How Speed Affects The Way Visual Information Is Used In Steering

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A driving simulator was used to model a winding road in which only narrow (1° vertically) segments of road edge were visible to the driver. It was found that with only one such region visible steering performance at slow speeds was as good as with the whole road visible, if the visible region was 7-8° down from the horizon. At higher speed, however, this was not true, and two regions of road were necessary for performance as good as with the whole road. The far region, 2-4° down, supplied information about road curvature, and the second region 7-8° down provided feedback about the position of the vehicle in lane. These findings strongly support a two-component model of steering first proposed by Donges (1978), and argue against driver models that employ a single 'preview' distance.

1. INTRODUCTION

We can steer a car in two ways. We can look into the distance, and judge from the way the road curves how to match this curvature by turning the steering wheel. If this match is accurate, then lane position will also be maintained. Alternatively, we can maintain our position-in-lane directly by looking at the near part of the road, and adjusting our position accordingly. Or we can adopt some combination of these strategies as suggested, for example by Donges (1978).

The first strategy requires that we obtain from vision a measure of the road's impending curvature. One way to do this would be to look at a point on the car's intended track a distance \( D \) ahead, and determine the size of the angle (\( \theta \)) between the present line of travel and the eye's gaze direction (Fig. 1a). Road curvature is then directly proportional to \( \sin \theta \), or to \( \theta \) if the angles are small. If we are strapped in, so that body direction and car direction are the same, \( \theta \) will be the sum of the eye/head angle and head/body angle, and both of these are 'known' to the brain. As Fig. 1a shows, this gaze angle increases as \( D \) increases, so that larger and hence better measurements are obtained from more distant points on the road (not too distant however, or the curvature will no longer be that of the relevant part of the bend). The position-in-lane strategy, however, has different requirements. If we look towards the kerb, our distance from it can again be judged from the angle of gaze relative to the direction of travel (Fig. 1b), but in this case the angle \( \theta \) decreases as \( D \) increases, implying a loss of precision. At the same time the measurement becomes corrupted by the curvature of the bend (Fig. 1b). Thus we should view the far road for curvature, and the near road for position-in-lane information.
In this paper we ask what strategy drivers actually use, and how this varies with speed. The method involves simulated drives in which only parts of the edges of the road are displayed, so that the drivers' visual information is restricted to small (1° vertically) segments at different apparent distances. The main conclusions are: First, that certain parts of the road give much better information than others, and that at low to moderate speeds the 'best' 1° segment can permit driving that is as accurate as when the whole (10°) view is available. Second, that there are profound differences between the way that 'far road' and 'near road' information is handled, and that at moderate to high speeds both regions are essential for accurate steering.

![Diagrams](image)

\[
curvature = \frac{1}{R} = \frac{2 \sin \theta}{D} \quad d = D \sin \theta
\]

Figure 1. Possible ways that a driver may estimate road curvature (a) and position in lane (b). In both cases the driver must estimate the angle (\(\alpha\)) between the vehicle's current heading (heavy arrow) and a suitable road feature. In a) this is a point on the vehicle's future track, and b) it is the kerb. An estimate of the distance \(D\) is also needed, but this could be obtained from the angle down from the horizon (\(\alpha\) in Fig. 2). The driver is shown in the middle of the road for simplicity, and the diagrams are not to scale. Note that in a) \(\alpha\) increases with \(D\), but in b) \(\alpha\) increases as \(D\) decreases.

2. METHODS

We used a driving simulator based on a program developed on an Archimedes A5000 RISC computer. This provided a perspective view of the moving edges (white on black, as in night driving) of a single lane, 3m wide road with many bends, modelled on a real road used in a previous study of drivers' gaze direction (Land & Lee, 1994). There was no other scenery. The view extended for 63m and was viewed from a height of 1.1m. It was updated at 7Hz and was presented on a 60cm wide screen at 80cm, providing a view with the same angular dimensions as the original road. The display was driven by a steering wheel monitored by a 'mouse'. The integration constants converting wheel angle to car direction and car direction to lateral road position were chosen to give as realistic a performance as possible, and drivers found it easy to negotiate the road successfully. After an initial few drives, accuracy changed
little. The measure of difficulty chosen to assess different experimental conditions was the reciprocal of the s.d. of the car's position relative to the road's centre line, measured over the whole drive (68s at 16.9 m.s\(^{-1}\), or 38mph). At normal speeds this s.d. was 0.1 - 0.2m.

The road was either viewed in its entirety, or else only one or more 1° high segments were visible, positioned in 9 locations between 1 and 10° below the horizon (Fig. 2). These segments moved exactly as they would in the full road.

Figure 2. Typical driver performance with only 1° segments of simulated road visible. Upper trace in each record gives curvature of both road and vehicle track, with the difference between them showing in black. Lower record gives vehicle position relative to centre-line of road. In A and B curvature matching is precise and almost smooth, but in C it is jerky, indicating instability. In B and to a lesser extent C position-in-lane is well maintained, but in A it is very poor. Subject ML, speed 16.9 m.s\(^{-1}\). From Land & Horwood (1995).
3. RESULTS

3.1 Steering performance with a single 1° road segment

Fig. 2 shows 3 typical examples of driver performance at 16.9 m.s\(^{-1}\). When only the distant part of the road was visible (A), the curvature was smoothly matched (upper traces), but the position-in-lane was not well maintained. With only the near region (C) steering was difficult and jerky. This was presumably because the short available response time (<0.4s) forced the driver to change from a smooth to a 'bang-bang' feedback strategy. However, position-in-lane was quite well maintained, compared with (A). With middle distance segments (B) both curvature and position were dealt with reasonably well, and this region gave the best driving performance.

The lane-keeping performance at different speeds, with only one segment present, is shown in Fig. 3 (●). At 16.9 m.s\(^{-1}\), which is a fast but not reckless speed for this road, Fig. 3b shows that there is an optimum position for the visible segment 5.5° down from the vanishing point, i.e. at 11.4 m or 0.68s ahead. However, the accuracy was only about 80% of that of drives made when the whole road was visible (dotted line). At the higher speed of 19.7 m.s\(^{-1}\) that percentage decreased to about 55% (Fig. 3c), but at low speeds (<12.5 m.s\(^{-1}\)), the accuracy with the optimum 1° segment was similar to or even better that the performance with the whole road visible (Fig. 3a). The implication is that at low speeds only a small visible part of the near road is needed for fully competent steering. Only a tenth or so of the whole flow-field needs to be visible. However, at higher speeds this is not true. The 'best' part of the road does not supply all the information needed, and so something else is involved.

3.2 Performance with two 1° segments

At the higher speeds a better performance was achieved when two road segments were available, above and below the single-segment optimum (Fig.3b & c, open symbols). The second road segment improved accuracy dramatically, depending on where it was positioned. With one visible region in the distant part of the road, a second region enhanced accuracy if it lay in the near region (O), and vice versa (□).

Looking at Fig. 3b we see that driving with a single distant segment 1.5° down from the horizon only permits an accuracy of 30%, and a near segment 9.5° down permits 60% accuracy, but when the two are combined, the accuracy rises to 90%. This enhancement of performance only occurs if the two road segments are in different parts of the road. This is shown by the fact that there is no difference between the ● and O graphs in the distant region between 1.5° and 4.5° down, or between the ● and □ graphs in the near region 6.5° to 9.5° down. Similarly, merely doubling the amount of road edge in the central region near the single-segment optimum at 5.5° had no enhancing effect. However, when both near and far segments are visible, steering accuracy rises to the same level as when the whole road is visible (e.g. O at 7° down). It appears that two 1° segments, properly selected, can provide the same information as the whole road. The whole flow-field is clearly not required (see Lee & Lishman, 1977; Warren et al., 1991).

At the higher speed of 19.7 m.s\(^{-1}\) (Fig. 3c) the enhancement effect is even more dramatic, so that accuracies of barely 50% for single segments in the near and far regions of the road (●) are again increased to match the performance with the whole road visible. At lower speeds, however, (12.5 m.s\(^{-1}\), Fig. 3a) the situation is different. The presence of an extra segment in the far part of the road (O) has little effect, and the graph is essentially identical to the
Figure 3. Accuracy of driving with single (●) and paired (O, □) 1° segments of road visible at different angular locations (α, Fig. 2), for three different speeds. Rectangles on the inserts indicate which fixed and variable (arrows) regions of road-edge were visible. Open circles show that adding a single distant segment enhances performance (except a), but only when the other visible segment is in the lower half of the field. Squares show that a near segment enhances performance only when the other segment is in the upper field of view. In both these situations accuracy is similar to having the whole road visible (dotted line). The differences between single and paired regions (in b where the s.e.'s are shown) are highly significant (p<0.001, t-test). Accuracy ratio is s.d. of the vehicle's track from the centre line with whole road visible at each speed, divided by s.d. with one or two segments visible at the selected speed. Abscissa angle is shown on Fig. 1. Points are means from 3 (a,c) or 5 (b) drives by each of 3 drivers (ML, 53y; JH, 36y; AM, 42y). Curves are fitted 4th-order polynomials.
performance with a single segment (●). However, when the extra segment was in the near region (□), the enhancement effect remained very substantial. The probable reason for this is that at slow speeds it is possible to drive entirely by using feedback from the lane edges, indeed this is what one does when driving in fog. However, as one speeds up this feedback becomes increasingly unstable (as in Fig. 2C), and is only usable if the curvature of the road has at least been approximated using information from the more distant part of the road. The improvement resulting from the curvature estimate is shown by the fact that the presence of a distant region greatly decreases the 'spikiness' of driving, even when the accuracy is not increased as in Fig. 3a (Land & Horwood, 1995).

A consequence of the two-segment result is that the apparent optima seen with one segment (●) are not really optima but compromises. In Fig. 3b, particularly, it is clear that the maximum at 5.5° is less accurate than either of the two-segment conditions at the same declination (α). Presumably what is happening is that this region provides some curvature and some position-in-lane information, but not quite enough of either.

4. CONCLUSIONS

The two-segment experiment strongly suggests that there is not one part of the road that is involved in steering, but two. A 'far-road' mechanism is concerned with curvature matching, and a 'near-road' mechanism is responsible for maintaining position in lane. These mechanisms can be identified with the peaks in the open symbol graphs in Fig. 3. Thus at 16.9 ms⁻¹ the far-road mechanism has an optimum about 4° below the horizon, which corresponds to 0.93s or 15.7m ahead. The near-road mechanism has an optimum 7.5° down, i.e. 0.49s or 8.3m ahead (Fig. 4).

![Curvature vs Position Graph](image)

Figure 4. The principal conclusions of this study are that at 16.9 ms⁻¹, the best curvature information is supplied by the segment of road 4.5° down from the horizon, and the best position-in-lane information by a segment about 7° down (see Fig. 3b). Drivers typically fixate the upper region, and simultaneously view the lower region with peripheral vision.

At moderate to fast speeds drivers actually look at the far part of the road, and view the near road edges with peripheral vision 5° or so from the fovea. The evidence for this comes from eye-movement recordings made during drives with the simulator (Land & Horwood,
1995) where it was found that the mean vertical location of the direction of gaze was about 4°
down from the horizon, coinciding with the far-road peak in Fig. 3b (1). In real drives, Land &
Lee (1994) found that drivers also viewed the more distant part of the road. Interestingly, they
did not look at a point on the future track of the vehicle, as implied by Fig. 1a, but at the'tangent-points' on the inside of the bends. These too can provide a means of obtaining road
curvature (Raviv & Herman (1993). On a road with the curvatures used here the tangent
points lie in the region 2-4° down from the horizon, which again is consistent with the far-
road mechanism proposed here. As Fig. 3 shows, the optimum of the far-road mechanism
becomes more distant (closer to the horizon) as speed increases. Interestingly, this implies that
the time that drivers look ahead is almost constant at about 0.9s, independent of speed (see
also Land, 1996). This is not inconsistent with the use of tangent points for judging curvature,
as these are visible over a range of distances, depending on the particular point on the bend;
faster drivers will simply use them at an earlier stage.

(Donges (1978) originally proposed a two-stage model of driver behaviour which involved
anticipatory feed-forward from the road some distance ahead, and feedback information of
three kinds, one of which concerned position-in-lane. This seems to fit very well with the
results described here. It seems likely that the far- and near-road mechanisms uncovered here
correspond to Donges' feed-forward and position feedback components. The far-road
mechanism is certainly an open-loop system in that on its own it provides very little feedback
about lane position, hence the poor performance when only this region is visible (D, Fig. 3).
The near-road mechanism on the other hand clearly involves closed-loop feedback, which is
why it becomes unstable at higher speeds. At lower speeds Fig. 3a indicates that the feedback
system is accurate on its own. The beauty of the double system seems to be that it is both fast
and forgiving. By getting the path of the vehicle almost right without feedback, the far-road
mechanism takes most of the load off the intrinsically slower but more accurate near-road
mechanism, whose function is then only to 'fine-tune' the system.

ACKNOWLEDGMENT

We are grateful to the Biotechnology and Biological Sciences Research Council of the UK
for financial support.

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