A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF AUTOMOBILE PATH DEVIATIONS WHEN DRIVER STEERS WITH NO VISUAL INPUT

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Theoretical and experimental investigations were conducted of automobile path deviations when a driver is attempting to steer his vehicle along a straight path with his vision occluded. A three-factor (car, subject, speed), two-level field experiment was carried out to test for main and interaction effects. Another field experiment was carried out to determine the effects of no steering control. In both experiments, the vehicle path deviations from the theoretical straight path were measured over several hundred feet and were used as the dependent variable. Both experiments were conducted on a flat airport runway under daylight and no-wind conditions. The experimental results indicate no significant car or subject effects but a highly significant speed effect and a significant car-subject interaction. Specifically, the standard deviations of the vehicle displacements from the theoretical straight path are considerably smaller at the higher speed for a given distance traveled under occluded vision. Further, the standard deviations of vehicle displacements for a given distance traveled are considerably larger for the no steering control condition than for the steering control condition with no visual input. The experimentally obtained data seem in basic agreement with the theoretical path deviation model. Based on the experimental data, the distribution of vehicle displacements for a given distance traveled under no visual input could be reasonably approximated by a normal distribution.

•AN UNCERTAINTY MODEL in which the driver is treated as an information processing device has been developed (4, 5). The analyses were based on steady-state driving in which the driver's vision was intermittently occluded, and on the assumption that a driver's uncertainty between two consecutive looks stems from (a) the loss of relevant road information ahead of him because he forgot or it became obsolete and (b) his uncertainty about the vehicle's lateral position on the road because of random disturbances in the orientation of the vehicle. This study, discussed in more detail elsewhere (1), deals only with vehicle position uncertainty and demonstrates that the functional relationship as derived (4, 5) cannot be supported by experimental evidence. A new functional relationship that is in better agreement with the experimental data is developed in this study. Theoretical studies dealing with driver steering control have been conducted by a number of authors (6) and are the background for the theoretical development of the new functional relationship.

THEORETICAL DEVELOPMENT

Review

As pointed out, this study deals only with lateral vehicle position uncertainty, which was derived (4, 5) as

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$$U_n(T) \propto V^2 \times T^{3/2} \tag{1}$$

where

$U_n(T)$ = uncertainty about the lateral position of the vehicle due to disturbances in the orientation of the vehicle for an occlusion time T in bits per second,
V = vehicle velocity in miles per second (km/s), and
T = occlusion time in seconds.

In developing Eq. 1, the researchers (4, 5) assumed that the uncertainty about the lateral position of the vehicle was proportional to the expected value of the root mean square displacement of the vehicle from the centerline of the lane, at time T. Hence, Eq. 1 can be rewritten as

$$\sigma_y \propto V^2 \times T^{3/2} \tag{2}$$

where σ_y = standard deviation of vehicle displacement from the centerline of the lane in inches (cm).

Therefore, point σ_y, rather than $U_n(T)$, will be used in this study. The functional relationship given by Eq. 2 implies that, for a given speed, σ_y increases with an increase in T. This agrees with what is observed in practice. To point out a further consequence of this functional relationship, we will compute the σ_y corresponding to the same distance of travel under occlusion and make comparisons at a low speed of 11 mph (18 km/h) and a high speed of 46 mph (74 km/h). To aid this comparison, we rewrite Eq. 2 as an equality.

$$\sigma_y = k \times D^2/T^{1/2} \tag{3}$$

where

D = distance traveled in feet (meters) at a constant velocity V during the occlusion time T,
V = D/T, and
k = a constant of proportionality that has been arbitrarily set at 0.0004 (0.011) to match an experimental estimate of standard deviation for 46 mph (74 km/h) at 210 feet (64 m).

Figure 1 shows the theoretically computed standard deviations of the lateral vehicle path displacements for the low speed and high speed obtained from Eq. 3 as a function of the distance traveled under occlusion. Figure 1 shows that, if a driver travels 200 feet (61 m) under occlusion at a constant speed, σ_y will be less for a low speed than for a high speed; i.e., the vehicle path variation will be greater at higher speeds than at lower speeds for the same distance traveled. This result clearly does not agree with the experimental evidence presented in this study.

Development of a New Functional Relationship

Let the position and orientation of the vehicle at time t seconds after the time occlusion started be as shown in Figure 2. It is assumed that the difference between the path angle and the heading angle on a straight road is negligible. Let y(t) be the lateral displacement of the vehicle after t seconds of occlusion. Then $\dot{y}(t)$ is the lateral velocity. Let V be the constant velocity and $\theta(t)$ be the heading angle of the vehicle with respect to the theoretical straight path. The lateral component of V can be expressed as $V \times \sin\theta(t)$. For small angles of $\theta(t)$, $\sin\theta(t) \simeq \theta(t)$. Hence,

$$\dot{y}(t) = V \times \theta(t) \tag{4}$$

$$\ddot{y}(t) = V \times \dot{\theta}(t) \tag{5}$$

The theory of driver steering control has been studied extensively by Weir and McRuer (6), who suggest three types of controls: heading angle, path angle, and lateral deviation. With visual feedback, lateral deviation control is the poorest of all. But during occlusion, when information on the path angle and heading angle does not exist, the lateral deviation model explains the possible steering control behavior of the drivers. In the lateral deviation control two types of information input exist. One is the actual deviation that the driver sees and the second is the lateral acceleration that he feels. For the situation considered here, the first type of input does not exist, and the lateral path change (2) is the double integral of the yaw velocity (rate of change of heading angle) response with an added minor effect, which is the integral of the side-slip velocity due to side-slip angle. If the difference between the path angle and the heading angle is considered negligible, then the lateral acceleration is assumed to be directly proportional to the rate of change of heading angle. Thus in the following theoretical development we will assume that the rate of change of heading angle is the only input for the driver-vehicle system and is characterized by Eq. 5. It should be noted that this assumption is very different from the assumption made by others (4, 5) that the rate of change of heading angle is related to the distance traveled, i.e., $\overline{\partial\theta/\partial x(t)}$. Based on the literature the assumption made in this study seems to be more reasonable and justifiable. From Eq. 5 it follows that

$$y(t) = V \times \int_t \left\{ \int_t \dot{\theta}(t)\, dt \right\} dt \tag{6}$$

Figure 3a shows the combined driver-vehicle system having $\dot{\theta}(t)$ as the input and y(t) as the output. The system is assumed to be linear in that the system function operates on the input to give the output in the frequency domain. The system basically consists of two integrators (Fig. 3b). The system function is given by

$$H(s) = \frac{V(1 - e^{-sT})^2}{s^2} \tag{7}$$

To develop the model for y(t), we make certain assumptions about $\dot{\theta}(t)$ and y(t). $\dot{\theta}(t)$ is assumed to be a continuous Gaussian random process with the properties of ergodicity and white noise. The Gaussian assumption implies that $\dot{\theta}(t)$ has a normal distribution with mean zero and some variance. The white noise assumption implies that the process $\dot{\theta}(t)$ has a constant spectral density over the entire frequency range (Fig. 4a). It is also assumed that the system is sensitive to frequencies in the range of 0 to w_1 rad/sec only and that beyond this range the spectral density is zero. Within the range 0 to w_1, the spectral density G_{θ} is constant (Fig. 4b). The ergodic assumption states that the time average of $\dot{\theta}(t)$ is equal to its ensemble average. The output y(t) is assumed to be normally distributed with zero mean and some variance and also to have ergodic properties.

By definition the power density spectrum of y(t) denoted by G_y is equal to the product of the power density spectrum of $\dot{\theta}(t)$ and the square of the magnitude of the system function.

$$G_y = G_{\theta} \left| H(jw) \right|^2 \tag{8}$$

By the property of conjugate complex numbers,

$$\left| H(jw) \right|^2 = \frac{V^2}{W^2}(1 - e^{-JWT})^2 \times (1 - e^{+JWT})^2$$

Figure 1. Theoretically computed standard deviations of the vehicle path displacements when driver's vision is occluded.

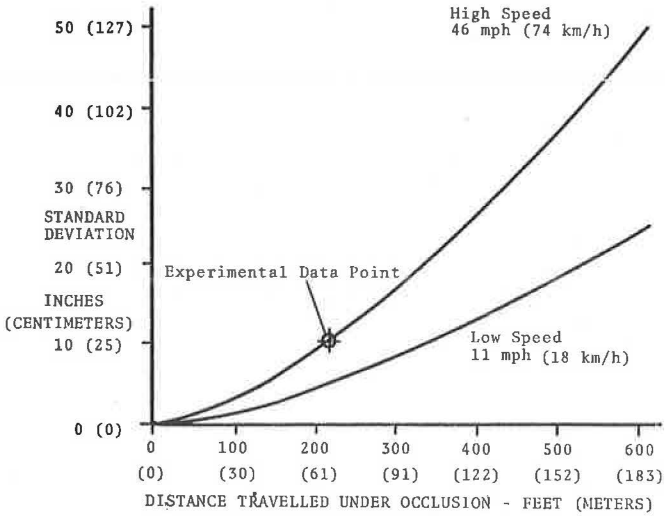


Figure 2. Vehicle position and heading angle after t seconds of occlusion.

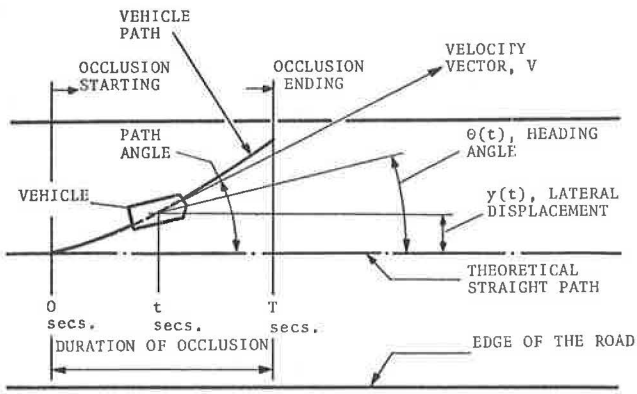
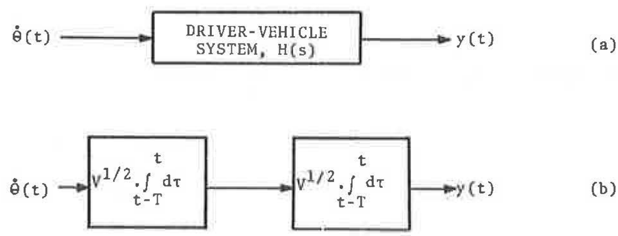
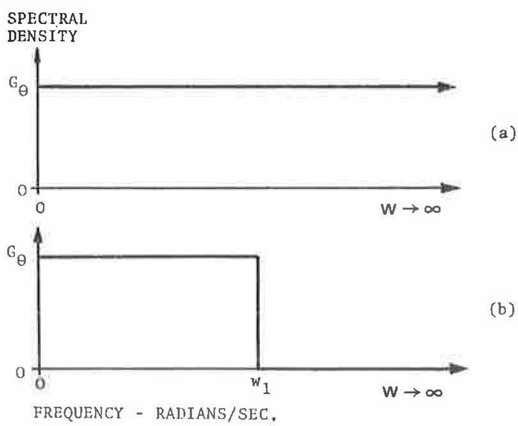


Figure 3. Combined driver-vehicle system.



Note: $\int_{t-T}^{t} d\tau = u(t) - u(t-T); \mathcal{L}\{u(t)-u(t-T)\} = \frac{1}{s} - \frac{e^{-sT}}{s}$

Figure 4. Spectral density of $\dot{\theta}(t)$.



Therefore,

$$G_y = G_\theta \frac{V^2}{w^4} (6 - 8 \cos wT + 2 \cos 2wT)$$

$$= \frac{4G_\theta V^2}{w^4} (1 - \cos wT)^2 \tag{9}$$

The average power of y(t), denoted by $\overline{y^2(t)}$, is the integral of G_y over the entire frequency range in rad/sec.

$$\overline{y^2(t)} = 4V^2 G_\theta \int_0^{w_1} \frac{(1 - \cos wT)^2}{w^4} dw \tag{10}$$

Substituting $w = (z/T)$ in Eq. 10 and extending the upper limit of the integral to infinity give the average power as

$$\overline{y^2(t)} = 4V^2 G_\theta \int_0^{\infty} \frac{(1 - \cos z)^2 \times T^4}{z^4 T} dz$$

$$= 4V^2 T^3 G_\theta \int_0^{\infty} \frac{(1 - \cos z)^2}{z^4} dz \tag{11}$$

The integral in Eq. 11 is a constant. Hence,

$$\overline{y^2(t)} = kV^2T^3 \tag{12}$$

where k is a constant of proportionality. Because y(t) is assumed to ergodic, its time average of the second moment should be equal to its ensemble average of the second moment. Therefore,

$$\overline{y^2(t)} = E(y_T^2)$$

$$= E\left[(y - \bar{y})^2\right] \text{since } \bar{y} = 0$$

$$= \left[\sigma_{y_T}\right]^2 \tag{13}$$

Therefore, Eq. 12 can be written as

$$\left[\sigma_{y_T}\right]^2 = kV^2T^3 \tag{14}$$

$$\sigma_{y_T} = kVT^{3/2} \tag{15}$$

where k is a constant of proportionality. Because V is constant it can be substituted by D/T where D is the distance traveled during T. Thus

$$\sigma_{y_T} = kDT^{1/2} \tag{16}$$

Equation 16 represents the new functional relationship describing the behavior of the driver-vehicle system under conditions of no visual input. Figure 5 shows the implications of the new functional relationship for the same speeds used in Figure 1. The value of k in Eq. 16 was arbitrarily set at 0.025 (0.683) to match an experimental estimated standard deviation for 46 mph (74 km/h) at 210 feet (64 m). The new theoretical functional relationship leads to the following conclusions:

1. The standard deviation for the lateral vehicle displacements increases as the occlusion time increases, and
2. For the same distance traveled, the standard deviation will be smaller at a high speed than at a low speed.

Although the first conclusion is in agreement with the results from the previous functional relationship, the second is opposite. This can be observed by comparing the reversed locations of the two curves in Figures 5 and 1.

EXPERIMENTAL INVESTIGATION

The experimental investigation had two major objectives. First, the effect of vehicle speed on the standard deviation of lateral vehicle displacements was investigated for different travel distances under steering with no visual input to compare the predicted standard deviations with the previous functional relationship and with the functional relationship derived in this study. Second, an experimental investigation was also needed to determine whether the driver exercised any steering control while steering without visual input and whether the lateral vehicle displacements at different travel distances under steering with no visual input could be assumed to come from normally distributed populations.

Subjects

The subjects were 23-year-old graduate students who had driven approximately 20,000 miles (32 000 km). Both subjects had no physical handicaps, participated in the experiment voluntarily, and were not paid.

Experimental Arrangement and Procedure

The experiments were conducted on a concrete airport runway. The two cars used were a 1965 Volkswagen two-door sedan and a 1971 AMC Ambassador. To determine the vehicle path on the runway, we attached a marking device at the center of the rear bumper of the vehicles. It was a cylindrical device filled with a colored liquid that was released by a spring-operated valve at the nozzle. When the vehicle was in motion, the experimenter inside the car operated the valve by means of a cable. The deviation of this liquid trace from the centerline of the runway was measured at intervals of 15 feet (accuracy of $\pm\frac{1}{2}$ inch or 1 cm).

Basically the first experiment was a two-level, three-factor (car, subject, speed) factorial design with four replications and complete randomization of the eight observations in each replication. The car factor was qualitative and fixed, whereas the subject factor was qualitative and random. The speed was quantitative and fixed at 10 and 40 mph (16 and 64 km/h).

The first experiment consisted of 32 runs, all in the same direction, on the same day, during daylight, and with relatively no wind conditions. During each run the subject drove the car at a specified speed and oriented the car centerline as closely as possible to the runway centerline. On reaching a reference cross line, the experimenter instructed the subject to close his eyes and continue steering as straight as possible along the centerline of the runway. The run was terminated either because of too large a deviation toward the edge of the runway or after a distance of 500 feet (152 m). A stopwatch with 0.01-minute accuracy was used to measure the occlusion period.

The second experiment was carried out with one subject only and the AMC car. A total of 60 runs were made at a speed of 30 mph (48 km/h). Of the 60 runs, 47 were with steering control and no visual input and 13 were with no steering control. The experimental arrangement and equipment and the procedure for conducting the experiment and measuring the vehicle path deviations were basically the same as those used in the first experiment except that, when the subject had no steering control, he was not asked to close his eyes. Instead, he was asked to take his hands off the steering wheel until the run was completed.

Figure 5. Theoretically computed standard deviations of the vehicle path displacements when driver's vision is occluded based on the new functional relationship.

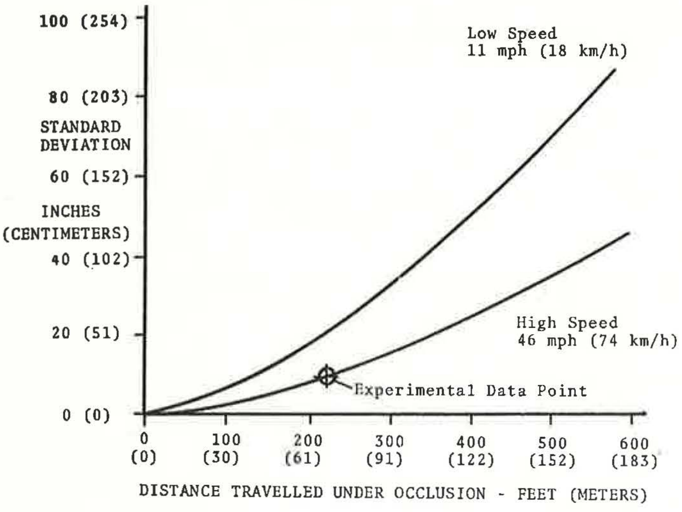
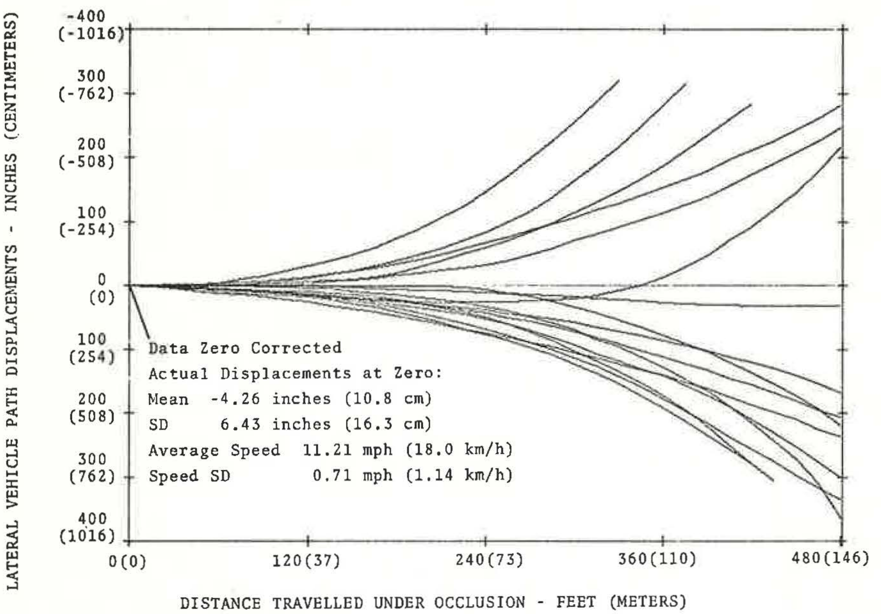


Figure 6. Vehicle paths of low-speed runs in experiment 1.



RESULTS

The vehicle paths for the two speed conditions in experiment 1 are shown in Figures 6 and 7. These data were zero corrected; i.e., the vehicle's lateral deviation from the centerline at the start of each occlusion run was subtracted from the measurements made at 15-foot (4.6-m) intervals. A cursory examination of Figures 6 and 7 reveals that the pattern of the vehicle paths is considerably wider at the low speed than at the high speed.

We used the zero-corrected vehicle path deviations to perform full-model analyses of variance of all 32 occlusion runs at 15-foot (4.6-m) intervals from 15 to 330 feet (4.6 to 101 m). These analyses showed that the car-speed and subject-speed interactions were not significant, and hence a revised model, without these two interactions, was formulated. Based on the ANOVA the speed effect was significant ($p < 0.05$) for all distances investigated beyond 75 feet (22.8 m). Further, the car-subject interaction was not insignificant. Hence, the standard deviations of vehicle displacements were computed from the zero-corrected path deviations for each 15-foot (4.6-m) interval for each of the car-subject-speed combinations. Figure 8 shows these standard deviations of the vehicle displacements as a function of the occlusion distance. The curves plotted in Figure 8 show that, for each car-subject combination, the standard deviation of the vehicle displacements is greater for the low-speed condition than for the high-speed condition. Hence the previously made observation from Figures 6 and 7 about the vehicle path patterns for the two instructed speeds is confirmed. Further, a comparison of Figures 5 and 8 shows that the functional relationships of the theoretical and the experimental curves are very similar.

The average speed for each of the 32 occlusion runs was computed by dividing the distance traveled by the corresponding time. These speeds were from 0 to 12 percent higher than the instructed speeds, and the relative speed variation, or the coefficient of variation, was between 6 and 8 percent within each speed-subject combination.

The vehicle path measurements for each 15-foot (4.6-m) interval from the second experiment were again zero corrected and also angle corrected; i.e., the heading angle of the vehicle at the start of occlusion was determined and used as the theoretical straight line. The standard deviations of vehicle displacements as a function of the distance traveled for zero- and angle-corrected path deviations for the no steering and the no visual input conditions are shown in Figure 9. The standard deviations for the angle-corrected data are somewhat smaller than for the zero-corrected data. However, the standard deviations for the no steering conditions are larger with both corrections than with the no visual input condition. The variances of the vehicle path displacements for the no steering and the steering with no visual input conditions were used to form F-ratios at every 15-foot (4.6-m) interval. For distances greater than 100 feet (30.5 m), these F-ratios were significant at the 0.01 level indicating that the variability in the path deviations with the two conditions is different.

The zero- and angle-corrected path deviations from the 47 runs with steering and no visual input were tested for normality at 15-foot (4.6-m) intervals beginning at the start of occlusion. Kolmogorov-Smirnov tests indicated that, for the investigated occlusion distance range of 0 to 450 feet (137 m), the observed maximum absolute differences for both zero- and angle-corrected path deviations were in most cases well below the allowable difference value of 0.21 for a sample size of 47 and a 0.05 significance level. The absolute differences were somewhat smaller for the angle-corrected path deviation data. These results indicate that the lateral vehicle displacements along the occlusion path can be reasonably assumed to come from normally distributed populations.

CONCLUSIONS

A new functional relationship describing the behavior of the driver-vehicle system under conditions of steering with no visual input was developed. According to this new relationship, the standard deviation for the vehicle path displacements at a given distance will be smaller at a high speed than a low speed at the same distance, which is opposite to what the functional relationship derived previously (4, 5) suggests. The results of the new functional relationship are well supported by the results of the first experiment.

Figure 7. Vehicle paths of high-speed runs in experiment 1.

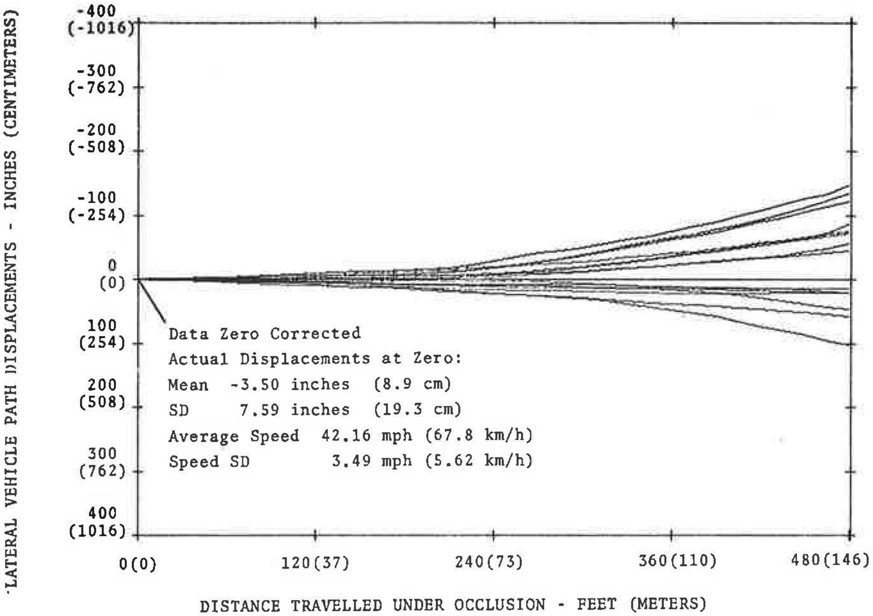


Figure 8. Standard deviations of vehicle displacements as a function of the occlusion distance for zero-corrected data for all car-subject-speed combinations.

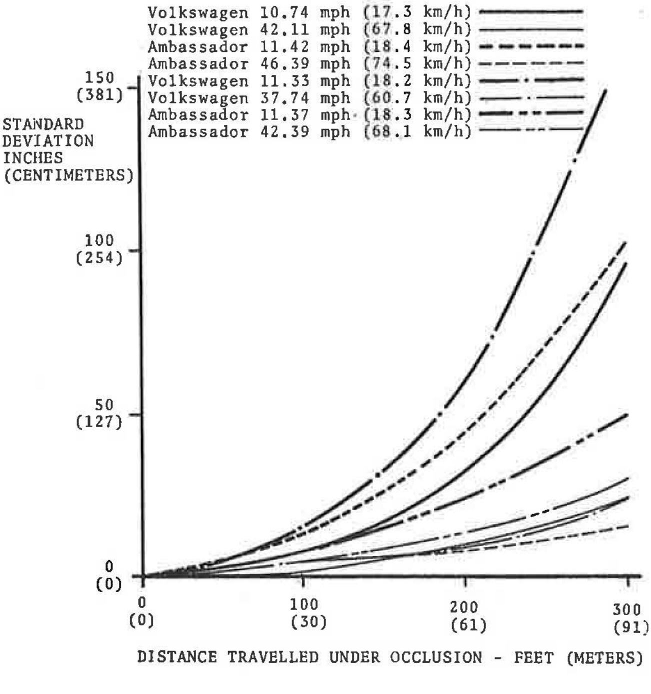


Figure 9. Standard deviations of vehicle displacements as a function of the occlusion distance for zero- and angle-corrected data for the no steering and steering with no visual input conditions.

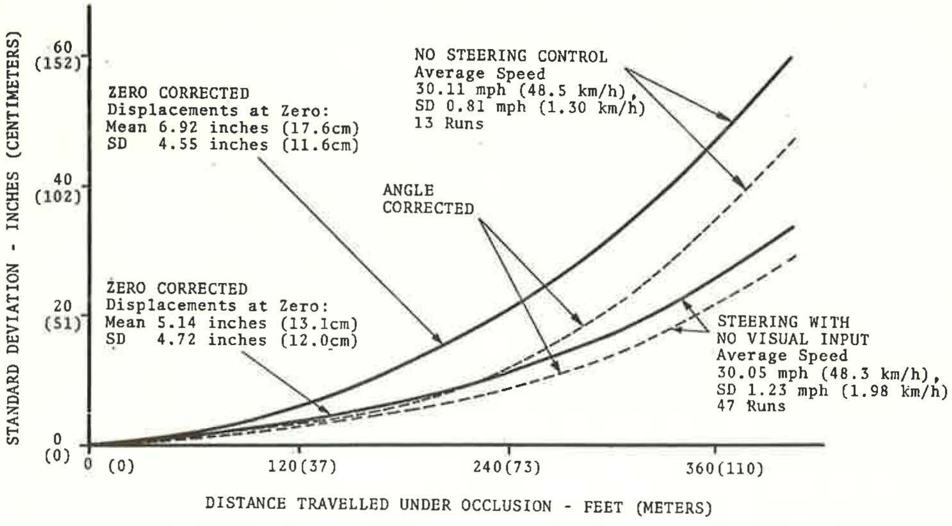
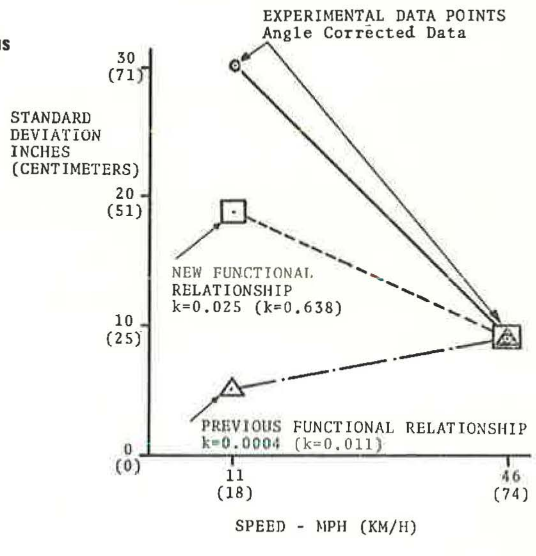


Figure 10. Standard deviation of vehicle path displacements at 210 feet (64 m) versus speed based on the two functional relationships and experimental data.



Analysis of the data in experiment 1 indicated that vehicle speed has a significant effect on the vehicle path displacements when the driver steers during occlusion. For any distance traveled the path variability about the intended straight path as indicated by the standard deviation of the lateral vehicle path displacements was significantly higher at the low speed than at the higher speed. Figure 10 shows the standard deviations at 210 feet (64 m) based on both functional relationships and on the angle-corrected data of the Ambassador driven at low and high speeds in experiment 1. The constants of proportionality used in both functional relationships were arbitrarily fixed so that the standard deviations obtained were equal to the standard deviation for one subject driving at the high speed. The new functional relationship shown in Figure 10 depicts the behavior of the driver-vehicle system under steering with no visual input much better. Another important result obtained by the analyses of variance of experiment 1 data is the relatively large effect of the car-subject interaction. Figure 8 showed that for each car-subject combination the standard deviation was always smaller for the higher speed than for the low speed; therefore, the speed effect conclusion is not affected.

What cues does the driver respond to when steering with no visual input, and why is there better lateral control at higher speeds than at lower speeds at a given distance traveled? In the first part of this study it was mentioned that the concept of lateral acceleration control may be assumed to exist under occlusion. It is an established fact in vehicular dynamics that the lateral accelerative forces are higher at high speeds than at low speeds. It is reasonable to assume that the driver is able to sense these higher lateral forces relatively efficiently. This means that the sensing of cues in the form of lateral forces related to vehicle displacement and the driver's responding to these cues are better at higher speeds than at lower speeds. Figure 10 shows that the standard deviation obtained by the new functional relationship for the low speed is considerably below the actual standard deviation obtained. This could be because the new functional relationship has an implied assumption that the driver's response is proportional to the lateral forces, whereas in practice the driver is sensitive to lateral forces only beyond a certain threshold value. This characteristic of human behavior has been clearly demonstrated in test-driver technique studies (3). It is left to future research to include a correction factor for a human threshold for lateral acceleration in the new theoretical model.

Based on the results of the second experiment, we may conclude that the vehicle path variability is significantly less when the driver steers with no visual input than when he has no steering control. This indicates that the driver does exercise some positive lateral control through steering even when he does not get the normally available cues such as heading angle, path angle, and lateral displacement. In addition, we may also conclude that the lateral vehicle path displacements at a given distance traveled with occluded vision are normally distributed. This result indicates the inherent nature of the vehicle path displacement data and is helpful in the selection of the appropriate statistical tests for analysis of lateral vehicle path displacement data.

This study has demonstrated that the vehicle position uncertainty component as derived (4, 5) cannot be supported by experimental evidence and is thus incorrect. The new model derived is in better agreement with the experimental data. The authors did not determine how much error this incorrect vehicle position uncertainty component introduces into the uncertainty model advanced by others (4, 5) nor in the estimates and conclusions derived from it because there is a high probability that the results of a pending experimental investigation will show that the uncertainty component can also not be validated experimentally.

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DISCUSSION

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The authors have provided an enlightening treatment of a relatively complex subject. Automobile handling and driver control are contributing factors in accidents, and quantification and clarification of the underlying parameters can be of potential benefit. The following comments relate mainly to clarification and interpretation; their basic approach, which combines analytical modeling and experimental verification, has yielded useful results.

The authors' model for the driver-vehicle system (Fig. 3) is a relatively simple one. It assumes that the primary perceptual cue for steering control is a lateral acceleration component due to heading rate times forward speed. Although this approximation for lateral acceleration can be reasonably good for nominal lane keeping in a straight line, the neglect of other lateral acceleration components (such as side-slip rate) may be important when the model is extended to large-amplitude maneuvers or limit-of-performance situations. Further, the lateral acceleration approximation used applies to motions of the vehicle mass center. If the driver is located ahead of (or behind) the vehicle mass center, an additional acceleration component that is the product of the moment arm from the mass center and the heading angle acceleration arises. This latter term can become significant if the displacement from the mass center is on the order of 1 or 2 feet (0.3 or 0.6 m) or more. This can occur, for example, in the case of a rear-engine automobile or with utility vehicle configurations such as vans where the driver is seated near the front. Rolling and pitching accelerations can also cause similar effects. Including these acceleration terms in the linear dynamic model of the vehicle is relatively straightforward, and this might be a useful step in extensions of the present work.

As the authors note, the driver can obtain the lateral acceleration cue from proprioceptive or tactile sensors. The cue can also be sensed vestibularly via the semicircular canals (heading rate) or from the otoliths (lagged linear acceleration). As noted above, the nature of the acceleration will vary depending on the sensor location within the vehicle and, hence, the point within the driver's body at which the acceleration is sensed. Furthermore, these several sensors can have different dynamic properties and thresholds, and it might be of interest to take such factors into account in any future studies of this particular driving situation.

The simple driver-vehicle model form shown in Figure 3 implies that the driver's steering response is proportional to the sensed lateral acceleration error when the driver is attempting to maintain a straight line. The data and theory of manual control indicate that a more complete model for this situation would include a driver time delay of a fraction of a second as well as some driver lag equalization or "smoothing" of his response. The driver would provide this equalization to obtain better low-frequency lateral placement control, while at the same time suppressing his response to relatively high-frequency disturbances and vehicle heading motions. The subjects in the experiments described may in fact have been using these more characteristic forms of steering control. Because the vehicle trajectory data shown provide only an overall response measure it would be difficult to distinguish the detailed form of the driver's response and adaptation, given only those data. Nevertheless, these driver processing factors could be taken into account in a more detailed analysis of this driving task.

The authors are to be commended for their ingenuity in obtaining the lateral placement and trajectory measures. These kinds of measures have always plagued experimenters, and their use of direct pavement markings seems to have worked well in this case.

When the results of experiment 1 are reviewed, it would be helpful to know what the specific instructions to the subjects were prior to the runs, inasmuch as the nature of the instructions may have influenced the form of control behavior the drivers adopted. Similarly, experiment 2 might have had a somewhat different outcome had the subjects been instructed to hold the steering wheel fixed in a centered position rather than releasing the steering wheel as was apparently the case. With the steering wheel free the directional dynamics of the vehicle change, because of the steering subsystem dynamics and the tire-aligning torques, whereas with the steering wheel held fixed the vehicle dynamics are the same as when the driver is providing active control of steer angle (position) as in experiment 1.

The results appear to confirm the authors' analytical interpretation of vehicle performance under these conditions, and they seem to provide a better explanation of the data than does the Senders' Hypothesis. Further experiments in this area could use the more detailed human operator response models available that take into account the effect of perceptual thresholds, for example, as suggested by the authors.

AUTHORS' CLOSURE

We wish to thank Weir for his comments, which indicate that the problem of driver steering control under the conditions discussed in this paper could be modeled by considering a number of vehicle and human variables giving explicit consideration to every one of them. Weir pointed out that the model could be extended by giving special consideration to side-slip rate, the position of the driver from the vehicle mass center, and also human operator lag.

Almost all the improvements suggested earlier have been incorporated in a number of earlier studies related to either vehicle dynamics or driver-vehicle system. The main reason for considering a simple model in this study was its sufficiency to carry out study objectives. The aim was to investigate the functional relationship that is frequently referred to and used in a number of human information processing studies (4, 5). Hence, a macroscopic approach was taken to consider the changes that take place because of changes in the driver-vehicle system as a stochastic process with the random input $\dot{\theta}(t)$. We feel that our experimental results are due to driver behavior at different speeds because the experimental design and procedures used kept the effects of variables other than driver behavior to a minimum or balanced them under different levels of experimental factors.

When this study is extended, the first step will be to incorporate the self-aligning torque and a time lag for the human operator into the present relationship. The driver could use lateral acceleration as a cue at high speeds and the feel of steering as a cue at low speeds.