Effect of Speed Change Information on Spacing Between Vehicles

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The purpose of this study was to determine whether advance information on speed changes through a visual signal system markedly changes car-following behavior. A simple signal system placed on a lead vehicle categorized speed changes into four classes—two for acceleration and two for deceleration. The driver of the "following" vehicle was instructed to follow as if he were in heavy traffic and wished to prevent anyone from cutting in front of him. He was instructed to watch the signal system for advance information on the speed changes of the lead vehicle. A distance measuring system was placed in the following vehicle with which it was possible to measure headway continuously to within an accuracy of 5 percent. The headway was converted to digital form and encoded on a digital recorder. Speed of the following vehicle, together with the nominal speed and acceleration of the lead vehicle, was also recorded.

Speed changes in the lead vehicle were either 3 or 6 mph per sec and occurred in random order. The occurrence of a speed change was randomized over time so that the following driver did not know when or what change was to take place. The advance speed change information was presented at one of four time intervals before the onset of the speed change. A control condition was used in which no information was transmitted.

Results indicated a significant reduction in mean headway when advance speed change information was presented and that headway was a minimum when the advance information was presented approximately 1 to 3 sec before the onset of the speed change. At these optimum times the variability in headway was also significantly reduced. In addition, headways were found to be independent of speed; thus, time headways decreased almost linearly with speed over the range from 36 to 54 mph.

• VARIATIONS in the spacing maintained between vehicles has been attributed primarily to the drivers' reactions to changes in the speed of the preceding vehicle. On this basis, tests were conducted, with two- and three-car queues, in which a communications system was employed to transmit advance speed change information to the driver of a rear test car. Test data were analyzed to determine the effectiveness of the communications system—the test drivers' responses were studied to determine whether intervehicle spacing had been modified as the result of transmission of the advance speed change information.

This study was undertaken because intervehicle spacing is considered one of the more important factors affecting the stability of car-following patterns and thereby influencing the volume of traffic that can be moved on a highway. Analysis of the two-car test data indicated that use of a communications system, similar to the one employed in the study reported here, could increase the traffic-carrying capacity of a highway. From analysis of the three-car test data, it was noted that most of the potential effect of the communications system had been eliminated by interposition of a third car. With use of the communications system, a relation between advance warning time and the distance headways was noted for two-car queues.

Variability in headways was substantially reduced when the driver of a rear car had advance information on the speed changes. The variability noted in driver responses to information provided by the communications system indicates that the stability of intervehicle spacing is greatly influenced by fluctuations in the individual driver's psychological state. The behavior of drivers following in queues may be subdivided into two parts: (a) operation in a queue, which concerns the response of drivers in a queue to an imposed speed change by the vehicle ahead; and (b) steady-state operation; that is, the time and space relations that exist when all vehicles are traveling at about the same speed.

Recent research (1) indicates that variations in spacing between vehicles operating in a queue are determined primarily by the drivers' reactions to changes in speed of the vehicle ahead and, secondarily, by the distance between vehicles. When a change in speed is imposed in the lead car, the driver of the second car, in order to maintain his spacing, reacts to the change in speed and not to the change in distance. Thus, he changes the speed at which his car is traveling to eliminate any difference in speed between the cars. The stability of the operation depends, therefore, on the length of time elapsing from the lead vehicle's change in speed to its detection by the driver of the following car, as well as to his ability to modify the speed of his car.

As pointed out by Brown (2), estimates of speed changes ultimately depend on the driver's ability to detect changes in visual angle (the angle, at the eye of the observer, subtended by the boundaries of an object), which governs the time a driver requires to detect changes in the speed of the lead vehicle. Because of human limitations, small changes in visual angle and hence in speed are not detectable. Consequently, in normal car-following patterns a time lapse occurs between the initiation of a speed change in the leading car and its detection by the driver of the following car. To a large extent, much of the instability of operation in queues as demonstrated by other car-following studies could have resulted from the relative insensitivity of the drivers to small changes in visual angle.

The foregoing factors should also influence the behavior of drivers during steady-state following. Thus, the following distance that a driver will adopt during constant speed following should be in the range that maximizes his discrimination of lead-vehicle speed changes. In addition, his mean following distance should be contingent on the fact that he has no prior knowledge of the occurrence of any acceleration of the lead vehicle. Neither does he have any knowledge of the magnitude of that change of speed. (Display of brake lights or hand signals may warn of deceleration.) Therefore, the following driver may be expected to adopt a steady-state spacing to compensate for his uncertainty stemming from these two factors: his inability to detect small changes in visual angle and his inability to anticipate the change in speed.

This view of car following suggests two methods for improving the stability of following during both accelerative changes and in the steady-state. One method is to improve the ability of drivers to detect changes in visual angle. The second method is to provide the drivers of following cars with advance information about the magnitude of the speed change and its occurrence in time. The second method provided the basis for the study discussed in this article.

From the foregoing analysis several hypotheses are possible about the behavior of the driver of a car, when he is given information on the type and magnitude of each change in speed to be made in the lead vehicle.

First, the driver of the following car, by responding to this advance information, should be able to compensate for changes in speed in the lead vehicle by beginning his maneuver before the onset of the change. The degree of compensation effected should depend on the interval of time between the driver's receipt of the information and the onset of the speed change in the lead vehicle.

Second, because the driver of the following car does not have to rely on his ability to detect changes in speed, he will not have to maintain a spacing commensurate with his maximum ability for such detection. Consequently, it is reasonable to assume that the average headway during a constant speed operation would be less with a communications system than without it. (Headway is the time or space interval between two vehicles traveling in the same lane. For precise reference, the terms "distance headway" and "time headway" are used.)

Third, the variance in headway between cars in a constant speed operation should be decreased when communication is employed.

In summary, the purpose of this study was to determine whether, in a simple pattern of one car following another, intervehicle spacing could be modified when drivers were provided advance information on speed changes. The effects of this kind of communication were to be determined in both the steady-state following and in response to speed changes.

METHOD

Recording Instruments and Their Use

A stadimeter (a range-finding device) was used in this study to measure the distance headway between a pair of vehicles. The stadimeter operates on the same principle as the sextant in that two images are brought into coincidence by use of a rotating mirror. Because use of the stadimeter requires specification of some dimensions of the target whose range is sought, the dimension was marked by two brightly painted targets mounted on the rear bumper of the lead vehicle (Fig. 1). The mounting of the stadimeter in the second car is shown in Figure 2.

The stadimeter operator viewed the lead car through the ring sight on the right of the instrument. While looking at one target, he slowly rotated the mirror on the left of the sight by turning the crank on the left side of the instrument, until the image of the second target coincided with that of the first. The hand crank also was geared to drive a precision potentiometer so that the angular displacement of the mirror was translated into a voltage change. The distance in feet between the vehicles is inversely related to the angular rotation of the mirror. By use of a calibration procedure the voltage change was converted to the distance in feet.

The task of the stadimeter operator was to keep the two targets in coincidence during the run. For distances of more than 50 ft, tracking error generally was less than 5 percent, which was adequate for purposes of this study. A digital recording system, described by Hopkins (3), was employed to store the data. Headway readings were converted to digital form by use of a digital voltmeter, were read out, and were stored by use of a digital printer. The speed of the rear vehicle also was determined, digitized, and stored in the printer. An equipment operator in the rear car manually coded the following listed data into the printer: each speed change made by the lead vehicle, its speed at the beginning and ending of each maneuver, and the time each maneuver was started and ended.

Figure 1. Two-vehicle platoon; lead vehicle with overhead communications system and vertical targets mounted on rear bumper; rear vehicle which had fifth wheel and generator atop car driven by test driver.

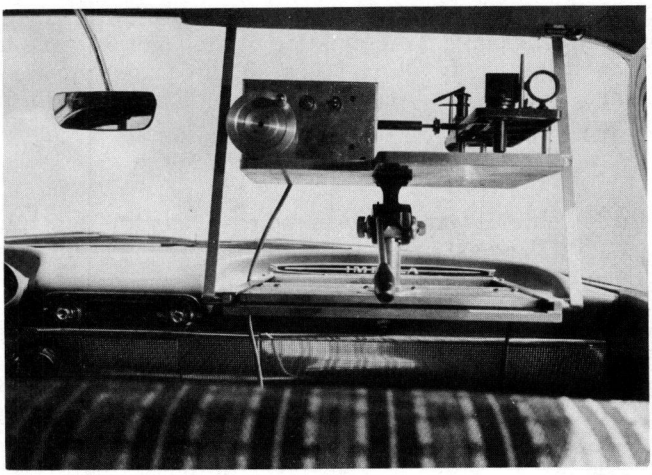

Figure 2. Stadimeter mounted in rear car used to measure headway between vehicles.

By means of radio equipment installed in the two vehicles, the lead car observer could notify the equipment operator in the following car what change of speed was to occur and when the change began and ended. This was done only when no visual communication signal was given. As the equipment operator used head phones, the driver of the following car could not hear these messages.

Four rates of acceleration were used for each series of maneuvers: +1, +3, -1, and -3 mph per sec. The interval between each maneuver in a series was either 15, 30, or 45 sec in duration. An automatic recycling timing system had been installed in the lead vehicle to specify the individual maneuver to be undertaken, the advance warning time (if any) to be signaled to the following car, the duration time of the maneuver, and the interval between the beginning of each maneuver in the series and the beginning of the next. By means of cue lights on the dashboard, the driver of the lead car was notified when to begin and end each maneuver. In general, the driver's control in making speed changes was accurate to within 5 percent.

The information display for the driver of the following car consisted of four traffic signal heads with white lenses, 8 in. in diameter, mounted above the lead vehicle, as shown in Figure 1. Each signal head represented one of the four possible speed change maneuvers. The size of the signal heads and the height at which they were mounted above the lead vehicle were dictated by possible conditions of grade, curvature, and length of queue that might be employed for any particular study to be made with this display.

Site of Study

A 7-mi portion of Interstate 70, located between Gaithersburg and Rockville, Md., and considered typical of a rural freeway, was selected as the study site. This freeway is a four-lane divided highway on which there is full control of access. Each of the four lanes, constructed of bituminous concrete, is 12 ft wide. Although the shoulders generally are 10 ft wide (8 ft of gravel and 2 ft of grass), a small part of the study site has gravel shoulders 12 ft wide. The dividing median is a grass strip 50 ft wide.

The speed limit at the test site is 60 mph and only a few vehicles were observed exceeding this limit. Typical of a rural freeway, the design speed for this section of the highway is 70 mph; maximum gradient is 3 percent, except for a length of 1,000 ft where the grade is 3.5 percent; and the maximum horizontal curvature is 1°.

The daily traffic volume on the section of the highway used for this study was about 10,000 vehicles. While the study was underway, daytime traffic averaged about 600 vehicles per hour or about 300 vehicles per hour on each one-way roadway—a relatively

low volume of traffic for a freeway near a large metropolitan area. This low traffic volume and the high-type design characteristics of the highway were the principal reasons for selection of this study site. These factors made it possible to drive at a reasonably wide range of speeds for the required length of time with little interference to or from other traffic.

Procedure

Either two or three vehicles were used in the test runs for this study in which headways were measured for the rear cars, which were driven by test drivers. In addition to the test driver, the rear car carried the stadimeter operator (observer) and the equipment operator.

Drivers.—Seven drivers were used for the study. Four were summer employees of the Bureau of Public Roads; their ages ranged from 18 to 24 years; all had had at least two years of driving experience. The other test drivers were the experimenters conducting the study. All seven drivers participated in the test runs made with the two cars but only the four test drivers participated in the three-car test runs. To isolate any effects of possible bias, the primary analyses of the data collected from two-car tests were made only for runs by the four test drivers. Because analyses of the data indicated responses of all seven drivers to be quite comparable, information collected from all two-car tests was used for some of the subsidiary analyses.

Before the beginning of each test run, each test driver was given the following instructions: "Assume you are driving in rush hour traffic. Assume that vehicles are in the left lane beside you as well as behind you. Drive as you would in this type of traffic by keeping pace with the vehicle ahead so as to minimize the possibility of other vehicles weaving in front of you."

Two-Car Studies.—In the test procedure with two cars, the speedometer of the rear vehicle was covered and all the tail lights of the lead vehicle were disconnected for all test runs. The lead car carried out precise maneuvers and the headway was measured between the two vehicles.

Before the beginning of each test run, the study's signal system was explained to the test driver. He was told that when the signal lamp on the extreme left of the lead car was lighted a fast acceleration would be made, and that the next three signals would indicate fast deceleration, slow acceleration, and slow deceleration, respectively. The signal lamp was lighted before the onset of the speed change for a period of time determined by the preselected warning condition and remained lighted until completion of the maneuver.

A run included 16 speed changes—four repetitions each of maneuvers from 36 to 45 mph, from 45 to 36 mph, from 45 to 54 mph, and from 54 to 45 mph. Just before the start of each run, the test driver was also informed as to which of the five test conditions would be used: without communications or with communications at one of the four warning times (0, 1, 3, or 5 sec). For the "without communications" condition, the signal lamps were not used and the test driver received no information concerning the maneuver to be executed. When the run was made with communications, the signal system was used to indicate the magnitude of the speed changes to be made during each maneuver (+1, +3, -1, or -3 mph per sec), as well as to show the preselected warning time conditions.

All runs were started when both vehicles were traveling at a speed of 45 mph. The programing device was then activated in the lead vehicle and one of the four preprogramed speed changes was presented on the appropriate signal lamp. At the end of the first maneuver of each run, the lead vehicle was traveling at a speed of either 36 or 54 mph. Therefore, the second maneuver of a run required acceleration from 36 mph or deceleration from 54 mph. Thus, the test driver's uncertainty as to the speed change that would be presented was only half that he experienced when the next maneuver was to be made from a speed of 45 mph.

At the end of each run, another warning time condition was randomly selected; the test driver was informed of the new condition; and another run was executed by the two cars. This procedure was repeated until the test driver had completed five runs in succession, one for each warning condition. Each of the seven test drivers made five

successive runs and the entire procedure was repeated four times for each of the five test conditions.

Three-Car Studies.—In the three-car studies, the signals for indicating speed changes and warning time were mounted above the first vehicle, which initiated all maneuvers, but the targets for headway measurement were mounted on the rear of the second car. The test driver operated the third car. Speedometers of both the second and third cars were taped over. The procedure for measuring the intervehicle spacing between the second and third cars was the same as that used for test runs with two cars. Runs were made with only three test conditions rather than five: without communications and with communications during which the warning time was either 1 or 5 sec. Only the four test drivers were used for tests with the three cars and test runs for each of the three conditions were repeated by each driver three times. The drivers of the second and third cars were given instructions similar to those given for the two-car runs.

ANALYSES

Choice of Headway at Constant Speed

Four independent variables were studied in the analysis of headway: (a) speed, (b) driver, (c) run, and (d) type of communications. Data were obtained for all 240 combinations of the four variables in the case of the two-car following situation. For the three-car data analysis, the 0- and 3-sec warning time conditions were omitted. Information was obtained from all possible combinations of the independent variables for the time intervals between maneuvers; that is, when the two vehicles were traveling at some constant speed. Samples of information, consisting of the record of speed and headway of both vehicles, were taken at 1-sec intervals by the digital recording system. To eliminate any time coherence among the sample points, additional samples were taken from recorded data at 5-sec intervals. In general, 10 to 15 samples were taken from each of the two speeds of 36 and 54 mph, which were maintained during four periods of time in each test run, and 20 to 40 samples were taken during the eight periods of time the speed was constant at 45 mph. To obtain a completely balanced block design for the analysis of variance, a final sampling of ten random observations was made for each of the three speeds of each run.

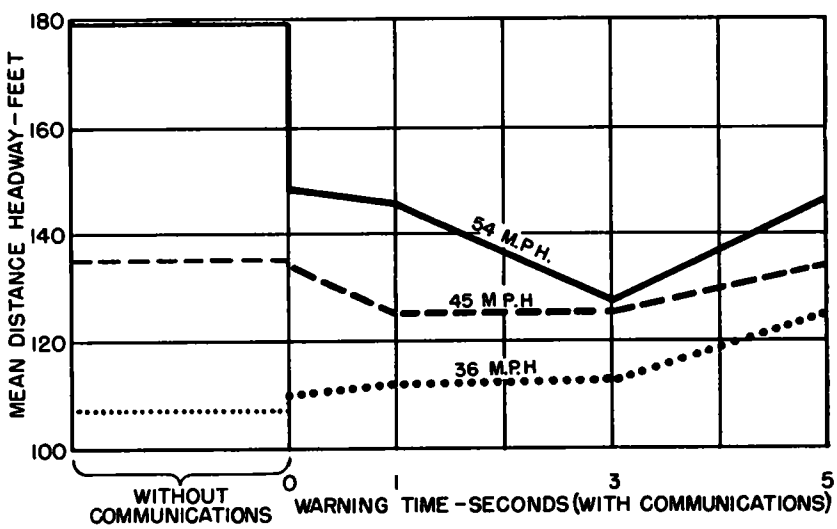

Figure 3. Effect of communications with various warning times on mean distance headway maintained at several speeds for a two-car platoon.

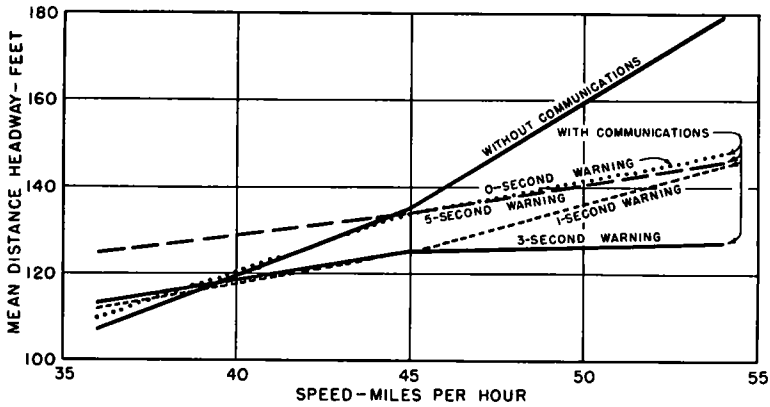

Figure 4. Effect of communications with several warning times on mean distance headway maintained at various speeds for a two-car platoon.

Analysis of Variance Data for Two-Car Runs

An analysis of variance was performed on the two-car data. Four main variables of three speeds, four drivers, four runs, and five communications conditions were used. For each of the 240 combinations of these variables, 10 headway measurements were employed, thus making 2,400 headway observations The analysis demonstrated that not only were the main variables significantly different at the 0.01 level, but also that all six first order, four second order, and the third order interaction terms were significant at the 0.01 level. As a check on the sampling procedure, an additional analysis of variance was performed on all the variable for one run (speed, driver, type of communications), and identical results of the analysis were obtained: all terms were significant at the 0.01 level.

Interaction of Speed and Warning Time. —For more detailed analysis of the effects of the communications system, data were separated on the basis of speed. At the highest speed of the runs, 54 mph, consideration of the data reveals a very significant reduction in mean distance headways when the communications system was used. This information is shown in Figure 3. With communications, the mean distance headways varied from a minimum of 127 ft to a maximum of 148 ft; without communications, the mean headway was 179 ft. True headway distances (from the rear end of the lead car to the rear end of the rear car) used for this analysis of the two-car test data were obtained by adding a constant of 10 ft to the recorded headway, which the stadimeter had measured from the dashboard of the following vehicle to the rear bumper of the leading vehicle. At the lowest speed used in the study, 36 mph, headways were no shorter with the communications system than without it. At the intermediate speed of 45 mph, the headways began to decrease with use of the communications system.

Warning Time. —Warning times had a considerable effect on the headways maintained as shown in Figure 3. With a 3-sec advance warning time at 54 mph, the drivers maintained minimum headways. At 45 mph, minimum headways appeared to have been maintained within the range of a 1- to 3-sec advance warning time. But at a speed of 36 mph, no differences in headway occurred when the warning time was less than 3 sec. However, with the longest advance warning time of 5 sec, headways maintained at all three speeds were much longer than those maintained with the 3-sec warning time. At 54 mph, headways maintained with a 5-sec warning time were about the same as those maintained with a 1-sec warning time and were 15 percent longer than those maintained with a 3-sec warning.

In Figure 4, the relationship of headway to speed is illustrated with warning time as the parameter. Without communications, distance headways increased sharply as speed increased. For each of the four test run conditions with communications, distance headways increased less as the speed increased. Most noteworthy is the fact that the shortest headways were maintained with the 3-sec warning time and, more importantly were practically independent of speed. Therefore, 3 sec may be considered the optimum warning time.

TABLE 1

MEAN DISTANCE AND TIME HEADWAYS MAINTAINED BY EACH OF FOUR DRIVERS AT THREE SPEEDS WITH AND WITHOUT COMMUNICATIONS IN A TWO-CAR PLATOON[1]

Speed (mph)	Communications Condition	Warning Time (sec)	Driver A		Driver B		Driver C		Driver D		Average	
			Ft	Sec	Ft	Sec	Ft	Sec	Ft	Sec	Ft	Sec
36	Without	—	92	1 7	113	2.1	116	2.2	106	2 0	107	2.0
	With	0	111	2 1	120	2.3	111	2 1	97	1.8	110	2.1
		1	116	2.2	108	2 0	130	2.5	94	1.8	112	2.1
		3	114	2.2	116	2.2	127	2.4	94	1.8	113	2.1
		5	132	2.5	132	2 5	134	2 5	102	1 9	125	2.4
45	Without	—	114	1 7	165	2 5	149	2 3	112	1.7	135	2.0
	With	0	131	2 0	173	2 6	124	1.9	110	1 7	134	2.0
		1	122	1.8	127	1.9	131	2.0	119	1.8	125	1.9
		3	114	1.7	136	2.1	142	2 2	108	1 6	125	1 9
		5	129	2 0	152	2 3	148	2 2	107	1.6	134	2.0
54	Without	—	155	2.0	224	2.8	182	2.3	157	2.0	179	2 3
	With	0	142	1.8	189	2.4	131	1 7	129	1.6	148	1.9
		1	128	1 6	176	2.2	144	1.8	136	1.7	145	1.8
		3	117	1 5	137	1.7	143	1.8	112	1 4	127	1.6
		5	120	1.5	189	2.4	156	2.0	118	1.5	146	1 8

[1]Headways in two-car platoons were measured from rear-end of lead car to rear-end of rear car.

A further comparison of the relation of speed to headways maintained was made by converting the distance headways (Fig. 3) to time headways for each speed range. These respective time headways were plotted against speeds for each test condition. Figure 5 shows that when maneuvers were performed without communications the time headways increased at the highest speed: but for each of the four warning-time conditions with communications, time headways decreased with increased speeds. The lowest value of time headway was obtained from the data on the 3-sec warning time at the speed of 54 mph. The relation of time headway shown (Fig. 5) for the condition without communications and that shown for the 3-sec warning time is noteworthy. At a speed of 36 mph, the difference in time headways shown for the two communications conditions is not statistically significant, but at speeds of 45 and 54 mph the time headways obtained with a 3-sec warning time were significantly shorter than those from the condition without communications. At a speed of 54 mph this reduction was 30 percent.

Summary of Tabulated Data

A summary of all data collected during this study for the two-car runs is given in Table 1. Each entry represents the average of 40 observations of data collected for all four runs averaged together.

The time headways (given in Table 1) were calculated from the distance headways, as noted previously. For the calculation, it was assumed that the lead and rear vehicles were traveling at an identical speed of either 36, 45, or 54 mph. Because the drivers of the lead cars were extremely careful to maintain precise speed relationships, this assumption was close to the actual situation.

A large variability in response of the four drivers both to speed and the type of communications employed is evident from consideration of the data. Because of these significant differences in driver reactions, the averaged data shown in the summary column of Table 1 should be interpreted with extreme caution; these data, of course, represent a combination obtained from different populations.

Figure 4 shows the mean distance headways when the warning time was 3 sec were practically the same at all three speeds—between 113 and 127 ft; this range of only 14 ft is also shown in Table 1. The range in mean distance headways over the three speeds for the other four communications conditions varied from 21 to 72 ft; generally the same range was noted in the headways maintained by each driver. Test data also revealed that among the four drivers the relationship of mean time headways noted for conditions of no communications and the 3-sec warning time is consistent (Table 1). Although the

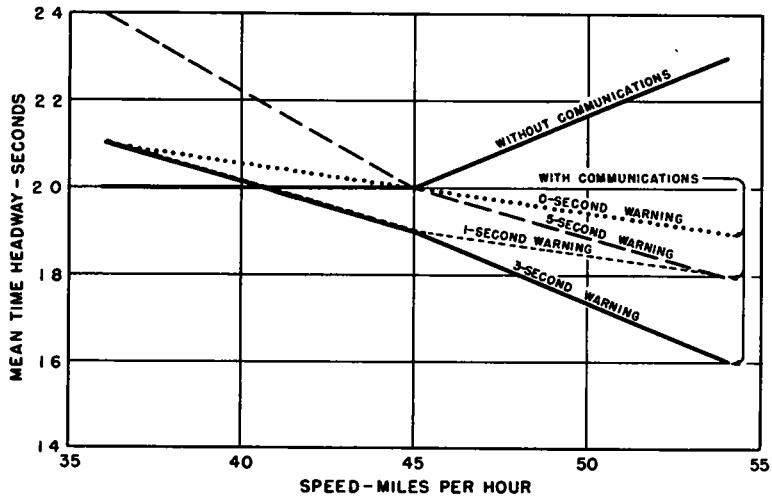

Figure 5. Effect of communications with several warning times on mean time headway maintained at various speeds for a two-car platoon.

TABLE 2

STANDARD DEVIATIONS OF DISTANCE HEADWAYS AND THEIR RATIOS WITHOUT AND WITH COMMUNICATIONS (3-SEC HEADWAY) FOR EACH OF SEVEN DRIVERS AT THREE SPEEDS IN A TWO-CAR PLATOON

Driver	36 Mph			45 Mph			54 Mph		
	Without Comm (ft)	With Comm (ft)	Ratio	Without Comm. (ft)	With Comm (ft)	Ratio	Without Comm. (ft)	With Comm (ft)	Ratio
A	16	16	1.00	24	21	0.88	24	15	0 63[a]
B	21	14	0.67[a]	25	17	0 68[a]	27	13	0 48[a]
C	78	16	0 21[a]	67	16	0 24[a]	67	24	0 36[a]
D	68	28	0 41[a]	56	30	0 54[a]	60	16	0.27[a]
E	15	10	0.67[a]	18	24	1 33	20	17	0.85
F	11	9	0.82	18	16	0 89	40	11	0.28[a]
G	14	8	0.57[a]	26	12	0.46[a]	29	13	0 45[a]
Median	—	—	0 67[a]	—	—	0 68[a]	—	—	0 45[a]

[a]Significantly different from 1.00 at the .05 level or less.

absolute values of the time headways for the four drivers differ significantly, the change in time headway as a function of speed is similar in that the time headways for the 3-sec warning time decreased sharply as the speed increased.

Communications

Data collected from runs made by the three experimenter drivers were added to the data for runs by the four test drivers for a further analysis of the variation in headways. Standard deviations of distance headways were calculated for each of the three speeds under two test conditions, without communications and with the optimum warning time of 3 sec. These calculations are given in Table 2. When data from the no-communications condition and the 3-sec warning time communication condition were compared, a reduction in standard deviation was noted for 19 of the 21 comparisons, and only 1 increase in standard deviation occurred. In most cases, the reduction was substantial and in 15 of the comparisons the differences were statistically significant. The median ratio of the standard deviation over all three speeds for all seven test drivers was 0.57, a reduction of 43 percent. In other words, communications reduced the variation in headway quite substantially.

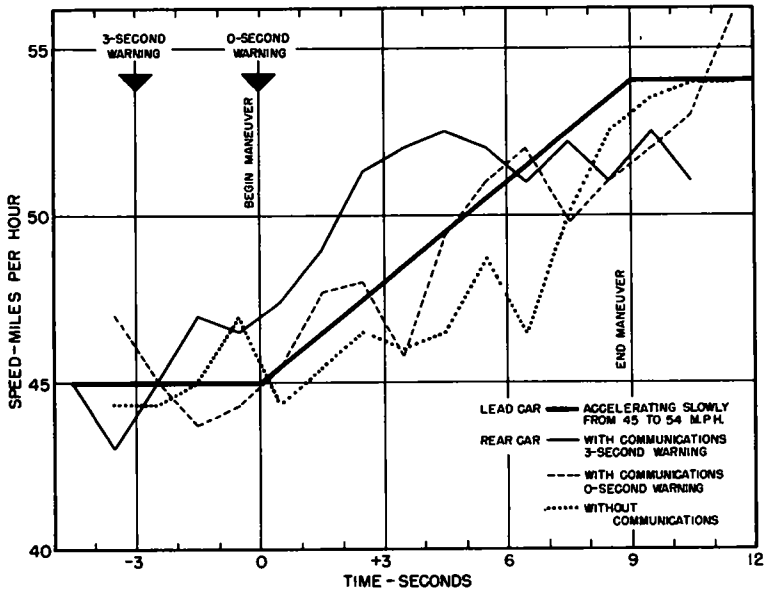

Figure 6. Typical example of rear car anticipating maneuver of lead car when 3-sec warning available in a two-car platoon.

Analysis of Speed Changes During a Maneuver

Another analysis of data obtained from test runs with two-cars was made of the speed changes carried out by the test drivers during the maneuvers. Although the limitations of the data-processing system prevented a precise analysis of the time course of the changes in speeds, it was possible to determine some of the effects of the communications system by the control responses of the test drivers. An example of typical responses is shown by the curves in Figure 6. When the speed change for the lead car was a slow acceleration from 45 to 54 mph at the rate of +1 mph per sec, the test drivers tended to respond so that the position of the rear vehicles changed from leading to lagging as the warning time decreased from 3 sec to 0 sec to a condition of no-communications.

This analysis also revealed some indication that the test or rear car drivers were using the warning intervals to begin the speed changes; such a response is shown clearly by the curve in Figure 6 for the 3-sec warning time. The drivers of the rear cars had closed on the lead vehicles during the initial part of a maneuver, when the optimum warning time of 3 sec was employed, then at some point toward the end of the maneuver had eased up on the accelerator thereby increasing the distance headways. The deceleration at the end of the maneuvers tended to show a great variability among the drivers and from one trial run to another.

Analysis of Data for Three Cars

For the portion of the study made with three cars, data on the effect of speed change information on intervehicle spacing were collected from only three test runs made by each of the four drivers.

For three cars, headways were measured from the rear of the second car to the rear of the third car; communications were transmitted from the lead car. The third or rear car was driven by a test driver.

An analysis of variance also was carried out on the data collected from test runs of the three cars. With one exception, all terms were significant at the 0.01 level; the third-order interaction term was significant at the 0.05 level.

TABLE 3

MEAN DISTANCE AND TIME HEADWAYS MAINTAINED BY EACH OF FOUR DRIVERS AT THREE SPEEDS WITH AND WITHOUT COMMUNICATIONS IN A THREE-CAR PLATOON[1]

Speed (mph)	Communications Condition	Warning Time (sec)	Driver									
			A		B		C		D		Average	
			Ft	Sec	Ft	Sec	Ft	Sec	Ft	Sec	Ft	Sec
36	Without	—	78	1.5	73	1.4	73	1.4	91	1.7	79	1.5
	With	1	90	1.7	71	1.3	97	1.8	88	1.7	87	1.6
		5	97	1.8	85	1.6	77	1.5	99	1.9	90	1.7
45	Without	—	92	1.4	100	1.5	84	1.3	107	1.6	96	1.5
	With	1	99	1.5	84	1.3	92	1.4	107	1.6	96	1.5
		5	110	1.7	103	1.6	89	1.3	103	1.6	101	1.5
54	Without	—	107	1.4	113	1.4	96	1.2	136	1.7	113	1.4
	With	1	109	1.4	97	1.2	91	1.1	116	1.5	103	1.3
		5	104	1.3	130	1.6	93	1.2	128	1.6	114	1.4

[1]Headways in three-car platoons were measured from rear-end of second car to rear-end of third car.

Analysis of three-car data showed that the mean headways were considerably less than those calculated for two cars, as can be seen by comparison of information given in Table 3 with that given in Table 1. In general, time headways were about ½ sec shorter for all communications conditions in three-car test runs. Moreover, the influence of the communications system was far less effective in causing the drivers to reduce following distance than it had been during the two-car runs.

With three cars and all three communications conditions, a small increase was noted in the mean distance headways as the speeds increased from 36 to 54 mph. However, decreases in mean time headways occurred both with and without communications; this decrease in time headways as speeds increased was larger when the test runs were made with communications. Table 3 contains headway data collected for three-car test runs.

When the interposition of a vehicle between the lead car and the rear car is considered, the 1-sec warning time for the three-car test runs appears to have had an influence on the headways maintained by the test drivers that is probably equivalent to the influence of the 3-sec warning time condition during two-car test runs. The summary column of Table 3 shows that with the 1-sec warning time a range of only 16 ft in distance headways occurred for 3-car runs between the speeds of 36 and 54 mph. When the 5-sec warning time condition was employed the range in headways increased to 24 ft, and when the condition was without communications it increased to 34 ft. The 16-ft minimum range with the 1-sec warning time is consistent with the lowest range in distance headways of 14 ft recorded at all three speeds for two-car tests with a 3-sec warning time condition.

Discussion of Data Analyses

Analyses of the data collected during this study indicate that substitution of an alternate information path for judgment of speed changes is possible, and that drivers are able to utilize a very simple coding scheme (communications system), at least in a two-car following situation. In other words, the driver of a car generally adapts his following distance according to the advance information he has about the changes in speed to be made by the lead car and his ability to make corresponding compensatory control changes in the speed of his own vehicle.

The major contribution of the signal system was its provision of information that permitted the test driver to begin his compensatory speed change before the onset of the speed change in the lead vehicle. Thus, a driver used the actual change in speed of the lead vehicle as a feedback on his speed control responses. This is shown by the curves in Figure 6.

Assistance from the communications system received by the test driver was least during an acceleration maneuver. Although limitations in the recording system precluded a complete analyses of the total effect of the communications system, some indication was noted of a lower rate of acceleration or deceleration with the display of speed change information than without it. However, considerable variation in acceleration or deceleration occurred during individual maneuvers, and this apparently resulted from the necessity for a driver to make visual angle discriminations and, more importantly, the predictions of future speed of the vehicle preceding his own. The experimental system employed in this study, of course, added nothing that a driver could use for such purposes.

The warning time (that is, the interval between display of the visual signal and the initiation of the speed change of the lead vehicle) was also observed to be an important factor in the following pattern adopted by the test driver in the rear car during constant speed operations. Analysis of the data showed that, dependent on the speed at which the test cars were traveling, minimum headways and minimum variance were obtained when the interval of warning time was between 1 and 3 sec. The warning time obviously was not employed solely as a reaction time but rather was used as a total response time of the system encompassing perception and translation into control and vehicle responses.

With the most favorable warning conditions, consideration of the analyses shows that spacing maintained between vehicles became independent of speed and indicated that another following system had been established by the driver. Although this system was speed dependent, the drivers employed a different information processing mode and adapted the headways to the remaining constraints on following—mostly random variations in speed between two vehicles.

Verification of Predictions Based on Hypothesis

On the basis of the hypothesis for this study, it was predicted that average distance headways between maneuvers would be less with communications than without. Analyses of the data from two-car tests indicated that this was true at the two higher speeds of 45 and 54 mph but not true for the low speed of 36 mph.

The prediction that the variability in headway would be reduced when the driver of the rear vehicle had prior information about speed changes to be initiated by the driver of the lead vehicle was confirmed by the analyses of test data.

Traffic Capacity of Freeway Lane.—Consideration of the data collected during test runs with two cars seems to indicate that a communications system could increase the traffic capacity of a freeway lane. As noted previously (Fig. 5), without communications the minimum time headways occurred at speeds below 45 mph and averaged 2.0 sec. If the time headways for a single lane of traffic averaged 2.0 sec for 1 hr, the total traffic volume would equal 1,800, which approaches the volume of 2,000 vehicles per hour that has been widely accepted as the possible capacity for a freeway lane. Few highways in the United States are known to carry a greater volume and other studies have shown that the minimum headways and maximum capacity usually are obtained when vehicles are traveling at speeds of less than 45 mph.

When communications were added, the speed-headway relationships changed markedly and the mean time headways decreased as the speeds increased. With the 3-sec optimum warning time, as shown in Figure 5, time headways of 1.6 sec were maintained at 54 mph, the highest speed used in this study. Were time headways to average 1.6 sec for 1 hr at 54 mph, the traffic capacity for a single freeway lane would exceed a volume of 2,200 vehicles per hour. Thus theoretically, utilization of a communications system, providing information similar to that of this study, would permit a one-third increase in the traffic capacity of a freeway lane. This increase was derived from the study data obtained when the test condition was without communications and the time headway at 54 mph was 2.3 sec, which would permit a volume of only 1,600 vehicles per hour. Therefore, what seems to be a fairly simple communications system would appear, by extrapolation, capable of generating a sizeable increase in the capacity of a freeway at the higher speeds. However, analysis of the three-car data does not allow such a conclusion. The addition of an interposed vehicle eliminated most of the benefits to be obtained from a communications system, as implied by the analysis of data from two-car tests.

The final column of Table 3 shows that without communications the average time headways between the second and third cars were considerably shorter at all three speeds than between the first and second cars with communication of a 3-sec warning time. Furthermore, with communication of a 1-sec warning and at speeds of 54 mph, the time headways in three-car runs were only 0.1 sec less than those maintained during the runs without communications. This elimination of most of the benefits, obtained by use of the communications system, with the interposition of a vehicle in a three-car queue may be attributed to several factors.

First, in a line of traffic a natural tendency exists to maintain stability of speed and spacing. Thus any speed change imposed by the lead vehicle may be expected to be compensated for by the drivers of successive vehicles as they perceive and thereby progressively reduce the effect of the speed change.

Second, if the driver of the third vehicle observed the speed change behavior of the first vehicle directly, he might very well receive as much advance warning as he would from the communications system. That such does take place has been suggested in a report by Forbes (4).

Third, automobiles in a line represent a very loosely coupled system, subject to considerable random fluctuations. A communications system such as the one used for this study should have a decreasing effect on the responses of the driver as the distance increases between the communications system and his vehicle. Any interposed vehicle prevents the following driver from directly coupling himself to the source. The driver, of necessity, must compensate primarily for the behavior of the vehicle immediately preceding his and secondarily for the behavior of those further ahead in the line. In essence, in the multiple car-following situation, the speed change display represents little more than a cue informing a driver that some change of speed will be made in the preceding line of traffic.

Variability of Drivers' Responses.—Another fact evident from analyses of these data is that a high degree of variability occurs both within and among drivers' responses. Considerable differences were noted in their responses concerning time relations and optimum following, minimum variance conditions, and at different speeds. Although the differences in mean headways with a 3-sec warning were quite small at all three test speeds, the analysis of variance showed a significant difference among speeds. As no systematic differences in variance occurred among the three speeds, it seems reasonable to conclude that the significance arises from inter- and intra-driver response changes from run to run. It would appear, then, that the driving system is greatly influenced by the moment-to-moment fluctuations in a driver's psychological state, as well as by his more stable behavioral characteristics. Sensitivity to such subtle qualities is not a characteristic of efficient man-machine systems.

SUMMARY AND CONCLUSIONS

From this study with two- and three-car queues, it was determined that the effect of the use of the communications system on the spacing between two vehicles varied with the speed at which they were moving; its use had little effect when the speed was 36 mph. but resulted in a large reduction in distance headway when the speed was 54 mph. However, when another vehicle was interposed, making a three-car queue, the communications system's effect on distance headway was nearly eliminated at all speeds. During constant speed operations, at any of the three speeds used, the variance in headways between the two cars was significantly reduced by the communication of speed change information to the test drivers. The transmission of this information approximately 3 sec before initiation of the speed change by the lead car permitted maintenance of the most uniform headways.

On the basis of data collected during the study, it is concluded that communication of advance speed change information from one driver to another is an extremely complex problem. Further, no simple or direct means exists for transmitting advance speed change information that will result in a universal or predictable modification of headway variance in the pattern of one car following another.

REFERENCES

1. Herman, R., and Potts, R. B., "Single-Lane Traffic Theory and Experiment." Proc., Symposium on Theory of Traffic Flow, Warren, Mich., pp. 120-146 (1961).
2. Brown, R. H., "Weber Ratio for Visual Discrimination of Velocity." Science, 131: 1809-1810 (June 17, 1960).
3. Hopkins, R. C., "Standard Electronic Units Interconnect to Provide Flexible Digital Recording." HRB Bull. 261, 44-49 (1960).
4. Forbes, T. W., Zagorski, H. J., Holshouser, E. L., and Deterline, W. A., "Measurement of Driver Reactions to Tunnel Conditions." HRB Proc., 37:345-357 (1958).