Active Lane Delineation Application: Simulator Trial and Recommendations on the Design (Deliverable D6.2)

SEVENTH FRAMEWORK PROGRAMME

INtelligent Renewable Optical ADvisory Systems

(INROADS)

Work Programme Topic: SST.5.2-2 Advanced and cost effective road infrastructure construction, management and maintenance

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Definitions and Acronyms used in this report

ALD	**Active lane delineation**
LED	**Light emitting diode**
M	**Mean**
SD	**Standard deviations**

Deliverable goals

This deliverable aims at a) detailing the design created, simulated and tested for the INROADS dynamic active lane delineation application, b) reporting the simulator trial evaluating its safety and discussing its key results, c) highlighting and discussing some of the costs of the illumination and information effects on driver performance and d) providing recommendations on the design and further discussion, relevant for future implementation of active road studs in general and for the design of the INROADS ALD application planned for the road trial to be conducted in Israel in 2014, in particular.

1. ALD application design

When considering the most basic, as well as less common, road delineation countermeasures, one may turn to a relatively large scientific literature for guidance. Unfortunately, crash statistics or any other scientific or pseudo-scientific English documentation reporting driver performance in the presence of active road studs and on active markings application design are limited to sporadic exceptions, such as case studies published by SolarLite road studs' manufacturers, Astucia, a simulator experiment conducted at Transport Research Laboratory (Reed, 2006), and guidelines on the use of active marking for road space, published by the Province of North Holland in the Netherlands.

The present design was driven by the intention to incorporate existing knowledge on travel behavior and from relevant disciplines including cognitive psychology, cognitive ergonomics and human factors engineering, and to adapt practices where such exist and when thought necessary to the specific attributes of our design, while taking some measures that would allow reducing the inevitable gaps between the simulator trial, the road trial planned to be conducted in Israel in 2014.

1.1. General description

The application consists of stud sections, which dim on when a vehicle has been detected and dim out after the vehicle passes them. The colours used were the same colours used for retroflective studs in the UK and with similarity to how they are used there (Department for Transport, 2003), only reversed to suit right-hand traffic. Thus, red, white and amber lights marked the right edge of the road, the central line and the left edge of the road, respectively. In accordance with the recommendations for use of active marking published by Province of North Holland in the Netherlands (2005), studded road sections consisted of an introductory straight road section preceding the curve, the curve and a subsequent straight road section (hereafter, curve preparation, curve and curve exit). The relatively long curve preparation section that we used (286 m) enabled us to add a speed reduction countermeasure - longer stud spacing farther away from the curve, which are then reduced by half nearer the curve. Longer stud spacing was also employed at the exit from curves to facilitate vision adaptation to darkness.

In more detail, studs were fixed with relatively short spacing inside the curves and just before them, whereas longer spacing was used at a greater distance before the curve entrance and at its exit. The reduction in the distance between studs at the approach to the curve was thought to lead drivers to perceive their approaching speeds as faster, thereby motivating them to slow down (e.g., Argent, 1980; Denton, 1980; Drakopoulos &Vergou, 2003). By doing so, we aimed at reducing the likelihood that the drivers will increase their speed in the presence of the ALD due a reduction in the perceived levels of risk, as compared to an unlit road (e.g., Wilde, 1988). Introducing longer spacing at the exit would facilitate vision adaptation in the transition back to the unlit road. In addition, under certain conditions the shift between short and long spacing may help drivers to perceive from a distance the beginning and the end of the curved sections. Figure 1 displays a studded zone incorporating a speed reduction countermeasure and a vision adaptation countermeasure.

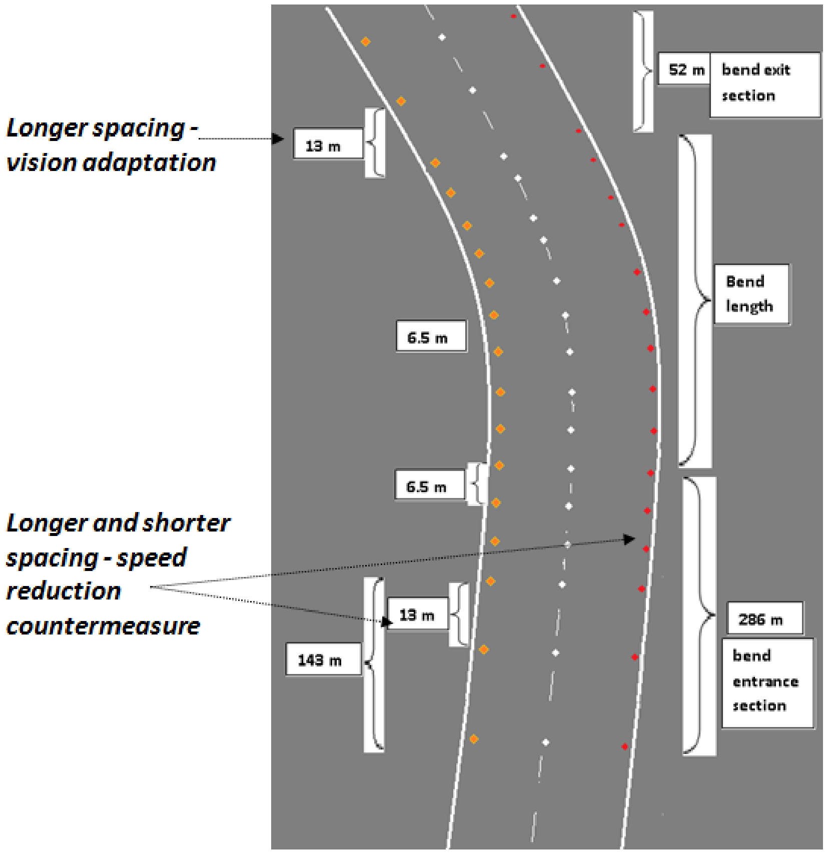

Figure 1. A studded road portion with studs spaced at short and long intervals, including a curve preparation section integrating short and long stud spacing, a curved section with short spacing and an exit section with long spacing.

1.2. Simulation

Two types of curves were simulated, 400 metre with a 300 metre curvature and 150 metre with a 200 metre curvature. By choosing two types of curves we facilitated generalizing our results to different types of bends. For the 286 metres long *curve preparation section* preceding all curves, 13 metres gaps separated the studs in the half (143 metres) more distant from the curve, whereas 6.5 metres gaps separated the studs in the half just before the curve. For the 150 metres long curves, a 202 metres long stud section followed the *curve preparation section.* It consisted of 6.5 metres spaced studs fixed across the 150 metres long curve, in addition to 13 metres spaced studs fixed across the 52 metres *exit subsection* that followed the curve. For the 400 metres long curves, the first *curve sub-section* after the entrance section consisted of 6.5 metres spaced studs across 286 metres. A third, 166 metres long, section covered the remaining 114 metres of the curve (6.5 metres gaps between studs), and the additional 52 metres *curve exit section* (13 metres gaps). At a distance of 300 metres from the *curve preparation section*, both that section and the one to follow dimmed on simultaneously. In the 400 metres long curves, the 3rd section switched on as soon as the vehicle crossed the *preparation section*. Figure 2 displays the stud sections for the two types of curves.

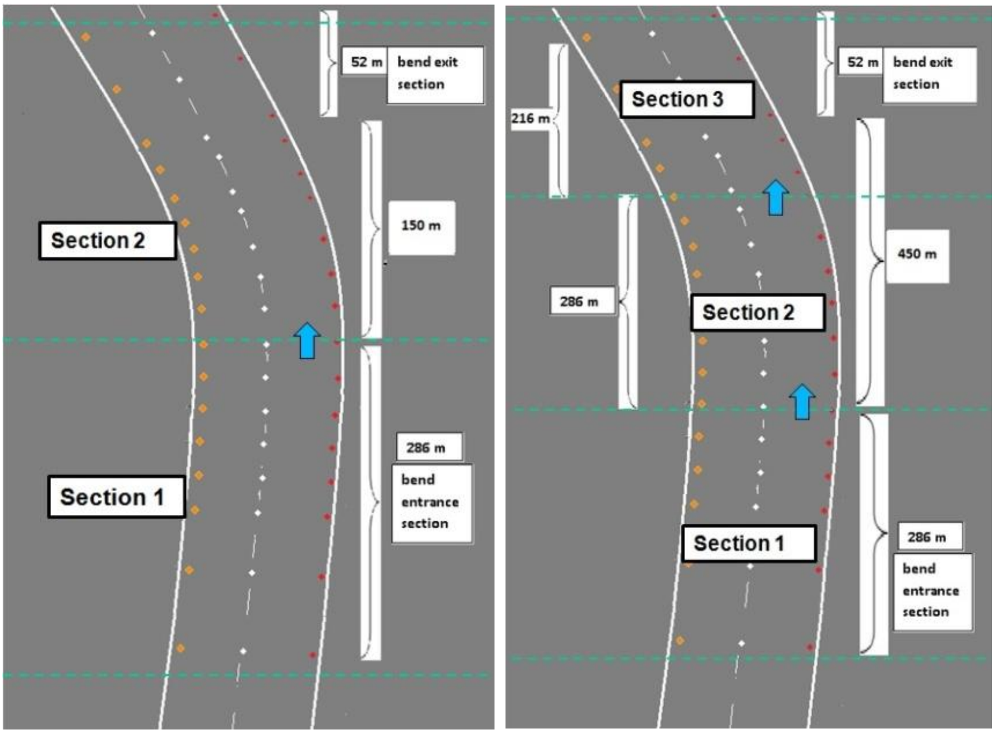

Figure 2. Stud sections for the 150 metres (left) and 400 metres (right) long curves. In both types of curves, sections 1 and 2 switch on simultaneously when the virtual car reaches a distance of 300 metres from section 1. In the 400 metres long curves, section 3 switches on as soon as the vehicle reaches section 2. Immediately after the vehicle (represented by the blue arrow) finalizes each of the sections, they extinguish.

2. Simulator experiment

A simulator experiment was conducted aiming at shedding some light on the safety of the ALD application. The experiment compared simulated night-time driving performance on a country road, with the above-described design for the ALD application, to an unlit road, allowing examining whether there was an advantage or a disadvantage of the ALD, as compared to the control condition.

All of the participants completed a night time drive on the same winding inter-urban route under conditions of the ALD (hereafter, studs) on an unlit road, and of an unlit road with only surface road markings. Each of these conditions consisted of a total of 16 curved and 16 straight road portions. The experiment also consisted of a third condition, without the ALD but with conventional road luminaries, but these data are yet to be analyzed and are not included in this report. The participants were compared on a number of subjective rating scales and objective (performance measures of speed and of lateral positioning) criteria.

Our primary measure for safety was lateral control. As such, our foremost important prediction was that smaller variability of the vehicle's lateral position would be found in the unlit condition as compared to the studded condition. This would provide evidence for superior lateral control of the virtual car in the latter than in the former condition, and would indicate that the application helps to inform the drivers about how they need to control the vehicle in order to negotiate the curves, most likely by enhancing delineation of the lane and road edges.

2.1. Method

2.1.1. Participants

Twelve drivers (mean age = 37.92 years, SD = 10.25; mean license seniority = 16 years, SD = 11.73) participated in the experiment. They were recruited through advertisements that were posted via a mailing list of the French Institute of Sciences and Technology for Transport, Development and Networks (IFSTTAR). All of them had normal or corrected-to-normal vision. The study was approved by the IFSTTAR's Ethics Committee.

2.1.2. Design

The basic design was a (2 x 3) within-subjects design. The first factor was *illumination*, comparing the studded condition to the unlit road condition (fully counterbalanced for order). The second variable was *road section, with three levels,* including a), the s*traight portions*, commencing where the *exit sub-section* in the studded condition terminates and terminating where the *curve preparation section* in the studded condition begins), b), the c*urve preparation* condition, equivalent to the *curve preparation section* in the studded condition, and c), the *curved sections* condition, commencing at the beginning of the curve and terminating just after the curve exit. The dependent variables were the mean (M) lateral position of the car, the standard deviations (SDs) of these means to reflect the vehicle's lateral variability, and the mean speed.

These variables were analyzed with (x 2) ANOVAs (studs, unlit) performed on the data of the straight road sections and (2 x 2) ANOVAs (*illumination x road section)* with two levels of *road section* (curve preparation, curved) performed on the data of right curves and separately on the data of left curves, with each of the two illumination conditions consisting of eight left and eight right curves.

2.1.3. Apparatus and stimuli

The simulator consisted of the basic controls including a steering wheel, a gearstick, accelerator, brake and clutch pedals. With an average individual seated 160 cm from the central of three 47 inch full high definition screens (screen resolution of 1920x1080), presenting a visual display approximating 114° x 21°. Figure 3 shows the simulator and the set-up.

Figure 3. Simulator set-up.

The track had four repetitions of the same portion of a single undivided French rural carriageway, consisting of a 150 metres long left curve with a 200 metres radius of curvature followed by a 400 metres long left curve with a 300 meters radius of curvature, which were followed by two identical right curves, all, separated by 1000 metres long straight sections. A medium volume of oncoming traffic in the contraflow lane was included. The virtual car's headlights illuminated a distance typical for low beam approximating 60 meters. The studded road sections were described in the section 1.2. The inclusion of the studs in the studded condition was the only difference between the two conditions. Figure 4 displays screenshots from the two experimental conditions.

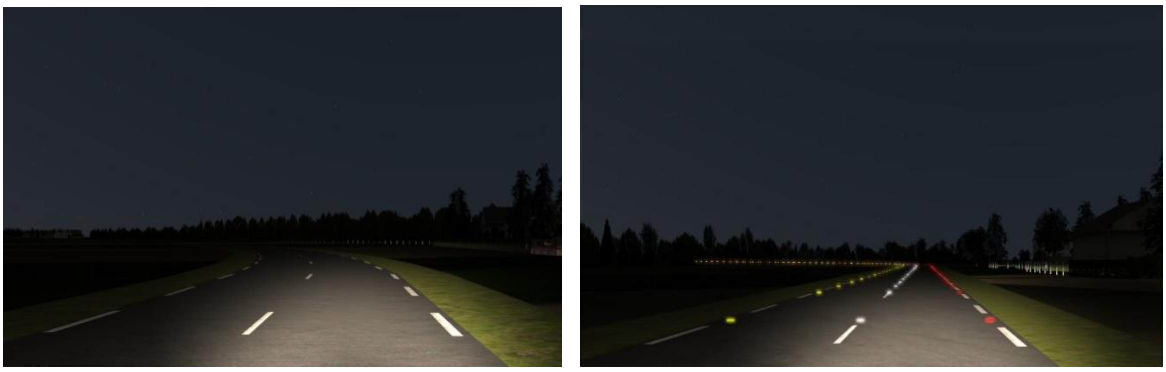

Figure 4. Screenshots of the unlit road and studded road conditions.

3.1.4 Procedure

The participants signed a consent form, provided some details about their driving history and read the instructions given to them. These instructions exposed that the participants were about to participate in an experiment about driving, which would include driving on a simulator that operated similarly to a normal car and completing a questionnaire. The instructions also revealed that the participants would drive on a route under varying night time conditions, while encouraging them to drive as they normally would. After the instructions, the participants completed a short practice drive on the same route but in daylight conditions. This was followed by the assessment drives for each of the conditions and by the post-simulator questionnaire immediately afterwards.

3.2 Results

3.2.1 Speed

The analysis of *speed* yielded significant differences between the unlit and studs conditions, but only in the straight road sections (Means = 91.76, 94.76 Km/h, respectively; $F(1, 191) = 9.15$, $p < .005$). For the curves preparation and curve road sections, neither the effect of *illumination* nor the interaction approached significance levels [$p > .10$], while significant road section effects in both left curves ($F(1, 95) = 51.30$, $p < .001$) and right curves ($F(1, 95) = 31.128$, $p < .001$), indicated that the participants were travelling at faster speeds before the curve than in the curve. Figure 5 displays the means speeds for the eight sub-conditions created by the road section (curve preparation, curve) x illumination x curve side design.

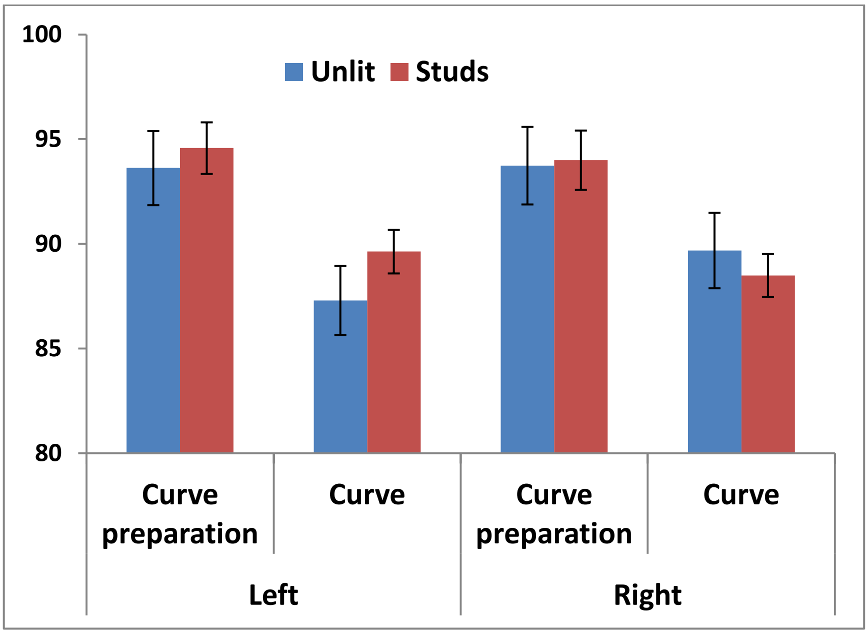

Figure 5. Means speeds for the eight sub-conditions created by the road section (curve preparation, curve) x illumination x curve side design. Error bars represent standard error of mean.

3.2.2 Lane positioning

3.2.2.1 Straight

The analysis of neither the *mean* nor the *standard deviations of the mean, lane positioning,* revealed any significant effects. In both the unlit and the studded conditions the participants drove the virtual car with its centreline positioned approximately 15 cm to the right of the lane centre, with a 5 centimetres non significant difference [p = .10] between the means for two conditions and with a similar 28 centimetres average of lateral position variability, in both conditions.

3.2.2.2 Curve preparation and curves

Figures 6 and 7 display the means lateral positioning (Fig. 6) and the means SDs of the mean lateral positioning (Fig. 7) for the eight sub-conditions created by the road section x illumination x curve side design.

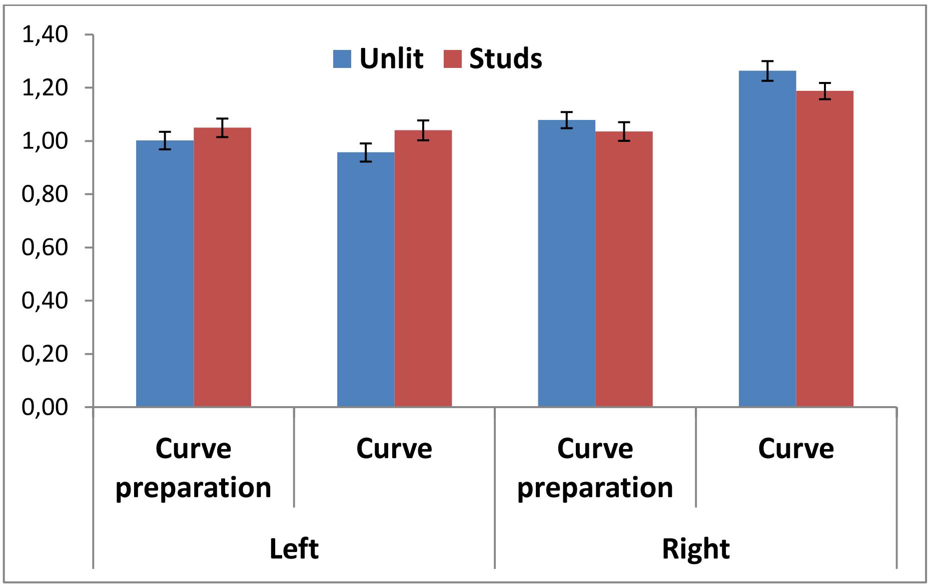

Figure 6. Means lateral position for the eight sub-conditions created by the road section x illumination x curve side design. At zero, the external left side of the car is at the centre marking of the undivided carriageway. At 0.90 the centreline of the 1.70 metre wide car is at the centre of the 3.50 metre wide lane. At 1.80 the right side of the car is at the marking of nearside road edge. Error bars represent standard error of mean.

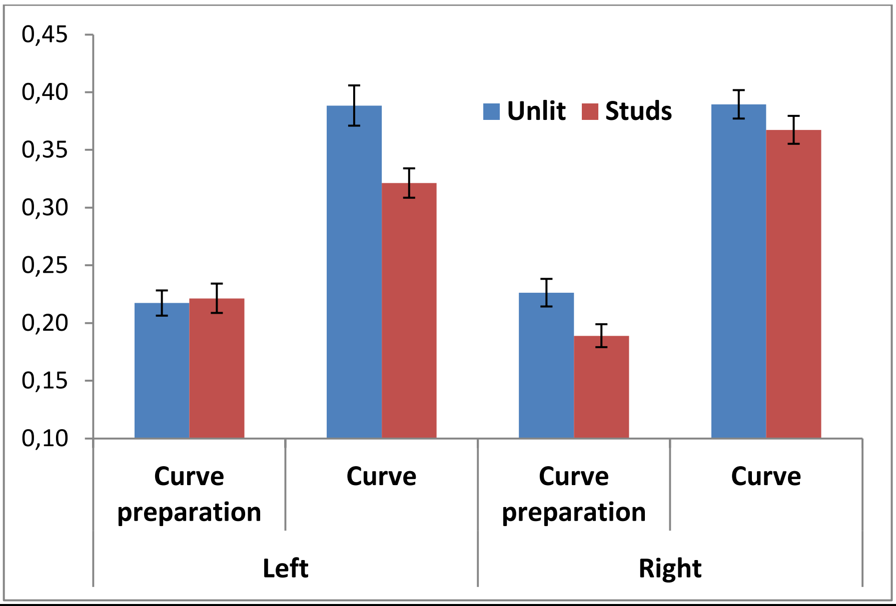

Figure 7. Means SDs of the mean lateral position for the eight sub-conditions created by the road section x illumination x curve side design. Error bars represent standard error of mean.

3.2.2.2.1 Right curves

The analysis of the mean lateral positioning of the right curves yielded a significant effect of road section, $F(1, 95) = 30.95$, $p < .001$. The participants drove the virtual car with its average centreline approximating 20 cm to the right of the lane centre, in the curve preparation section, and 20 centimetres significantly further to the right (with the external right side of the car at a distance of 50 cm from the nearside edge of the road), inside the curve. The illumination effect was marginally significant, $F(1, 95) = 3.58$, $p = .06$, suggesting that the participants drove the virtual car with its centreline positioned approximately 5 centimetres closer to the centre of the lane, in the studs conditions as compared to the unlit condition. The interaction did not approach significance [$p > .10$].

The analysis of the standard deviations revealed significant effects of illumination $F(1, 95) = 6.91$, $p < .01$, and of road section ($F(1, 95) = 168.16$, $p < .001$), but not an interaction. Larger SDs were found inside the curves, as compared to the section preceding the curves, and in the unlit condition as compared to the studs condition.

3.2.2.2.2 Left curves

The analysis of the mean lateral position for the left curves revealed a significant effect of illumination, $F(1, 95) = 5.61$, $p < .05$. The participants drove the virtual car with its centreline positioned approximately 15 centimetres to the right of the lane centre in the unlit condition, and approximately 5 centimetres further yet in the studs condition. Neither the effect of road section, nor the interaction approached level of significance [$p > .10$].

The analysis of the standard deviations revealed significant effects of road section ($F(1, 95) = 91.20$, $p < .001$), illumination ($F(1, 95) = 6.92$, $p < .01$) and of the interaction ($F(1, 95) = 10.46$, $p < .005$). Larger SDs were found inside the curves, as compared to before the curves and in the unlit condition as compared to the studded condition. As can be seen in Figure 7 (left), the pattern of the interaction indicated larger SDs in the unlit than in the studs condition only inside the curve.

3.2.3 Subjective assessment

A French adaptation of questions presented by Reed (2006) was used as the basis for the subjective assessment of the ALD application. On 7 point scales ranging from very unsafe to very safe, from very uncomfortable to very comfortable and from allowing poor vehicle control to excellent vehicle control, the participants rated the studded condition, as compared to the unlit condition, as safer (Ms =5.44 vs. 3.44; SDs = 1.46 vs. 1.62), $F(1, 17) = 18.55$, $p < .001$, more comfortable (Ms = 5.50 vs. 3.28; SDs = 1.58 vs. 1.84), $F(1, 17) = 26.46$, $p < .001$ and as allowing better vehicle control (Ms = 5.44 vs. 4.06; SDs = 1.10 vs. 1.43) $F(1, 17) = 12.22$, $p < .005$.

3.2.3 Summary of results and discussion

The analysis showed small variation in average speeds, about 5 Km/h between the road sections, with slowest speeds inside the curves and with the studded condition inducing speeds that were on average 3 Km/h faster than the unlit condition, but significant differences between the unlit and studded conditions were only revealed in straight road sections. The absence of significant speed differences between these conditions at distances nearer and inside the curves may indeed be due to the reduction in the gaps separating the studs at the approach to the curve, but it is up to future research to directly target this question.

The analysis of the lane positioning of the straight road sections showed that in both the unlit and studded conditions, the participants drove near the centre of their lane, with a similar average of lateral position variability in both conditions.

For the curve preparation and curved sections, the analysis of the means lateral positioning showed some small differences between the conditions, overall indicating that the participants followed the same trajectory, driving at or slightly to the right of the centre of their lane, in both the studded and the unlit road conditions, in all road sections.

Importantly, the analysis of the standard deviations in these road sections revealed significant effects indicating that at closer distances to the curves (i.e., curve preparation) and inside the curves, the unlit condition induced greater lateral variability than the studded condition, in both right and left curves. This finding coupled with those of the results of the mean lateral positioning (helping to rule out the unlikely possibility that the differences in SDs were due to a different trajectory) provide strong evidence demonstrating better lateral vehicle control with the studs, as compared to without them. Finally, at a subjective level, the participants perceived the studded road as safer, more comfortable and allowing better control than the unlit road.

In sum, the simulator experiment's results indicated a) small variation in speed, with the studded condition inducing slightly faster speeds, but only in straight road sections, b), minor variations of the mean lateral position with drivers in both conditions travelling at or near the centre of the lane, c), greater lateral variability in the unlit condition, and d) subjective experience of greater safety, comfort and vehicle control in the studded condition.

The results of this simulator experiment and real driving performance may well be dependent on gross characteristics of the design and such that clearly are more noticeable by the road users, such as stud colours. They also are most likely not independent of the exact parameters used for matters that are less, or even unnoticeable by the average road user, such as stud spacing and others. Indeed, there is good reason to believe that the results of the simulation would be influenced if other spacing, for example, were used or different lengths of light chunks, hence, stud sections. We favored the most basic safety questions to be tested empirically, at the expense of comparing different designs, but future research must compare other alternatives that may have advantages over the design tested in this study, in producing the safest driving performance, while eliminating or minimizing any potential adverse effects that might result from any of the causes discussed next in this report, or due to other causes that are not discussed.

A final note is made about generalization of the results from the simulator trial to the road trial. Even if the design for the road trial's ALD and the characteristics of the road (length, curvature, markings) were all to be identical to the simulator trial, it would still be suggested generalizing results from a single 'modest' simulator experiment to a real road, with caution. Especially, given road studs which have never been tested and a road application on which there is very little knowledge and even more so, due to the large gaps existing between the design that was tested for the simulator trial and the road trial, with respect to the precise road characteristics, to colours, section lengths and so forth. All of these differences, coupled with others which exist between simulation-based and real world-based, perception, drastically hamper the capability to generalize from the simulator experiment to the road trial.

In conclusion, this simulator study provides evidence demonstrating that the active lane delineation application designed, simulated and tested in the present study enhanced, as compared to an unlit road condition, the ability of drivers to control their virtual vehicle and to reduce its lateral displacement.

3. Potential adverse effects

The simulator trial examined the basic design in a relatively 'sterile' environment. There were no obscured vulnerable road users such as cyclists along the side of the road, or any other road hazards. Concerns are raised about possible adverse effects of an activated ALD on the ability of drivers to notice and identify safety reflectors, especially of obscured road users such as cyclists or other hazardous road events which may demand an immediate response. In the simulator experiment, there also was no traffic preceding the participants' virtual car and which might have triggered the application, but on a real road, such circumstances would result in what may be perceived to some drivers at greater distances as random chunks of lights switching on and off, or as a light 'wave' progressing in the opposite direction. Vehicles would illuminate studs that would then become visible in the mirrors of vehicles travelling in the opposite direction, possibly producing glare and potentially 'masking' traffic from behind that is about to overtake. These light points might induce delays in detection of the headlights of an oncoming vehicle. On single undivided carriageway this would increase the risk of head-on collisions. The difficulty to perceive the headlights of an oncoming vehicle on a studded road relative to an unlit road is illustrated in Figure 8. With this design implemented on an undivided carriageway, a continuous separation line (i.e., zone where overtaking is not allowed) would help reducing the risk of head-on collisions.

Figure 8. Headlights of oncoming traffic on an unlit road and on a studded road with nearside, central and offside studs.

In addition, road studs may pose a threat to powered-two-wheelers through loss of control and skidding, especially when lanes on a dual or multilane carriageway and/or the central line on undivided carriageways are being delineated. Finally, system failures may be the cause of some unpredicted ‘illumination patterns’ capable of confusing drivers. Control centers allowing repairing the application in case of malfunction are useful, whereas the ability to manually deactivate the application, likewise automatic unit malfunction detection and shutdown are mandatory.

4. Recommendations on the design - Toward a design for the road trial

Through personal communications at INROADS group meetings and via emails and teleconferences, while recommendations were still being prepared for this report, the most relevant information has been made available to INROADS partners and guidelines and recommendations were laid out - in accordance with how they are described next, but typically with greater detail. At each step of the way, on the basis of the coordinator’s and partners' preferences regarding implementation of the ALD application in the road trial, further recommendations were laid out. These recommendations attempt to take into account the inevitable gaps between the simulator trial and the road trial, due to the limited number of studs available for the road trial, national practices and restrictions (such that relate to the use of colours in Israel to delineate road space), the site structure and the Dutch guidelines; they were and require to, also be taken into consideration in conjunction with the above discussions. The recommendations highlight the pros and cons associated with implementing on a single undivided carriageway each of several specific designs, which have been considered for the road trial. The topics included but were not limited to most of the issues discussed below.

4.1.1. Lines delineated and colours of studs

a) Stud delineation of both the nearside edge and the centre line of the road, likewise, delineation of also the offside road edge.
b) Stud delineation of only the nearside road edge, or only the central line.

The main problem associated with **a** is the greater difficulty in noticing oncoming traffic, thereby increasing the risk for a head-on collision. Given the restrictions on the use of colours other than white/yellow in Israel and because yellow lines are used for marking Israel’s suburban road edges and white mark the centre, it would be reasonable to recommend studding these lines in studs coloured similar colours to what drivers have been habituated, thus, amber and white studs, respectively to the nearside edge and centerline. This recommendation would also be consistent with the Dutch guidelines to use the same colours of the markings. At the same time, it is noted that the difficulty in noticing an oncoming vehicle is increased if the stud colours do not allow clear differentiation from the vehicles headlights (such as with amber and white).

The main concern with **b** is the risk of confused drivers accidentally proceeding to the wrong side of the studded delineation (at the beginning of the studded section), on undivided carriageways.

Implementation in conjunction with a continuous separation line (i.e., zone where overtaking is not allowed) and with clearly marked central and edge lines (i.e., redoing paint) was recommended as means to reduce these two types of risks that are associated with a and b.

4.1.2. Direction dependent vs. direction independent

a) Direction dependent design: a direction illuminates only in response to traffic approaching from that direction.
b) Direction independent design: illumination in both directions occurs when an approaching vehicle is detected from either side of the studded zone.

The advantage of design **a** is that as long as there is no oncoming traffic approaching from the counter direction, there are also no lights flashing in the mirrors of the vehicle travelling in the illuminated zone. The drawback in **a** is that a vehicle approaching the zone from the counter direction would lead to sudden illumination in that direction; lights surprisingly turn on and flash in the mirrors. With **b**, the advantage is that there are no lights flashing by surprise in the mirrors, though it is disadvantageous that they appear in the mirrors constantly irrespective of oncoming traffic, also under conditions that in **a,** they would not appear.

4.1.3. Asymmetry at the edges of the illumination zone

The asymmetry is with respect to the unequal lengths of the curve preparation section and the exit section. This was the case in the simulator trial (and is in accordance with the Dutch guidelines). Briefly, there are fewer light points in the exit sections in both directions, relative to the curve preparation section. To achieve this, the studs in the central line illuminate to both directions only until the end of the exit sub-sections (from a driver’s perspective). After the exit, it is only the LEDs facing in the direction counter to the centre of the zone, which illuminate to mark the entrance to the zone for the counter direction.

4.1.4. Pros and cons with respect to curve preparation and exit sections

The purpose of the curve preparation section is warning drivers before the curve on changes in curvature. The long curve preparation section in the simulator trial (286 meters) enabled the speed reduction countermeasure (reduction of stud spacing at the approach to the curve). At the same time, in undivided single carriageways and with the type of design INROADS chose to proceed in - consisting of two lines being delineated rather than one - the longer the introduction section, the greater the risks associated with 'masking' oncoming traffic headlights. Note that because the curve preparation section is always a straight road section, this threat of head-on collisions is further increased due to the higher likelihood for overtaking maneuvers in that section, as compared to inside the curve. On this basis, with this design choice, there is strong justification in shortening the curve preparation section, while keeping in mind the possible negative implications that eliminating the speed reduction countermeasure may have on speed. The Dutch advise using a curve preparation section of 75 metres on 90 Km/h roads.

For the same reasons, with two lines being delineated on an undivided single carriageways, rather than one line, a long exit section has the exact same problems, hence, increased risk of head-on collisions due to masking on a straight road section. In both cases, implementation in conjunction with a continuous separation line - zone where overtaking is not allowed - would reduce the risk. If in order to facilitate communication requirements or for any other reason, a symmetrical design - with respect to the lengths of the curve preparation and the exit sections - is chosen, a 75 metres long **exit** section still may be considered quite long, in general, all the more so with a design that marks two lines rather than one on an undivided carriageway, more so when these colours do not allow clear differentiation from vehicle headlights and especially if the exit section does not consist of double spaced light points (because double the light points, double the 'masking'). In addition, introducing longer spacing at the exit section would facilitate vision adaptation in the transition to an unlit road; eliminating the double spaced light points may therefore also have negative impact on vision adaptation.

4.1.5. Vehicle detection and Skidding

Given the limited number of studs available for the road trial, it was proposed by the partners that the sensor equipped (non-illuminating) studs responsible for transmitting the message from the beginning of the detection zone to the illuminated zone, would be fixed along the central line. Non-illuminating studs fixed on a non-continuous centre line would dramatically increase the chances that drivers would drive on top of them; on an unlit road these studs obviously would be less or completely unnoticeable. Although, assuming implementation in conjunction with a continuous separation line, it is not very likely that this would happen, it is nonetheless more likely than it is with lit studs. The increased risk for powered-two-wheelers in this dark section preceding the lit [curve preparation] section, would therefore need to be taken into account.

One practical solution is external transmission, which following the initial detection of the vehicle would proceed along the roadside to the illuminating zone, via external broadcast/transmission. Another alternative is fixing the studs in the detection zone so that they are both completely aligned with the road surface and possess appropriate skid resistance. Several problems were presented to INROADS partners that are associated with substituting the LEDs in the detection (i.e., dark) zone preceding the illuminated studs, with retro-reflective devices, as means to cope with that problem; overall this was considered non-practical especially for the road trial.

It is also noted that the installation of sensor equipped (non-illuminating) studs only along the centre line may not guarantee the detection of vehicles travelling in the right hand side of their lane, especially powered-two-wheelers. At the same time, studs fixed only along the nearside road edge would not allow detecting overtaking traffic, travelling in the contraflow lane. The latter option is somewhat less worrying with a continuous separation line and even with a non continuous line, because even if an overtaking vehicle is missed, the vehicles which are being overtaken would be detected soon after. Staggering the studs in the detection zone and placing studs at both sides in the entrance to the detection zone are yet other options to consider.

4.1.6. System malfunction detection and shutdown

The ability to monitor and manually deactivate the application and automatic unit malfunction detection and shutdown are mandatory. The minimal number of non-functional studs that should lead to shut-down of the application in the complete zone should be determined. The exact number may depend on a number of factors influencing separately and in interaction, such as whether these are consecutive studs or not, the section (preparation or curve), the number of light points used within the sub-section and the spacing that is employed.

4.1.7. Vertical aperture and vertical curvature in the geometry of the site

On a flat road, studs with appropriate luminance levels and that possess a minimum vertical aperture of 0.5° would be seen from a distance of 137 metres by a car driver, or 286 metres by a truck driver (eye level of 1.20 and 2.5 meters above road surface, respectively). If the minimum aperture is increased to 1 degree, these distances are reduced by half. A minimum vertical aperture falling somewhere between 0.25° and 0.5° (or maximum 0.5°), coupled with lighting activation at a distance of about 300 meters before the first light point, should ensure that the lights are switched on before they become visible and that when they do become visible, the driver is far enough and therefore is not startled. According to the Dutch guidelines, in order to guarantee that the studs can still be observed at near enough distances, but not too near (this would result in dazzle inside the vehicle), the maximum vertical aperture should fall between minimum 8° to maximum 12°, ideally 10°.

However, if studs that are identical with respect to their vertical aperture are fixed on a road with a vertical curvature, the precise distances in which the light points would become visible and invisible would depend on the exact geometry of the site. Vertical curvature in the geometry of the site may result in light points that become visible or invisible, earlier or later then they should be, as well as in patterns of illumination that may include more distant light points which appear or disappear before closer ones and what might be perceived by an approaching driver as random lights flashing at varying distances.

4.1.8. Adverse effects due to novelty - Advertisement campaign

The exposure of drivers to a new road application may be the cause of unexpected and undesired patterns of driver behavior, such as distracted curious drivers unexpectedly slowing down while observing the new light points instead of the road ahead. Notifying the public well in advance, on the inclusion of the new road application, its potential benefits and the adverse effects to watch out for, both the inherent (e.g., speeding, masking of headlights, brake lights and reflectors, glare in the mirrors) and those that are due to novelty (as described in this section), may help to cope with at least some of these problems. At the same time, an advertisement campaign might achieve the opposite effects, for example, by drawing attention and attracting more curious drivers that would come to see the application, increasing traffic volume and so forth.

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