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**POST-MOUNTED DELINEATORS
AND PERCEPTUAL CUES FOR
LONG-RANGE GUIDANCE
DURING NIGHT DRIVING**

Josef Schumann

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16. Abstract <p>In order to perform the steering task for lane keeping, drivers rely on both short-range and long-range guidance cues. However, at night, because of reduced visibility, drivers have to rely primarily on short-range guidance. Consequently, improvements to long-range guidance at night should improve nighttime driving performance. Previous research showed that retroreflective lane markings, while assisting in short-range guidance, do not provide long-range guidance. On the other hand, there is some evidence that post-mounted delineators can provide valuable long-range information concerning the road ahead. This evidence (briefly reviewed in this report) comes from information-processing and driver-steering models, as well as from some limited, prior, empirical studies.</p> <p>Frequency analysis of steering performance is a possible approach for obtaining information about the effects of post-mounted delineators on driving at night. An exploratory field study was performed using this approach. The results indicate that adding post-mounted delineators to regular lane markings tended to decrease compensatory steering actions. Consequently, these results suggest that a combination of lane markings and post-mounted delineators might be optimal for night guidance, with lane markings assisting in short-range guidance and post-mounted delineators assisting in long-range guidance.</p>					
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INTRODUCTION

In a recent review of the literature on the effects of lane markings in night driving, Rumar and Marsh (1998) refer to the concept of two complementary road guidance functions—long-range and short-range guidance—that are employed by drivers to support the task of steering. Long-range guidance enables the driver to predict the path of the road ahead and to anticipate necessary steering actions, while short-range guidance is needed for compensatory steering actions to keep the vehicle properly positioned in the lane. Although this two-stage steering model is generally accepted for daytime driving, there is less evidence that drivers use the same steering strategy during night driving. On the contrary, past research showed that at night drivers have to rely on a different steering strategy because of reduced visibility of the road ahead. Specifically, it has been argued that under night driving conditions drivers mainly have to rely on short-range guidance, because long-range guidance is usually unavailable. Any efforts to support long-range guidance at night, either through improved vehicle lighting or through improved road markings, should therefore support drivers' steering behavior and thus possibly improve safety during night driving. This report deals with the effects of post-mounted delineators—a type of road markings—on long-range visual guidance at night by examining driver steering behavior.

REVIEW OF RELEVANT LITERATURE

There is extensive research on increasing the visibility distance of retroreflective markings on the road through the use of improved retroreflective materials. In a recent review of the relevant literature, Rumar and Marsh (1998) reported that the resulting preview times provided by lane markings are well under a safety criterion of 5 seconds. Therefore, they concluded that current lane markings alone are not optimal for safe night driving. (In comparison, a recent joint project by the European Community (COST, 1999) indicated a desirable absolute minimum preview time for visibility of lane markings of about 1.8 seconds.)

While lane markings assist short-range guidance, they probably have little or no effect on long-range guidance at night. This is the case because the visibility distances required to provide long-range guidance cannot be achieved at night by lane markings, especially during adverse weather conditions. One way of extending the distances at which visual information about the road ahead is available is through the use post-mounted delineators (PMDs). The limited available empirical evidence suggests that PMDs could, indeed, be helpful for long-range guidance at night (Good and Baxter, 1985; Triggs and Fildes, 1986).

There is considerable evidence in the literature that the steering task during daytime driving is based on two parallel mechanisms:

- Preview of the road ahead (long-range control).
- Continuous compensatory tracking of the lane in front of the vehicle (short-range control).

Although tracking of the lane close to the vehicle is performed by the driver continuously, with the experienced driver picking up the necessary information mainly peripherally through visual cues of the lane boundaries, the driver also previews the road by frequent eye fixations near the road expansion point.

In the following, I will discuss the evidence for two types of steering. Specifically, I will discuss perceptual information that the driver uses as input for steering, and how the steering response is influenced by different types of information. Next, the main previous findings on the effects of lane markings on the nighttime visibility of the road will be summarized. Finally, a possible approach to evaluating the effects of lane markings on driver steering at night will be presented.

Perceptual cues for steering

Analyses of driver eye-fixation patterns indicate that during daytime, driver eye fixations are more frequent to the far field than to the road edges (e.g., Serafin, 1994). However, Mortimer and Jorgeson (1974) showed that at night this pattern changes. Specifically, at night drivers tend to fixate at shorter distances because of the reduced visibility.

Eye-fixation patterns of experienced drivers at night tend to resemble those of inexperienced drivers during the daytime. Mourant and Rockwell (1970, 1972) found that there is a qualitative shift with increased driving experience:

- Inexperienced drivers perform compensatory steering actions that rely primarily on visual input close to the vehicle.
- Experienced drivers also use preview information about the road ahead to structure their steering behavior.

With increasing driving experience, eye fixations tend to shift to farther away from the vehicle. Experienced drivers spend more time fixating the focus of expansion and use peripheral visual information for lane keeping. For example, Summala (1998) showed that experienced drivers were better able to keep the car in the lane than novice drivers when they were forced to do a simultaneous, foveal, in-vehicle task. A likely explanation for this finding is that because of their improved lane-keeping skills, experienced drivers can focus their attention at a greater distance ahead of the vehicle. This change of focus allows drivers to better anticipate and control the steering task, and to improve hazard control and management of potential critical driving situations.

Land and Horwood (1998) distinguished two different visual search regions during daytime driving:

- A distant region, which requires foveal vision and is used for preview.
- A near region, which can be utilized foveally and peripherally and is used for position-in-lane feedback.

Riemersma (1981) identified changes in heading angle and lateral position as the main visual cues for course control during straight-road driving. Drivers can perceive changes of these visual cues through the information in the optical flow field. However, they are much less sensitive to changes in heading angle, especially under reduced visibility, such as at night. Therefore, drivers in such situations rely primarily on information about changes in lateral position close to the vehicle for their steering task.

Driver steering models

Driver steering models divide the steering control task into two components: control of lateral position and control of heading angle. When there is sufficient roadway preview and good roadway visibility, experienced drivers take advantage of preview information to structure their steering control task. In control terms, this structure consists of an outer loop operating on lateral position and an inner loop operating on heading angle, where the modification in the control of the heading angle is used to control lateral position (Baxter and Harrison, 1979; McRuer, Allen, Weir, and Klein, 1977; Smiley, Reid, and Fraser, 1980).

While these steering control models are based on the assumption that drivers act like an error-correcting mechanism with continuous attention allocated to the steering task, Godthelp, Milgram, and Blaauw (1984) demonstrated that drivers temporarily switch to a fixed steering strategy when it is necessary to allocate their attention to different driving tasks. Godthelp et al. (1984) introduced the time-to-line-crossing (TLC) concept for this fixed steering strategy, which can be calculated based on the lateral lane position, heading angle, and vehicle speed. TLC represents the time necessary for the vehicle to reach either edge of the lane, assuming a fixed steering strategy. If TLC falls below a driver-specific value (e.g., a necessary minimum time to react), or if the driver leaves a field of safe travel (Gibson and Crooks, 1938), the driver has to allocate attention to the steering task again to compensate for lane deviations.

Donges (1978) suggests a similar steering model with the following two levels:

- A guidance level, involving the perception of the future road course and a response to it as an anticipatory open-loop control mode.
- A stabilization level, where deviations from the path are compensated in a closed-loop control mode.

The better the anticipatory steering, which is provided by a good preview of the road ahead and by clear visibility conditions, the less compensatory steering the driver has to do. This allows the driver to allocate more attention to other driving tasks.

All these driver steering models rely on the concept of preview, and the lack of sufficient preview is one reason that the driving task is more difficult at night. With decreasing preview, the perceptible heading angle diminishes, and thus the driver has to rely primarily on the lateral position for the steering task (Baxter and Harrison, 1979). Interestingly, a steering strategy based on control for lateral position error is also found in

novice drivers (Smiley et al., 1980). As learning progresses, the shift of eye fixations farther ahead of the vehicle allows the driver to better use the heading angle as a visual cue for the steering task, but also enables the driver to better monitor the environment.

Driver steering models reveal the dependence of steering behavior on specific visual cues that were already identified in eye-movement studies (Hildreth, Beusmans, Boer, and Royden, 2000). The most critical variable for steering is preview of the road ahead, allowing anticipatory steering. With reduced preview, as is the case at night, the driver has to rely on visual lateral position cues closer to the vehicle. In such situations, the driver has to allocate more attention to the steering task, and the attention is directed closer to the vehicle. According to Sayed and Lim (1999), the driver's visual attention is influenced by two mechanisms: internal and external focusing. The internal focusing mechanism is proactive, orienting the driver's head and eyes to gather relevant information for the current task. The external focusing mechanism is reactive, and it is based on various characteristics (such as conspicuity) of objects in the visual field. According to this model, improvements of the nighttime preview distance should extend the internal focusing farther away from the vehicle and allow better external focusing in that extended area, making the steering task easier and thus making driving safer.

Nighttime visibility of post-mounted delineators

Post-mounted delineators (PMDs) are normally spaced at equal distances along the side of the road, supplementing continuous lane marking. PMDs are designed to provide additional visual cues about the road alignment. Because they are mounted at a substantial vertical elevation above the ground, their primary function is to provide better long-range guidance at night.

In the U.S., the design guidelines call for retroreflector units that are capable of retroreflecting light under normal conditions from a distance as far as 300 m (1,000 ft) under high beam illumination (MUTCD, 1988, 2000). These guidelines clearly allow PMDs to be used to support long-range guidance. However, it must still be demonstrated whether drivers use these additional cues for their steering control task. Surprisingly, only limited research has been undertaken thus far to evaluate the effects of PMDs on the steering control task at night.

Good and Baxter (1985) analyzed the effects of different road-marking conditions on compensatory steering behavior (relying primarily on short-range information) and on

subjective ratings of the ease of forward planning (conceptually closely related to the quality of long-range guidance). The results showed, as expected, that there was an improvement of the compensatory steering behavior when lane markings were present. No improvement in the compensatory steering behavior was found when lane markings were supplemented with PMDs. However, these results could have been expected because Good and Baxter's analysis was performed only on compensatory steering, without including preview steering. On the other hand, the addition of PMDs had a positive effect on subjective ratings of the ease of forward planning. Therefore, these results support the assumption that PMDs are useful for long-range guidance, but have no effect on short-range guidance.

Triggs and Fildes (1986) offered further evidence of the long-range guidance information provided by PMDs. In an experiment to evaluate driver performance near rural road curves, Triggs and Fildes (1986) found that the addition of PMDs to lane markings was beneficial by providing long-range information about the direction of curves before entering them. Curve-negotiation prior to the curve entrance has been identified by Donges (1978) as an important anticipatory steering control behavior, which relies on long-range guidance information.

Although the above reported studies showed positive effects of PMDs on long-range guidance, Kallberg (1993) draws a pessimistic conclusion concerning PMDs. In this study, twenty pairs of similar rural road sections were selected in Finland. PMDs were installed on half of these roads. The results showed an increase in speed and an increase in the accident rate on roads with PMDs. The increased speed indicates that drivers use the PMDs as long-range guidance support. However, the increased accident risk due to the increased speed appears to offset any advantage of the PMDs. Although road authorities must take this increased accident risk seriously in their decision of whether to install PMDs on rural roads, a closer look at Kallberg's accident data reveals a possibility of a very different interpretation. Kallberg attempts to explain the increased accident rate with the theory of selective visual degradation (e.g., Owens and Andre, 1996). According to this theory, the visual system consists of two parallel modes that are affected very differently by reduced illumination at night. The ambient mode, which is used by drivers primarily for peripheral perception close to the vehicle, degrades much less than the focal mode, which the driver needs in order to detect obstacles on the road. At night, drivers feel confident because they are still able to perform the lane-keeping task rather well. However, the deficiencies of focal vision become apparent only if there is an obstacle on the road, which

the driver then detects too late. (Late detection is considered the main driving error at night [Rumar, 1990].)

Kallberg claims that PMDs support the ambient mode and therefore increase the driver's comfort for lane keeping at night. However, a different interpretation is possible. If PMDs support long-range guidance, this support could enable the driver to direct attention farther away from the vehicle and thus reduce the accident risk for objects on the road. The accident data cited by Kallberg (1993) even show some evidence that this might have been the case, because pedestrian and bicycle data show a *decrease* in the accident rate with PMDs. However, because these accident types are rare, they have only a minor influence on the overall accident rate. If, on the other hand, Kallberg's claim about a support of the ambient mode due to PMDs is true, there should be a decrease in single-vehicle accidents. However, this claim is not supported by his accident data, which show an increase in single-vehicle accidents.

Consistent with Kallberg's findings, Steyvers and De Waard (2000) also found that driving speed increased on roads with lane markings compared to control roads. Steyvers and De Waard (2000) explained this increased speed in terms of behavioral adaptation, which is always a concern when introducing extra safety measures in driving. According to Wilde's risk-homeostasis theory (one version of behavioral adaptation), drivers tend to compensate for traffic safety improvements by faster or less cautious driving to maintain a constant level of risk. The possibility of risk homeostasis has created considerable controversy (see e.g., Ranney, 1994).

In a recent literature review, COST (2000) concluded that increased visibility of lane markings has a net positive effect on preview times, despite increased speed. Specifically, COST (2000) concluded that although drivers consumed some of the benefits of more visible lane markings by driving faster, they did not increase their speed enough to eliminate all benefits of the increased visibility.

Information from drivers' steering movements

One way of gaining better insight into the possible effect of PMDs on long-range guidance is through an analysis of drivers' steering behavior. Analyses of the steering behavior in the frequency domain suggest that two frequency bands characterize driving steering behavior (McLean and Hoffmann, 1971):

- A peak in the frequency band between 0.1 to 0.2 Hz corresponds to preview steering.
- A peak in the frequency band between 0.3 to 0.6 Hz corresponds to compensatory steering.

Blaauw (1984) analyzed steering data by calculating the proportion of the steering energy in the higher frequency band (0.3 to 0.6 Hz). The results of these analyses suggest that there is a shift to higher frequencies as a result of higher task-demands for lateral control (e.g., with narrow lanes, at high speeds, and with restricted preview). Analogously, McLean and Hoffmann (1973) demonstrated that the proportion of compensatory steering increased with reduced preview during daytime driving.

These studies suggest that the analysis of drivers' steering output could be used to make inferences concerning the visual input drivers use for steering actions at night. Specifically, it is predicted that steering data based on a strategy that has to rely only on lane markings should result in more steering activity in the higher frequency band, as compared to steering data based on a strategy that can use long-range guidance provided by additional PMDs.

To test this possibility, an exploratory study was performed to obtain insight about the feasibility of this approach. The data were collected on a straight road section only. There were two reasons for this restriction:

- A peak around 0.1 Hz could be masked by steering control movements necessary to follow a curve (McLean and Hoffmann, 1971).
- Curve steering behavior relies mainly on a compensatory steering strategy based on short-range guidance (Donges, 1978).

It should also be kept in mind that the proportions in the higher-frequency band represent control effort rather than an absolute measure of steering accuracy (Macdonald and Hoffmann, 1980).

Finally, it is difficult to directly compare nighttime and daytime steering data. A richer visual environment on rural roads during the daytime might lead to a switch of attention from the steering task to other driving tasks (e.g., looking for something in the environment). Such an attention switch would lead to a very low steering effort and could not be compared to a situation where the driver's attention is exclusively on the steering task (Macdonald and Hoffmann, 1980).

EXPLORATORY FIELD STUDY

Method

Task. The subject's task was to drive on a rural road at night in an instrumented test vehicle with low-beam headlights on. The UMTRI Driver Interface Research Vehicle was used as the test vehicle, allowing the recording of steering data and speed (Katz, Green, and Fleming, 1995). Subjects were told that driving data would be collected during the test drive.

Experimental conditions. Two different road-marking conditions were tested: lane markings, and lane markings plus PMDs. The lane markings were on the outer edges of the roadway. They were 10-cm wide, continuous, and painted white. (The roadway also contained standard, yellow, 10-cm wide center lines.)

Twenty PMDs were placed at the right side of the road, 0.6 m to the right of the roadway edge, spaced at 60 m from each other. The PMDs were equipped with two 7.6-cm-wide retroreflective bands made of encapsulated lens sheeting, separated by 5.7 cm. The bands were mounted on 91-cm-high round posts, with the top of the higher band 86 cm above the ground.

Ambient conditions. Each experimental session commenced at least one hour after sunset. At the test site, there was no street lighting and no other traffic was present during data collection.

Experimental setup. The study was conducted on a two-lane rural roadway north of Ann Arbor (in Northfield Township). The total length of the test route was 2.4 km. Data were collected on a straight section of road. Although the road was not completely level, the preview distance provided by the PMDs that were not obscured by the roadway exceeded 5 second at all times. The data of primary interest consists of about 35 seconds of steering data, sampled at 30 Hz, beginning when the test vehicle passed the second PMD. (A total of 1024 data points were analyzed per subject). After the subjects passed the data collection section, they drove 8 km back to the beginning of the test route by using connecting roads (not the test route in reverse). The last five PMDs were past the point on the road at which the data sampling was complete, so that the driver would have a long preview throughout the data sample (a minimum of about 300 m, within the guidelines of MUTCD, 1988, 2000).

Data analysis. To analyze the driver's steering behavior in the frequency domain during the 35-second test section, spectral density functions were computed for each subject by using a direct Fast-Fourier Transform (FFT). Spectral resolution was 0.03 Hz. The spectra were studied in detail by analyzing the proportion of activity in two specific frequency bands (Band I and Band II, see Table 1). The limits of these bands were chosen in accordance with the recommendations by Blaauw (1984). The critical proportion was defined as follows:

$$(\text{Activity in Band II/Combined Activity in Bands I and II}) \times 100$$

Under normal driving conditions with no extra tasks, this calculated steering proportion can be interpreted as steering effort, with higher values representing higher steering effort (Blaauw, 1984).

Table 1
The limits of the two frequency bands for the analysis of the driver's steering control movements.

Band	Frequency (Hz)
Band I	0 - 0.3
Band II	0.3 - 0.6

Subjects. Four male licensed drivers participated. They ranged in age from 35 to 53 years old, with a mean of 42.

Design. The subjects were tested individually in sessions lasting about 75 minutes each. The subjects drove the test vehicle 11 km to the test site to get acquainted with the experimental car. At the test site, they drove the test road section three times, the first two times with PMDs. After the subjects completed the second trial, the PMDs were removed. Because this was an exploratory study, the order of the two treatment conditions (lane markings vs. lane markings with PMDs) was not counterbalanced. However, pilot tests showed that there was an order effect, mostly evident in comparing the first and second run through the route. Therefore, the condition with PMDs was driven twice by each subject.

Procedure. Two experimenters ran the experiment. One experimenter was seated in the back of the test vehicle to control the data recording. The other experimenter waited at the end of the test road to monitor oncoming traffic. If the road was clear, he informed the first experimenter via radio that the test run could be started.

The subject was instructed to drive as normally as possible and not to exceed the posted speed limit of 72 km/h (45 mph). The subject was instructed to use only low-beam headlamps during the experiment. There was no additional explanation with regard to lane markings or PMDs.

Results and Discussion

The main results are presented in Figures 1 and 2. Figure 1 shows the steering effort for all four subjects under the different driving conditions, while Figure 2 shows the average speed.

As expected, the subjects showed reduced steering effort during the second trial, which can be attributed to learning. After removing the PMDs, the steering effort did not decrease further for three subjects (Subjects 1, 2, and 3). On the contrary, there appears to be an increase in steering effort for these three subjects. This increase in steering effort can be attributed to the decreased preview available when only the lane markings were present (McLean and Hoffmann, 1973). These trends are consistent with the hypothesis that PMDs can be used as long-range guidance to assist steering.

While the data of three subjects showed that a frequency analysis of the steering behavior could be promising in identifying the use of long-range guidance at night, the data of Subject 4 do not support this hypothesis. Contrary to the expectation, Subject 4 showed a *decrease* in steering effort even during the third trial, during which only the lane markings were present. Discussion with Subject 4 after the data analysis suggested a possible explanation for his discrepant steering behavior. Subject 4 was very concerned about possible encounters with deer during the experiment, as he had already stated during the experiment. With more experience because of the repeated exposure to the experimental route, the subject may have switched some of his attention away from the relatively easy steering task and devoted attention to the road environment and possible deer crossing. Switching attention from the steering task to other driving tasks has been identified with reduced steering effort (Macdonald and Hoffmann, 1980). This could explain the subject's very low steering effort during the third trial.

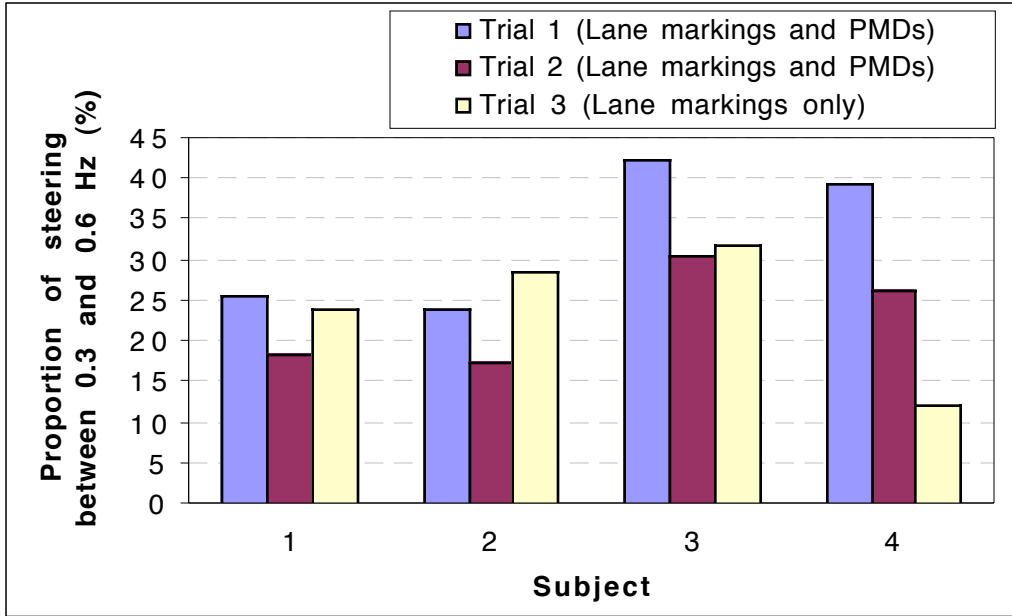


Figure 1. Steering performance in each of the three consecutive driving conditions.

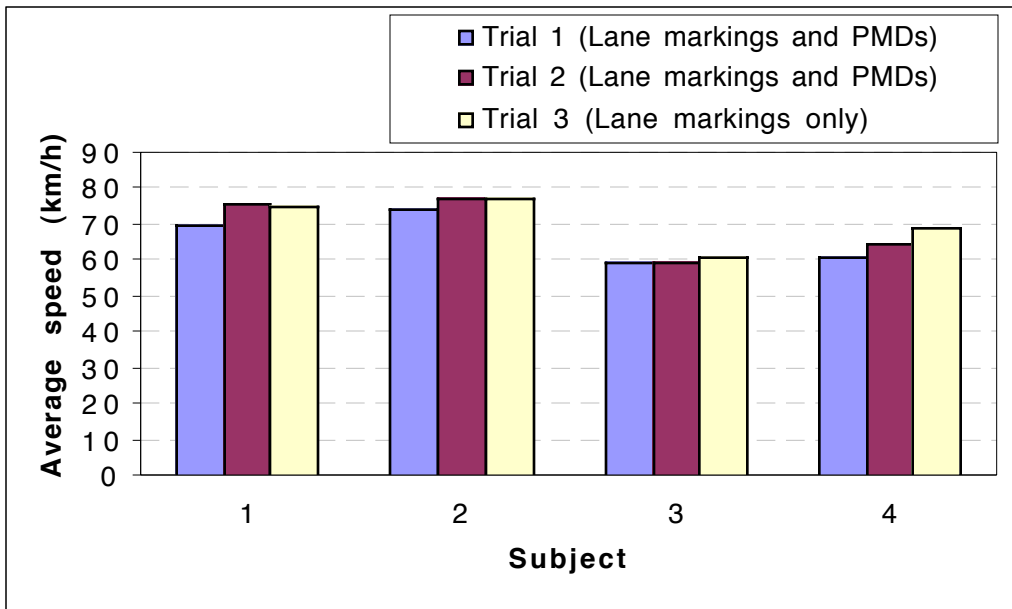


Figure 2. Average speed in each of the three consecutive driving conditions.

The average speed driven on this road section further supports this assumption (see Figure 2). After the expected speed increase from the first to the second trial, the first two subjects did not exhibit further speed increase from the second to the third trial, and the increase in the speed for the third subject was only minor. This is consistent with the notion that the driving task became more difficult for these three subjects after the PMDs were removed. The average speed data of Subject 4 show a somewhat different pattern. Subject 4 increased his average speed even between the second and third trial, indicating that he felt more comfortable about the road section as the experiment progressed, possibly allowing him to switch attention away from the steering task.

The results of this exploratory study suggest that steering output is a promising method for studying long-range guidance provided by post-mounted delineators. However, using repeated trials on the same road sections is problematic because an effect of experience cannot be ruled out. Therefore, different, but comparable road sections should be used in future studies to test the influence of different road marking configurations on steering behavior.

CONCLUSIONS AND IMPLICATIONS

There is some empirical evidence from prior research that PMDs are used by drivers to support long-range guidance at night (Good and Baxter, 1985; Triggs and Fildes, 1986; Kallberg, 1993). The results of this exploratory study, using frequency analysis of steering behavior, also support that claim. The present findings are consistent with information-processing and visual-search models. PMDs provide long-range guidance cues, and at the same time can enlarge the driver's field of attention farther away from the vehicle. Such an attentional shift might be especially helpful on dark rural roads, where visual search is often not top-down (i.e., not guided by drivers' expectations) but rather bottom-up (i.e., guided by conspicuous stimuli).

In order to be usable for long-range guidance, PMDs should be visible at a preview time of at least 5 seconds (about 140 m at 100 km/h) under low-beam illumination. PMDs should be used in combination with lane markings, which provide suitable short-range guidance.

The issue of spacing between PMDs was not addressed in this study, but is of theoretical and practical interest. Very close spacing of PMDs in curves is likely to be unnecessary, because drivers mainly rely on short-range guidance from lane markings for their lateral control task in curves (Donges, 1978).

In summary, analyzing steering data in the frequency domain could prove valuable in obtaining information about the use of PMDs for long-range guidance. However, more extensive data are needed to explore this promising possibility.

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