Effects of a Vision Enhancement System on Drivers' Ability to Drive Safely in Fog

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1. INTRODUCTION

Car driving is to a large extent a visual task. Therefore, poor visibility conditions like fog may impose severe demands on drivers, because the possibility to collect necessary information is markedly degraded. If, however, car driving is seen as a self-paced task, the drivers should be able to adjust their behaviour in accordance with the increased demands.

Speed reductions have been reported for driving in fog on rural roads and highways [1]. Using a fixed base simulator, Tenkink [2] found that poor visibility not only resulted in speed reduction, but also introduced lane keeping problems. He concluded that the lateral position becomes more uncertain and inconsistent with reduced sight distance. Tenkink [3] has also pointed out the importance of the presence of obstacles, and of the behaviour of leading vehicles, for the speed choice in poor visibility conditions. Using a moving base simulator, Harms [4] found that sight distance influenced drivers' mean speed, whereas their lateral position and variation in lateral position were not systematically influenced, implying that reduced sight increases the amount of random variation in lateral position. The speed adjustments obtained under poor visibility conditions have often been insufficient, in the meaning that the stopping distance has remained longer than the actual visibility distance. For example, more than half the number of drivers were exceeding the speed, at which they could stop within the sight distance, in an English motorway study of fog effects [5].

Fog is a relatively rare event, and the accidents occurring in fog constitute a small proportion of the total number of accidents. But, the percentage of fatalities and seriously injured persons, as well as the number of vehicles involved in each fog accident are higher than average [5]. One way to reduce the number of accidents in fog, or at least their consequences, may be to develop a Vision Enhancement System (a VES), that facilitates road following and speed choice, and that helps the driver to detect obstacles and information in time to take appropriate actions.

Using sensors, for the detection of what drivers are unable to see, and presenting the information in the form of a picture directly on the windscreen (a Head Up Display, HUD) has been suggested as one VES solution. A small but "clear" representation of the traffic environment, shown on a monitor placed on the bonnet of the car, can be used as a simple simulation of a HUD for vision enhancement. The purpose of this study was to investigate if it was possible to drive safely in heavy fog when such a simulated VES was available. Because the study focused on traffic safety, the effects on driver behaviour (in terms of speed, lateral position, reaction time and
distance) and on workload were investigated, and compared to driving in clear sight and in fog without VES support.

2. METHOD

2.1 Subjects

Twenty-four subjects, 12 men and 12 women, participated in the study. They were between 23 and 46 years of age (mean 33.5, sd 7.5 years). All were experienced drivers, meaning that they had had a driving licence for at least five years and that they drive at least 10,000 km per year. Many of them were also experienced "simulator drivers", from participating in simulator studies before. The subjects were paid 250 SEK.

2.2 Apparatus

The study was conducted in the VTI driving simulator [6, 7]. It consists of six subsystems: a computer system with the simulation model, a moving base system, a 120° wide visual system, a vibration-generating system, a sound system, and a temperature-regulating system. The subsystems are controlled to evoke impressions, reactions and actions which are very similar to those experienced by a driver during real driving. The additional time delay introduced in the simulator is extremely short (40 ms).

2.3 Driving task

Road. The road type presented to the subjects was a two-lane, high friction asphalt road, 7 m wide and with shoulders. A 15 km long practice route and a 40 km long test route with the given characteristics were used. Both routes were rather straight, imposing very low workload on the subjects from road following.

Visibility. Two visibility levels, fog and clear sight, were used in the study. They were characterised by their maximum theoretical sight distances, which were 50 and 480 m, respectively, and generated by the fog function available in the simulator. The two maximum sight distances were absolute sight limits, beyond which the subjects could not see anything at all. From these limits towards the driver's position the sight was exponentially improved with distance.

Car. An ordinary Saab 9000 with a manual gearbox was used. The simulated physical environment corresponded to that in modern passenger cars.

Visual stimulus. A red square was used to simulate an unexpected event in the traffic environment outside the car. It appeared four times along the test route, at a fixed position, slightly to the left of the road. When the subjects passed certain specified route positions, the red square was presented 400 m ahead.

Obstacles. A van standing still ahead of the subjects' car was used as a stationary obstacle. It was positioned on the right road markings, occupying 1.5 m of the right lane and 0.4 m of the right shoulder. The obstacle appeared four times along the test route. When the subjects passed certain specified route positions, the van was presented 400 m ahead. The subjects had to overtake the vans to reach the destination.

Oncoming traffic. Oncoming vehicles appeared, and were controlled to drive with the subjects' speed. The meeting positions were fixed along the test route, and the oncoming vehicles never appeared in such positions that they disturbed overtaking of the vans.
2.4. Vision Enhancement System (VES)
The VES generated a "clear", black and white picture of the traffic environment (a copy of the "clear sight" video picture generated in the simulator's visual system). It was 17x12 cm in size, and presented on a monitor positioned directly on the bonnet of the car, in the drivers' central line of view, approximately 1.4 m in front of their eyes. The visual stimulus, the obstacle, and the oncoming traffic all appeared "clearly" on the monitor.

2.5. Design
A between-subject design was used. The varied factor was visibility. Three visibility conditions were studied: 1) a clear sight (control) condition with 480 m sight distance, 2) a fog condition with 50 m sight distance, and 3) a fog plus VES condition with 50 m sight distance supported by the VES. The 24 subjects were randomly assigned to the different conditions, with the only restriction of an equal number of men and women in each condition.

2.6. Measures
The speed was recorded, and its standard deviation (sd) was used to estimate the variation in speed. The lateral position on the road was measured in relation to a zero-position, defined as the position where the centre line of the road coincides with the centre line through the driver's body. A more negative value indicates a position more to the right. The standard deviation was used to estimate the variation in lateral position. The brake reaction time was calculated as the time elapsing from the onset of the red square until it was put out by a sufficiently hard braking (brake pedal depressed approximately 10 mm or more). The resolution was 20 ms. If no driver reaction (sufficiently hard braking) had been detected within 400 m after the red square presentation, the stimulus was regarded as unanswered and put out. Correspondingly, the brake reaction distance was calculated as the distance driven from the onset of the red square until it was put out by a sufficiently hard braking. The subjects' workload was measured using the Task Load Index (NASA-TLX) [8]. The subjects had to rate the six factors mental demand, physical demand, time pressure, performance, effort, and frustration level on continuous scales, ranging from very low to very high. They also had to rate the relative weights of the different workload factors.

2.7. Procedure
Firstly, the subjects answered a questionnaire about background variables. Then, written and verbal instructions were given, describing the experimental task, and how to handle the car. The subjects were asked to drive as they would normally drive, on a real highway with corresponding traffic and visibility conditions. They were informed that they had to brake as fast as possible when the red square appeared, and that they had to overtake the stationary vans. The function of the VES was explained to the subjects in the fog plus VES condition.

Then the subjects were introduced to the driving simulator. The handling of the car was practised. For the subjects in the fog plus VES condition, the function of the VES was repeated. The subjects drove the practice route, to get used to simulator driving, the traffic condition, and the respective visibility condition, in order to avoid learning to influence the results. The red square appeared four times, and the subjects could practice to "brake it away". Also the stationary vans appeared four times, so the subjects could practice to overtake them. The experiment leader made
sure that the subjects noticed what was shown on the VES monitor, and that they got familiar with the overall functioning of the system.

After a brake, the real test phase took place. The subjects performed the driving task, including the specific reaction (red square) and interaction (van) subtasks. Driving performance data were recorded via the simulator's main computer. When the test route was completed, the subjects rated their workload on the NASA-TLX scales. The running of each subject took 1 to 2 hours in total.

3. RESULTS

3.1. Speed and speed variation

The mean speed levels and the variations in speed level for the three visibility conditions are listed in Table 1. When the VES was available while driving in fog, the speed level was markedly higher than that for driving in fog without the VES, but did not fully reach the speed level chosen when driving in clear sight (control). A one-way ANOVA showed a significant effect of visibility condition on speed ($F(2,21)=36.13$, p = .0001), and the posteriori test Tukey HSD revealed that all three visibility conditions differed significantly in speed level. A one-way ANOVA failed to show any difference in speed variation between the visibility conditions. Mean speed was thus affected by visibility, but the variation in speed was not. Using a help system, presenting a small but "perfect" representation of the road and its closest environment while driving in fog, seems to lead to a speed choice that is a compromise between the speed choices in clear sight and in heavy fog conditions, respectively.

Table 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>Speed Mean (km/h)</th>
<th>Speed sd (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fog</td>
<td>60.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Fog plus VES</td>
<td>90.9</td>
<td>12.3</td>
</tr>
<tr>
<td>Control</td>
<td>104.6</td>
<td>10.1</td>
</tr>
</tbody>
</table>

3.2. Lateral position and variation in lateral position

The mean lateral positions for the three visibility conditions are shown in Table 2. Small differences can be seen between driving in fog without the VES, and the other two conditions. The subjects in the fog condition drove closer to the centre line of the road. The positioning of the car was similar in the clear sight (control) condition and the fog plus VES condition. A one-way ANOVA showed a significant effect of visibility condition on lateral position ($F(2,21)=4.64$, p = .0215), and the posteriori test Tukey HSD revealed that the lateral position when driving in clear sight (control) differed significantly from the lateral position when driving in fog without the VES. The differences in lateral position between the fog plus VES condition and the other two conditions did not reach statistical significance.
Table 2
Mean lateral positions and variations (sd) in lateral position

<table>
<thead>
<tr>
<th>Condition</th>
<th>Lateral position</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (m)</td>
<td>sd (m)</td>
</tr>
<tr>
<td>Fog</td>
<td>-1.39</td>
<td>0.21</td>
</tr>
<tr>
<td>Fog plus VES</td>
<td>-1.66</td>
<td>0.41</td>
</tr>
<tr>
<td>Control</td>
<td>-1.70</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Also for the variation in lateral position (Table 2), a significant effect of visibility condition ($F(2,21)=14.91$, $p=.0001$) was obtained using a one-way ANOVA. According to the posteriori test Tukey HSD, all three conditions differed significantly. Table 2 shows that the subjects in the fog plus VES condition varied their lateral position most, followed by the subjects in the clear sight (control) condition, and the subjects in the fog condition, who varied their lateral position least.

3.3 Brake reaction time and brake reaction distance

Table 3 shows how fast the subjects reacted (by braking), when a simulated unexpected event (the red square) appeared 400 m in front of them. It also shows how far the subjects drove, from that the red square appeared until they reacted by braking.

The much longer reaction time in the fog condition reflects the fact that the subjects had no possibility to detect the red square until it came out of the fog, 50 m in front of them. The difference in reaction time between the clear sight (control) condition and the fog plus VES condition is more interesting. A one-way ANOVA showed that reaction time was significantly influenced by visibility condition ($F(2,21)=362.32$, $p=.0001$). The posteriori test Tukey HSD revealed, however, that only the differences between the fog condition and the two other conditions were significant. The 0.25 s prolongation of brake reaction time, when driving in fog with the VES available compared to driving in clear sight (control), was thus not found to be statistically significant.

Table 3
Mean reaction times (4 stimulations) and mean reaction distances (4 stimulations)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Reaction time</th>
<th>Reaction distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fog</td>
<td>23.14</td>
<td>385.0</td>
</tr>
<tr>
<td>Fog plus VES</td>
<td>1.07</td>
<td>27.6</td>
</tr>
<tr>
<td>Control</td>
<td>0.82</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Also the much longer distance travelled, before the subjects in the fog condition reacted (braked) to the presented red square, results from the fact that these subjects had to drive aprr. 350 m to the sight distance limit, before they could possibly discern the red square in the fog. Thus, again the difference in reaction distance between driving in clear sight (control) and VES supported driving in fog is more interesting. A one-way ANOVA showed that reaction distance was significantly influenced by visibility condition ($F(2,21)=8756.53$, $p=.0001$). The posteriori test Tukey HSD revealed, however, that only the differences between the fog condition and the two other conditions were significant. The 3 m prolongation of brake reaction distance, when
driving in fog with the VES available compared to driving in clear sight (control), was thus not found to be statistically significant.

3.4. Workload

For each subject, the scale values for the workload factors mental demand, physical demand, time pressure, performance, effort, and frustration level were multiplied with their corresponding weights. Table 4 shows the resulting means of the workload ratings, associated with driving under the various visibility conditions.

Table 4
Mean ratings of six workload factors

<table>
<thead>
<tr>
<th>Workload factor</th>
<th>Fog</th>
<th>Fog plus VES</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental demand</td>
<td>297.9</td>
<td>190.9</td>
<td>125.4</td>
</tr>
<tr>
<td>Physical demand</td>
<td>121.0</td>
<td>59.9</td>
<td>32.0</td>
</tr>
<tr>
<td>Time pressure</td>
<td>59.8</td>
<td>59.6</td>
<td>13.9</td>
</tr>
<tr>
<td>Performance</td>
<td>151.8</td>
<td>149.1</td>
<td>202.5</td>
</tr>
<tr>
<td>Effort</td>
<td>131.9</td>
<td>212.3</td>
<td>102.8</td>
</tr>
<tr>
<td>Frustation</td>
<td>95.1</td>
<td>155.9</td>
<td>105.1</td>
</tr>
</tbody>
</table>

Using one-way ANOVAS, only the workload factors mental demand (F(2,21)=4.56, p=.0226), and physical demand (F(2,21)=3.63, p=.0443) showed significant effects of visibility. The workload factors time pressure, performance, effort, and frustration level, did not show any statistically significant differences between the three visibility conditions.

From Table 4 it is obvious that the mental demand was rated highest for driving in fog without the VES, lower for VES supported driving in fog, and lowest for driving in clear sight (control). The posteriori test Tukey HSD revealed that mental demand ratings differed significantly between the fog and clear sight (control) conditions, whereas the differences between the fog plus VES and the other two conditions were found to be non significant.

For physical demand, the highest rating was again obtained for the fog condition, followed by the rating for the fog plus VES condition and the clear sight (control) condition, in that order. The posteriori test Tukey HSD showed that a significant difference was present between the fog and clear sight (control) conditions. The differences in physical demand ratings between the fog plus VES and the other two conditions were not found to be significant.

4. DISCUSSION

The use of a VES, presenting a small black and white picture of the road and its closest environment on a monitor in front of the driver, has been shown to influence driver behaviour, or more precisely speed choice, variation in lateral position, and reaction time.

As reported for real driving [1], and more or less self-evident, the speed decreased in the fog condition. The mean level (60.5 km/h) was of the same order of magnitude as that in another simulator study [4], with comparable visibility, but with a more curved road. Introducing the VES when driving in the fog, increased the speed level by 30.4 km/h to 90.9 km/h, which still was 13.7
km/h below the speed level obtained in clear sight. This result indicates that drivers still could have experienced some problems when they used the VES. Even though the VES presented a true representation, the road and the traffic were not equally easy to see on the monitor as through the windscreen; especially not the far away sections, as the small size of the monitor picture probably lead to a reduction of the actual sight distance. The speed results therefore partly support the hypothesis that drivers adjust their speed so the sight distance remains constant in time [2]. Another explanation may be that the obtained speed reductions were caused by lane keeping problems.

The variation (sd) in lateral position on the road was increased when the VES was used, indicating that these drivers seem to have larger problems than the other drivers to keep a steady course. Also, large deflections in lateral position during overtaking of the vans imply that it was difficult to control lateral manoeuvres by looking at the monitor. The problems may have been caused by the strategy for system use. Most drivers moved their eyes between the VES monitor and the real road. An additional reason could have been the fact that the bonnet was not reproduced on the monitor, leading to the picture "floating around" without a stationary reference. That unsupported driving in fog shows the smallest variation in lateral position is in disagreement with earlier results [2], but indicates that these drivers probably kept to the centre line as a reference. The increase in lateral position was not so large, that the drivers using the VES spent more time in the left lane, compared to other drivers.

The differences in reaction time and reaction distance between the fog plus VES and the clear sight conditions were not significant, meaning that the drivers' ability to react quickly to an unexpected event was not negatively influenced by the VES. Instead, this ability was strongly improved compared to unsupported driving in fog. But, in the fog condition it was impossible to perceive the stimulus until it came out of the fog, ca 350 m after presentation. To overcome this design restriction, the reaction times and reaction distances for the fog condition were theoretically recalculated, assuming that the red square was presented at the fog limit, 50 m ahead of the drivers. The resulting mean values were 2.1 s and 35 m, respectively. The compensated reaction time for unsupported driving in the fog was still longer than the reaction time when the VES was used (one-way ANOVA; F(2,21)=76.24; p=.0001). The compensated difference in reaction distance did not reach statistical significance. An explanation for the reaction time improvement can be that the VES gave the drivers the opportunity to detect the red square at the moment it occurred, that is to detect a distinct change which humans are good at. In the fog condition, the red square appeared more like a gradual change growing out of the fog. Such changes are more difficult to detect.

Different strategies for system use were adopted among the drivers using the VES. Some reacted very quickly to the red square (mean reaction time 0.76 s), indicating that they looked at the monitor most of the time, while others seemed to be more uncertain about how to divide their attention between the monitor picture and the real road, and therefore reacted somewhat slower (mean reaction time 1.25 s). The strategy for VES use also varied for the same individual, in different situations along the test route. Especially in more critical situations like overtaking and meeting oncoming vehicles, the drivers tended to look more through the windscreen. Thus, introduction of the VES probably made the driving task somewhat more complicated, because the two sources for visual information acquisition resulted in a choice situation for the driver, making divided attention a potential risk factor.
It is desirable that a driver can stop within the sight distance, making stopping distance an important factor. Assuming a deceleration near maximum (7 m/s²), and using the speeds and reaction times obtained in the study, the theoretical stopping distances were: 84 m in clear sight, 56 m (compensated) in fog, and 74 m in VES supported fog driving. For a more moderate deceleration of 3 m/s², the corresponding values were: 165 m, 82 m, and 135 m, respectively. Thus, in clear sight and when the VES was used in fog, the drivers could easily stop within the sight distance, for both deceleration levels. The margin seems to be large enough, for the interpretation to hold, even if the sight distance on the monitor is somewhat reduced because of picture size. In the fog condition, drivers seem to have driven too fast, or reacted to slow to be able to stop within the sight distance.

The subjective assessment of workload did not reveal any significant effects of the VES, even though tendencies towards higher workload rates compared to clear sight rates, and lower workload rates compared to unsupported driving in fog, could be seen.

5. CONCLUSIONS

Use of the VES when driving in fog
- resulted in a speed level between the speed levels in clear sight and in fog.
- resulted in a larger variation in lateral position than in clear sight and in fog.
- improved the ability to react quickly, compared to unsupported driving in fog.
- did not degrade the ability to react quickly, compared to driving in clear sight.
- did not influence the workload level.

It seems both possible and acceptable to use a small representation of the traffic environment, in order to support drivers in poor visibility.

Further studies are necessary concerning long-term effects, MMI aspects, and effects of varying driver strategies for information acquisition.

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The Swedish Road and Transport Research Institute has laboratories and know-how for advanced research commissions in transport and welfare economics, road safety, vehicles and the environment. It also has research capabilities for the construction, operation and maintenance of roads and railways.

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