Investigation of an Intervehicle Spacing Display

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Unstable spacing between automobiles tends to affect efficient traffic flow adversely. Two experiments were undertaken to test the effect of two types of driver information displays (meters) on vehicle spacing. The first meter showed the driver the actual distance between his car and the car ahead. The second meter showed the driver the algebraic sum of the distance between the two cars and their relative velocity. The latter display increased spacing stability. No marketable device has been designed.

Actual spacing data were compared with theoretical curves obtained from standard car-following laws. A reasonable approximation was obtained.

• TRAFFIC SAFETY and highway capacity are two prime concerns of the traffic engineer. Unfortunately, safety and maximum highway capacity are diametrically opposed in purpose. To achieve maximum highway capacity, vehicles would have to be traveling bumper to bumper, a condition that would obviously be quite dangerous. Conversely, to achieve optimum safety the spacing would be too great to satisfy any reasonable highway capacity requirement. A large number of light signal systems have been proposed to aid the driver following another car. The conventional stop light is the simplest device of this type but it provides only limited information. One solution to this problem would be to automate the driving task fully so that optimum safety and maximum capacity requirements could be maintained. A more economically feasible solution to the problem would be to see if any additional spacing information given to the driver would improve his following performance. This experiment was performed to establish the effect on spacing control of more information about vehicle spacing and relative speed.

Standard car-following laws were used to predict experimental results for display and nondisplay car-following situations.

PROCEDURE

A 1961 Chevrolet was equipped with a car-follower apparatus. The car follower (1) is a device that measures relative speed and distance between two cars. It consists of a reel, attached to the front bumper of a car, holding over 200 ft of piano wire. The wire is fastened to the lead vehicle and a direct current tachometer generator measures the reel-rotating speed which is proportional to the relative speed between the connected vehicles. The number of turns of wire unwound from the reel, as measured by a 10-turn Helipot, indicates the distance between the two cars. A picture and front view drawing of the car follower are shown in Figures 1 and 2. A strain gage accelerometer was mounted in the back seat of the following car. Relative speed, spacing, acceleration, and speed of the following car were all automatically recorded by an oscillograph recorder. The spacing display was mounted on the left side of the front hood of the following car so as not to interfere with vision and yet placed so that only accommodation changes would be necessary when looking at the lead car or the display. A photograph of the indicator mounted on the car is shown in Figure 3.

To test the effectiveness of the spacing display, driver performance was measured with and without additional information. Two identical experiments were performed.

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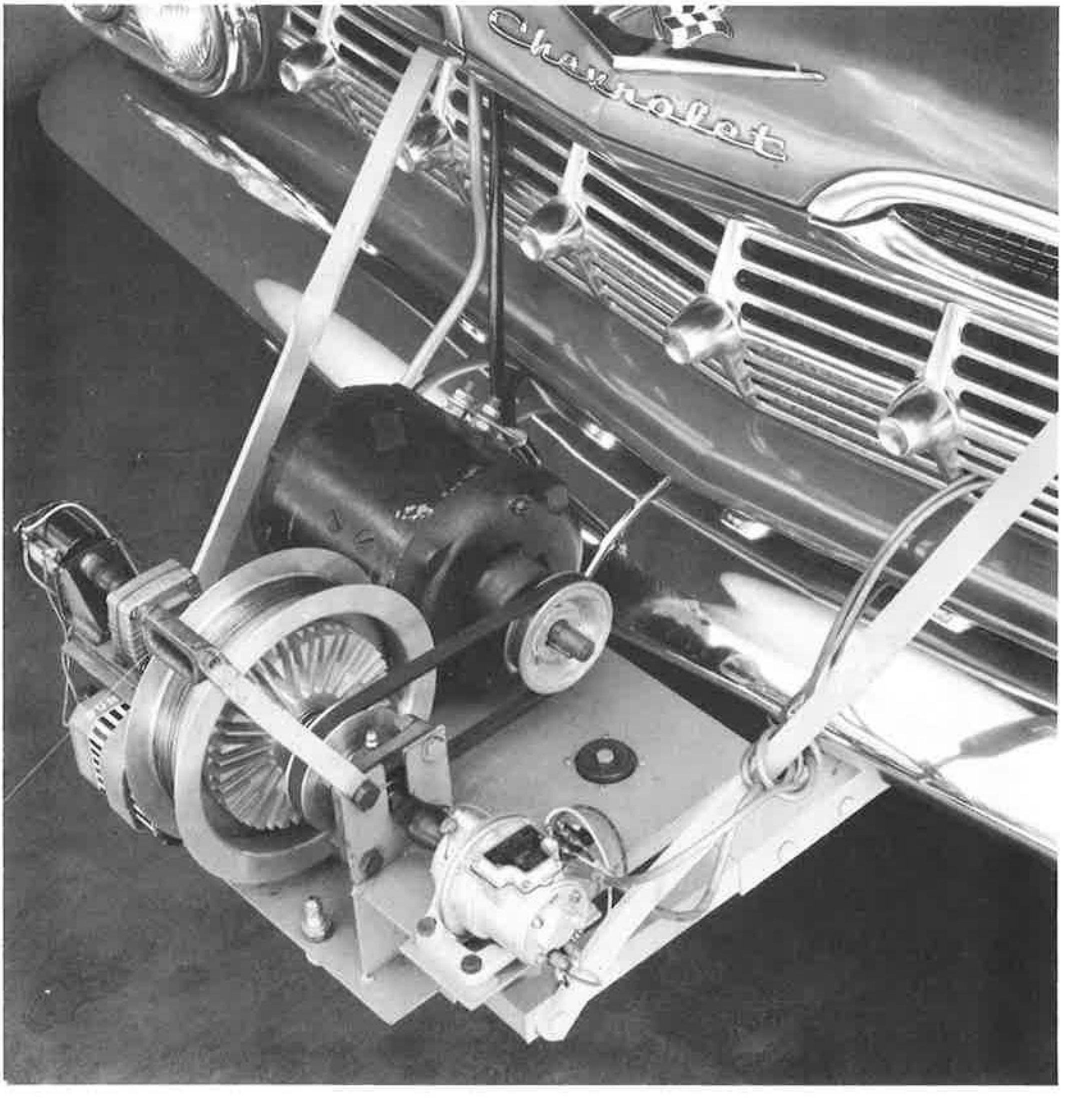


Figure 1. Car-follower apparatus.

The display used in the first experiment was simply a meter which indicated spacing between the two cars from 0 to 160 ft. In the second experiment, the same meter was used with the relative speed between the two cars algebraically added to the relative spacing signal. Full scale for the meter was 0 to 160 ft and ± 6 mph. This produced more exaggerated changes in the meter pointer in response to changes in relative spacing between the two vehicles. This is normally called first-order or velocity-aided information. Figure 4 shows representation of the two displays.

For the spacing display, the output is 0 at a spacing of 80 ft and the pointer moves up the scale as the distance decreases (Fig. 5). The display is analogous to a speedometer indicator that the driver is asked to keep in the center. When it moves up scale, he must reduce speed and vice versa.

In the case of the aided display, the velocity is added in the proper sense to provide anticipatory information. In these experiments the gains were set to produce full-scale positive deflection (from zero center) with $X_1 = 0$ or $X_1 = 6$ mph; i.e., $K_1 = 0.0125$ ft and $K_1K_2 = 0.1667$ per mph.

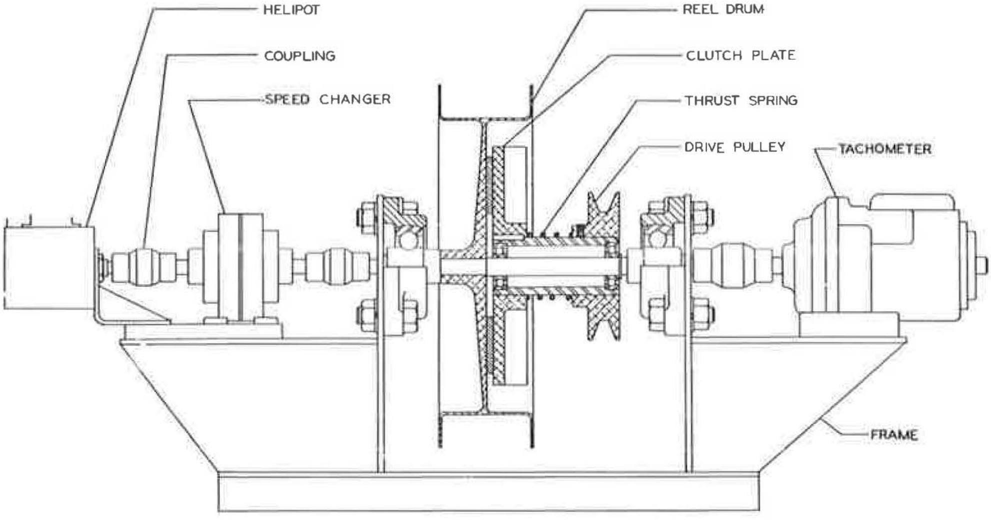
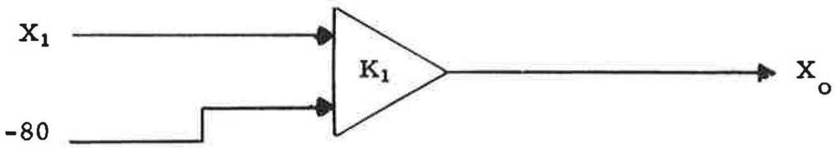


Figure 2. Front view drawing of car-follower apparatus.

Figure 3. Indicator mounted on car.

Zero-Order or Spacing Display

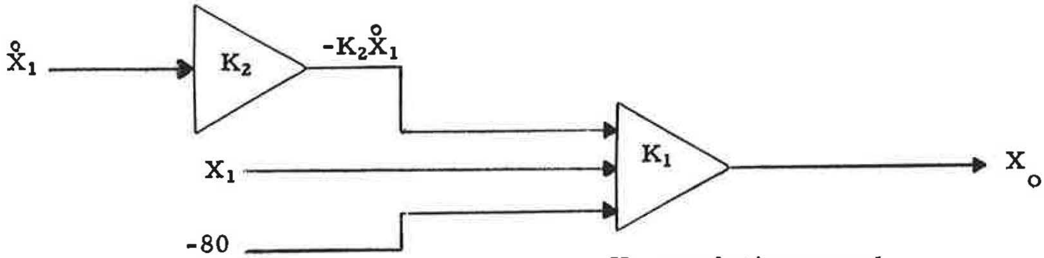


X_1 = intervehicle spacing

X_o = output displacement of zero-centered meter

$X_o = K_1\ (80 - X_1)$

First-Order or Velocity-Aided Spacing Display



X_1 = relative speed

$X_o = K_1\ (80 - X_1 + K_2\mathring{X}_1)$

Figure 4. Representation of the two displays.

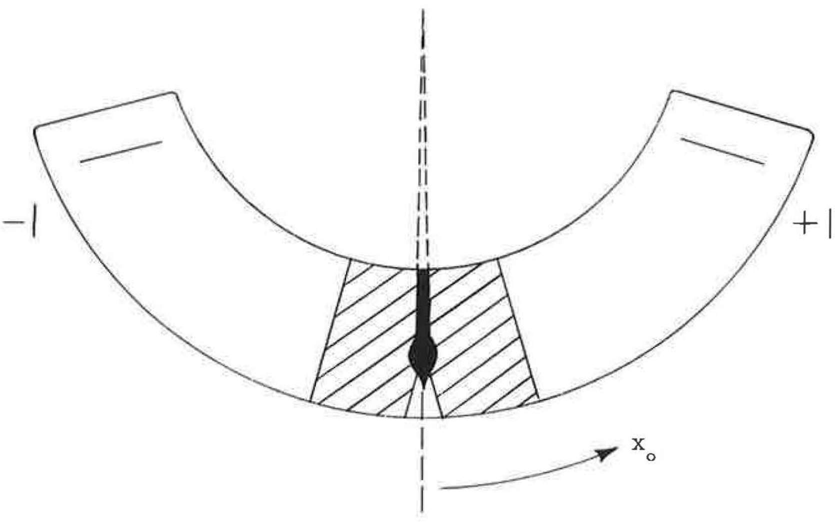


Figure 5. Display face.

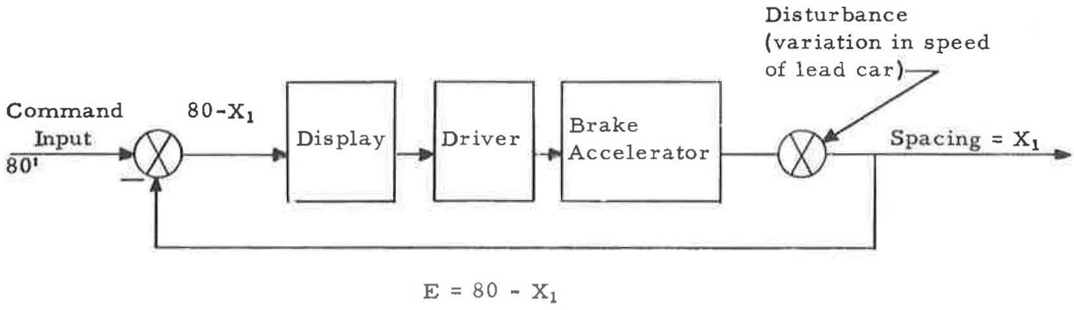


Figure 6. Compensatory display.

The prime advantage of aiding is that the display gives the appropriate derivative terms to provide the driver adequate warning of approaching spacing error. Experimental evidence indicates that a compensatory display should be used in preference to a pursuit display when the system is quickened or aided (2, 3). Both displays are of a compensatory nature in that the driver is provided the error signal and attempts to keep the pointer in the center of the red zone. Any change from the center of the red zone is interpreted as error (E). Figure 6 shows the form of the compensatory display.

The test track at the General Motors Technical Center was used for both experiments. The test track is 1 mi in length and one trip down the straightaway is defined as a trial. Drivers were given two practice trials with the meter to familiarize themselves with its operation. Three variations in lead car behavior were used: constant speed trials (in which the lead vehicle maintained a speed of 45 mph), acceleration trials, and deceleration trials. Both the acceleration and deceleration trials were started at 45 mph and then the lead vehicle at some random point on the test track accelerated or decelerated at 3 ft per sq sec until a speed change of 10 mph had occurred. The lead vehicle then maintained the new speed until the end of the trial. The brake lights of the lead vehicle were disconnected so that they would not influence the driver's judgment of relative speed change. A balanced design has been incorporated to eliminate possible experimental bias. The actual order of presentation is given in Table 1.

One-half the drivers received the preceding order of presentation, and the other half received the conditions ND and SD interchanged. The drivers were told that they were to keep the pointer of the meter in the center of the red zone, which was 80 ft. They were told to treat the display as additional information and to use it as often or as little as they needed to maintain the 80-ft spacing. During the nondisplay trials, the drivers were spaced at 80 ft before records were taken and then the display was turned off. Twelve drivers were used in each experiment. The lead car driver was the same for both experiments as was the lead vehicle.

RESULTS

It was hypothesized that a spacing display should improve driver-following performance. Specifically, it was believed that reaction time to changes in lead vehicle be-

TABLE 1

ORDER OF PRESENTATION[a]

Trial No.	1	2	3	4	5	6	7	8	9	10	11	12
Direction	N	S	N	S	N	S	N	S	N	S	N	S
Condition	NDA	SDB	SDC	NDC	NDB	SDA	SDA	NDB	NDC	SDC	SDB	NDA

[a]ND = no display; SD = spacing display; N = north; S = south; A = constant speed; B = acceleration; C = deceleration.

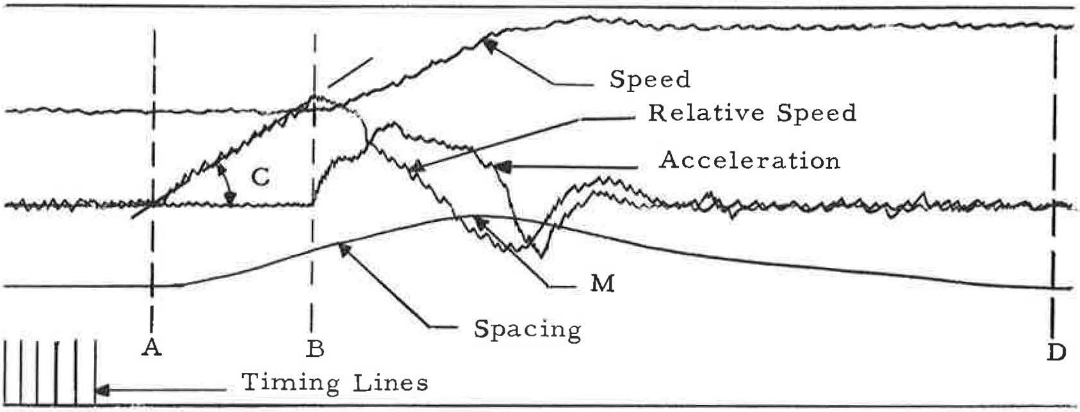


Figure 7. Typical oscillograph record.

havior should decrease, and that maximum spacing change should be reduced. Furthermore, not only should the average spacing error be reduced but the variability in spacing should also be less. A typical oscillograph record of an acceleration trial is shown in Figure 7.

At point A the lead car accelerated at the rate C, which is the slope of the relative speed curve. (Slope of the relative speed curve is only the first car acceleration if the following car speed is constant.) At point B the following car accelerates in response to the lead vehicle. The reaction time or lag time is the time elapsed from A to B. An initial spacing reading is taken at point A and the amount of maximum spacing change in relation to initial spacing is measured at M. Fifteen data points were sampled at equal intervals from A to D which was 20 sec for the acceleration and deceleration trials and the middle 40 sec of the constant speed trials. From some preliminary pilot data it was determined sampling more frequently did not give any additional information.

Experiment Using Spacing Display

It was hoped that the average initial spacing and average acceleration and deceleration rates for display and nondisplay trials would not differ so that unbiased comparisons could be made. Average initial spacing was compared for display and nondisplay trials over all test conditions with no statistically significant difference noted (Table 2). No statistically significant differences were noted for acceleration and deceleration rates for both display and nondisplay trials (Table 3).

An analysis of variance (4, 5) yielded no significant difference in reaction time between display and nondisplay trials for either deceleration or acceleration conditions. Furthermore, no differences were found to exist between acceleration and deceleration conditions (Table 4).

TABLE 2

AVERAGE INITIAL SPACING OVER ALL TEST CONDITIONS

Type of Trial	Spacing (ft)			
	Constant Speed	On Acceleration	On Deceleration	Combined
Display	84.9	87.8	84.0	85.5
Nondisplay	86.4	88.8	87.8	87.6

Similarly, another analysis of variance revealed no significant differences in average maximum spacing change for display vs nondisplay trials (Table 5). There was, however, a significant decrease in average absolute spacing error collapsed across all conditions for the display vs nondisplay trials, $P < 0.025$. Initial spacing was used as the base for determining absolute spacing error (Table 6).

As hypothesized, there was an over-all reduction in the spacing variability for the display trials of 25 percent, with the greatest improvement under the constant speed condition. The three curves (Figs. 8, 9, and 10) show the average absolute spacing error with respect to time for display and nondisplay trials. Virtually no improvement was made during the deceleration trials. The acceleration curves show no differences up to the 6- or 7-sec mark. This would be expected because there was no difference in mean reaction time, average maximum spacing change, and mean acceleration rate for the display and nondisplay trials. However, the "intensity" of the correction for the display trials seems to be much greater than that for the nondisplay trials, resulting in a wide separation at the end of the 20-sec time period. The curves for constant speed show an increase in spacing error with time for both the nondisplay and display trials. However, the error is approximately twice as great for the nondisplay trials at the end of the 40-sec time interval.

It is concluded, then, that the spacing display significantly reduced the average absolute spacing error, with an even greater reduction in the error variability. However, it did not affect the reaction time or the maximum spacing change. In other words, under the best conditions, the drivers were just as sensitive to changes in the lead vehicle without the display as with the display.

TABLE 3

AVERAGE ACCELERATION AND DECELERATION OVER ALL TEST CONDITIONS

Type of Trial	Average Rate (ft/sec^2)	
	Acceleration	Deceleration
Display	2.96	3.23
Nondisplay	2.96	3.06

TABLE 4

AVERAGE REACTION TIME

Type of Trial	Avg. Reaction Time (sec)		
	Accel.	Decel.	Combined
Display	1.58	1.59	1.58
Nondisplay	1.72	1.59	1.65

TABLE 5

AVERAGE MAXIMUM SPACING CHANGE

Type of Trial	Average Maximum Spacing Change (ft)			
	For Constant Speed	On Acceleration	On Deceleration	Combined
Display	11.4	30.9	20.6	21.0
Nondisplay	14.6	34.0	19.8	22.8

TABLE 6

AVERAGE SPACING ERROR

Type of Trial	Average Spacing Error (ft)			
	For Constant Speed	For Acceleration	For Deceleration	Combined
Display	5.1	15.6	9.8	10.2
Nondisplay	7.6	19.9	10.0	12.5

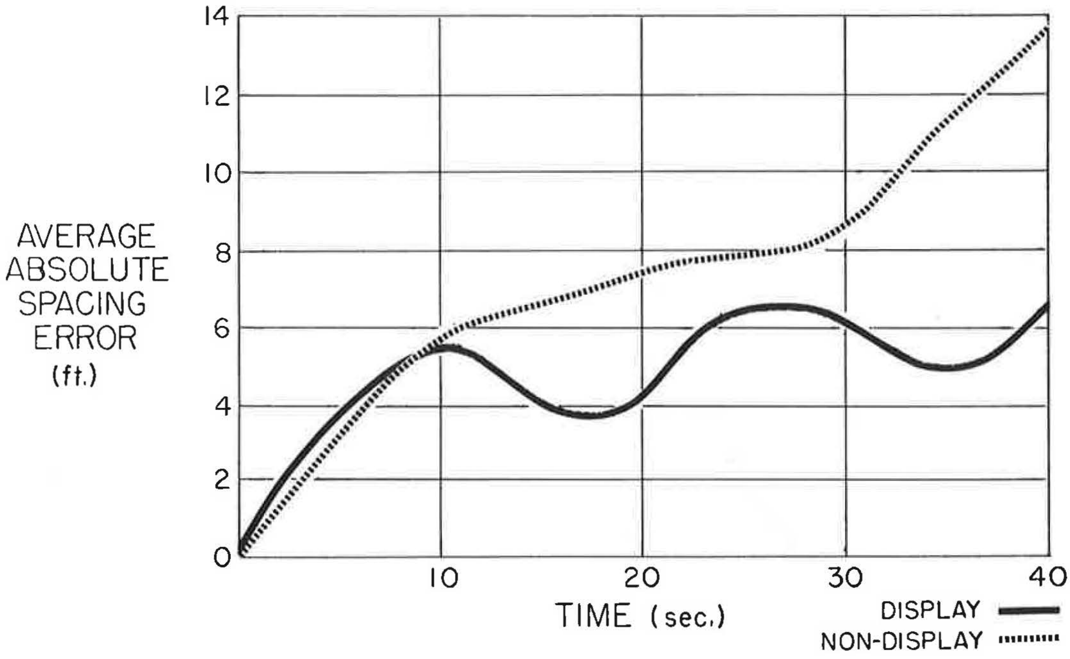


Figure 8. Average absolute spacing error vs time for display and nondisplay trials at constant speed.

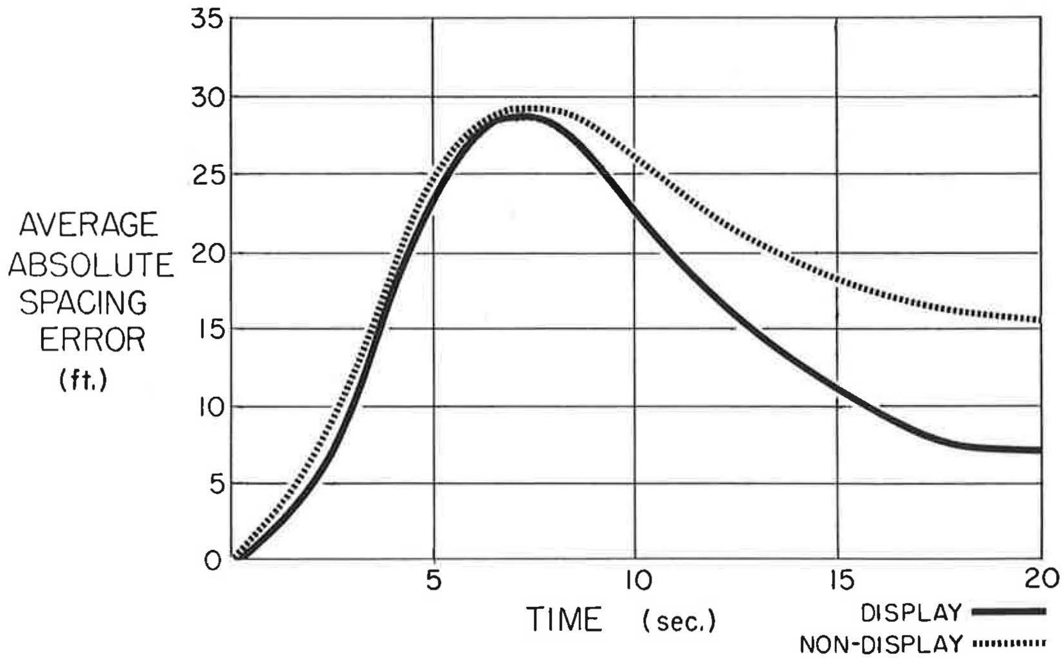


Figure 9. Average absolute spacing error vs time for display and nondisplay trials at acceleration.

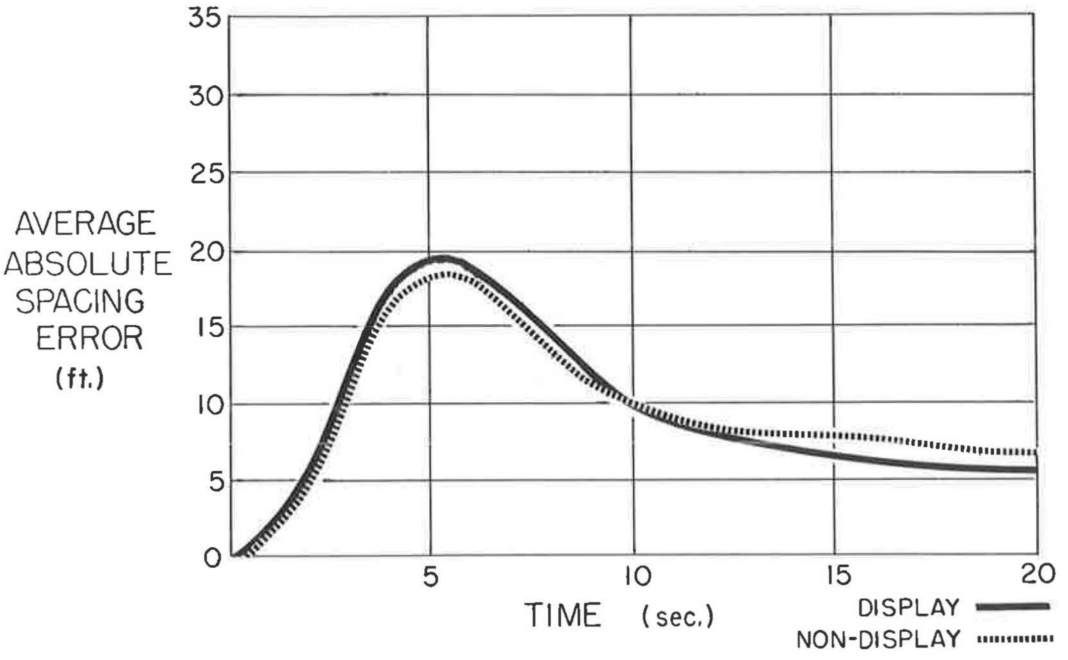


Figure 10. Average absolute spacing error vs time for display and nondisplay trials at decelerations.

Experiment Using Velocity-Aided Spacing Display

Again, it was determined that no significant differences existed between average initial spacing for the display and nondisplay trials (Table 7). The average acceleration and deceleration rates did not differ and compared favorably with the average values obtained in the first experiment (Table 8).

An analysis of variance was performed on the reaction time data and the average reaction time for the display trials was found to be significantly less than for the nondisplay trials, $P < 0.005$ (Table 9). The interaction between displays and conditions was significant at the 0.05 level of confidence. This means that the display had a greater effect on reaction time for acceleration trials than it did for deceleration trials. Again, no significant differences were noted between the acceleration and deceleration conditions.

The average maximum spacing change was significantly reduced ($P < 0.005$) for the display trials as would be expected by the decrease in reaction time. The nondisplay results are nearly the same as those of Table 5, further verifying the consistency of the tests (Table 10). Again, as with the spacing display, a significant decrease in

TABLE 7

AVERAGE INITIAL SPACING

Type of Trial	Average Initial Spacing (ft)			
	Constant Speed	Acceleration	Deceleration	Combined
Display	81.0	82.1	80.5	81.2
Nondisplay	81.0	86.9	81.3	83.1

average spacing error for the display trials ($P < 0.025$) was found to exist. Once again, the nondisplay results (Table 11) may be compared with Table 6.

An even greater reduction in spacing variability for the display trials was shown for the velocity-aided spacing display, 47.5 as compared with 25 percent for the position display. Decreases in variability of 71.5, 60 and 25 percent were observed for the constant speed, acceleration, and deceleration conditions, respectively. The three average absolute spacing error curves with the velocity-aided spacing display are shown in Figures 11, 12, and 13. For the acceleration condition the peak for the display trials is significantly less than for the nondisplay trials. This is true to a somewhat lesser degree in the deceleration trials. During the constant speed condition, spacing error again increases with time for the nondisplay trials, while leveling off for the display trials.

TABLE 8

AVERAGE ACCELERATION RATE

Type of Trial	Avg. Accel. Rate (ft/sec^2)	
	Acceleration	Deceleration
Display	3.09	2.96
Nondisplay	2.85	2.98

TABLE 9

AVERAGE REACTION TIME

Type of Trial	Avg. Reaction Time (sec)		
	Accel.	Decel.	Combined
Display	1.11	1.34	1.23
Nondisplay	1.68	1.68	1.68

One interesting result of both experiments was the qualitative way the drivers reacted to inputs of the lead vehicle. The response time was virtually independent of the different acceleration and deceleration rates. Although the average acceleration and deceleration rates were approximately 3 ft per sq sec, rates ranging from 2 to 4 ft per sq sec were experienced. The correlation between acceleration rate and response time was essentially zero. This result agrees with previous research which found response time relatively independent of the slope of the ramp input (6). Undershooting (undercorrecting) by the drivers was more common during deceleration than acceleration conditions. During the deceleration condition, the driver would remove his foot from the accelerator pedal and, after seeing that the car in front was slowing down at a more rapid rate than expected, then apply the brake. This may be due to the normal cue of the brake lights not being available. In about 30 percent of the acceleration

TABLE 10

AVERAGE MAXIMUM SPACING CHANGE

Type of Trial	Average Maximum Spacing Change (ft)			
	Constant Speed	Acceleration	Deceleration	Combined
Display	7.0	26.3	19.9	17.7
Nondisplay	14.8	32.5	23.0	23.4

TABLE 11

AVERAGE SPACING ERROR

Type of Trial	Average Spacing Error (ft)			
	Constant Speed	Acceleration	Deceleration	Combined
Display	4.0	15.0	9.1	9.4
Nondisplay	7.1	18.8	11.2	12.4

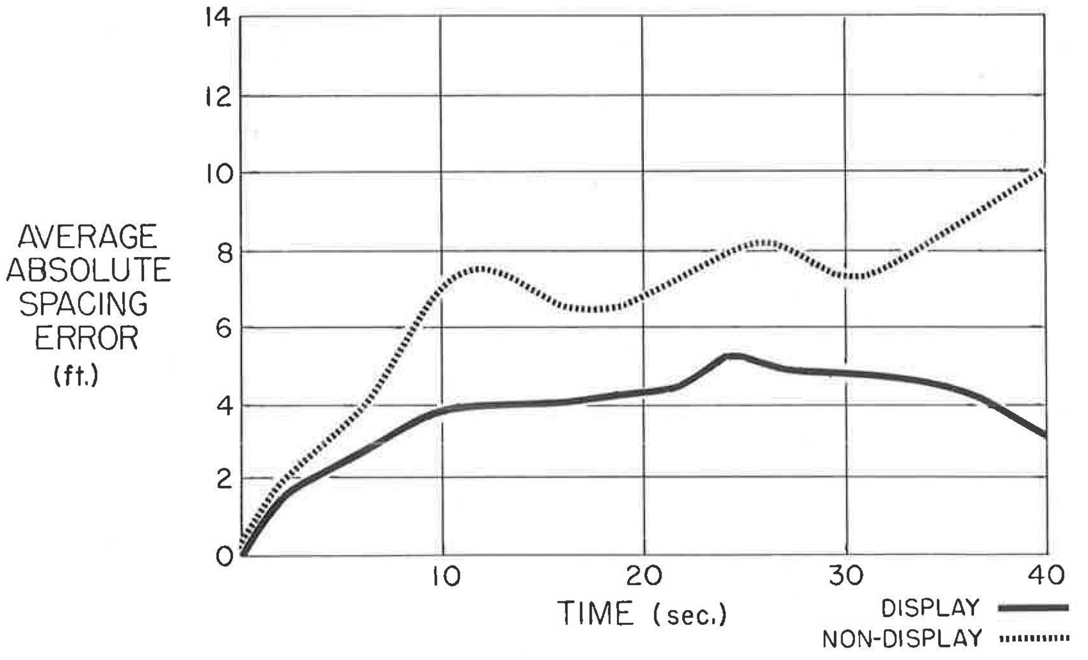


Figure 11. Average absolute spacing error curve with velocity-aided spacing display, for constant speed.

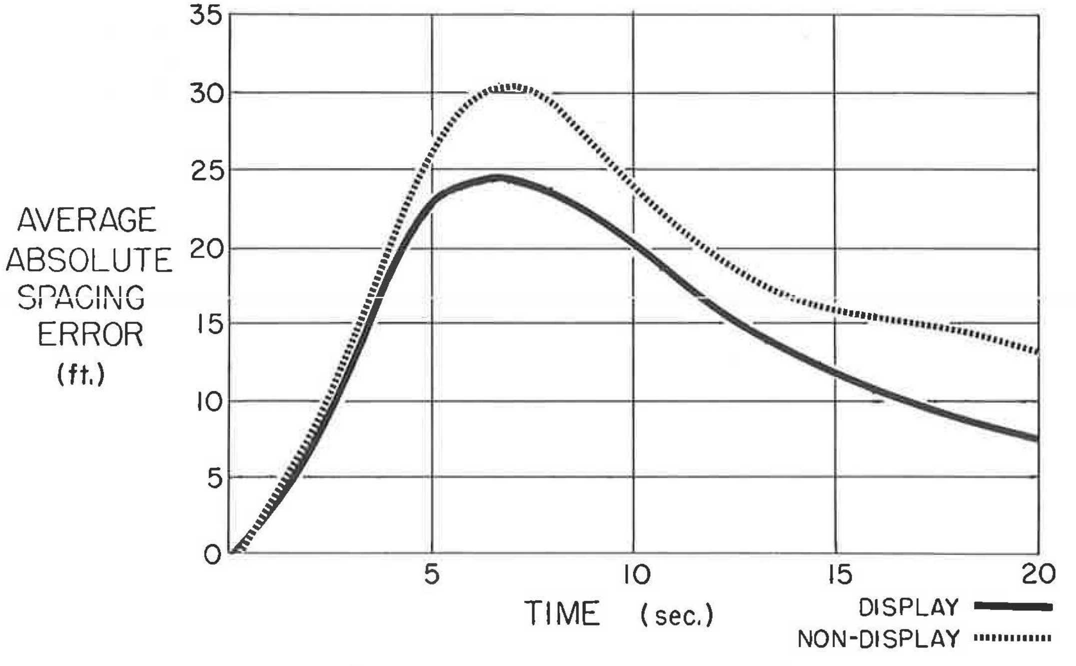


Figure 12. Average absolute spacing error curve with velocity-aided spacing display, for acceleration.

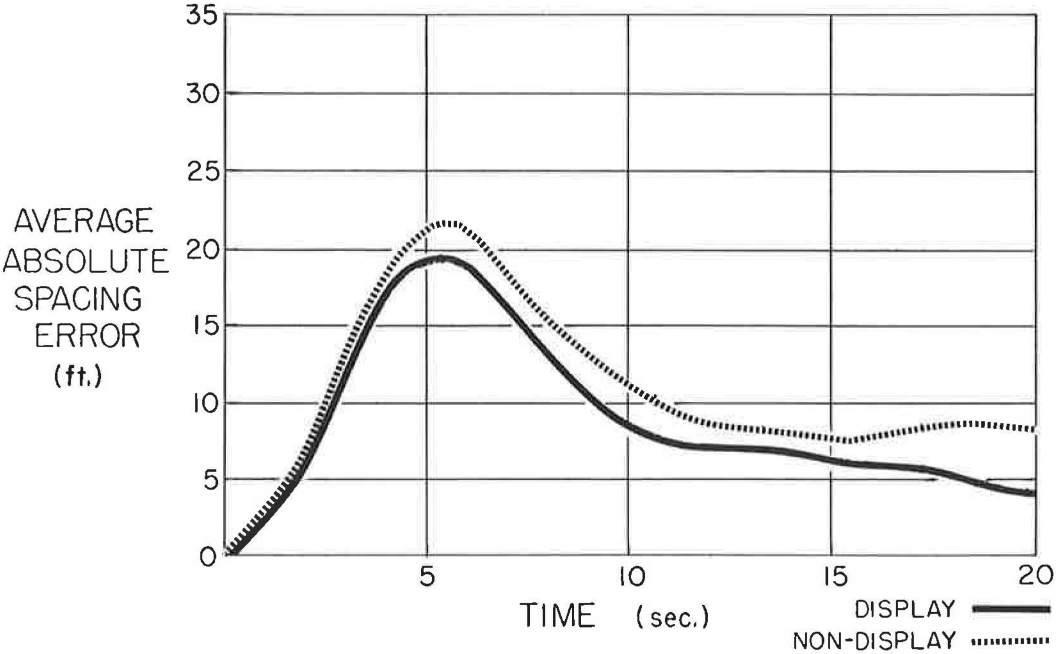


Figure 13. Average absolute spacing error curve with velocity-aided spacing display, for deceleration.

trials drivers made an initial correction and then had to correct harder. This second correction also took place to a lesser degree after initial braking. The percentage of second corrections was significantly reduced for the velocity-aided display trials.

Because both experiments were identical, with the exception of the type of displays used, the nondisplay group's performance should be quite homogeneous. Tests for homogeneity of variance between the two groups of drivers were performed on reaction time, maximum spacing, and average spacing data. The values of F obtained were all nonsignificant. The two groups' variances are said to be homogeneous; that is, they are both assumed to be estimates of the same population variance.

SUMMARY AND CONCLUSIONS

By changing the position display into a velocity-aided spacing display, following performance was significantly improved. Not only was there a greater reduction in the average spacing error variance, but significant decreases in maximum absolute spacing change were observed. Also, driver reaction time was reduced markedly. By analyzing the reaction time data a little further, the total reaction time is found to be made up of a number of different reaction times, such as detection time (the time it takes a driver to notice a change in lead vehicle behavior), decision time (the time involved in deciding whether to step on the gas or to use the brake), and simple response time (time elapsed from the decision until the actual response is initiated). There are some relatively accurate estimates of these reaction times from previous research (7); for example, decision time for a two-choice situation is usually between 0.25 and 0.30 sec; simple response time is normally between 0.19 and 0.26 sec (an additional 0.19 sec is involved in moving the foot from the gas pedal to brake (8). Therefore,

Total Reaction Time = Detection Time + 0.225 + 0.275 = D.T. + 0.50

and for deceleration,

Total Reaction Time = Detection Time + 0.225 + 0.275 + 0.19 = D.T. + 0.69

TABLE 12

DETECTION TIME

Type of Time	Type of Rate	Detection Time (sec)	
		Velocity-Aided Display	Nondisplay
Total response	Acc.	1.11	1.68
	Dec.	1.34	1.68
Detection	Acc.	0.61	1.18
	Dec.	0.65	0.99

Detection time is the only place where an immediate improvement in driver response can be made with indicators of the type used here. The improvement made by the velocity-aided display is shown in Table 12 (assuming the preceding average decision and response times).

The reduction in detection time for the acceleration condition was 48 percent, whereas the detection time for deceleration was reduced by 34 percent.

The particular experiments described have attempted to see if driver-following performance could be improved, even under the best possible conditions. The driver was given a specific task (to maintain an 80-ft spacing) and was told to perform as well as he could. It was felt that if an improvement in performance could be realized when the driver was performing optimally that any device that could be developed would be worth even more for the normal driving situations. Because the veloctiy-aided spacing display improved following behavior significantly, it is feasible to assume that a device similar to it would be a great help in limited-access highway driving situations. Although the display used in the present experiment was of a visual nature, this does not mean it is the best possible means of displaying spacing information. No attempt was made in the current test to establish optimum values of the constants K_1 and K_2. Further research is necessary to establish the effectiveness of different displays. Because the visual channel is quite overloaded, an obvious alternative would be a display that utilizes one of the other sense modalities, such as audition. Finally, some practical means of determining spacing and relative speed must be found.

THEORETICAL IMPLICATIONS

A number of theories have been proposed concerning single-lane traffic following in which the driver responds to stimuli from cars in front or behind him (9, 10, 11, 12). These follow-the-leader theories can be represented by a differential-difference equation:

$$\text{Driver Response} = \text{sensitivity} \times \text{stimulus} \tag{1}$$

The driver response to some stimulus can be either acceleration or braking. Previous research has been quite successful in establishing a high correlation between the acceleration response of a driver and the relative speed between the following and lead vehicles (10). The equation describing the following vehicle's acceleration is

$$\ddot{X}_F (t + T) = \lambda \left[\dot{X}_L (t) - \dot{X}_F (t) \right] \tag{2}$$

in which

$\dot{X}_L$ = speed of lead vehicle;

$\dot{X}_F$ = speed of following vehicle;

λ = sensitivity; and

T = reaction time of the driver-car system.

It has been shown that if λ is a constant a fairly good approximation to the actual data

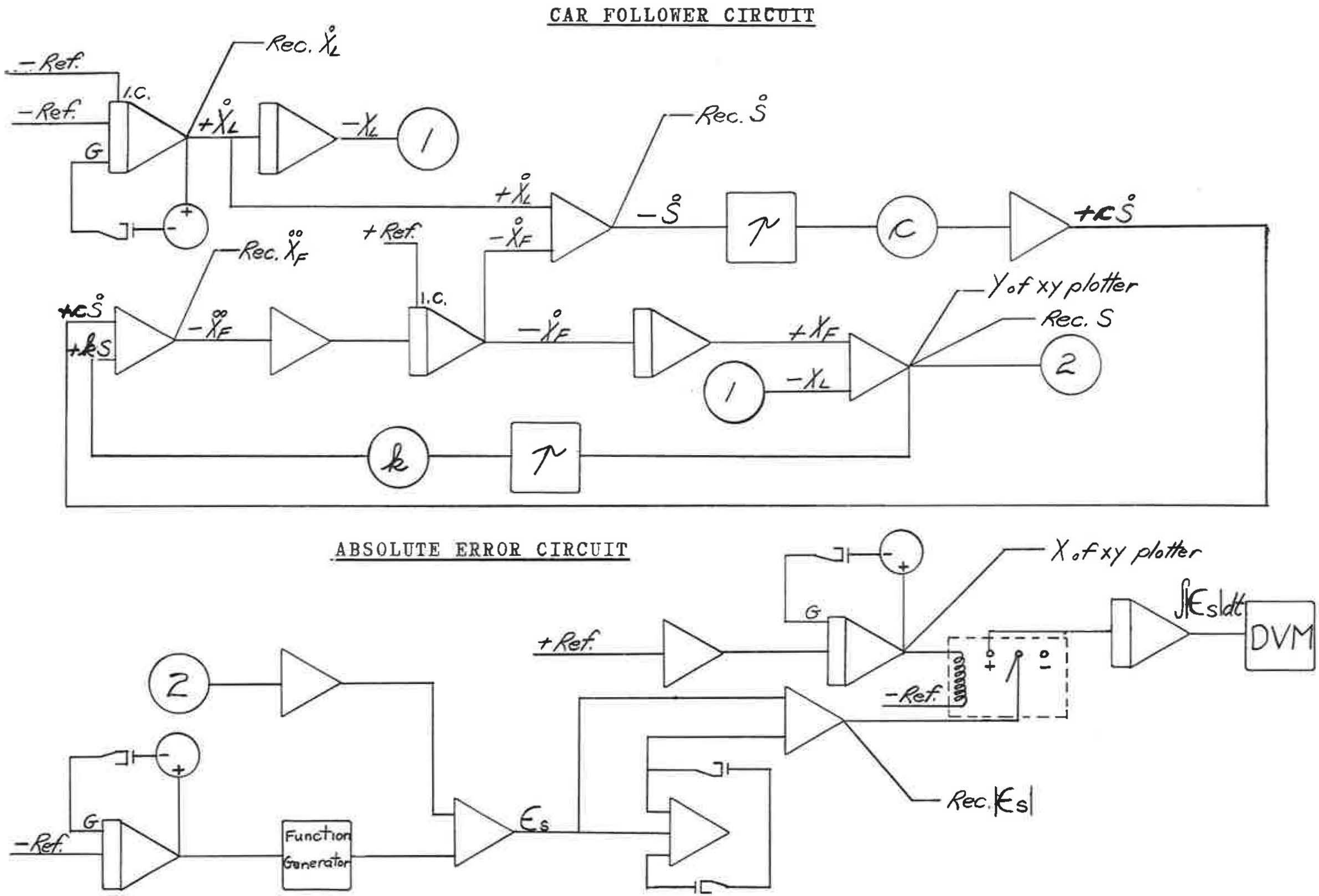


Figure 14. Circuits for car-following law and measurement of absolute error.

can be obtained by the car-following law (Eq. 2). An even better approximation to the data can be made by assuming that λ is inversely proportional to the spacing (11, 12).

Because the initial spacing was relatively constant in the present experiment, Eq. 2 was chosen with λ being a constant to describe the driver's response. It is believed that the driver is using two types of information in responding to changes in the lead vehicle. Not only does the driver react to relative speed differences but he corrects for changes in relative spacing:

$$\overset{\circ\circ}{X}_F (t + T) = c [\overset{\circ}{X}_L (t) - \overset{\circ}{X}_F (t)] + k [X_L (t) - X_F (t)] \tag{3}$$

in which

X_L, X_F = positions of the two cars at time t; and

c, k = sensitivity constants for relative speed and relative spacing, respectively.

If $\overset{\circ}{S}$ and S represent the relative speed and relative spacing terms in Eq. 3, then

$$\overset{\circ\circ}{X}_F (t + T) = c (\overset{\circ}{S}) + k (S) \tag{4}$$

An analog simulation of Eq. 4 was made and compared with the actual spacing data in the present experiment. Two circuits (one for the car-following law and the other for measuring absolute error) are shown in Figure 14. The absolute error circuit compares the theoretical relative spacing from the car-following law with the actual relative spacing data obtained in the experiment. The experimental data are reproduced by using an XY plotter as a function generator. The absolute error $|E_S|$ is cumulated and is displayed in digital form on a digital voltmeter. The initial conditions for the simulation were the same as the actual experiment. In other words, the simulated initial speed of the lead and following vehicles was 45 mph or 66 ft per sec. The lead vehicle accelerated or decelerated at the average rate of 3 ft per sq sec until a 10-mph or 14.7-ft per sec change was reached. The time delays used for the simulation were the same as those in Table 9. Each simulation lasted 20 sec. Values of c and k were varied until the $|E_S|$ was a minimum. The values of c and k which produced the best fit to the experimental data are given in Table 13, in addition to the average error between theoretical and actual relative spacing curves. A change of approximately ± 5 percent in the c and k values does not significantly affect the average error ($|E_S|$).

The values of c were greater for deceleration than acceleration; however, the k values remained fairly constant. Values of c and k were greater for the display curves of acceleration and deceleration than for the nondisplay curves. In other words, the velocity-aided spacing display increased the driver's sensitivity to changes in relative speed and spacing. Figures 15 through 18 show the agreement between the theoretical and actual relative spacing curves.

The value of c is analogous to the damping factor in a physical mass-spring-damper

TABLE 13

AVERAGE ERROR[a]

Type of Trial	Type of Rate	Average Error c	k	$\overline{E}_S$(ft)
Display	Accel.	0.530	0.020	0.74
	Decel.	0.760	0.032	1.08
Nondisplay	Accel.	0.470	0.014	1.02
	Decel.	0.710	0.014	1.73

[a] $(\overline{E}_S) = \dfrac{\int_0^T |E_S| dt}{T}$

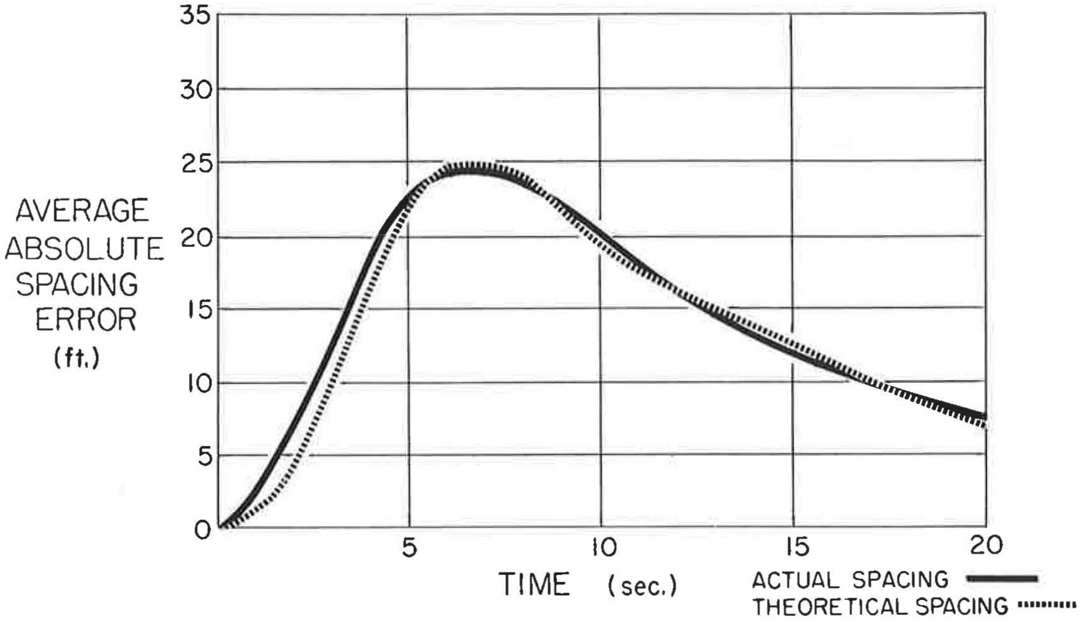


Figure 15. Agreement between theoretical and actual relative spacing curves for acceleration in display trials.

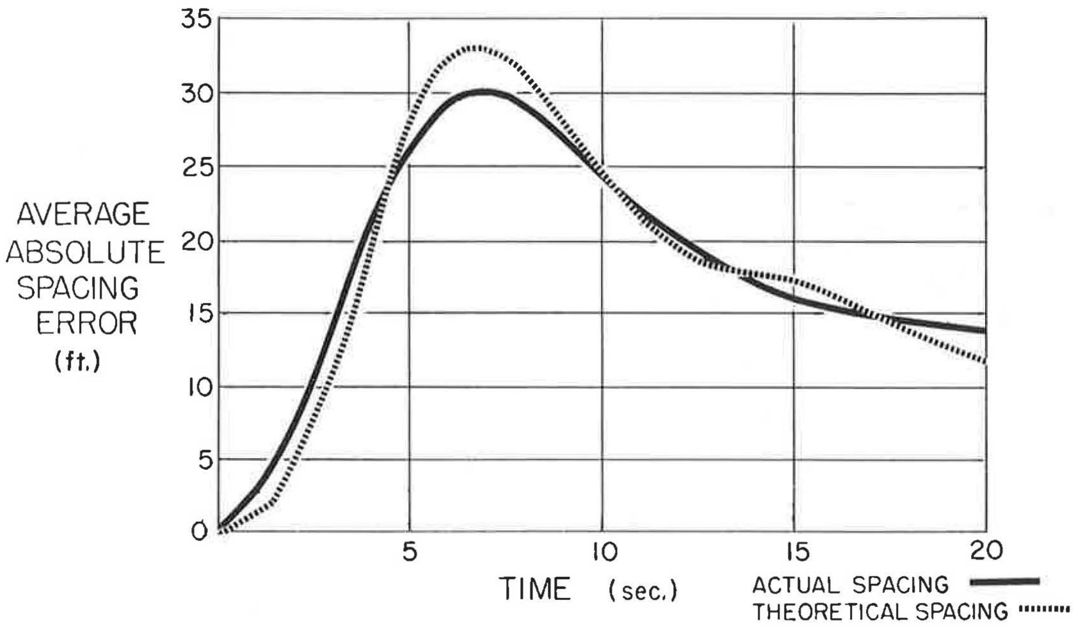


Figure 16. Agreement between theoretical and actual relative spacing curves for acceleration in nondisplay trials.

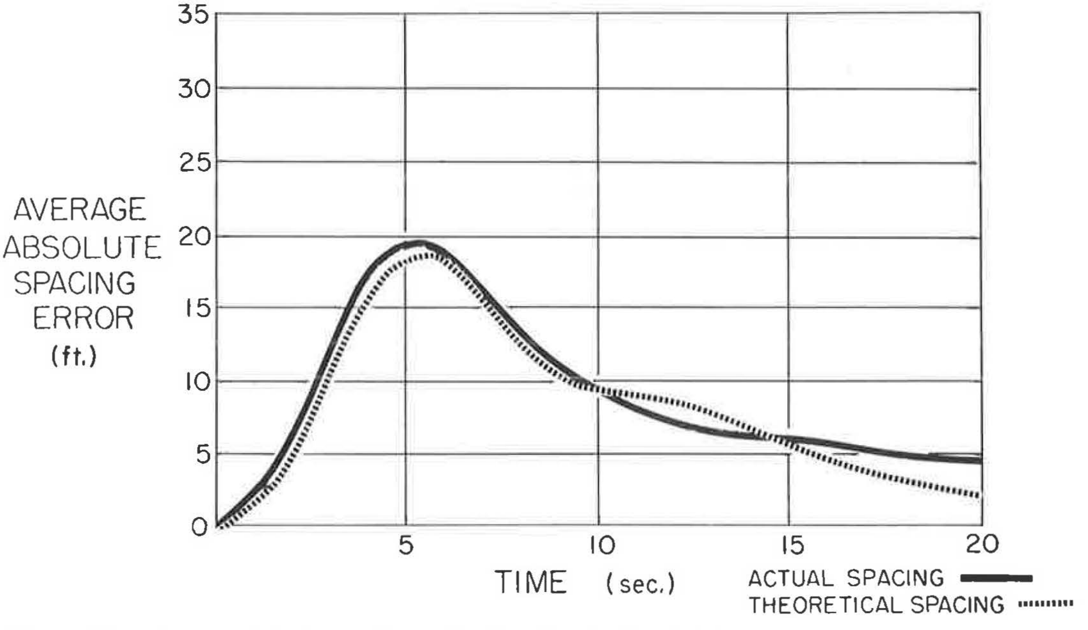


Figure 17. Agreement between theoretical and actual relative spacing curves for deceleration in display trials.

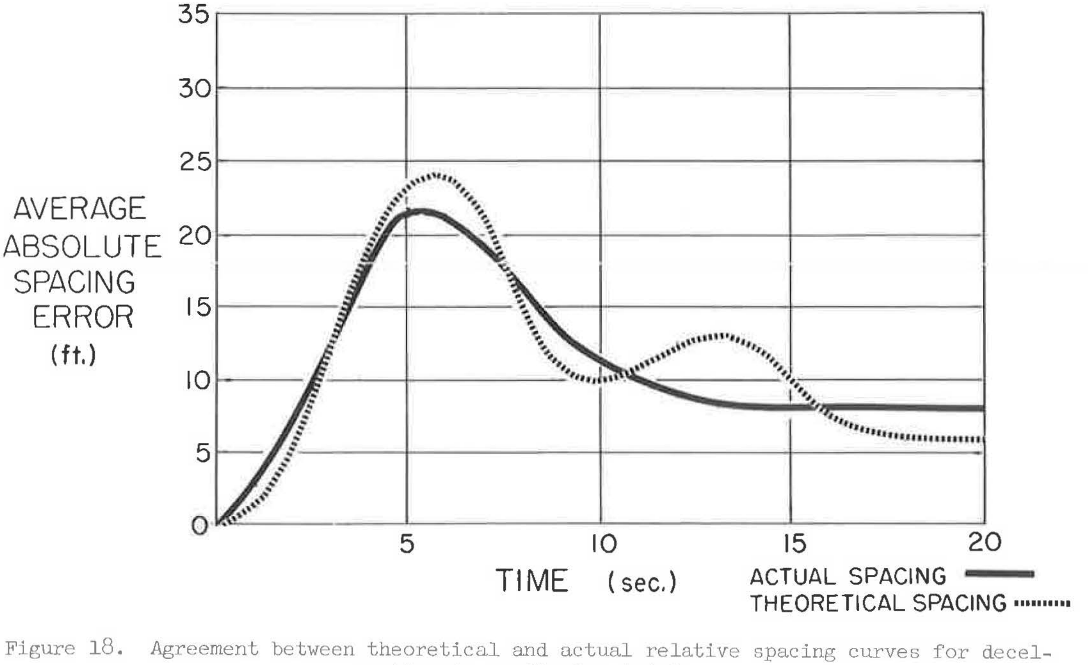


Figure 18. Agreement between theoretical and actual relative spacing curves for deceleration in nondisplay trials.

system and limits the relative velocity between the two cars, whereas the k term is analogous to the spring constant and determines the rate of recovery to initial spacing. Further research will attempt to determine the amount of change in c and k for various initial spacings, relative speeds, and reaction times. Also, the values of c and k for individual drivers rather than average group performance will be obtained.

ACKNOWLEDGMENT

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