COST 331, REQUIREMENTS FOR HORIZONTAL ROAD MARKING

Task 300, Evaluation of drivers’ visual needs

Sub-task B, Drivers’ needs to perceive the road at night by the use of road markings – An experiment in the VTI driving simulator

by

Gabriel Helmers and Lisa Herland
Swedish Road and Transport Research Institute (VTI).
SE-581 95 LINKOPING, Sweden


Preface

A draft version of the report was approved at the Management Committee meeting in Reykjavik, May 29, 1998. Brian Lyus has kindly helped us with proof reading and correction of language in the final report.

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Drivers’ needs to perceive the road at night by the use of road markings – An experiment in the VTI driving simulator

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1 Introduction

The aim of Task 300B is to acquire basic data on drivers’ needs or demands for visibility of road markings at night. The driver must be able to see the road in front of the car at a certain minimum distance or preview time in order to keep the car under full control in the driving lane. This problem is difficult to answer by carrying out full-scale experiments on real roads or test tracks. This is because the visibility distance or the preview time to road markings cannot be well controlled, for at least two reasons: First, the driver’s visibility of the road is uncertain beyond a certain distance because of the absence of strong visual cues in this area. Second, visual performance varies between drivers, which implies that what can be seen by one driver cannot be seen by another. Therefore, very little firm empirical evidence can be found in the literature, although preview times in the range from 2 to 5 seconds have been proposed.

One possible approach to overcome this difficulty is to carry out experiments in a driving simulator in which the picture of the road scene is generated by a computer. The driving simulator of the Swedish Road and Transport Research Institute (VTI) was used for the study. The information to the driver from the simulated road scene is therefore under total control of the experimenter. Using this technology the road scene is shown to the driver up to a specified distance, beyond which no visual information is available.

The aim of this study is to answer the problem of Task 300B: “What visibility distance or preview time to the visibility limits of road markings does the driver require in order to keep the car under full control in the driving lane?” Note that this task is neither to find the most comfortable nor the safest level of the driver’s visibility of road markings.

In order to answer this question, an experiment has been carried out in the VTI driving simulator. This experiment, its results and the conclusions that can be drawn from the results are presented in the following sections of this report.
2 The driving simulator experiment

2.1 The driving simulator
The driver or test subject in the simulator is "driving” a Volvo 850 saloon with automatic transmission. The car is simulated by a "mock up” with the bonnet and windscreen and with the original interior of a Volvo 850 from the front up to a point behind the driver’s seat. This mock up is mounted on a moving base with mainly transverse movement that makes the driving simulator especially valid for driving through curves and for making quick lane changes. The performance and driving qualities of the car in the simulator correspond well with a Volvo 850 on the road. The road scene in front of the driver is presented on a screen in front of the car by three video projectors. This screen has a visual angle of 120° seen from the driver’s seat.

The video technique also has limitations. The maximum range of luminances in the video picture on the screen is very small compared to luminances in the road scene under real driving conditions. Furthermore, the resolution of the picture is considerably lower compared to normal eyesight. These limitations have consequences for what the driver’s visual tasks in the simulator should be. It follows that all visual stimuli on the screen should be clearly visible.

2.2 Planning the experiment
Work started in January 1997 with the development of supplementary hard-ware in order to generate a high quality picture of a night driving scene. Parallel to this work the simulated route was programmed. This program also allows quick changes between two conditions of speed (driver’s free choice of speed and 90 km/h set by a cruise control) as well as a random order of presentation of the levels of visibility of the road.

Measures of driver behaviour when driving the route are the dependent variables. The overall experimental situation and the picture of the driving scene were tested in a number of pilot trials before summer. The simulator was demonstrated for participants of the Task 300 Meeting in Linköping in July. The proposed design of the experiment was also discussed at this meeting. After further consideration the exact procedures and conditions for the experiment were fixed early in August.

The experiment was then carried out in late August and beginning of September.

2.3 The experimental route
The simulated road had two lanes. The lane width was 3.5 m measured from the centre of the road to the outer edge of the edge line. The centre of the road was marked with a broken centre line (3 m long marks with 9 m gaps = modules of 12 m). The outer edges of the driving lanes were marked with broken edge lines (1 m long marks with 2 m gaps = modules of 3 m). (These modules correspond to the Swedish rules for application of centre and edge lines.) The width of the road markings was 0.14 m.

Continuous edge lines were compared with broken edge lines in pilot tests. As broken edge lines gave a more valid perception of motion and speed in the simulator, this type of edge line was chosen for the experiment. The reason for choosing lines somewhat wider than 0.10 m was to compensate for the limited resolution of the video technique.

The road scene shown on the screen was a driving situation at night in which the road was exclusively shown by its centre and edge lines. There was no other contrast in the picture, either between the road surface and the environment or in the environment
itself. So there was no complementary visual information beside the road markings in the computer-generated picture.

The simulated road had horizontal curves and a straight stretch of road between curves. There were therefore no S-curves or vertical curves. The road was shown on a screen in front of the car (mock up) and in a correct perspective from a driver’s point of view.

The subjects drove a route a number of times. A number of curved sections and a number of straight stretches of road created the route. Turning direction, radius and length specified each specific curve section. Its length specified each straight section.

The curved sections and the sections of the straight stretches were selected in random order, using a computer, for each drive of the route. Therefore, the route had a constant length (sum of length of all sections is 5000 m) but it was also unique for each drive.

The route in summary:
- Two lane road
- Lane width: 3.5 m
- Centre line: 3 m long road markings with 9 m gaps
- Edge line: 1 m long road markings with 2 m gaps
- Only horizontal curves on the route (no S-curves or vertical curves)
- Every curve preceded by a straight stretch of road
- Length of straight stretches of road, 4 levels: 100 m, 110 m, 140 m, and 180 m
- Curve radii (varied by a factor 1.5), 4 levels: 200 m, 300 m, 450 m, and 675 m
- Length of curves, 4 levels: 120 m, 130 m, 140 m and 150 m
- Total length of the route (simulated road): 5 000 m

- Number, type, and radii of curves:

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>Yes</th>
<th>No</th>
<th>Σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>300</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>450</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>675</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total number</td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

The radius for the transition or clothoid curves decreased down to the constant radius over a transition distance of 20 m.

2.4 Visibility conditions

The general road scene is a two-lane road at night without opposing traffic. Sight distance of the road ahead (controlled by making the road markings visible) is varied (by a factor of 1.5) in 5 levels: 20 m, 30 m, 45 m, 67 and 100 m.

The luminance of the road markings ahead is varied for every visibility distance in the following way: 100 % luminance for the nearest half of the sight distance available. From that distance the luminance continuously decreases to 30 % of its original luminance at the limit of the available sight distance. There is therefore a sharp cut-off at the end of the sight distance, beyond which there are no cues of the road at all. (This situation simulates a symmetric European dipped headlight with no light above a very
sharp cut off.) The road markings were clearly visible to the subjects throughout the sight distance but there was no visibility beyond this distance.

2.5 The driving task
There are two conditions of driving speed. In the first condition the subject has free choice of speed by the normal use of the accelerator. The subjects were instructed to drive as they normally would under these sight conditions and to keep the car in their driving lane. There is feedback through the steering wheel while driving on centre and edge lines. (This feedback is similar to that received in real driving when driving on longitudinal broken 3-4 mm high thermoplastic road markings.)

In the second condition the subjects drive with the cruise control set at a constant speed of 90 km/h. In the latter condition the subjects were instructed to keep the car in their driving lane and not to use the brakes.

2.6 Experimental design and procedure
Every subject is exposed to all experimental conditions (“within subject design”). This means that each subject is his own ”control” and that the number of subjects can be relatively small.

The experimental session begins with a verbal instruction followed by a practice drive in order to make the subject familiar with the driving situation. This practice drive is identical for all subjects, starting with the longest sight distance followed by successively shorter and shorter distances until the subject has been exposed to the 30 m level of visibility.

When the practice drive is finished and the subject’s questions, if any, are answered the main experiment starts. The first condition is the driver’s free choice of speed. The visibility distances are varied in 4 levels: 30, 45, 67, and 100 m. The subjects drive the simulated 5 km long simulated road for each of these visibility conditions. These conditions are presented one at a time and in random order.

After this drive there is a short break and new instructions are given for the cruise control condition. This condition is somewhat extreme, with the range of visibility distance being shorter but also varied in 4 levels: 20, 30, 45, and 67 m. The procedures of the previous drive are then repeated at a constant speed of 90 km/h.

2.7 Experimental control
The test road consists of 16 curves preceded and followed by straight stretches of road. The order of road sections (straight stretches and curves and the length of these sections) was varied for every drive (subject, speed and sight distance). ”Random sampling without replacement” was used to make every drive through the route unique even though it consisted of the same curves and straight stretches.

The four levels of visibility distances are also exposed for each subject in random order.
2.8 Dependent variables
1. Condition of free choice of speed
   • Driving speed
   • Lateral position of the car in the driving lane
     - Lateral position in the driving lane
     - Extreme lateral position in the driving lane
     - Standard deviation of lateral position
     - Distance driven outside road marking

2. Cruise control condition (90 km/h)
   • Lateral position of the car in the driving lane
     - Lateral position in the driving lane
     - Extreme lateral position in the driving lane
     - Standard deviation of lateral position
     - Distance driven outside road marking

2.9 Interview with questionnaire
The subject filled in a questionnaire after the experiment in order to collect information about driving experience. In the questionnaire the following information was asked for:
   • Age
   • Sex
   • Number of years with driver’s licence
   • Kilometres usually driven per year
   • Kilometres driven during last year
   • How often the subject drives in the dark during the dark season (winter).
     Alternatives: 1. Several times a week, 2. Once a week, 3. Once a month, 4. Almost never.
   • If the subject finds that s/he has a harder time to drive in the dark than other people.
     Alternatives: 1. Yes, 2. No. If “yes” they are asked to fill in why.
   • If the subject has driven the simulator before. Alternatives: 1. Yes, 2. No.
The information collected is presented below.

2.10 Subjects
The subjects were 24 experienced drivers in two age groups: 25-35 and 55-65 years of age with an equal number of men and women: 6 young men, 6 young women, 6 older men, and 6 older women.

The information collected about the subjects in the questionnaire is presented in tables 2.1 and 2.2 below. Two persons answered “yes” to the question whether they find that they have a harder time than others in driving in the dark. They were a man and a woman from the “older driver” category. One explained that glare from oncoming traffic was the cause, the other the short sight distance and an eye defect. Half of the older men and the older women had driven the simulator before. All but one of the young females had driven it before and just one of the young males.
Table 2.1  Group mean values regarding age, and driving experience.

<table>
<thead>
<tr>
<th>Group</th>
<th>Age</th>
<th>Years with driver’s licence</th>
<th>Distance driven per year [km]</th>
<th>Distance driven during last year [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young female</td>
<td>30</td>
<td>12</td>
<td>11 500</td>
<td>10 000</td>
</tr>
<tr>
<td>Older female</td>
<td>59</td>
<td>36</td>
<td>8 500</td>
<td>7 100</td>
</tr>
<tr>
<td>Young male</td>
<td>29</td>
<td>11</td>
<td>23 750</td>
<td>23 330</td>
</tr>
<tr>
<td>Older male</td>
<td>62</td>
<td>44</td>
<td>20 670</td>
<td>17 330</td>
</tr>
</tbody>
</table>

Table 2.2  Results from the question how often the subjects drive in the dark during the dark season (winter).

<table>
<thead>
<tr>
<th>Group</th>
<th>Almost never (4)</th>
<th>Once a month (3)</th>
<th>Once a week (2)</th>
<th>Several times a week (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young female</td>
<td></td>
<td></td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Older female</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Young male</td>
<td></td>
<td></td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Older male</td>
<td>1</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

2.11 The experimental session in summary

1. Instruction
2. Training drive
   - Driving distance: 10 km
3. Main experiment
   3.1 Condition of free choice of speed - Instruction
      - One drive for each of the 4 sight distances, 30, 45, 67, and 100 m
      - Driving distance: (5 km x 4 =) 20 km
   3.2 Cruise control (90 km/h) condition - Instruction
      - One drive for each of 4 sight distances, 20, 30, 45, and 67 m
      - Driving distance: (5 km x 4 =) 20 km
4. Final interview with questionnaire

Time needed for the subjects to carry out the experiment: about 1 hour.
3 Results with comments

3.1 Choice of speed

When the driver has the possibility to choose speed he adjusts it to the sight conditions. Speed increases with visibility of the road marking ahead up to a distance of about 67 m. Above this distance there is no increase in speed. The speed at free choice of speed is shown in Table 3.1 and Figure 3.1. Sight distance has a significant effect on speed (F(3;69) = 55.4; p<0.001). The test is based on a "within-subject-design". Paired samples test shows that there is a significant (p<0.05) difference in speed between all sight distances except between 67 and 100 m.

<table>
<thead>
<tr>
<th>Sight distance [m]</th>
<th>30</th>
<th>45</th>
<th>67</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean speed [km/h]</td>
<td>60.3</td>
<td>71.3</td>
<td>76.3</td>
<td>75.3</td>
</tr>
<tr>
<td>S.D. of speed [km/h]</td>
<td>11.8</td>
<td>11.3</td>
<td>8.1</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Figure 3.1 Mean speed (km/h) for the four levels of visibility of road markings. (Group mean values).

The speed is affected not only by sight distance but also by the radius of the curve. The smaller the radius, the lower is the speed. This can be seen in figure 3.2 that shows the average speed for each radius with or without a transition, and for straight sections. 10 m at the beginning and end are excluded from the average.
In figure 3.3 the speed differences between mean speed on straight sections and different curves are shown. The driver lowers the speed more at longer sight distances than at a short sight distance when approaching a curve with a small radius. With the 30 m visibility distance and a short preview time there is little time for adjustment of speed before sharp curves. (Preview times are calculated in section 3.2.) Drivers cope with this situation by keeping a low speed with little variation in speed over the route. With longer visibility distances of road markings drivers have longer time to adjust speed to the curve they are approaching. There is a larger decrease of speed in sharp curves with increasing visibility distance of the road marking.

The average speed on straight sections is slightly lower than the speed in curves with large radius. This can be seen in figure 3.2 and is the cause of the negative differences in figure 3.3. This is because the speed on the straight sections is affected by the speed in the preceding and following curve.
Figure 3.3  Difference of mean speed on straight stretch and in curves at four levels of sight distance. 10 m in the beginning and end of every curve or straight stretch are excluded from the average. (Group mean values).

A second analysis of variance regarding sex and age shows no significant difference between men and women and no difference according to age.

3.2 Preview time

The preview time is the time it will take the driver to travel from the present location to the most distant road marking visible. This is a useful variable because it takes both sight distance and speed into consideration. It is calculated by dividing the sight distance by the driving speed. See table 3.2.

Table 3.2  Preview time at the different sight distances for both speed conditions: free choice of speed and cruise control (90 km/h). (Group mean values).

<table>
<thead>
<tr>
<th>Sight distance [m]</th>
<th>20</th>
<th>30</th>
<th>45</th>
<th>67</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean speed at free choice [km/h]</td>
<td>60.3</td>
<td>71.3</td>
<td>76.3</td>
<td>75.3</td>
<td></td>
</tr>
<tr>
<td>Preview time at free choice [s]</td>
<td>1.8</td>
<td>2.3</td>
<td>3.2</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>Mean speed at cruise control [km/h]</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Preview time at cruise control [s]</td>
<td>0.8</td>
<td>1.2</td>
<td>1.8</td>
<td>2.7</td>
<td></td>
</tr>
</tbody>
</table>

Notice that the shortest preview time at the condition free choice of speed is 1.8 seconds. At the condition cruise control the same preview time is at 45 m sight distance.

3.3 Mean lateral position

The lateral position is the distance in metres between the centre of the car and the centre of the road.

An Analysis of Variance was made for each of the two speed conditions, free choice of speed and cruise control. The “within-subject-design” of the experiment is considered in the analysis. The design of the analysis is as follows:
Dependent variable  Independent variables (number of levels)
\textit{lateral position}  \textit{sight distances} (4)
\textit{radius} (4)
\textit{transition curves} (2, with and without a clothoid)
\textit{right or left} (2)

All curves with the smallest radius began with a clothoid, and all curves with the largest radius were entirely circular. This made the design non-symmetric.

### 3.3.1 Free choice of speed

On straight stretches of road at the condition free choice of speed, variations in sight distance resulted in very little difference in lateral position. (Figure 3.4)

![Lateral position at free choice of speed](image)

**Figure 3.4** Mean lateral position for right and left curves and straight stretches at the condition free choice of speed. Lateral position is the distance between the centre of car and the centre of road. 0 m lateral position is the centre line and 3.5 m is the outer edge of the right edge line. (Group mean values).

In right and left curves the driver behaves differently. In the right curve the lateral position is further to the right and in the left curve further to the left. The tendency is stronger for longer sight distances than for shorter. This might be because the drivers are cutting the curves and cutting more at longer sight distances. The Analysis of Variance shows a significant interaction between sight distance and the direction of the curve, right or left (F(3;1465) = 144; p<0.001).

It is not very clear how radius affects lateral position but it seems that the smaller the radius the further to the right the car is positioned in a right curve, and the further to the left in a left curve. An Analysis of Variance shows that the interaction between radius and right and left curve has a significant effect on the lateral position of the car (F(3;1465) = 35.9; p<0.001). The graph of the lateral position for different radii can be found in figure 3.5 with the different radii on the x-axis and in Appendix A shown with the sight distance on the x-axis as in figure 3.4.
Lateral position [m] in every curve at the condition free choice of speed at the four levels of sight distance. Lateral position is the distance between the centre of car and the centre of road. Centre line at the lateral position 0 m, outer edge of right edge line at 3.5 m. Left curves are labelled (L), right curves (R). C stands for transition curve, oo for straight stretches. (Group mean values).

It is not clear from the results of the statistical analysis whether transition curves have any effect on lateral position. Because of the non-symmetry, the possibility cannot be excluded that the effect of a transition curve is combined with an effect of radius.

### 3.3.2 Cruise control at 90 km/h

For the condition 90 km/h the lateral positions on straight stretches differ very little for different sight distances. (Figure 3.6)
Figure 3.6  Mean lateral position for right and left curves and straight stretches at the condition cruise control. Lateral position is the distance between the centre of car and the centre of road. 0 m lateral position is the centre line and 3.5 m is the outer edge of the right edge line. (Group mean values).

For right curves, the longer the sight distance the further to the right the driver’s lateral position. In left curves, the lateral position is further to the left the longer the sight distance. At the two longer sight distances (45, 67 m) the driver has a mean lateral position to the right of the position on the straight stretch and the other way around in left curves. This behaviour is similar to the condition free choice of speed and might be because the driver is cutting the curves. At the shorter sight distances (20, 30 m) the lateral position in right curves is to the left of that on straight stretches. In left curves the lateral position is to the right compared to straight stretches. This could be because the driver is "missing " the curve. The Analysis of Variance shows that the interaction between sight distance and right or left curve has a significant effect on lateral position (F(3;1465) = 376.0; p<0.001).

The effect of radius is not totally clear but for longer sight distances (45, 67 m) there is a tendency for the lateral position to be further to the right in a right curve, the smaller the radius is. In a left curve the lateral position is further to the left the smaller the radius. This is probably because drivers are cutting the curves more at smaller radius. At the short sight distances (20, 30 m) there is a tendency for drivers to "miss" curves more the smaller the radius is. The Analysis of Variance also shows an interaction between sight distance, right or left and radius that has a significant effect on lateral position (F(9;1465) = 6.1; p<0.001). The effect of radius is illustrated by figure 3.7 with the different radii on the x-axis and in Appendix A shown with the sight distance on the x-axis as in figure 3.6.
Transition curves are not considered in the analysis for the same reason as for free choice of speed.

### 3.4 Extreme lateral position in curves

The extreme lateral position, which is the lateral position of the right wheel when it is furthest to the right and the left wheel when it is furthest to the left, is measured for each test person in each curve. If just the mean lateral position is studied, this information is lost. It is the outside wheel in the curve that is most interesting to study. For instance, in a right curve it would be the lateral position of the left wheel that is furthest to the left. The extreme lateral position of the wheel is of interest because it shows how close the wheel gets to the edge or the centre of the driving lane in curves, and under what circumstances the driver ”stagger” or ”misses” the curve. This is important information because having one wheel too far out the extreme lateral position is hazardous.

An important feature is that no systematic tendencies have been found for these extremes to occur in any particular part of a curve. Drivers seem to have very different ways of driving and lateral position also differs between curves.
An Analysis of Variance of the two extreme lateral positions in curves was made for right and left curves, with and without transition curves. That is four analyses, one for each extreme and for each speed condition. The “within-subject-design” is considered. The design of the analysis is as follows:

**Dependent variable**          **Independent variables (number of levels)**

- extreme lateral position
  - sight distances (4)
  - radius (4)

The effect of transition curves was examined in a separate analysis with the following design:

**Dependent variable**          **Independent variables (number of levels)**

- extreme lateral position
  - sight distances (4)
  - transition curve (2, with and without)

### 3.4.1 Free choice of speed

In right curves the minimum distance between the right wheel and the edge marking decreases with increasing sight distance. In left curves the effects are the same but in the reverse direction, that is the minimum distance between the left wheel and the centre line decreases with increasing sight distance.

For the condition free choice of speed, the outer wheel is closest to the outer road marking at the shortest sight distances. It can be seen from figures 3.8 and 3.9 that this is probably not hazardous. The shortest distance with the outer wheel to outer road marking is similar to that of the inner wheel when the curve turns in the other direction, and also probably similar to the mean extreme lateral position. This merely shows how the driver when the sight distance decreases lowers his speed to keep control. The extreme lateral positions of the wheels are shown in figure 3.8 for curves without clothoids and in figure 3.9 with clothoids. The same graphs but with right and left curves separated are shown in Appendix B. The reader might find it helpful first to look at these graphs. The main effect of sight distance on the extreme lateral position of the wheels on the outside of the curves are in all cases significant (\(F(3;349) = \) in the range of 10 to 48; \(p>0.001\)). All results from the Analysis of Variance are included in Appendix C.

Radius does not in general have a significant effect on the extreme lateral position of the outside wheel in curves. Nor is there any interaction.

When the two radii with and without clothoids are compared, it can be seen that the extreme lateral position of the outer wheel is further out in curves with clothoids, for right curves (\(F(1;353) = 19.6; p> 0.001\)) and for left curves (\(F(1;353) = 9.0; p< 0.005\)). There is no significant interaction with sight distance.
Extreme lateral position for the wheels in curves without clothoids

Figure 3.8 The extreme lateral position of the outside wheel in curves without clothoids at the condition free choice of speed. The centre line of the road is 0 m lateral position and 3.5 m is outer edge of right edge line. There is one line for each radius. The lines with squares are right curves and the lines without are left curves. (Group mean values).

Extreme lateral positions of the wheels in curves with clothoids

Figure 3.9 The extreme lateral position of the wheel in the curves with clothoids at the condition free choice of speed. The centre line of the road is 0 m lateral position and 3.5 m is the outer edge of the right edge line. There is one line for each radius. The lines with squares are right curves and the lines without are left curves. (Group mean values).
3.4.2 Cruise control at 90 km/h

For the condition cruise control also, it is mainly the extreme lateral position of the outside wheel in the curve that is interesting. There is a tendency at longer sight distances for the extreme lateral position of the outer wheel to occur further into the curve. It is probable that the driver is “cutting” the curve or allowing himself to “stagger”. This is similar to what happened at the condition free choice of speed.

For the shorter sight distances the situation is the reverse, the extreme lateral position of the outer wheel moves out in the curve. This could be because the driver is "staggering" or "missing" the curve. This tendency is stronger the smaller the radius is.

The interaction between sight distance and radius is, for all extreme positions of the outer wheel, significant (F(6;349) = in the range of 2.9 to 4.6; p>0.01). All results from the Analysis of Variance are included in Appendix C. The extreme lateral positions of the wheels are shown in figure 3.10 for curves without clothoids and in figure 3.11 with clothoids. The same curves separated in right and left curves are shown in Appendix B.

**Figure 3.10** The extreme lateral position of the outside wheel in curves at the condition cruise control. These are the right curves with clothoids. The centre line has the lateral position 0 m and outer edge of the right edge line 3.5 m. There is one line for each radius. The ones with squares are right curves and the lines without are left curves. (Group mean values).
The extreme lateral position of the outer wheel is further out in a curve with clothoids (F(1; 353) = 13.0; p < 0.001 for right and F(1; 353) = 6.9; p < 0.001 for left curve). There is no significant interaction with sight distance.

### 3.5 Standard deviation of lateral position

Standard deviation of lateral position gives information about cutting curves or "missing" curves as well as "staggering". The average of the standard deviation of lateral position for the 24 subjects is shown in figure 3.12. By using the average, the standard deviation between subjects is excluded.

The standard deviation at the condition free choice of speed is larger at longer sight distances. Cutting of curves might cause this outcome. At the condition 90 km/h the standard deviation is higher at both very short and very long sight distances. In between it is lower. The higher values at longer sight distances might be because the driver is cutting curves and the higher values at shorter sight distance might be because of both "staggering" and "missing" of curves.
Figure 3.12 Standard deviation of lateral position at both speed conditions. (Group mean values)

3.6 Distance outside road marking

This measure identifies how long distance either the right or the left wheel pair have been outside either road marking. The results show that the driver drives outside the road markings to a larger extent when the speed is set to 90 km/h than at own choice of speed. The average distance outside road marking for the 24 subjects is shown in figures 3.13 and 3.14. It can also be seen that the car is driven for a longer distance outside the centre line than outside the edge line.
At free choice of speed the distance driven outside the centre line increases for longer sight distances. This might be because drivers are cutting the curves or allowing themselves to “stagger”. At 90 km/h the distance is larger at short sight distances. This is true for both centre and edge lines. This might be because the driver is “missing” the curve or “staggering”. The distance outside the line is also longer at 67 than at 45 m. This might be because the driver is cutting the curves or allowing himself to “stagger”, just as for the longer sight distances at the condition free choice of speed.

![Figure 3.14 Distance (m) driven on or outside road marking at 90 km/h. (Group mean values)](image-url)
4 Discussion

This study was carried out to investigate the extent of the driver’s need for visibility of road markings when relying upon the vehicle’s lighting system. The need for visibility was defined in the following way: “The shortest visibility distance or limit of road marking that the driver needs in order to handle the car in a safe and controlled way.” The purpose of this study is neither to find the level of visibility that is most comfortable for driving nor to find the safest level of visibility of road marking.

It is very important to be aware that the data collected in the simulator study are not to be directly generalised to real driving situations. Even though the simulator is advanced, it is not a perfect copy of real driving. Data should therefore be used with caution. But, as discussed in the introduction, this study would have been very difficult if not impossible to carry out as a full-scale experiment on a road or a test track. Some validation studies of the VTI Driving Simulator have been carried out [J. Törnros, L. Harms, and H. Alm. 1997]. In one study, driving behaviour on a country road was compared to driving on a simulated road with identical geometry though without traffic. The speed was found to be similar but the lateral position was further away from the centre on the real road. In a second study the surroundings and other traffic were added to the simulation, resulting in both similar speed and lateral position. In a third study driving behaviour in the same real and simulated tunnel was compared. The results showed that the speed was higher and that drivers positioned themselves somewhat closer to the tunnel wall in the simulator than in the real tunnel.

Another point of discussion is the design of the experiment, with the two test conditions and their validity and what information they supply. The condition free choice of speed is of course closest to real driving. But the result from this condition doesn’t give much information regarding drivers’ need for visibility. It shows that drivers are very good at compensating for poor visibility conditions by lowering speed and reducing their variation in lateral position in the driving lane. Drivers act in this way in order to keep control. The other condition, driving with cruise control set at 90 km/h, is an unrealistic situation but it exposes the limits of driver performance much better. This driving situation is not totally unrealistic, because there is evidence that drivers often do not lower their speed enough in poor visibility conditions, but maintain too high a speed. This may be because of the speed limit or their habit of driving at a certain speed on a specific road. The two experimental conditions expose different aspects of the driver’s need for visibility of the road marking ahead. Combined, they give valuable insights into how good sight conditions have to be for the driver to manage the driving task without problems.

When studying level of speed at the condition free choice of speed, we assume that the driver reduces speed for shorter sight distances to compensate for the more difficult conditions. The results show that the driver does not find it more difficult to drive with 67 m sight distance than with 100 m, because there is no difference in choice of speed. Somewhere between 67 m and 45 m the sight distance starts to affect the driver’s choice of speed. From this it can be concluded that the visibility of road markings on the test route does not need to be greater than 67 m.

It can be seen from speed and the speed difference per radius that the driver reduces speed more at longer sight distances than at short sight distances when approaching a curve with a small radius. At shorter sight distances the driver in general keeps to a lower speed because the preview time to the start of the curve is shorter and
that forces him to do so. This result shows that the driver is good at compensating for poor visibility by choosing a lower speed.

The **lateral position** at the condition free choice of speed shows clearly how the subjects, by adjusting speed, stay in control of the situation and do not "miss" the curves. At the condition 90 km/h it can be seen that the subject starts "missing" the curves at sight distances shorter than somewhere between 30 and 45 m. The lateral position shows that the driver can handle the car when the sight distance is 45 m. It should be noted that this result only is valid for 90 km/h.

The **extreme lateral position** of the wheels at the condition free choice of speed gives the same information as the lateral position. The result shows that the driver is good at adjusting the speed to the sight conditions so the car does not move towards the outer edge of the driving lane in the curves.

In the cruise control condition the extreme lateral position of the car in a curve moves toward the outer edge of the driving lane at short sight distances. At a sight distance of 45 m the car moves toward the inner edge of the driving lane in the curve, but at 30 m sight distance the car moves toward the outer edge. If the extreme lateral positions for right and left curves are compared it can be seen that they cross. This could be a sign that at sight distances lower then the point where the curves in the graph cross the visibility of road markings is below what the driver needs. This happens at a sight distance somewhere between 45 and 30 m exactly where depends on the characteristics of the radius of the curve.

**Standard deviation** of the lateral position at free choice of speed shows that the driver does not have any problems with "staggering" or "missing" the curve when the sight distance decreases. The driver decreases the speed when the sight distance is shorter and at the same time the variation in lateral position decreases. This shows that drivers are good at adjusting speed and lateral position to compensate for bad sight conditions.

At the condition 90 km/h the standard deviation seems to have a minimum somewhere between 30 and 45 m sight distance. The increased standard deviation at longer sight distances than this minimum is probably caused by cutting curves or "staggering" that the driver allows himself because he experiences a large safety margin. The increase of standard deviation at shorter sight distances than the minimum is probably caused by "missing" curves and increased "staggering" and is a sign of driver’s loss of control. These results show that down to the sight distance 45 m the driver has full control at 90 km/h.

The **distance driven outside road marking** gives similar conclusions to the standard deviation of lateral position. The driver seems to be cutting curves to a larger extent at longer sight distances at the condition free choice of speed. At the condition 90 km/h there is probably a minimum in distance driven outside road marking close to 45 m sight distance. This is the case both for centre and edge lines. Distance outside the road marking therefore also indicates that the driver is able to handle a sight distance of 45 m at 90 km/h.

Many of the different results from the condition cruise control indicates that the visibility limit for safe lane keeping and driver behaviour is somewhere between 30 and 45 m. 45 m might seem short but not compared to the **retroreflectivity** conditions on the road at certain times. For a road marking to be visible at 45 m distance on dry pavement about 62 and 155 (mcd/m²)/lux retroreflectivity is needed for high and low beam respectively, for damp pavement about 69 and 89 (mcd/m²)/lux is needed for high and low beam. These values are predicted using a relationship between visibility
distance of road markings and their retroreflectivity determined in a Swedish experimental study. [G Helmers & S-O Lundkvist, 1991] The road markings studied were 0.1 m wide and 3 m long with 9 m gap, which is the common design for centre line in Sweden. At the time of the study the requirements on retroreflectivity were 75 (mcd/m²)/lux in dry conditions [BYA 84]. At present it is 100 (mcd/m²)/lux [VU 94]. For damp road markings there are no requirements.

45 m at 90 km/h equals 1.8 s in preview time. The preview time at the condition free choice of speed become shorter with shorter sight distances but never less than 1.8 s. It is not possible to judge whether the chosen preview time would have been shorter or the same at 20 m sight distance at the condition free choice of speed, but it is clear that the drivers choose preview times as short as 1.8 s and still handle the driving task well.

When setting the lower limit for visibility of the road marking ahead, the aspect of safety is important. The results show not one lower limit, rather a range of sight distances that varies for every driver and situation. The results of this experiment indicate that a safe limit of visibility of road marking for the driver to keep the car in the driving lane is somewhere in the interval 30 - 45 m when driving at a speed of 90 km/h. If one single figure must be chosen the choice should be 45 m. This corresponds to a preview time of 1.8 seconds. Preview time should be used as the measure because this measure is independent of driving speed. For instance when driving at a speed of 120 km/h a preview time of 1.8 s gives a safe preview distance of 60 m.

The driver’s preview time of 1.8 seconds to the visibility limit of road marking ahead should be regarded as the more general measure. It must though be kept in mind that this is a minimum limit. In real driving the driver now and then also must have time to check the rear view mirrors and the instruments on the dashboard. For this reason a short time period should be added to the preview time of 1.8 s. To fix the size of this time period needs a literature review or further research. An additional allowance will also be needed for unexpected incidents, as well as a margin for comfort.
5 Conclusion

Drivers’ need for visibility of the road at night has been studied when the driving task is to keep the car in the driving lane.

Drivers are in general very good at compensating for poor visibility conditions by reducing speed and by restricting the variation in lateral position of the car to keep the car in the driving lane under full control. This is the main interpretation of the results from the condition of drivers’ free choice of speed.

The results of the cruise control condition indicate that there is a minimum preview time for visibility of road markings of about 1.8 s. to keep the car with full control in the driving lane. A short time period should be added to allow the driver to look in his rear view mirrors and to read the instruments on the dashboard.

Any conclusion about safe visibility conditions for detection of unexpected obstacles on the road surface cannot be made from these results.

6 References


Lateral position for each type of curve at the condition free choice of speed. (Sight distance on the x-axis). The centre line is at lateral position 0 m and the right edge of the edge line is at 3.5 m. The radii marked - are left curves. The radii marked C are with clothoid.
Appendix A

Lateral position for each type of curve at the condition 90 km/h. (Sight distance on the x-axis). The centre line is at lateral position 0 m and the right edge of the edge line is at 3.5 m. The radii marked - are left curves. The radii marked C are with clothoid.
Appendix B

Extreme lateral position of the wheels in right curves without clothoid at free choice of speed. The centre line is at lateral position 0 m and the right edge line is at 3.5 m.

Extreme lateral position of the wheels in left curves without clothoid at free choice of speed. The centre line is at the lateral position 0 m and the right edge line is at 3.5 m.
Appendix B

Extreme lateral position of the wheels in right curves with clothoid

![Graph](image)

Extrem lateral position of the wheels in right curve with clothoid at free choice of speed. The centre line is at the lateral position 0 m and the right edge line is at 3.5 m.

Extreme lateral position of the wheels in left curves with clothoid

![Graph](image)

Extreme lateral position of the wheels in left curve with clothoid at free choice of speed. The centre line is at the side position 0 m and the right edge line is at 3.5 m.
Appendix B

**Extreme lateral position of the wheels at right curves without clothoid**

![Graph](image)

*Extreme lateral position of the wheels in right curve without clothoid at 90 km/h. The centre line is at the side position 0 m and the right edge line is at 3.5 m.*

**Extreme lateral position of the wheels in left curves without clothoid**

![Graph](image)

*Extreme lateral position of the wheels in left curve without clothoid at 90 km/h. The centre line is at the side position 0 m and the right edge line is at 3.5 m.*
Appendix B

Extreme lateral position of the wheels in right curve with clothoid at 90 km/h. The centre line is at the side position 0 m and the right edge line is at 3.5 m.

Extreme lateral position of the wheels in left curve with clothoid at 90 km/h. The centre line is at the side position 0 m and the right edge line is at 3.5 m.
Appendix C

Results from Analysis of Variance for extreme lateral position at free choice of speed.

The effect that sight distance (s), radius (r) or the interaction (s x r) have on the extreme lateral position is tested. The boxes for the outside wheel in the curve are tinted. Only effects significant at the 0.05 level are included.

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Results from Analysis of Variance for extreme lateral position at 90 km/h.

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