Report on Tasks:

S-1, Analysis of Driver Response Delays and S-2, Lane Changes

Report Title:

ANALYSIS OF DATA ON SPEED-CHANGE AND LANE-CHANGE BEHAVIOR IN MANUAL AND ACC DRIVING

This report was prepared for the
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OVERALL PROGRAM OBJECTIVES

The overall goal of the FOCAS program is to facilitate the development of sensors and associated applications systems that supplement the forward crash avoidance performance of drivers. To aid in achieving this goal, the program seeks to develop evaluation tools, methodologies, and knowledge bases through which the development of forward crash avoidance system (FOCAS) products is expedited, and the performance of these products is assessed.

The third annual report provided detailed information on test results and system-development experience involving engineering and human factors performance issues presented when service brakes become engaged by either an ACC function or a medium deceleration crash avoidance function.

Based upon the knowledge gained during the third year, the current objectives are to

1. assess system-level issues associated with a “basic” ACC-with-braking function,
2. assess the need for and provision of an ACC intervention prompt, in an “enhanced” ACC-with-braking function,
3. identify testing methods suitable for human use of an ACC-with-braking function on a proving grounds facility, and
4. make an initial assessment of the Forward Crash Avoidance function.

This report pertains to supplementary tasks whose goals are to provide results indicating how the presence of an ACC system influences driving behavior when the preceding vehicle changes speed or when the driver decides to change lanes. These results contribute to objectives 1, 2, and 4 listed above.

1.0 INTRODUCTION

This document reports on analyses of data performed by the University of Michigan Transportation Research Institute (UMTRI) for the National Highway Traffic Safety Administration (NHTSA). The data analyzed were first obtained in a separate study entitled “Intelligent Cruise Control Field Operational Test (ICC FOT)” [1]. These data provide measurements from driving manually and from driving with an adaptive cruise control (ACC) in operation.

In this part of the FOCAS study, the ICC FOT data have been examined electronically to gather information on driver behavior and ACC system performance when the preceding vehicle is braking or maintaining nearly constant speed. Also information has been gathered on situations when the driver of the following vehicle is changing lanes to pass the preceding vehicle. These data sets have been analyzed to provide results and findings associated with driver response delays (Task S-1) and characteristics of lane-changing situations (Task S-2).

Results on headway control from Task S-1 have been subdivided into two parts concerned with

1) driver waiting time (delay or latency) during brake intervention by the driver of the following vehicle as caused by the preceding vehicle decelerating more rapidly than typical coasting, and
2) delay during continuous control of speed as needed to follow a preceding vehicle that is moving at approximately constant speed.

Differences between manual and ACC modes of headway control are presented and compared in the next section of this report.

Results on lane changing from Task S-2 have been divided into four parts pertaining to

1) creating data arrays containing time history segments of pertinent variables during periods of lane changing activity,
2) obtaining measures of lane changing performance such as
   - lane-change frequency in ACC and manual driving,
   - range at which the preceding vehicle was cleared,
   - range-rate at which the preceding vehicle was cleared,
   - time-to-collision at which the preceding vehicle was cleared,
   - headway time margin at which the preceding vehicle was cleared;
3) examining throttle usage during pulling out to pass maneuvers when ACC was in operation; and

4) examining differences in ACC lane-change activity on freeways and rural state highways.

Results on manual and ACC driving in lane-changing maneuvers are presented in section 3. The report has two more sections — a section summarizing the results and findings and a final section presenting the conclusions and recommendations derived from this work.

2.0 TASK S-1, RESPONSE TO THE SPEED OF THE PRECEDING VEHICLE

2.1 Response to braking

The data do not include a direct indication of when the driver of the preceding vehicle pressed on the brake pedal. The time when the brake lights of the preceding vehicle are illuminated is not automatically recorded. In addition the level of brake application is not measured. Hence it is necessary to compute an estimate of the deceleration rate of the preceding vehicle for use in identifying when and how much the preceding vehicle decelerates.

The method for determining the deceleration of the preceding vehicle is as follows. First the speed of the preceding vehicle is calculated using the velocity (V) of vehicle equipped with the ACC system (the ACC vehicle) and the range rate (Rdot) measured by the ACC sensor. (The sensor signals (range (R) and Rdot) and velocity V are measured regardless of whether the driver is driving manually or with the ACC system engaged.) The velocity of the preceding vehicle (Vp) is equal to the sum of V and the relative velocity Rdot between the vehicles. Hence,

$$\mathrm{Vp} = \mathrm{V} + \mathrm{Rdot} \qquad (1)$$

The calculated value for Vp is then differentiated numerically to obtain an approximation to Vpdot. Since the signals for V and Rdot are recorded, past and future values of Vp can be used in determining Vpdot at any chosen time. However, the resolution on V is to the nearest 0.5 mph and the data rate is 10 samples per second. This means that the raw Vpdot signal is quite noisy and can have frequent spikes as well as relatively long periods of zero acceleration. To compensate for this situation, smoothing and regression techniques are used to remove some of the higher frequency content from the Vpdot signal.

Furthermore drivers do not tend to brake in a square-wave fashion. There are situations in which the driver coasts or brakes modestly before resorting to hard braking. When situations that start with modest braking arise, it is difficult to choose a value for the time when hard braking started. A special technique was devised in this study to identify and assign the time when the preceding vehicle started to decelerate rapidly. This same technique was also used to assign and identify the time when the ACC-equipped vehicle started to decelerate rapidly.

The procedures for determining the times when significant decelerations were initiated are shown in figure 1. The figure is divided into three plots and shows a braking event for FOT driver 59 on trip 67 at a Vactime of 14.06 minutes [1]. The top plot shows acceleration for the ACC and preceding vehicle along with the brake signal indicating application of the brake pedal in the ACC vehicle. The center plot shows the velocity of the ACC and preceding vehicle along with four constant-slope best-fit lines (two lines for each signal). The bottom plot shows range and range-rate during the braking event.

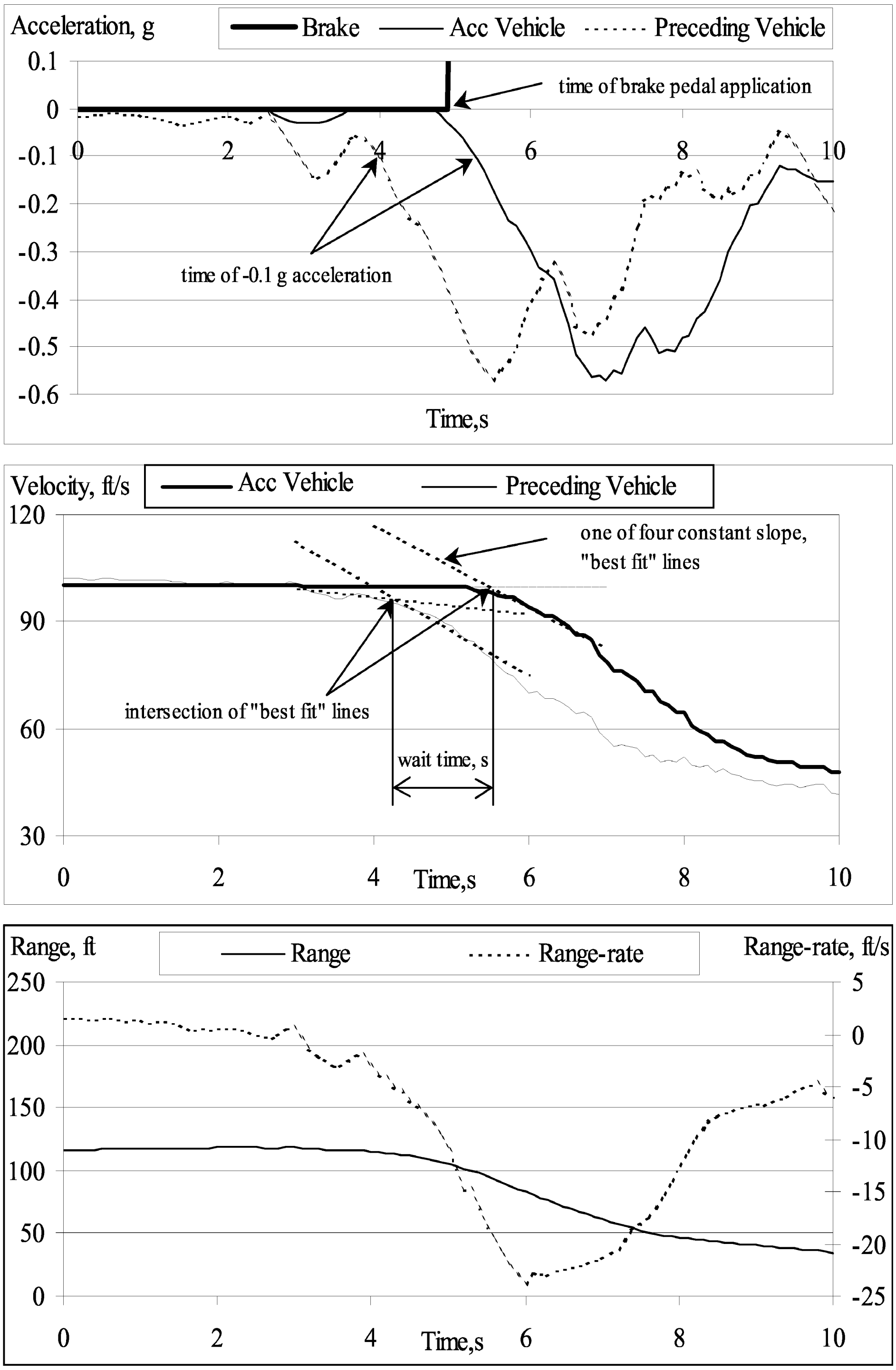
The basic idea is to fit two straight-line segments to the velocity signal. The first line is fitted to the velocity signal prior to a rapid deceleration. The second line is fitted to the velocity signal during the time of rapid deceleration period. The slopes of these lines indicate an approximation to the deceleration before (slope m1) and during braking (slope m2). The time corresponding to the point where these lines intersect is taken as the time when significant deceleration starts.

Thus for selected braking events there is a time called the "preceding vehicle intersection" time that indicates approximately when the preceding vehicle started to decelerate significantly. There is also a similar time called the "ACC vehicle intersection" time. For a particular braking event, the difference between ACC vehicle intersection time and the preceding vehicle intersection time is called the "wait" time (Wt). Hence, wait time (Wt) is a measure of how long the driver waited before intervening with significant braking in the situation being examined. (Wait time is shown in the center plot of figure 1.)

The results to be presented next are for a set of braking events that satisfy the following inequalities:

$V \geq 50$ mph (80 kph) at the ACC vehicle intersection time and

$-0.05g \leq m1 \leq 0.0g$ and $m2 \leq -0.1g$ for both Vp and V.



These inequalities require that the vehicles are traveling at highway speeds and that they are braking at a relatively hard level.

Figure 1. Illustration of wait time calculation

The entire set of data measured in the FOT covered approximately 114,000 miles of driving by 108 different drivers in normal transportation service [1]. The data analysis found 67 hard braking cases during ACC driving when the ACC system was operating on a target. There were 303 such cases during manual driving.

Although drivers tended to drive manually or use ACC with approximately equal frequency in the speed range above 50 mph, it was observed in the FOT study that drivers tend to use ACC when they believe that braking will not be necessary. In general, they tend to operate manually when the situation is more difficult to predict. Nevertheless, regardless of whether the driver is using ACC or not, braking events where both the preceding and the following vehicle decelerate at a magnitude greater than 0.1g are relatively infrequent events at speeds above 50 mph.

Table 1 presents a summary of results including averages and standard deviations of pertinent quantities for the sets of manual and ACC brake interventions. Examination of the table indicates that on average the ACC braking cases appear to be slightly more severe than the manual cases because the decelerations are slightly larger and the relative velocities (Rdot) are more negative. (Negative Rdot indicates that range to the preceding vehicle is getting smaller.) In addition, the brake time (that is the duration of the braking period for the ACC-equipped vehicle) is longer for the ACC cases than it is for the manual driving cases. Hence the speed change (delta V) for the ACC-equipped vehicle is greater for ACC driving than it is for manual driving.

However, the standard deviations for these results are so large that the differences in the averages may not be regarded as statistically trustworthy.

Table 1 also contains results pertaining to the headway situation at the preceding vehicle and ACC vehicle intersection times. Again the standard deviations are large compared to the average values, but on average the headway distances (R) and headway time margins (Htm = R/V) are larger for ACC driving. The additional headway time margin for ACC driving means that the ACC system provides more time to react than that which drivers choose to use in manual driving.

Table 1 contains results for time to impact (Tti = -R/Rdot) but they do not appear to provide us with any useful interpretation except that they seem to be relatively large and benign when the preceding vehicle commences to decelerate rapidly. We have not made extensive use of Tti at the time the preceding vehicle braked hard in this report except to make a plot showing the relationship between wait time and Tti . The results (shown in figure 2) indicate that there were only two cases (both manual driving) in which time to impact (R/Rdot) was less than 6 sec. However, data shown in Table D-1 in appendix D indicate that time to impact values that are less than 6 seconds are not uncommon by the time the ACC-equipped following vehicle starts to brake heavily.

Table 1. Summary of results for ACC and manual brake interventions

		Wait time and other statistics during brake application time				
		Wait time, s	Delta V, ft/s	Brake time,s	Decel., g	Max decel, g
Manual	Average	1.05	22.66	4.49	0.16	0.25
	Std dev	0.81	17.94	3.51	0.05	0.09
ACC	Average	1.26	32.06	6.10	0.17	0.27
	Std dev	0.91	20.92	4.70	0.06	0.09
		Preceding vehicle intersection				
		Range, ft	Rdot, ft/s	Velocity, ft/s	Htm, s	Tti, s
Manual	Average	102.23	-3.48	87.65	1.18	23.12
	Std dev	55.34	4.52	10.14	0.65	11.40
ACC	Average	144.50	-5.20	91.39	1.59	23.25
	Std dev	66.09	6.36	9.67	0.73	11.80
		ACC vehicle Intersection				
		Range, ft	Rdot, ft/s	Velocity, ft/s	Htm, s	Tti, s
Manual	Average	92.89	-7.89	86.42	1.09	14.72
	Stand dev	47.26	5.75	10.07	0.57	8.57
ACC	Average	129.99	-11.42	90.26	1.44	14.69
	Stand dev	58.30	7.98	9.95	0.64	10.41

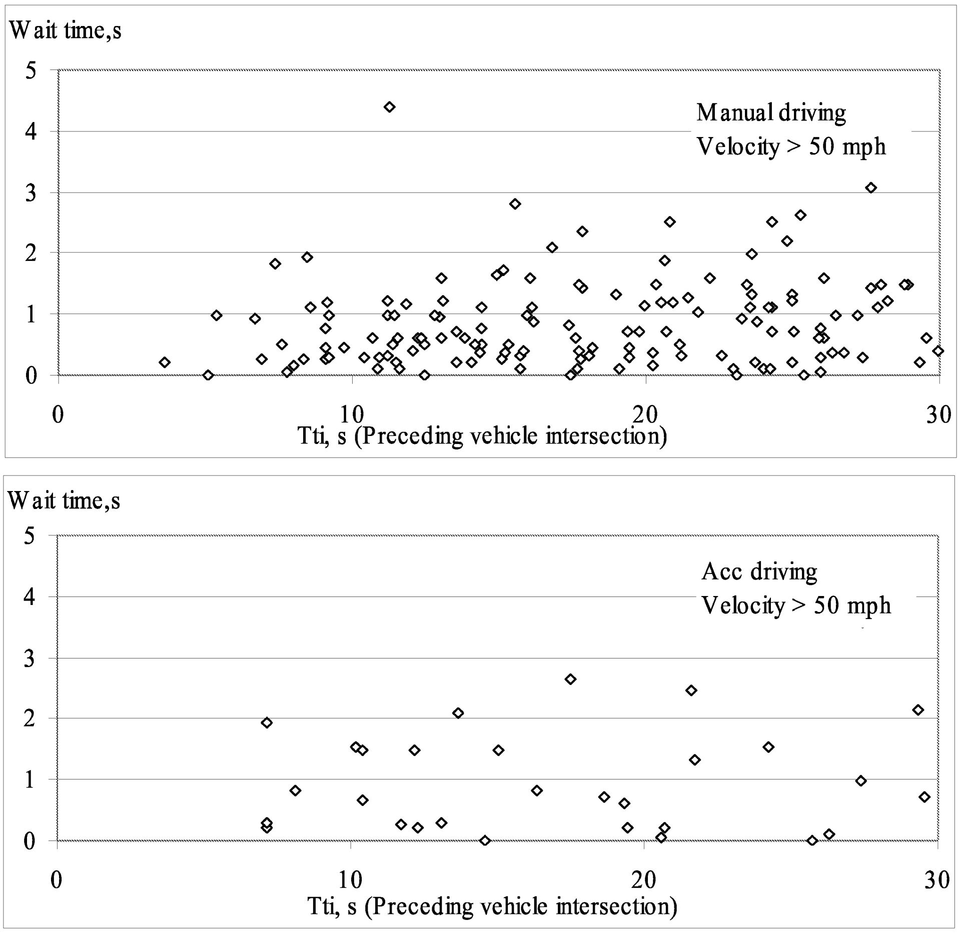


Figure 2. Wait time versus time-to-impact (Tti)

Figures 3, 4, and 5 all deal with the relationship between headway time margin and the wait time exhibited by the driver.

Figure 3 is based upon data gathered at the beginning of the braking event (that is, at the preceding vehicle intersection time). There are no data points in the region of the figure characterized by relatively long wait time compared to the headway time margin. Qualitatively, this is because the driver does not wait very long if the headway time margin is small—otherwise the driver would come close to crashing or crash. However, there are many wait times that are longer than the headway time margin as indicated by the superimposed line with a slope of unity passing through the point, Htm = 5 and Wt = 5 in figure 3.

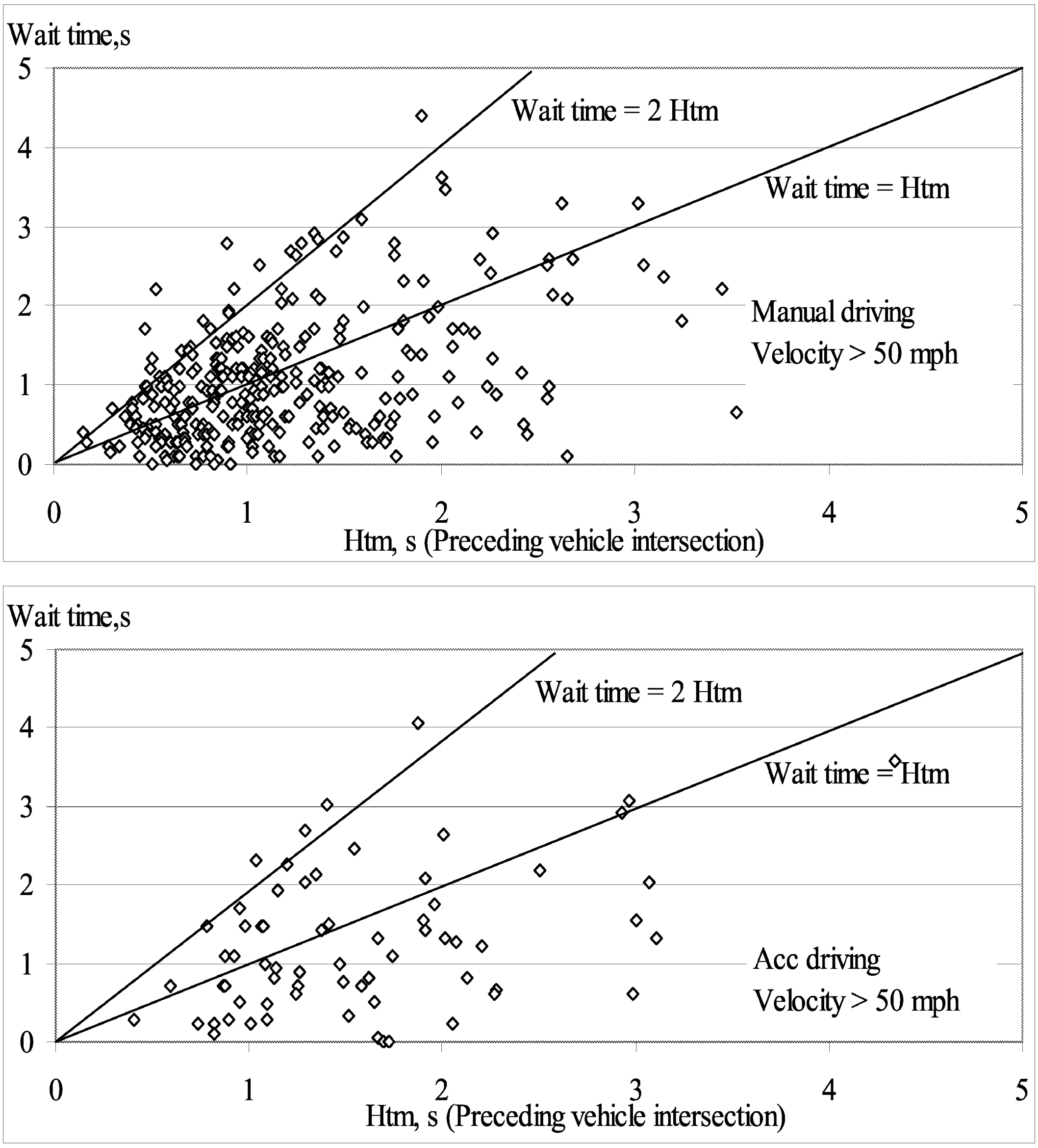


Figure 3. Wait time versus headway time margin at the preceding vehicle intersection time

Figure 4 is similar to figure 3 except the variable used for the horizontal axis is Htm at the time when the ACC-equipped vehicle starts hard braking. Overall the appearances of figures 3 and 4 are similar. However, an important difference is shown in figure 5. Figure 5 shows that the driver does not wait so long that the headway time margin changes by much more than 0.2 times the wait time. This result indicates a tendency for drivers to try to maintain headway time margin by braking promptly when necessary.

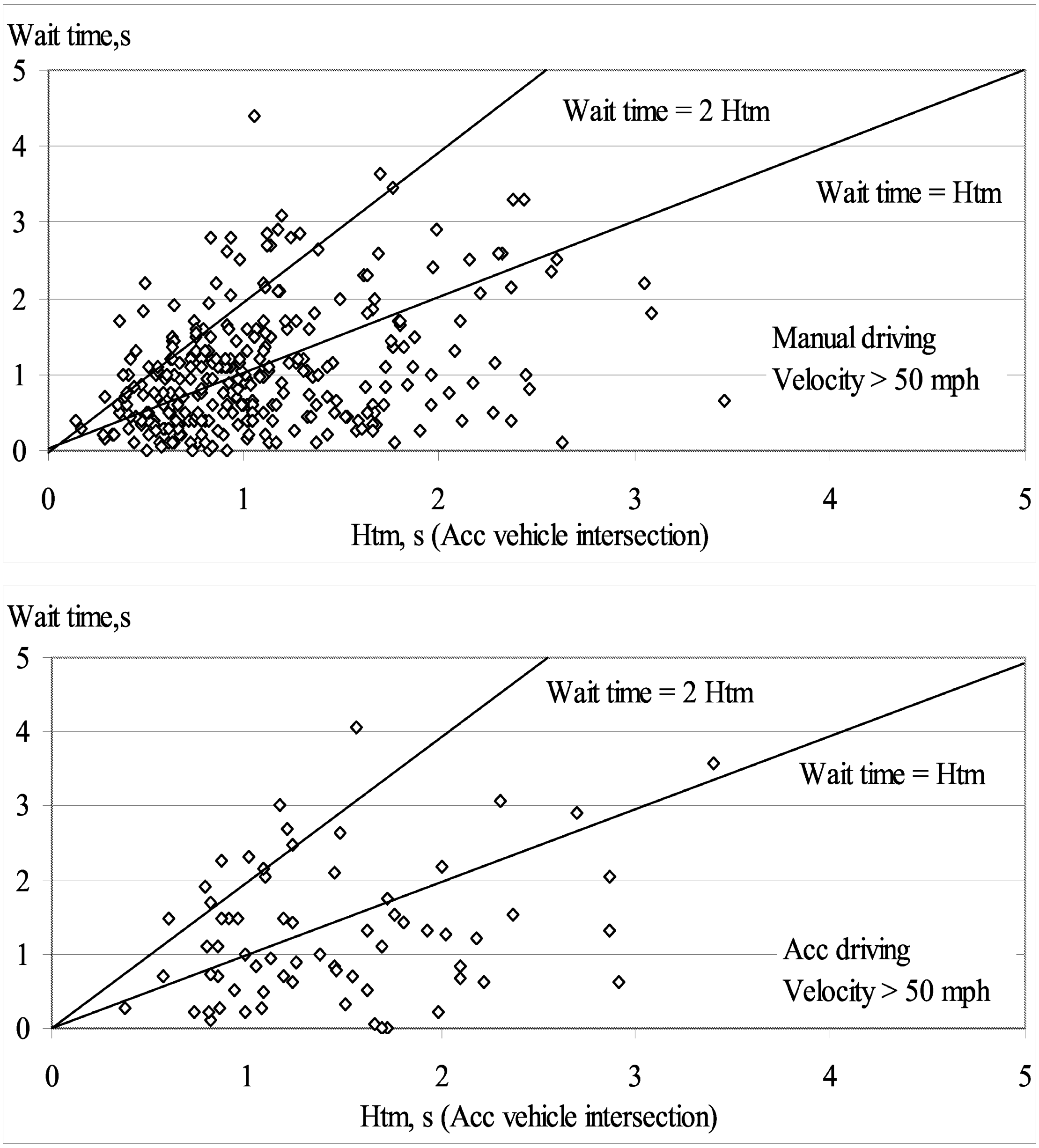
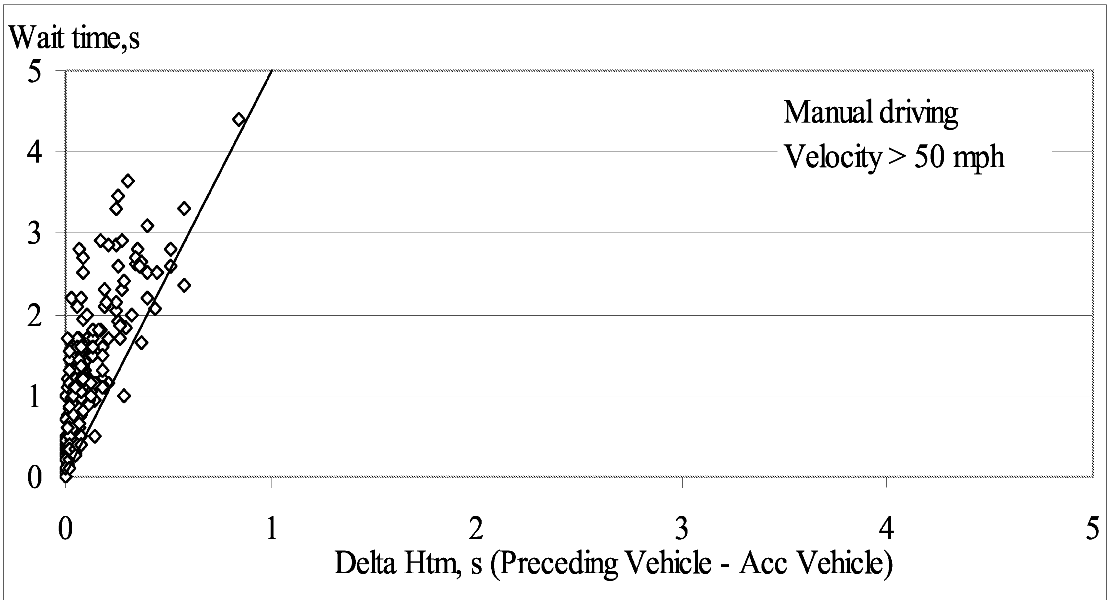


Figure 4. Wait time versus headway time margin at the ACC vehicle intersection time

The physical basis for comparing the wait time with the headway time margin lies in the following observation. If the preceding and following vehicles are initially traveling at approximately the same speed at a constant range, the headway time margin would be R/V = Htm. Then, let us assume that the preceding vehicle braked at nearly a constant deceleration Dp, and the following vehicle delays any braking for Htm seconds but then the following vehicle brakes at the rate Dp also. In this scenario the vehicles would not crash but the front of the following vehicle would end up next to the rear of the preceding vehicle, if both vehicles proceeded to a stop. Hence one might expect Htm to be something like the wait time if this scenario were representative of the test results.



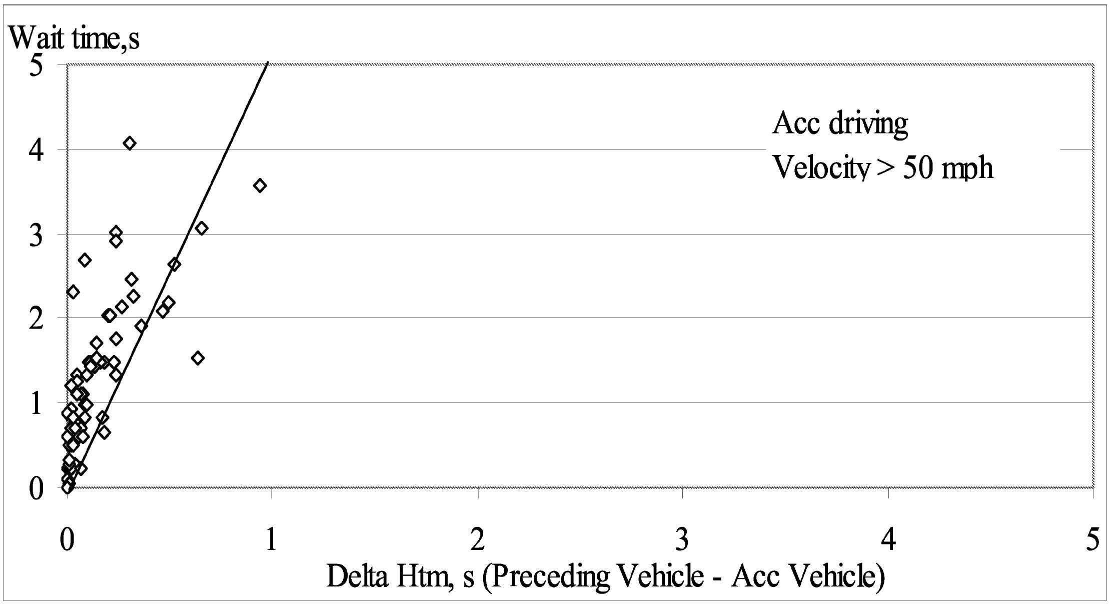


Figure 5. Change in wait time versus headway time margin

Examination of figure 3 shows that the data are spread about the line of unity slope (Htm = wait time) with points ranging from Wt ≈ 0 to Wt ≈ 2·Htm. This means that on occasion (when Wt ≈ 0) the driver of the following vehicle braked at practically the same time as the driver of the preceding vehicle. In these cases, it is postulated that the driver of the following vehicle saw and knew of the impediment that caused the preceding vehicle to brake. The driver of the following vehicle was essentially responding to the impediment and not to the braking of the preceding vehicle per se. At the other extreme when Wt ≈ 2· Htm, the driver of the following vehicle waited for what appears to be an exceptionally long time after the preceding vehicle started to decelerate rapidly. In these cases, it seems that the driver of the following vehicle would need to brake much harder than the driver of the preceding vehicle to avoid a near miss.

The following idealized analysis provides a basis for thinking and reasoning about the relationship between Htm and Wt. The analysis has been simplified by considering the equations for constant deceleration stops. Hence it constitutes a substantial abstraction from the realities of the situations in which the data were obtained. Nevertheless it serves as a reference for use in examining certain aspects of driver braking behavior.

A standard stopping distance equation for the following vehicle is:

$$\mathrm{Xf} = \mathrm{Wt} \cdot \mathrm{Vo} + \frac{\mathrm{Vo}^2}{(2 \cdot \mathrm{Ax})} \tag{2}$$

where Xf is the total distance covered by the following vehicle during the stop,

Vo is the velocity before and up to the time when braking started, and

Ax is the deceleration level of the following vehicle (Ax > 0).

The stopping distance available to the following vehicle is the initial range to the preceding vehicle (Ro) plus the stopping distance of the preceding vehicle, viz.,

$$\mathrm{Xp} = \mathrm{Ro} + \frac{\mathrm{Vo}^2}{(2 \cdot \mathrm{Axp})} \tag{3}$$

where Axp is the deceleration level of the preceding vehicle (Axp > 0).

Clearly Xf = Xp if Ax = Axp and Ro = Wt·Vo. Since Ro/Vo is equal to Htm at the time hard braking started, the unity slope line, as presented earlier in figure 3, corresponds to this analytical result.

But what if Wt is greater than Htm? What do equations 2 and 3 imply about the relationship between Ax and Axp? To answer these questions, consider what equations 2 and 3 imply if Xf is set equal to Xp. After performing several algebraic steps the following equation is obtained:

$$\frac{\mathrm{Ax}}{\mathrm{Axp}} = \left[\frac{1}{(1 + (\mathrm{Axp} \cdot 2 \cdot \frac{(\mathrm{Htm} - \mathrm{Wt})}{\mathrm{Vo}}))} \right] \tag{4}$$

Examination of equation 4 indicates that if Wt > Htm , Ax will be greater than Axp. Equation 4 also indicates that if Wt < Htm, Ax < Axp. However, in noncritical situations, the driver can choose to decelerate slightly faster than necessary without any serious consequences. Nevertheless, even though equation 4 is an idealized abstraction, it has relevance to driver behavior in cases where Wt is enough larger than Htm that Ax needs to be large to prevent a close encounter or a crash.

Examination of the data in figure 3 indicates that rarely does the driver get into situations where Wt is greater than 2·Htm. Also examination of Table D-1 in appendix D shows that the ratio of the initial deceleration of the following vehicle (as represented by M2_following) is seldom greater than twice the deceleration of the preceding vehicle (as represented by M2_preceding).

Table D-1 in appendix D presents a comprehensive set of data for all 303 manual cases with hard braking as well as the 67 cases for ACC driving.

The results and findings presented next have been obtained by sorting the table in various manners. The version given in appendix D has been sorted by values of Htm – Wt in ascending order. This choice of sorting is based upon the relationship given in equation 4.

The table contains values of pertinent variables such as R, Rdot, V, Htm, and Tti as well as M2 for the preceding vehicle at the preceding vehicle intersection time (when the preceding vehicle started to brake at 0.1 g or greater). The table also contains values of the same variables as well as M2 for the ACC-equipped vehicle at the ACC vehicle intersection time (when the ACC-equipped vehicle started to brake at 0.1 g or greater). In addition, values of the maximum deceleration for each vehicle (Max Ax) during each braking event are included in the table.

The data for each stop have been processed to determine the wait time (Wt), Htm – Wt, the change in speed of the ACC-equipped vehicle, and the time period of brake application for the ACC vehicle. In addition, three deceleration ratios have been computed:

1) "Slope Ratio" which is the ratio of the initial decelerations given by M2 (ACC vehicle) divided by M2 (preceding vehicle).

2) "Max Ratio" which is the ratio of Ax maximum for the ACC vehicle divided by Ax maximum for the preceding vehicle.

3) "Est. Ax Ratio" which is calculated from measured results using equation 4 to estimate the amount of braking just sufficient to avoid a crash if the initial braking by the preceding vehicle were to persist to a stop.

Clearly, we are trying to explain what has turned out to be a complex situation. There is a mixture of deterministic as well as probabilistic factors to consider. As in all events involving human psychology, one can only infer what the driver is thinking. We cannot measure what is in the driver's mind in the same manner as we can measure range (R) or some other physical quantity. Although we have a large amount of information concerning these braking situations, we only have limited knowledge concerning only a few of the many things the driver uses to decide on braking actions.

Simple results appear to explain something about wait times and deceleration levels in these braking events. However, the data are too scattered to fit a simple statistical analysis involving one or two variables. Given these difficulties, it seems surprising that sorting the processed data using various measured quantities and deceleration ratios provides interesting information. Perhaps, repeated ordering of the data by values of each variable has some utility as a practical, pragmatic approach to data mining in general. Nevertheless, a simple model such as that given by equation 4 is a great help in structuring the process of mining the data. There are too many possibilities to examine all possible relationships. In order to limit the number of possibilities to be examined, researchers need to select a strategy for trying to discover information that is useful to them. In this case our strategic goal is to find information that addresses whether drivers tend to wait too long and consequently brake too hard when ACC is in use.

The data presented in table D-1 in appendix D have been used to create histograms of wait time behavior in manual and ACC driving. Figure 6 shows that approximately 30 percent of the wait time values in manual driving fall in a ±0.25 second band centered at 0.5 seconds. The next most likely bin is centered at a wait time value of 1.0 second. For manual driving, wait times longer than 1.75 seconds only occur in 47 out of 303 cases, that is in only 15.5 percent of the cases. These results may be compared with the results for ACC driving shown in figure 7. Figure 7 indicates that given a braking event, there is a greater chance of longer wait times when the ACC system is in use. Of course, since there were only 67 ACC events versus 303 manual braking events, the absolute number of long wait times in braking events is not as large for ACC as it is for manual driving. For ACC driving, wait times longer than 1.75 seconds occur in 17 out of 67 cases or in 25 percent of the cases. Given that drivers brake much more frequently in manual driving, it is difficult to ascertain if these data indicate that ACC driving involves greater exposure to excessively long wait times.

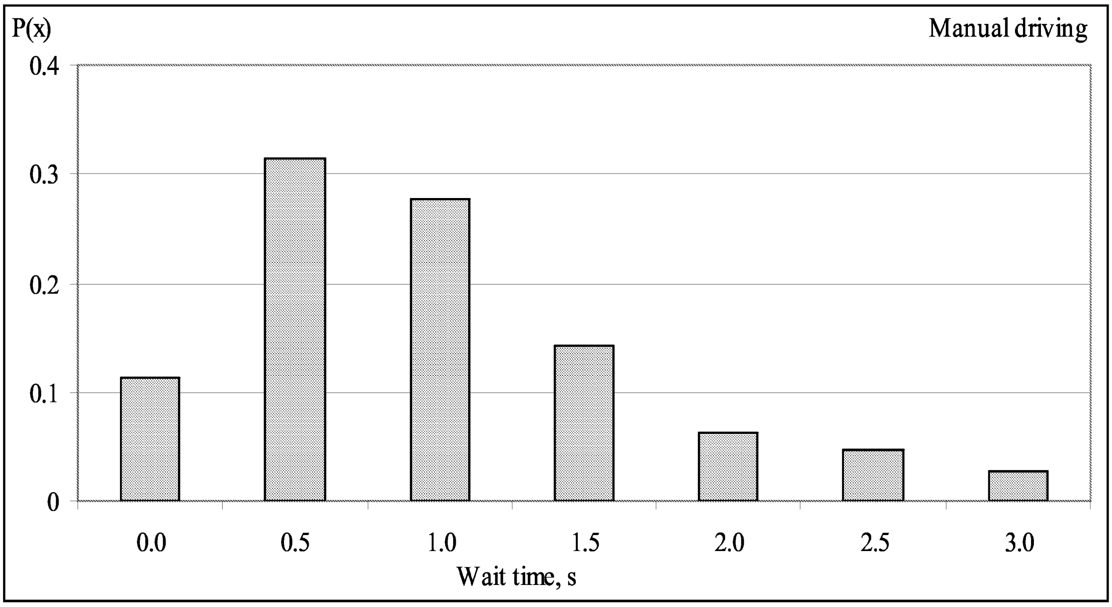


Figure 6. Wait time behavior in manual driving

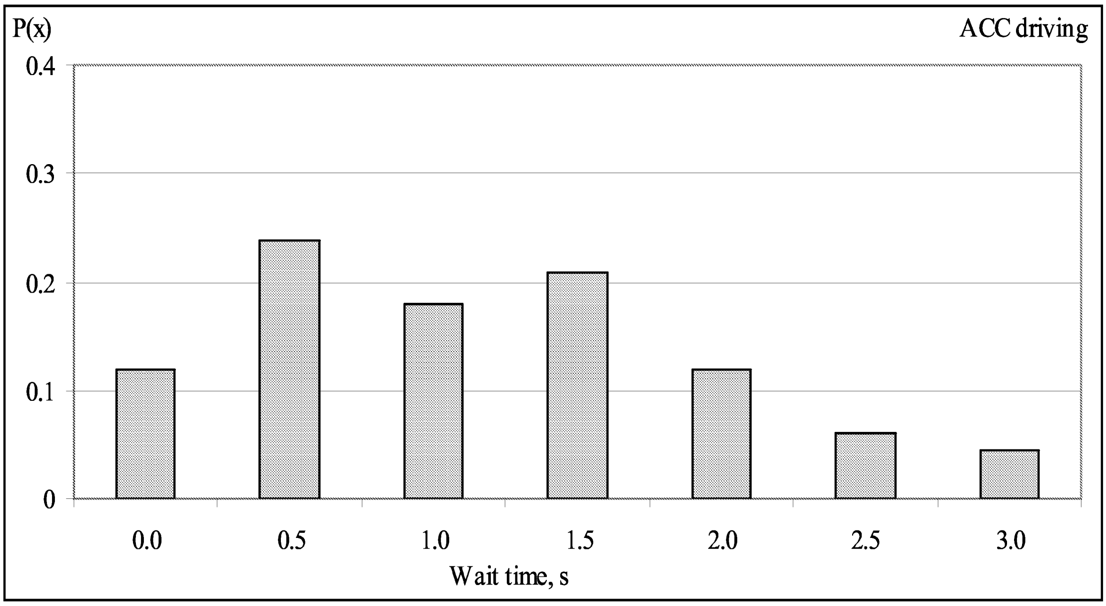


Figure 7. Wait time behavior in ACC driving

To examine the wait time information further, histograms of Htm – Wt have been constructed for manual and ACC driving. See figures 8 and 9. Figure 8 shows that Htm – Wt is near zero (± 0.5 seconds) for nearly 55 percent of the cases involving manual driving. In comparison, the results for ACC driving indicate that 35 percent of the cases are in the bin centered at zero where Wt ≈ Htm. The next most likely bin, which is centered at 1.0 second, contains almost as many cases as the bin centered at zero. With respect to the headway time available, these results show that longer wait times are more likely to occur during braking events in ACC driving than they are during braking events in manual driving.

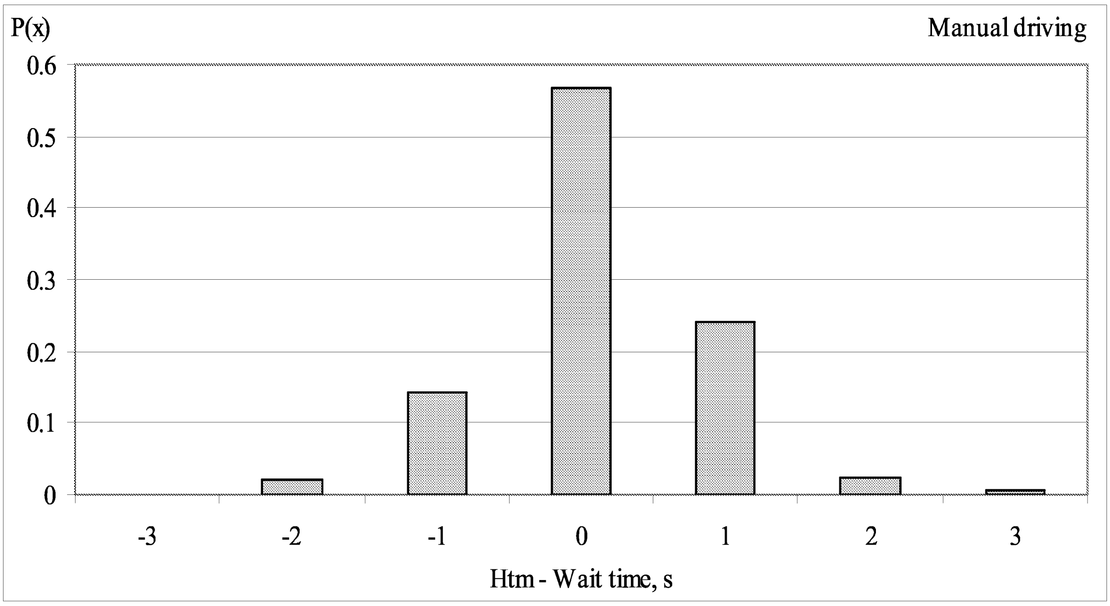


Figure 8. Htm-Wt behavior in manual driving

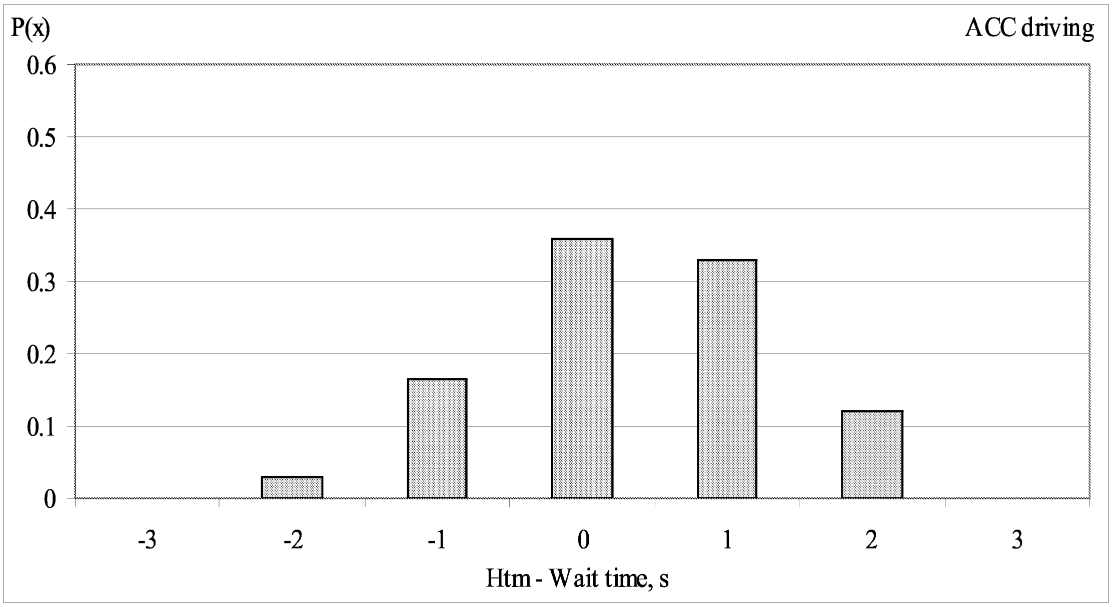


Figure 9. Htm-Wt behavior in ACC driving

However, a major feature of the ACC system used in the FOT was that it provided much longer headway times than those that drivers chose to use in manual driving. The driver had a choice of approximately 1.0, 1.4, or 2.0 seconds when the ACC system was engaged. During manual driving, headway time margins less than 0.6 seconds are not uncommon [1]. In processing the data for task S-1, the data in Table D-1 in appendix D were arranged by headway time margin (Htm) in ascending order. This facilitated the examination of Htm at the beginning of hard braking situations.

The shortest headway time margin was 0.15 seconds. In this manual driving case, the driver of the following vehicle was travelling at 100 ft/s (68 mph) at a range of 15 ft when the preceding vehicle started to brake at a deceleration level of 0.11 g. Although it would be very difficult for some drivers to cope with this situation, this case was resolved without a crash. Several factors contributed to the resolution of the situation. First, the driver's wait time was only 0.39 seconds. Clearly, the driver was alert. Second, the maximum braking of the preceding vehicle only reached 0.14 g and braking did not last for very long because the driver of the following vehicle only needed to brake for 1.9 seconds. Perhaps this was an accident waiting to happen. Perhaps this situation might be classified as a narrow escape. —What if the driver of the preceding vehicle had braked harder or longer? —What if the driver of the ACC-equipped vehicle had not been as alert? In any event, people driving manually are able to handle these types of situations sometimes.

Many drivers do not choose to follow this closely, but according to the original FOT study [1], about 23 percent of drivers (25 out of 108) have a driving style classified as hunter/tailgaters. This type of driver tends to operate at short ranges and high speed. With the ACC in operation, no driver in the FOT study was able to operate in the hunter/tailgater style. This finding is reflected in the headway time values for cases with hard braking during ACC operation. The minimum Htm at brake intervention was 0.40 seconds and this was the only case below 0.5 seconds when the ACC system was in operation. In contrast, there were 23 cases with the initial Htm less than 0.5 seconds when driving manually. In terms of percentages, manual driving below 0.5 seconds of Htm was 7.5 percent (23/303) and ACC was 1.5 percent (1/67). With regard to Htm less than 1 second, the percentage for ACC driving was 20.8 percent (14 out of 67) and for manual driving it was 46.9 percent (142 out of 303). These results for Htm imply that a person driving with ACC can afford to wait longer than they can when driving manually. They have more headway time margin available when operating with ACC. However, the ultimate question is did the drivers wait so long that they needed to brake much harder than the preceding vehicle?

The issue of how long drivers waited in ACC versus manual driving can be addressed by further examination of table D-1 in appendix D. This table is sorted by (Htm–Wt). One approach to evaluating the results in the table is to recall the meaning of (Htm–Wt) in equation 4. In the sense of equation 4, if (Htm–Wt) is negative, the driver appears to have waited too long and the estimated Ax ratio (given in table D-1) will be greater than one. This means that the driver needs to brake harder than the preceding vehicle braked.

The results show that in 41.6 percent (126 out of 303) of the manual driving cases, wait time is greater than Htm, while in ACC the result is 32.8 percent (22 out of 67). This difference equalizes if the comparison is made for (Htm-Wt) < - 0.4 seconds rather than for (Htm-Wt) < 0.0 seconds. The results are 20.8 percent (63 out of 303) for manual driving and 20.9 percent (14 out of 67) for ACC driving. According to equation 4, if Htm – Wt = -0.4 seconds, and Axp (the deceleration of the preceding vehicle) equals 0.2 g, and the initial speed is 100 ft/s, the acceleration of the following vehicle needs to be 0.21 g. Thus, Ax needs to be 5 percent greater than Axp. Perhaps, Htm – Wt = -0.4 seconds is a reasonable boundary to use. The point is that the driver could wait a little longer than Htm without paying a large penalty in the deceleration needed. On this basis, it appears that drivers tend to conserve headway time margin by not waiting too long in either ACC or manual driving.

Another approach to processing the data is to examine the values of the estimated Ax ratio appearing in table D-1. A number of factors need to be considered when examining this ratio. The deceleration ratios (labeled Est. Ax ratio and Slope ratio and Max ratio in table D-1) are sometimes not close to being equal. These differences are sometimes explained by the fact that the initial braking level and the maximum braking level are often not the same for both the preceding and following vehicles.

Figure 10 provides data showing that the initial braking level (M2) for the preceding vehicle is frequently equal or close to the maximum level. However, the data also show that the maximum braking level is just as frequently more than 1.5 times the initial braking level. Figure 11 shows similar results for the following vehicle. In addition, inspection of table D-1 indicates that the timing of initial and maximum braking is often not the same for both vehicles in a particular braking event. The net result is that the Slope ratio (which is M2 preceding vehicle divided by M2 following vehicle) may not be close to the Max ratio (which is Ax maximum divided by Axp maximum). Furthermore, the Est. Ax ratio may fall in between the other two ratios when initial and maximum braking levels are not close to each other.

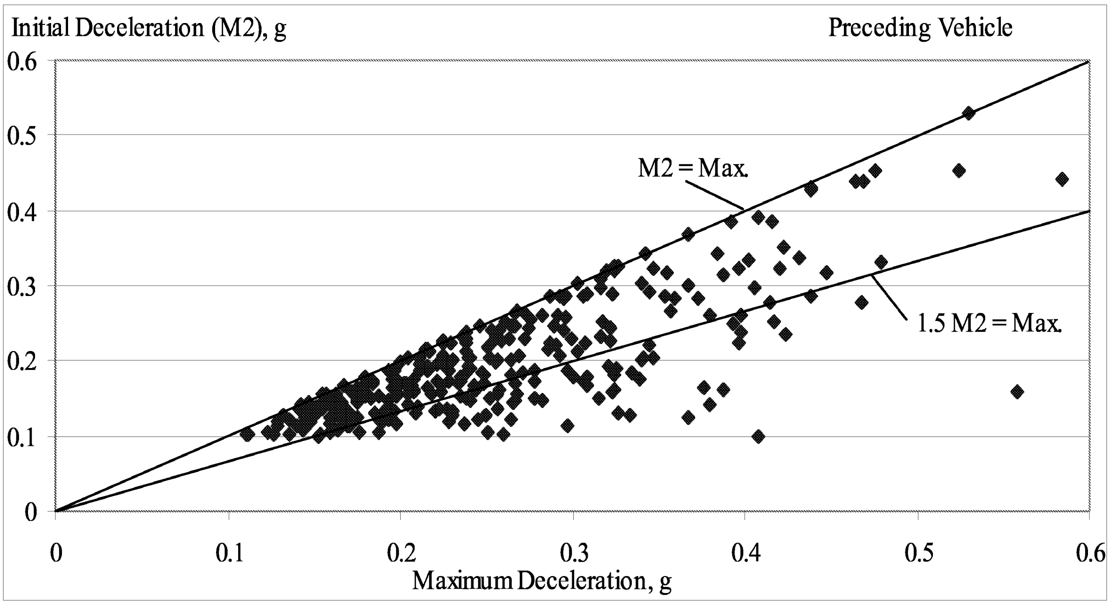


Figure 10. Initial deceleration versus maximum deceleration for the preceding vehicle

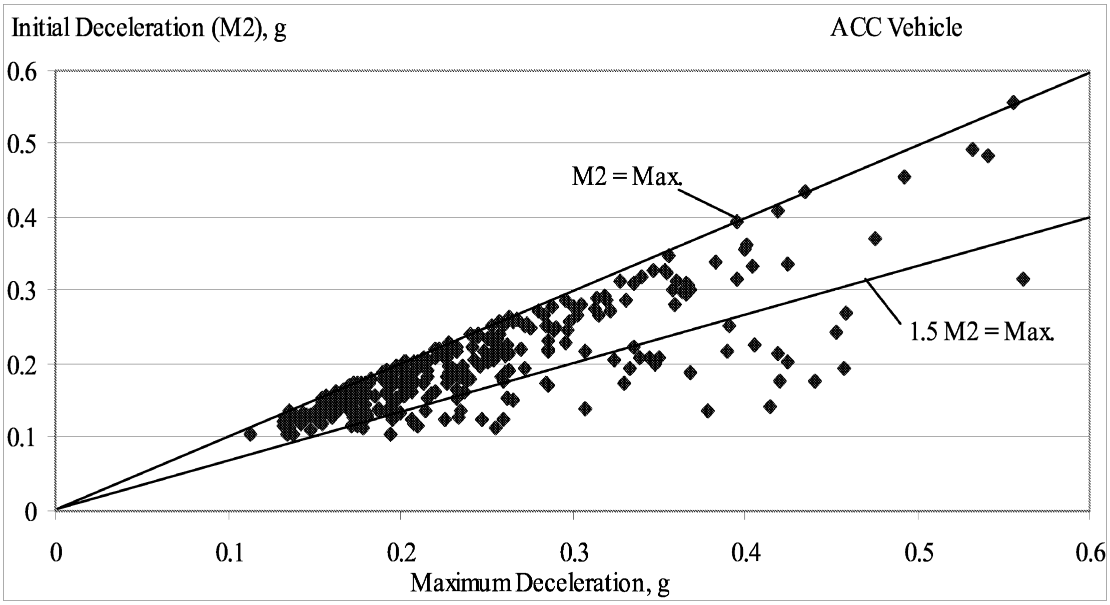


Figure 11. Initial deceleration versus maximum deceleration for the following vehicle

Apparently, the driver of the following vehicle can sometimes correctly predict that the preceding vehicle is going to need to brake harder than its initial deceleration. In this case, the driver of the following vehicle may apply maximum or near maximum braking initially. In addition, it appears that the driver of the following vehicle often over-predicts the level of braking that will be needed. Then, the driver of the following vehicle brakes too hard initially, thereby distorting the meaning of the ratios. On the other hand, the driver of the preceding vehicle may apply the brakes briefly. In many of these cases, the driver of the following vehicle seems to recognize and/or adapt the deceleration of the following vehicle by not braking as hard as would be expected. In these cases, the Est. Ax level based on the initial deceleration of the preceding vehicle will be larger than the Slope ratio. (And so it goes. The details of individual braking events vary in many different ways, thereby making it difficult to generalize.)

Examination of table D-1 with respect to the column labeled ΔT provides insight into the frequency of those cases with short braking events. To understand the amount of time involved in a typical braking event, consider for example a hard braking situation involving a stop from an initial velocity 96 ft per second at a nearly constant deceleration level of 0.2 g. The stopping time would be 15 seconds in a case like this. However many of the braking events in table D-1 last for less than 3.5 seconds. Specifically, 33 percent of the ACC (22 out of 67) and 52 percent of the manual driving cases (157 out of 303) last for less than 3.5 seconds. In many of these cases, drivers of the following vehicle seem to recognize that they do not need to brake as hard as they would for a complete stop. Perhaps in some of these cases the preceding vehicle's deceleration is already diminishing by the time the following vehicle starts to brake. The data appear to indicate that there is a tendency for substantially more of the short braking cases in manual driving. In a sense, drivers appear to wait longer in ACC, thereby not braking as frequently when the preceding vehicle makes a small, quick speed adjustment.

The Est. Ax ratio does not accurately predict how drivers will brake because of the irregularity of maximum and initial braking levels and the shortness of some braking events. Nevertheless, it is the best indicator we have for assessing whether the driver waited too long and appeared to need to brake substantially more than the preceding vehicle braked. Again, we have reordered the braking data to aid in understanding hard braking events. A sorting of the data in table D-1 by the Est. Ax ratio shows that the maximum value of this ratio is 1.45 for manual driving and 1.33 for ACC driving. For the estimated ratio greater than 1.2, there were 11 out of 303 cases (3.6 percent) for manual driving and 2 out of 67 cases (3.0 percent) for ACC driving. The conclusion here seems to be that manual and ACC driving are not much different with regard to waiting too long and then braking too hard.

The results in table D-1 show that the Est. Ax ratio is a better predictor of the Max ratio than it is of the Slope ratio. This happens although both the Slope ratio and the Est. Ax ratio use the initial deceleration of the preceding vehicle in their evaluations. We believe that this is because the Slope ratio reflects the drivers initial reaction to the braking situation. The data indicate that except for some braking events that are characterized by short braking times, Slope ratio is frequently substantially larger than the Est. Ax ratio. This phenomenon is interpreted to mean that drivers sometimes decide to brake harder than is necessary. In a sense, this is a safety conservative approach with respect to rear-ending the preceding vehicle.

Another way to view this phenomenon is to consider high Slope ratios as indicators of when drivers initially thought that they needed to apply hard braking. For example, in manual driving there were 33 out of 303 cases (10.9 percent) where the initial braking by the following vehicle was more than 1.5 times the initial braking level of the preceding vehicle. In contrast, for ACC driving there were 10 out of 67 cases where the initial Slope ratio exceeded 1.5. Perhaps the drivers thought that they needed to brake hard more frequently in ACC driving. In many of these cases, the drivers did need to brake harder than the initial braking would indicate. In 23 of the manual driving cases and in 8 of the ACC driving cases the initial slope for the preceding vehicle was much less than the maximum deceleration ultimately attained by the preceding vehicle. In these cases, the high values of Slope ratio are mostly due to the relatively low initial decelerations exhibited by the preceding vehicles. This means that in most cases with high Slope ratios the drivers of the following vehicles were doing what needed to be done in the end.

The net conclusion from this examination of hard braking cases is that the drivers in the FOT did a remarkably good job of coping with braking events by the preceding vehicle. This discussion of the data does not provide evidence supporting a reason to expect that ACC driving would be any less safe with regard to waiting too long before responding to braking by a preceding vehicle traveling at highway speeds. On the contrary, the additional headway time provided by the ACC system gives the driver more time to react. However, drivers appear to use this time in a manner that makes performance in ACC braking events much like that in manual braking events. The main difference between ACC and manual driving seems to be that there were fewer cases of hard braking in ACC driving than there were in manual driving.

2.2 Continuous Control

Data from the FOT were used to compare response times in manual and ACC-engaged control modes. Here, continuous control refers to episodes of manual and ACC-engaged driving where the ACC-equipped vehicle is following a preceding vehicle for an extended period of time (greater than 14 s) at velocities above 50 mph. The basis of the continuous-control analysis is a cross-correlation between ACC-vehicle velocity and preceding-vehicle velocity signals to determine the shift or delay time that results in the highest level of correlation between the two velocity signals.

An example is given in figure 12. The figure shows the preceding-vehicle velocity, Vp, the unshifted velocity (thick line) and the shifted velocity. In this example, a shift of 3.0 s results in the highest level of correlation between the two velocity signals—hence, for this segment of following data, there is a delay or shift-time of 3 s.

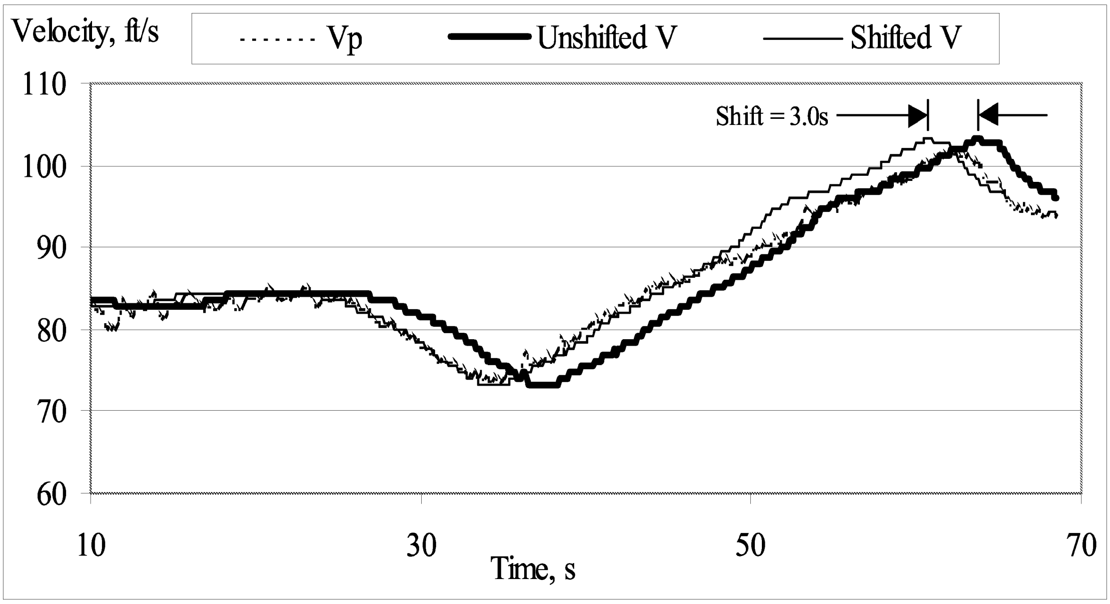


Figure 12. Example of shift time for continuous correlation

Summary results for the continuous control analyses are shown in table 2. The table shows average and standard deviation values of shift-time, duration, range, range-rate, velocity, and headway time, for both manual and ACC-engaged control mode. The right-most column shows the total number of continuous data streams found in the FOT database.

Table 2. Summary of continuous control results

Shift time and other statistics during same-target streams								
		Shift time, s	Avg. Dur., s	Avg. Range, ft	Avg. Rdot, ft/s	Avg. Vel., ft/s	Avg. Htm, s	Count
Manual	Average	2.86	255.28	93.13	-0.26	99.89	0.94	320
	Std dev	1.26	157.28	33.66	0.59	6.84	0.36	
ACC	Average	5.80	252.95	145.01	-0.27	98.09	1.49	261
	Std dev	1.35	131.48	33.04	0.62	7.43	0.37	

The primary finding is that for manual driving, a shift-time of 3 s is typical for the drivers in the FOT. In some regards, this delay time represents a fundamental human control characteristic—namely, that a driver tends to respond to changes in range and range-rate of the preceding vehicle with a 3 second delay. The application for such a basic measure of driving behavior could be broad. For example, a fatigue monitoring device may have a control algorithm that is tuned for a given driver response after a given time. Conceptually, the system would continuously monitor and compare the input from the preceding vehicle and the response from the driver and produce an auditory or visual warning if the response of the driver remained outside an acceptable region for a given period of time.

For the ACC controller, the delay is approximately twice that of manual driving or about 6 s. Whether the driver is actually aware of the change in shift-time between the two modes is not clear. Certainly, if the ACC controller were to operate at the distances or headway times typically seen in manual driving, then delay times 6 s may cause some anxiety. However, since the range and headway times for ACC operation are typically much greater than in manual driving (as shown in table 2), the delays are not a distraction nor do they cause any noteworthy stress, at least according to the driver responses from the FOT, which were very favorable.

One interesting observation from table 2 is the similarity in the standard deviations between manual and ACC driving. In all the measures, the standard deviations did not change much for the different driving modes. Assuming that standard deviation of these measures maps into the regions of the driving environment that most drivers find acceptable in terms of comfort and stress level, then the table shows that the ACC controller does a good job of staying within this acceptable range most of the time. This is probably another reason why most of the FOT drivers felt comfortable with ACC-engaged driving.

A more detailed display of the shift-time, range, range-rate and headway time is shown in the form of histograms in figures 13 through 16. Each of these figures compares the results for manual and ACC continuous control. The manual results are shown as bars in the figures and the ACC as a thick line. At the bottom of each figure are three summary values calculated from the histogram results. These numbers are the most likely value, mean and standard deviation of the data used to make the histogram.

The shift time difference between manual and ACC-engaged driving is clearly demonstrated in figure 13 while figure 14 shows the range histogram for the continuous control data. The range data are not surprising and very similar to the results reported in [2]. Figure 15 shows a histogram of the range-rate for the continuous control data. It is not surprising that these histograms are similar since the data were restricted to only times when the ACC vehicle was following the preceding vehicle. The headway time histogram, figure 16, clearly shows how the ACC controller strives to maintain the user defined headway time, which is reflected in the three peaks of the ACC histogram.

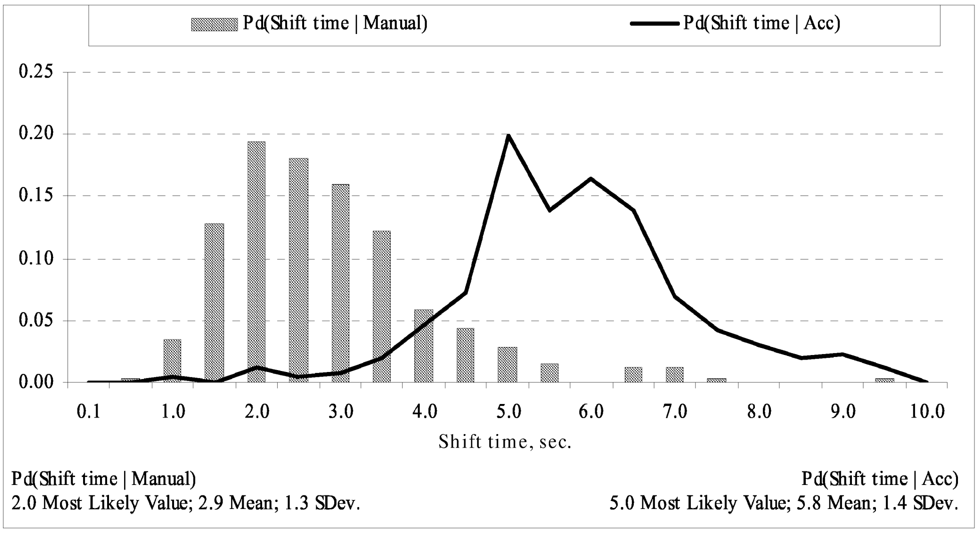


Figure 13 Shift-time histogram for manual and ACC continuous control

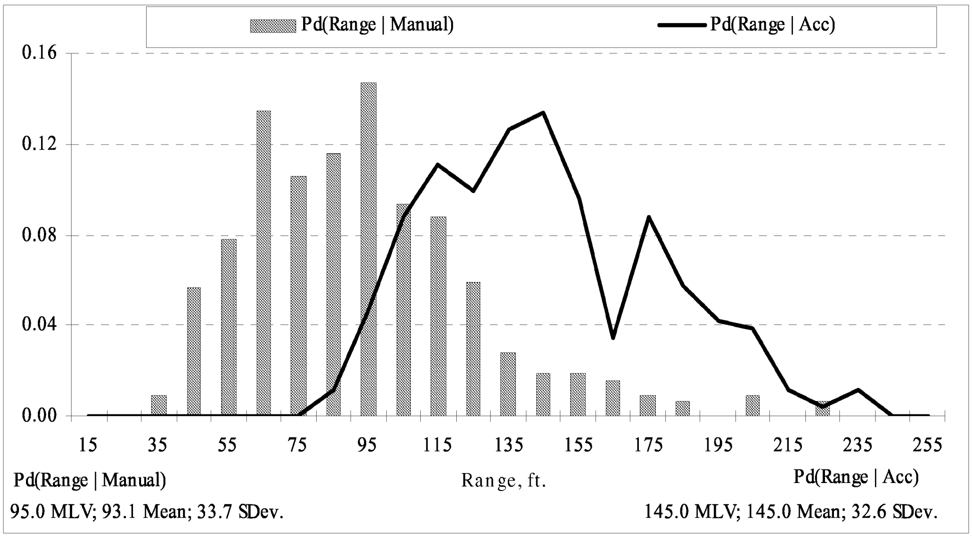
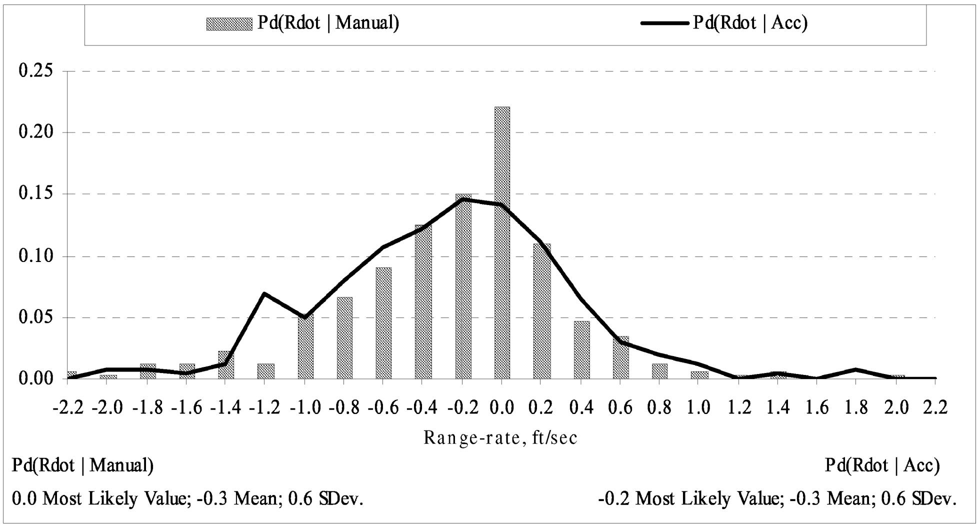


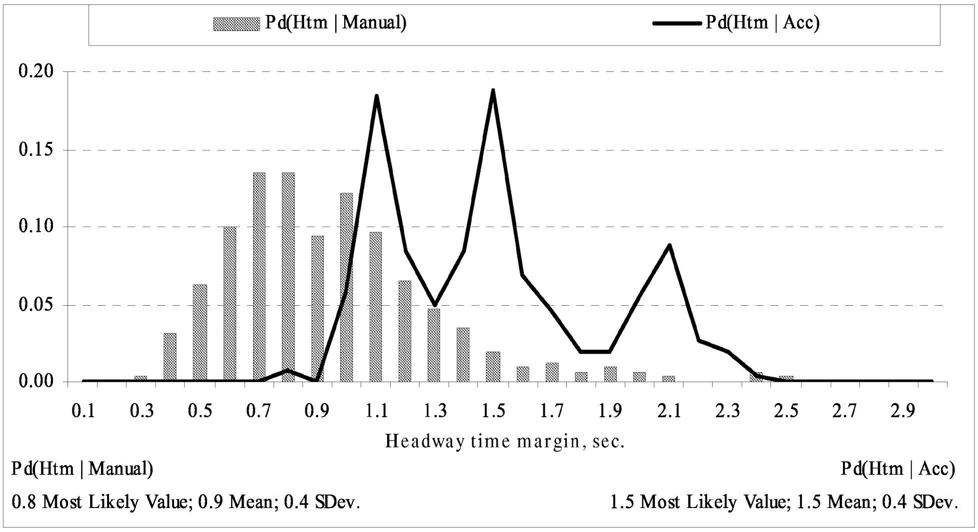
Figure 14 Range histogram for manual and ACC continuous control



Pd(Rdot | Manual)
0.0 Most Likely Value; -0.3 Mean; 0.6 SDev.

Pd(Rdot | Acc)
-0.2 Most Likely Value; -0.3 Mean; 0.6 SDev.

Figure 15. Range-rate histogram for manual and ACC continuous control



Pd(Htm | Manual)
0.8 Most Likely Value; 0.9 Mean; 0.4 SDev.

Pd(Htm | Acc)
1.5 Most Likely Value; 1.5 Mean; 0.4 SDev.

Figure 16. Headway time histogram for manual and ACC continuous control

3.0 TASK S-2, LANE-CHANGE EVENTS

The FOT report went into considerable detail explaining phenomena that concern the longitudinal characteristics of driving, such as, braking, headway keeping, target validity, forward velocity, etc. However, the report did not address many of the lateral aspects of driving, like, lane changes and lane keeping. The former of these two, lane changes, is important and the subject of this section of the report. Understanding how an ACC system in conjunction with lane changes effects traffic flow and highway safety are the two primary reasons for further analysis of the data collected in the FOT. The four subtasks of this section discuss a) isolating lane-change events and creating a lane-change table that explicitly identifies them in the FOT database, b) summarizing the important driving measures, such as, headway time, range, and range-rate at the onset of a lane-change maneuver, c) identifying and analyzing the use of the throttle pedal to override the ACC system during lane-change events, and d) studying the differences in lane-change activity on freeways and two-lane rural highways.

3.1 Identifying lane-change events

Although, not as easily quantified as the longitudinal behavior of driving (after all ACC functionality depends on a longitudinal range measure, its derivative range-rate, and the forward velocity), the data acquisition system on each FOT vehicle recorded two signals that could be used to characterize the lateral behavior of the vehicle. These signals came from the Global Positioning System (GPS) and the sensor systems. Although the primary purpose of these two systems was not to identify lane changes, they both contain information that could be used to flag them in the time-history data. The GPS was installed as a means of tracking time and location of each FOT vehicle but it also produced information on vehicle heading. The sensor system contained a solid-state gyro that dynamically responded to changes in path curvature and was used to steer the ACC-sweep sensor and, hence, provide better target detection while on curves. Signals from both the GPS and the gyro can be used to generate heading, estimated yaw-rate and yaw-acceleration for the ACC vehicle. Although, the gyro data was eventually used to find lane changes a short discussion of the GPS data follows in the next section. This is then followed by a more rigorous discussion of data processing used to find lane changes with the gyro signal.

Using the GPS data to identify lane changes

The GPS record contains five channels, time, grade, heading angle, latitude position, longitude position, and was recorded at 2 Hz. Of the five signals, heading angle can be used to identify lane-change maneuvers. Shown in figure 17 is an example plot of heading angle as a function of time. These data are for the westbound lanes of a major interstate highway. Segments of the plot that are horizontal show sections of road that are virtually straight at 270 degrees or due west. Areas of the plot where heading is changing, for example, from 38 through 80 seconds, show constant radius curves in the road. Here the heading angle is changing at a fairly constant rate which agrees with the way road engineers construct highways, i.e., they are built with constant radius curves. Indicated on the plot are small, quick changes in heading where a lane change occurred. There are three single lane changes and one double lane change highlighted in the figure. The maneuvers of the double lane change are separated by approximately 13 seconds.

The polarity of the lane change indicates how the vehicle moved lateral (i.e., lane change to the right or left). For example, the lane change at time equal to100 seconds indicates a move from a left lane to an adjacent right lane, and conversely, the maneuver at time equal 170 seconds shows a lane change from the right lane to the adjacent left lane.

Although the GPS heading data shows lane-change activity, the signal does have drawbacks. First, it is only collected at 2 Hz, or two samples per second. Assuming a highway lane change of 10 seconds results in a maximum of twenty points to distinguish the maneuver from the noise of simple lane keeping. Furthermore, results from the FOT show that the GPS system reliably tracked and recorded vehicle position only 80 percent of the time. It was due to these reasons that the GPS data did not become the primary signal for identifying lane changes in the FOT data.

Using the path-curvature data to identify lane changes

The path-curvature signal generated by the ACC-system gyro became the primary signal used to identify lane changes in the FOT data. Plots of the signal and its integral, heading, are similar to figure 17, however, the signal has some advantages in terms of reliability and collection frequency. Unlike the GPS data which is collected at 2 Hz, the path-curvature signal was collected at 10 Hz. Steps 1 through 6 below give a short outline of the process used to identify lane changes using this signal. The details of the process follow in the subsequent subsections below. The six steps, in chronological order, were

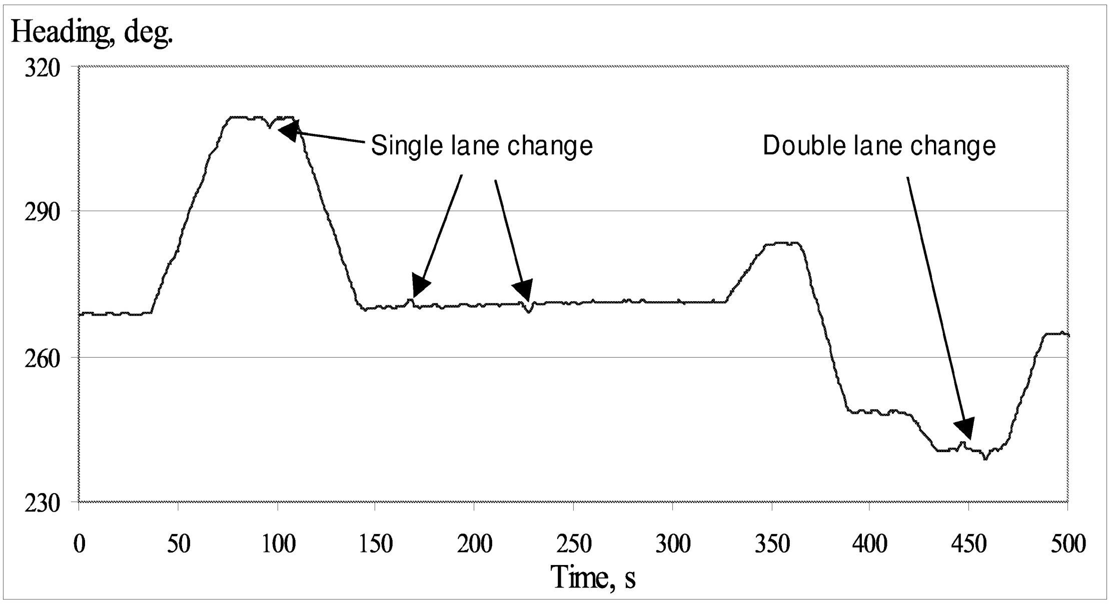


Figure 17. Heading angle versus time showing lane changes in the GPS data

1. calculate vehicle yaw-rate from path-curvature and integrate it to get heading angle,
2. differentiate yaw-rate to get yaw-acceleration,
3. identify the corners in heading based on the yaw-acceleration signal,
4. fit a reference line between the corners of the heading signal,
5. calculate the difference between the reference line and the heading signal, and
6. calculate the area between the reference line and the heading signal.

The signal generated by the gyro on each FOT vehicle was path-radius, R. Based on this signal and with the equation a constant radius turn, the yaw rate, r (rad/s), of the vehicle is given by:

$$r = \frac{V}{R}$$

where V is velocity (ft/s) and

R (ft) is path-radius (Note: For a straight path R=∞, and $r = 0$)

The heading angle (Step 1), Ψ, is approximated by:

$$\Psi \approx \int r dt$$

The yaw-acceleration (Step 2), $\dot{r}$, is simply the given by:

$$\dot{r} = \frac{dr}{dt}$$

The yaw-acceleration signal was used to identify heading corners where the roadway curvature changes (Step 3). Figure 18 is a 13 minute plot of the heading angle for driver 13 on trip 38. (During this time the velocity was always greater than 50 mph.) Also shown in the figure are triangles indicating where transitions between curved and tangent sections of the roadway occur. The heading corners were identified using the yaw-acceleration signal. Figure 19 shows this signal for the 200 to 300 second time period highlighted in figure 18. The heading-change rule was simply that the absolute value of the yaw acceleration exceeded 0.01 deg/s^2 for more than 5 seconds. When the signal met these conditions the center of the zero crossing time was used as the marker for a heading corner.

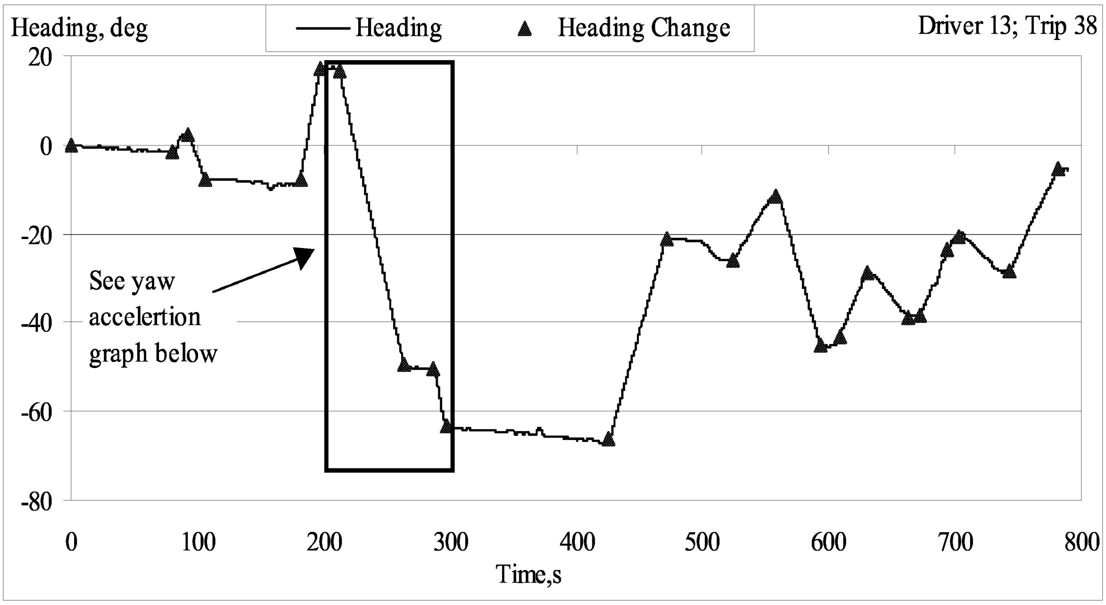


Figure 18. Heading angle versus time showing heading changes or corners

Identifying the heading corners was a critical step in finding lane changes because it defined the points on the heading plot where a linear reference line would closely approximate the actual heading of the roadway. The reference line (Step 4) is based on a least squares fit of the heading points between adjacent heading corners.[1] Figure 20 is plot of 125 seconds of the heading signal from the same trip. This figure shows the best-fit reference line and a lane-change maneuver that occurs at approximately 370 seconds.

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[1] To avoid the bias that a lane change or multiple lane changes may have on the reference line, some of the heading points were excluded from the least-squares calculation. The method used to exclude points was based on the average and standard deviation of the corresponding yaw-rate signal. When a yaw-rate point was outside one standard deviation of the average, the corresponding heading point was excluded from the linear regression.

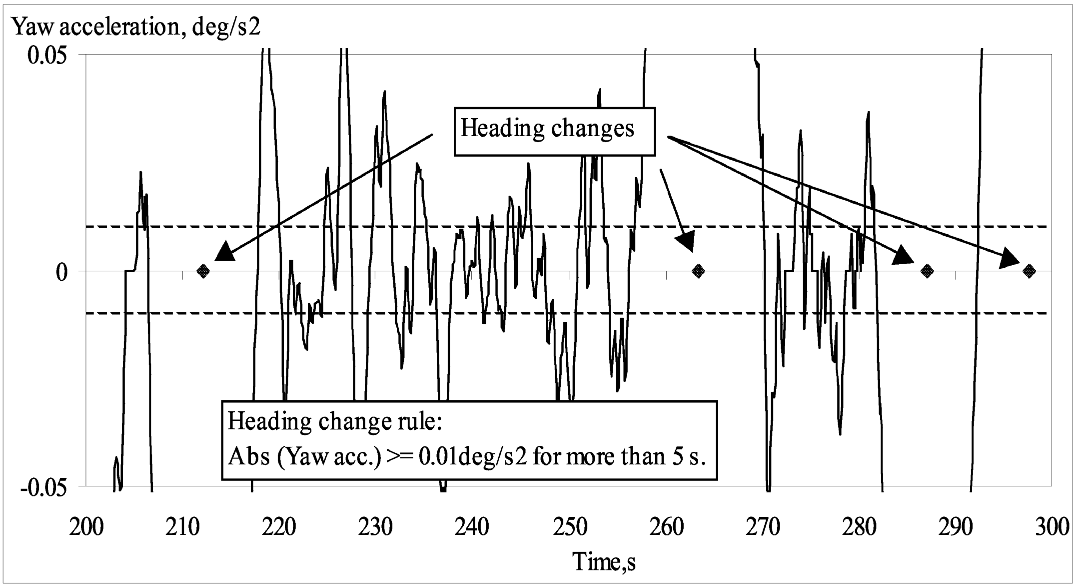


Figure 19. Yaw-acceleration versus time showing heading changes or corners

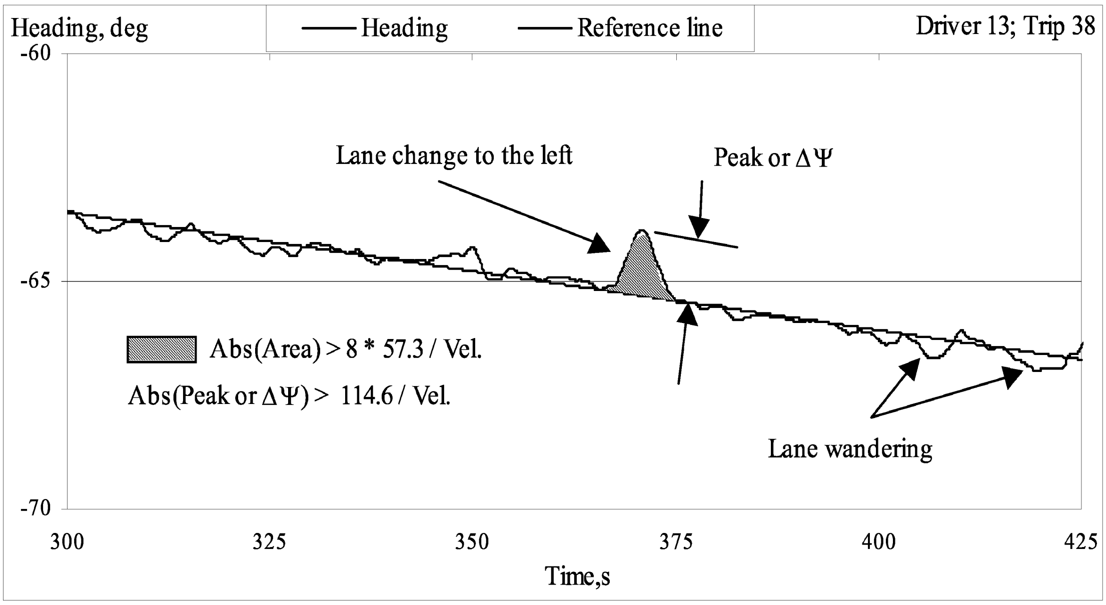


Figure 20. Heading versus time showing the reference line and a lane change

After the reference line is defined, the data processing algorithm subsets the heading signal based on the crossing points of the signal and the reference line. For each subset, the area above or below the reference line and the peak difference with the reference line were calculated and saved (Steps 5 and 6).

Finally, lane changes were identified based on the three conditions given below

a) The quality of fit of the reference line to the heading signal, as measured by a correlation coefficient, R, had to exceed 0.75.

b) The number of points used to fit the reference line had to be greater then 50 percent of all the points between heading corners.

c) Lane changes are identified by searching for an area and a peak value that meet two criteria. Both criteria are based on a lateral lane-change distance of at least 8 ft and both are functions of forward velocity. The two rules are given in figure 20. See appendix A for technical discussion of these rules.

Shortfalls of the current lane-change algorithm

The lane-change algorithm depends on straight and constant radius road segments. For interstate highways this is not a bad assumption since, for the most part, that is how these type of roads are built. However, for rural two-lane roads, the assumption that the heading signal can be fit with a straight line will not be as robust. Rural two-lane roads can have numerous direction changes with curves of varying radii, and clearly, on roads like this the heading corner finder may not perform as well. However, the road type exposure results from the FOT show that velocity can serve as a reasonable surrogate for road type[1]. In the FOT it was shown that, for the mapping region and speeds above 55 mph, 91 percent of the miles driven were on interstate-type roads. Based on this, the algorithm only searches for lane changes at velocities above 50 mph. (The 50 mph threshold was chosen in order to facilitate the study of lane changes on two lane highways where the speed limit may be 55 mph or less).

The current search algorithm will also miss lane changes that occur as a driver enters or leaves a curve. Lane changes of this nature are very difficult to detect without an explicit map of the roadway. Without knowing “where” the road is relative to the vehicle, lane changes of this nature simply look like the curve starts or ends a little sooner or later as the case may be.

3.2 The lane-change table

The current algorithm identified a total of 14,076 lane changes in the 108 driver FOT database. These lane changes were for velocities above 50 mph and were based on the conditions mentioned in the previous section. A summary of these lane changes is shown in table 3. Columns one and two (counting from the left) show different driver categories that are used to subset the data into groups such as driving styles, cruise usage, cruise control mode, road types, brake pedal application, throttle use and acceleration level. Results for throttle and acceleration activity in the form needed to construct histograms are shown at the bottom of the table. Columns three, four and five show the number of drivers, miles traveled and number of lane-change events. The sixth and seventh columns contain a percentage of lane-change events for a given group and the average number of lane changes per 100 miles. Finally, the remaining three columns show the average velocity, acceleration, and throttle percentage.

(Note: The discussion below is based on table 3. Despite a very rigorous effort to capture all lane changes in the FOT database, there undoubtedly were some lane-changes missed or maneuvers that "appeared" to be lane changes in the data but in reality were not. An example of the later would be a lane shift for a construction zone which typically has the same frequency content as a lane change. Regardless of these uncertainties, the values in table 3 can be used to draw useful insights, particularly, when making comparisons within a particular group.)

Table 3 shows that, on average, high speed driving involves about 22 lane changes per 100 miles and that these lane changes will most likely occur while the driver is not braking (98 percent) nor accelerating (92 percent). Young drivers tend to change lanes more frequently than both middle age and older drivers (25, 19, 21/100 miles, respectively) and female drivers tend to change lanes more often than male drivers (23 versus 20, respectively). It appears that drivers who consider themselves cruise control users tended to change lanes more often than nonusers (23 versus 18, respectively) and that drivers are more likely to change lanes while driving manually than with ACC or CCC engaged (29, 18, 15 respectively). This finding agrees with observations from the FOT that drivers appeared to choose manual mode in situations with a higher likelihood of conflict. (The assumption being that changing lanes is one method of reducing conflict).

In terms of driving style, drivers classified as hunters/tailgaters change lanes more often than drivers in the other categories (27/100 miles). Planners (these are the drivers that manage to go fast and remain far from other drivers) had the second highest rate of lane-change activity and it would appear that part of their driving strategy is to change lanes to achieve their goal of "fast" and "far." Extremists (drivers that fit into more than one of the other four categories) and ultraconservatives (tendency toward far and/or slow driving) had the lowest lane-change rate at 18 per 100 miles. For the definition and a discussion on driving style see appendix C.

Table 3. All lane-change events distributed by different categories and groups

Category	Group	No. Drvrs	Distance, miles	No. of lane changes	Percent lane changes	Lane ch. per 100 miles	Avg. V, ft/s	Avg. Vdot, g	Avg. Throttle, percent
All	All	108	65463	14076	100.00	21.5	97.6	0.002	9.9
Age	20-30	36	24052	6001	42.63	25.0	99.4	0.002	10.4
	40-50	36	24696	4562	32.41	18.5	97.4	0.002	9.4
	60-70	36	16715	3513	24.96	21.0	94.6	0.002	9.5
Gender	Female	54	27722	6449	45.82	23.3	97.3	0.001	9.8
	Male	54	37742	7627	54.18	20.2	97.8	0.002	9.9
Style	Extremist	15	7284	1328	9.43	18.2	95.4	0.002	9.6
	Flow Conformists	29	20791	4038	28.69	19.4	98.3	0.002	9.7
	Hunter/Tailgater	25	17587	4674	33.21	26.6	99.5	0.002	10.5
	Planner	19	14122	3006	21.36	21.3	96.4	0.002	9.6
	Ultra Conservative	20	5679	1030	7.32	18.1	92.1	0.002	8.5
Usage	Nonuser	42	18558	3281	23.31	17.7	96.4	0.002	9.6
	User	66	46905	10795	76.69	23.0	97.9	0.002	10.0
Mode	Manual	▨	23875	6800	48.31	28.5	95.5	0.004	10.6
	CCC	▨	9749	1475	10.48	15.1	100.0	0.000	8.8
	ACC	▨	31839	5801	41.21	18.2	99.4	0.000	9.2
Road Type	Interstate	▨	32591	6079	43.19	18.7	98.0	0.002	9.8
	StateHighway	▨	159	264	1.88	165.9	84.0	0.001	8.0
	Arterial	▨	663	360	2.56	54.3	83.1	0.003	8.4
	Other	▨	86	144	1.02	167.0	88.9	-0.003	7.3
	No Mapping Point	▨	31963	7229	51.36	22.6	98.7	0.002	10.1
Direction	Left	▨	▨	7141	50.73	▨	97.2	0.005	10.7
	Right	▨	▨	6935	49.26	▨	98.0	-0.001	9.1
Brake	Off	▨	▨	13803	98.06	▨	97.7	0.004	10.1
	On	▨	▨	273	1.94	▨	90.1	-0.089	0.1
Throttle	0 percent	▨	▨	1765	12.54	▨	93.9	-0.040	0.0
	0 < Throttle <=10	▨	▨	6885	48.91	▨	97.4	-0.003	6.7
	10 < Throttle <=20	▨	▨	4161	29.56	▨	99.7	0.013	13.7
	20 < Throttle <=30	▨	▨	876	6.22	▨	96.9	0.040	23.9
	30 < Throttle <=40	▨	▨	285	2.02	▨	95.0	0.063	34.4
	40 < Throttle <=50	▨	▨	68	0.48	▨	98.2	0.076	44.1
	50 < Throttle <=60	▨	▨	17	0.12	▨	96.9	0.095	53.4
	60 < Throttle <=70	▨	▨	12	0.09	▨	99.8	0.130	64.8
	70 < Throttle <=100	▨	▨	7	0.05	▨	95.8	0.145	77.6
Vdot	Vdot <= -.25	▨	▨	5	0.04	▨	82.5	-0.472	0.8
	-0.25<Vdot<=-0.15	▨	▨	31	0.22	▨	89.4	-0.172	0.0
	-0.15<Vdot<=-0.05	▨	▨	407	2.89	▨	94.1	-0.072	0.1
	-0.05<Vdot<=0.05	▨	▨	12957	92.05	▨	98.0	0.001	9.2
	0.05<Vdot<=0.15	▨	▨	665	4.72	▨	92.8	0.070	29.2
	0.15<Vdot<=0.25	▨	▨	11	0.08	▨	91.1	0.177	64.8

▨ Distribution of drivers, distance, and/or lane changes per 100 miles not available for these cells

The road type data show a lane-change rate of more than 160 per 100 miles for state highways and other types of roads, but there is not much confidence in these numbers since the number of miles (denominator) for these road types is small when compared to the interstate and no mapping point numbers. Generally, though, the interstate and no mapping point data support the overall estimate of approximately 20 lane changes per 100 miles of travel.

The direction category shows the distribution of lane changes to the left or to the right. These counts are close for both left (51 percent) and right (49 percent) lane changes. It is important not to confuse these data, which are simply counts, with data that would show the choice of which lane to use while making a passing maneuver. In highway driving, there is a long-standing practice or courtesy of allowing faster traffic to occupy the left-most lanes of highways and that passing a slower moving vehicle is more customary if done on the left. However, these data do not reflect the choice of which side a driver might choose when passing a slower vehicle. Instead, these data only show that for every lane change to the left there most likely will be a lane change to the right. In general, most vehicles enter the highway with a lane change to the left and exit with a lane change to the right. To be in the proper lane for exiting the highway, an equal number of left and right lane changes must have occurred while on the highway. Hence, it is not surprising that when counting all lane changes the number to the left and right are nearly identical.

Columns eight, nine and ten of table 3 show the average velocity, acceleration and throttle percentage for the various categories and groups, respectively. In general, these averages are consistent across the driver groupings. They show that velocity is typically about 98 ft/s (66 mph), acceleration is virtually zero, and throttle is bounded between 8.5 and 10.5 percent. These data also support intuitive trends within the various categories. For example, in the driving style category, Hunters/Tailgaters had the highest average velocity (99.5 ft/s) and throttle percentage (10.5), while the Ultra conservatives had the lowest average velocity (92.1 ft/s) and throttle percentage (8.5). In the age category, the younger drivers had the highest average velocity and throttle usage as compared to the middle-aged and older drivers. Furthermore, drivers who are not regular cruise users (and hence probably more conservative in terms of their driving style and risk behavior) had a lower average velocity and corresponding throttle percentage.

In general, it would appear that average velocity and throttle usage correlate quite well; however, there is one category where this trend reverses. The cruise control mode category is interesting from the perspective of fuel economy and driver work load. The category shows that for manual driving, the average velocity is 95.5 ft/s with a corresponding average throttle of 10.6 percent. However, for conventional cruise control (CCC) the average velocity is 100 ft/s, with an average throttle of only 8.8 percent. The critical observation is CCC driving results in an increase in average velocity but a decrease in average throttle relative to manual and thus implies an optimization between velocity and throttle usage. (The results for ACC are between CCC and manual for both speed and throttle usage.)

With respect to fuel economy, the FOT final report [1] made two observations that supported the hypothesis that cruise control reduced fuel consumption. The first observation was based on acceleration histograms of driving in the different modes. It showed that manual, high-speed driving, typically involves a much broader distribution of longitudinal accelerations, implying that poorer energy efficiencies would prevail in the broadly defined range of manual operations than in cruise control driving.

The second observation that cruise control may have some implication for fuel consumption is simply that of the differences in throttle modulation as shown in figure 21 and as shown here in the lane-change data. The data show that the ACC throttle controller, during episodes of sustained modulation of headway behind a more or less steady-speed preceding vehicle, exercises many fewer cycles of throttle actuation and makes many fewer corrections down to the fully dropped throttle position. If manual throttle modulation, per se, is indeed detrimental to fuel consumption, then the data would support the hypothesis that the tendency of ACC to displace manual control over some portion of the driving spectrum will surely have an energy conservation benefit. For cases in which no impeding vehicle is causing throttle modulation to control headway, the ACC controller reverts to a throttle-control characteristic that matches that of CCC—a characteristic that outperforms the human throttle modulator even better than that shown in figure 21 for ACC.

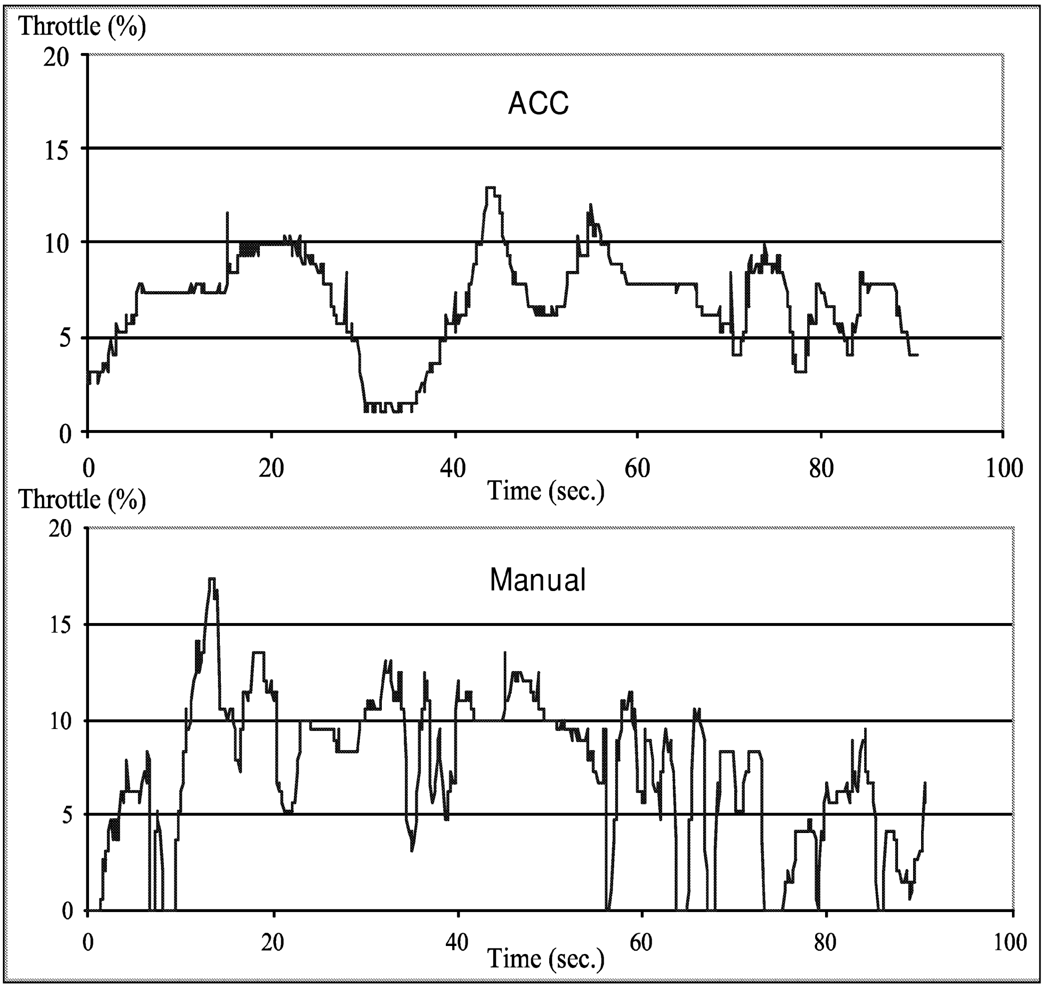


Figure 21. Throttle modulation under ACC and under manual control

Regarding driver work load, these lane-change data also support the assertion that active throttle modulation, also referred to as "throttle stress," adds to the driver work load. It was pointed out in [1] that throttle stress not only includes the physical activity in modulating the throttle but more importantly it includes the mental activity (mental workload) involved in all the choices associated with deciding to increase or decrease the throttle setting. Throttle stress is important because it is associated with a direct benefit of both conventional and adaptive cruise control and although most people may feel that they can drive manually with little effort, the popularity of conventional cruise control appears to indicate that relief from throttle stress is valuable to many people.

The bottom two categories in table 1 are histograms of throttle and acceleration or Vdot. The throttle histogram is shown graphically in figure 22. The figure and the table show that most (97 percent) of throttle activity is between 0 and 30 percent throttle. The table also shows the average acceleration for each bin of the throttle histogram. Of note here, is the –0.04 g acceleration that corresponds to 0 throttle. This acceleration level is the parasitic drag of the FOT vehicles at highway speeds. The data also show that to maintain a highway speed (Vdot = 0) in a FOT vehicle requires a throttle position between 7 and 9 percent.

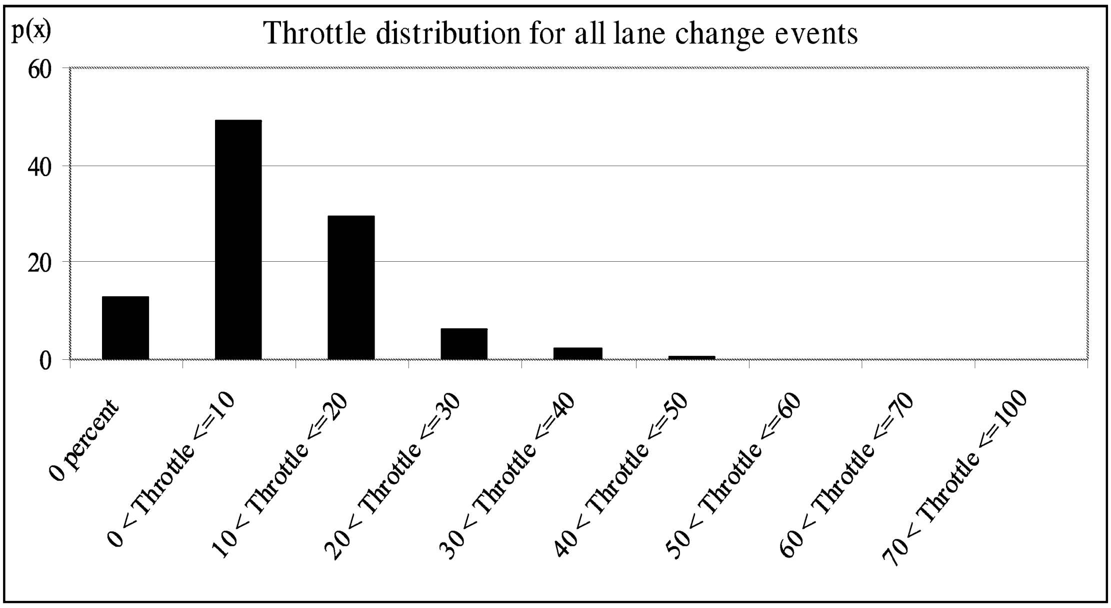


Figure 22. Throttle histogram for all lane-change events

The acceleration histogram is shown in figure 23. These data show that 92 percent of all lane changes occur at approximately zero acceleration. Also, if the driver is accelerating during a lane change, there appears to be an inclination toward a positive acceleration as opposed to braking, albeit a small difference, 5 and 3 percent, respectively.

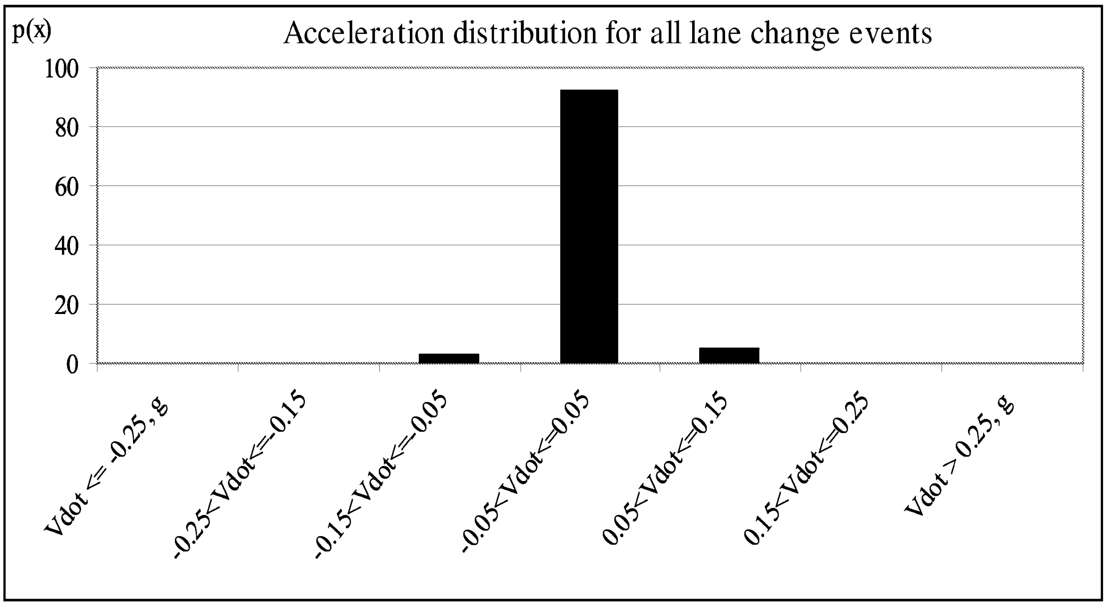


Figure 23. Acceleration histogram for all lane changes

3.3 Lane changes with a preceding vehicle

Of the 14,076 lane-change events reported above, only a subset of 5,192 or 37 percent had a preceding vehicle present shortly before the lane change took place. These lane changes are summarized in Table 4. Similar to table 3, the first three columns show different categories and groups along with the number of drivers for each group. Columns four and five show the number of lane changes and percent of the total for that group, while the remaining six columns show the average range, range-rate, velocity, acceleration, headway time, and throttle percent for each group. The table is divided into three sections. The first section shows the statistics for all 5,192 lane changes along with a breakdown as a function of driving mode. The second and third sections, namely manual and ACC, show the breakdown by age, gender, style, usage, direction, and driving regime.

The results show that on average for all the FOT drivers, lane changes occurred at a speed of 97 ft/s, near zero acceleration, and approximately 180 ft behind the preceding vehicle (1.9 s headway time) and with a closing relative velocity of 3.4 ft/s. In terms of driving mode, table 4 shows that for manual driving, lane changes occurred at a closer range as compared to the ACC or CCC driving mode (153, 206, 206 ft, respectively). Headway time margin is also less in manual versus ACC or CCC driving modes (1.6, 2.1, 2.1s, respectively)

In general, when comparing manual to ACC lane changes, table 4 shows differences in the range, htm, Vdot, and throttle columns. Within corresponding groups, the range and headway time margin values are always larger in ACC driving mode as compared to manual. The acceleration data show that, on average, virtually all lane changes in manual mode involve slightly positive accelerations, while nearly all the acceleration values in ACC are slightly negative. Also, the average percent throttle for ACC-lane changes is less than in the corresponding manual groups.

In terms of age, driving style, and driving regime, the data show that ACC has a smoothing effect that acts to reduce the extremes within the various divisions of the group. For example, in the age groups for manual lane changes, 53 percent were made by younger drivers, 27 percent for the middle age drivers and 20 percent for the older drivers. However, when ACC is engaged, the ratio of lane changes for the three groups becomes 34, 36, and 30, respectively.

Table 4. Lane-change events with a preceding vehicle

Category	Group	No. Drvrs	No. of lane changes	Percent lane change	Avg. Range, ft	Avg. Rdot, ft/s	Avg. V, ft/s	Avg. Vdot, g	Avg. Htm, s	Avg. Throttle, Percent
All	All	108	5192	100.00	179.6	-3.4	97.5	0.006	1.9	11.3
Mode	Manual	108	2607	50.21	153.3	-4.1	95.9	0.016	1.6	14.3
	CCC	108	502	9.67	206.4	-3.2	101.0	0.002	2.1	9.5
	ACC	108	2083	40.12	205.9	-2.5	98.8	-0.004	2.1	8.1
Manual										
Age	20-30	36	1382	53.01	145.7	-5.6	98.6	0.016	1.5	14.9
	40-50	36	697	26.74	155.5	-2.8	93.3	0.015	1.7	13.4
	60-70	36	528	20.25	170.4	-1.8	92.1	0.016	1.9	13.9
Gender	Female	54	1182	45.34	156.7	-3.1	95.2	0.012	1.7	13.3
	Male	54	1425	54.66	150.5	-4.9	96.5	0.018	1.6	15.1
Style	Extremist	15	219	8.40	164.3	-4.7	96.0	0.013	1.8	13.8
	Flow Conformists	29	767	29.42	161.3	-3.5	96.2	0.012	1.7	12.6
	Hunter/Tailgater	25	990	37.97	131.1	-5.6	98.0	0.019	1.3	16.4
	Planner	19	411	15.77	154.9	-4.1	93.6	0.017	1.7	14.3
	Ultra Conservative	20	220	8.44	211.7	1.5	89.7	0.011	2.4	11.1
Usage	Nonuser	42	759	29.11	159.7	-3.8	95.7	0.015	1.7	13.7
	User	66	1848	70.89	150.7	-4.2	96.0	0.016	1.6	14.5
Direction	Left	108	1478	56.69	148.8	-5.3	96.0	0.017	1.6	14.8
	Right	108	1129	43.31	159.2	-2.5	95.7	0.013	1.7	13.7
Regime	Following	108	910	34.91	162.8	-0.3	93.9	0.011	1.7	12.3
	Near	108	486	18.64	51.1	-11.4	100.0	0.037	0.5	22.9
	Closing	108	767	29.42	172.4	-11.9	99.5	0.007	1.7	12.1
	Separating	108	392	15.04	235.3	10.4	89.3	0.013	2.7	11.3
	Cutin	108	49	1.88	39.3	3.5	92.6	0.046	0.4	24.9
ACC										
Age	20-30	36	704	33.80	192.9	-4.1	100.3	-0.006	1.9	8.1
	40-50	36	760	36.49	204.8	-2.6	99.9	-0.005	2.0	8.0
	60-70	36	619	29.72	222.1	-0.5	95.7	-0.002	2.3	8.1
Gender	Female	54	918	44.07	203.3	-2.3	98.4	-0.005	2.1	7.9
	Male	54	1165	55.93	208.0	-2.7	99.0	-0.004	2.1	8.2
Style	Extremist	15	218	10.47	204.4	-2.4	95.6	-0.006	2.1	7.1
	Flow Conformists	29	598	28.71	209.9	-3.5	101.0	-0.005	2.1	8.1
	Hunter/Tailgater	25	530	25.44	182.9	-3.4	100.0	-0.006	1.8	8.1
	Planner	19	598	28.71	212.5	-2.2	97.9	-0.003	2.2	8.5
	Ultra Conservative	20	139	6.67	251.0	3.9	92.9	-0.002	2.7	7.2
Usage	Nonuser	42	328	15.75	214.6	-1.0	95.9	-0.007	2.2	7.0
	User	66	1755	84.25	204.3	-2.8	99.3	-0.004	2.1	8.3
Direction	Left	108	1329	63.80	197.6	-4.1	98.3	-0.007	2.0	7.5
	Right	108	754	36.20	220.7	0.3	99.5	0.000	2.2	9.0
Regime	Following	108	952	45.70	183.2	-0.2	97.6	-0.001	1.9	8.2
	Near	108	53	2.54	63.9	-15.8	100.1	0.016	0.6	17.7
	Closing	108	688	33.03	218.3	-12.2	102.1	-0.015	2.1	6.4
	Separating	108	380	18.24	263.4	10.8	95.4	0.005	2.8	9.2
	Cutin	108	10	0.48	85.0	15.3	96.5	-0.002	0.9	10.2

Similarly, the differences between driving styles are reduced when ACC is engaged. Figure 24 shows the distribution of lane changes for manual and ACC as a function of driving style (as determined by the driver's manual driving style). For the manual lane changes, the hunter/tailgater's (driving characterized as close and fast) had the largest relative percentage of lane changes. However, when ACC was engaged the percentage of lane changes by hunters/tailgaters dropped (from 38 to 25 percent) while the percentage of planners increased (from 16 to 28 percent). Thus, in a sense, having ACC engaged resulted in fewer lane changes for the hunter/tailgaters and more for the planners. (The relative percentage of the other three driving styles remained roughly constant between modes.) These data support previous findings in [1] that driving with the ACC system engaged reduced hunter/tailgater behavior and increased planner behavior.

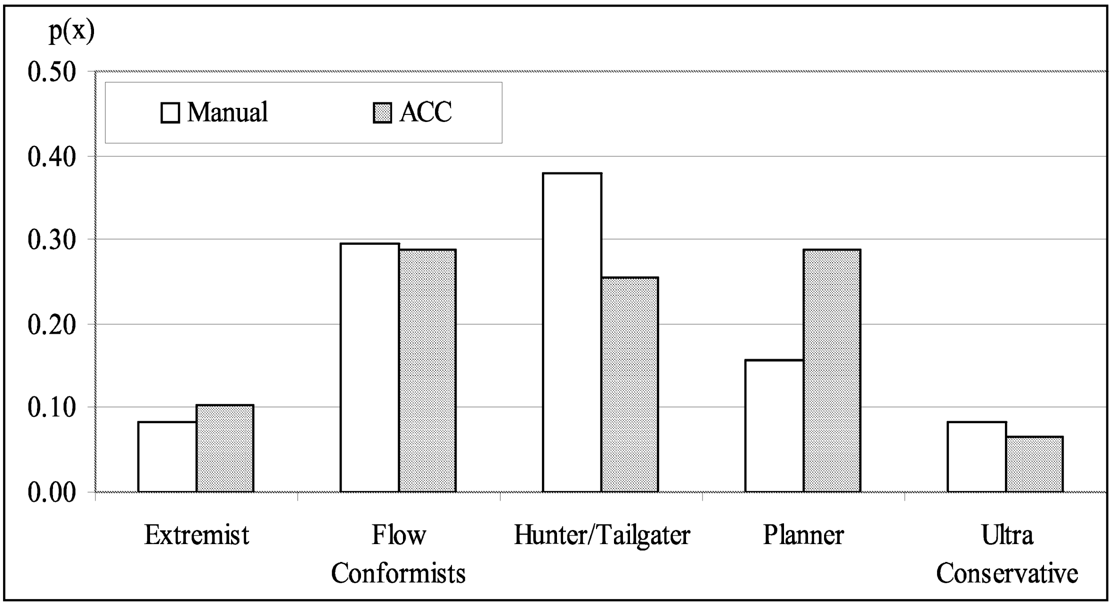


Figure 24. Distribution of lane-change events with a preceding vehicle for manual and ACC driving modes as a function of driving style

The driving regime data show a similar effect. (For a mathematical definition of the regions of the driving regime space, see appendix B.) Figure 25 shows the distribution of lane changes for manual and ACC as a function of driving regime. In this space, the near condition changes dramatically, from 19 to 3 percent while ACC is engaged. This reduction results in a large increase in the following regime while ACC is engaged.

The ACC data show that there were only 53 lane changes in the near region. However, these events did result in the most extreme averages shown for ACC lane changes, i.e., range = 64 ft, rdot = -16 ft/s, vdot = 0.016 g, htm = 0.6 s, and throttle = 18 percent. Clearly, these results for ACC lane-changes are only possible by overriding the ACC with the throttle. Throttle override is the topic of the next section of this report.

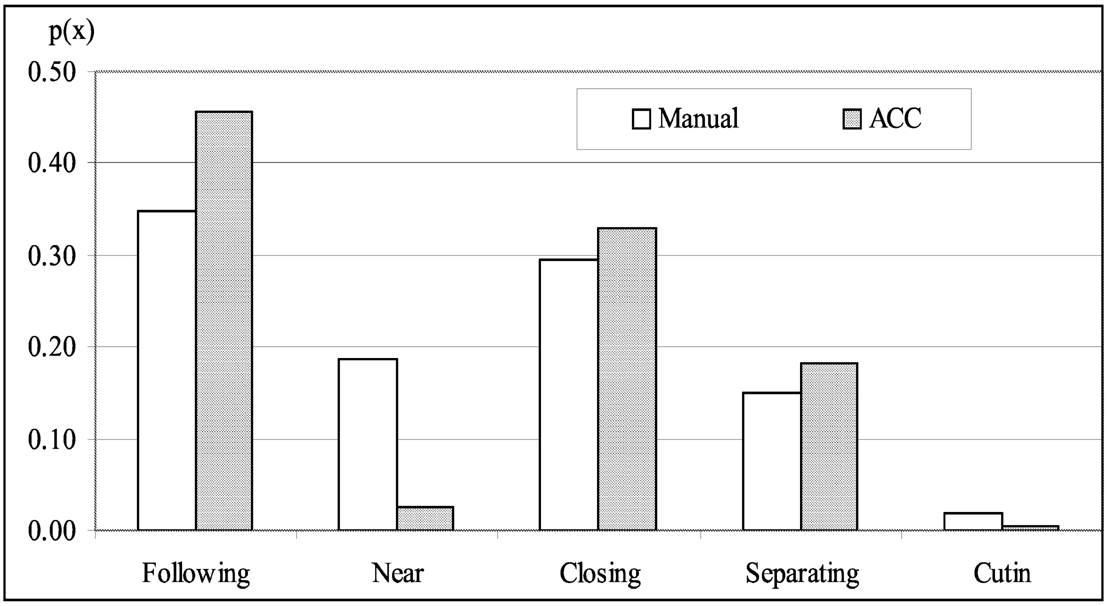


Figure 25. Distribution of lane-change events with a preceding vehicle for manual and ACC driving modes as a function of driving regime

The left and right lane-change results reported in table 4 are interesting. Unlike the left and right results for all lane changes, here we would not necessarily expect the two counts to be equal. For manual driving the distribution shows that 57 percent of the lane changes were to the left while 43 percent were to the right. However, the ACC results show an even more biased choice with 64 percent of the lane changes to the left and only 36 percent to the right. One hypothesis that may explain why there is a bias toward changing lanes to the left is related to a driver's choice of which lane to use when passing a preceding vehicle. Support for this hypothesis is based on two assumptions. The first assumption is that, overall, on two- and three-lane highways, there is less traffic in the left-most lane versus the center and right lane, and second, that vehicles travel faster in the left lane versus the center and right lanes. In general, if first assumption is true, then both manual and ACC lane changes would be biased toward lane changes to the left because subsequent lane changes to the right are less likely to have a preceding vehicle present (and hence counted in this subset of lane changes) as compared to lane changes to the right where the likelihood of there being another preceding vehicle is greater.

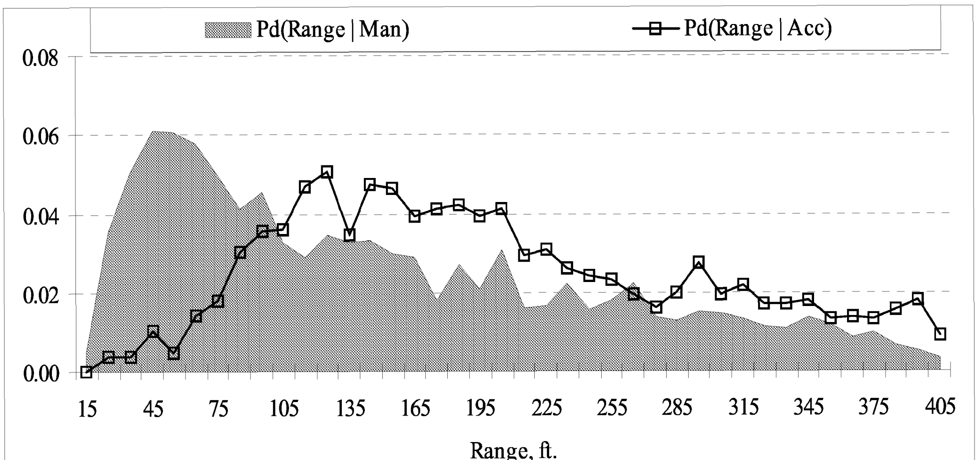
The second assumption, that vehicles travel faster in the left-most lanes of highways, would help explain why there is more bias toward lane changes to the left in the ACC engaged data as compared to the manual data. By virtue of the way ACC works, in order to pass a slower moving vehicle (without throttle override) either the adjacent lane must be virtually empty (at least beyond the range where the ACC "acts" on a preceding vehicle) or the traffic in the adjacent lane must be moving faster than the impeding vehicle. Unlike manual driving, where the driver has more fidelity to make a passing maneuver by considering the combination of relative velocity of the vehicles in the immediate environment along with the spacing between vehicles, ACC places a greater emphasis on relative velocity rather than gap size. (The ACC system will not allow the driver, during a passing maneuver, to close in on a preceding vehicle and change lanes to fill an open gap between vehicles.) Hence, when ACC is engaged, it is more effective to pass a vehicle by switching to a lane with faster moving vehicles which most likely means changing lanes to the left rather the right.

Histograms of range, range-rate, and headway time margin

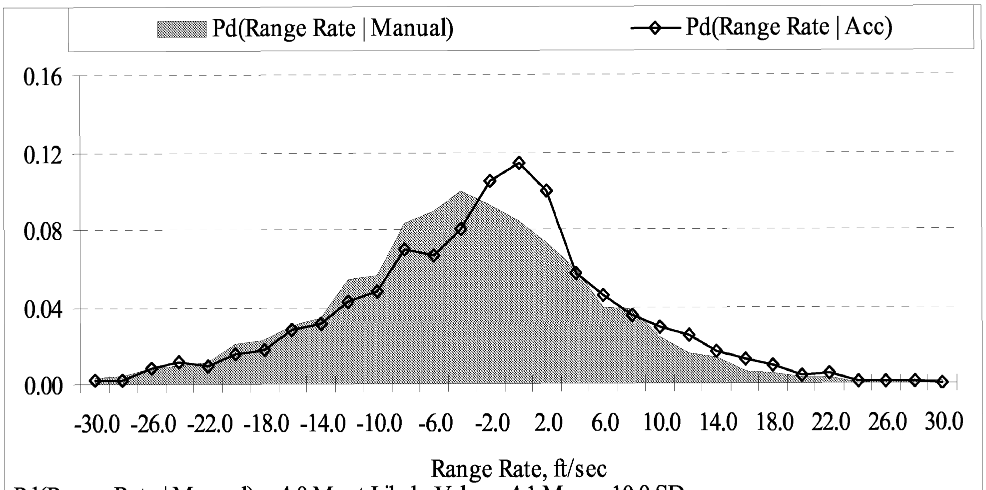
Figure 26 and 27 below shows histograms of range, range-rate, headway time, and time to impact as a function of manual and ACC lane changes. These data show large differences between lane-change behavior in the different driving modes. (The most likely value, mean, and standard deviation are shown at the bottom of each histogram.) Some of these differences can be seen by the simple statistics shown in table 4, however, having the full distribution of these measures shows a more striking difference. The top histogram of figure 26 gives the range distribution. These data show a clear bias toward longer ranges when making lane changes with ACC. For example, 27 percent of the manual lane changes occur within 70 ft of the preceding vehicle versus 4 percent for the ACC.

Similarly, the headway time histogram (bottom histogram of figure 26) shows an equally striking shift toward making lane changes at a longer headway time when ACC is engaged. (Note: the average value reported at the bottom of the Htm histogram is less then what is shown in table 4. This difference is due to the Htm histogram ignoring values above 3.0 s.)

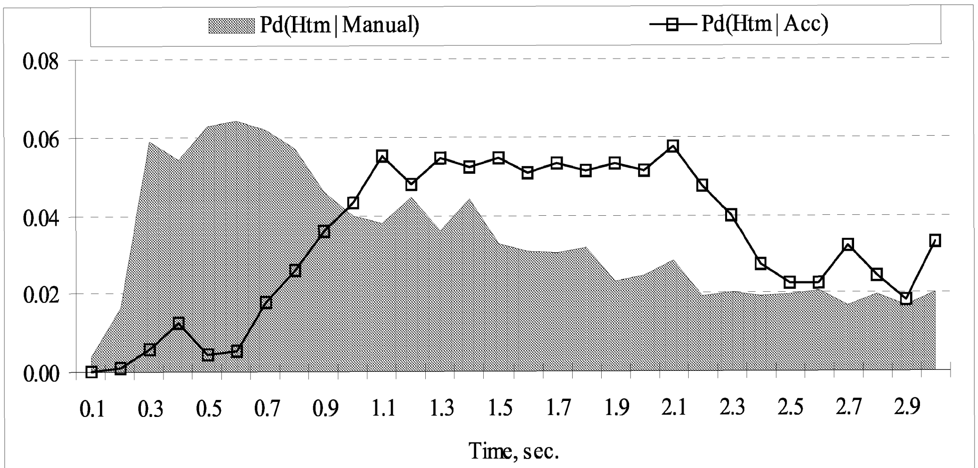
The range-rate histogram is shown in the center of figure 26. In general, these data show a bias toward changing lanes while closing on the preceding vehicle, however, the rate of closing is larger for lane changes during manual driving. The histogram also shows that the most likely value of Rdot for ACC lane changes is near zero, whereas, for lane changes while driving manually, the most likely value is –4.0 ft/s.



Pd(Range | Man); 45.0 Most Likely Value; 154.0 Mean; 103.6 SDev.
Pd(Range | Acc); 125.0 Most Likely Value; 206.3 Mean; 96.2 SDev.



Pd(Range Rate | Manual) ; -4.0 Most Likely Value; -4.1 Mean; 10.0 SDev.
Pd(Range Rate | Acc); 0.0 Most Likely Value; -2.5 Mean; 9.8 SDev.



Pd(Htm | Manual); 0.6 Most Likely Value; 1.3 Mean; 0.8 SDev.
Pd(Htm | Acc); 2.1 Most Likely Value; 1.7 Mean; 0.6 SDev.

Figure 26. Range, range-rate, and htm histograms for manual and ACC lane changes with a preceding vehicle

The time-to-impact histogram, figure 27, shows a much larger percentage of lane changes occurring below a 6 s value than when ACC is engaged.

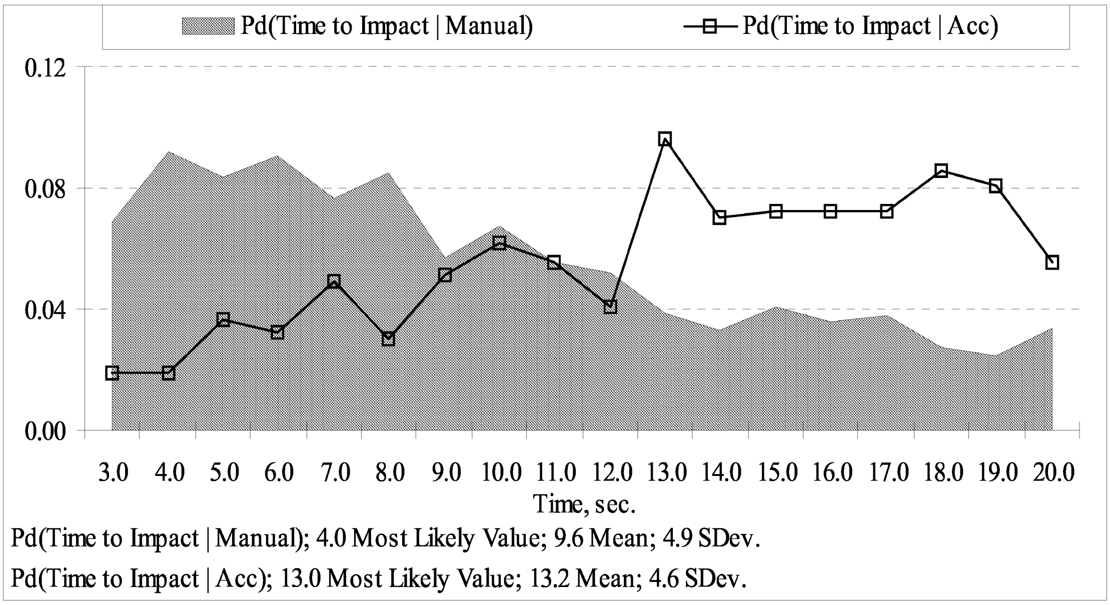
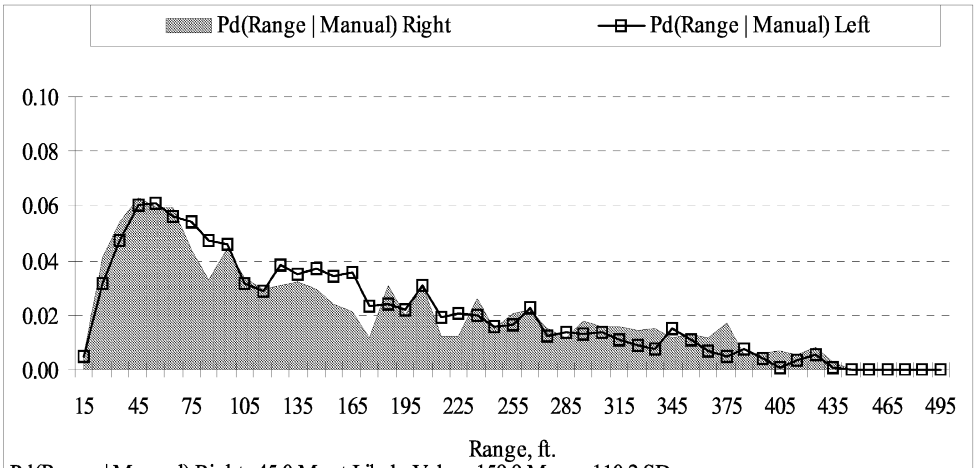


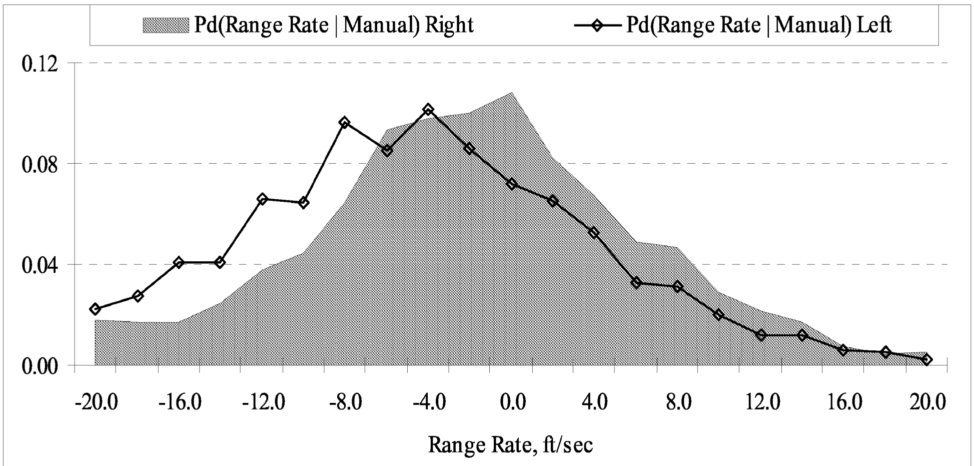
Figure 27. Time-to-impact histogram for manual and ACC lane changes with a preceding vehicle

Figure 28 presents the range, range-rate, and headway time histograms for right and left manual lane changes. The range and headway histograms show very similar distributions for lane changes in both directions. Apparently, regardless of the reason for lane changes, in general, the range and Htm remain about the same despite the direction to left or right. However, the range-rate histogram is different. It shows a more negative bias for lane changes to the left. This difference could have resulted for a variety of reasons, however, one explanation may be due to drivers choosing to pass slower moving vehicles by changing lanes to the left more often than to the right.



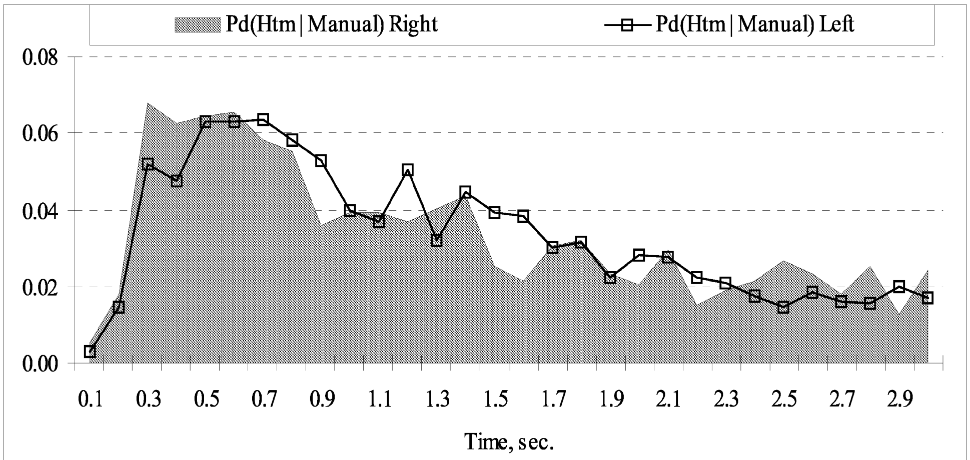
Pd(Range | Manual) Right; 45.0 Most Likely Value; 159.9 Mean; 110.2 SDev.

Pd(Range | Manual) Left; 55.0 Most Likely Value; 149.5 Mean; 98.0 SDev.



Pd(Range Rate | Manual) Right; 0.0 Most Likely Value; -2.5 Mean; 9.7 SDev.

Pd(Range Rate | Manual) Left; -4.0 Most Likely Value; -5.3 Mean; 10.0 SDev.



Pd(Htm | Manual) Right; 0.3 Most Likely Value; 1.3 Mean; 0.8 SDev.

Pd(Htm | Manual) Left; 0.7 Most Likely Value; 1.3 Mean; 0.8 SDev.

Figure 28. Range, range-rate, and htm histograms for manual right and left lane changes with a preceding vehicle

3.4 Throttle pedal override during ACC lane changes

Throttle override is defined as the driver of a vehicle intentionally using the accelerator pedal to override the throttle setting of a cruise control system. For this report, throttle override is of interest during lane changes because it is a manual action which nominally displaces the ACC system. The intention here is to study the use of this type of driver intervention to better understand the frequency and conditions when these actions are taken. Result from the FOT showed many drivers felt the system was too slow to accelerate when passing, but that only eight drivers indicated that they intervened to accelerate during passing. An analysis of the lane-change events found a total of 40 throttle override events during lane changes with the ACC was engaged. Of the 108 drivers that participated in the study, these results showed nine drivers had two or more episodes of throttle override, and one driver was responsible for nine of the 40 override events.

The override events were identified by generating a list of lane changes where velocity was greater than either Vset (the cruise control set-speed velocity) or Vcommand (the cruise control commanded velocity). From this list, a 30 second time history of the relevant measures was generated and inspected to determine the likelihood of a throttle override. An example of an override event is shown in figure 29. The figure is composed of three plots. Along the bottom axis of each plot is time. Although not directly indicated on the plots, the lane-change event occurred at 15 seconds. The top plot in the figure, shows velocity, Vset, Vcommand, and Vdot. The center plot shows range and range-rate, and the bottom plot shows throttle and mode. Cruise control mode corresponds to the state of the cruise control system. At any given time the cruise control system is in one of four states. A mode of 0 corresponds to the system being turned off. A mode equal to 1 means the system was in standby, i.e., it was turned on but not engaged. A mode of 2 indicates the system was engaged and Vcommand was equal to Vset. A mode equal to 3 designates that the system was engaged and Vcommand was less than Vset, i.e., the system was tracking a target and commanding the velocity necessary to achieve the headway time selected by the driver.

In this example, there is no throttle override for the first 8 seconds as the ACC system is tracking the preceding vehicle, as indicated by a mode value of 3 in the bottom plot. During this time, Vset is 94 ft/s, velocity and Vcommand are about 82 ft/s, range is around 115 ft, range-rate hovers around 0 ft/s, and throttle and Vdot are more or less constant at 7 percent and 0 gs, respectively. The manual override begins at around 9 s and lasts through the lane change (15 s) until about 18 s as indicated by the large change in the throttle signal. The top plot shows the primary indication of throttle override, specifically, that throttle was nonzero while velocity increased well above Vcommand during a time when the cruise mode was 3 (from 9 to 15 s). At 15 seconds, the lane change occurs, and the target is lost (range and range-rate go to zero). Mode changes to 2 and Vcommand is set to Vset. Following the override (from 18 to 30 s), velocity is greater than Vset, so throttle is set to zero to slow the vehicle down to the Vset. This override event had a maximum throttle of 54 percent and lasted 10 s.

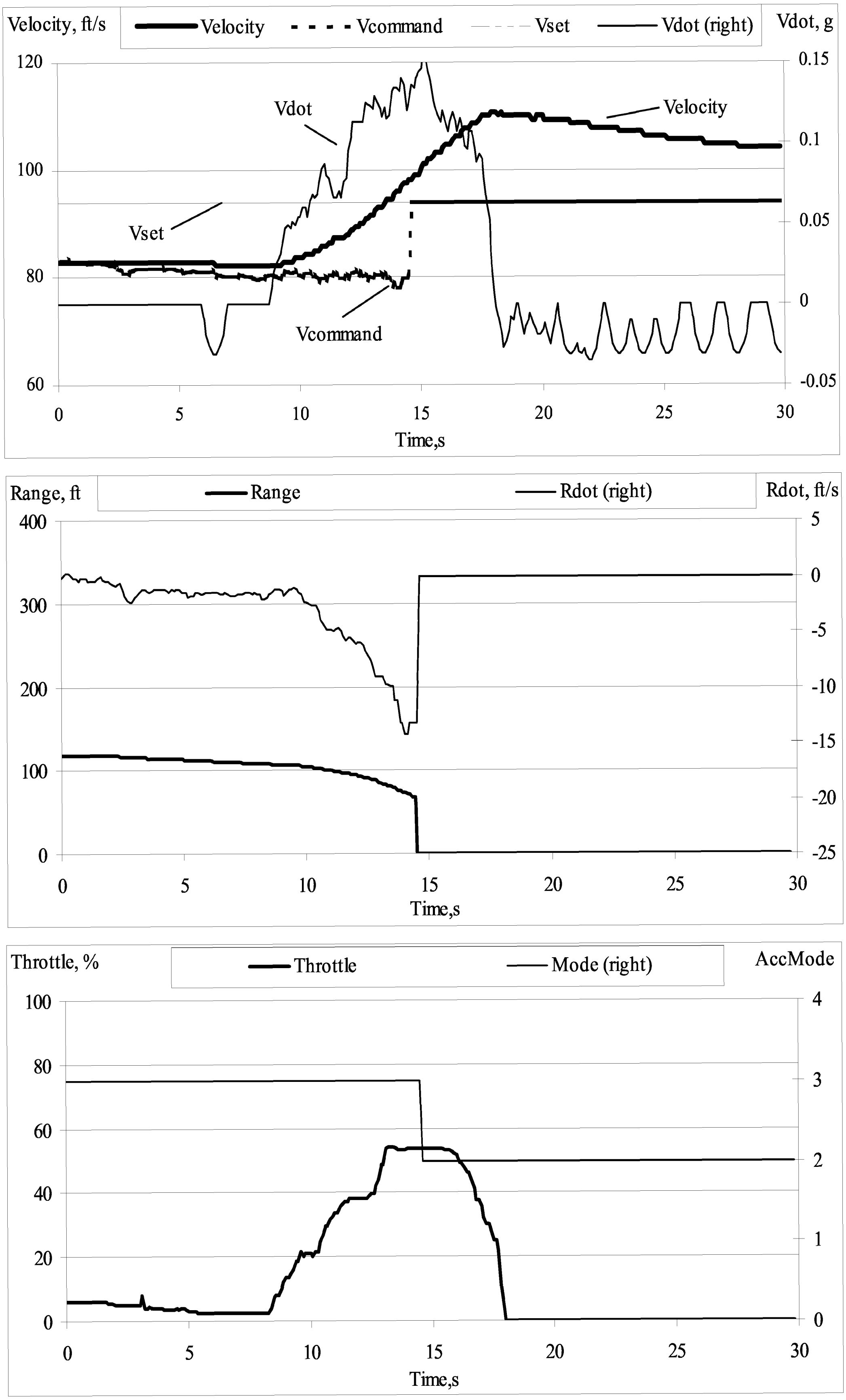


Figure 29. Example of an ACC-engaged lane change with throttle override

Table 5 shows summary statistics for the 40 throttle override events as a function of driver groups and lane-change direction. On average, drivers seem to perform throttle overrides and lane changes at distances of about 126 ft and with closing range-rates of 10 ft/s. The data indicate that males were more likely to override than females (60 versus 40 percent, respectively) and that cruise users did 87.5 percent of the overrides versus nonusers. The older drivers were responsible for roughly 48 percent of the overrides while the middle-aged and younger drivers had 30 and 22 percent, respectively. However, the younger drivers tended to get closer and close in on the preceding vehicle at a faster rate than the other two age groups. Flow conformists, hunters/tailgaters, and planners all had similar numbers of overriding events, however, like the young drivers, the hunters/tailgaters tended to be more aggressive with closer range values and larger closing rates than the other groups. Drivers in the ultraconservative group did not have any throttle-override lane-change events. Seventy-five percent of these events resulted in lane changes to the left, however, lane changes to the right, on average, were done at closer range than to the left (84 versus 140 ft).

Table 5. ACC lane changes with throttle override

Category	Group	No.	Percent	Avg. Range, ft	Avg. Rdot, ft/s	Avg. Vel, ft/s	Avg. Htm, s	Avg. Tti, s	Avg. Vset, ft/s	Avg. Throttle, %
All	All	40	100.00	126.1	-9.7	102.2	1.2	20.1	103.7	25.9
Gender	Female	16	40.00	133.6	-7.7	102.4	1.3	15.0	104.3	25.6
	Male	24	60.00	121.1	-11.0	102.1	1.2	23.4	103.3	26.0
Usage	Nonuser	5	12.50	135.6	-18.1	104.1	1.3	7.2	103.2	32.0
	User	35	87.50	124.8	-8.5	102.0	1.2	21.9	103.8	25.0
Age	20-30	9	22.50	98.6	-13.9	101.4	0.9	7.5	102.3	27.2
	40-50	12	30.00	119.1	-8.8	103.9	1.1	13.8	106.0	35.3
	60-70	19	47.50	143.6	-8.2	101.6	1.4	30.0	103.0	19.3
Style	Extremist	2	5.00	138.6	-8.2	103.4	1.2	16.3	106.3	14.6
	Flow Conformists	14	35.00	134.6	-9.4	102.5	1.3	15.0	102.9	24.0
	Hunter/Tailgater	12	30.00	88.0	-11.1	102.3	0.8	7.9	104.3	33.0
	Planner	12	30.00	152.3	-8.7	101.7	1.5	38.8	103.7	22.8
Time	5 week drvr (n=24)	28	70.00	129.9	-8.4	102.1	1.3	23.8	104.0	24.8
	2 week drvr (n=84)	12	30.00	117.3	-12.6	102.5	1.1	11.3	103.2	28.3
Direction	Left	30	75.00	140.1	-10.4	102.4	1.3	27.4	104.0	24.4
	Right	10	25.00	84.1	-7.5	101.8	0.8	-1.9	102.9	30.4

Table 6 is a listing of all 40 ACC engaged lane changes with throttle override. The eight highlighted events in the table show four lane-change pairs that represent sequential double lane changes, where the driver used the throttle to perform a “flying pass” while ACC was engaged.

Table 6. ACC-engaged throttle-override lane changes

No.	Drv	Trp	Evnt	Sub Evnt	V, ft/s	Rng, ft	Rdot, ft/s	Htm, s	Tti, s	Vset, ft/s	Thrtle, %	Vcmd, ft/s	Time	Age	Crus Usge	Sex	Style
1	4	61	144	11	95	46	-12.2	0.5	4	92	58.0	79.0	2	20-30	Non	M	Hunter
2	4	61	193	57	108	92	-19.1	0.8	5	105	26.6	88.9	2	20-30	Non	M	Hunter
3	4	61	193	60	108	92	-19.1	0.8	5	105	26.6	88.9	2	20-30	Non	M	Hunter
4	4	68	24	0	109	287	-26.6	2.6	11	106	8.8	102.6	2	20-30	Non	M	Hunter
5	15	49	21	0	103	108	-5.9	1.0	18	108	8.3	94.9	2	20-30	Usr	F	FlowCo
6	18	90	70	0	97	73	-6.3	0.7	12	103	13.0	85.6	2	60-70	Usr	M	FlowCo
7	24	106	37	27	125	233	-8.7	1.9	27	122	13.5	111.5	2	40-50	Usr	F	Extrmst
8	26	62	70	17	101	162	-13.6	1.6	12	108	40.2	91.1	2	40-50	Non	F	FlowCo
9	40	42	129	18	83	145	-7.7	1.8	19	95	24.0	74.7	5	60-70	Usr	M	Planner
10	40	44	170	3	92	133	1.6	1.5	0	97	13.0	88.4	5	60-70	Usr	M	Planner
11	40	136	61	3	111	230	-6.7	2.1	35	108	19.8	104.8	5	60-70	Usr	M	Planner
12	40	136	90	0	100	191	-0.4	1.9	524	102	17.7	98.6	5	60-70	Usr	M	Planner
13	40	137	220	7	103	164	1.4	1.6	0	106	24.5	100.0	5	60-70	Usr	M	Planner
14	40	137	249	12	114	204	-16.2	1.8	13	111	14.6	98.2	5	60-70	Usr	M	Planner
15	40	137	254	11	112	159	-10.4	1.4	15	109	16.7	97.7	5	60-70	Usr	M	Planner
16	40	146	146	17	92	139	-8.9	1.5	16	100	12.5	80.3	5	60-70	Usr	M	Planner
17	40	146	250	0	90	145	-5.2	1.6	28	99	33.4	82.7	5	60-70	Usr	M	Planner
18	51	16	241	4	82	44	-7.8	0.5	6	91	15.6	71.5	2	20-30	Usr	F	Extrmst
19	76	77	18	0	88	27	-3.8	0.3	7	100	34.5	78.9	5	20-30	Usr	M	Hunter
20	78	159	148	1	106	125	-21.8	1.2	6	106	30.8	87.5	5	40-50	Usr	M	Planner
21	85	100	42	2	103	22	-13.7	0.2	2	106	23.0	83.6	5	60-70	Usr	M	Hunter
22	85	118	29	4	101	71	-7.8	0.7	9	106	13.5	91.2	5	60-70	Usr	M	Hunter
23	85	143	79	0	119	99	-18.7	0.8	5	116	18.3	100.7	5	60-70	Usr	M	Hunter
24	88	147	16	1	99	123	-3.3	1.2	38	108	64.8	94.7	5	40-50	Usr	F	Hunter
25	88	147	16	2	99	123	-3.3	1.2	38	108	64.8	94.7	5	40-50	Usr	F	Hunter
26	89	111	212	66	110	91	-15.8	0.8	6	107	35.5	85.3	5	20-30	Usr	M	Planner
27	89	111	213	33	110	101	-14.9	0.9	7	107	31.3	86.9	5	20-30	Usr	M	Planner
28	90	110	25	2	94	26	-5.4	0.3	5	91	38.6	79.6	5	60-70	Usr	F	FlowC
29	90	110	25	3	94	26	-5.4	0.3	5	91	38.6	79.6	5	60-70	Usr	F	FlowC
30	90	183	72	0	105	67	-9.5	0.6	7	107	18.8	89.3	5	60-70	Usr	F	FlowCo
31	90	183	76	0	115	348	-8.0	3.0	43	112	8.3	110.0	5	60-70	Usr	F	FlowCo
32	90	183	256	29	102	221	-15.9	2.2	14	99	9.9	95.1	5	60-70	Usr	F	FlowCo
33	96	206	199	3	100	150	-9.1	1.5	16	108	12.0	88.3	5	40-50	Usr	F	FlowCo
34	96	206	265	7	115	167	-8.5	1.5	20	112	11.5	102.4	5	40-50	Usr	F	FlowCo
35	97	112	25	6	106	266	-12.9	2.5	21	103	8.3	99.7	5	60-70	Usr	F	FlowCo
36	99	140	47	2	104	42	-6.5	0.4	7	108	25.6	92.6	5	40-50	Usr	F	Hunter
37	99	159	12	0	95	31	0.9	0.3	0	92	31.3	85.0	5	40-50	Usr	F	Hunter
38	105	47	80	17	98	68	-13.3	0.7	5	95	53.8	80.3	2	40-50	Usr	M	FlowC
39	105	47	80	18	98	68	-13.3	0.7	5	95	53.8	80.3	2	40-50	Usr	M	FlowC
40	105	83	88	3	106	136	-5.0	1.3	27	108	20.9	104.4	2	40-50	Usr	M	FlowCo

3.5 Throttle override of ACC to pass on a two-lane rural highway

The previous sections have reported on lane-change activity in general. In this section the emphasis will be on lane-change activity on freeways versus two-lane rural highways. While data suggests that most ACC usage will be on multilane highways, there will be some usage on rural two-lane roads where lane-change activity most likely involves passing a slower moving vehicle. These types of passing maneuvers pose a very different set of challenges than similar maneuvers on multilane highways. In these events, a driver is minimizing the time spent in the opposing traffic lane, by employing strategies that may not lend themselves to ACC driving. For example, in a flying-pass maneuver the driver closes the headway gap and maintains a large negative range-rate before changing lanes—something that without throttle override, an ACC system is designed to avoid.

The FOT database contains some road-type and related population (rural versus urban) information for a seven county region in Southeast Michigan. Of the 114,000 miles driven in the FOT, approximately 60 percent were within this mapping region. Driving within the region constituted about 44,000 miles of manual driving and 16,500 miles of ACC driving for all velocities. The mapping algorithm used ten road classes and four population categories to distinguish the different types of roads in the region. These classes are shown in table 7. Driving that was done outside the mapped region was flagged in the database with the term "No mapping point."

Table 7. FOT road type and population classes

Road Type
Class0—HighSpeedRamp
Class1—Interstate
Class2—StateHighway
Class3—Arterial
Class4—Collector
Class5—LightDuty
Class6—AlleyorUnpaved
Class8—Unknown
Class9—LowSpeedRamp
Population classes
Population density—Rural
Population density—Urban 0 to 5000
Population density—Urban 5000 to 50000
Population density—Urban > 50000

In addition to road type and population density, lane changes on two-lane roads were segregated from other lane changes by identifying lane-change pairs. Clearly, passing maneuvers on two-lane roads involve lane-change pairs, more specifically, a lane change to the left followed by a lane change to the right. Table 8 shows summary results for all lane-change pairs that occurred while closing (Rdot < 0), had a maximum passing time of 40 s and were of opposite polarity (i.e., left to right or right to left).

Aside from of the type of road that the passing maneuver was performed on, it appears that on average these maneuvers take about 14 s to complete. Typically, they involve closing rates of 11 ft/s, a headway time of 1.5 s and the first lane change occurs 146 ft from the preceding vehicle. Not surprisingly, the table shows that when ACC is used the range and headway time increases to 189 ft and 1.9 s, respectively, as does the time to pass (peak to peak value—column labeled pass time in table 7) from 14.1 s to 15.6 s. Users tend to pass more often than nonusers, and they do it from closer range (145 versus 151 ft) and take less time (13.6 versus 16 s). By age, the younger drivers tend to pass more often than the other two groups, however, the older drivers pass from the closest range and spend the least amount of time performing the maneuver, only 11 s versus 13.5 and 16.5 for younger and middle-aged, respectively. The gender results show males passing slightly more often than females (55 versus 45 percent, respectively). Hunter/tailgaters performed nearly 44 percent of the passing maneuvers versus flow conformists, the second highest group with 23 percent. It is also the hunter/tailgaters that spend the least amount of time doing the passing maneuver, only 12.8 s versus planners who spend 13.4 s. By far, more of the passing maneuvers are done with a lane change to the left followed by one to the right, i.e., passing on the left, as opposed to passing on the right (67 versus 33 percent, respectively).

In terms of road type and population (excluding data not in the mapping region), the majority of the passing maneuvers where done on interstates in a rural setting. In terms of passing maneuvers that may qualify as being on two-lane roads, there are only two on state highways and seven on arterial roads. So in general terms, there are not many candidates for two-lane passing maneuvers in all the FOT data.

Table 8. Passing maneuver lane-change pairs

Category	Group	No.	Percent	Avg. Range, ft	Avg. Rdot, ft/s	Avg. V, ft/s	Avg. Htm, s	Avg. Tti, s	Avg. Pass Time, s	Avg. Vp, ft/s
All	All	198	100.00	146.1	-11.2	99.1	1.5	37.7	14.1	87.1
Mode	Manual	127	64.14	121.6	-11.0	99.0	1.2	29.0	12.9	86.6
	ACC	56	28.28	189.2	-11.2	99.0	1.9	53.8	15.6	88.1
	CCC	15	7.58	192.1	-12.4	99.9	1.9	51.4	18.6	87.2
Usage	Nonuser	39	19.70	151.2	-12.8	100.6	1.5	30.4	16.0	86.9
	User	159	80.30	144.8	-10.8	98.7	1.5	39.5	13.6	87.2
Age	20-30	100	50.51	146.5	-11.8	100.5	1.4	34.2	13.5	88.1
	40-50	66	33.33	161.3	-10.8	98.8	1.6	50.6	16.5	87.0
	60-70	32	16.16	113.3	-10.1	95.5	1.2	22.1	10.9	84.3
Gender	Female	90	45.45	141.2	-10.5	98.3	1.4	35.0	14.5	87.1
	Male	108	54.55	150.1	-11.8	99.7	1.5	40.0	13.7	87.1
Style	Extremist	17	8.59	157.4	-6.4	97.7	1.6	51.4	20.2	89.9
	Flow Conformists	46	23.23	167.2	-11.5	98.8	1.7	52.2	14.6	86.8
	Hunter/Tailgater	87	43.94	124.9	-11.9	101.1	1.2	22.0	12.8	88.1
	Planner	37	18.69	159.3	-11.4	97.3	1.6	51.8	13.4	85.6
	Ultra Conservat.	11	5.56	162.9	-11.1	92.5	1.7	32.8	14.9	81.4
Direction	Left then right	133	67.17	133.8	-12.2	98.3	1.4	29.8	14.8	85.5
	Right then left	65	32.83	171.1	-9.2	100.7	1.7	53.8	12.5	90.5
Road type	Class1-Interstate	89	44.95	142.1	-10.1	99.4	1.4	50.0	14.2	88.2
	Class2-StateHwy	2	1.01	68.9	-5.4	85.8	0.8	15.6	7.1	77.8
	Class3-Arterial	7	3.54	132.7	-8.5	87.6	1.5	36.8	12.0	78.3
	Class5-LightDuty	1	0.51	45.3	-1.6	83.6	0.5	27.6	30.8	79.7
	No Mapping Pt.	99	50.00	153.1	-12.5	100.1	1.5	27.2	14.1	87.0
Pop. Density	Rural	44	22.22	139.2	-12.3	99.0	1.4	23.3	15.0	86.1
	Urb0to5000	5	2.53	137.3	-12.3	93.3	1.5	13.2	10.1	81.8
	Urb5000to50000	16	8.08	141.6	-11.0	101.6	1.4	86.3	13.2	88.1
	UrbGT50000	34	17.17	137.8	-5.7	96.1	1.4	67.5	13.9	89.1
	No Mapping Pt.	99	50.00	153.1	-12.5	100.1	1.5	27.2	14.1	87.0

The data are even more selective if queried for only ACC engaged passing maneuvers (to the left of the preceding vehicle) while on state highways with a rural population density. There were only two events that met these conditions. Table 9 shows the results for this query.

Table 9. Possible two-lane passing maneuvers with ACC engaged

Drvr	Trp	Evnt	SubE	Road	Pop	Rng, ft	Rdot,ft/s	Htm, s	Tti, s	V, ft/s	Time, s	Vp, ft/s
88	75	10	10	Arterial	Rural	78.4	-10.4	0.8418	7.4815	93.141	7.0900	81.099
92	54	25	0	StateHw	Rural	97.8	-3.82	1.2013	25.542	81.385	7.6899	75.370

None of the events in table 9 were captured on video by the ACC-equipped vehicle—hence they could not be absolutely confirmed as two-lane passing events. However, it was possible to search the "no mapping point" data by joining the passing maneuvers table with the throttle override table to generate a list of candidate passing maneuvers where the ACC was engaged and the driver used the throttle to override the system.

Investigations of these events (there were five total) did yield one ACC-engaged passing event on a two-lane rural highway. Select video clips from this event are shown in figure 30 and the summary statistics are shown in table 10.[2] The figure shows (from top to bottom) the ACC vehicle approaching a van on a rural highway. (Here the road has three lanes, because the on-coming traffic has a passing lane.) In the center of the figure, the driver of the ACC vehicle eventually gets to within 25 ft of the van before changing lanes and beginning to pass. At the start of the passing maneuver, the relative velocity of the two vehicles is approximate -5 ft/s. In the center frame of figure 28, the ACC vehicle is completely in the oncoming lane while the last two frames show the completion of the passing maneuver. The passing time for this maneuver was 7 s.

Although it was thought that differences in lane-change activity on a two-lane highway versus a freeway could be studied using the FOT database, this investigation has not revealed enough confirmed two-lane passing events to draw many conclusions. Probably, the most noteworthy conclusion is simply that passing maneuvers, like the one shown in figure 30, are very rare.

Table 10. Two-lane passing maneuvers with ACC engaged and throttle override

Drvr	Trp	Evnt	SubE	Road	Pop	Rng, ft	Rdot,ft/s	Htm,	Tti, s	V, ft/s	Time, s	Vp, ft/s
90	110	25	2	No map	No map	25.6	-5.4	0.3	4.8	95.3	7.0	88.5

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[2] As the video clips show, this was not your typical two-lane rural highway. In this case, there was a passing lane for the oncoming traffic.

Figure 30. ACC-engaged passing maneuver on a rural road

4.0 SUMMARY OF RESULTS AND FINDINGS

Delay during brake intervention—Results were obtained from the examination of cases where both the following and preceding vehicles decelerated at levels above 0.1 g. These results show that the initial level of deceleration is frequently close to the maximum level of deceleration, but just as often the maximum level of deceleration is considerably larger than the initial level of deceleration during the braking event. It was not uncommon for the maximum level of deceleration to exceed 1.5 times the initial level of deceleration for both ACC and manual driving.

The number of hard braking events at speeds above 50 mph was considerably more for manual driving, although in general, hard braking events (those exceeding 0.1 g by both vehicles) are rare. In the data from the FOT [1], there were 303 hard braking cases in manual driving and 67 cases in ACC driving. The miles traveled in ACC driving exceeded the miles of manual driving for speeds above 50 mph. Nevertheless, drivers appear to choose to drive manually when the need for hard braking is likely to be greater.

The wait time (Wt) between the initiation of hard braking was greater for ACC driving than it was for manual driving. However, the headway time margin (Htm) was usually also greater for ACC driving than it was for manual driving. In a sense, the ACC driver could afford to wait longer than the manual driver. The results provide evidence indicating that drivers tend to wait by an amount of time corresponding to the headway time margin available when the preceding vehicle initiated hard braking. The results show that for manual driving, $|Htm-Wt| < 0.5$ seconds occurs in over 55 percent of the hard braking cases. For ACC driving, $|Htm-Wt|<0.5$ seconds occurs in approximately 35 percent of the cases. In ACC driving, drivers do not wait as long with respect to the headway time available. In approximately 33 percent of the ACC cases, the wait time was 0.5 to 1.5 seconds shorter than the available headway time margin. These results provide evidence supporting the proposition that, when driving with ACC, the FOT drivers did not, as a rule, wait too long given the headway time margins available to them. Whether this finding can be extended to the very rare circumstances associated with rear-end crashes is not clear, but the drivers in the FOT were alert enough to be aware of their situations when hard braking was needed.

Perhaps there were fewer brake interventions in ACC because ACC drivers have more headway time margin available to them and because the deceleration provided by the ACC system served to call their attention to the forward scene.

Continuous control—The continuous control analysis showed that for manual driving, a shift-time of approximately 3 s is typical for the drivers in the FOT. This finding represents a fundamental human control characteristic—namely, that a driver tends to respond to changes in range and range-rate of the preceding vehicle with a 3 second delay. For the ACC controller, the delay is approximately twice that of manual driving or about 6 s. However, since the range and headway time values for ACC operation are typically much greater (50 percent in most cases) than in manual driving the increased delays are not a distraction nor do they cause any noteworthy stress, at least according to the favorable driver responses from the FOT.

Lane-change events—The algorithm used in this study identified a total of 14,076 lane changes in the 108 driver FOT database. These lane changes were for velocities above 50 mph and they were based on changes in the heading angle of the vehicle as measured by the ACC-system gyro. On average, high-speed driving involves about 22 lane changes per 100 miles.

In terms of different driver groups within the FOT, the young drivers tended to change lanes more frequently than both middle-aged and older drivers on a per mile basis. It also appears that drivers who consider themselves cruise control users tended to change lanes more often than nonusers and that drivers are more likely to change lanes while driving manually than with ACC or CCC engaged.

In terms of driving mode, the results showed that drivers were much more likely to change lanes in manual versus ACC-engaged driving mode. The manual lane-change results showed 29 lane changes per 100 miles, while the ACC results were 18 lane-changes per 100 miles. Driving with conventional cruise control resulted in even fewer normalized lane changes (15 per 100 miles).

For the different driving styles defined in the FOT, those drivers categorized as hunters/tailgaters change lanes more often than drivers in the other four categories. The second highest lane-change rate was for those drivers classified as planners. Apparently, part of their driving strategy was to change lanes to achieve their goal of driving fast and far. Extremists and ultraconservatives had the lowest lane-change activity.

As an aside, the results from the lane-change analysis also support the hypothesis that ACC usage results in less throttle modulation and hence greater fuel efficiency and less driver workload when compared to the throttle modulation normally associated with manual driving.

Lane changes with a preceding vehicle—Of the 14,076 lane-change events reported, a subset of 5,192 or 37 percent had a preceding vehicle present shortly before the lane change took place. These results show that the average lane change occurred at a speed of 97 ft/s, and approximately 180 ft behind the preceding vehicle (1.9 s headway time) and with a closing relative velocity of 3.4 ft/s. In terms of driving mode, the results show that for manual driving, lane changes occurred at a closer range when compared to the ACC or CCC (153, 206, 206 ft, respectively).

The left and right lane changes for manual driving shows that 57 percent of the lane changes were to the left while 43 percent were to the right. However, the ACC results show an even more biased choice with 64 percent of the lane changes to the left and only 36 percent to the right. The increased bias toward lane changes to the left for ACC-engaged driving may be due to both the traffic environment (density, relative lane velocity) and the limitations imposed by the ACC system. It appears that the combination of restricted close range driving, by the ACC system tends to favor changing lanes to the left where the odds of less traffic density and higher speeds is more likely to result in a successful passing maneuver.

Throttle override during ACC-engaged lane changes—There were 40 throttle override events identified in the ACC-engaged lane-change results. On average, drivers seem to perform throttle overrides and lane changes at distances of about 126 ft and with closing range-rates of 10 ft/s. The data indicate that males were more likely to override than females (60 versus 40 percent, respectively) and that cruise users did 87.5 percent of the overrides versus nonusers. The older drivers were responsible for roughly 48 percent of the overrides while the middle-aged and younger drivers had 30 and 22 percent, respectively. Flow conformists, hunters/tailgaters, and planners all had similar numbers of overriding events, however, like the young drivers the hunters/tailgaters tended to be more aggressive with closer range values and larger closing rates than the other groups. Drivers in the ultraconservative group did not have any throttle-override lane-change events. Seventy-five percent of these events resulted in lane changes to the left versus lane-changes to the right.

Lane-change activity on freeways versus two-lane rural highways—Passing maneuvers on two-lane roads involve lane-change pairs, more specifically, a lane change to the left followed by a lane change to the right. Linking this information to the road classification, a search was done to identify potential passing maneuvers on 2-lane highways. The results of this query showed that there were only two on state highways and seven on arterial roads. So in general terms, there were not many candidates for two-lane passing maneuvers in all the FOT data and none of these events could be confirmed as two-lane passing events using the database of video clips captured during the FOT.

However, a search of the potential passing maneuvers outside of the road mapping region did result in one confirmed passing event on a two-lane highway. During this event, the driver of the ACC vehicle eventually gets to within 25 ft of the preceding vehicle before changing lanes and beginning to pass. At the start of the passing maneuver, the relative velocity of the two vehicles is approximate -5 ft/s. The passing time for this maneuver was 7 s. Based on the rarity of these types of maneuvers in the FOT database, the most noteworthy finding is simply that passing maneuvers on two-lane roads with ACC engaged are very rare.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results and findings of this study support the following conclusion statements regarding:

The Quantification of Waiting Time

- A special data processing procedure was developed to quantify the driver's waiting time in cases where hard braking interventions were applied by the driver of the following vehicle. The procedure proved to be very effective. Without it, the study of brake intervention would have been superficial.

Brake Intervention Events

- The amount of time a driver waits to intervene by hard braking is related to 1) the headway time margin available at the onset of hard braking by the preceding vehicle and 2) the level of deceleration of the preceding vehicle.
- Drivers of following vehicles usually brake harder than the braking rate of the preceding vehicle.
- With ACC in operation, drivers usually have longer headway time margins available and they use this time margin to avoid waiting too long and having to brake very hard to make up for delay due to waiting too long.
- The basic stopping distance equations provide a good reference base to use in qualitative evaluations of situations involving brake intervention.

Continuous Control of Headway (ACC versus Manual)

- The ACC system used in the FOT did not react as quickly to small speed fluctuations as drivers did when manually following a preceding vehicle. In this sense, ACC driving was smoother than manual driving.

The Identification of Lane-Change Events

- A special procedure for processing the FOT data was developed to find when and where lane changes occurred during the FOT. This procedure was effective in identifying lane changes on straight (tangent) sections of highway and on constant radius curves. The development of the procedure is an important step, enabling this and future studies of lane-change maneuvers.

Lane-Change Maneuvers

- Lane-change maneuvers are relatively frequent events which (as anticipated) are more likely for drivers that tend to travel considerably faster than the average speed of neighboring traffic.
- Drivers will not change lanes as frequently when using ACC systems as they will when driving manually.
- The lane-change data support the proposition that ACC driving saves on throttle modulation ("throttle stress") and increases fuel savings as compared to manual driving. (Driving in conventional cruise control is the most energy efficient mode of driving.)
- Drivers change lanes at speeds above 50 mph more without a preceding vehicle present than they do when a preceding vehicle is present.
- Drivers do not tend to pass other vehicles as often when driving in the ACC mode as they do when driving manually.
- Drivers come much closer to the preceding vehicle when passing in manual driving than they do in ACC driving.
- Drivers do not frequently override with the accelerator pedal during ACC driving, and they seldom try to pass on a two-lane rural highways when the ACC is in operation.

Recommendations Concerning Forward Crash Avoidance Systems

The following recommendations are based on the observation that headway time margin (R/V) has a substantial impact on how long a driver will wait before intervening by braking. Although, many factors influence when a driver will decide to slow down, the findings of this study indicate that drivers tend to initiate braking after their tolerance for short headway times has been exceeded.

Hence, we have given consideration to envisioning how driver behavior, as related to the conservation of headway time, could serve as the basis for driver assistance systems. These driver assistance systems would alert the driver to situations in which the driver would ordinarily consider intervening by braking.

1) Recommendation for a simple alert system

Based on the data processed in tasks S-1 and S-2, the following simple system is recommended as a candidate for further evaluation in the FOCAS project.

An alert signal is given to the driver when the headway time margin becomes less than a predetermined (perhaps driver selected) threshold, (Twt), on waiting time. In analytical terms, this means considering whether $(R/V) - Twt$ is greater than zero. Algebraically, rearranging the terms an alert would be issued if $(R/V) < Twt$, or (to handle the zero velocity condition) when:

$$R < V \cdot Twt \qquad \text{(R1)}$$

Although (R1) is a very simple rule, it requires a sensor for measuring range to the preceding vehicle (remote sensing) as well as an internal sensor for measuring velocity. Values of the parameter Twt would need to be established so that alerts were given at times and in situations that make sense to the driver. This means that the alert signal would be expected to occur in situations that exceed the driver's normal tolerance for exposure to risk. In summary, the purpose of the system is to enhance the driver's situation awareness by alerting the driver to when the exposure to risk exceeds a tolerable level of anxiety. From the standpoint of injury prevention, the purpose of the system is to reduce the likelihood of driving in crash risky situations.

It is anticipated that systems of this type would need to be driver centered. This means getting the driver's attention in a manner that does not offend the driver. The idea is to engineer a system that the driver will view as a cooperative partner and not as an adversary competing for domination.

2) Recommendation for a system that actively strives to conserve headway time

This second system is based on extensions of the ideas presented in connection with the simple system just recommended. However, in this system, drag forces as well as brake forces would be employed in part as a kinesthetic alert cue and in part as an active system for making modest speed adjustments in order to conserve headway time margin. The ACC systems employed in the FOCAS project already provide these alerting and headway control functions. However, the system proposed in this recommendation focuses on headway time margin directly in its conceptualization and, as such, emphasizes the alerting qualities presented by slowing the vehicle.

In concept, the functional goal is to actively decelerate the vehicle when R/V becomes less than Twt. In a sense, the goal is to provide an alert when deceleration is needed by applying enough deceleration to get the driver's attention to the forward scene. Past experience in studying ACC systems indicates that even a very modest change in deceleration (such as dropping the throttle quickly) will be noticeable to the driver and prompt the driver to pay attention to the forward scene.

In a sense, this system is the same as a special type of braking algorithm for an ACC system. (To extend the following ideas to a complete ACC system would require an algorithm for generating commands to the throttle control.) However, the development here will only be carried to the point where deceleration commands are specified. It is expected that these commands would be carried out using an electronic braking system such as that used in the ACC-with-braking car developed for the FOCAS project.

The design of the braking command unit follows from a process consisting of selecting a goal, defining the difference between the current driving situation and the goal, and then, deciding on a deceleration command that will reduce the difference between the situation and the goal towards zero. The following equation expresses this process in symbolic form suitable for implementation in the computer algorithm.

The goal:

$$\frac{R}{V} - \mathrm{Twt} = 0 \tag{R2}$$

The difference, (e):

$$\frac{R}{V} - \mathrm{Twt} = e \tag{R3}$$

The reduction decision:

$$\mathrm{Te} \cdot \dot{\mathrm{e}} + \mathrm{e} = 0 \qquad \text{(R4)}$$

If (R3) and (R4) are solved for the desired deceleration command (Vcdot) the result is as follows[3]:

$$\mathrm{Vcdot} = (\frac{\mathrm{V}}{\mathrm{R}})[\dot{\mathrm{R}} + (\frac{\mathrm{R} - \mathrm{Twt} \cdot \mathrm{V}}{\mathrm{Te}})] \qquad \text{(R5)}$$

Equation (R5) has some interesting features. First, braking commands are only given when Vcdot is less than zero. If $\dot{\mathrm{R}} = 0$ and $\mathrm{R} = \mathrm{Twt} \cdot \mathrm{V}$, Vcdot equals zero. The multiplication gain factor in (R5) is (V/R), and it equals the reciprocal of the headway time margin, Htm. If Htm is small and the quantity in the square bracket of (R5) is negative, the amount of deceleration represented by Vcdot is large. Conversely, Vcdot is small, if Htm is large. These qualities arise from the focus on keeping $\mathrm{R} < \mathrm{Twt} \cdot \mathrm{V}$ (as in (R1)). However, the kinesthetic alert resulting from the application of Vcdot will be inversely scaled in amplitude by Htm. This means that the alert function will have a continuous scaling depending upon the level of risk for the situation.

In closing, it is recommended that the active system just outlined be developed further in the FOCAS project.

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[3] To obtain Vcdot, equations (R3) and (R4) are solved formally for Vdot which represents the desired deceleration needed to approach the chosen goal. This symbolic expression for Vdot is set equal to Vcdot since it represents the input to the brake control unit not the actual deceleration of the vehicle when the system is in operation.

6.0 REFERENCES

1. Fancher, P., Ervin, R., Sayer, J., Hagan, M., Bogard, S., Bareket, Z., Mefford, M., Haugen, J., *Intelligent Cruise Control Field Operational Test (Final Report)* Final Report, NHTSA Contract No. DTNH22-95-H-07428, The University of Michigan Transportation Research Institute, UMTRI-98-17, Ann Arbor, Michigan May, 1998.

2. Fancher, P., Ervin, R., Sayer, J., Hagan, M., Bogard, S., Bareket, Z., Mefford, M., Haugen, J., *Intelligent Cruise Control Field Operational Test (Interim Report)* Interim Report, NHTSA Contract No. DTNH22-95-H-07428, The University of Michigan Transportation Research Institute, UMTRI-97-11, Ann Arbor, Michigan March, 1997.

APPENDIX A—LANE-CHANGE RULES

There are corners between circular curves and tangent sections. We identify when corners occur but we do not count lane changes on corners.

During a lane change, there is a bump in the heading angle time history caused primarily by a yaw rate wave form of one polarity (right or left) at the start of the lateral motion and then of the other polarity to return to the original direction of travel. Examination of data from typical lane-change maneuvers on the highway indicates that lane-changes frequently take less than 10 seconds to perform.

Since most lanes on limited-access highways are 12 ft. wide, the nominal lateral translation relative to the path of road is 12 ft. However, people don't always travel in the center of their lane and they cut-corners, etc. We have chosen to use a lateral displacement of 8 ft. as the minimum displacement for the maneuvers analyzed here. A boundary of this type is needed to distinguish path corrections and small obstacle avoidance situations from maneuvers whose purpose is to change lanes.

Lateral displacement does not appear directly in the FOT data. Hence we need to estimate lateral displacement. For situations involving small angles the rate of change of lateral displacement (y) is given by $\dot{y} = v + u\Psi$ where v is the lateral or side slip velocity component perpendicular to the longitudinal axis of the vehicle and u is the forward velocity component along the longitudinal is of the vehicle. For practical vehicles doing normal lane-changes v is approximately zero with nearly equal small excursions of one polarity and then the other. This means that we assume that the integral of v over a lane-change period of time is approximately equal to zero. Hence we assume that

$$\left|\Delta y(t+5)\right| \approx \left|u \int_{t-5}^{t+5} \Delta\Psi dt\right| \approx u\left|(Area)\right|$$

where u is the average or nominal forward velocity (v) over the lane-change period and the area. For $\Delta y \geq 8$ ft., this means that $|(Area)| > (8)(57.3)/V$ as shown in figure 20.

Furthermore, a second criteria is added to check that $\Delta\ \varphi$ is large enough so that the lane change could take place approximately 8 seconds. The resulting inequality is $|\Delta\psi| > 114.6/V$.

In summary, the technique used to isolate lane changes involves fitting straight line segments to nearly straight portions of the heading angle time history. Then deviations from these straight line fits are examined to see if they satisfy the more then 8 ft. and less than 10 second criteria. The result is a reasonably robust technique for finding maneuvers that produce more than 8 ft. of lateral movement in less then 10 seconds. These maneuvers represent purposeful lane changes such as those used in passing preceding vehicles.

APPENDIX B—REGIMES OF THE RANGE VERSUS RANGE-RATE SPACE

For purposes of examining different types of driving situations (regimes), the range-versus range rate space has been divided into the five regions shown labeled in Figure as “closing”, “following”, “separating”, “near”, and “cut-in”. Definitions of these regions are presented in mathematical terms in table B-1. From a pragmatic point of view the boundaries between these regions have been chosen to separate different types of driving regimes. A prominent feature on figure B-1is the parabola that has been chosen to separate short range conflict situations from the operations appearing at longer range. This parabola intercepts the range axis at a point that corresponds to a time gap of 0.5 seconds. The shape of the parabola corresponds to a deceleration of 0.1 g. The region below this boundary is divided into “near” and “cut-in” regions depending upon whether range rate (RDot) is negative (R is decreasing) or positive (R is increasing). Above the parabola the space is divided into three regions that also depend upon range rate. If range rate is between -5 ft/sec and +5 ft/sec, the subject vehicle is deemed to be following the preceding vehicle with little difference in relative velocity (range rate). The region to the left of following is called closing because in this region the subject vehicle is overtaking the preceding vehicle. The upper right region is called separating because the preceding vehicle is going faster than the subject vehicle thereby causing the vehicles to separate. Clearly, since measures of R and RDot are collected only when the sensor sees a valid target ahead, none of the five regions is satisfied when no valid target exists.

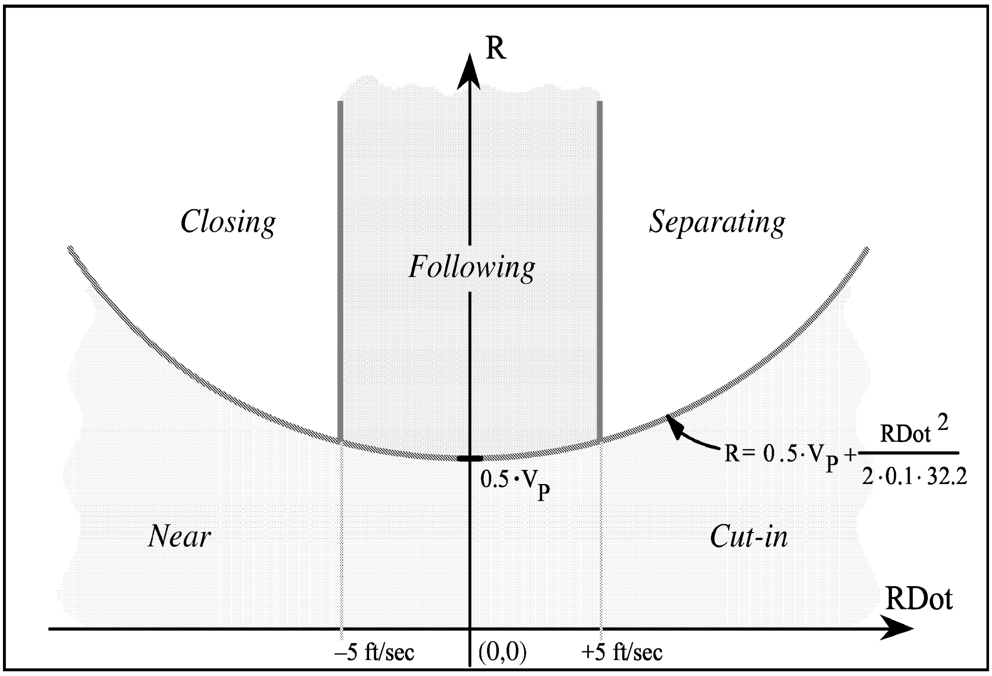

Figure B-1. Driving situation (regimes) in the range-range rate space

Table B-1. Definitions of driving regimes

$$R_b = 0.5 \cdot V_p + \frac{\mathrm{RDot}^2}{2 \cdot 0.1 \cdot 32.2} \quad \mathrm{ft}$$

$$\mathrm{RDot}-b = -5 \quad \mathrm{ft}/\mathrm{sec}$$

$$\mathrm{RDot}+b = +5 \quad \mathrm{ft}/\mathrm{sec}$$

$$\mathrm{Near} \equiv \left[R \le R_b \ \ \mathrm{AND} \ \ \mathrm{RDot} \le 0\right]$$

$$\mathrm{Cutin} \equiv \left[R \le R_b \ \ \mathrm{AND} \ \ \mathrm{RDot} > 0\right]$$

$$\mathrm{Closing} \equiv \left[R > R_b \ \ \mathrm{AND} \ \ \mathrm{RDot} \le \mathrm{RDot}-b\right]$$

$$\mathrm{Following} \equiv \left[R > R_b \ \ \mathrm{AND} \ \ \mathrm{RDot}-b < \mathrm{RDot} < \mathrm{RDot}+b\right]$$

$$\mathrm{Separating} \equiv \left[R > R_b \ \ \mathrm{AND} \ \ \mathrm{RDot} \ge \mathrm{RDot}+b\right]$$

APPENDIX C—DRIVING STYLES

This appendix shows the scheme to quantify driving styles at highway speeds above 55 mph (80.7 ft/sec, 24.5 m/sec) using the following boundaries, which are displayed in the normalized range-versus-range-rate diagram presented in figure C-1:

R/V ≤ 0.65 sec, R/V ≥ 2.25 sec, Rdot/V ≤ -0.075, and Rdot/V ≥ 0.075.

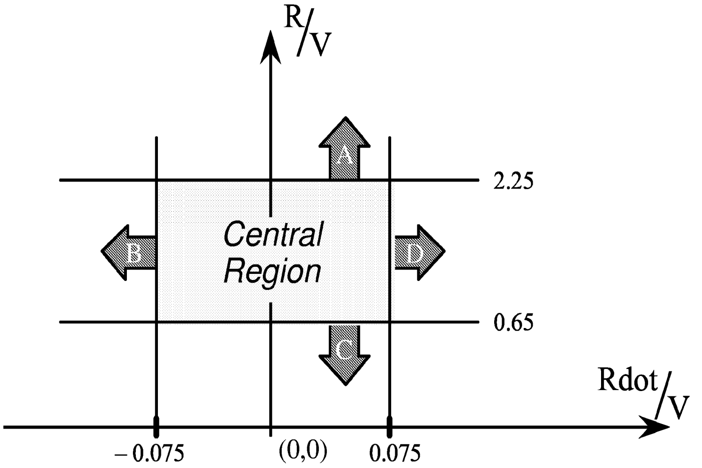

Figure C-1. Boundaries used in defining driving styles

These boundaries and the data associated with a given driver are used to evaluate certain probabilities symbolized as A, B, C, and D:

A = P(R/V>2.25)

B = P(Rdot/V<-0.075)

C = P(R/V<0.65)

D = P(Rdot/V>0.075)

where P(····) means the probability of the event enclosed in the parentheses.

The quantity A is a measure of the “far” tendency of a driver; B represents the “fast” tendency; C represents “close”; and D represents “slow.”

In order to use a technique known as “small multiples” to display and compare driving styles between individual drivers, the probabilities A, B, C, and D for a given driver are displayed as illustrated in figure C-2.

Seven items appearing in figure C-2 are used in classifying driving style. The items used are A, B, C, and D plus the products AB, BC, and AD. These products are proportional to the areas of three of the four triangles shaded in figure C-2. For example, the triangle associated with AD is characterized by the labels “far” and “slow” in figure

C-2. The area of this triangle provides a graphical indication of the amount of driving that is characterized by the tendency to drive slower and farther away than other drivers. If A and D are large, then the area AD/2 of the AD triangle will be large. In a similar manner, the triangles AB and BC are related to "far" and "fast" and "fast" and "close" respectively.

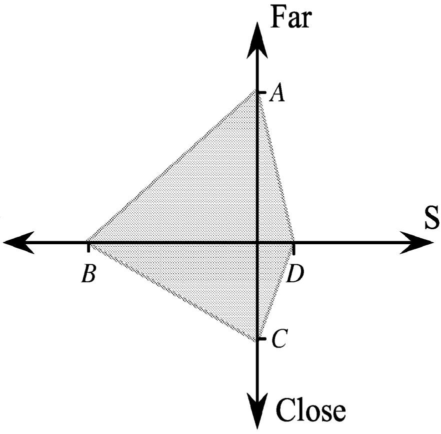

Figure C-2. Plotting the quantities that define driving styles

The triangle CD, if it were to be used, would be related to driving at close range while traveling slower than the preceding vehicle. Since this is a physically difficult situation to maintain, it has not been used in rating driving style.

The 75th percentiles for values of the seven items defined above are determined by examining the data for all 108 drivers. This information is used to classify drivers using the following names to provide a descriptive portrayal of five types of driving styles:

1. "Ultraconservative" means that AD or D is greater than the 75th percentile. Ultraconservative means an unusual tendency towards far and/or slow driving.
2. "Planner" means that AB or B or A is greater than the 75th percentile. Planner means an unusual tendency towards far and/or fast driving.
3. "Hunter/tailgater" means that BC or C is greater than the 75th percentile. Hunter/tailgater means an unusual tendency towards fast and/or close driving.
4. "Extremist" means that the driver satisfies more than one of the above tendencies. This means that types 1, 2, and 3 are not resolved until the extremist designation has been considered.
5. "Flow conformist" means that the driver satisfies none of the above. A flow conformist tends to travel at the same speed as other cars and at approximately the median headway time gap.

The process of classifying drivers starts with determining the 75th percentile as illustrated by the example portrayed in figure C-3. Once the drivers with tendencies to operate in the tails of the distributions are determined, they are classified into one of the five classifications listed above. For example, driver number 55 is classified as a planner, which means the tendency to travel relatively fast while somehow planning ahead to be able to remain far away from the vehicle ahead. figure C-4 shows how driver number 55 is represented using the probabilities of far, fast, close, and slow driving.

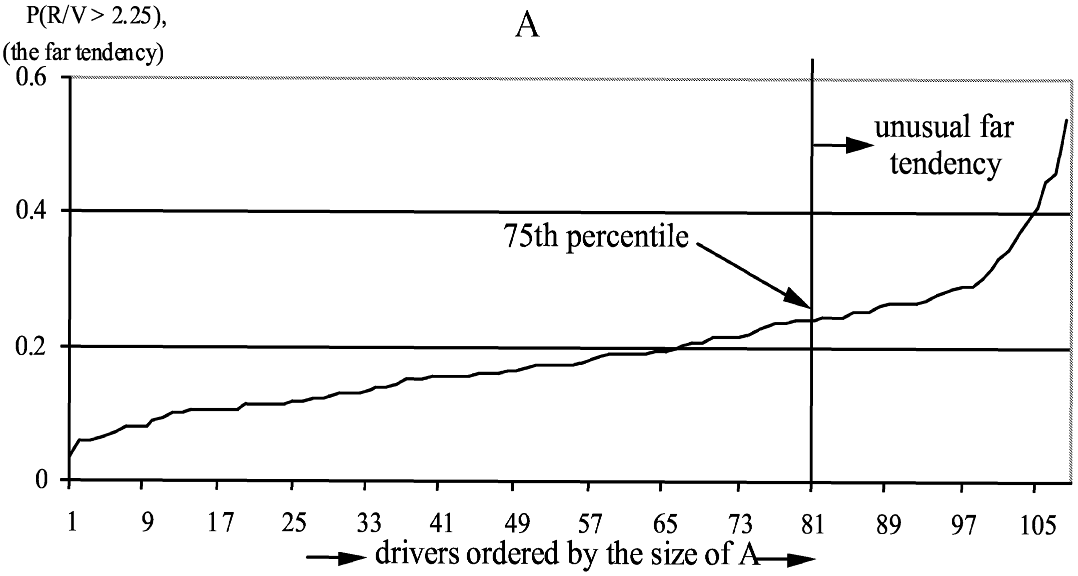

Figure C-3. Example showing 75th percentile of P(R/V>2.25 seconds)

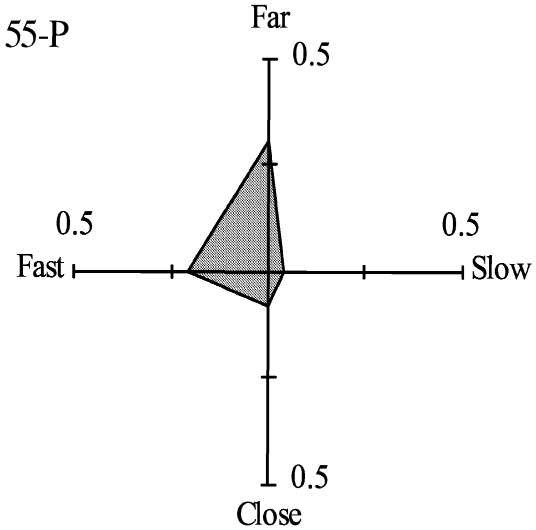

Figure C-4. Example of a planner (driver number 55)

APPENDIX D—RESPONSE TO BRAKING TABLE