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A Driving Simulator Study


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Reprint from Technical Report Volume 3, pp 927–938,
Xth PIARC International Winter Road Congress,
16–19 March 1998 in Luleå, Sweden

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Abstract

To optimise road maintenance and operation, road administrators are increasingly using management systems. An important requirement of such systems is the assessment of how different road conditions and measures of maintenance and operation effect road users.

Knowledge of the relationship between road conditions and driver behaviour is often insufficient. Major factors influencing a driver's operation of a vehicle include visual and kinesthetic information about the friction conditions of the road surface. Low friction is an especially obvious problem under winter conditions.

This project attempted to
1. answer the question of whether the simulator environment is sufficiently realistic for experiments with varying road conditions,
and
2. clarify the importance of visual and kinesthetic information for the driver.

The experiment was designed around six scenarios: a road in summer condition, and five in winter conditions with different states of friction.

The results demonstrated that driver behaviour in the simulator was realistic. Regarding speed and lateral position the behaviour was very consistent; there were always significant differences in speed levels between the summer scenario and all of the winter scenarios, and no significant differences between the winter scenarios. There were no significant differences in the lateral positions. The conclusions are that visual information is by far the most important for the choice of speed, and that drivers are very poor at evaluating different friction conditions.
Background

Road networks must be kept in good condition to meet drivers’ needs for safety and trafficability. Pavement should be even and free of ruts, cracks and other damage. To maintain good friction in winter measures against snow and ice must be undertaken. Currently the limited resources available to road administrators means that these goals cannot always be achieved and that priorities must be established: what to do, when, where, and how? To optimise maintenance activities (or at least make good choices) administrators use management systems. These systems require assessing the effects of road conditions and maintenance efforts on road users. Unfortunately, the relationship between road conditions and, for example, driver behaviour is not well known. Improved knowledge in this area would certainly lead to better management of roads through more cost-effective measures to improve safety.

Driving a car is a complex task placing high demands on drivers’ perceptual and cognitive processes. Relationships between environmental variables are entangled, and when a variable cannot be perceived directly it can only be assessed through cues associated with it in some probabilistic way. Social Judgement Theory (e.g., Hammond et al., 1986) may be used to describe this kind of relationship between drivers and the road environment.

Driver behaviour on winter roads is — in contrast to summer conditions — affected by darkness, frost and snow. The main factor influencing a driver's operation of a vehicle is the friction (or lack of it) between the tyres and the road surface. It is unlikely that a direct estimate of the friction can be made; instead the driver uses different cues to obtain an indirect, expected value. Figure 1 presents a so-called lens model of the relationship between friction, cues and driver judgement.

![Figure 1 Lens Model for a Driver's Experience of Low Friction](image)

**Figure 1** Lens Model for a Driver's Experience of Low Friction
Three cues affecting different senses are shown in the figure: a visual cue (white road surface), a kinesthetic cue (the vehicle skids), and an auditory cue (the sound from the tyres is not normal). However, ecologically the relation between each cue and the friction is not perfect, so the probability is less than one. Subjectively drivers are inconsistent or do not fully utilise the cues, so the probability here is also less than one. The compound effect of validity and utilisation produces the achievement: the extent to which the driver makes a correct judgement.

Of course, many other cues – more or less subtle – are involved: weather, weather reports, temperature information, the road conditions the driver perceived while walking to the parking lot, etc. Complete knowledge of the cognitive process even for such a comparatively simple task as estimating friction seems almost impossible to achieve. However, through confined and controlled studies valuable knowledge about driver behaviour in relation to different cues of low friction on winter roads should be attainable.

**Problem**

To measure driver behaviour it is necessary to determine which variables and cues to study, and to what extent the experiment can be controlled. The latter is fundamental.

An experimental study conducted under real traffic conditions would be almost completely uncontrolled. Weather, precipitation, and the presence of other traffic could not be controlled. Road surface conditions could be controlled to some extent through operational measures, but the friction would still vary along the road and there would be no way to track it at all places all the time. Furthermore, comprehensive experimental equipment comprising sensors, computers, etc., would be needed in the car. Even if these problems could be solved it would be necessary to maintain a research group which could be activated on very short notice when the right winter weather conditions occurred.

Safety would be an additional concern. Road administrators must take measures against ice and snow, so the most interesting (and dangerous) road conditions are comparatively infrequent. Exposing drivers and equipment to serious hazards is not acceptable in any case, consequently it is desirable to find an alternative to experimenting under real conditions.

The VTI driving simulator might constitute such an alternative (Nordmark, 1994). In the simulator the experimental situation is as controlled as possible: the road alignment and condition (including friction), other traffic, and the time of the experiment can be freely chosen. Even the most dangerous conditions can safely be simulated. There are problems: the simulated scenery of the road environment is obviously somewhat artificial and stereotypic, and the vehicle movements are restricted.

To this point no simulator experiment has addressed the impact of road surface conditions on driver behaviour. The effect of winter road conditions on speed levels has been measured in several field studies, but only on an aggregate level without detailed consideration of driver behaviour.
Hypothesis

This work is primarily a methodological study intended to answer the crucial question of whether the simulator environment is sufficiently realistic for experiments with varying road conditions.

The hypothesis is that driver behaviour is influenced by visual and kinesthetic cues in the simulated road environment and that this influence can be observed through variables related to driver behaviour. If this hypothesis proves correct, the next question would be whether driver behaviour in the simulator corresponds to driver behaviour on real roads.

Variability in driver behaviour throughout the population is very large, and the same driver does not always behave in the same manner. Road conditions also vary, even under similar weather conditions. Therefore, it will be difficult to establish statistically significant correlations between real and simulated driving. However, comparative studies across real and simulated environments may be valid.

Driver behaviour will be measured in terms of speed, lateral position, steering-wheel action, yaw movements of the vehicle, and lateral acceleration.

Visual information is obviously the most important for driving.\(^1\) It is therefore reasonable to assume that the visual cue will explain the largest part of the variance in driver behaviour.

The Road

The characteristics of the road used in the experiment were taken from a real rural road, no. 621, south-west of Linköping. Its length is eight kilometres and width is seven metres. The posted speed limits on two different sections are 70 and 90 km/h. There are 14 bends with radii less than 600 metres.

A suitable length for the simulated drive was assumed to be 20 kilometres, with a driving time of about 15 minutes. Consequently, the road was lengthened to 10 kilometres by adding an artificial section that included a couple of curves with large radii. The road was then doubled so that the geometry of section S and section S + 10,000 metres were identical. The posted speed was set at 90 km/h for the whole road.

The Simulator

The VTI driving simulator is an advanced simulator that includes moving-base, wide angle (120 degrees) visual, vibration generating, sound, and temperature regulating systems (Nordmark, 1990; Nilsson, 1993). These five subsystems can be controlled to give the impression that the driver is in a real car.

The car body used in the simulator was a SAAB 9000. The driving characteristics of the car in this experiment were like that of a vehicle with rear-wheel drive, however, to facilitate the early onset of skidding conditions.

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\(^1\) Rockwell (1972) and others state that the driving task is based on visual information to the extent of 90%. However, there is no empirical support for this figure (Sivak, 1996).
The Subjects

Given the many variables already present in the experiment, the subjects were chosen from a homogenous group: males, 25 - 40 years of age, possessing a driver’s license for at least five years, and driving at least 10,000 kilometres per year. They also had experience from earlier simulator studies.

Design and Realisation

Although there are several more or less relevant cues relating to perception of road friction, it was desirable to limit the number present in the experiment. To begin this process the cues were restricted to those perceived from within the car. As the driving task is mainly based on visual information, a white road in winter should be a very strong cue. Kinesthetic information is certainly also important, especially during acceleration or deceleration and in negotiating curves. Auditory cues like sloshing mud and skidding tyres give valuable information as well.

These three cues would have been suitable for this experiment. However, the sound system could reproduce only engine and normal road sounds. There was no possibility of simulating sounds related to surface conditions in this study, such as the sloshing of mud or the skidding of tyres, hence the experiment was limited to visual and kinesthetic cues.

Two road environments were created. One was a dry black road, set in summer conditions, and one was a very illusory white road with four greyish black wheel-tracks, set in a winter landscape. The tracks were about 0.70 metres wide, the distance between their centres was 1.80 metres, and the outer edge of the left track ran 0.73 metres from the centre line of the road.

Scenarios

Four initial scenarios were established:

A. A dry summer road with friction coefficient $f = 0.8$.
B. A winter road with summer friction, $f = 0.8$.
C. A winter road with mostly summer friction, $f = 0.8$, but also with fairly slippery sections, $f = 0.25$.
D. A winter road with fairly good winter friction, $f = 0.4$, but with some fairly slippery sections, $f = 0.25$.

The friction value of 0.4 corresponds to slush or loose snow but where the tyres have some contact with the pavement. The value 0.25 represents dry, hard-packed snow. The values were chosen after driving trials in the simulator.

Scenario A was the reference scenario, with perfect driving circumstances. Scenario B tested the significance of the visual cue. Scenario C introduced slippery sections without prior kinesthetic indication of low friction. Scenario D combined slippery sections with normal winter friction which, although good in comparison to the slippery sections, should provide some warning that lower friction could occur. The sections with low friction were situated where interesting driver behaviour was anticipated, and always included curves.

After a preliminary analysis two more scenarios were included:

E. A winter road with fairly good winter friction, $f = 0.4$, on the entire road.
F. A winter road with fairly slippery conditions, $f = 0.25$, on the entire road.
The preliminary analysis indicated no variation in speeds across scenarios B, C, and D, consequently it seemed interesting to examine the effect of homogenous low friction over the entire driving distance.

There was no traffic moving in the same direction as the test driver. Eleven cars were encountered on different parts of the road, mostly at the curves.

**Results**

The results were analysed on two levels: the aggregate to determine if the cues had any impact on mean speed and mean lateral position over the entire 20 kilometre test road, and in detail for some sections of the road to determine if and how behaviour is influenced by friction level, curves, and oncoming traffic.

A preliminary analysis was done after the first four subjects completed their drives. The difference between the mean speeds in scenarios B, C, and D were so small that two additional scenarios, E and F, were devised with the friction coefficient for the whole test road set at 0.4 and 0.25, respectively.

**Aggregate Analysis**

The average speed for each subject in each scenario is shown in Figure 2. There is remarkable consistency in the behaviour of the different drivers. The differences between the winter scenarios are relatively small, indicating that the visual cue is by far the most important. The kinesthetic differences are fully noticeable when driving under different friction conditions, but they seem to be of practically no importance when the results are viewed over the whole route, even for a friction coefficient as low as 0.25.

The mean speeds, mean lateral positions, and standard deviations for each scenario are indicated in Tables 1 and 2. In both Design I and Design II the speeds in scenario A differ significantly from the speeds in the other scenarios. There are no significant differences between the winter scenarios B, C, and D in Design I and between E and F in Design II. There are no significant differences at all between the lateral positions. Yet, there is a tendency to keep closer to the centre of the road during winter conditions. This might be an effect of the visible tracks on the winter roads.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tbody>
<tr>
<td>Speed (km/h)</td>
<td>95.9 ± 2.8</td>
<td>84.8 ± 5.0</td>
<td>84.3 ± 4.0</td>
<td>83.5 ± 3.7</td>
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<tr>
<td>Lateral position (m)</td>
<td>-1.39 ± 0.13</td>
<td>-1.32 ± 0.10</td>
<td>-1.31 ± 0.13</td>
<td>-1.31 ± 0.12</td>
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<table>
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<tr>
<th>Scenario</th>
<th>A</th>
<th>E</th>
<th>F</th>
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<tbody>
<tr>
<td>Speed (km/h)</td>
<td>98.2 ± 8.9</td>
<td>82.0 ± 7.6</td>
<td>81.2 ± 5.6</td>
</tr>
<tr>
<td>Lateral position (m)</td>
<td>-1.35 ± 0.14</td>
<td>-1.31 ± 0.11</td>
<td>-1.31 ± 0.09</td>
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Detailed Analysis

In the detailed analysis driver behaviour on a number of short sections of the road was studied. It was assumed that three factors would have an influence on the driver response variables: first, the visual impact and friction coefficient of the scenario, second, the alignment of the road as a left-hand curve, right-hand curve, or straight section, and third, the presence of oncoming vehicles.

Some general conclusions can be drawn. There is a common tendency for high speed or low friction to be associated with greater yaw angles and steering-wheel activity, and this seems realistic even if significant differences are not always established.

Decreases in speed in the winter scenarios partly compensates for lower friction. Thus, for Design I, the behaviour at scenario A (where $f = 0.8$) is rather similar to that at scenario D (where $f = 0.4$). The behaviour at scenario B (in which the friction is
high and speed is low), differs from all the other scenarios, except for those parts of C where \( f = 0.8 \). On the other hand, behaviour where C and D both have \( f = 0.25 \) is very similar.

This suggests that the behaviour in scenarios A and E in Design II should be similar. In these cases there are greater speed differences between summer and winter conditions so the behaviour at scenarios A, E, and F differ more. However, the distinctions are always consistent relative to speed and friction.

An interesting point is that the variance of steering-wheel angle is larger the lower the friction. Steering-wheel activity is evidently more pronounced in low friction conditions.

Driving behaviour seems to be very consistent when friction conditions are constant. Unequal friction conditions, on the other hand, produce significant differences in steering-wheel and yaw variables. Oncoming vehicles produced no significant impact on lateral position.

**Other Studies**

A complete study of the validity of the experiment must include the driving pattern on an aggregate as well as a detailed level. To this point detailed validity studies have been impossible, but on the aggregate level comparisons can be made to Swedish and Finnish field studies.

In two VTI bulletins Öberg (1994) and Wallman (1997) have measured and compiled car speeds under different road conditions. For roads 7 metres wide with a typical posted speed of 90 km/h, average speeds are 85 to 95 km/h on dry, bare roads. Speeds are reduced in winter conditions with ice or hard snow on the road surface, typically by 6 to 10 km/h. There are large deviations from these characteristic values: average speed reductions up to 16 km/h have been recorded, and "ice or hard snow" is not a very rigorous measure of the road condition.

A couple of reports from the Finnish National Road Administration contain very interesting results. Heinijoki (1994) examined the extent to which drivers take slipperiness into consideration in winter through driver interviews and measurements of car speeds. Road slipperiness was measured and divided into four categories: good grip \( (f > 0.45) \), fairly good grip \( (0.35 < f \leq 0.45) \), fairly slippery \( (0.25 < f \leq 0.35) \), and slippery \( (f \leq 0.25) \). The drivers were asked to evaluate the slipperiness on the same scale. Generally, the drivers were poor at evaluating the actual road conditions. Less than 30% of the evaluations coincided with the measured values, and more than 27% differed by 2-3 categories. The more slippery the conditions the more evaluations differed from reality, consequently the slipperiness of the road did not have any appreciable effect on driving speed.

Saastamoinen (1993) found that driving speed declined mostly as a function of wintry weather or reduced speed limits. Road conditions were significant, then, only in the case of snowy weather. Compared with good driving conditions, speed decreased by 0–3 km/h when the grip was only fairly good (see above), 3–6 km/h under fairly slippery conditions, and 4–7 km/h under slippery conditions. The speed did not change to any appreciable extent when the conditions changed from fairly slippery to slippery.
Conclusions and Discussion

The crucial question formulated above was "Is the simulated environment realistic enough that a driver acts in the same way as under real circumstances?" Within the limitations of this project there is strong evidence that the answer is yes. The aggregate speed values do match the results from field studies described in the previous section, and there is strong agreement on speed reductions during winter conditions. The reductions seem to be closely related to visual impact; the prevailing friction values seem to have a very small effect on the drivers' speed in both simulated and real driving.

The speed levels in the simulator are somewhat higher than for real conditions. This effect has also been noticed in other studies, e.g. (Alm, 1995).

In a detailed analysis the different friction levels are reflected in driver variables such that the combined effect of speed and friction give credible changes in lateral position, steering-wheel and yaw indicators. Even for subtle modifications in the simulated driving environment such as decreasing the friction coefficient from 0.8 to 0.4 or from 0.4 to 0.25, there are consistent and credible shifts in the driving pattern. The subjects also seem to take the experiments very seriously; the inhibitions against colliding with oncoming vehicles or driving off the road seem to be almost as strong as in reality.

It is very easy to be carried away by this seemingly true behaviour, but one has to bear in mind that the simulation experiment is only realistic, not real! Consequently, the validity of the experiment has yet to be determined on the detailed level. Moreover, while the driving simulator was not intended to simulate adverse conditions or reckless driving, it may be interesting to examine its capabilities concerning those matters.

Are there any alternatives to simulation for performing a study like this? In this study, experiments under real traffic conditions were excluded because of control and safety reasons. Such studies should nevertheless be undertaken in the future to calibrate and validate the results of the simulation.

Some reflections on the subjects' choice of speed levels are appropriate. When driving on dry summer roads the speed level is probably chosen on the basis of legality and comfort rather than safety. The utilised friction is usually much lower than what is available.

In winter conditions speeds decrease because safety considerations become much more relevant. However, it is evident that the prevailing level of friction has little to do with the choice of speed, at least for the friction interval in this study. The adaptation of speed to low friction levels is very poor. This probably reflects the fact that even for a comparably low friction coefficient such as 0.25, the handling of the vehicle is not very aggravated during normal driving. One may be startled by a sudden event like skidding in a sharp curve and momentarily decrease speed, but apparently there are no persisting effects on driving behaviour.

The conclusion: friction has to be so low that normal manoeuvrability is restricted to effect the chosen speed level. Subjectively experienced, this behaviour also seems to be present in real traffic.

A brief example may provide additional perspective. If the speed on a summer road is selected to maintain a "safe braking distance", in the experiment this distance would be about 45 metres. On a winter road this value implies that the average
subject adapt to a coefficient of friction of about 0.6 with respect to the decreased speed. Such a high friction value is not very likely for a typical white winter road.

It should be noted that there is more than one way for drivers to deal with poor road conditions: they can also get more attentive. This may partially explain the poor speed adaptation to different friction levels, for instead of decreasing their speed drivers may be increasing their attention.

Future Research

This experiment indicates that car drivers adapt their speed very poorly to slippery road surface conditions, at least down to a friction coefficient of 0.25, a result supported by earlier field studies. A natural continuation of the research would be to perform the same experiment with lower coefficients of friction to find out where the choice of speed really starts to become affected and how it changes in response to successively lower friction.

Additional future studies could include whether a driver’s attention increases with decreasing friction levels, the significance of lateral variations in the friction level across the road, the importance of auditory cues, and variation in vehicle characteristics, e.g. ABS brakes. Also, through the acquisition of a car with proper experimental equipment it is now possible to make validation studies at VTI on the level of detailed driver behaviour.

References


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Statens väg- och transportforskningsinstitut (VTI) har kompetens och laboratorier för kvalificerade
forskningsuppdrag inom transporter och samhällsekonomi, trafiksäkerhet, fordon, miljö samt för byggnade,
drift och underhåll av vägar och järnvägar.

The Swedish National Road and Transport Research Institute (VTI) 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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