Master of Science in Civil Engineering

The Impact of Coloured Road Studs on Driver Behaviour: A Driving Simulation Study

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Contents

Abstract

The absence of street lighting in night-time conditions, is a considerable cause of hazardous driving conditions. A potential solution to increase road safety in such conditions consists of the use of road studs. These devices improve the visual perception of the carriageway through the generation of low intensity light. However, it is not clear which colours are best to use and in which configurations.
The goal of this driving simulation study is to examine different colours of Light Emitting Diode (LED) road studs to improve the visibility of curves in night-time driving. Three situations were considered along a two-lane rural highway setting: (i) the baseline condition, without road stud devices, (ii) white LED road studs, and (iii) red LED road studs. Thirty participants drove the three scenarios, where longitudinal and transverse driving behaviour data was collected and analysed. The influence of colours on the emotions of drivers involved in the experiment was also studied. Participants were asked to evaluate how they felt while visualising projected image stimuli of the three situations analysed. They were asked to make a judgment about the positive/negative and calm/agitating sensations caused by the different colours of LED devices.
Results revealed that the colours of LED road studs influenced the driving behaviour and the perception of the devices. The driving simulator study revealed that the red-light devices were able to produce a reduction in speed in curves of about 3%. This reduction in speed by the use of red LED road studs was associated with an increased discomfort while driving and an increased provocation of an agitated state of the driver. Conversely, white LED studs did not elicit a change in speed with respect to the baseline without road studs. White LED road studs were shown to influence just the lateral behaviour within the curve. A reduction of lateral transverse movement was obtained inside the curves up to 15% in comparison to the baseline condition without road studs. Additionally, the curves illuminated with white LED road studs were perceived as less dangerous, more pleasant and less “alarming/exiting”.
From these results, the installation of white LED devices is preferable as they were shown to improve the comfortable driving conditions. Conversely, the red road studs should be used only to highlight dangerous road segments and dangerous curves.

Key words: *LED road studs; road safety; road markings; road perception; driving behaviour*

Sintesi

La guida notturna in assenza di illuminazione stradale, è fattore nella generazione di condizioni di guida pericolose. Una soluzione per aumentare la sicurezza stradale in tali condizioni consiste nell'utilizzo di dispositivi luminosi come segnaletica orizzontale. Questi dispositivi migliorano la percezione visiva della carreggiata stradale attraverso la generazione di una luce a bassa intensità. Un problema con questa soluzione è che non è chiaro quali colori è meglio usare e in quali sezioni dell'asse stradale. L'obiettivo di questo studio è quello di esaminare i diversi colori di questi dispositivi stradali a Light Emitting Diode (LED) per migliorare la visibilità delle curve durante la guida notturna. Sono state considerate tre situazioni su una strada extraurbana a due corsie: (i) la condizione di base, senza dispositivi luminosi; LED stradali a luci (ii) bianche e (iii) rosse. In questo studio sul simulatore di guida i partecipanti hanno guidato i tre scenari, in cui viene analizzato il comportamento di guida longitudinale e trasversale. Viene inoltre studiato come i diversi colori dei dispostivi stradali influenzano le emozioni dei guidatori. Ai partecipanti è stato chiesto di valutare come si sentivano emotivamente mentre venivano proiettati su un monitor, alcuni stimoli di immagine delle tre situazioni analizzate. È stato chiesto di esprimere un giudizio sulla sensazione positiva-negativa e di calma-agitazione causata dai diversi colori dei dispositivi LED.

I risultati rivelano che il colore dei dispositivi LED è in grado di influenzare significativamente il comportamento alla guida e la loro percezione. Con lo studio al simulatore di guida, è stata ottenuta una riduzione del 3% di velocità in curve con una illuminazione a luce rossa. A questo miglioramento viene però associato un aumento di stato di agitazione e una riduzione del comfort nella guida. I LED a luce bianca invece, hanno portato ad una riduzione del 15% nel movimento trasversale dei guidatori lungo le curve. In aggiunta, la luce bianca fa percepire le curve come meno rischiose e meno "allarmanti", producendo tra l'altro un miglior comfort di guida.

Da questi risultati, l'utilizzo dei dispositivi LED a luce bianca è preferibile perché essi migliorano sia il comportamento alla guida che le condizioni di comfort della guida. Invece, i LED a luce rossa dovrebbero essere usati solo per evidenziare curve pericolose o altre situazione di possibile pericolo.

Parole chiave: *LED stradali; sicurezza stradale; segnaletica orizzontale; percezione della strada; comportamento alla guida.*

1 Introduction

The number of fatalities per vehicle-miles driven is significantly higher at night than during the day, with a crash rate difference around 60% (*Plainis et al., 2006*). Road crashes that occur at night lead to a severity that is 50% higher with respect daytime crashes (*Elvik, 1995; Goswamy et al., 2018*). However, the number of night-time crashes can be reduced with the installation of adequate road lighting systems (*Plainis et al, 2006*). It is therefore important to evaluate innovative countermeasures in night-time driving conditions, especially where road lighting cannot be installed.

In all driving conditions, road accidents can also be attributed to different causes, most of them associated with user errors. Visual perception errors while driving can lead to incorrect driving decisions and thus the execution of dangerous maneuvers (*Insurance Institute for Highway Safety, 2020*). In particular, errors due to incorrect visual perception of the road are the major factors of a possible collision, especially in night-time condition with little or no illumination. The difficulty of seeing objects, the surrounding environment and the road carriageway margins may lead to a reduced ability to judge the proper travel speed and possible dangerous situations (*Hills, 1980*). Transition zones, speed reduction zones, curves and other geometrical factors, are also very important points of interest for road safety. Along these road elements, the possibility of generating road accidents are greater than in straight road sections. (*Hasibul et al., 2019*).

The study of new solutions is crucial for road accident reduction. In general, the possibility to improve drivers' perceptions and confidence can be evaluated by analysing different factors such as a better control of vehicle speed control, reduction of lateral movement and reduction of reaction time. The use of enhanced optical road markings, such as transverse speed bars, traffic calming markings, etc., may be a solution to achieve these goals. These solutions have proven to be effective by improving vehicle handling on the road *(Babić et al., 2020*). However, optical markings are not as effective in night-time and low visibility conditions, such as in fog *(Dianamandouros et al., 2016)*. The introduction of different strategies in low-light conditions, as the road studs, could be a good element to improve drivers' perceptions and confidence of road safety. Road stud devices can be installed to outline the presence of the carriageway edge line as well as the centreline. However, there are not specific rules about the installation of these devices. These solutions generally do not follow any precise guidelines and the use of any coloured road stud is possible. In fact, it is possible to find devices of many colours on the market with no specific instructions regarding their application on the road and specific uses of various colours.

Colours are able to facilitate the perception of reality (*Belinda et al., 1989*). They have the ability to capture the attention of people to provide safety information and evoke a rapid response. It is shown that colours can produce different emotional states in people and emphasize the relation between colours and perception. Colour psychology plays an important role, generating emotional and physiological effects (*Elliot et al., 2013*). They can carry important meaning and can have an impact on people's cognition and behaviour, directly linking colour and psychological function in humans. Colours like red, yellow and orange, associated with a long wavelength, are able to produce forceful actions. On the other hand, green and blue, with a shorter wavelength, are associated with relaxation, producing calm and stable actions (*Calvi, 2018*). The various colours can produce different driving behaviour and perception as well as provide different results in the field of the driving behaviour and road safety.

1.1 Literature Review

Road studs are devices bonded or anchored to the road surface for lane marking and delineation. Compared to horizontal road markings, they are designed to improve drivers' perception of the lane, specifically in night-time conditions. Their presence along the road, especially in curved sections, has the goal to generate benefits in terms of driving behaviour, providing visual guidance of the road and by delineating the carriageway margins. Road studs can be divided into two main families: (i) the reflective raised pavement markers (RPMs), i.e. cat's eyes, that are not reliant on any energy source, and (ii) the energized elements that emit light, usually generated by a LED, due to being connected to a power supply system. The latter category harvests energy from the power network or from photovoltaic panels installed on their upper surface. The cat's eyes are usually made from plastic or metal and work by retroreflecting cars' headlights. For that reason, LED road studs are much more visible than cat's eyes. Figure 1 shows the major types of road stud devices.

Figure 1: Examples of road stud devices: a standard reflective (left), a cat eye's solution in UK application (centre) and a solar LED stud (right)

Road stud devices are able to produce a reduction in lateral movement, both in leftward and rightward curves, with safer vehicle control. (*Shahar et al., 2014*). *Sharhar* also showed that changes in speed due to the devices are also significant, with a variation up to 5 km/h in the absence of the illuminated element. An interesting note is that a general reduction of speed was more accentuated in rightward curve direction in comparison to a leftward curve direction in which variation of speed was not so evident. Another result of the installation of these devices was a faster speed in straight section and before entering a curved segment of road. Moreover, *Horberry* (*2006*) observed that higher visibility markings lead to more accurately controlled driving, as well as more relaxed driving, through a possible reduction of a driver's workload. With visibility from distances greater than 600 m, the LED devices were able to increase the confidence in driving and clarify the characteristics of junctions and curves, especially in areas in which streetlights are not suitable (*Llewellyn et al., 2020*). *Villa et al.,* (*2015*) also investigated the benefit of LED road studs in curved sections in night-time conditions compared to an illuminated road. It was shown that when compared to unlit conditions, a possible increase in travel speed due to the use of road studs was possible, but when compared to an illuminated road, lower speed were observed. Moreover, the analysis of lateral position showed that in the case of road stud conditions, the drivers drove closer to the centreline, except in leftward curves, where drivers was found to drive more to the right. Of course, road devices must be sufficiently visible to road users to be effective. The illumination of the road devices depends on the road surface condition, wet or dry, and on the external light intensity (*Brémond et al, 2014*). To avoid potential glare phenomena, the brightness of the road devices, should be tuned according to the illuminated condition (*Brémond et al., 2014*).

Nevertheless, it is not clear how other factors such as road stud colour can influence the effects of these devices on road users as no specific scientific studies in the literature were found. The effect of colours may play a fundamental role on the perception of the signals. The analysis of luminance of reflective road studs under headlight illumination, carried out by Bullough and Liu (*2019*), showed that white and yellow are more visible than red and blue reflective devices. Consequently, the sight distance at which the devices are visible could be strongly reduced by the use of different colours.

1.2 Problem Statement

Although different studies have analysed the use of road studs, there has yet to be studies paying particular attention to the effect generated by different light colours on drivers. The study conducted by Horst et al., (*2018*), integrated a system of interactive LED studs with an Arduino platform. This system was able to modify the stud colour to provide different visual information to the drivers. In that study, no results were elucidated regarding the benefits of different light colours. Now, following this advanced solution, it is even more important to clarify the gap in knowledge about how the colours of road stud devices can affect driving behaviour. The possibility to transmit different road perceptions and emotions through different colours has not yet been studied in enhanced marking devices. Of course, if we want to use standard devices, equipped with lighting emission diode, we can find many different colours. To date, the main colours of LED road studs, present in already made solutions are white, yellow, green, red and blue; the possibility of changing colour is related to the capacity of the LEDs. These different colours can induce different perceptual and emotional states in drivers. In fact, emotions are a multicomponent process, divided into several components with a temporal course activated by internal or external stimuli. An example is the stimulus that varying amounts of light, that can be seen during conduction, can have on night-time driving to generate various emotional states of drivers, like anxiety, fear, sadness etc. Karlsen et al., (2020) studied the relation between colours and cognition along different cycle path in Norway. It was shown that colours are not able to significantly modify the behaviour and impact on cyclist. Despite that, the researchers indicated that red was found to be associated with danger. Although this study brought important concepts of colours into their methods, it did not concentrate deeply on the effect of colours produced by the horizontal markings. So, this study of the effect of colours of LED road studs provides a further step in investigating alternative solutions for situations in which street lights are not suitable along roads.

Moreover, is not clear how the relation between spacing, frequency and degree of continuously of the devices can answer questions relating to drivers' speed perception, much like what has already been studied in regards to optical speed markings. In fact, from the experience gained by studying optical road marking, the different spacing between two consecutive devices, could produce a different operating speed of the drivers.

1.3 Study Objective

The main objective of this study was to evaluate the effect of different LED road stud colours on driver behaviour through the use of a driving simulator. The intent was to focus on the night-time driving situation, with an important geometric element of road alignment: the curves. Longitudinal and lateral behaviour of drivers was monitored by the support of the driving simulator. Moreover, an emotional perception study was carried out. Emotions are a complex psychological state of feeling that influences our performance by having significant effects on our perception, thinking and behaviour (*Bynion et al., 2017*). The analyses of the emotional information were performed thanks to a static visual experimental study in which stimuli about different colours and conditions of road studs were projected to the participants. Results of emotional states were collected by using a Self-Assessment Manikin scale (SAM). Each manikin represents a human emotional state in terms of happiness, calmness or agitation, with a scale ranging from the best to worst emotional states. The information about driving behaviour and emotional perception state, although obtained in a different way, were connected to each other. In fact, as studied by *Steinhauser et al., (2015)*, the driving behaviour of the participant is generally influence by the emotional state of them. So, the goal was to define how the different colours of LED road studs can influence the drivers' perception and emotions. With the driving simulation was studied how the colours can affect the driving performance. Moreover, the emotional study was carried out in order to understand how these colours affect the perception of the road studs.

The design and modelling of the driving simulation scenarios were created at the Neuroergonomics & Operator Performance Lab at the Universidad de Granada (Spain). The experimental phase and data analysis was carried out at the *Road Safety and Driving Simulation Laboratory* at the *Polytechnic of Turin*. The goal of this collaboration between the two universities was to merge knowledge of neuroergonomics and driving psychology, within the context of road engineering.

2 Methods

2.1 Experimental design

In this research experiment three different road scenarios were analysed: (i) the baseline, where no LED road studs were present along the curves, (ii) with the white and (iii) with the red LED road studs. The devices were positioned on the two external road markings in all the curves of the track. The three simulation scenarios were built on the same road alignment in a rural environment, without the presence of streetlights. Dedicated rules for the design and installation of the road stud devices were not found in the technical literature. Hence, the position of the LED devices was partially based on past research, taking it as starting point study conducted by *Villa*, (*2014*) and *Brémond*, (*2015*). Moreover, this study is also based on solutions already implemented on roads, especially present on UK and USA roads.

In addition, curve radius and curve direction were taken into consideration as independent factors. Therefore, in both the driving simulator and into the emotion's computer study, different radii of curvature were explored, in left and right direction, ranging from 440m to 120m; in the conduction phase these eight different curves were duplicate, to have a better control on the results data, with the final sixteen different curves. In the table 1 is summarised the description of the independent factors of the experiment.

Table 1: Summary description of the independent factors of the experiment.

Independent factor	Levels and values			
Curve radius [m]	120	210	300	440
Curve Direction	L	R		
Scenario Configuration	Unlit	White LED	Red LED	

Thirty drivers with no division in groups were involved. Drivers completed three simulating scenario of the driving simulation phase and the studio about the emotions. The sceneries were given in six possible combinations, different for six consecutive participants. This order was done to avoid as much as possible familiarity with the driving simulation task into the results. At the end of the driving session, participants were asked to fill the post-drive questionnaire to check any simulation sickness effect and eventually exclude those data from the final processing.

2.2 Road scenarios

The three driving simulating scenarios were based on a road alignment of a two-lane rural highway, 11.63 km long and including 16 curves. The scenarios were diversified by the presence of the LED road studs in two of them (white and red) and the only one without LED devices (unlit). They were made with the same characteristics of landscape, environments, and road geometric elements, to evaluate the results in only one terrain model. The only different elements of the three scenarios, except the presence and coulors of LED road studs, were the decorations of road signals, trees and building. These different decoration elements were located in different points in the scenarios, in order to avoid as much as possible situation of familiarity within two simulations.

The road alignment was designed according to the *Italian Geometric Design Standards for Road Construction* (*Norme funzionali e geometriche per la costruzione delle strade, 2001*) for highway and motorway and the *Italian Highway Code* (*Codice della Strada*).

Figure 2 reports an extraction of the Italian standard. The road was classified as a two-lane rural highway (*class C1* according to the Italian standard), with a lane width of 3.75 m and a shoulder width of 1.5 m. Four different curve radii levels were adopted: 120 m, 210 m, 300 m, and 440 m.

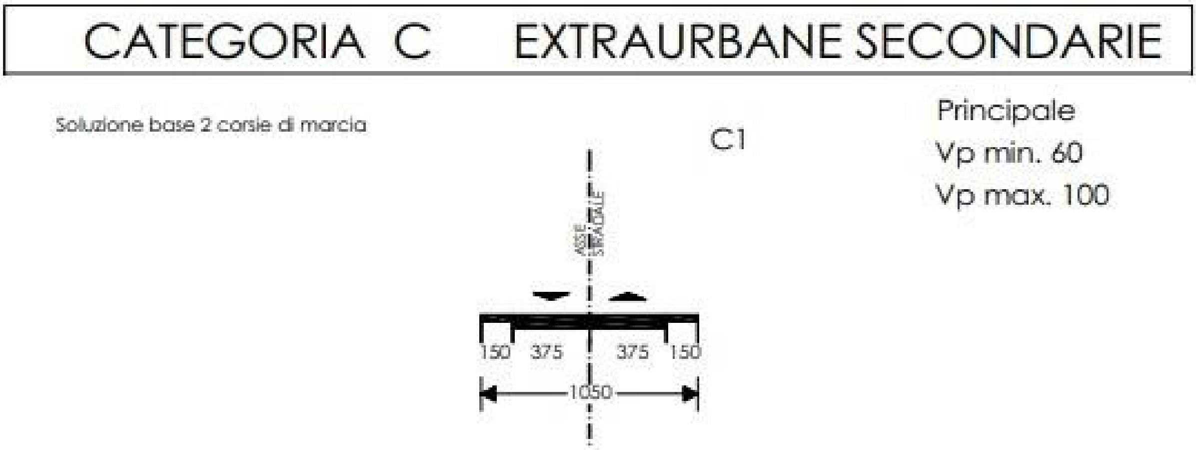

Figure 2: Extract of Italian Geometric Design Standards for two lane rural Highway, defined as category "C1", "*Strade Extraurbane Secondarie*".

The single alignment was composed by repeating the four radii curves, in left and right direction for two times, to have two elements of analysis for each radius and direction. Between two successive horizontal curves, a straight segment was included. The idea was to prevent that a previous curve could influence the behaviour of the next curve. Assuming the prescription of the *Italian Road Geometric Policy*, the length of tangent section was set in a 110–300 m range. Summarizing, the presence of four curves, both leftward and rightward direction, repeated two times for each scenario, we have a final amount of 48 curves (16 for each scenery).

According to the design Policy (*art. 5.2.5* about *variable radius curve)*, circular curves were included between two transition clothoids, one before and one after each curve. Moreover, all the curves must respect the prescription at *art. 5.2.2.* where two consecutive curves, should have not too high differences in radii. In this case the gradually passage from 440m to 300m to 210m to 120m and vice-versa, respects this rule. Note that the only curve number 14 (refer to figure 7) does not respect the prescription of maximum radius variation between two curves; following the direction of the alignment, in this last case, we pass from a radius of 440m, to a sharp curve of 120m. An example of the three road scenarios, with the representation of the curve number 12 (right direction and 300m of radii), is shown in the next figure 3

Figure 3: A curve screenshot of the three scenarios: the unlit road configuration without LED (upper); the red LED road stud configuration (middle), and the white LED configuration (bottom).

The width of horizontal road marking was equal to 0.125m for both external and central lines. Dashed lines were included where the passing sight distance was guaranteed. Note that, to improve the effect of the active LED and did not affect the research study, the road markings were created with a low resolution and low quality, simulating an ageing of the lines. By this way, the white element of the lines affected in a minor dimension the perception of the drivers. In each scenario, vertical road delineators were positioned at 0.5m far from the road edge and separated with a distance of 30m in straight elements and 20m in curves with small radius, according to the prescriptions. In the next figure 4 is represented the road alignment of the scenarios.

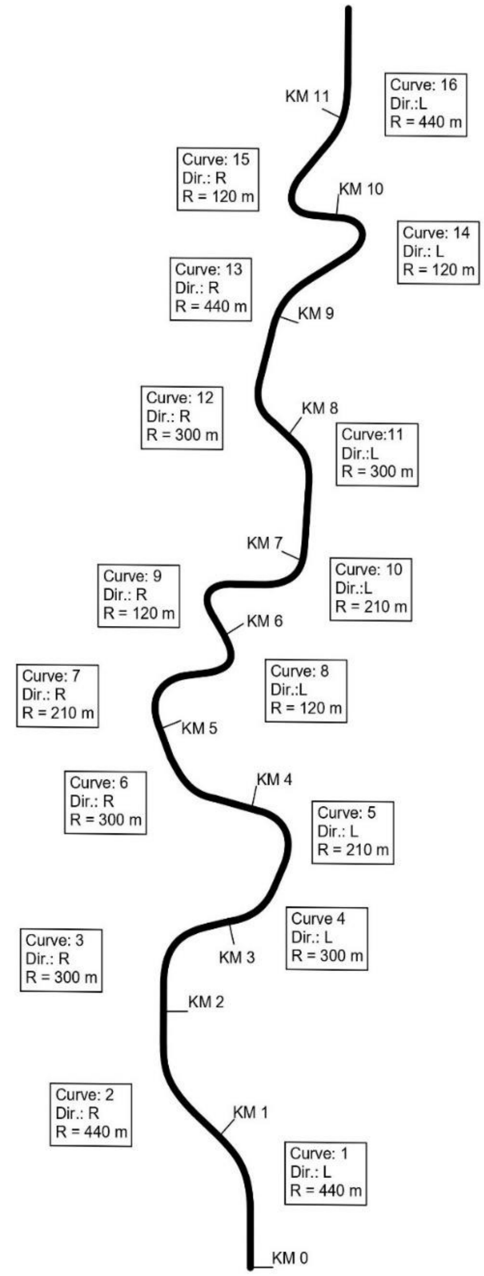

Figure 4: Description of the scenario alignment with the indication of the 16 curves of each scenario

The three simulating scenarios were equipped as well by the presence of a low vehicle traffic, only in some straight element, with the goal to improve the effect of the immersion into the simulation by the participants. This traffic was activatedstep by step by driver's vehicle, when passes over some virtual points called "trigged" not visible on the road. Passing over this target point, an algorithm was able to generate the traffic vehicle only along the straight element of the road.

In this experiment, a simulated passenger car having a 130 HP engine car with six-gear manual transmission was selected. At the beginning, the vehicle was found with engine off and in the neutral mode. The participant interacts started turning on the engine and settingthe light in low beam mode: all the experiment was created in order to keep the light in a fixed low beam mode. The participants were not allowed to use the high beam lights.

2.3 LED road stud modelling

For this study, a simplified road stud 3D model with a square base of 100 mm and a thickness of 25 mm outside the road surface was created, as represented in figure 5. The recreated LED devices is represented in the next figure 8. This 3D model deal with 10 polygons and two surfaces were able to emit a light source (the two red surfaces in the figure 8). *3Ds MAX* was used to generate the light intensity of the given surface. *Blender* was used to better improve the glow effect of the 3D object. The emitted light was at least visible 300 m far from the driver's point of view in the simulating scenarios.

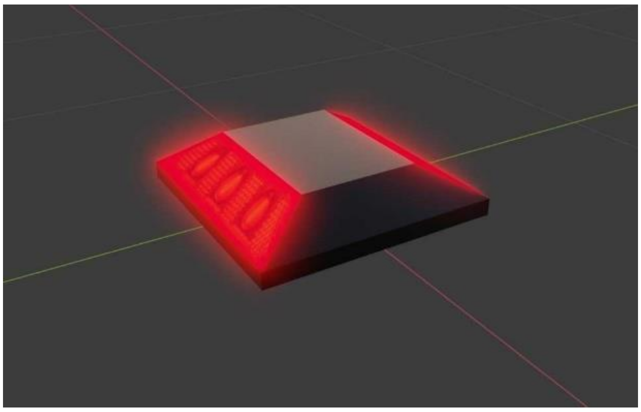

Figure 5: 3D representation of the simplified recreated Red LED Road studs for the driving simulation experiment, with the two emitting surface and the light effects.

2.4 Emotional study

Matlab® and *Psychtoolbox* (*Psychtoolbox project, 2005)* were used to recreate a process where a series of 24 images (regarding the experiment just before completed) were projected on a computer monitor (figure 6). In detail, after the projection for 7 seconds of the stimuli, we asked to the participant to evaluate in a numerical scale, the variables of the emotions and the risk level perceived. Before starting to this study, a first brief practice of the stimuli and questions was made with three additional curves, made by a complete differential colour respect the research study.

These images stimuli were representative of the entry points of curves transitions of the driving simulator experiment. Basically, they were the four curves with different radius (440m, 300m,210m and 120m) in left and right direction. These eight curves were represented for each of the three scenarios, with the total amount of 24 stimuli. By this way we can represent as stimuli all the curves meet in the three driving scenario experiments.

Figure 6: The 24 stimuli (left figure) and the questionnaire (right figure) of perceived risk with a graduate scale; valence and arouse by a SAM analysis.

The interaction of the participants with the computer and so to answer the question proposed by this study, happens thanks to a numeric keypad.

2.5 Equipment

The driving simulation experiments were performed by using the fixed-base driving simulator available at *the Road Safety and Driving Simulation Laboratory* (*RSDS Lab*) of the *Politecnico di Torino*. The simulation equipment consists of a fixed-base driving simulator with force-feedback steering wheel, manual gearbox, pedals, dashboard, and adjustable seat. The simulated environment was reproduced by means of three 32-inch sized screens with resolution of 1920x1080 pixel and a frequency of 60 Hz, which cover 130 degrees of the horizontal field of view. A speedometer was built into a dashboard placed behind the steering wheel, while a 5.1 surrounding sound system provides realistic car engine and other environmental noises. *SCANeR™ Studio software* was used to model the scenarios and run the simulations. The simulator has been already validated in terms of speed and trajectory (*Bassani et al., 2018, & Bassani et al., 2019*). The driving simulator works thanks to three computer that manages the different characteristics of the simulation: the main computer manages the simulation software, the second the visual projection on the three monitors and the last manages additional effects, such as the seat vibration. These computers are equipped with an Intel Xeon E5-1620 v2 processor of 3.70 GHz with a graphic card NVIDIA GTX 780 Ti, RAM of 8 GB and a Hard Disk of 512 GB.

Figure 7: Driving simulator set-up

2.6 Participants

Thirty participants took part to the study. All drivers had a driving license for more than one year. The average age of the participant was 31.2. Nine drivers aged less than 26 years (mean age 22.8 years, range 19–25,) and four drivers aged over 54 years (mean age 59.5 years, range 55–63). Figure 8 describes the age distribution and as well the kilometres averagely covered in one year by the participants. All participants were active drivers, having driven a vehicle at night recently. Drivers did not receive any benefit or payment from their involvement in the investigation and signed an informed consent in accordance with the European General Data Protection Regulation form prior to the experimental session. All the participants are invited to participate at the research experiment by selecting them in a list of more than 500 possible candidates. This list is formed by all those gave availability to participate at driving simulator study at the Politecnico di Torino. The first selection was made in order to keep as much as possible uniformity into the age and gender. So, to the selected candidates was sent an email to ask the new availability to participate and, in case of positive answer, they were finally contacted by phone to get the date and hours of the meeting for the experiment. Finally, a total of 62 possible participants were contacted by email for the first availability. Eight of them did not gave their availability and other 23 didn't answer. One participant that had given the availability and had taken part at the experiment does not finish the driving simulator part, stopping at the first's minutes of the initial scenario due problems of nausea.

Table 2 summarizes the characteristics of the participants in the experiment.

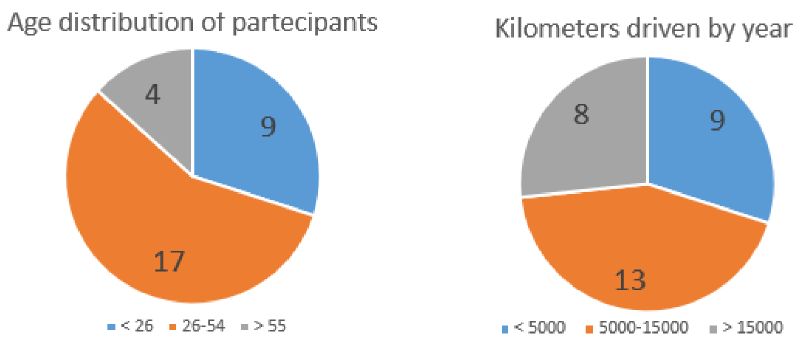

Figure 8: Distribution of participant by age and average kilometres covered in one year

Table 2: Description of the participants that positively complete the experiment.

Gender	-	Male	Female	Total
Participants (number)	-	22	8	30
Age [years]	Min	21	19	19
	Mean	33	26.4	31.2
	Max	63	40	63
Class Age (number)	19 -25	5	4	10
	26 -50	13	4	17
	51 - 63	4	0	4
Driving experience [years]	Min	2	1	1
	Mean	13.4	7.9	11.9
	Max	39	20	39
Driving experience [Km/year]	Min	1000	500	500
	Mean	10786	7000	9742
	Max	35000	28000	35000
Driving experience class [Km/year]	500-4999	5	4	9
	5000-14999	11	3	14
	15000-35000	6	1	7

2.7 Experimental Protocol

Each participant was tested individually, completing the five-step protocol summarized graphically in figure 8, consisting of: (I) a pre-drive questionnaire, (II) pre-drive tests (with a circuit test drive scenario), (III) the three-driving simulation, (IV) the emotional computer study and finally (V) the post-drive questionnaire.

After completing a questionnaire of basic information, such as age and driving information and to evaluate the health and physical condition, they were introduced to an initial driving simulator test where the functions of the vehicle have been shown. They took part in a practice trial on a test circuit for approximately 5 min, to familiarize with the simulator vehicle and experimental tasks. This introductory scenario is followed by the driving simulator experiments, where the three scenarios (unlit, red and white LED) are given in in a different combination order for each participant, in order to avoid as much as possible, impact related to the familiarity ofthe scenario in the results data. The experiment is composed by six possible combinations of scenarios, described in the table 3.

Table 3: The six possible combinations of the submission of the scenery: "U": Unlit; "R": Red LEDdevices; "W": White LED devices.

Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	Experiment 6	...
U – W – R	U – R – W	W – U – R	W – R – U	R – W – U	R – U – W	...

After completing each driving scenario, it follows a time of rest at least of one minute after each driving scenario. So, the experiment keeps going with the computer emotional study. The experiment ends with the post-drive questionnaire, collecting information relating to the experience of participants and the state of health after the drive simulator and computer study experiment. The post-questionnaire data resulted extremely important to understand eventually problems that could happen during the test, that were not directly visible, and how the participant is felt at ease and in comfort during the about sixty minutes of experiments. Figure 9 describe the experimental protocol adopted during each experiment.

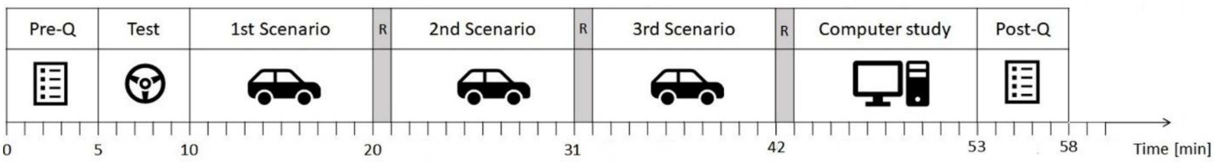

Figure 9: Experimental protocol dispensed to participant, of: pre-drive questionnaire (PRE- Q), test circuit (test), driving on the scenario (Scenario 1st, 2nd and 3rd), Rest time after driving (R), computer test about perceived risk, dimension of valence and arouse (Computer study) and finally, the post-drive questionnaire (Post-Q).

2.8 Observed Measures

Through the study with the driving simulator phase and the emotional state study, different dependent variable was measured. The typical data of the driving behaviours, as the speed variation and the reduction of speed along the curve elements; the lateral vehicle control and the position of the car respect the central point of the road lane. Was studied as well the level of the risk perceived and the emotional state along the different curves.

2.8.1 Driving simulation data output

Behavioural data were determined from the space-time coordinates of the vehicle centre of gravity (CoG) with an acquisition frequency of 100 Hz. The output data were collected in function of the simulation time, in .csv format, and respect each road section. The road abscissa was divided in several road section, with their own reference system. So, the data were converted respect to the road abscissa, considered as zero the first point of the alignment.

From the driving simulator software all the values of velocity and lateral position were extracted along the alignment. Then was selected in some specific point, the speed data and lateral position data. So the standards deviation were calculated.
The following dependent variables were analysed at specific section (see Figure 10):

- the *longitudinal speed* at the starting point of the curve transition (SP) *entry speed (s')* and at the central point of the curve (CP) *central speed (s")*;
- the *standard deviation of speed* (*sds*) form starting point of the curve transition (SP) up to the end point of the curve transition (EP);
- the lateral position, which is the distances between the mass centre of the vehicle and the centre line of the driving lane, valuated at SP, *entry lane gap (lp')* and at CP, *central lane gap (lp")*;
- the *standard deviation of lateral position* (*sdlp*) evaluated from SP to EP;
- the *mean speed* (*ms*) along all the alignment.
- the *standard deviation of the lateral position* for all the alignment (*mlp*);

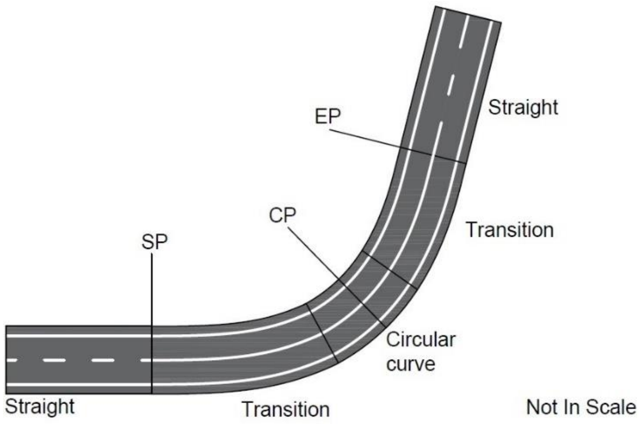

Figure 10: Scenario experiment data analysis, in section SP (starting point of transition), CP (centre pointof the curve) and EP (ending point of transition) of the 16 curves along the alignment

The evaluation of the single value of the longitudinal speed and lateral position was done in the entry point of the transition section (SP) and in the centre abscissa of the curve (CP) (referring to figure 10). Instead, the value of the standard deviation was evaluated along all the curve element, starting from the first point of the transition element (SP), up to the end point of the transition (EP).

About the analysis of the data along the entire alignment, we extracted the values starting from the end point of the first straight element (prog. km 0+400) up the end of the last curve element (prog. km 11+330), avoiding situation where drivers were still accelerating after the departure and braking before the end.

2.8.2 Drivers emotional state and perceived risk data

The data regarding the emotional state perceived by the drivers, were collected thanks to the use of the Self-Assessment Manikin (SAM) scale (*Bradley et al, 1994*). The SAM consists of nine manikins that represent the emotional state of the drivers (figure 11). Moreover, the perceived risk level felt by the participant was as well collected.

After the projection of each stimulus, to the participant was asked to evaluate the following aspects, as dependent variable:

- The level of risk perceived with a numerical scale;
- The *dimension of valence* in a manikin scale;
- The *dimension of arousal* in a manikin scale.

The first variable had the goal to evaluate the sensation of risk felt by the participants during the travelling along the curve. As showed in figure 13, it was only composed by a numerical scale, selected with the numerical keyboard, that started for 1 (low risk perceived) up to 9 (high risk perceived).
The second variable in analysis talked about the feeling of positive or negative sensation. Moreover, the third variable was related to the sensation of calm or agitation.

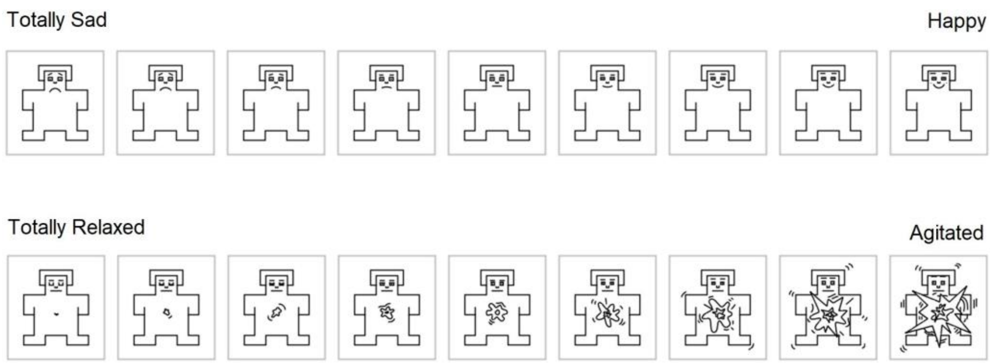

Figure 11: Self-Assessment Manikin representation about dimension of *Valence* (positive or negative feeling) and about dimension of *Arousal* (calm or agitated feeling)

As regards the dimension of valence, we have a sequence of manikins that starts from the first left serious (totally sad, annoyed, dissatisfied) up to a one smiling at the right (satisfied, complacent and happy). For the dimension of arousal, we start from the left of a calm manikin (totally relaxed, calm, inactive) up to the right of active manikin (stimulated, excited, active and agitated).

The selection of the best manikin that represented the dimension of valence and dimension of arousal was done again by using the numerical keyboard. Each number of the keyboard (from 1 to 9) was associated to a manikin into the SAM scale (figure 12).

- In case of valence, 1 for the most negative sensation (totally sad) up 9 to the most positive sensation (happy).
- About the arousal, 1 for the most relaxed situation (totally relaxed) up 9 to the most agitated situation (agitated).

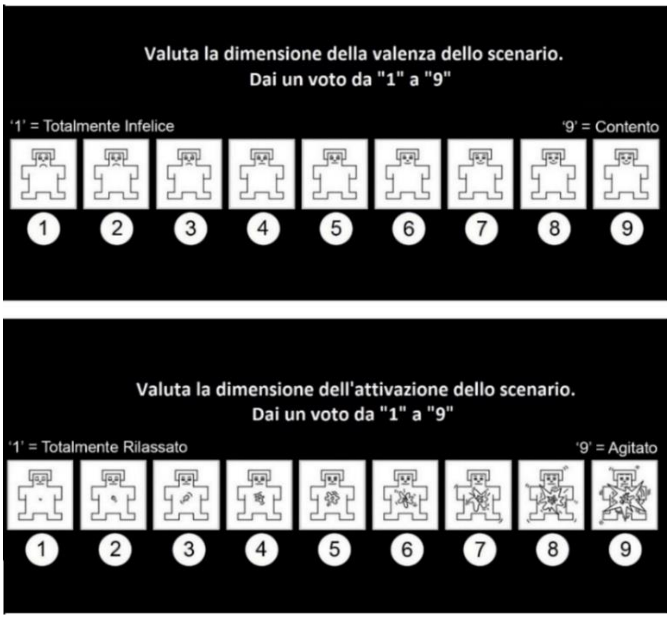

Figure 12: Question provided to the participant regarding valence and arousal with a numerical scale of SAM, to be selected with the numerical keyboard after each image stimuli.

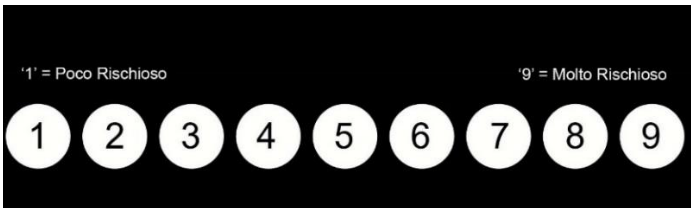

Figure 13: Numerical questionnaire provided about the level of risk perceived, starting from 1: low risk perceived, up to 9: high risk perceived.

2.9 Data Analysis

After the first control and organization in the average values of the data, they were statistically analysed by Linear Mixed Models (LMM). These models include both fixed and random effects. Fixed effects are the independent factors of the experiment. Random effects associated with personal characteristics may be also included in the model. The characteristics of the driver can be considered as cluster variables of the experiment (the test driver ID was considered as a random effect).

In this experiment, separate LMMs were calibrated for each observed dependent variable. The model so includes the three longitudinal variables of speed (*s'; s"* and *sds*) and the three lateral position variables (*lp', lp"* and *sdlp*). Finally models for perceived risk variable, dimension of valence and dimension of arousal were also calibrated.
To set the LMM it was used a *backward elimination technique* which is a stepwise regression able to eliminate step by step the unsignificant factors of the model to find a reduced model that best explains the data. The general formulation of the LMM considers the independent factors, their combinations, and random factors. A general formulation of the model is the following:

$$Y \sim 1 + Fixed\ Factors + Combination\ of\ Fixed\ factors + \\ + Random\ Factors + Errors \qquad (1)$$

The dependent variables (Y) are *s', s", sds, lp', lp", sdlp, risk level, dimension of valence and dimension of arousal* respectively. The experimental factors are the LED colours, the curve radii and the curve direction. The model allowed to evaluate the significance of each factor and their combinations through "p-value" observations. The selected confidence interval is 95 % (α = 0.05), and when the p-value associated to the factor is lower than α, the factor had a significant effect on the output. After fitting the LMM, the post-hoc tests with Holm correction on the significant factors were carried out. This method allowed to control and evaluate possible significance between the combination of two or more factors of the analysed variables. The final model summary contains the R-squared factor, that is the percentage of variation in the response explained by the model. The model summary reports other two results, which are the *Akaike's information criterion (AIC)* and the *Bayesian information criterion (BIC)*. The *AIC* provides a measurement of quality of the estimation, considering both the complexity of the model and the goodness of fit. The *BIC* is a criterion devoted to the selection of a model among a set of different parametric model.

3 Results and Analysis

3.1 Post Questionnaire Data

Before going directly into the numerical data, the results of the questionnaire completed by each participant at the end of experiment are here reported. The analysis of these data was done to evaluate the behavioural quality of the experiment and how the participant felt of about 50 minutes of the experiment. The post-questionnaire revealed that most of the participants were not affect by fatigue or general malaise at the end of the study. This was true for most of the participant except one, that at the first scenery of simulation stopped due to a condition of nausea during the driving. Two participants also have suffered nausea and increased of sweating in heavy form, according on what they declared in the questionnaire. Following this state of malaise, it was decided to remove the data of these two participants, because their results could be affected by the discomfort state with which they carried out the experiment. Following this data removal, the total amount of participant analysed was 28.

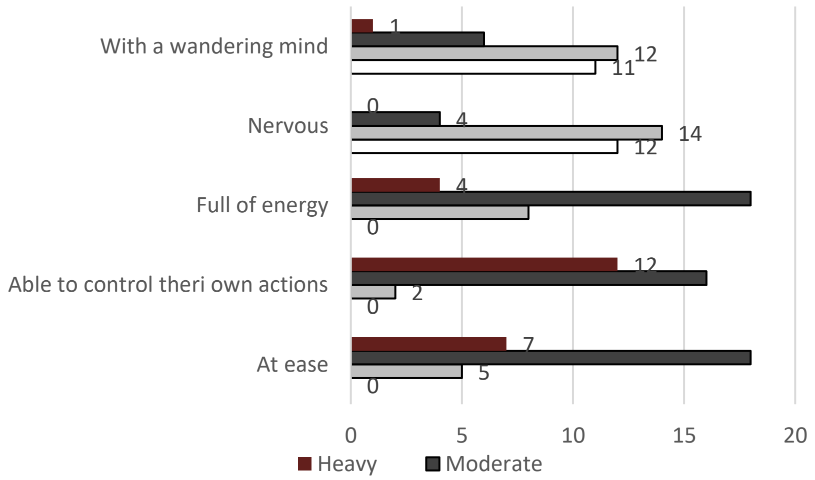

Figure 14: Post-Drive questionnaire results, about the feeling at the end of the experiment by the thirty participants that positively ended the study.

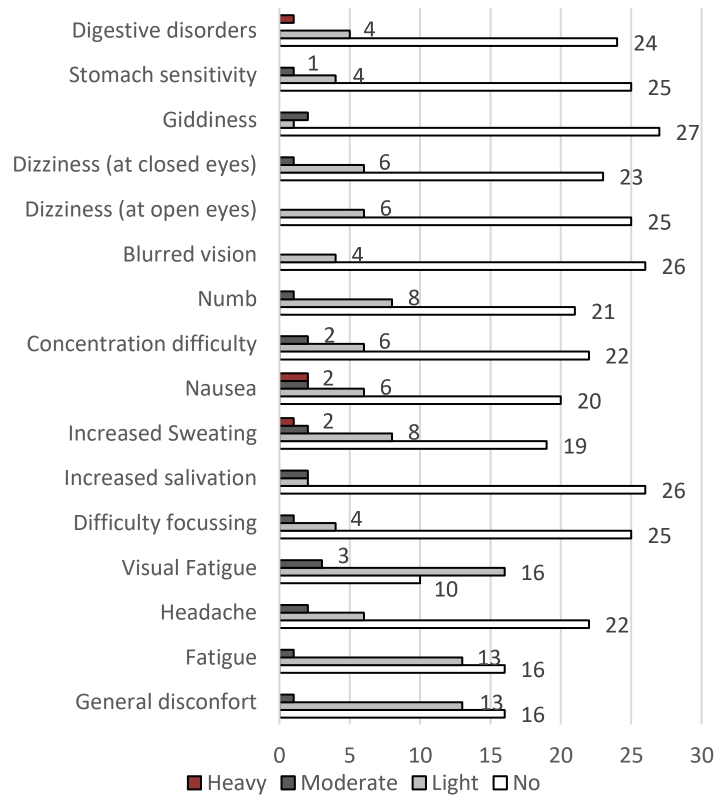

Figure 15: Post-Drive questionnaire results, about the sensation and discomfort at the end of the experiment by the all thirty participants that ended the experiment.

Generally, as shown in figure 14, most of the participants were felt at ease during the experiments, without showing signs of nervousness and other possible discomforts. Anyway, in some cases it was possible to see that some participants felt a sensation of loss of concentration during the experiment and in some cases, it was considered as a strong, but this did not generate particular problems during the participations (figure 15). Following the elimination from the data of the two participants who felt a strong sensation of nausea, no more data were removed.

3.2 Driving simulation outcomes

3.2.1 Longitudinal behaviour

In tables 4 are summarized the averages values of entry speed (*s'*), central speed (s''), and standard deviation of speed (sds). Each mean value was referred to each of the 16 curves of the road alignment, in the significative sections of the curve (SP, CP) and as well the mean value of the standard deviation (*sds)*. The mean values were obtained by averaging all the results of all the thirty participants, for each curve and light condition.

Table 4: Mean values and standard deviations in brackets of entry speed, central speed and standard deviation of speed for each of the 16 curves of the alignment for all the participants of the experiment.

			Entry Speed (s')			Central Speed (s'')			Stand. dev. of Speed (sds)		
Curve [-]	Radius [m]	Dir. [-]	Unlit [km/h]	White LED [km/h]	Red LED [km/h]	Unlit [km/h]	White LED [km/h]	Red LED [km/h]	Unlit [km/h]	White LED [km/h]	Red LED [km/h]
1	440	L	83.73 (±12.48)	78.32 (±11.33)	79.86 (±10.91)	83.13 (±9.17)	80.27 (±10.02)	79.64 (±10.55)	4.21 (±1.98)	4.71 (±1.74)	4.83 (±1.84)
2	440	R	94.84 (±10.78)	91.77 (±10.45)	93.03 (±11.01)	93.92 (±9.98)	91.93 (±10.39)	92.44 (±10.65)	1.03 (±2.06)	0.92 (±1.46)	1.27 (±2.04)
3	300	R	95.75 (±14.71)	94.48 (±12.73)	94.51 (±13.14)	92.31 (±12.50)	89.91 (±13.45)	89.28 (±14.61)	2.46 (±1.15)	2.66 (±1.72)	2.56 (±1.61)
4	300	L	94.57 (±13.12)	92.02 (±15.48)	91.88 (±13.51)	89.16 (±13.71)	87.56 (±14.66)	87.62 (±11.20)	2.89 (±1.22)	2.70 (±1.27)	2.48 (±1.76)
5	210	L	90.87 (±12.44)	89.74 (±14.66)	89.49 (±13.54)	85.58 (±10.45)	84.86 (±14.01)	84.22 (±13.67)	3.57 (±1.40)	3.27 (±1.36)	3.49 (±1.42)
6	300	R	92.91 (±10.98)	92.13 (±11.87)	88.32 (±12.54)	90.82 (±9.45)	90.31 (±10.35)	89.71 (±11.06)	2.66 (±1.81)	2.10 (±1.12)	2.91 (±1.58)
7	210	R	91.66 (±8.23)	91.82 (±7.99)	87.13 (±7.56)	86.33 (±8.39)	86.02 (±8.42)	82.25 (±8.39)	2.89 (±1.90)	3.10 (±1.97)	3.17 (±1.84)
8	120	L	85.39 (±9.45)	86.85 (±10.19)	83.21 (±10.20)	72.47 (±8.78)	74.59 (±8.14)	71.36 (±9.12)	4.91 (±1.41)	4.64 (±1.45)	4.99 (±1.55)
9	120	R	82.80 (±8.12)	84.53 (±9.33)	80.89 (±8.65)	74.19 (±9.69)	75.17 (±8.37)	72.72 (±10.80)	4.47 (±1.13)	4.51 (±1.25)	4.41 (±1.68)
10	210	L	84.94 (±11.31)	85.86 (±9.38)	84.29 (±10.54)	86.23 (±12.54)	86.90 (±11.46)	84.83 (±11.16)	3.25 (±1.19)	3.36 (±1.59)	3.49 (±1.43)
11	300	L	93.10 (±12.23)	92.52 (±14.17)	89.13 (±12.15)	89.30 (±13.35)	88.78 (±12.36)	86.05 (±12.32)	2.39 (±1.48)	2.51 (±1.33)	2.19 (±1.45)
12	210	R	92.75 (±12.84)	93.67 (±11.67)	89.14 (±13.26)	88.29 (±13.65)	87.93 (±14.89)	83.98 (±14.26)	2.65 (±1.12)	2.71 (±1.15)	2.83 (±1.22)
13	440	R	95.68 (±9.33)	95.32 (±11.11)	93.48 (±12.90)	94.55 (±9.33)	93.99 (±8.05)	92.21 (±10.54)	2.77 (±1.09)	2.53 (±1.02)	2.48 (±1.09)
14	120	L	84.84 (±12.79)	88.62 (±14.55)	86.28 (±14.58)	74.61 (±15.01)	74.97 (±16.19)	74.59 (±14.87)	4.86 (±2.71)	5.73 (±2.69)	4.89 (±2.68)
15	120	R	84.60 (±9.96)	81.84 (±11.12)	80.14 (±12.31)	76.07 (±12.55)	73.97 (±11.35)	70.96 (±11.99)	4.22 (±2.50)	4.17 (±2.50)	4.60 (±2.58)
16	440	L	95.82 (±11.65)	96.08 (±12.93)	94.46 (±13.75)	91.67 (±10.55)	91.17 (±11.80)	89.47 (±10.37)	4.24 (±1.18)	3,.94 (±1.12)	3.93 (±1.28)

An important note for the next analysis of the speed data was the outlier produced by the first curve, where the entry speed, and consequentially the central speed and standard deviation, had a mean value that was well below respect curves with smaller radius. The reason of this error in speed was due to the no familiarity of the participant with the scenario, that face up the first curve in a simulation environment new for her/him. For some participant the first 400m of straight was not enough long to reach the desired operating speed. It was so decided to replace the longitudinal results of the first curve with just a copy and paste of the data results of the last curve, with same direction and radius. This action permit to maintain the structure of the experiment with four different radii, in left and right direction, repeated two times, with a final sixteen curve in analysis for each scenario. Instead, no modification was done for the lateral behaviour results.

Albeit these average results did not provide a clear view of the situation, seem that the LED device equipped with a red-light colour, tend to generate a reduction of mean speed, respect the other two situation with white LED and without road studs. But it seems as well that talking about standard deviation of speed, this difference with colours was not evident. It follows in the next table 5 the summary of the LMM of the driving simulation outcomes regarding the longitudinal speed behaviour.

Table 5: Summary of Linear Mixed-Effect Models of longitudinal behaviour Outputs: Estimate (and p-Value) with Summary Statistics Including the AIC (Akaike's Information Criterion), BIC (Schwarz's Bayesian Criterion)

Outputs	Factors	Estimate (p-value)		
		s'	s''	sds
Fixed effects:				
Intercept		90.640 (<.001)	85.551 (<.001)	3.372 (<.001)
Light colour	Red-Unlit	- 1.771 (<.001)	-1.904 (<.001)	-
	White - Unlit	-	-	-
Curve Dir.	R-L	-	0.974 (.009)	-0.928 (<.001)
Curve Radius	210m – 120m	5.215 (<.001)	11,964 (<.001)	-1.572 (<.001)
	300m – 120m	8.586 (<.001)	15.355 (<.001)	-2.143 (<.001)
	440m - 120m	11.181 (<.001)	19.002 (<.001)	-1.580 (<.001)
Light colour * curve Dir.	Red – Unlit * R-L	-	-1.983 (.030)	-
Light colour * curve Dir.	White – Unlit * R-L	-	-	-
Curve Dir. * Curve radius	R-L *210m – 120m	6.824 (<.001)	-	-
Curve Dir. * Curve radius	R-L *300m – 120m	4.200 (<.001)	-	0.732 (=.004)
Curve Dir. * Curve radius	R-L *440m – 120m	-	-	-1.759 (<.001)
Random Effects:				
Test driver ID		(<.001)	(<.001)	(<.001)
ICC		.5903	.659	.362
Model statistics:				
AIC		9273.051	9124.591	5288.188
BIC		9325.387	9174.700	5355.061
R^2 marginal		.134	.274	.198
R^2 conditional		.6453	.753	.488
Observations		1344	1344	1344
Participants		28	28	28
Observation/participants		48	48	48
KS Test for normality of residuals		.145	.382	<.001

Results of the LMM for longitudinal behaviour confirm that the different colours generate a significant effect in both the entry speed at the first section of the curve transition and as well into the speed recorded in the central section of the curve. The reduction of variation of speed along the curve did not provide any significant results with both the red-light devices and with as well the white road studs.

The residuals are normally distributed, highlighted by the KS Test ($p>0.05$), which confirms the hypothesis of the LMM for the entry speed and central speed. About the standard deviation of speed, the KS Test evidence that the hypothesis of normality is not respected. In this case thanks to a huge number of observations (1344), the variable *sds* was however analysed in detail.

The results of entry speed and central speed were conditioned by the characteristics of the drivers, showing a moderately similar behaviour between all the participant, with a value of ICC>0.50 (*Koo et al., 2016).* Instead, the values of the standard deviation of speed were not resulted conditioned by the characteristic of drivers (ICC = 0.36). Similar considerations can be done by observing the results of the R-squared values. For *s'* and *s"* the model was capable of reading 64% and 75% of the overall variance of the data respectively. The random effects were able to explain most of the variance components, so of the subjectivity of the participants (R^2 conditional - R^2 marginal > 0.50). In these two cases of speed values the fixed values were able to explain the 13,4% and 27.4% of the variance, so the effect of the factors in study of light colour, curve radii and direction cannot be neglected.

It follows a more accurate discussion of the results, analysing the data of all the three variables descripting the longitudinal behaviour.

3.2.1.1 Entry curve speed (*s'*)

The Linear Mixed Model revels that the presence of LED road studs had a significant effect on the entry speed of the curves. The condition red-light with respect to the unlit condition resulted significant with a p-value lower that 0.001 and a reduction of speed of about 1.7 km/h. In opposite, the effect produced by the white-light seems to have not produced important changes in the operating entry speed, with a p-value >0.05. As expected, also the effect due the different radii strongly influence the variable of entry speed (p<0.001). This is clear how between 210m and 120m of radius we have a speed reduction of 5.2 km/h; between 300m and 120m a reduction of entry speed of about 8.586 km/h and finally the last condition, 400m – 120m, with a difference of speed greater than 11 km/h. Moreover, the combination between the direction of the curve and the light colours of the road studs, did not provide significant value in the entry speed of the curve. The combination between the right and left direction and the radius of curvature results significant, with a p-value <0.001, except for the last condition where for the case R-L*440m – 120m we have no significant differences into the statistical model.

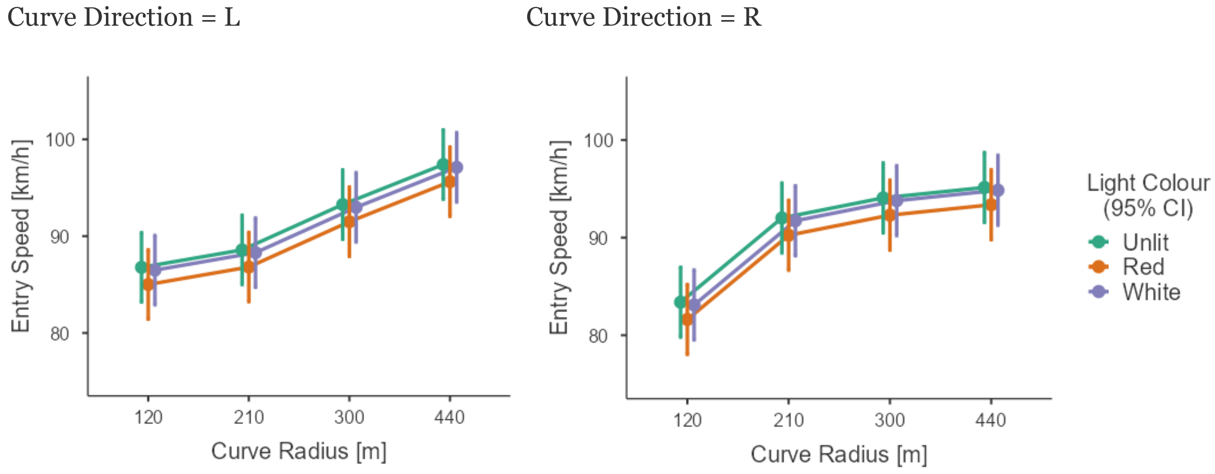

Figure 16: Entry speed (s') at the entry section of the curve (SP) values, separating the factor via the colours of LED road studs.

These final plots (Figure 16) confirms that the colours light of LED devices influence the entry speed of the curves, and the most effective results were obtained with red colour devices. The model confirms an important speed variation between red and white colours. Furthermore, we can observe how to an increased value of radii, we have obtained an increased value into entry speed. In both left and right direction we start from an entry speed around 80/85 km/h with the smaller radius, up to about 95 km/h with the higher radius. Anyway, both in leftward and rightward direction, the red-light condition generated a reduction into the entering speed of the curves.

3.2.1.2 Central curve speed (*s''*)

A significant result with the LMM was obtained also in terms of speed at the central section of the curve (CP), where the value of significance was very high ($p<0.001$) for the combinate factor of light colour red-unlit, with an estimate reduction of speed of -1.904 km/h. This effect reveals that the perception of red light of LED devices have generated a significant reduction of speed in driving along the curves. Also in this case, the effect produced by the white colours compared with the unlit configuration, did not show important changes, with a p-value > 0.05. In both cases of entry speed and central speed the combination between colours and radius did not provide important results with a p-value greater than 0.005. Note that anyway, the combination of *Red-unlit* * *R-L*, has proven to have a very important level of significance with a reduction of speed of about 2 km/h. These results indicate how the drivers, in the presence of red-light devices, reduced majority the speed in driving along rightward curves direction, respect the leftward. This fact can be explained with the position of the LED devices that were positioned only on the two external road markings. Traveling on right direction curves they appear closer and so these devices generated a greater perception, with a consequent reduction of speed. This effect disappeared in left curve direction.

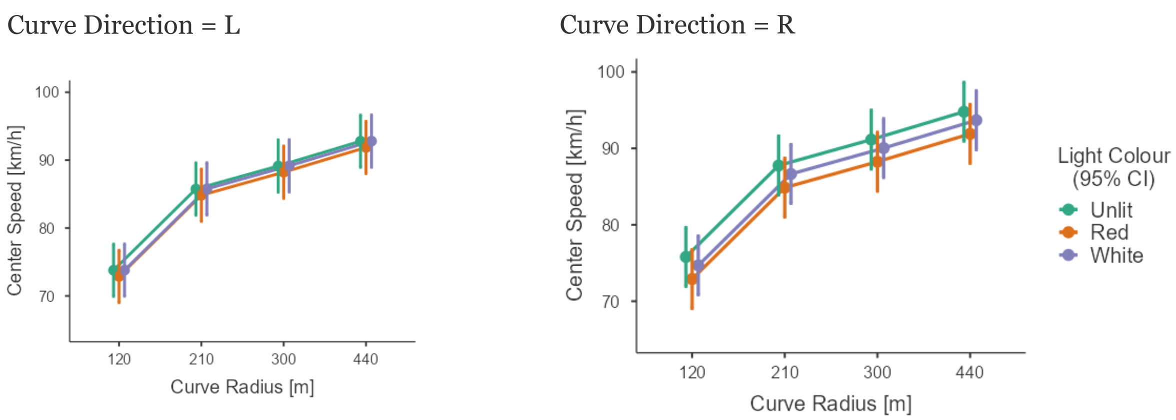

Figure 17: Speed (s) at the central section of the curve (CP) values.

From Figure 17, it is possible to observe that the reduction of curve radius caused a reduction of travel speed along the curves, with an estimate value that is 19 km/h below from a curve of 440m of radius up to the curve with 120m of radius. It is also interesting to notice the different operating speed when red light devices are installed, compared to the unlit condition. In this light condition, in rightward curves, the reduction of speed is more evident. Anyway, different result in leftward and rightward direction was found in the all the condition. The estimate value of factor R-L has generated a reduction of speed of about 1km/h with a significance p-value of 0.009. This last factor evidence how the drivers tend to drive faster in right curve direction, respect the left curve direction.

3.2.1.3 Standard deviation of the speed (*sds*)

Results of LMM show that the colours of the LED and in general the presence of these devices, did not imprint a significant variation in the standard deviation of the speed along the curve in both the comparison case red – unlit and white – unlit ($p>0.05$). Instead about the average values of the previous table 4, only a very small difference of standard deviation with the use of red-light arose. This factor does not represent a significant actor in this analysed variable. Clearly as we can aspect, the radius of curvature instead was an important factor in the variation of standard deviation of speed along the curve. The significant results were only obtained so with the geometric factor of the road alignment, were the single data of radius and the combination with Left and right direction, provides variations on standard deviation of speed.

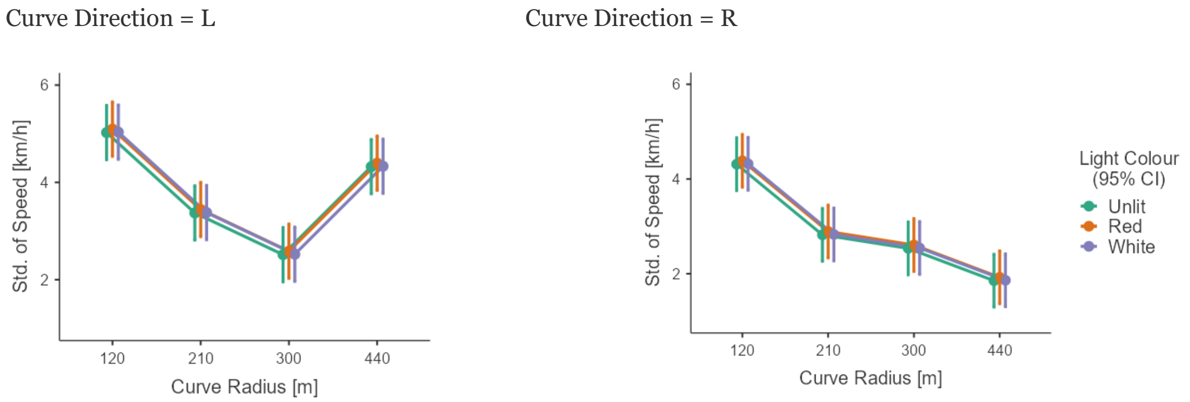

Figure 18: Standard deviation of Speed (sds) all along the curve element.

From the plots (Figure 18), it is interesting to note that the values of *sds* are about similar in right and left direction of curve in radii 120m, 210m and 300m with a variation from 5 km/h up to 2.5 km/h or slightly higher or lower. This is not true with the radius of 440m, where the case of left direction the variation of standard deviation is about 2km/h higher in the case of right direction. The 440m radius curve in left direction has a standard deviation of speed very high, close to the curve with the smaller radius. This particular last result was only to be associated with an uncorrected design in the road alignment for the experiment.

3.2.2 Lateral behaviour

Behavioural driving data about the lateral position of the vehicle, respect the centre of mass of vehicle and the central line of the driving lane are here analysed. In the next table 8 are summarised all the average values from the obtained data of the software simulator for all the participant at the experiment. These average results were collected for all the 16 curves of the alignment in different section of the curve, at the starting point of the clothoid (SP) and central point (CP), where instead the value of standard deviation was obtained all along the curve element, between SP and the exit point of the transition (EP). The sign convention of this data is organized with positive value if the vehicle is more to the left respect the centre-lane, in opposite, negative values indicate that the vehicle CoG is positioned at right with respect to the lane centre. The Table 6, summarize all the averages value for all the thirty participants with respect to the 16 curves of the alignment.

Table 6: Mean values and standard deviation in brackets of entry lateral position, central lateral position and standard deviation of lateral position for each of the 16 curves of the alignment for all the participant to the experiment.

			Entry Lat. Position (*lp'*)			Central Lat. Position (*lp"*)			Stand. dev. of Lat. Position (*sdlp*)		
Curve	Radius	Direction	Unlit	White LED	Red LED	Unlit	White LED	Red LED	Unlit	White LED	Red LED
[-]	[m]	[-]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
1	440	L	0.368 (±0.524)	0.366 (±0.593)	0.257 (±0.372)	0.512 (±0.597)	0.546 (±0.401)	0.572 (±0.335)	0.190 (±0.112)	0.196 (±0.093)	0.190 (±0.066)
2	440	R	0.479 (±0.562)	0.434 (±0.468)	0.304 (±0.361)	-0.107 (±0.553)	0.341 (±0.398)	0.391 (±0.471)	0.140 (±0.080)	0.131 (±0.080)	0.159 (±0.064)
3	300	R	0.479 (±0.493)	0.398 (±0.373)	0.237 (±0.431)	-0.120 (±0.539)	0.354 (±0.507)	0.434 (±0.534)	0.278 (±0.123)	0.186 (±0.065)	0.235 (±0.111)
4	300	L	0.483 (±0.477)	0.370 (±0.525)	0.226 (±0.458)	0.270 (±0.687)	0.544 (±0.447)	0.672 (±0.553)	0.272 (±0.138)	0.253 (±0.114)	0.254 (±0.108)
5	210	L	0.472 (±0.449)	0.326 (±0.484)	0.089 (±0.432)	0.205 (±0.635)	0.275 (±0.799)	0.422 (±0.535)	0.244 (±0.088)	0.306 (±0.189)	0.259 (±0.100)
6	300	R	0.448 (±0.654)	0.269 (±0.445)	0.127 (±0.561)	-0.209 (±0.551)	0.341 (±0.442)	0.518 (±0.615)	0.319 (±0.084)	0.196 (±0.114)	0.221 (±0.161)
7	210	R	0.591 (±0.527)	0.384 (±0.456)	0.278 (±0.390)	-0.238 (±0.541)	0.357 (±0.543)	0.565 (±0.621)	0.245 (±0.188)	0.229 (±0.097)	0.265 (±0.107)
8	120	L	0.807 (±0.512)	0.575 (±0.455)	0.432 (±0.392)	0.563 (±0.791)	0.425 (±0.897)	0.662 (±0.740)	0.429 (±0.449)	0.368 (±0.371)	0.358 (±0.597)
9	120	R	0.573 (±0.446)	0.301 (±0.465)	0.134 (±0.483)	-0.328 (±0.646)	0.329 (±0.708)	0.600 (±0.588)	0.345 (±0.102)	0.308 (±0.286)	0.261 (±0.135)
10	210	L	0.813 (±0.468)	0.516 (±0.433)	0.339 (±0.344)	0.149 (±0.433)	0.422 (±0.479)	0.721 (±0.276)	0.305 (±0.221)	0.331 (±0.388)	0.264 (±0.152)
11	300	L	0.531 (±0.414)	0.194 (±0.483)	0.230 (±0.342)	0.342 (±0.553)	0.524 (±0.510)	0.851 (±0.367)	0.233 (±0.430)	0.287 (±0.345)	0.288 (±0.100)
12	210	R	0.681 (±0.437)	0.316 (±0.358)	0.160 (±0.553)	-0.297 (±0.560)	0.291 (±0.431)	0.657 (±0.571)	0.327 (±0.067)	0.240 (±0.138)	0.249 (±0.181)
13	440	R	0.816 (±0.585)	0.423 (±0.378)	0.213 (±0.398)	-0.122 (±0.601)	0.324 (±0.329)	0.721 (±0.557)	0.239 (±0.101)	0.186 (±0.072)	0.197 (±0.082)
14	120	L	1.057 (±0.532)	0.639 (±0.483)	0.497 (±0.456)	0.354 (±0.566)	0.453 (±0.502)	0.877 (±0.682)	0.421 (±0.375)	0.387 (±0.451)	0.387 (±0.470)
15	120	R	0.684 (±0.584)	0.222 (±0.531)	0.012 (±0.545)	-0.442 (±0.588)	0.272 (±0.538)	0.732 (±0.706)	0.325 (±0.094)	0.271 (±0.100)	0.261 (±0.138)
16	440	L	0.832 (±0.492)	0.343 (±0.381)	0.190 (±0.382)	0.282 (±0.610)	0.451 (±0.538)	0.937 (±0.430)	0.202 (±0.294)	0.200 (±0.080)	0.258 (±0.098)

It follows in table 7, the summary result of the Linear Mixed Model, regarding the variables of entry lateral gap (lp'), the central lateral gap (lp'') and the standard deviation of the lateral position (sdlp). Are so reported only the significance parameters with a p-value lower than 0.001 and the relative estimate values, expressed in meters.

Table 7: Summary of Linear Mixed-Effect Models of the lateral behaviour: Estimate (and p-Value) with Summary Statistics Including the AIC (Akaike's Information Criterion), BIC (Schwarz's Bayesian Criterion)

Outputs	Factors	Estimate (p-value)		
		lp'	*lp''*	*sdlp*
Fixed effects:				
Intercept		0.2005 (<.001)	0.2073 (<.001)	0.2640 (<.001)
Light colour	Red-Unlit	0.1092 (<.001)	0.1936 (<.001)	-0.0255 (.015)
	White - Unlit	0.2952 (<.001)	0.3349 (<.001)	-0.0327 (.002)
Curve Dir.	R-L	-0.1523 (<.001)	-0.2886 (<.001)	-0.0501 (<.001)
Curve Radius	210m – 120m	-	-	-0.0684(<.001)
	300m – 120m	-0.0893 (.001)	0.0711 (<.001)	-0.882 (<.001)
	440m - 120m	-	0.0953 (.003)	-0.1490 (<.001)
Light colour * curve Dir.	Red – Unlit * R-L	0.1577 (<.001)	0.4144 (<.001)	-0.0409 (.050)
Light colour * curve Dir.	White – Unlit * R-L	0.1684(<.001)	0.4251 (<.001)	-0.0651 (.002)
Curve Dir. * Curve radius	R-L *210m – 120m	0.4090 (<.001)	0.1514 (.020)	0.0817 (<.001)
Curve Dir. * Curve radius	R-L *300m – 120m	0.4354 (<.001)	-	0.0842 (<.001)
Curve Dir. * Curve radius	R-L *440m – 120m	0.4763 (<.001)	-	0.0747 (.002)
Random Effects:				
Test driver ID		(<.001)	(<.001)	(<.001)
ICC		.414	.659	.290
Model statistics:				
AIC		699.384	1598.750	-1076.014
BIC		834.383	1825.430	-923.182
R^2 marginal		0.172	0.192	0.108
R^2 conditional		0.514	0.384	0.367
Observations		1344	1344	1344
Participants		28	28	28
Observation/participants		48	48	48
KS Test for normality of residuals		0.575	.002	<.001

Results confirm that both the effects of white light and red light respect the unlit condition strongly influence the position of the vehicle along the curve. For all the dependent variable in

analysis, the factors red-unlit and white-unlit, shown a significant p-value lower than 0.05. In particular, the effect generated by the white LED light colours has generate a more significant estimate result, respect the white illumination, both for the lp' and lp'' and for the reduction of the sdlp.
In this case the hypothesis of normal distribution of the residual of the LMM, is confirmed only in the dependent variable of entry lane gap values with a KS value of 0.575, referring to table 7. About the central lane gap and standard deviation of lateral position, the value of KS Test is lower than 0.05, not respecting the hypothesis about the residuals. In order continue with the analysis, the high number of observations is therefore considered.

The value of *lp'* and *sdlp* are not particularly conditioned by the characteristics of the drivers, showing a poor correlation of behaviour between all the participant, with a value of ICC<0.50. Conversely, the values of the *lp''* resulted conditioned by the characteristic of drivers. Moreover, about the statistic of *R^2 conditional*, the model could interpretate the 51,4% (lp'), the 38,4% (lp'') and 36,7% (*sdlp*) of the variance of the results, in a lower form respect the previous results of longitudinal speed behaviours. The fixed effect are able to explain the 17,2% and 19,2% for the *lp'* and *lp''* and 10.8% for *sdlp* of the variance of the results, obtained in the table 7, about the statistical value of *R^2 marginal* data.

3.2.2.1 Entry curve lateral position

The factor of the light colour have influenced the entry curve lateral position. With both red light and white light was obtained a significant statistic result respect the unlit condition (p<.001). These results show that just the presence of the LED devices, can influence the entry curve lateral position of the participants. The effect provided by the white-light anyway resulted of major impact respect the red-light condition. The results of *lp'* led to move more to the left the drivers of 0.2952m (p<0.001) with white LED devices. Instead more to the left of 0.1092 m (p<.001) with red LED devices, respect the unlit condition. The direction of the curve results significant respect the *lp'* variable (p<.001). As well the position of the drivers in the entry point of rightward curves, was estimated as -0.1523m respect the leftward curves with a p-value <.001.

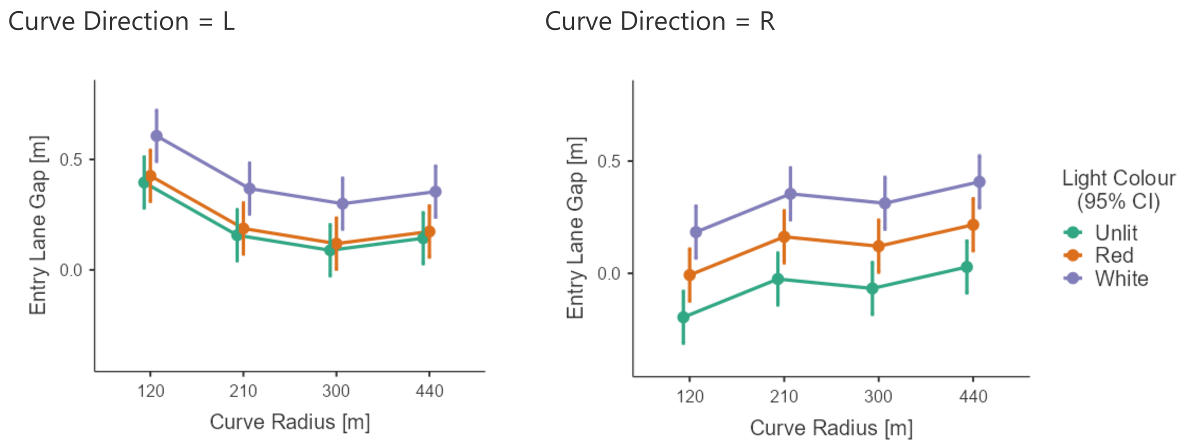

Figure 19: Entry curve lateral position, at the starting point of the curve transition.

In figure 19, the separation of the four radii, highlight that the effect of curve direction is more evident into the curves with radius 120m, respect the other. These results could be subjected to the geometric design of the road alignment. The curve n° 14 (120 m or radii in left direction) was designed without respecting the prescription of the Italian road standards. In fact, this curve was preceded by a 440m radii curve. A passage from a curve of very high radius directly to the curve with a sharp radius, led to an unexpected and not optimal curve entry. Anyway, appear that, this aspect at the entry point of the curves, seems to be not particularly corrected with the adoption of LED road stud devices.

3.2.2.2 Central curve lateral position

LMM results indicate that the light has influenced the decision of the lateral position, as well in the central part of the curve. The red-light devices proven to move in a left position the drivers, with an estimate value of 0.1936m and a p-value of 0.001. The white light LED devices as in the previous case, amplify even more this left-move effect, with an estimate average translation of 0.3349m ($p<0.001$). This last result confirms how the effect of white LED road studs decisively influenced the position of the drivers inside the curves.

In the figure 20 instead, the difference in leftward and rightward direction is even more evident. The presence of LED devices influences majority the driving in rightward curves directions. The installation of illumined road stud devices could work as an object, that can modify the perception of the internal points of the roads. This condition led the participants to drive much more to the left in the rightward curves.

The situation changes in the left curve, where for the purpose of this experiment, the central road lane marking was not equipped with LED devices, and so the effect of tangent point is not present, due to much distance of the road stud devices in the left road margin.

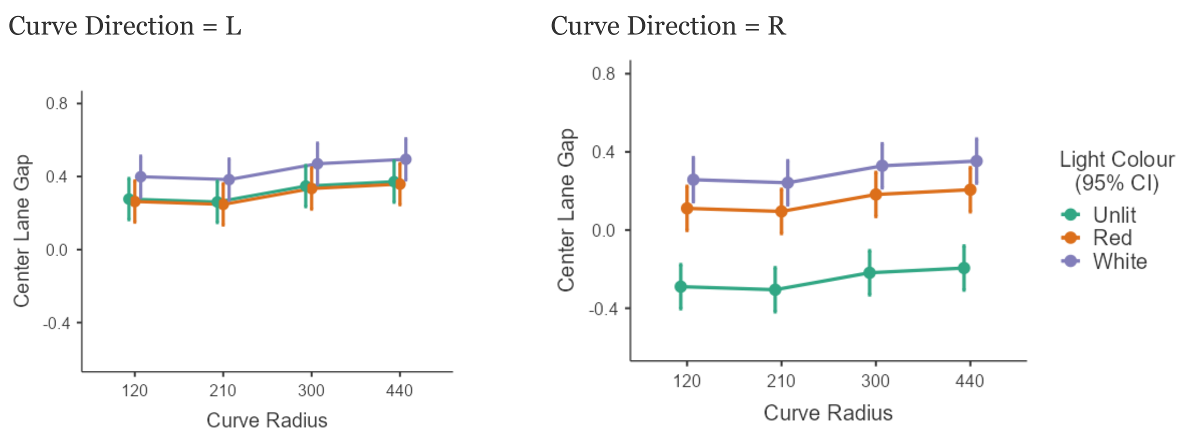

Figure 20: Central curve lateral position, at the central point of the curve.

Especially in right curve direction, the effect of the LED road studs is evident. In fact, they have led to a very strong deviation in driving the car along the curve. Starting from an estimate value of around -0.30m of lane gap, it was significantly reduced with the adoption of LED devices, indicating a centred driving. It is also demonstrated by the factor combination of "Red – Unlit * R-L" and "White – Unlit * R-L", where for the both case a p-value lower of 0.001 was obtained combining the effect of the LED devices and the curve direction.

3.2.2.3 Standard deviation of lateral position

The standard deviation of lateral position was influenced by the presence of LED devices. In both colours, the reduction of lateral movement inside the curve, respect the unlit condition, was evident and so just the presence of these road studs improve the vehicle control inside the curves. Moreover, the white light colour confirms the behaviour to improve majority the lateral behaviour of the drivers respect the red light. Results show how the light condition white-unlit, with an estimate value of -0.0327m (p=0.002), generates a lower value of *sdlp* respect the same comparison with the red light, -0.0255m (p=0.015). Interesting anyway to notice that the direction of the curve resulted significant on the standard deviation of the lateral position (*sdlp* = 0.0501 and p<.001), where in right direction we have a significant reduction of *sdlp* inside the curves. Anyway, the next plot of figure 21, can clarify better these aspect.

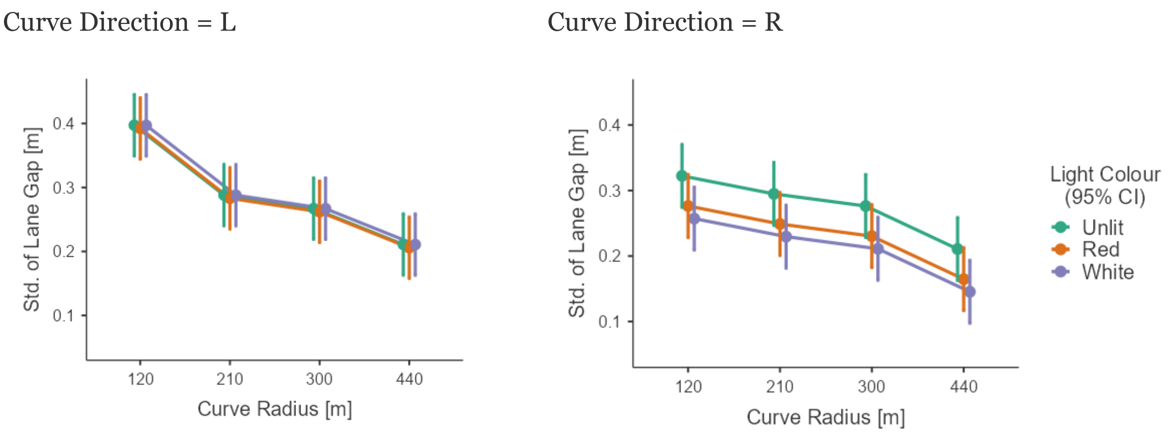

Figure 21: Plot of standard deviation of lateral position results.

As it was possible to see both on the plotted figure 21 and on the summary table 7 of the “LMM Summary”, the combination of the factors “Light colour * curve Direction” generates significant results on the variable in analysis. It is evident a reduction *sdlp* in right curve in presence of LED devices. Moreover, due to the installation of the devices only into the external road markings, the combined effect of direction and colours is not evident in left direction, due to the bigger distance of the LED devices traveling in left direction curves, that did not improve particularly the perception of the enhanced road markings.

3.3 Effectiveness of our colour-based manipulation: Emotional drivers' behaviour and perceived risk level

3.3.1 SAM analysis

They are first presented the average values of the collected data from the use of the Self-assessment Manikin, and so about the variable of valence and arousal. By stimulating the perception of the drivers through the generation of some stimuli of the three light configuration, the state of positive or negative and calm or agitated emotions were studied.

Table 8: Average values of valence and arousal form SAM analysis, for all the 24 images stimuli projected to the participant by the computer study. For the valence higher values indicates a happier status. About the arousal higher values indicates a more agitated situation.

			Valence			Arousal		
Curve	R [m]	Dir.	Unlit	White	Red	Unlit	White	Red
1	120	L	5.13 (±1.31)	6.33 (±1.33)	5.93 (±1.88)	4.03 (±1.29)	3.17 (±1.44)	4.10 (±2.02)
2	120	R	5.47 (±1.78)	6.13 (±1.49)	5.63 (±1.87)	3.80 (±1.87)	3.23 (±1.09)	4.00 (±1.97)
3	210	L	5.63 (±1.71)	6.03 (±1.44)	5.73 (±1.86)	3.67 (±1.78)	3.10 (±1.17)	4.23 (±2.05)
4	210	R	5.63 (±1.73)	6.23 (±1.24)	5.97 (±1.90)	3.93 (±1.83)	3.13 (±1.31)	3.63 (±1.77)
5	300	L	5.53 (±1.81)	6.43 (±1.51)	5.90 (±1.89)	3.87 (±1.56)	3.00 (±1.00)	3.93 (±1.83)
6	300	R	5.90 (±1.83)	6.40 (±1.30)	5.80 (±1.51)	3.63 (±1.44)	2.53 (±0.99)	3.50 (±1.78)
7	440	L	5.77 (±1.75)	6.83 (±1.48)	6.13 (±1.77)	3.73 (±1.76)	2.60 (±0.99)	3.70 (±1.66)
8	440	R	5.80 (±1.68)	6.77 (±1.60)	5.90 (±1.56)	3.50 (±1.59)	2.87 (±0.87)	3.57 (±1.56)

The different colours were able to manipulate the two variables in analysis. The presence of the white light colours leads to have results of the valence with higher values, indicating that the white colours were associated to a more pleasant driving situation. A very significant result with white colours was associated to the case of the Arouse, where the curves were perceived less alarming, thus managing to maintain a greater calm. Anyway, to analyse better the two colours, and to confirm as well in a more accurate way the results just before obtained, the analysis was advanced with the study of the *Linear Mixed Model*. As in the previous cases, a summary table 9, of the statistical results, is shown below.

Table 9: Summary of Linear Mixed-Effect Models of the emotional state of valence and arouse. Indication of the estimate and p-value.

Outputs	Factors	Estimate (p-value)	
		Valence	Arousal
Fixed effects			
intercept		5.865 (<0.001)	3.5089 (<0.001)
Light colour	Red-Unlit	0.192 (0.046)	-
	White - Unlit	0.768 (<0.001)	-0.8348 (<0.001)
Curve Dir.	R-L	-	-
Curve Radius	210m – 120m	-	-
	300m – 120m	-	-0.3214 (p=0.003)
	440m - 120m	0.476 (<0.001)	-0.3571 (p=0.001)
Light colour * curve Dir.	Red – Unlit * R-L	-	-
Light colour * curve Dir.	White – Unlit * R-L	-	-
intercept		5.865 (<0.001)	3.5089 (<0.001)
Light colour	Red-Unlit	0.192 (0.046)	-
	White - Unlit	0.768 (<0.001)	-0.8348 (<0.001)
Random Effects			
Test driver ID		(<.001)	(<.001)
ICC		0.600	0.572
Model statistics			
AIC		2008.92	2040.47
BIC		2068.53	2099.83
R^2 marginal		.0635	.0536
R^2 conditional		.6258	.5951
Observations		672	672
Participants		28	28
Observation/participants		24	24
KS Test for normality of residuals		.097	.098

The statistical analysis confirms how in both case of valence and arouse the effect provided by the white light colours devices was more impactive than the red ones. In the case of the dimension of the valence, the estimate average result was equal to 0.768 respect the unlit condition, with a p-value lower than 0.001. In a similar way for the dimension of the arouse the estimate value obtained has been -0.8348 ($p<0.001$), compared to the situation without light. These results shown so that the curves illuminated with white LED were perceived more pleasant and less "alarming/exciting". The same cannot be said for curves equipped with red lights. Although, results demonstrate a slight level of significance in the variable of the valence, the red colour was not able to significantly modify the results in term of driving emotions. It was as well possible to notify that the radius of curvature participates as significant factor into the emotive state of the drivers. Although it was not directly evident form small radii, as the radius of curve increased, it improved the relaxed perception of the curves. To an increase of radii of curvature has been associated a favourable and more comfortable driving. In contrary the effect of curve direction and a combination of left and right direction with the colours, did not provide important results into the analysis.

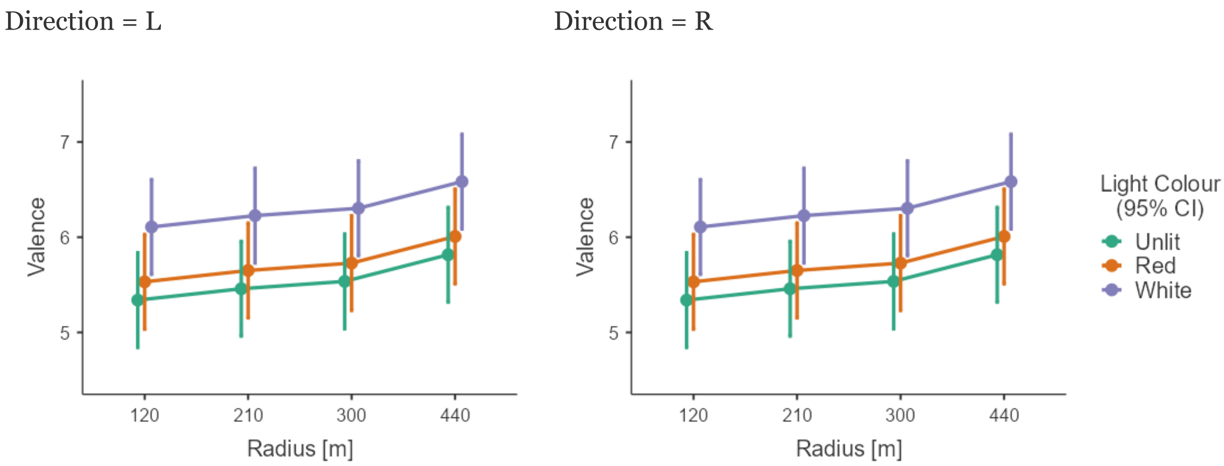

Figure 22: Linear Mixed Model plot results of the dimension of valence for the factor in analysis. Lower values indicated an unhappy status, instead higher values indicate a happier status.

The plot of figure 22, about the variable of dimension of valence, evidence how the effect of the LED devices was amplified in terms of pleasantness, with the white colour illumination. Instead, the red colour seems to provide similar results compared to the unlit condition. The state of positiveness is amplified by increasing the radii of curvature. The plot in both directions anyway evidence how the factor left-right did not contribute to the dimension of valence. We did not find significant combination between factor of interest about their results. So, the combination between curve direction or curve radius of LED colours was of no significance.

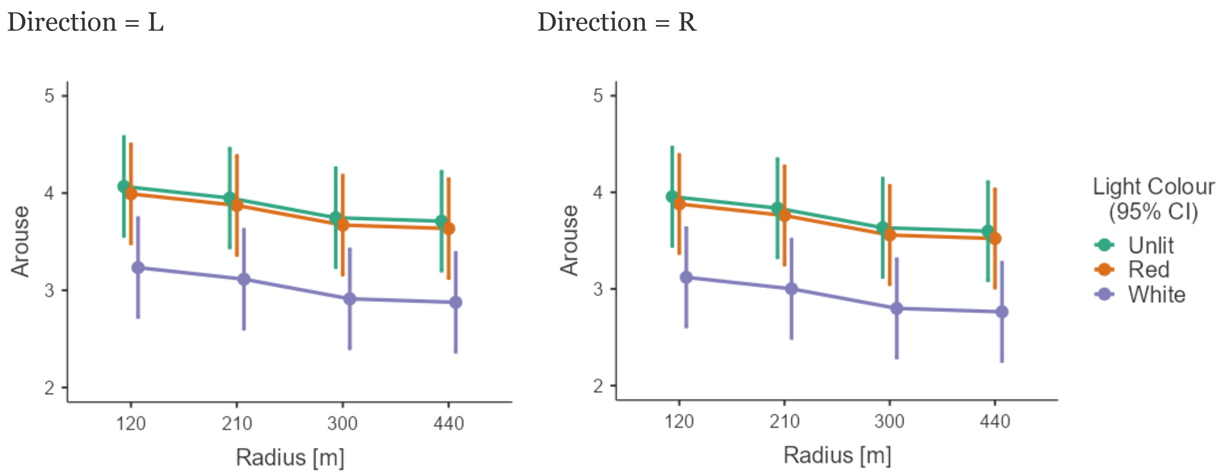

Figure 23: Linear Mixed Model plot results of the dimension of arousal for the factor in analysis. Higher values are for agitated status respect the lower ones associated to more calm emotions

Observing the figure 23, about the agitation on driving along the curve, it is highlighted once more the significance value provided by the white illumination, respect both the unlit condition and the red LED. The white LED road studs have produced an increment of the comfort in driving, thanks to a reduction of agitates emotions and a more calm and relaxed status. Again, at an increase of radii of curvature, the relaxation in driving along the curves increase. Higher value of calm emotions was visible with the higher radii, higher values of agitated states were visible instead with lower radii of curvature.

3.3.2 Perceived Risk level

The data were extracted directly form the three scenario and are obtained in the first entry point at the transition point of the curve (SP). They are presented first in table 10, the mean value of the perceived risk level results:

Table 10: Average values of perceived risk during the projected stimuli, form a range of 0, very low up to 9, very high.

			Perceived Risk		
Curve	Radius [m]	Direction	Unlit	White	Red
1	120	L	4.40 (±2.07)	3.37 (±1.81)	4.53 (±1.08)
2	120	R	4.07 (±2.02)	3.43 (±1.98)	4.37 (±0.78)
3	210	L	4.00 (±2.34)	3.13 (±2.06)	4.63 (±1.34)
4	210	R	3.83 (±1.70)	3.30 (±1.83)	3.77 (±1.51)
5	300	L	3.67 (±1.75)	2.80 (±1.73)	3.67 (±1.08)
6	300	R	3.47 (±1.52)	2.50 (±1.27)	3.70 (±0.98)
7	440	L	3.23 (±1.57)	2.30 (±1.28)	3.60 (±0.84)
8	440	R	3.13 (±1.51)	2.63 (±1.06)	3.10 (±0.87)

From the results data present into the table, it was possible to observe how the devices equipped with a red light colours could generate a small sensation of higher perceived risk respect the other situations. It is possible to observe that this fact is as well evident almost for all the curve, both in left and right direction. It is also more evident that the white LED generate a less risky situation perceived to the participants, where it is possible to observe lowest value for both the red colours and the situation without devices. From this first analysis it seems that the scenario without illuminate devices is places in an intermediate position of perceived risk, between the scenarios with white and red LED devices.

Table 11: Summary of Linear Mixed-Effect Models of the perceived risk around the curves. Indication of the estimate and p-value.

Outputs	Factors	Estimate (p-value)
		Perceived Risk
Fixed effects		
intercept		3.565 (<.001)
Light colour	Red-Unlit	-
	White - Unlit	-0.795 (<.001)
Curve Dir.	R-L	-0.137 (.090)
Curve Radius	210m – 120m	-0.286 (.013)
	300m – 120m	-0.690(<.001)
	440m - 120m	-1.000 (<.001)
Light colour * curve Dir.	Red – Unlit * R-L	-
Light colour * curve Dir.	White – Unlit * R-L	0.286 (.149)
intercept		3.565 (<.001)
Light colour	Red-Unlit	-
	White - Unlit	-0.795 (<.001)
Random Effects		
Test driver ID		(<.001)
ICC		0.608
Model statistics		
AIC		2082.166
BIC		2153.154
R^2 marginal		.104
R^2 conditional		.649
Observations		672
Participants		28
Observation/participants		24
KS Test for normality of residuals		.100

From the Linear Mixed Model outcomes, in contrary on how was defined before, the effect of the red devices did not provide a particular significant factor, but a greater effect was obtained by the curves illuminated with white road studs. The comparison *white – unlit* provide a estimate value with a reduction of perceived risk equal to -0.795 with a p-value lower than 0.001. From these results it is possible to define those curves illuminated with white LED colours are perceived as less risky and dangerous. As in the previous analysis about the emotional state via the SAM, the factor of the radii modifies the perception of the risk into curve entrance. Curves with 440m of radii were seen one point less dangerous compared the sharp curves of 120m in radii. Although not particularly significant, the effect of left and right direction could implicate to a different perception of the curves. With the goal to clarify better all the dubs, the next figure 24 of the perceived risk, is plotted separating the curve radii and indicating as well the curve direction.

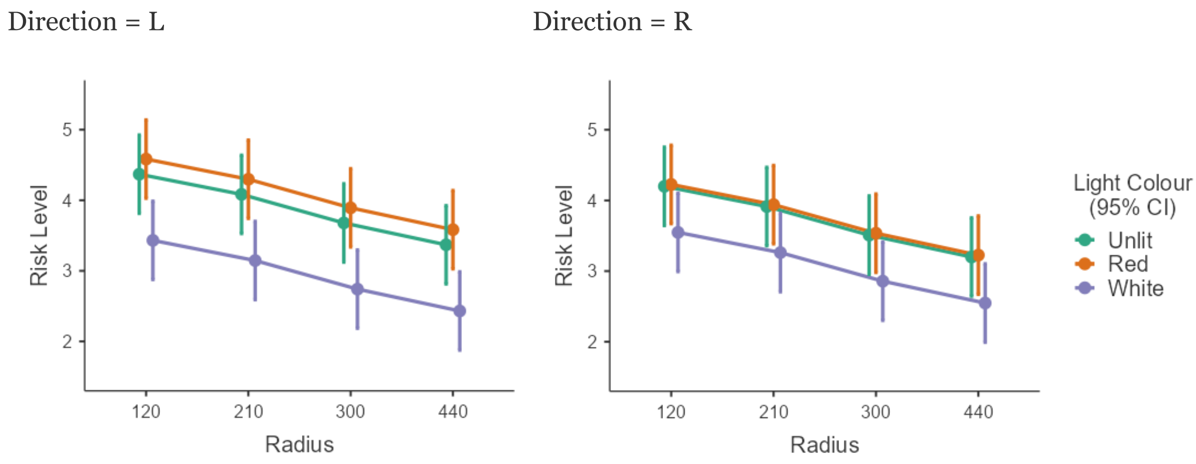

Figure 24: Linear Mixed Model plot results of the perceived risk for the factor in analysis.

As first impact, all the four plots highlight how the effect of curve illuminated with white LED devices generate a very strong reduction on perceived risk, confirming the numerical results of the LMM. Moreover, the condition of curve direction is clarified thanks to this figure, where no particularly important significant factors was highlighted. The direction of the curve could influence the perception of the risk in curve. This effect results more evident into the curves with red devices. From the figure appear that with red devices, the right curve direction appear less risk respect the left direction.

4 Discussion

The results confirm that the presence of LED road stud devices significantly modified the driving behaviour along the curves and can also modify the visual perception felt by the drivers. The different driving behaviour in darkness also finds confirmation in the study on the effects of active LED road stud devices conducted by *Llewellyn (2020)*. The effect of the road stud devices can significantly change the operating speed of the drivers in night-time driving condition. About the lateral behaviour, results obtained with the LED devices are in line with the research studies of *Brémond (2014)*, and *Ville (2015)* with a reduction in the *sdlp* along curves. In our case this reduction results can be seen with both red and white light respect to the standard condition without devices, with an average reduction around 10% and 15%. In any case, this reduction of standard deviation of lateral position inside the curve, was associated particularly to white colour. Also, the biggest different position of the vehicle along the curve was mainly seen with the use of white LED devices, respect to the red ones.
About the longitudinal behaviour, the unlit and white conditions of illumination, produced similar results in terms of speeds. It is showed a more elevated operating speed result compared to the red-light condition. A reduction in speed between 2% and 3% was seen with the installation of red LED devices, both in entry speed and central speed in the curves. This speed reduction, related to the red-light colour, was not correlated to different radii of curvature. In this light condition a higher reduction of speed was seen in rightward curves, instead in leftward curve this speed reduction was not appreciated. This result could be affected by the position of the road studs only on the two external road markings. Consequently, turning into the right, these devices appear closer to the drivers, influencing in a grater way the visual perception. Nevertheless, in all the three scenarios no significant differences were revealed for standard deviation of speed along all the curves.

An important variation of the emotional state of the drivers was seen not only by the presence of the devices, but as well thanks to the two different colours of the light. The curves illuminated with white LED road studs, were perceived less risky and were felt as more comfortable and relaxing, showing result of less agitated and calm emotional status. Instead, the results obtained with red light colour devices, in similar results to the unlit case, were associated to a more uncomforting, agitated status and riskier situation. A comparison with these results can be done with the study conducted by *Karlsen K et al., (2020*). In this study about the paint colours of cycle path, to the case study of red colour, was associated a greater risk and dangerous situations perceived by the cyclist, respect other colours like green and black. Moreover, it is important to define better why the lateral behaviour of the drivers was more influenced with white light devices colour with respect to the red ones. In a similar way is interesting to ask why the red colours in opposite has influenced majority the operation speed, respect the white light. A possible explanation can be attributed to the greater impact of the white colour compared to the red one. The white colour, associated to a shorter wavelength and a high temperature, seems to provide more visual information, without agitates the drivers. Instead, the red coulor with a very long wavelength and lower temperature, resulted less impactful to the driving, generating discomfort. Moreover, a study conducted on the combination between two colours about the readability of various text on a computer monitor showed that the combination of white text over a black background generated the greater contrast with the better readability (*Hill A., 1997*). This fact could answer partially the results of the experiment and the differences between white and red colour. In fact, the curves illuminated only with red devices could produce a status of confusion to the drivers, because were less visible and less clear and defined into the darkens, but at the same time connecting the red colours to a situation of danger. The combinations of these two facts, could have led to a reduction in speed in curve illuminated with red LED road studs. The white light colours, although providing more relaxed emotion, are visually more impactful to the drivers and they are more visible from a greater distance, with even more detail, against a night background. The red-light colours due to the generation of discomfort, can increase stress and agitated status and should be used with more attention.

The road devices were installed only in the two external road markings, and not in the central road marking. This condition generates a particular perception in the drivers, where the road stud has seen as an object that leads the drivers to travel in a more centred position of the road. This centred driving was more evident in right curves, where the LED devices highlight the tangent point of the curve and so the drivers tent to avoid cutting inside the curves. In left curve direction, due to the greater distance of the LED devices positioned on the opposite marking, this effect of increased perception almost completely disappears. This result can find again a partial confirmation by the study of *Brémond (2014),* where drivers resulted more affected by the LED devices driving on rightward curves. Moreover, this directional effect could find confirmation by the study conducted on the observation points along curves, especially of the tangent points of the curves in right direction by *Land (1994*).

5 Conclusions

The main goal of this study was to evaluate how the colours of LED road stud devices as enhanced road markings, can influence the drivers in terms of driving behaviour and change in emotional state. Via the support of a driving simulator study, the analyses were done in a virtual night-time driving scenario, where each scenario was illuminated with a different colours of LED devices, only installed along the curve sections of the alignment. Moreover, an emotional perception study was carried out. The projection of some stimuli regarding the different colours of LED devices, was presented to understand whether the drivers are emotively subjected to the different colours while driving. For this research study, the attention was focused only on two colours of LED road stud devices (i.e., red and white). The behavioural results obtained from the driving simulation and the emotional study were compared respect the unlit road condition. The three scenarios in study were built on a single alignment of a rural highway. The analysis was focused also comparing the driving behaviour for different radii of the curves and their direction. The analysis was carried out comparing the longitudinal and transversal behaviour of the drivers. About the longitudinal behaviour was studied how the travel speed was subjected to the factor of colour of the devices, radii and direction of the curve. In detail were studied all the changes in entry speed, the central speed and standard deviation of speed all along the curves. In a similar way the analysis of the dependent variable of lateral behaviour, respect the factor of study was done. In this case the attention was focused on the lateral position of the car in the entry curve point, in the central point of the curve and finally, the standard deviation of lateral position. About the emotional state were studied the variable of risk perceived, the valence and the arousal, respect the same factor of colours, curve direction and curve radii. With the risk perceived was studied how a possible curve can generate to the drivers a perception lower or higher of risk. About the valence was analysed the positive or negative situation felt by the drivers in driving along the curves and finally with the arouse was studied the state of calm or agitation.

As main result of this study, the effect produced by LED road studs, depends on the light colours of these devices. The two colours analysed, (white and red) have modified in a different way the perception of the drivers and the ability to control the vehicle, both for the selection of the travel speed and the travel lateral position along the curves. White LED colour has proven to be more efficient thanks to a better control of the vehicle by the drivers and to a clear better road delineation. This colour as well was associated to a more relaxed driving, improving the comfort of the participant at the experiment. Instead, red colour was associated to the generation of discomfort and agitated status in driving. The speed reduction observed by the red-light colour, was also associated to an increasing into the perceived risks level of the curves. As resulted, the red-light colours are less impactive to the drivers and can induce possible status of confusion, delineating in a lower way the road markings.

The road markings provide visual guidance of the road delineating so the two external margin of the road in night-time condition. They are of fundamental use and are present in about all the road infrastructure. In case of night-time drive condition, the effectiveness of these road elements could be significantly reduced if they are not adequate illuminated and so when the light present in the around environment is very low. A solution in night-time condition, where the use of road light was not suitable, is the installation of reflective margin delineator. Thanks to the reflection of the car's headlights they could provide a visual guidance of the road, delineating so the two external margin of the road in night-time condition. This solution is fundamental to help the drivers in dark condition, but the reflection of these devices generate a very low intensity of the light and so are visible only very close to the drivers. Therefore, the use of the LED road stud devices is an advantage solution in night-time driving because they thanks to the generation of a light, are more visible in night and fog condition and as far away as well. So they can improve the road safety, via the better perception of the road markings and thanks to the generation of a visual guidance of the road. Moreover, as seen, with the development of the LED technology, they can be installed with any type of colours. So every application has the possibility to use the own colour selection.

From the previous results, a proper use of LED road studs should be the installation of white-light devices. In fact, an improved comfort in driving is always associated to an improved road safety, although keeping the operating speed of the drives, like the unlit condition. Instead, the use of red-light colours should be avoided because they generate a sensation of agitation and discomfort, with a possible unsafe driving. The use of red-light devices could be done only to highlight dangerous situations, like curves with sudden reduction of radii or curves with very small radii. Anyway, a possible good practice could be to illuminate, in these road sections, both white and red light, alternating so the two lights, but anyway an accurate analysis is released to possible future studies. Another aspect to discuss is the installation of the LED devices only on

to the external road markings. This design decision is favourable to a cost reduction, but it makes effective only the devices positioned to the same side of driving. In right curves direction the presence of illuminated devices helped a lot the driving behaviour, but in left curves, the external devices were too far to imprint significant changes.
This LED application could be use as well in important arteria and in motorway. Is not to exclude the possible benefit in old road that do not respect the construction standards.

Several limitations were present in this study. One is the limitations of the study only on a two lane rural highway. Moreover, other of factors were not taken in account. First of all, what about the other colours? Green and blue, generally associated to a comfort situation, can play a role like the white illumination. The orange and yellow colours instead can be substitutes to the red-light devices. Another aspect that is not present in literature, is the spacing between two devices. If we reduce the spacing, could be possible to understand if we can obtain a reduction of speed. An idea could be to use a long distance in entry and exit points of the curves, reducing the distance of the devices in the central points of the curves. Also, a variation of intensity of illumination, angle of illumination, glare etc, could be studied to better understanding the benefit of this devices in term of driving behaviour. Regarding the data of the emotional state perceived by the drivers, for sure other parameters can be studied on an advanced psychological study. Some examples could be the attention during the drive with possible distractions due the colours; or tiredness produced by certain colours of the LED lights. Finally, what about the effect of the traffic headlights? More specifically, in this experiment a low traffic was present in some long straight elements and did not impact with the illuminated curves. A further study could verify if the presence of a higher traffic flow, can reduce significantly, or not, the effect provided by the LED road stud devices.

List of Figures

List of Tables

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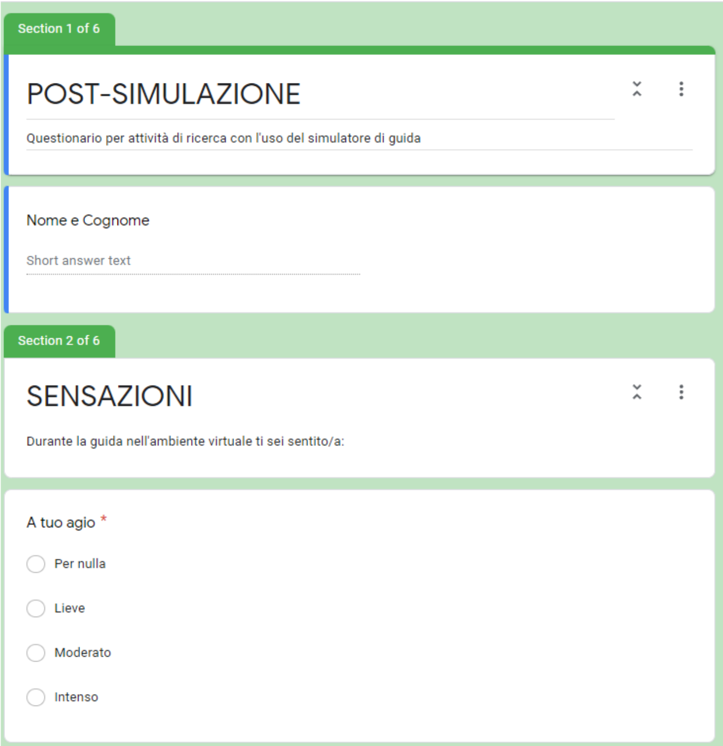
Appendix

A. Post-Driving Questionnaire



Section 1 of 6

POST-SIMULAZIONE

Questionario per attività di ricerca con l'uso del simulatore di guida

Nome e Cognome

Short answer text

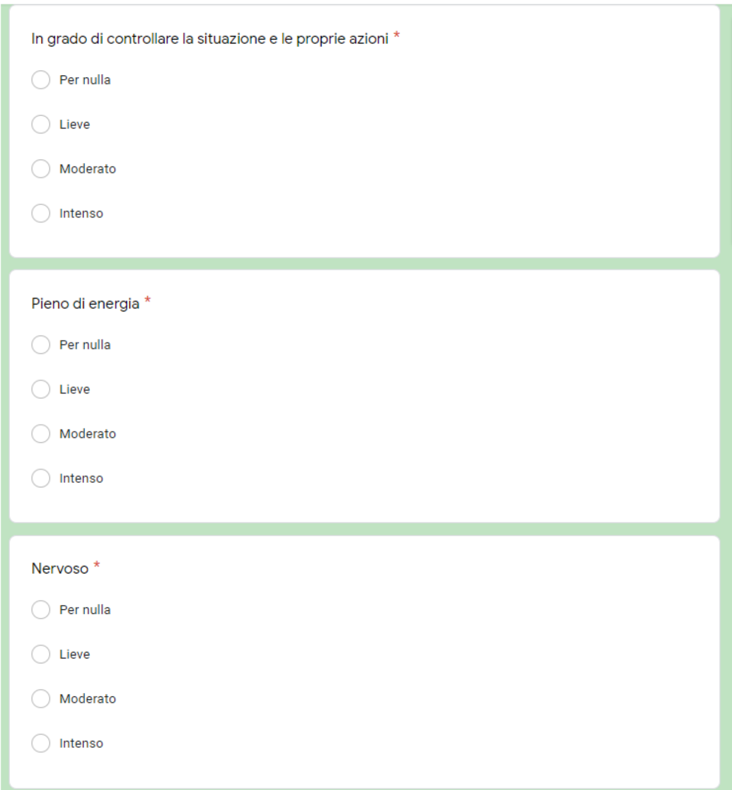
Section 2 of 6

SENSAZIONI

Durante la guida nell'ambiente virtuale ti sei sentito/a:

A tuo agio *

- Per nulla
- Lieve
- Moderato
- Intenso



In grado di controllare la situazione e le proprie azioni *

- Per nulla
- Lieve
- Moderato
- Intenso

Pieno di energia *

- Per nulla
- Lieve
- Moderato
- Intenso

Nervoso *

- Per nulla
- Lieve
- Moderato
- Intenso

Con la mente che vagava *

- Per nulla
- Lieve
- Moderato
- Intenso

Sarebbe disposto a guidare ancora? *

- Si
- No

Se si per quanto tempo?

- < 15 minuti
- < 30 minuti
- < 45 minuti
- > 1 ora

Section 3 of 6

CONSEGUENZE DELL'ESPERIMENTO

Indicare se attualmente percepisci uno o più dei seguenti sintomi:

Generale disagio *

- Per nulla
- Lieve
- Moderato
- Intenso

Fatica *

- Per nulla
- Lieve
- Moderato
- Intenso

Mal di testa *

- Per nulla
- Lieve
- Moderato
- Intenso

Stanchezza visiva *

- Per nulla
- Lieve
- Moderato
- Intenso

Difficoltà nella messa a fuoco *

- Per nulla
- Lieve
- Moderato
- Intenso

Incremento di salivazione *

- Per nulla
- Lieve
- Moderato
- Intenso

Incremento di sudorazione *

- Per nulla
- Lieve
- Moderato
- Intenso

Nausea *

- Per nulla
- Lieve
- Moderato
- Intenso

Difficoltà di concentrazione *

- Per nulla
- Lieve
- Moderato
- Intenso

Intontimento *

- Per nulla
- Lieve
- Moderato
- Intenso

Visione offuscata *

- Per nulla
- Lieve
- Moderato
- Intenso

Capogiro (a occhi aperti) *

- Per nulla
- Lieve
- Moderato
- Intenso

Capogiro (a occhi chiusi) *

- Per nulla
- Lieve
- Moderato
- Intenso

Vertigini *

- Per nulla
- Lieve
- Moderato
- Intenso

Sensibilità di stomaco *

- Per nulla
- Lieve
- Moderato
- Intenso

Disturbi digestivi *

- Per nulla
- Lieve
- Moderato
- Intenso

Section 4 of 6

IMMERSIONE

Esprimi un giudizio sulla veridicità dello scenario stradale

Qualità dell'immagine *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Corrispondenza alla realtà -> Ambiente esterno alla strada (edifici, panorama, vegetazione) *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Corrispondenza alla realtà -> Margini stradali *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Corrispondenza alla realtà -> Sede stradale *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Corrispondenza alla realtà -> Segnaletica orizzontale *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Corrispondenza alla realtà -> Segnaletica verticale *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Corrispondenza alla realtà -> Presenza di altri veicoli *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Section 5 of 6

IMMERSIONE

Esprimi un giudizio sull'interazione con i dispositivi audio-visivi e meccanici:

Riproduzione del campo visivo *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Percezione degli specchietti *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Veridicità degli effetti sonori *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Veridicità della strumentazione di bordo *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Risposta del volante *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Risposta del cambio *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Percezione dell'acceleratore *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Percezione del freno *

- Pessimo
- Sufficiente
- Buono
- Ottimo

Section 6 of 6

PRESENZA

è lo stato di coscienza legato al "senso di trovarsi lì", è il senso psicologico di trovarsi nell'ambiente virtuale.
Rispondi ai seguenti quesiti:

Si è sentito fisicamente inserito nell'ambiente virtuale? *

- Per nulla
- Poco
- Abbastanza
- Molto

Si è sentito stimolato dall'ambiente virtuale? *

- Per nulla
- Poco
- Abbastanza
- Molto

Durante la guida, ti sei sentito/a coinvolto/a come se fossi dentro l'ambiente virtuale e non stessi guardando uno schermo o utilizzando le componenti del simulatore? *

- ◯ Per nulla
- ◯ Poco
- ◯ Abbastanza
- ◯ Molto

Durante la guida ti sei sentito/a coinvolto/a al punto tale da non sapere cosa stesse accadendo attorno a te? *

- ◯ Per nulla
- ◯ Poco
- ◯ Abbastanza
- ◯ Molto

Durante la guida ti sei sentito/a coinvolto/a dall'ambiente virtuale al punto tale da perdere la cognizione del tempo? *

- ◯ Per nulla
- ◯ Poco
- ◯ Abbastanza
- ◯ Molto

Quanto pensi sia durata la guida? *

Duration

Di quali elementi o strumenti ti sei servito/a per valutare la velocità di marcia? *

- ☐ Tachimetro
- ☐ Vegetazione e oggetti al lato della strada
- ☐ Rumore del motore
- ☐ Non ho prestato attenzione alla velocità
- ☐ Other...

B. Alignment Description

	Element	N.	Dir	Length	Progr.	R	A
				[m]	[km]	[m]	[m]
1	Straight			400.000	+		
2	Transition		L	210.000	0+400		440
3	Curve	1	L	**150.000**	0+610	**440**	
4	Transition		L	210.000	0+760		440
5	Straight			250.000	0+970		
6	Transition		R	210.000	1+220		440
7	Curve	2	R	**150.000**	1+430	**440**	
8	Transition		R	210.000	1+580		440
9	Straight			127.992	1+790		
10	Intersection			45.180	1+918		
11	Straight			181.828	1+963		
12	Transition		R	210.000	2+145		300
13	Curve	3	R	**210.000**	2+355	**300**	
14	Transition		R	180.000	2+565		300
15	Straight			150.000	2+745		
16	Transition		L	180.000	2+895		300
17	Curve	4	L	**130.000**	3+075	**300**	
18	Transition		L	100.000	3+205		300
19	Straight			150.000	3+305		
20	Transition		L	160.000	3+455		210
21	Curve	5	L	**200.000**	3+615	**210**	
22	Transition		L	180.000	3+815		210
23	Straight			300.000	3+995		
24	Transition		R	180.000	4+295		300
25	Curve	6	R	**100.000**	4+475	**300**	
26	Transition		R	180.000	4+575		300
27	Straight			200.000	4+755		
28	Transition		R	160.000	4+955		210
29	Curve	7	R	**250.000**	5+115	**210**	
30	Transition		R	100.000	5+365		210
31	Straight			150.000	5+465		
32	Transition		L	140.000	5+615		120
33	Curve	8	L	**100.000**	5+755	**120**	
34	Transition		L	140.000	5+855		120
35	Straight			130.000	5+995		

	Element	N.	Dir	Length	Progr.	R	A
				[m]	[km]	[m]	[m]
36	Transition		R	140.000	6+125		120
37	Curve	9	R	**120.000**	6+265	**120**	
38	Transition		R	140.000	6+385		120
39	Straight			200.000	6+525		
40	Transition		L	160.000	6+725		120
41	Curve	10	L	**160.000**	6+885	**210**	
42	Transition		L	160.000	7+045		210
43	Straight			67.120	7+205		
44	Intersection			15.785	7+272		
45	Straight			267.095	7+288		
46	Transition		L	180.000	7+555		300
47	Curve	11	L	**130.000**	7+735	**300**	
48	Transition		L	100.000	7+865		300
49	Straight			150.000	7+965		
50	Transition		R	160.000	8+115		120
51	Curve	12	R	**100.000**	8+275	**210**	
52	Transition		R	100.000	8+375		210
53	Straight			300.000	8+475		
54	Transition		R	210.000	8+775		440
55	Curve	13	R	**150.000**	8+985	**440**	
56	Transition		R	210.000	9+135		440
57	Straight			200.000	9+345		
58	Transition		L	160.000	9+545		120
59	Curve	14	L	**160.000**	9+705	**120**	
60	Transition		L	140.000	9+865		120
61	Straight			150.000	10+005		
62	Transition		R	140.000	10+155		120
63	Curve	15	R	**125.000**	10+295	**120**	
64	Transition		R	140.000	10+420		120
65	Straight			250.000	10+560		
66	Transition		L	210.000	10+810		440
67	Curve	16	L	**100.000**	11+020	**440**	
68	Transition		L	210.000	11+120		440
69	Straight			300.000	11+330		
				TOT [km]	**11.630**		

C. Computer Study: Experiment Stimuli

Curve 1 (Led: Red, R=120 m, Dir: Left)

Curve 2 (Led: Red, R=210 m, Dir: Left)

Curve 3 (Led: Red, R=300 m, Dir: Left)

Curve 3 (Led: Red, R=440 m, Dir: Left)

Curve 5 (Led: Red, R=120 m, Dir: Right)

Curve 6 (Led: Red, R=210 m, Dir: Right)

Curve 7 (Led: Red, R=300 m, Dir: Right)

Curve 8 (Led: Red, R=440 m, Dir: Right)

Curve 9 (Led: White, R=120 m, Dir: Left)

Curve 10 (Led: White, R=210 m, Dir: Left)

Curve 11 (Led: White, R=300 m, Dir: Left)

Curve 12 (Led: White, R=440 m, Dir: Left)

Curve 13 (Led: White, R=120 m, Dir: Right)

Curve 14 (Led: White, R=210 m, Dir: Right)

Curve 15 (Led: White, R=300 m, Dir: Right)

Curve 16 (Led: White, R=440 m, Dir: Right)

Curve 17 (Led: Unlit, R=120 m, Dir: Left)

Curve 18 (Led: Unlit, R=210 m, Dir: Left)

Curve 19 (Led: Unlit, R=300 m, Dir: Left)

Curve 20 (Led: Unlit, R=440 m, Dir: Left)

Curve 21 (Led: Unlit, R=120 m, Dir: Right)

Curve 22 (Led: Unlit, R=210 m, Dir: Right)

Curve 23 (Led: Unlit, R=300 m, Dir: Right)

Curve 24 (Led: Unlit, R=440 m, Dir: Right)