DRIVER WORK LOAD FOR VARIOUS TURN RADII AND SPEEDS

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The need exists for a method by which a highway designer can determine, during the design stage, whether a highway design will demand so much of a driver's attention that there is insufficient time to look for and avoid accidents. One aspect of attentional demand is tracking the lane in curves and tangent sections. A study was done to determine (by use of a secondary task) what percentage of a driver's attention is required to track a lane while various curves are negotiated at various speeds. In addition, data were gathered about how drivers control their lane position. Results indicated that lane tracking in a 17-deg turn demanded 26 percent of the subject's attention at 20 mph (32 km/h) and 42 percent at 40 mph (64 km/h) and that attentional demand in the straightaway remained around 23 percent for speeds from 40 to 80 mph (64 to 129 km/h). Lane-tracking data indicated that the median location was 5 in. (13 cm) to the left of the lane center in straightaways, 7 in. (18 cm) to the left in left turns, and 6 in. (15 cm) to the right in right turns. Distributions of drift distances from these three median locations were also determined.

•AS freeway interchanges and other highway design features increase in complexity and sophistication, the limit of one's ability to perceive and process information is approached. Current freeway speed zones, requirements for sign information processing, and planned changes in each of these areas suggest that the driver may not be left with sufficient spare time to look for and avoid accidents. Drivers today need that extra margin of safety, and it can frequently be provided by highway design. This research is concerned with one phase of the development of a driver-work-load model (6). The essential purpose of the model is to predict how busy a driver will be while driving on highways of varying designs. The model may be used to assist a designer in evaluating a proposed roadway design for identifying and alleviating unacceptable work loads imposed on the driver by the roadway.

The primary objective of this study was to determine the work load forced on the driver while a lane was tracked at various speeds in turns of various radii. A secondary objective was to gather data on how drivers control their lane position.

BACKGROUND

Work load has many different connotations. It may refer to a subjective feeling of the difficulty of a task or to the physical exertion required. Senders (10) defined work load as "a measure of the 'effort' expended by a human operator while performing a task, independently of the performance of the task itself." Knowles (5) defined work load, in part, as the answer to the following two questions: How much attention is required? and How well will the operator be able to perform additional tasks?

Publication of this paper sponsored by Committee on Road User Characteristics.

The definition of work load to be used here will be similar to that suggested by Knowles: the attention demanded by the task under consideration and its subsequent reduction in the attention available for other tasks.

Of the three major approaches to work-load theory (5, 10, 12), the most extensive work is by Siegel and Wolf (12). The primary purpose of their model is to predict the effectiveness with which operators will be able to carry out their tasks under specified conditions.

Siegel and Wolf began with a list of tasks that the operator must perform. Empirical data had been previously gathered concerning the time required and the time available for completing each of these tasks. The authors used a concept, "stress," which is defined as the time required to execute a series of tasks at average speed divided by the time available for execution of these tasks. A stress value of less than 1 would indicate that the operator has more time available than is required for executing the task. A stress value of more than 1 would indicate that the operator has less time available than is normally required for executing the task and that he must, therefore, work at greater than average speed to complete the tasks in the allotted time.

Siegel, Wolf, and Sorenson (13) indicated that as long as stress value was less than 1, the average task execution time remained unchanged. However, mild stress (ratios from 1 to 2.3) acted as an organizing agent and led to shorter execution times. But at a stress value of 2.3 (stress threshold), the operator became disorganized, and execution time returned to the original average length. Above 2.3, execution time increased until at 3.3 execution time was double the value at a stress value of 1 or less. Therefore, an operator may work at up to 2.3 times his average speed without falling behind. When required to operate 2.3 times faster than one's average speed, a driver will tend to fall behind and not complete all of the tasks in the allotted time. These statements hold true for physical tasks performed over short time frames because of fatigue. In nonphysical (monitoring) tasks, the operator may operate at above average speed over longer time frames. Because we believe that most of the work done by a driver is visual monitoring, driving will be considered a nonphysical task.

Knowles' (5) approach to work load was quite different from that of Siegel and Wolf (12). Knowles used a secondary task to directly measure the attention demanded by a primary task. An example of a primary task could be steering an automobile. The secondary task could be monitoring a display on which numbers appear and in which a subject is required to repeat the numbers as they appear. In estimating work load, the procedure is as follows:

1. The subject is asked to perform the secondary task independent of the primary task.
2. The subject's performance on the secondary task is scored, and the score is designated as a 100 percent performance.
3. The subject is asked to perform the primary task and to devote all spare attention to the secondary task.
4. The subject's performance on the secondary task is again scored, and the performance is compared to the 100 percent performance score.
5. The percentage of reduction in performance on the secondary task is assumed to be the percentage of the subject's attention required to carry out the primary task and to shift eyes from one task to the other.

Senders (10) outlined the requirements for a model that would predict the operator work load of a system still in the design stage. The model was designed to be used on control panels of aerospace vehicles. The assumption was that almost all information was derived from instruments instead of from direct observation of the environment. The steps in developing the model are as follows:

1. Describe the physical system by a set of differential equations;
2. Calculate, from the equations of the system, the frequency characteristics of the signals that will flow in the control loops;

3. Determine, from the mission specifications and the stability requirements of the system, the required accuracy for each signal;
4. Calculate, from frequency and accuracy requirements, on the basis of the model chosen the frequencies and durations of observations;
5. Give the percentage of the total time available that must be spent observing that signal as the product of mean frequency and mean duration of observation for each signal; and
6. Estimate by the sum of these products the mean loading placed by the system on the human operator.

Another model of operator work load gives us insight into how drivers respond to overload conditions. The model developed by King and Lunenfeld (4) divides driving into three major levels of performance: microperformance, situational, and macroperformance. The microperformance level consists of steering and speed control. Both of these tasks are highly overlearned reflex actions. The situational level consists of monitoring and responding to elements of the road, traffic, and external environment. Tasks in the situational level are more cognitive than those in the microperformance level. The macroperformance level consists mainly of trip preparation and direction finding—the most highly cognitive tasks of driving.

King and Lunenfeld also order the levels in terms of primacy. They believe that drivers satisfy their driving information needs by placing highest priority on obtaining microperformance information; therefore, full attention is devoted to the microperformance level until they feel they have sufficient information to successfully carry out the microperformance duties of driving. When these microperformance needs are satisfied, attention is shifted to the situational level until situational level information needs are satisfied. When the two higher priority levels are satisfied, drivers shift attention to the macroperformance level. The primary result of this primacy system appears when drivers are presented with more information than can possibly be processed. When this situation occurs, drivers will be forced to ignore some of the information. The primacy concept states that the first group of information to be ignored is associated with the macroperformance level. If there is still too much information, drivers will ignore the situational information. The primacy concept will be useful for predicting driver response to unacceptably high work loads. For example, as work loads on drivers become too high, the first omitted task should be reading of directional signs.

Other contributions to the area of work-load theory have been made. Michaels (7) measured the galvanic skin response (GSR) of subjects driving on arterial routes and alternate routes. He found a significantly higher GSR on the arterial routes, but the technique was not sensitive to design factors along the roadway.

One study has been done that relates directly to driver work load. Senders et al. (11) used a translucent visor to occlude the view of the driver. The visor was raised and lowered by the experimenters in some cases and by the subjects in others. When the drivers were allowed less frequent and shorter observations, they tended to drive at lower speeds. When drivers had control of the visor, they tended to make longer and more frequent observations as the speed at which they were instructed to drive increased. Senders et al. (11) theorized that a driver is capable of processing information at a certain maximum rate. In addition, a given roadway contains a certain amount of information per mile that the driver must process. The faster the driver passes through the roadway, the faster he must process the information. Therefore, a driver will not exceed a certain speed on a roadway (11) because

> . . . drivers tend to drive to a limit. We suggest that the limit is determined by that point when the driver's information processing capacity, either real or imagined, is matched by the information generation rate of the road, either real or estimated.

Farber and Gallagher (1) used the occluding visor technique to detect the effect of visibility conditions on driving task difficulty in a slalom course. The standard measures of driving performance (maneuver smoothness and cones knocked down) were insensitive to task difficulty, but attentional demand was sensitive.

Several studies have been carried out concerning the design of vehicle controls. Hoffman and Joubert (2) found that the optimum response time for a turning vehicle is 0.2 s. Changes in steering ratio and steering wheel torque had no effect on driver performance, but sight distance (controlled by a shield on the front of the vehicle) did have a significant effect. Olson and Thompson (8) found that steering ratio had a significant effect on driver preference, but performance was not significantly affected. These findings agree with those of Segel (9), which state that pilot ratings are the only methods sensitive to changes in control characteristics. Kidd and Harper (3) have also demonstrated that objective performance measures are insensitive to control situations. Knowles (5) agrees with Kidd and Harper (3) about the inability of objective measures to detect differences in two control systems. He further states that his secondary loading task approach is an objective method of detecting this difference. Therefore, there is a consensus that objective performance measures are insensitive to reasonable changes in vehicle control characteristics. Two methods are sensitive to this difference: driver opinion, which is subject to the biases and preconceptions inherent in human beings, and driver work load, as measured by a secondary loading task.

Even an approximate index of driver work load for various driving maneuvers would be useful to the highway designer. Knowledge of what percentage of the driver's attention is required for driving and, therefore, how much is left over for sign reading would be helpful. Designers know that drivers are busier in turns than in tangent sections, but they do not know how much busier. This study does not provide the full answer to the questions, but it does represent a first step toward it.

METHOD

The primary objective of the study was to determine how much tracking work load is imposed on the driver by various driving maneuvers. A secondary objective of the study was to gather information on how the average driver steers a vehicle.

The study was accomplished in two parts executed simultaneously: (a) Driver work load was measured in a series of maneuvers at varying speeds, and (b) data were gathered on how the average driver steers a vehicle in a highway lane.

Driver work load was measured by the Knowles technique. A number display (secondary task) was mounted on the hood of the vehicle. This display consisted of a motion picture projector that showed two or three numbers per second on a small screen. Subjects would, first, repeat as many numbers as possible while the vehicle was stationary. This number was the 100 percent attention score. Then they would execute the driving maneuver and devote all of their spare attention to the number display. The percentage of reduction in numbers repeated was assumed to be the percentage of the driver's attention required to execute the maneuver.

The secondary task method of work-load measurement was chosen over the occluding visor method because it more closely approximated the sign-reading task of the driver. In addition, the driver is able to pick up some driving cues with his peripheral vision while reading signs and fixating on the secondary task. This is not true with the occluding visor.

Subjects

Subjects were drawn from the office staff at the Texas Transportation Institute Research Annex. Table 1 gives pertinent information about the subjects, all of whom had valid driver licenses.

Apparatus and Procedure

A 1968 Plymouth Fury (Fig. 1) was used as the study vehicle. The steering linkage of the vehicle and front-end alignment were inspected by the chief mechanic at the Texas Transportation Institute Research Annex. Based on the physical condition and adjustment of the system, the vehicle was classified as representative of the average full-sized sedan on the road. The secondary task, i.e., number display, was mounted on the hood above and to the right of the driver's line of sight (Fig. 2). Figure 2 was photographed at the beginning of the sharpest right turn in the study. Note that the view is more than sufficient for tracking the lane, but the sight distance around the turn is restricted. This was considered acceptable because the objective of the study was to measure the microperformance, tracking work load (4), and not the situational work load.

Instrumentation recorded steering wheel position and velocity on a Vetter FM tape recorder. A time-lapse Super 8 motion picture camera mounted on the right side of the vehicle was aimed at the road surface beside the right front tire (Fig. 3) to monitor lane position. A target was mounted 3 in. (7.6 cm) to the right of the fender and in the view of the camera. At the beginning of each series of runs, a calibration bar marked in inches was placed on the road surface below the target, and the 3-in. (7.6-cm) mark on the bar was aligned with the target by use of a plum bob. Several pictures of the target and bar were filmed for later data analysis. Power for the projector and camera was supplied by a portable generator mounted in the vehicle trunk.

The study took place at the Texas Transportation Institute Research Annex, which is a former Air Force base. A lane, 12.5 ft (3.8 m) wide, was delineated by standard 4-in. (10-cm) white striping on the runways and taxiways.

The maneuver types, speeds, and direction of turns were administered to the subjects in a counterbalanced order based on a Latin square design. There were three maneuver types: sharp turn, wide turn, and straightaway. There were two different sharp turns, and, because they were close together, the subjects drove through both turns in one data run. The degree of curvature of the turns is given in Table 2. Sharp-turn speeds were 20, 30, and 40 mph (32, 48, and 64 km/h); wide-turn speeds were 20, 40, and 60 mph (32, 64, and 97 km/h); and straightaway speeds were 40, 60, and 80 mph (64, 97, and 129 km/h).

Instructions were given to subjects by a tape recorder. Subjects were instructed to drive normally and to repeat as many numbers as possible without neglecting their primary task of driving the vehicle. In addition, they were instructed to establish their speed before entering the maneuver and to ignore the speedometer during the maneuver. This was done to eliminate speed control work load and to measure work load caused solely by tracking.

Subjects were first familiarized with the equipment and maneuver by executing the task in alternate directions at increasing speeds. During the four practice runs, subjects repeated the numbers, but the responses were not recorded. After the practice runs, when the vehicle stopped, 100 percent attention was obtained. The maneuvers were then executed, and responses of subjects were recorded on a tape recorder. Another measurement of 100 percent attention was obtained at the end of the data runs. The procedure was essentially the same for all maneuvers.

In the original study plan, the driver work load was to be measured on 18 subjects. Data for lane position, steering input, and work load were to be gathered simultaneously on six subjects. Equipment failure forced termination of the study after 11 subjects. Both sets of data were obtained on subjects 9, 10, and 11. A decision was made to rerun the 11 subjects and to gather lane position and steering input data when the secondary task was removed from the hood of the vehicle. Subjects were instructed by tape-recorded instructions to drive normally.

Before each phase of the study to gather lane position and steering input, a calibration bar was placed on the road surface within the view of the motion picture camera, and several frames of film were exposed. During each data run, the camera was activated before each maneuver. The camera photographed the lane stripe and

Table 1. Analysis of drivers in study.

Testing Order	Sex	Age	Miles per Year	Years Formal Education
1	M	24	25,000	17
2	F	23	15,000	16
3	M	23	28,000	15
4	F	21	5,000	15
5	M	22	10,000	15
6	F	39	5,000	12
7	M	18	23,000	13
8	F	20	10,000	12
9	M	21	20,000	16
10	F	20	18,000	12
11	M	24	25,000	17

Note: 1 mile = 1.6 km.

Figure 1. Research vehicle.

Figure 2. Driver view of secondary loading task.

Figure 3. View from lane-monitoring motion picture camera.

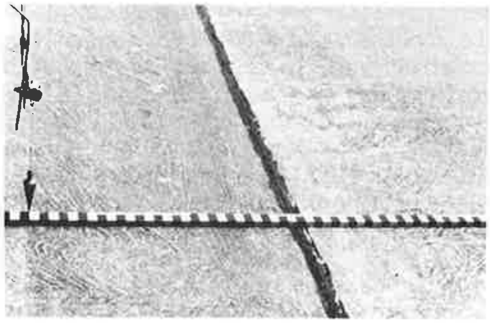
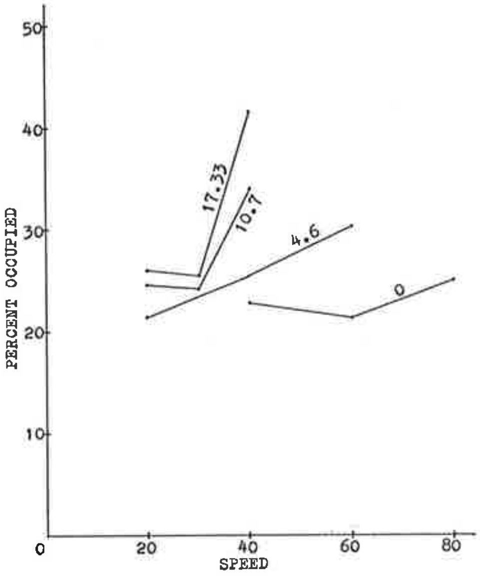


Table 2. Degree of curvature of turns.

Turn	Curvature (deg)	Radius (ft)
A	17.33	330
B	10.70	530
C	4.60	1,273

Note: 1 ft = 0.3 m.

Figure 4. Work load at various speeds and curvatures for right turns.



target at a rate of 2 frames/s throughout the data run. The target contained a light that could be activated by the experimenter. When the event marker switch was depressed, the target light and an event channel on the FM data recorder were activated. The target light, the event marker, and the steering and velocity data were recorded simultaneously, and this served to synchronize the information gathered by the two methods. At the end of each session, the experimenter had obtained a data tape containing steering wheel position, velocity, and event marks and a film with photographs of the calibration bar, the lane stripe position, and event marks during the data runs.

RESULTS

The data were analyzed in two parts. In the first part, work-load data were analyzed to determine the work load associated with each maneuver at each speed. In the second part, control data were analyzed to determine how a driver steers a vehicle in a lane.

Work-Load Data

Tape recordings of subject responses (repeating numbers) were scored for the percentage correct. Driver work load was calculated for each subject on each speed, direction, and maneuver. Because the study was terminated with 11 subjects, there were not an equal number of data points under each of the 3 orders of maneuver presentation. Therefore, an analysis of variance was done on the work-load data to check for an order effect that was at the 0.05 level of significance. This finding required that the data be balanced according to order effect; therefore, a dummy twelfth subject was added and given the average work-load score of the other three subjects in the third order of presentation.

Figures 4 and 5 show the average visual work load (in percentage occupied) for the 12 subjects at each speed used. Each line connecting the points in the figures is labeled with the degree of curvature of the turn in which the data were gathered. Note that the work load generally increased both with degree of curvature and speed. This finding is, of course, expected and lends support for data validity. A polynomial regression was applied to the data points in each of the seven curves shown in Figures 4 and 5, and the results are given in Table 3. The effect of speed was found to be significant beyond the 0.01 level of significance for all curves except the 10.7-deg curve turning left. This result may be explained by noting that drivers had to negotiate a sharp turn (not used in the study) just before they entered the 10.7-deg left turn. Apparently the short, 50-ft (15.2-m), straight section between the two turns was not sufficient to allow the drivers to enter the turn without some aftereffects from the previous turn. There was no approach problem from the other direction, and the data fit the expectations better. In that the data for the 10.7-deg left turn were considered invalid, they were replaced by another curve for predicting driver work load. The substitute data exhibit the same relationship to the other left-turn data as that in the right-turn data.

Figures 6 and 7 show the relationship between degree of curvature and percentage occupied. Each line connecting the points is labeled with the speed at which the data were gathered. Results of a polynomial regression applied to the data (Figs. 6 and 7) are given in Table 4. The effect of curvature was significant beyond the 0.01 level for all but the 20-mph (32-km/h) left curve, which was significant beyond the 0.05 level. Again this finding supports the validity of the study data. It was anticipated that degree of curvature would have a stronger effect on driver work load than speed. Observation of the F-ratios confirms this expectation.

Figure 5. Work load at various speeds and curvatures for left turns.

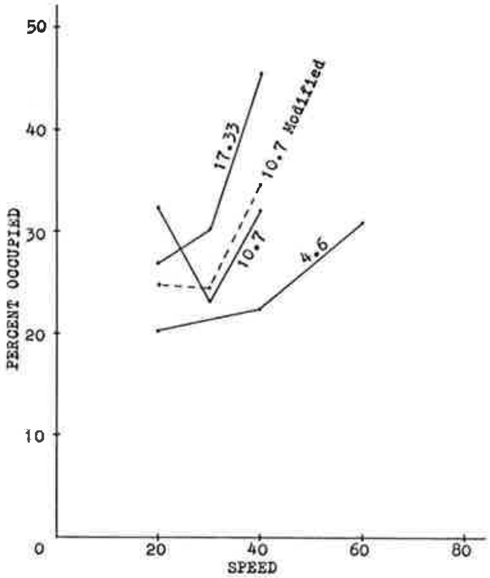


Table 3. Analysis of variance data for curves in Figures 4 and 5.

Curvature (deg)	Regression Equation	Correlation Coefficient	F-Value
17.33[a]	$Y = 7.90 + 0.77 X$	0.84	23.03
10.70[a]	$Y = 14.24 + 0.44 X$	0.83	22.56
4.60[a]	$Y = 17.03 + 0.14 X$	0.98	194.51
0.00	$Y = 18.93 + 0.06 X$	0.68	8.49
17.33[b]	$Y = 6.47 + 0.91 X$	0.94	79.38
10.70[b]	$Y = 30.21 + 0.05 X$	0.09	0.09
4.60[b]	$Y = 13.47 + 0.18 X$	0.87	31.53

Note: $F_{0.99}(2,20) = 5.85$.

[a] To the right. [b] To the left.

Figure 6. Work load at various curvatures and speeds for right turns.

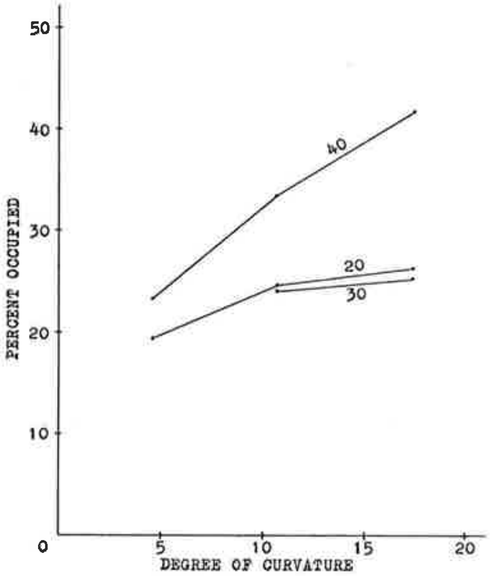


Figure 7. Work load at various curvatures and speeds for left turns.

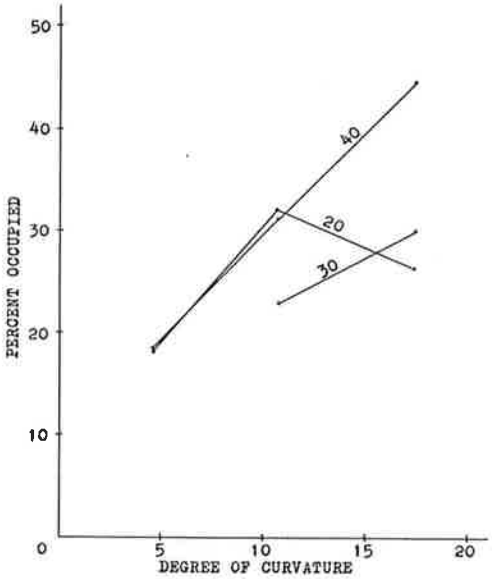


Table 4. Analysis of variance data for curves in Figures 6 and 7.

Speed (mph)	Regression Equation	Correlation Coefficient	F-Value
20[a]	$Y = 17.65 + 0.54 X$	0.95	88.93
40[a]	$Y = 17.05 + 1.45 X$	0.99	1450.73
20[b]	$Y = 18.90 + 0.62 X$	0.57	4.74
40[b]	$Y = 17.53 + 0.15 X$	0.98	217.66

Note: 1 mile = 1.6 km.
$F_{0.99}(2,20) = 5.85$; $F_{0.95}(2,20) = 3.49$.

[a] To the right. [b] To the left.

Figure 8. Frequency of occurrence of median locations in straightaway maneuvers.

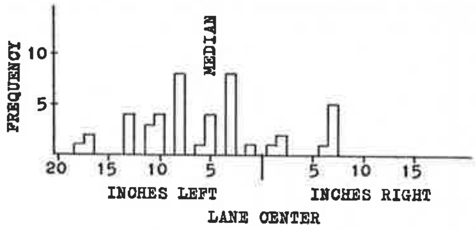


Figure 9. Frequency of occurrence of median locations for left turns.

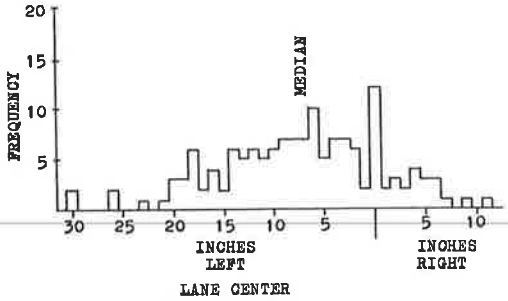


Figure 10. Frequency of occurrence of median locations for right turns.

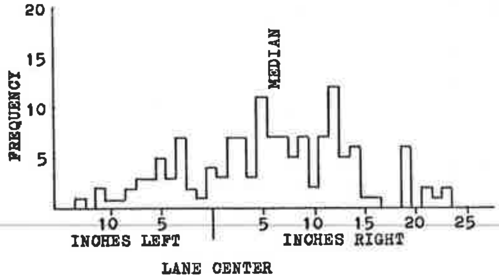
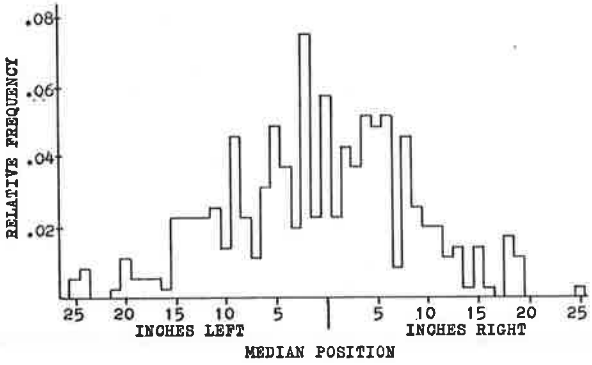


Figure 11. Frequency of drift distances—straightaway.



Control Data

During this study, films were made that contained photographs of the calibration bar and the right-lane stripe during the maneuvers. The films were later analyzed to determine how a driver steers a vehicle in a lane.

When the films were analyzed, the photograph of the calibration bar and target was projected onto a screen with a plastic overlay. The scale on the calibration bar was copied onto the plastic overlay, and the target was circled. Frames of film were then advanced one at a time, and the location of the stripe on the scale was read and recorded. As each frame was advanced, a check was made to determine whether or not the target was inside the circle on the screen. This was done to guard against improper framing by the projector or inadvertent movement of it.

At the end of the film reading, a sequential list was obtained that indicated the number of inches apart the stripe and right edge of the vehicle were at each 0.5 s during the data run. Data were analyzed to determine the median location of the vehicle in the lane for each data run. The median value was chosen because of its relative insensitivity to skewed distributions.

Figure 8 shows the frequency with which each median location occurred for all subjects while they were driving straight ahead. The median score is 5 in. (12.7 cm) to the left of lane center, which may be because drivers are better able to judge clearance on the left side of the vehicle and, consequently, leave more room for error on the right side.

Figures 9 and 10 show the frequency of each median location while drivers were turning left and right. Note that the data agree with the commonly observed tendency for drivers to move to the inside of a turn. The median location of the vehicle was assumed as the position to which subjects were continually steering the vehicle.

After the original data for vehicle location were reexamined, another analysis was performed. Steering wheel and lane position data were compared to determine the location of the vehicle in the lane at the time of each steering wheel input. These corrections were compared to the median location of the vehicle during that data run to determine how far drivers allowed the vehicle to drift from the median location before correcting its path.

Figure 11 shows the number of times each drift distance occurred for all subjects driving on the straightaway. Figures 12 and 13 show the number of times each drift distance occurred while the drivers were turning left and right respectively.

Table 5 gives the average lateral motion in in./s, which was induced by steering corrections at each speed used in the study. These data will be required when one attempts to simulate the steering inputs of a driver for computing the predicted stress.

Lane position and steering input data were gathered for three subjects under two conditions—repeating numbers and driving normally. Observations of the lane position data under these conditions revealed no significant differences; therefore, based on a sample of three subjects, it is assumed that the 11 subjects in the study were driving normally while their driver work loads were measured.

This study produced two sets of results. From the work-load data, the degree of tracking work load imposed on the driver by different maneuvers and speeds is now known. Further research will be required to determine the driver work load generated by higher level driving tasks. The control data results will be useful in simulating driver control inputs for calculating work load by use of the Senders method.

DISCUSSION OF RESULTS

The results represent a first step toward filling the gaps in knowledge in highway design so that driver work load can be predicted. The literature contains data on the time required to read signs of various designs and methods that exist by which the work load imposed on a driver by monitoring other vehicles on the roadway can be calculated. However, no data have previously existed on the attentional demand of lane tracking. Now that these data are available, the highway designer can calculate

Figure 12. Frequency of drift distances for left turns.

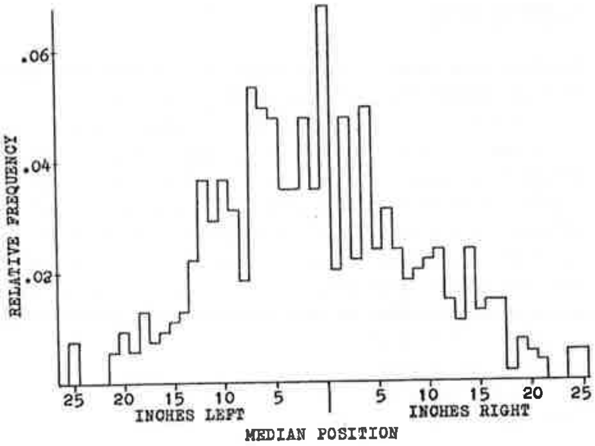


Figure 13. Frequency of drift distances for right turns.

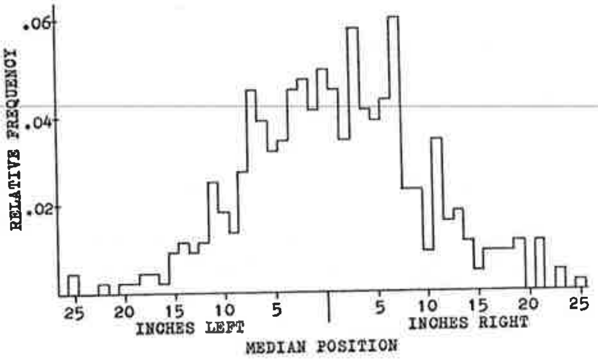


Table 5. Average lateral speed induced by steering inputs.

Maneuver	Speed (mph)	Lateral Speed (in./s)
Sharp turn	20	3.88
	30	5.59
	40	4.23
Wide turn	20	3.21
	40	3.75
	60	3.65
Straightaway	40	2.21
	60	3.47
	80	3.36

Note: 1 mile = 1.6 km. 1 in. = 2.54 cm.

the work load of the total driving task.

Admittedly, the highway design features used in the study did not cover the full range of possible design features. Further research will be required to determine the attentional demand of highway designs outside this range. One obvious option is to directly measure driver work load on other highway design features to expand the data base. Another option is to calculate the driver work load by simulating the driving task by using the Calspan vehicle dynamics model and data for lane tracking.

The vehicle dynamics model is a computer simulation of a complete automobile including its steering and suspension systems. By defining the path and surface properties of a roadway, one can simulate the reactions of the vehicle to that roadway. However, the model currently steers itself as if it were driven by an autopilot. The model could be reprogrammed to steer itself in the way that a driver steers a vehicle. By use of a Monte Carlo technique, the vehicle could be allowed to drift from the lane center, and steering corrections would be input at various drift distances in keeping with the probabilities found for drivers in this study. The steering inputs would be those required to produce the lateral speeds also found in the study. When the vehicle dynamics model has been reprogrammed to steer itself as a driver would steer an automobile, the simulated steering corrections could be input to the Senders work-load model to calculate driver work load for the specific highway design.

In conclusion, a method for calculating driver work load based on highway design has been delayed because driver work load from lane tracking was unknown. A work load based on lane tracking has been determined on a limited range of highway characteristics, and a method for calculating work load for characteristics outside this range has been formulated.

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