THE DRIVER IN SINGLE LANE TRAFFIC

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A study was made of the reactions of drivers who were impeded by an experimental car moving at constant slow speed on a single-lane road. The situation was arranged so that the 20 subject drivers were not aware that they were being observed. The photographic records indicated the distances of the drivers behind the experimental car over the 3-mile course. Three modes of driver response were noted: (a) avoidance, where drivers moved backward out of the influence of the experimental car, 10 percent of the drivers; (b) car-following, where drivers stayed close to the experimental car and did not execute large backward or forward movements, 30 percent of the drivers; and (c) a combination of avoidance and car-following, 60 percent of the drivers. Drivers' lead distance patterns did not conform to Herman's car-following equation. The equation may apply better to the situation where a driver reacts to disturbances introduced by the car in front. Drivers showed an indifference threshold. They accepted a range of positions behind the experimental car and reacted only when lead distance exceeded certain limits. A statistically significant resemblance was found in the driving patterns of operators who stayed close to the plant. This and previous studies suggest that the driver should be regarded as a strategist who continually adjusts his actions to fit his travel purpose and the road conditions he faces. He is not a stereotyped reacting element or "black box" to be simply described by a fixed equation.

•ALTHOUGH many studies have been made of traffic flow (1, 2, 4), the research has not generally been related to the actions of the individual driver. Yet, the driver is the active element in the vehicle-highway-driver system. To a considerable extent, traffic flow reflects his behavior and psychology.

The aim of this study is to describe driver behavior in single-lane traffic. In this situation, the actions of the driver affect subsequent drivers in the traffic stream and, hence, are of considerable interest to the traffic engineer. An experimental vehicle or plant was deliberately introduced into the traffic stream and driven at a speed slower than that of the traffic stream itself. Impeded drivers behind the plant reacted to it, and their responses of slowing, matching pace, and so on were photographed and later analyzed.

In this study the plant moved at constant speed. All changes in velocity between the plant and the observed vehicle were made by the rear driver. Driver responses would be expected to be more clearly revealed in this simplified setting than would have been the case if the lead driver had also altered speed. It was also considered important for methodological reasons that drivers not be aware that they were under surveillance. The author knows of no form of experimental instructions that would ensure that a driver, knowing that he is being observed, would drive as he normally does.

BACKGROUND OF THE PROBLEM

The best known theory of drivers' reactions on single-lane roads is associated with the work of Herman and his co-workers (7). On the basis of experimental observations

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on a test track and in New York City tunnels, Herman derived the following equation to describe what has been called "car-following":

$$[(d^2x)/dt^2]_{n+1} = \alpha_0 \left[\frac{(dx/dt)_n - (dx/dt)_{n+1}}{x_n - x_{n+1}} \right] \quad (1)$$

where

$[(d^2x)/dt^2]_{n+1}$ = acceleration of the following car;
α_0 = constant related to speed;
$(dx/dt)_n - (dx/dt)_{n+1}$ = difference in speed between cars; and
$x_n - x_{n+1}$ = headway distance between cars.

(Herman included a term to account for man-machine lag. This term is omitted in Eq. 1 because the lead car was driven at constant speed.) The equation states that the acceleration of the following car is directly proportional to the difference in speed between the 2 cars and inversely proportional to the distance between the vehicles.

If Herman's equation is integrated, the following relationship is obtained:

$$(dx/dt)_{n+1} = \alpha_0 \log \left[\frac{x_n(t) - x_{n+1}(t)}{L} \right] \quad (2)$$

where

L = effective length of the following car.

The variables in this equation, velocity of the following car and distance between cars, are convertible in steady-state traffic to concentration and flow, the master variables of traffic flow. The implication is that Herman has found a basis for traffic flow in the reactions of the individual following driver.

To a psychologist, the term car-following seems to imply that the rear driver has the intention of following the car in front. This interpretation is implicit in experimental studies where the driver has been instructed to "follow that car" or "follow the lead car at what you consider to be a minimum safe distance at all times" (1). This motivational interpretation of car-following is not valid. In freeway studies, where the driver had freedom of movement, it has been shown that his intention is not to follow but to move ahead toward his destination (5). Genuine car-following might be said to occur in funeral processions, in situations where the driver follows a proceeding car in fog, or in situations where the driver is being guided by someone in front to an unfamiliar address. But even in these cases, it is doubtful that the driver follows at minimum safe distance.

A more operational definition of car-following is given by Eq. 1. The equation states that acceleration of the rear driver is directly proportional to the difference in velocity between the vehicles and inversely proportional to lead distance. The validity of this formulation may be tested by comparison with actual driver reactions. Such a comparison is made in a later section of this study.

That the driver is influenced by factors other than the actions of the car ahead is suggested by several experimental studies. Forbes found that the lag between the second pair of cars in a 3-car queue was much shorter than that between the first pair (3). The rear driver was responding to the first vehicle in the queue rather than to the actions of the vehicle directly ahead. This finding has been confirmed by Michaels and Solomon (10). Forbes also showed that the driver slowed on right curves where visibility is limited, on downgrades, and under conditions of low illumination and limited visibility.

EQUIPMENT AND PROCEDURE

Photographic Procedure

Two 16-mm cameras bolted to the frame in the rear of the vehicle were used to photograph the experimental scene. One camera was aimed at the road behind the plant;

the other was pointed over the shoulder of the driver toward the speedometer. The cameras were activated by solenoids that tripped every 0.47 sec. Analysis of the speedometer photographs showed that plant speed did not vary by more than ±2 mph, hence speedometer photographs were omitted on the last 10 runs.

Experimental Vehicle

The plant was a gray, 1965 Dodge sedan, equipped with a speed governor. The tripod and cameras were positioned in the rear of the vehicle in place of the rear cushions. The experimenters sat in the front and faced forward, away from the subject driver being photographed.

Courses

The experimental course was a long 2-lane, high-traffic road section in the Langley, Virginia, area. A bridge road in the neighborhood was also considered. It was not used because it was too short and complex. A long tunnel might have made an acceptable course; but there is none in the Washington area. The selected course (course A) runs 2.7 miles along Old Dominion Road between Chain Bridge Road and Williamsburg Boulevard (Fig. 1). It begins and ends with a traffic light. A second course (course B) was provided by the opposite lane. As indicated on the map, the courses had intersecting roads and curves but did not have stop lights or stop signs. Despite the inhomogeneities of the course, it was usually possible to maintain a fixed pace along it.

Procedure

At the start of a run, the plant car was parked on the shoulder of the road on the course side of the traffic light. When the signal changed from red to green, the plant

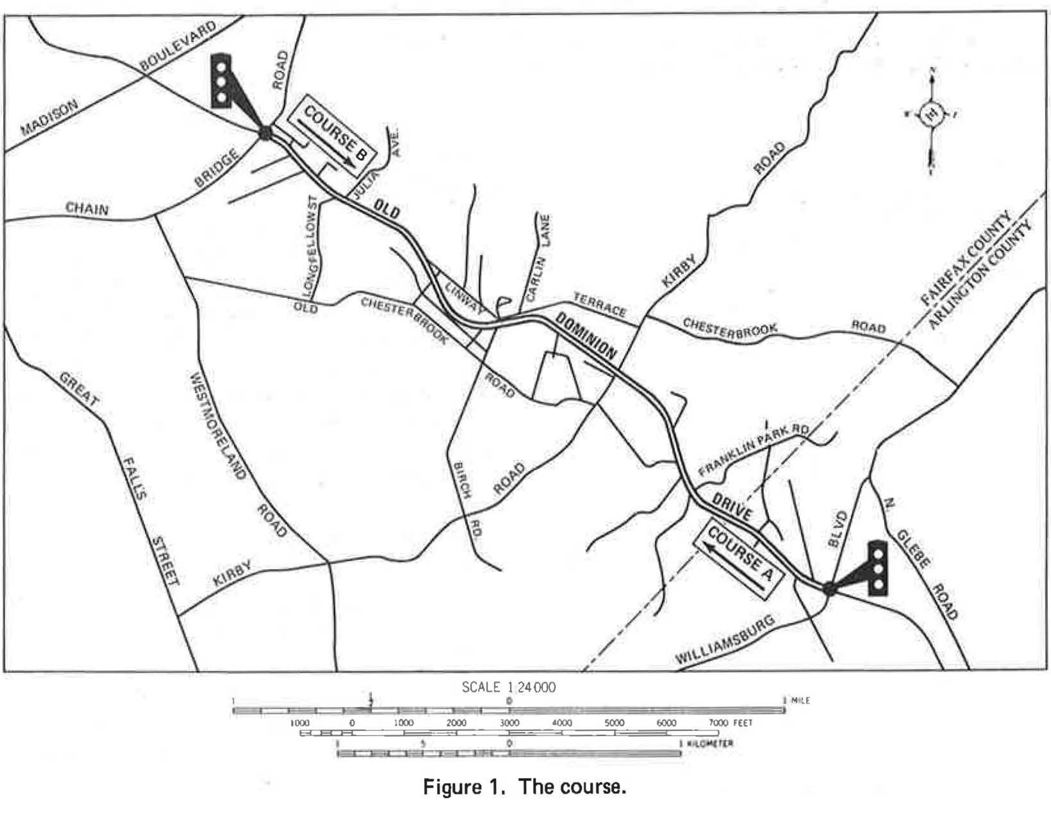

Figure 1. The course.

driver swung into the road and assumed scheduled pace ahead of traffic. A speed of 30 mph was maintainted on the lane from Williamsburg Boulevard to Chain Bridge Road; a 35-mph pace was maintained in the other direction. At slower speeds traffic queued behind the plant, and the driver behind tended to take risks to pass. At faster speeds, the rear driver was left behind.

Ten runs were made on each course. If the photographed car passed, turned off the course, or moved back out of sight, the run was aborted. Another run was then attempted, starting at the beginning of the course.

Analysis of Data

Lead distance was calculated from perspective changes recorded on the films. As the vehicle approached the plant, its angle increased inversely with distance. The relationship is expressed in the formula

$$d = k/\beta \qquad (3)$$

where

d = distance from focal plane of camera to the front of observed vehicle;
β = angle of some particular feature on front of vehicle, such as between headlight centers, convenient to measure on its projected screen image; and
k = constant that depends on size of vehicular feature, focal lengths of camera and projector lenses, and distance from projector to screen.

The approximation to the tangent function in Eq. 3 is justified because the angles of interest are almost all less than 6 deg. The formula was applied by projecting a photograph where distance d from the camera to the vehicle was known. From known d and β, k could be determined. Once k was known, the distance associated with any β could be found. A correction of 7 ft was subtracted to correct for the camera to rear bumper distance of the plant car. The precision of these measurements is a function of the vehicle feature measured, illumination, and camera-vehicle distance. It is believed sufficient to support the study findings.

TABLE 1

VEHICLES OBSERVED IN QUEUE BEHIND SUBJECT VEHICLE

Course	Vehicle	Part of Course Completed		
		One-Third	Two-Thirds	All
A	A-3	3	5	5
	A-5	3	5	6
	B-4	4	2	3
	C-1	2	1	3
	C-2	3	4	4
	C-3	3	1	2
	D-1	3	4	4
	D-3	5	6	7
	D-4	3	2	5
	F-2	2	3	7
	Mean	3.1	3.2	4.6
B	F-1	2	2	2
	F-3	1	0	0
	G-1	1	2	4
	G-2	2	2	1
	G-3	4	4	2
	H-1	2	2	3
	H-2	2	2	1
	H-3	2	3	4
	I-1	1	1	1
	I-2	2	1	1
	Mean	1.9	1.9	1.9

RESULTS

Traffic Environment of Observed Vehicles

Cars tended to line up behind the slowly moving plant. The number of cars seen behind the subject vehicles is given in Table 1. It may be seen that all observed vehicles except F-3 had one or more cars behind. Evidently, the drivers' traffic environment consisted of the plant in front and vehicles behind. It will be noted that longer queues occurred on course A where the plant maintained a faster pace.

Drivers' Reactions in Single-Lane Traffic

When impeded in front, drivers show 3 distinct types of reactions, as evidenced by the records:

1. Avoidance—The driver dropped back out of the influence of the plant vehicle (one driver on each course showed this type of reaction);

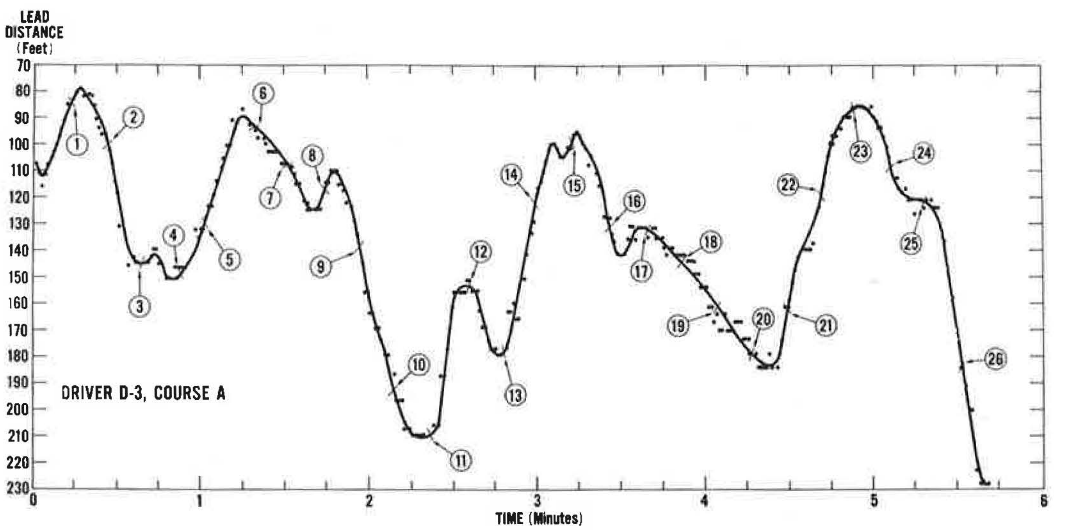

Figure 2. Avoidance reactions of driver D-3.

2. Car-following or pacing—The driver appeared to stay close and roughly match pace with the plant (4 drivers on course A and 2 on course B showed this reaction); and

3. Mixed—Mingled avoidance and car-following (5 drivers on course A and 7 on course B showed mixed reactions).

Avoidance Reactions—Avoidance reactions are shown in Figures 2 and 3. The numbered circles in the figures indicate tenths of miles on the course. Drivers who avoided the plant moved back; but because the plant was moving at a slow pace they tended to

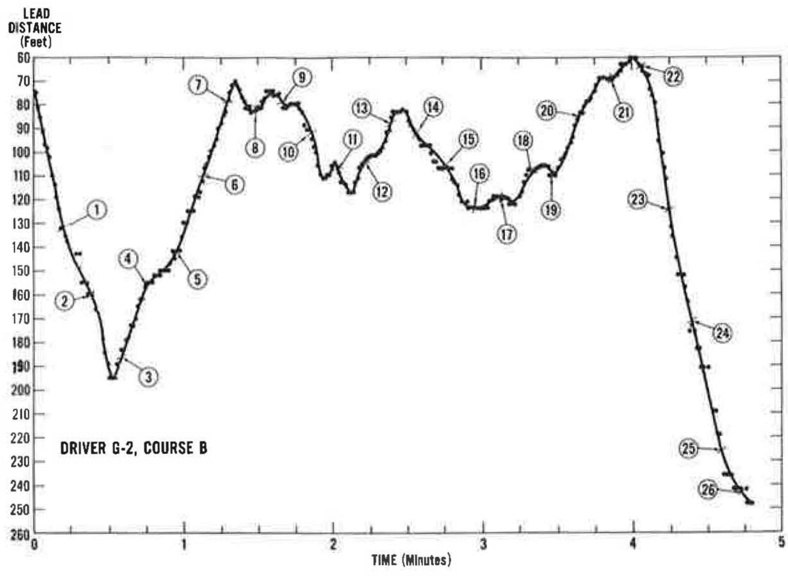

Figure 3. Avoidance reactions of driver G-2.

drift closer again. If a driver moved so far back that he could no longer be seen, the run was discontinued and the record was not analyzed.

The record of driver D-3 (Fig. 2) shows large following distances ranging from 80 to 210 ft. Aside from trying to avoid coming too close, there is little evidence that this driver was trying to maintain any positional relationship with the plant. Driver G-2 also moved out of the influence of the plant car. Lead distances varied from 60 to 195 ft if we exclude the final slowing down at the Williamsburg traffic light. Small adjustive movements are obscured by the large swings away and toward the plant.

On a crowded road, avoidance reactions may result in platooning. Queues of cars would be lined up behind the avoiding vehicle, leaving a space ahead. Platooning may be caused also by reasons other than the desire of the driver to avoid the influence of the vehicle, e.g., by inability to keep up or by engine failure.

Car-Following Reactions (Pacing)—Six of the 20 drivers reacted by pacing or car-following. The behavior is arbitrarily defined here by 3 rules: (a) The driver is in the same lane as the plant; (b) the driver keeps close to the plant (lead distances were always less than 75 ft); and (c) the driver does not show adjustive movements forward or backward of more than 30 ft. The distances found useful in defining car-following might be different under other road conditions. The term "car-following" is used because it is part of the traffic engineering literature; but, it should be understood that these rules are quite different from Herman's car-following equation. In any case, it is not implied that the driver is actively following the car in front.

The record of driver D-1, shown in Figure 4, is an example of car-following. After an initial approach in the first $^3/_{10}$ mile, during which the plant was gaining speed, the record shows continual adjustment of speed and position, at lead distance all closer than 54 ft. In the last $^1/_{10}$ mile of the course, the driver fell back in relation to the plant. Driver H-3 also car-followed (Fig. 5). After a slow approach in the first half mile, the driver paced the plant at a distance that never exceeded 50 ft. There are close approaches at 0.5, 1.4, 2, and 2.5 miles, followed by dropping back. The record is irregular and is not well fitted by a simple mathematical equation.

Mixed Reactions

The majority of drivers (12 of the 20) showed both avoidance and following reactions. Typical mixed reactions are shown in Figures 6 and 7. The record of driver C-1 re-

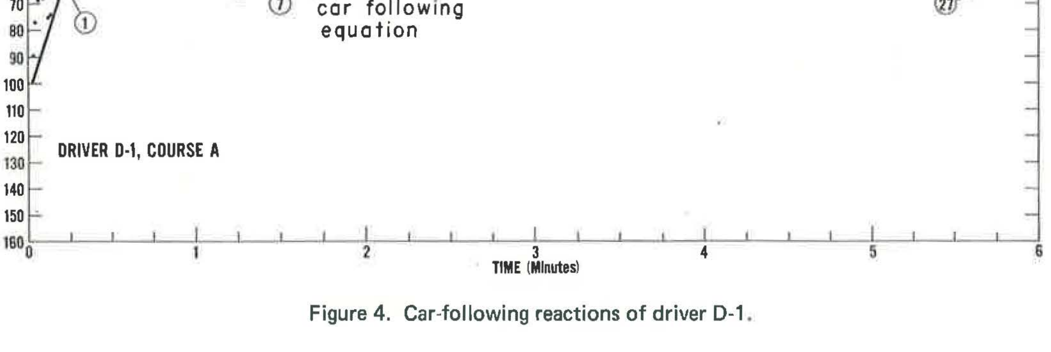

Figure 4. Car-following reactions of driver D-1.

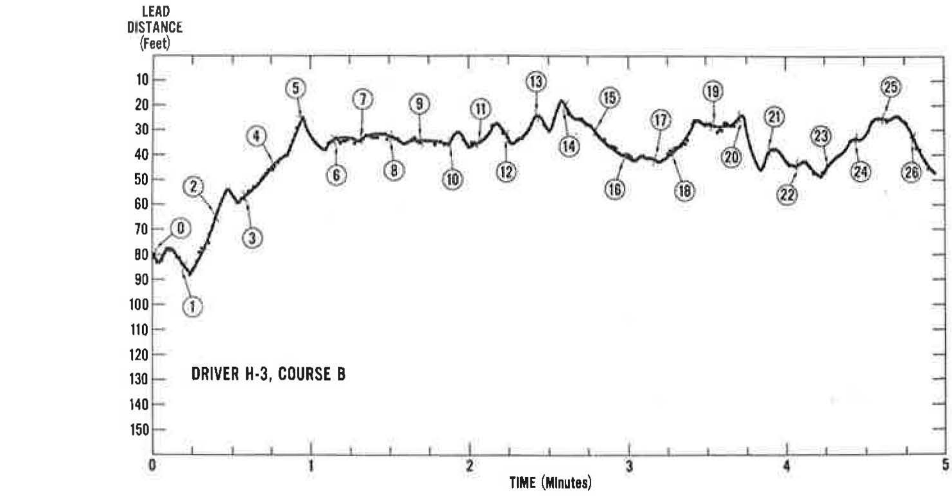

Figure 5. Car-following reactions of driver H-3.

sembles car-following between 0.5 and 1.4 miles, and shows avoidance and drifting up in the next half mile. The car-following (or pacing) portion of the record is at considerably larger distances than those of drivers D-1 and H-3 who car-followed. Another mixed reaction is shown by driver H-1 (Fig. 7). After a slow approach, he dropped back from 41 to 152 ft. The record between 1.5 and 1.8 and between 2.0 and 2.5 miles resembles car-following, although not at very close distance.

Validity of Car-Following Equations

The records of this study are poorly fitted by a car-following equation of the Herman type. Only 7 of the 20 drivers chose to match pace with the plant in front. The others

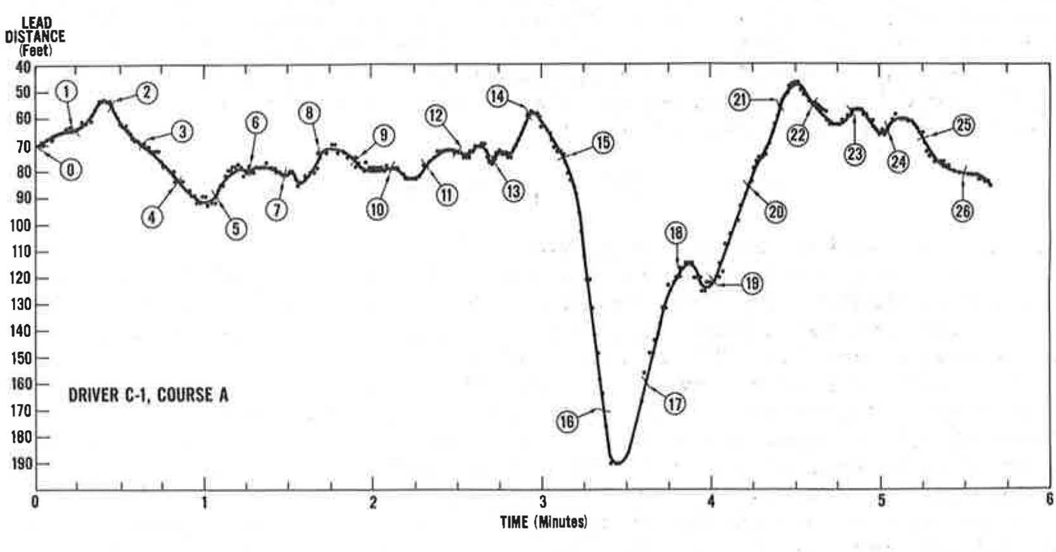

Figure 6. Mixed reactions of driver C-1.

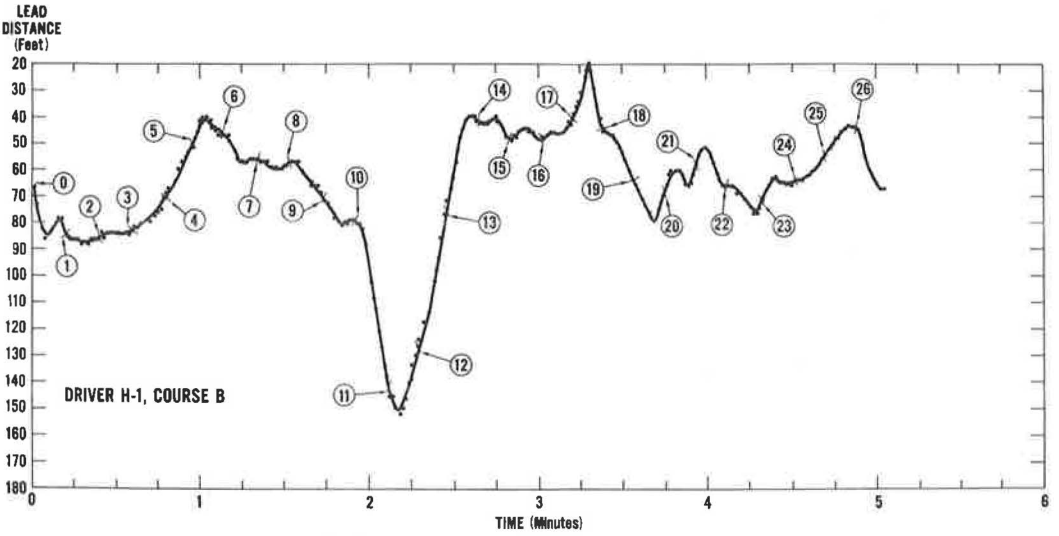

Figure 7. Mixed reactions of driver H-1.

showed avoidance and mixed reactions so irregular that they are not easily matched by an equation.

A comparison of results with the predictions of Herman's car-following equation has been made for the record of driver D-1 who stayed close to the plant vehicle (Fig. 4). A car-following equation of the form

$$(dx/dt)_{n+1} = \alpha_0 \log \left[\frac{x_n(t) - x_{n+1}(t)}{L}\right]$$

was fitted to the data of driver D-1 under the condition that D-1 be 53 ft behind the plant at 17 miles and 40 ft behind the plant $^3/_{10}$ mile farther. These were positions actually assumed by the rear driver. Initial relative velocity was taken as 1.5 fps in the direction of the plant and final velocity at the 1-mile position was taken as zero. It seemed reasonable that the driver has an initial velocity toward the plant; and from the data, it appeared that this driver matched pace at a distance of about 40 ft from the plant. The required equation, solved for α_0 and L is,

$$(dx/dt)_{n+1} = 12.3 \log \left[x_n(t) - x_{n+1}(t)\right] - 19.7$$

The path presented by this equation is shown in Figure 4.

It may be seen that the car-following equation does not give a good fit to the movements of driver D-1. The equation appears to describe the responses to velocity changes of the driver of the car in front rather than in the rear. In the fitted equation, the rear driver cannot come closer than 40 ft to the plant.

The record does not conform to Herman's car-following equation; but it does present some orderly characteristics. The trace consists of a series of small waves or scallops that make up larger movements of advance and retreat from the plant. The driver dithered the accelerator to change distance from the car in front. Each dither served to move the car forward or backward in relation to the plant.

It may be seen that after the initial approach phase, the record consists of a series of back-and-forth movements. The trough of each scallop, from the 0.2- to 0.7-mile position, is below or more distant from the plant than the previous one. This recession

TABLE 2

SIMILARITY OF CAR-FOLLOWING PATTERNS—CHI-SQUARE CALCULATION

Course (1)	Occurrence Frequency: Driver Reaction to Plant (2)	Occurrence Frequency: No. of Tenth-Miles (3)	Percent (4)	Percent Expected by Chance (5)	Difference (Col. 5 - Col. 4) (6)	Difference Squared (7)	Col. 7/Col. 5 (8)
A	4 closer, 0 farther	2	9.1	3.7	-5.4	29.16	7.88
	3 closer, 1 farther	3	13.6	19.1	5.5	30.25	1.58
	2 closer, 2 farther	8	36.4	36.4	0	-	-
	1 closer, 3 farther	6	27.3	30.9	3.6	12.96	0.42
	0 closer, 4 farther	3	13.6	9.9	-3.7	13.69	1.38
Total		22	100.0	100.0			11.26[a]
B	3 closer, 0 farther	2	9.1	10.4	1.3	1.7	0.16
	2 closer, 1 farther	11	50.0	35.1	-14.9	222.0	6.32
	1 closer, 2 farther	3	13.6	39.6	26.0	676.0	17.07
	0 closer, 3 farther	6	27.3	14.9	-12.4	153.8	10.27
Total		22	100.0	100.0			33.82[b]

[a] $11.26 = \Sigma(D^2/Th)$; $\chi^2 < 0.05$ level. [b] $33.82 = \Sigma(D^2/Th)$; $\chi^2 < 0.01$ level.

is followed by a movement forward to 0.8 mile. Lead distance increases again to 1.2 miles and so forth. The bounds of backward-and-forward movement are distinct and without overlap. The same sort of pattern is also found in the other (5) car-following records. The driver appears to dither his accelerator to control a larger oscillation of separation distance from the car in front.

Similarity of Drivers' Reactions

A resemblance was found in the lead distance patterns of drivers who car-followed. Table 2 gives a summary of how drivers who car-followed approached or increased distance from the plant in each tenth-mile from the fourth to the twenty-sixth. (The record of driver G-1, who showed mixed reactions, was also included in the computations on course B.) Drivers' initial approach and final slowing down were not analyzed. There were 4 drivers who car-followed on course A and 3 on course B. It may be seen that, on course A, 5 of the 22 tenth-miles analyzed show all the following drivers making the same reaction (2 in which drivers were moving closer to the plant, 3 in which they were moving farther from the plant). The theoretical expectation is that in only 1.4 (13.6 percent) of the tenth-miles analyzed would this occur. The total chi-square of departure from randomness is beyond the 0.05 level for both groups, indicating that drivers tended to perform similarly. Analyses were made to determine the effects on drivers' approach patterns of road features such as horizontal and vertical curves, passing zones, and intersections. No uniform effects of these features were shown. Probably the effects of curves and the like are superimposed on ongoing approach and receding movements. Moreover the driver tends to anticipate and reacts to road features before they are reached. In the extreme, on steeper hills and sharper curves, some effect would probably have been shown.

DISCUSSION OF RESULTS

The driver's reactions on single-lane roads is understandable in the light of the traffic problem faced. If a driver is impeded and cannot pass, he must accept the situation in one way or another. He can drop back to a comfortable rear position or he can stay close to the car in front to pass when possible. He will not generally press so close as to be damaged if the front driver slows unexpectedly. Nor will he lag so far that he delays or is passed by the driver in back. Within these limits, there is considerable room for individual differences such as found in this study.

From this and other studies (5, 6) the driver emerges as a strategist who makes more or less rational responses that reconcile his need to move ahead with the particular road condition he faces. Considering the wide variety of driver missions and highway conditions, it seems evident that the driver is not successfully modeled by a simple equation or represented as a "black box" element. On the freeway, the driver moves at high speed and does not slow down unless he has to do so (5). On single-lane roads, as shown here, he takes a quite different approach. There is good reason to believe that the driver reacts differently when he is sightseeing, hurrying home from work, bringing an injured person to the hospital, or looking for an unfamiliar address. A simplistic approach to driver modeling appears unwarranted.

SUMMARY AND FINDINGS

A study was made of the reactions of drivers who were impeded and were not aware that they were being observed. The photographic records indicated the distances of the drivers behind the plant car over the 3-mile course.

Three modes of driver response were noted: (a) avoidance, where drivers moved backward out of the influence of the plant, 10 percent of the drivers; (b) car-following, where drivers stayed close to the plant and did not execute large backward or forward movements, 30 percent of the drivers; and (c) a combining of avoidance and car-following, 60 percent of the drivers. Drivers who avoided the plant may have been trying to ease their driving task. Those who followed closely may have been looking for the opportunity to pass.

Driver's lead distance patterns did not conform to Herman's car-following equation. The equation may apply better to the situation where a driver reacts to disturbances introduced by the car in front. The records of drivers who car-followed consist of small waves or scallops that combine into larger movements of approach and recession. The driver appears to dither his accelerator to control a larger oscillation in separation distance from the car in front. There was also a tendency for drivers to approach and move back from the plant at similar parts of the course.

This and previous studies suggest that the driver should be regarded as a strategist who continually adjusts his actions to fit his travel purpose and the road conditions he faces. He is not a stereotyped reacting element or "black box" to be simply described by a fixed equation.

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