figure 3 shows the variations observed in drivers' SSS scores. Post-test SSS scores were significantly increased when compared with pre-test values [Wilcoxon Test: $Z = 0$, $p < 0.001$ for all conditions tested], meaning that drivers increased their perceived sleepiness due to the experiment. This was particularly evident in the afternoons, when SSS scores were higher than in the mornings, both before and after the experiment.

	Mean	Median	Range
Morning - Pre	1.70	2	1-3
Morning – Post	2.85	3	1-6
Afternoon - Pre	2.30	2	1-4
Afternoon - Post	3.70	3	2-6
Overall - Pre	2.00	2	1-4
Overall – Post	3.275	3	1-6

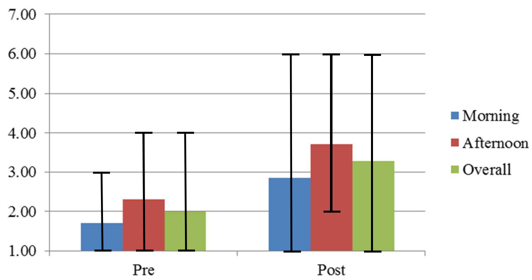

Fig. 3. Drivers' mean SSS scores, before and after the experiment.

4.2. Standard Deviation of Lateral Position

A repeated-measures ANOVA with Task Time (5 levels: 8’, 12’, 20’, 28’, 32’), Environment (2 levels: varied, monotonous), and Day Time (2 levels: morning, afternoon) as within-subject factors was performed on variable Standard Deviation of Lateral Position. Table 2 lists the summary statistics (means and standard deviations) according to the experimental conditions.

Table 2. Standard Deviation of Lateral Position. Summary statistics.

	Morning Varied (VEM)		Morning Monotonous (MEM)		Afternoon Varied (VEA)		Afternoon Monotonous (MEA)	
Time[min]	Mean[m]	St.Dev.[m]	Mean[m]	St.Dev.[m]	Mean[m]	St.Dev.[m]	Mean[m]	St.Dev.[m]
8	0.177	0.069	0.164	0.058	0.177	0.071	0.164	0.052
12	0.180	0.073	0.160	0.056	0.173	0.076	0.175	0.041
20	0.188	0.055	0.188	0.056	0.227	0.111	0.224	0.087
28	0.188	0.062	0.167	0.043	0.230	0.103	0.238	0.105
32	0.180	0.045	0.182	0.062	0.197	0.071	0.221	0.080

The analysis showed the significant main effects of Task Time ($F(4,36) = 7.319$, $p < .001$, $\eta_p^2 = .448$) and Day Time ($F(1,9) = 5.711$, $p = 0,041$, $\eta_p^2 = .388$) and also significant interactions between Day Time and Task-Time factors ($F(4, 36) = 3.328$, $p = .020$, $\eta_p^2 = .270$). The main effects of Environment and the other interactions among factors were not significant. Figure 4 shows the mean values of the response variables in the experimental conditions.

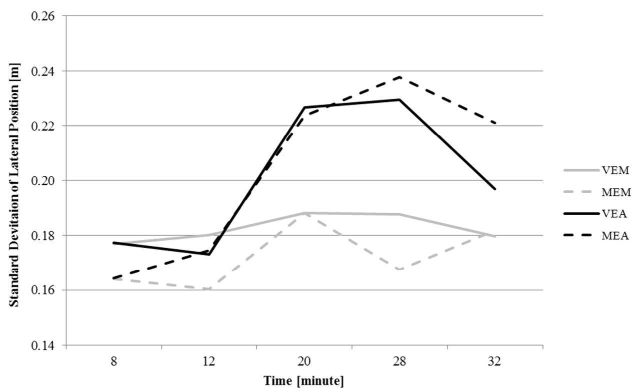

Fig. 4. Standard Deviation of Lateral Position. Mean values in experimental conditions.

4.3. Mean of Absolute Steering Error

A repeated-measures ANOVA with Task Time (5 levels: 8', 12', 20', 28', 32'), Environment (2 levels: varied, monotonous), and Day Time (2 levels: morning, afternoon) as within-subject factors was also carried out for the Mean.Steer.Error response variable. Table 3 lists the summary statistics for this variable in the test conditions.

Table 3. Mean of Absolute Steering Error. Summary statistics.

	Morning Varied (VEM)		Morning Monotonous (MEM)		Afternoon Varied (VEA)		Afternoon Monotonous (MEA)	
Time[min]	Mean [°]	St.Dev. [°]	Mean [°]	St.Dev. [°]	Mean [°]	St.Dev. [°]	Mean [°]	St.Dev. [°]
8	1.309	0.471	1.258	0.433	1.384	0.533	1.308	0.376
12	1.410	0.424	1.137	0.413	1.346	0.507	1.360	0.354
20	1.632	0.585	1.440	0.407	2.101	0.925	1.851	0.746
28	1.615	0.425	1.328	0.356	2.002	0.835	2.227	1.025
32	1.625	0.510	1.487	0.541	1.594	0.734	2.248	1.627

The analysis showed the significant main effects of Task Time ($F(4,36) = 16.228$, $p < .001$, $\eta_p^2 = .643$) and Day Time ($F(1,9) = 8.830$, $p = .016$, $\eta_p^2 = .495$); the interaction between these factors was also significant ($F(4, 36) = 3.539$, $p = .038$, $\eta_p^2 = .282$). The main effect of environment was not significant ($F(1,9) = .150$, $p = .708$, $\eta_p^2 = .016$); neither were the interactions Task Time x Environment, Day Time x Environment, Day Time x Environment x Task Time. The mean values of the response variable in the experimental conditions are shown in Figure 5.

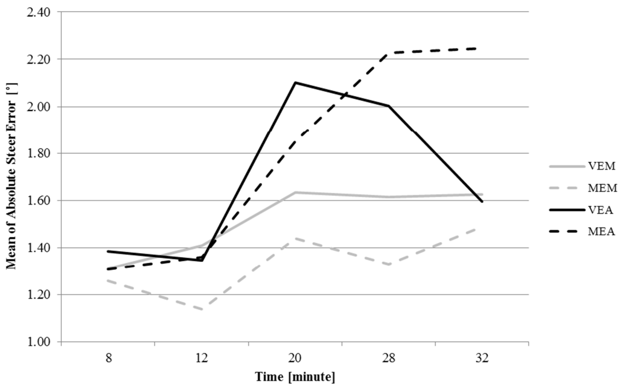

Fig. 5. Mean of Absolute Steering Error. Mean values in experimental conditions.

4.4. Discussion

A general examination of the results can be made by highlighting some main findings common to the response variables. The results are clear-cut and support several hypotheses regarding the concept of driver fatigue.

According to previous studies, as the duration of a driving task increases, driving performance decreases [(Thiffault & Bergeron, 2003), (Otmani, Pebayle, Roge, & Muzet, 2005)] and a peak in driving impairment occurs between 20 and 30 minutes of driving (Thiffault & Bergeron, 2003) (Figures 4 and 5). These findings suggest that the proposed simulator design can reproduce the onset of the driver fatigue phenomenon and how it first manifests itself.

Similarly, the time of day affects increments in the response variables, as already found for SD.Lat.Pos. (Lenné, Triggs, & Redman, 1997): experiments conducted in the early afternoon revealed that these variables reached higher values than those in the morning (circadian rhythm effect).

The results concerning effects produced by the monotony of the environment are also interesting. Although the influence on the response variables of a monotonous environment was not statistically significant, from a qualitative point of view, the differences between driving performance observed in the Varied and Monotonous conditions show that environmental stimuli can interfere with driver alertness.

This is a problem which, at this point, must be addressed in greater depth. Figures 4 and 5 show the effects of environmental changes according to time of day. As expected, in the afternoon, driving through a monotonous environment impairs performance with respect to driving through a varied environment; in the morning, the opposite occurs. This is explained by assuming that, in the morning, when the circadian effect is absent, a varied environment may distract drivers (as indeed some of our participants reported). However, this effect, not supported by statistical analysis, needs to be further analysed in future research. Developments should include better definition of the level of monotony/variety of the environment [(Fletcher, Petersson, & Zelinsky, 2005); (Zhao, Mao, Rong, & Ma, 2012)] and deeper analysis of drivers' characteristics, including age, gender and driving style (Taubman-Ben-Ari, Mikulincer, & Gillath, 2004).

Lastly, it should be noted that, since this experiment compared driving performance in two road environments with only small differences in exogenous stimuli, the extent of the observed effects of monotony on driver alertness may have been underestimated.

5. Summary and conclusions

This paper analyses driver fatigue behavior, with special attention to the passive task-related (TR) effects of highway driving in monotonous environments. Data collected with an interactive driving simulator in laboratory experiments were used to determine the influence of drivers' characteristics and to measure changes in driving performance with high precision.

Ten subjects were asked to drive for 40 minutes along a stretch of road with two scenarios: Monotonous environment and Varied environment. All drivers drove in both environments in the morning (9:00-11:00 a.m.) and early afternoon (1:00-3:00 p.m.), since the experimental design was specifically intended to consider the relative importance of both monotony and time of day. The Mean of Absolute Steering Error (Mean.Steer.Error) and Standard Deviation of Lateral Position (SD.Lat.Pos.), calculated on 4-minute sub-intervals, were chosen as response variables.

The results were clear-cut:

- in previous studies, the circadian effect was found to interfere with driving tasks. The negative effect on driver performance, which leads to more hazardous driving conditions in the early afternoon, was experimentally proven;
- in accordance with previous studies, a negative influence of the duration of driving task was observed;

- in addition to previous studies, the qualitative effect of driving in a monotonous environment was observed. Although the effect on the response variables of the road environment were not statistically significant, there was an interaction with time of day. This point must be further analysed in future research;
- it is worth noting that the monotony factor was only superficially varied in this study: as such a small variation in scenario did produce some variation in driver fatigue, it is intuitive that greater variations in environmental stimuli may significantly influence driver performance.

These results provide an improved view of the fatigue problem, isolating different aspects which concur to impair driving performance. Since each aspect of fatigue is related to specific causal factors and must be addressed with specific countermeasures, the search for practical solutions to help drivers must be developed in several directions. In particular, the aspect of driving in monotonous environments has not been specifically addressed in the past, so that deeper analysis of the characteristics of this phenomenon (e.g., definition of measures of environmental monotony) and testing of possible countermeasures are needed.

Some interesting directions for future research are:

- extending the sample size (number and stratification), to better represent the population of drivers and their driving characteristics;
- considering other variables as predictors (age, gender, driving style, etc.);
- analysing physiological measures of fatigue (bio-response or eye-tracking) to better represent some aspects of the fatigue phenomenon;
- since driving is, in itself, a highly complex cognitive activity, involving the integration and coordination of a multitude of sub-processes, evaluation of the potential effects of fatigue on critical tasks involved in driving, such as driver braking response, is necessary;
- in a long-term perspective, testing should include both the adoption of in-vehicle and environmental countermeasures to passive task-related effects. As regards environmental countermeasures, evaluation of the effects of various visual stimuli, in terms of shape, size and color, on driver fatigue, represents a very interesting research field.

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