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Measuring the effect of the rainfall on the windshield in terms of visual performance

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ABSTRACT

Driving through rain results in reduced visual performance, and car designers have proposed countermeasures in order to reduce the impact of rain on driving performance. In this paper, we propose a methodology dedicated to the quantitative estimation of the loss of visual performance due to the falling rain. We have considered the rain falling on the windshield as the main factor which reduces visual performance in driving. A laboratory experiment was conducted with 40 participants. The reduction of visual performance through rain was considered with respect to two driving tasks: the detection of an object on the road (contrast threshold) and reading a road sign. This experiment was conducted in a laboratory under controlled artificial rain. Two levels of rain intensity were compared, as well as two wiper conditions (new and worn), while the reference condition was without rain. The reference driving situation was night driving. Effects of both the rain level and the wipers characteristics were found, which validates the proposed methodology for the quantitative estimation of rain countermeasures in terms of visual performance.

1. Road safety under rain

Rain may affect driving performance, and since the beginning of automotive transport, car designers have considered this issue. They have proposed countermeasures in order to reduce the impact of rain as early as 1903, when Mary Anderson proposed the first patent for a windshield wiper (Anderson, 1903). In addition to wipers, rain effects are also mitigated by improved windshield design, automotive lighting and road lighting. Considering the high impact of rain on vision, and even though the main impact of rain on driving addresses the road skid resistance, one may be surprised that the quantitative impact of rain on the driver's visual performance led to very few studies to date.

In his accidentology review, Parkarri (2009) found that low visibility conditions, such as rain, fog and night driving, increase the risk of having an accident. More specifically, in rainy conditions, accidents with three and more vehicles are more frequent. The risk increases due to rain also depend on road conditions (higher on motorways, in curves and slopes) and on the road user (higher for cars and pedestrians). He also found that the risk increase is higher under strong rain compared to light rain.

Based on a comparison of accident data with and without rain, Andrey and Yagar (1993) found that the crash risk was 70% higher under falling rain compared to without rain. Interestingly, they found that this higher risk does not appear after rain, driving on a wet road. They proposed an explanation in terms of risk compensation (Wilde, 1988), arguing that drivers compensate for the skid resistance risk associated to a wet road, but not for the lowered visibility due to the falling rain. These results were confirmed by Chung et al. (2005) on the Tokyo Metropolitan Expressway, with an accident rate of 1.5/h under rain vs. 0.8 without rain. Another study in Melbourne (Australia) found that rain, rain intensity and night situation all three result in higher risk levels (Keay and Simmonds, 2005).

These results about accident rates are however mitigated by the accident severity data. From 10 years of accident studies in the UK, Edwards (1998) found that the severity of accidents under rain is less important compared to without rain, which may be due to the lower speed (Khatak et al., 1998).

In addition to the higher risk due to a lower skid resistance, these results from accident studies could be expected from the visual effects of rain on visual performance. Three main effects can be anticipated: first, wet surfaces differ in their visual appearance from dry surfaces; second, the rain lowers the contrast between the objects and their background, thus lowering the driver's detection performance; third and most important, the raindrops on the windshield alter the visibility, in a way which is not well understood.

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A wet road surface changes the conditions of perception on the road by two main factors. First, a wet road is specular, and thus reflects in some situations the adverse light sources toward the driver (from either automotive or road lighting), which may lead to disability glare and discomfort glare (CIE, 2002). Second, retro-reflective road markings are almost inefficient under a water film, motivating the development of all-weather pavement markings as a countermeasure.

Rain drops are similar to optical lenses. According to Garg and Nayar (2007), they are close to fish-eye lenses with 165° of opening. Light is refracted and attenuated when crossing a rain drop, resulting in dynamic changes in the visual signal the driver receives. From far away, rain can be thought to as a diffusive media, just as fog. In that sense, light intensity is attenuated when crossing a distance d according to:

$$I = I_0 \cdot e^{-kd} \qquad (1)$$

where I_0 is the light intensity without rain, d the distance between the object and the driver, and k the extinction coefficient, which depends on the rain intensity and on the raindrops size.

On a windshield, raindrops do not coalesce in water films, they rather behave as small moving balls, with dynamic properties in relation to the windshield material and shape, wiper speed and shape, and the driver's speed. The raindrops optical perturbation lowers the driver's visual performance, even in the presence of wipers (Green et al., 2008). These perturbations result, for instance, in eye glances at nearer distances, compared to rain-free situations (Zwahlen, 1980), which can be understood as a reduced driving anticipation or an increased mental workload (Shinar, 2007). Sayer and Mefford (2001) tested the impact of hydrophobic and hydrophilic windshields in terms of the driver's performance and comfort. They found a positive impact of hydrophobic windshield on both visual acuity and subjective feeling, but no effect of hydrophilic windshields. According to Andrey and Knaper (2003), the reduced visibility under rainy conditions is mainly due to the visual perturbation on the windshield, rather than the atmospheric effect of the falling rain (Eq. (1)). The reduction of visibility is even higher under low luminance levels (such as in night driving), low speed wipers, and small raindrops (OECD, 1976; Ivey and Mounce, 1984). In this paper, we focus on the "raindrops on the windshield" factor, and on night driving conditions.

If one wishes to link rainfall and visual performance, quantitative approaches are not easy. Thirty years ago, Bhise et al. (1981) conducted two series of experiments, on a closed test track and on the road. They measured the visibility distance as a function of ambient lighting, rain intensity and vehicle speed. Based on these experiments, they proposed a quantitative model of the detection distance of a vehicle, under rain, without wipers. From a field test too, Morris et al. (1977) proposed a quantitative model to link visual acuity to wiper speed and rain intensity. More recently, a comparison of visual performances under wet and rainy conditions was conducted on the Smart Road, at the VTTI (Blanco, 2002). Various automotive lighting systems were tested, and detection distances were recorded on various targets. The authors found a decrease in distance detection around 70% under rain.

From this body of results, rain appears as an important road safety issue. At the same time, there seems to be a lack of reference methodologies for the assessment of countermeasures (such as wipers) in terms of visual performance. In this paper, we propose such an experimental methodology, in order to measure two key visual performances with respect to the driving activity: target detection and reading. Two rainfall levels were considered, as the visual performance was expected to decrease with increasing rain level; and two wiper systems were considered, because it is the main countermeasure to the loss of visibility due to rain. This methodology was demonstrated in night-time conditions, and proved to be selective enough to discriminate the visual performance both with respect to the wiper characteristics and with respect to the rainfall level.

2. Materials and methods

Based on our literature review, we have considered the rain falling on the windshield as the main factor which reduces the visual performance in driving. An experiment was conducted in order to quantify the reduction of visual performance through rain with respect to two reference driving tasks: the detection of an object on the road and reading a road sign. This experiment was conducted in a laboratory under controlled artificial rain. Two levels of rain intensity were compared, as well as two wiper conditions, while the reference condition was without rain. Visual performance was measured in terms of contrast threshold for the target detection task and reaction time for the reading task.

2.1. Participants

Forty volunteers (12 women, 28 men), with a mean age of 42 years (SD = 12), participated in the experiment. They were all licensed drivers with normal or optically corrected vision.

Although they were recruited among DLCF employees, all participants were naive to the purpose of the experiment. They were given a full explanation of the experimental procedure, and a written informed consent was obtained before participation, with the option to withdraw from the study at any time.

2.2. Apparatus

2.2.1. Experimental room

The experiment took place in a 15 m long dark tunnel dedicated to photometrically controlled psycho-visual experiments in fog and rain conditions, at the Département Laboratoire de Clermond-Ferrand (DLCF), Clermont-Ferrand, France (Cavallo et al., 2001). The participants sat in a Renault Clio situated at one end of the tunnel.

During the experiment, low light levels were used, around 1 cd/m^2, in order to be close to the light levels usually encountered in urban places at night. The volunteers participated in two successive experiments, in order to measure two kinds of visual performance: target detection and reading performance. Two main variables were manipulated: the rainfall intensity and the wiper characteristics. Two more variables were considered: the target contrast with the background in the target detection task, and the "words" vs. "non-words" condition in the reading task.

The visual stimuli were displayed on a PC screen, at a distance of 5.15 meters from the participants. The reaction time was recorded using the RT Direct software, defined as the elapsed time between the stimulus onset and the key pressed on a keyboard.

2.2.2. Rain simulation

The rain projection system was manufactured by the SPRAI SAS Company. It was adapted in order to simulate rain on a car's windshield while controlling the rain intensity and a methodology was defined in order to produce artificial rain. This system can project various rain levels on the windshield of a vehicle installed in the platform. It allows producing artificial rain whose characteristics are very close to those of natural rain (rainfall, size, number and velocity of droplets): the range of rain intensity is relevant for natural rainfall, that is from 2 to 25 mm/h and the droplets' velocity ranges between 1 and 8 m/s. The system (see Fig. 1) consists of a removable structure, a reservoir, a hydraulic wardrobe and two sprayers, along with a control panel and a control software.

The sprayers are two meters above the windshield and can be controlled in terms of flow rate and rotational speed. Selected