# In Situ Study Determining Lane-Maneuvering Distance for Three- and Four-Lane Freeways for Various Traffic-Volume Conditions

ROGER W. McNEES

**The objective of this research was to determine on the basis of driver performance the distance it takes a driver to maneuver across several lanes in light, medium, and heavy traffic. The distance was expected to vary with a number of situational variables, several of which were investigated in this research. To obtain actual freeway distances associated with components of the model, an instrumented vehicle study was performed. Twenty drivers from Houston, Texas, drove sections of two freeways near downtown Houston. Interstate 45 was used for the lane-maneuvering study. All drivers were required to drive a three- and a four-lane section of the freeway and maneuver from the extreme left lane to the extreme right lane in light, medium, and heavy traffic. To determine an estimate of maneuvering distance, each driver was required (by instructions) to perform in succession three lane-change maneuvers on both the three- and the four-lane sections in each of the three traffic volumes. The distances were determined indirectly by recording the time required for a particular test and the speed of the test vehicle during each particular test. The major contribution of this research was a set of empirically determined maneuvering distances based on actual driving performance on a three- and a four-lane freeway under various traffic-volume conditions. Rather than a single value, the research findings offer several distances appropriate under various assumptions regarding the number of lanes, traffic volumes and speed, visibility, driver familiarity, and the percentage of drivers to be accommodated by the distance. The results indicate that traffic volumes and the number of lanes have a significant effect on maneuvering distance. Another finding was that when a driver is traveling at low speed in heavy traffic, the distance required to maneuver is significantly less than that when the speed of the vehicle is higher.**

One portion of a much larger project funded by the Federal Highway Administration (FHWA) entitled "Human Factors Requirements for Real-Time Motorist Information Displays" is presented. The objective of this research was to determine and evaluate current standards on the placement of the advanced-warning (exit) signs based on actual performance data relating to sign reading, lane maneuvering, and deceleration distances.

Due to the length of the research effort, only the lane-maneuvering portion of this study will be presented here. Although the intent is not to slight the sign-reading or deceleration portions, the lane-maneuvering portion has a greater impact on sign placement and many more applications in other areas unrelated to sign placement than do the other portions of this study.

## RESEARCH OBJECTIVES

The objective of this research was to develop initial placement locations of advanced-warning (exit) signs relating to diversions from a freeway or transition from one freeway to another freeway as incurred during route guidance. These placement locations were derived from actual driving performance and are appropriate under various assumptions regarding the number of lanes, traffic volumes, visibility, driver familiarity, and percentage of drivers to be accommodated by the distance.

The locations developed in this research considered factors such as the distance required to make several lane changes, the distance required for the driver to read the sign and start the initial lane change, and the distance required to decelerate the vehicle to the exit-ramp speed so it would not impede traffic along the freeway.

The specific objectives of this research included the following:

1. To obtain human performance criteria related to distances required for sign reading, lane maneuvering, and decision;
2. To develop a model that will allow computation of the longitudinal distance from the gore point to the sign location based on a set of measured distances; and
3. To determine recommended sign-placement distances for exit direction signs upstream of the gore point based on the number of lanes on the freeway, ambient light conditions, and traffic volumes on the freeway.

## LITERATURE REVIEW

The basic principles and standards that govern the design and use of all traffic control devices are set forth in the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) (1). The objective of this research was to determine sign-placement criteria. Therefore, it is directly relevant to the MUTCD. Traffic control devices include all signs, signals, markings, and devices placed on or adjacent to a public roadway by an agency or official that has jurisdiction to regulate, warn, or guide traffic. The principles and standards set forth in the manual apply on a national level, and each state develops its own manual, which must be in compliance with the national standards.

There are five basic considerations employed to ensure compliance with these standards--design, placement, operation, maintenance, and uniformity. Current standards for sign placement are directly relevant to the present research. The MUTCD states (1, p. 1A-2):

> Placement of the device should assure that it is within the cone of vision of the viewer so that it will command attention; that it is positioned with respect to the point, object, or situation to which it applies to aid in conveying the proper meaning; and that its location, combined with suitable legibility, is such that a driver traveling at normal speed has adequate time to make proper response.

Basically, there are three types of signs used in any exiting maneuver. These signs are the advance-guide sign, interchange-sequence signs, and the exit-direction sign. This research is directly related to the placement location of the exit-direction sign. The advance-guide sign is the sign that warns the driver well in advance of the upcoming exit. The interchange-sequence signs are the series of signs that warn the driver of the remaining distance prior to the exit. The exit-direction sign is the last sign prior to the exit at which the motorist will be able to make the appropriate lane changes and decelerate to a safe exit speed. The gore sign is not considered in this research due to its placement position.

The present research was conducted to determine the actual distance required by drivers to perform several lane changes as a part of their exit maneuver.

The distance at which an exit sign should be placed is dependent on the distance required by a driver to maneuver across a freeway and enter the exit lane. One approach to the evaluation of sign-placement distances reported in the literature (2,3) has been determining whether drivers have sufficient distance to maneuver into the exit lane for existing sign-placement locations. To evaluate whether a particular sign location provides sufficient distance, several techniques have been used. One of these techniques was to determine whether the location affects the driver's behavior while he or she is preparing to exit the freeway. The driver's behavior in this respect relates to activities such as steering reversals, brake application and reversals, lane positioning, and passing. The second technique for evaluating the location is by analytic methods of estimating distances associated with task times presumably required to perform part of the task. The third technique is to evaluate the sign location by determining, in vehicles, the actual distance required by drivers to change lanes and exit a freeway.

Although these three techniques appear to be similar, each method provides a different approach to determine placement distance. The first technique investigates driver-related factors and the effect sign placement has on them. These factors may be studied either in a laboratory (simulator) study or in a field (instrumented-vehicle) study. This method evaluates existing placement locations by determining what effect a particular location has on the driver's behavior. Those placement locations that have no effect on the driver are assumed to provide sufficient distance to exit the freeway. The second and third techniques determine placement locations based on distances required to exit the freeway. The only difference between these two techniques is the manner in which the distances are calculated. In the second technique, distance is determined by using an analytic approach in the form of a task analysis. This technique does not involve actual driving to determine the distance. The third technique uses an instrumented vehicle in actual freeway traffic to determine the distance required to exit the freeway. Several studies employing these techniques will be reviewed.

A study using the first technique to evaluate the distance from an exit that the advanced-information sign should be placed was conducted by Mace, Hostetter and Seguin (2). To determine the effect on the driver's behavior, three methods of analyses were used. The first method was to use a conceptual model to determine the nature of the interface linking the individual driver to other components of the traffic system. The components relating to information lead distance were first studied by using a driving simulator, which was the second method employed. Lead distances were approximated by varying the location of the sign on a filmstrip, which was run at a speed corresponding to the speed of the vehicle. In addition to providing information on the effects of lead distance, these simulation studies were used to provide inputs to determine the amount of task loading required of the driver during the in situ phase.

To provide a more direct test of the hypothesis concerning lead distance, a third method was applied in situ by using an instrumented vehicle under actual traffic conditions. Variables associated with the driver, the signs, and the environment in which the signs exist were investigated. Directional information signs were not used: Rather, commands when to exit and the direction of the exit were displayed on a screen mounted on the dashboard of the vehicle. The 18 subjects were given the command to exit coinciding to lead distances of 0.25-mile, 0.50-mile, and 1-mile intervals.

In the instrumented-vehicle study, the following variables were recorded: (a) speed, (b) steering reversals, (c) brake applications, (d) turn signal use, (e) lane position, (f) passing, and (g) significant unpredictable occurrences. The variables recorded associated with the traffic and the environment were (a) experimental vehicle in the right lane, in the center lane, and in the left lane; (b) passing vehicle, (c) vehicle passed, (d) display activation, and (e) unpredictable events. To record these variables, an Esterline-Augus chart recorder with two discrete and three analog channels was used.

The test site was a section of Interstate 495, the Washington Beltway, between Exits 27 (College Park, Maryland) and 37 (Indian Head Highway). This test was performed during heavy traffic volumes.

The general conclusions derived from the study indicated that the effects of the information lead distances on driving behavior were negligible, except for the 0.25-mile lead distance. The 0.25-mile lead distance frequently resulted in late entries into the extreme right lane. It was also concluded that if a number of performance variables are considered, the 0.25-mile information lead distance is less desirable than the 0.50-mile information lead distance.

The 0.25-mile lead distance would result in either mainstream turbulences or missing an exit under moderate to heavy traffic conditions. One driver error, reduction of speed in the mainstream, was prevalent for all lead distances. This study provided a method of evaluating specific distances at which exit signs may be located. In general, the study indicated that the 0.25-mile lead distance is inadequate in providing drivers sufficient distance to exit the freeway and that both the 0.50-mile and the 1-mile lead distances had negligible effects on driver behavior.

Levin (3) used the third technique, directed at determining the accuracy of sign placements based on lane changing in traffic. Levin evaluated signs placed at the gore 0.25 mile in advance, 0.50 mile in advance, and 0.75 mile in advance for service levels B and C. Level-of-service B is associated with a speed of between 55 and 60 mph and a freeway volume of 2800-3200 vehicles/h.

Levin used two methods to determine the lane-changing distance. His first method was a mathematical model describing the lane-changing process from one lane to the next adjacent lane to either the left or right. His mathematical model used a gap-acceptance and/or gap-rejection concept. This model allows computation of the required distance to complete the maneuver if the probabilities of occurrences associated with each of the three forms of the process, the traffic volume, and the speed of the vehicle are given.

Levin attempted to validate his model by using one subject driving a test vehicle on a freeway in Houston, Texas. He made 1000 lane changes from one lane to an adjacent lane in service-level-B and service-level-C traffic conditions. He was interested in determining the distance required for the lane change in each of those traffic conditions. Distance was determined by using magnets on the brake drum and the chassis of the test vehicle. By using a constant tire pressure and knowing the revolutions per minute at a set speed, distance can be determined.

The results obtained from Levin's model indicate that in most situations, drivers can perform their lane change for an exit with a 0.50-mile or greater advanced warning. This model, however, assumes only one lane change to perform the exiting maneuver. In situations where drivers must perform several lane changes, the effectiveness of the sign at the 0.50-mile location and the 0.75-mile location may be reduced to an unacceptable level. Levin determined that for four-lane freeways (two lanes in each direction) the effectiveness of the 0.25-mile sign was low and that the effectiveness of the 1- and 2-mile signs was high in level-B and level-C traffic volumes.

One question raised by Levin was concerned with the necessity of having both a 1-mile and a 2-mile sign. It may be possible to have a 1-mile sign alone or the sign could be moved closer to the gore point since the effectiveness of the 0.50- and the 0.75-mile signs was the same.

Other significant results from Levin's research were as follows:

1. The behavior of the lane-changing vehicle within the accepted gap in delayed lane changes may satisfactorily be described by a model based on the concepts of the car-following model.
2. The higher the traffic volume on the freeway, the higher the sensitivity of the model to changes in lane mean speeds.
3. The delay and distance involved in the lane-changing process depend on traffic volume and increase as volume increases.
4. As the driver's critical gap increases, the delay and distance experienced with the lane-changing process also increase.

The results obtained by Levin, even though they support Mace's results, were based on an incomplete study of the exiting process. Levin used only one subject, who drove an instrumented vehicle on a Houston freeway. This subject was required to make one lane change for each test run. The subject performed 500 test runs in traffic level B and 500 in traffic level C. These traffic levels are associated with speeds that range from 45 to 60 mph and a traffic volume between 1800 and 3200 vehicles/h. This is equivalent to making one lane change in light and in medium traffic conditions in this research effort. Two or three lane changes in heavy traffic might well require a significantly greater distance than that determined by Levin.

Eberhard (4), by using the second technique, performed an analytic study of sign-placement distance. In this research effort, Eberhard established information lead distances based on estimates, rather than an actual driving test, of the times required by drivers with a wide range of capabilities to perform tasks involved in negotiating an intersection. The hypothetical situation posed in this study involved a driver who was required to change one lane from right to left and then turn left at the next intersection.

During the task analysis, two elements emerged as the most relevant for the determination of the information lead distance. These elements were changing lanes to prepare for a maneuver and changing speed to perform the maneuver.

Eberhard estimated the lane-changing distance and the speed-change distance for the worst-case situation. This worst-case situation assumed a truck merging left; traffic density of 1000 vehicles/h; approach speed of 40 mph; an aged driver with long perception, decision, and maneuvering times; and conditions of poor visibility on a wet surface. His results indicate that under the worst possible case the driver requires 2459 ft from the point at which the sign is noticed until changing lanes has been accomplished.

In general, the distance reported by Eberhard seems extremely large for a one-lane change. He estimated from the results obtained from his questionnaire that it required approximately 50 s from the time the signal was presented to the driver until lanes had been changed. Eberhard estimated that it took approximately 18 s for a driver to detect the driving situation present and that there would then be a wait for a gap before changing lanes. Another 25.5 s are spent in waiting for the gap to occur. These worst-case response times appear to be out of line in relation to what is required by the 85th-percentile driver. It is very difficult to estimate times accurately by analytic methods. More realistic estimates should be obtainable by timing the drivers' responses in traffic.

These three studies (2-4) provide a basis for evaluating sign-placement locations; however, the authors did not provide an in-depth study of the exiting process. In his research, Mace performed the exiting in heavy traffic during the day. The major criticism of the study was that he did not determine the actual distance traveled by the vehicle to determine whether there was a correlation between the actual distance traveled and the drivers' behavior. He did not study the light or medium traffic conditions.

Levin, on the other hand, studied the light and medium traffic during the day but did not study the heavy traffic condition. He used only one subject to obtain his data. This subject will eventually incur a learning effect and distances will become progressively shorter as the number of tests increases. The subject was also required to make only one lane change. On most freeways, at least two lane changes will be required. The results obtained by Levin apply to an isolated situation in which the driver needs to change one lane.

Eberhard's task analysis assumed several conditions that are not consistent with freeway operations. This study was not designed to study a freeway exiting maneuver; however, the tasks required to negotiate a turning maneuver at an intersection are similar to those tasks required to exit a freeway. Eberhard's study estimated distances based on a task analysis and not on actual field test data. The study was based on a hypothetical situation in which a driver must detect guidance information, change one lane from the right to the left, and wait for an acceptable gap. The distance estimated by Eberhard could be shorter than those determined during actual driving tests, because the vehicle is traveling at a lower initial speed, the driver makes only one lane change, and the response times may be much shorter.

## METHOD

The approach used to conduct this study was an in situ instrumented-vehicle study. The maneuvering test was a 2x3x20 repeated-measures design. There were two levels of the number of lanes on the freeway (three and four lanes); three levels of traffic volumes (light, medium, and heavy); 20 drivers; and three replications per driver per condition. This design would provide 360 data points from which maneuvering distance was determined.

Maneuvering distance was the major emphasis of this research. Maneuvering distance was dependent on factors such as the type of vehicle, maximum traffic volumes, number of lanes, and differences in driving behavior between drivers. All these factors were studied in this project except the type of vehicle.

To determine distance, the test vehicle recorded the speed of the vehicle and the time required for each event. It should be noted that it was thought that total distance would deviate significantly from longitudinal distance (distance along the freeway from the gore point to the sign-placement location) due to the width of the freeway. However, in practice the width of the freeway is so small in relation to the total maneuvering distance that the width of the lanes does not make a significant difference. Therefore, total linear distance was defined as equal to longitudinal distance. The sign-placement distance computed from the human performance measurements was then compared with the sign-placement distances as set forth in the MUTCD (1).

## Subjects

The subjects for this research were 20 drivers from the Houston area. The drivers were obtained from two sources. Eight are employed by the Texas Transportation Institute (TTI) and 12 are employed by the Texas State Department of Highways and Public Transportation (TSDHPT) at the Urban Office in Houston.

The selection criteria in obtaining drivers were sex, age, and a valid driver's license. The distribution of these drivers was determined by using national statistics of the driving population based on age and sex (U.S. Statistical Abstract, 1971). The driver's sample consisted of 13 males and 7 females. The males constituted 65 percent and the females constituted 35 percent. Ten drivers, or 50 percent, were in the 18-34 age group. Based on a statistical distribution provided the employers, drivers were selected to participate on a completely voluntary basis in this research project. It is for this reason that the male-female ratio does not coincide exactly with the national norm of 55 percent males and 45 percent females (U.S. Statistical Abstract, 1971).

All drivers held current driver's licenses. They had an average of 22 years of driving experience.

## Instrumented Vehicle

The instrumented vehicle was a 1969 Plymouth Fury I four-door sedan equipped with a V-8 engine, automatic transmission, power steering, power brakes, and air conditioning. The front and rear seats were removed and bucket seats were installed to replace the front bench seat. The rear compartment was left open to accommodate the instrumentation.

The instrumentation package consisted of a power inverter, power supply, master control panel, Rustrak four-channel event recorder, and Rustrak analog recorder.

This research required driving a test section along one freeway located near downtown Houston, Texas. The selection of this location was dictated by the requirements of the research. The maneuvering test required the use of a three-lane and a four-lane section of freeway, which were monitored for traffic volumes and traffic speed. These volumes and speeds were independent variables in this study. The Gulf Freeway (I-45 North) has three- and four-lane sections that were monitored by the Texas Transportation Institute-Freeway Surveillance Center (TTI-FSC).

The Gulf Freeway test strip was a 6.5-mile section beginning at Park Place Boulevard and continuing inbound to the Pease Street exit. This section of freeway had a sufficiently diverse traffic volume that 725 vehicles/h or less (light), 726-1225 vehicles/h (medium), and 1226 vehicles/h and more (heavy) were observed several times during a 24-h period in one direction on both the three- and the four-lane sections.

## Scheduling of Test Drivers

For scheduling purposes, the drivers from TTI were assigned to two groups of four drivers each and those from SDHPT were placed into three groups of four drivers each. Groups of drivers were assigned to volume conditions according to a Latin square design such that the sequence of runs was not the same for all drivers. This method of scheduling drivers provided a method of measuring any learning effect that might be associated with the sequence of administration and simultaneously attempted to equalize sequence effects across conditions.

## Data-Collection and Reduction Method

The approach used to acquire the data consisted of an in situ instrumented-vehicle study in which distance was determined indirectly by recording vehicle speed and time required to complete each run. Vehicle speed was not fixed; however, a maximum speed of 55 mph was established for each driver. This maximum was established to coincide with the legal speed limit and for safety purposes. In a few instances this imposed maximum speed was violated. It was also felt that by maintaining a fixed speed, an additional loading factor would be placed on the driver. All drivers were instructed to drive in their usual manner to reduce the negative psychological effects of being a test driver.

For the maneuvering study, the independent variables were traffic volume (light, medium, and heavy) and number of lanes (three or four) on the freeway. Vehicles per hour on a per-lane basis was used as the criterion for establishment of traffic volume. The experimental design required that each driver negotiate three lane-change maneuvers for each traffic volume on both the three- and the four-lane sections of I-45 inbound.

The pushbutton on the experimenter's master control panel was used to synchronize both recording devices for each run. The button made the recording mechanism on the recorder deflect equivalent to an instantaneous 4-mph increase in speed and held the recording mechanism for channel 1 of the four-channel event recorder in the on position for as long as the button was depressed.

For an accurate synchronization, the button was depressed by the experimenter for a full 5 s. Any synchronization period of less than 5 s would be difficult to locate. The synchronization procedure was required because the paper speed of the analog recorder was slightly faster than the four-channel event recorder due to the differential in the power supplies. The analog recorder paper drive required 12 V DC and the four-channel event recorder required 110 V AC.

The events recorded on channels 2, 3, and 4 of the event recorder were manually input by the experimenter through the master control panel. In the maneuvering test, channel 2 recorded the length of time required to make the first lane change, channel 3 recorded the length of time required to make the second lane change, and channel 4 recorded the length of time required to make the third lane change.

The Rustrak analog recorder continuously recorded the speed of the vehicle while the master control switch was in the on position. In situations of rapid acceleration or deceleration, the recorder indicated every 4-mph differential in speed. In all other situations, 1-mph differentials in speed could be determined.

The procedure used to reduce the data from these two tapes included aligning both tapes by using the synchronization marks for each run. In this way, time and speed could be read directly from both tapes. After the tapes had been aligned, each lane change was marked off to isolate total time required and speed of the vehicle during the lane change. In situations where speed varied during the lane change, each variation equivalent to 1 mph or greater was subdivided, and the associated time was marked off corresponding to that speed level.

To determine the distance associated with each lane change, the time associated with that lane change and the vehicle speed were recorded. The procedure allows distances to be calculated by using the following formula:

Total distance = vehicle speed (mph) x 1.467 x time (s),

where 1.467 is a constant to convert miles per hour to feet per second.

In situations where speed fluctuated, the distances traveled during each speed fluctuation were determined and then added together to obtain the total distance for that lane change.

A lane change began when the drivers signaled their intention to change lanes by turning on the directional signal and continued until all four wheels of the test vehicle were in the adjacent lane. To obtain the distance that the driver stayed in a lane, it was necessary to isolate the time and the speed of the vehicle between each lane change. This required a visual inspection of two channels on the event recorder tape. The time interval and speed of the vehicle between the end of one lane change and beginning of the next lane change were noted. After the time and the speed had been isolated, the procedure to determine lane-changing distance was used to determine distance in the lane. The response time of the experimenter was 0.2 ± 0.1 s in flipping the switches. The distance associated with this time (0.2 s) was subtracted from the driver's distance to eliminate the experimenter's response time. After the lane-changing distances and distance in each lane had been computed, a summation of these resulted in the total maneuvering distance for each run.

After an extensive analysis of the heavy-traffic maneuvering distance, it was determined that two separate subclassifications of heavy traffic would be necessary. These two subclassifications are heavy high-speed (HS) and heavy low-speed (LS) traffic. This decision was reached based on the large differences in maneuvering distance associated with the differences in speed. Speeds were arbitrarily classified in terms of those above and those below 35 mph so that the sample sizes of HS and LS groups would be as nearly equal as possible for statistical purposes.

After the distances required for each maneuvering run had been computed for all drivers, these distances were analyzed with regard to traffic volume and the number of lanes on the freeway.

After the distances had been tallied for each classification category, they were ranked from the shortest distance to the longest distance within categories. A cumulative distribution for each type was then determined. From this cumulative distribution the 25th-, 50th-, 75th-, 85th-, 90th-, 95th-, and 100th-percentile levels were determined.

The first analysis of variance was a 2x3x7 two-way classification repeated-measure design. This analysis of variance tested the threeand four-lane freeway under light, medium, and heavy LS traffic volumes for seven drivers. These seven drivers were selected because they had test runs on both the three-lane and the four-lane freeways in heavy LS traffic. The second analysis of variance was a 2x3x15 two-way classification repeated-measure design. This analysis of variance tested the three- and the four-lane freeways under light, medium, and heavy HS traffic volumes for 15 drivers. These 15 drivers had test runs on both the three- and the four-lane freeways in heavy HS traffic. Four drivers had at least one test run in both heavy LS and heavy HS traffic conditions. These drivers' test runs were used in both analyses of variance.

## RESULTS AND DISCUSSION

The major emphasis of this study was to determine from actual driving tests the distances required for a driver to maneuver from the extreme left lane to the extreme right lane in light, medium, and heavy traffic. Lane changing in heavy traffic was a worst-case maneuver for drivers attempting to exit a freeway. It was also expected that there would be a significant difference in maneuvering distance associated with the number of lanes a driver must maneuver across. Tests were performed on a three-lane and a four-lane section of freeway, but results could be generalized to freeways with more lanes or fewer lanes.

The manner in which the maneuvering test was conducted creates a situation in which each driver may incur a learning effect. The maneuvering test required that each driver perform a number of maneuvers for each condition being investigated. Those maneuvers performed first could require a greater distance than those performed last, due to the driver's unfamiliarity with the test vehicle. A Spearman's rank correlation test was subsequently performed on each driver's test runs to determine whether there was any learning effect due to this ordering of the drivers. This test indicated there was no significant correlation ($\rho_{12}$ = 0.254, $\rho_{13}$ = 0.159, and $\rho_{23}$ = 0.167) due to the order in which the drivers performed the test.

After all the distances had been determined, they were classified according to the number of lanes and traffic volumes investigated. The mean maneuvering distances were determined and are reported in Table 1. Inspection of these results indicates that maneuvering distance is affected by traffic volumes on both the three-lane and the four-lane sections of freeway although there is clearly not a linear increase in the maneuvering distance with increasing traffic volume. As predicted, medium traffic volume required greater distance than did light traffic volume. However, on both the three-lane and the four-lane sections, the drivers required as much or more maneuvering distance in medium traffic as in heavy traffic.

To determine the cause of this reversal, an analysis of the time required to maneuver and the speed of the vehicle during the maneuver was performed. It was suspected that those traveling at low speeds (20-25 mph) in heavy traffic would take longer to perform the lane-change maneuver than would those who were able to travel at higher speeds (45 mph) in heavy traffic. In other words, traffic speed as well as volume might be critical in lane-changing time and associated distance.

In order to perform this analysis, an arbitrary speed of 35 mph was selected as the cutoff for selecting those maneuvers classified as LS maneuvers, so that sample sizes associated with both speeds would be as close as possible for statistical purposes. The results of this analysis are given in Table 2. The data indicate that those traveling at low speeds required more time to perform the maneuver than did those traveling at high speeds when both are traveling in heavy traffic.

It may be noted that when the HS and LS distances are compared, the distances are substantially greater for the HS group and the travel times, as expected, were substantially less. The drivers at low speeds were apparently able to maneuver across lanes in a shorter distance because they accepted smaller gaps, whereas the HS drivers took a greater distance to maneuver. This analysis points out that the time required to complete the LS maneuver was between 2.1 and 4.1 (for the three-lane and the four-lane conditions, respectively) times greater than the time required in the HS maneuver. Speed, on the other hand, was between 2.5 and 1.7 (for the three-lane and the four-lane conditions, respectively) times slower during the LS maneuver than during the HS maneuver. This difference in time and speed resulted in the shorter distance during the LS maneuver.

Two repeated-measure analyses of variance were performed to determine whether there was a significant difference between the maneuvering distances associated with the LS light, medium, and heavy traffic conditions and the HS light, medium, and heavy traffic conditions (Table 3). The results of these two analyses of variance substantiated the original hypothesis that traffic volume has a significant effect on lane-maneuvering distance. As was pointed out earlier, maneuvers during LS heavy traffic require less distance than maneuvers during HS heavy traffic. This research has indicated that in certain situations speed more than volume affects maneuvering distance.

It was also originally hypothesized that for a given traffic volume, maneuvering distance would increase as the number of lanes increased. This hypothesis was based on the assumption that the addition of another lane would necessarily increase the distance required to maneuver across all the lanes.

Analyses of variance performed to determine whether the number of lanes affected lane-maneuvering distance are also presented in Table 3. Both of these analyses of variance indicate that the number of lanes had a significant effect on lane-maneuvering distance. Although only the three- and the four-lane conditions were investigated, these results might be generalized to mean that as the number of lanes increases, the lane-maneuvering distance increases, and as the number of lanes decreases, the maneuvering distance decreases.

**Table 1. Mean maneuvering distance during light, medium, and heavy traffic.**

| Condition | N | Mean Distance (ft) | Standard Deviation (ft) |
|---|---|---|---|
| Three-lane | | | |
| Light | 56 | 925 | 270 |
| Medium | 56 | 1009 | 308 |
| Heavy | 59 | 1002 | 527 |
| Four-lane | | | |
| Light | 48 | 1205 | 382 |
| Medium | 57 | 1521 | 391 |
| Heavy | 63 | 1375 | 377 |

Note: The difference in the number of observations for each traffic volume was due primarily to unexpected changes in traffic volumes during the maneuvering test.

**Table 2. Means of maneuvering time, speed, and distance for three and four lanes in light, medium, and heavy LS traffic.**

| Condition | N | Mean Time (s) | Mean Speed (mph) | Mean Distance (ft) |
|---|---|---|---|---|
| Low Speed (<35 mph) | | | | |
| Three-lane | | | | |
| Light | 21 | 13 | 47 | 892 |
| Medium | 21 | 14 | 47 | 984 |
| Heavy | 14 | 35 | 19 | 809 |
| Four-lane | | | | |
| Light | 17 | 16 | 45 | 1043 |
| Medium | 19 | 25 | 43 | 1538 |
| Heavy | 13 | 34 | 26 | 1178 |
| High Speed (>35 mph) | | | | |
| Three-lane | | | | |
| Light | 41 | 13 | 50 | 941 |
| Medium | 41 | 15 | 48 | 1024 |
| Heavy | 32 | 17 | 47 | 1164 |
| Four-lane | | | | |
| Light | 35 | 17 | 47 | 1136 |
| Medium | 44 | 24 | 44 | 1529 |
| Heavy | 37 | 24 | 43 | 1453 |

**Table 3. Analysis of variance: maneuvering distances associated with LS and HS light, medium, and heavy traffic.**

| Source | df | Mean Square | F-Statistic |
|---|---|---|---|
| Low Speed | | | |
| Blocks | 6 | 87 238 | 1.27 |
| Treatment | | | |
| A | 1 | 1 224 363 | 17.76[a] |
| B | 2 | 318 017 | 4.61[b] |
| AB | 2 | 143 417 | 2.08 |
| Residual | 30 | 68 940 | |
| Total | 41 | | |
| High Speed | | | |
| Blocks | 14 | 92 804 | 1.32 |
| Treatment | | | |
| A | 1 | 2 364 228 | 33.53[c] |
| B | 2 | 694 666 | 9.85[c] |
| AB | 2 | 194 674 | 2.76 |
| Residual | 70 | 70 501 | |
| Total | 89 | | |

Note: A = number of lanes; B = volume.
[a] $p < 0.01$. [b] $p < 0.05$. [c] $p < 0.001$.

SUMMARY OF CONCLUSIONS

In this in situ instrumented-vehicle study, a set of required distances was determined to be used to estimate advanced sign-placement distances. The following is a brief summary of the findings and conclusions of this research:

1. Maneuvering distances were affected by traffic volumes on both the three- and the four-lane freeways. As volume increased, maneuvering distance also increased.
2. After the mean maneuvering distance in medium traffic and heavy traffic on both the three- and the four-lane freeways had been computed, the mean maneuvering distance in medium traffic was larger than that in heavy traffic. An analysis of the time required to complete the maneuver indicated that the time required in heavy traffic was significantly longer than that in medium traffic. An analysis of the speed of the test vehicle indicated that during maneuvers in which the test vehicle was very slow (8-17 mph), the time required to complete the maneuver was very long and the maneuvering distance was substantially shorter than the maneuvering distances in heavy traffic at higher speeds (40-47 mph). It was therefore concluded that recommended distances should be based on two types of maneuvering in heavy traffic. These two types were heavy LS and heavy HS maneuvers.