



U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**



DOT HS 808 849

July 1998

**Final Report
Volume III: Performance of a String or Cluster of ACC-Equipped Cars**

Intelligent Cruise Control Field Operational Test

This publication is distributed by the U.S. Department of Transportation, National Highway Traffic Safety Administration, in the interest of information exchange. The opinion, findings, and conclusions expressed in this publication are those of the author(s) and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration. The United States Government assumes no liability for its contents or use therefore. If trade or manufacturer's name or products are mentioned, it is because they are considered essential to the object of the publication and should not be construed as an endorsement. The United States Government does not endorsement products or manufacturers.

1. Report No. DOT HS 808 849	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Intelligent Cruise Control Field Operational Test (Final Report) Vol. III: Performance of a String or Cluster of ACC-Equipped Cars		5. Report Date June 1998	
		6. Performing Organization Code	
7. Author(s) S. Bogard, P. Fancher, R. Ervin, M. Hagan, Z. Bareket		8. Performing Organization Report No. UMTRI-98-28	
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, MI 48109-2150		10. Work Unit No. (TR AIS)	
		11. Contract or Grant No. DTNH22-95-H-07428	
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration U.S. Department of Transportation 400 7th Street S.W. Washington, D.C. 20590		13. Type of Report and Period Covered Final Report (Volume III) November 1997 to July 1998	
		14. Sponsoring Agency Code	
15. Supplementary Notes UMTRI's partners in the field operational test are Automotive Distance Control Systems (ADC) GmbH, Haugen Associates, and the Michigan Department of Transportation. The Volpe National Transportation Systems Center is to produce a separate report as the independent evaluator.			
16. Abstract <p>This report is one element of a cooperative agreement between NHTSA and UMTRI entitled Intelligent Cruise Control (ICC) Field Operational Test (FOT). It addresses the operation of a serial string or dense cluster of passenger cars equipped with a new automotive technology called adaptive cruise control (ACC). The string or cluster conditions are expected to arise commonly on public roadways in the future if ACC reaches high levels of penetration in the vehicle population. This report presents results derived from a very limited experimental study of string and cluster operations, as enabled by the availability of vehicles equipped with ACC systems after their use in an extensive field operational test (see volumes I and II of this report). The experiments involved a naturalistic traffic setting but a contrived procedure for inserting a dense grouping of ACC-equipped vehicles within the traffic stream. This work also served as a probing attempt to evaluate the impact of multiple ACC-equipped vehicles on such general issues as safety, traffic flow, and interference with unequipped vehicles. Conclusions from this activity pertain both to the issue of test methodology and to the long-term impacts of ACC on traffic operations.</p>			
17. Key Words Platoon, String, Cluster, Adaptive or Intelligent Cruise Control, Headway or Longitudinal Control, Crash Avoidance, ACC, ICC, Field Operational Test		18. Distribution Statement Unrestricted	
19. Security Classif. (of this report) None	20. Security Classif. (of this page) None	21. No. of Pages 31	22. Price

Table of Contents for Volume 3

RETURN TO VOLUME I

EXECUTIVE SUMMARY	1
1.0 BACKGROUND.....	3
2.0 DESCRIPTION OF THE VEHICLE OPERATIONS AND PROCEDURES	5
2.1 Longitudinal String Tests.....	5
2.2 Cluster Tests	6
3.0 OBSERVATIONS AND OBJECTIVE RESULTS FOR THE FOUR-VEHICLE STRING TESTS	7
3.1 Driver Observations	7
3.1.1 <i>Naturalistic occurrence of vehicle strings</i>	7
3.1.2 <i>Harmonic nature of FOT vehicles in a string</i>	7
3.1.3 <i>Effect of a four-vehicle string on other traffic</i>	8
3.2 Objective Results	8
4.0 OBSERVATIONS AND OBJECTIVE RESULTS FOR THE EIGHT-VEHICLE STRING TESTS	13
4.1 Two-Lane Interstate Highway.....	13
4.2 Driver Observations	13
4.2.1 <i>Formation concerns</i>	13
4.2.2 <i>Harmonic nature of FOT vehicles in a string</i>	14
4.2.3 <i>Effect of an eight-vehicle string on other traffic</i>	14
4.3 Three-Lane Interstate Highway.....	15
4.4 Driver Observations	15
4.4.1 <i>Formation concerns</i>	15
4.4.2 <i>Harmonic nature of FOT vehicles in a string</i>	15
4.4.3 <i>Effect of an eight-vehicle string on other traffic</i>	15
4.5 Objective Results	16
5.0 OBSERVATIONS AND OBJECTIVE RESULTS FOR THE EIGHT-VEHICLE CLUSTER TESTS	19
5.1 Driver Observations for Cluster Test 1	19
5.2 Objective Results	20
5.3 Driver Observations for Cluster Test 2	21
6.0 CONCLUSIONS	23
6.1 Test Methodology	23
6.2 Interactions between Multiple ACC Vehicles and Nearby Traffic	24
6.3 Future Test Possibilities	25
7.0 REFERENCES.....	27

RETURN TO VOLUME II

Executive Summary

This report addresses the operation of a serial string or dense cluster of passenger cars equipped with a new automotive technology called adaptive cruise control (ACC). The string or cluster conditions are expected to arise commonly on public roadways in the future if ACC reaches high levels of penetration in the vehicle population. The report presents results derived from a very limited experimental study of string and cluster operations, as enabled by the availability of vehicles equipped with ACC systems after their use in an extensive field operational test (FOT) [1]. This work also served as a probing attempt to evaluate the impact of multiple ACC-equipped vehicles on such general issues as safety, traffic flow, and interference with unequipped vehicles. As with other automotive-control technologies in the early design stages, these broad issues may serve to influence product design and public policy.

The ACC function enhances conventional cruise control by automatically adjusting the speed of the host vehicle so as to maintain a driver-specified headway time between the host and an impeding (target) vehicle. The technology's primary component is a sensor¹ mounted on the front of the host vehicle that measures the distance between it and the impeding vehicle. This basic range information and its derivative, range-rate, are used by a control algorithm to perform the task of maintaining headway. Currently, ACC is not an available automotive feature in the U.S., however, all the major automobile manufacturers are considering the technology, and at least one European automobile manufacturer plans to have it available in the U.S. within the next few years. ACC is already available as an option on Mitsubishi and Toyota vehicles sold in Japan.

This report first comments briefly on prior studies addressing ACC string performance and then presents a summary of the test procedures used here to roughly explore operational issues. Results are then presented, followed by conclusions and recommendations.

¹ In some applications, more than one sensor is used. Current generation sensors use either infrared or radar beams to detect objects in the path of the host vehicle. The sensors used in this study were of the infrared type.

1.0 Background

There has been considerable effort by traffic flow analysts to studying the dynamics of streams of vehicles [2]. For example, there are results showing the development of shock waves in such vehicle streams, as generated by disturbances. One general idea is that, once a disturbance is started, if trailing vehicles have sufficiently delayed responses to the motions of preceding vehicles, eventually some vehicle back in the stream will need to brake to a stop or change lanes to avoid hitting the rear of the preceding vehicle.

In considering the development of automated highway systems, researchers have recently examined requirements for assuring that the headway gap does not go to zero. Results from such analyses have helped to quantify impacts of string size and separation showing that highway capacity could be greatly increased by means of automatically controlled string operations.

In the course of such research the conditions for string stability have been rigorously described in mathematical terms by Swaroop and Hedrick [3]. Although the application of these rigorous results would show that the FOT cars employed here would not exhibit string stability, the lack of such a stability quality is readily demonstrated using conceptually simpler approaches. For example, direct simulation of the problem using MATLAB/SIMULINK to create a string of 25 vehicles has shown the influence of disturbance size on the gap-keeping capability of a hypothetical string of ACC-equipped vehicles [4]. Based upon practical reasoning (or examining simulation results), it is straightforward to see that if each successive vehicle closes beyond (i.e., undershoots) a desired headway gap when the preceding vehicle slows down, the minimum headway gap will get smaller and smaller as one examines each vehicle back into the stream. Eventually, a driver needs to intervene suddenly or there will be a crash.

In this study, it was clear before testing that a string of cars equipped with the elementary ACC system used in the FOT would not have string stability in general. Hence, the purpose of operating a string of FOT cars was not to demonstrate the stability property per se, but rather to expose the broad practical issues that attend ACC string operations in normal freeway traffic. An important distinction in this context is the case in which drivers are free to proceed as they see fit, coming in and out of proximity to other vehicles equipped with ACC.

2.0 Description of the Vehicle Operations and Procedures

The study involved operating eight ACC-equipped vehicles on limited access freeways. These vehicles were driven by researchers having considerable experience in driving ACC systems in traffic on real roads. The reader is advised to consult reference [1] to obtain a technical description of the ACC system, itself, and of the data acquisition system by which vehicle responses and driver control input data were recorded.

Three distinct types of tests were performed with the FOT vehicles. These tests were performed on highways in southeast Michigan during a weekday at approximately mid-morning when traffic density is moderate to light and travel is at or near posted speed limits. The road surface for all tests was dry. Drivers were given simple instructions for each test scenario (detailed below) and were asked to drive in a safe, normal manner within the boundaries of the test and to continue the test only if there was no increased threat of an accident.

2.1 Longitudinal String Tests

The first procedure in this series of tests is best described as a longitudinal performance and traffic conflict test. In this scenario, the test vehicles formed strings of four or eight successive ACC cars in a string or platoon on a two-lane limited access-highway². The eight-vehicle test was also performed on a three-lane highway of which approximately half the travel distance was designated as an express-configuration freeway, with no access ramps.

The primary purposes of operating the four-car strings was to evaluate a) how difficult the string is to maintain and b) to collect objective data on the longitudinal performance of the ACC-vehicles in this configuration (i.e., evaluate how longitudinal disturbances will affect the string.).

The purpose of the eight-vehicle string was to a) investigate a more exaggerated case than that posed by a four-vehicle stream on the same road type under similar traffic speeds and densities; b) evaluate how difficult the string is to maintain; c) make observations about its effect on the surrounding traffic; d) evaluate the likelihood of the

² The term platoon in this context is used to describe a line of vehicles travelling in series behind one another at headway times of 1.0 to 2.0 seconds.

formation of an eight-car string; and e) to collect objective data on the longitudinal performance of the ACC-vehicles in this configuration.

Additionally, the eight-vehicle test was performed on a three-lane highway to a) discover differences in ACC string operations that arise on multi-lane versus two-lane freeway segments; b) investigate if the presence of many tight headway controllers, in the lane adjacent to the right-most lane, might impede the cross-lane movements of vehicles intending to enter or exit the freeway; and c) investigate the effect of a 1.0 and 1.4-second headway time on the cross-lane movement of vehicles intending to enter or exit the freeway.

2.2 Cluster Tests

Two tests were conducted to explore issues arising from the presence of multiple ACC-equipped vehicles that might appear in a cluster when traveling near each other (and, in some cases, passing each other) on a two-lane highway. In these tests the drivers were given specific set-speed and headway-time assignments and were instructed to simply engage the ACC-system and drive as they would normally toward the destination point. The purposes of these tests were to: a) experience ACC driving in which a substantial percentage of ACC-equipped vehicles appeared in the traffic stream without the anomalies introduced by deliberate string-formation instructions as had been followed in other tests; b) see if ACC cars might tend to form a spontaneous string; and c) determine if the presence of a cluster of ACC vehicles in a confined group disrupted the traffic stream in some way.

3.0 Observations and Objective Results for the Four-Vehicle String Tests

The first test scenario consisted of a string of four ACC-equipped vehicles traveling on a two lane, class-1 interstate highway. The test was conducted two times by two groups of four vehicles. The distance traveled for each test was approximately 12 miles. The drivers were instructed to stay in the same order for the duration of each test and make a reasonable effort to maintain an uninterrupted series of four ACC-equipped vehicles. Each set of four vehicles performed the test using a set-speed value of 111 ft/sec (76 mph). With the exception of the lead vehicle, the drivers were instructed to use a headway time setting of 1.0 and 1.4 seconds for the two tests, respectively. The driver of the lead vehicle was instructed to vary speeds during the test (thus providing some longitudinal disturbance in the string) either by using the cruise control coast and acceleration buttons or by following slower-moving, non-ACC vehicles.

3.1 Driver Observations

Following the test the drivers were asked to record their observations. In general, observations fell into three categories, that is ease of string formation, harmonic nature of the string, and effect of the string on traffic. A summary of these observations follows.

3.1.1 Naturalistic occurrence of vehicle strings

Most drivers felt that driving in a four-vehicle string was tolerable but not completely natural. It took a conscious effort on each driver's part to maintain a deliberate string formation in real traffic.

3.1.2 Harmonic nature of FOT vehicles in a string

During most of the test, drivers observed that the control algorithm and deceleration authority of the FOT vehicles was sufficient to handle the speed changes of the lead vehicle. This was particularly true when these changes were within the normal range of acceleration and deceleration encountered during typical highway driving. (The driver of the lead car generally used the coast and acceleration buttons to change speed, which meant that the lead vehicle's level of acceleration and deceleration were within the control authority of the ACC system.) Drivers reported events (also verified in the electronic data collected on each vehicle) in which the ACC controller implemented a

transmission downshift to increase the level of deceleration.³ In general, the longitudinal string showed fully stable responses in the sense that the control authority of the vehicles could handle routine disturbances by the first car in the string without causing the driver to intervene by either disengaging the ACC or changing lanes.

3.1.3 Effect of a four-vehicle string on other traffic

On a two-lane freeway, much of the experience depends upon the choice of lane in which to form the string. If formed in the left-most, or high-speed lane, the string presents an unusual traffic impediment unless it is travelling at a speed that tends to satisfy the passing intentions of other motorists using that lane. If the string forms in the right-most, low-speed lane, the string becomes disrupted when encountering distinctly slower vehicles. If such vehicles must be passed, the string must proceed toward the left and then recover the right lane again. That is, the process of moving a string of vehicles through a passing and re-forming maneuver encounters the conundrum of a) impeding left-lane traffic while proceeding at a pace determined by the set-speed of the lead vehicle in the string and b) having difficulty forming again in the same order in the right lane if, upon recovery of the lane by the first few vehicles, other vehicles in the right lane move forward and close up the tail end of the string segment, leaving the remainder unable to resume position in the string. In the process of encountering conflict (b) the remaining string members must linger in the left lane, assuming the totally unnatural posture, of waiting for the adjacent spaces in the right lane to open up (precisely adjacent to their assigned spaces in the string). The response of motorists expecting to move ahead in the passing lane reveals their frustration with the decidedly odd behavior that is manifest ahead of them.

3.2 Objective Results

A subset of the objective results for the four-vehicle string tests are shown in figures 1 through 3 below. These data present a case in which the drivers needed to intervene because of the amplitude of the speed change. Figure 1 shows the velocity of the four vehicles during and after a disturbance introduced by the first car in the string. (The 1.4-second headway-time value was selected during this test.) Figure 2 shows the

³ Throttle-off deceleration at highway speed on a zero grade road is about 0.03g for the FOT vehicles. A transmission downshift from overdrive to third gear increases the deceleration level to approximately - 0.06 g.

corresponding range values for the following vehicles, and figure 3 shows a range, range-rate phase diagram for the same time segment.

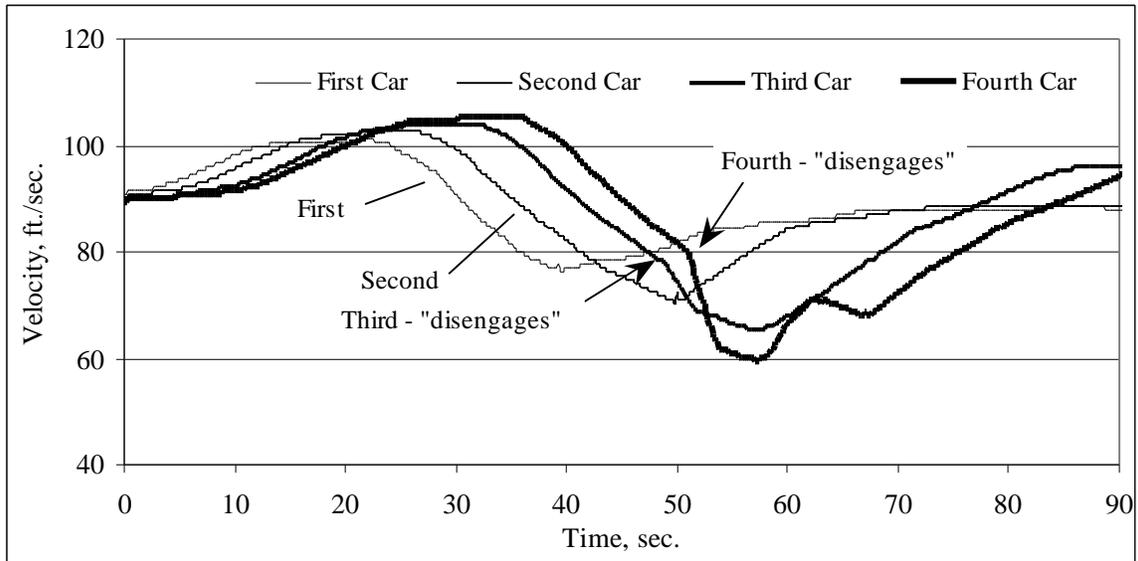


Figure 1. Velocity time history of four FOT vehicles in a string following a longitudinal disturbance

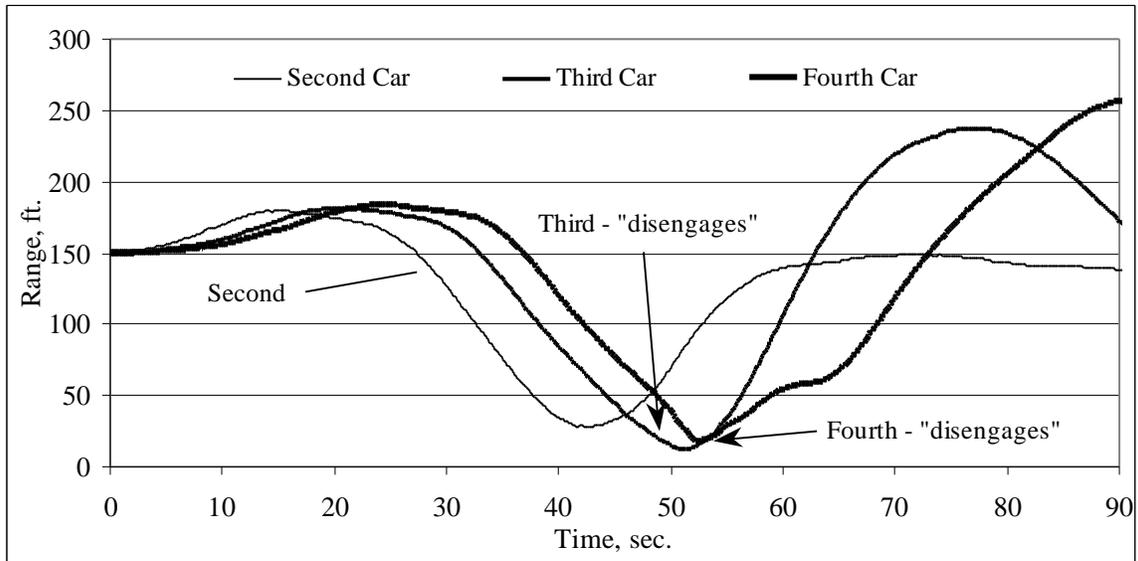


Figure 2. Range time history of three FOT vehicles in a string with a longitudinal disturbance

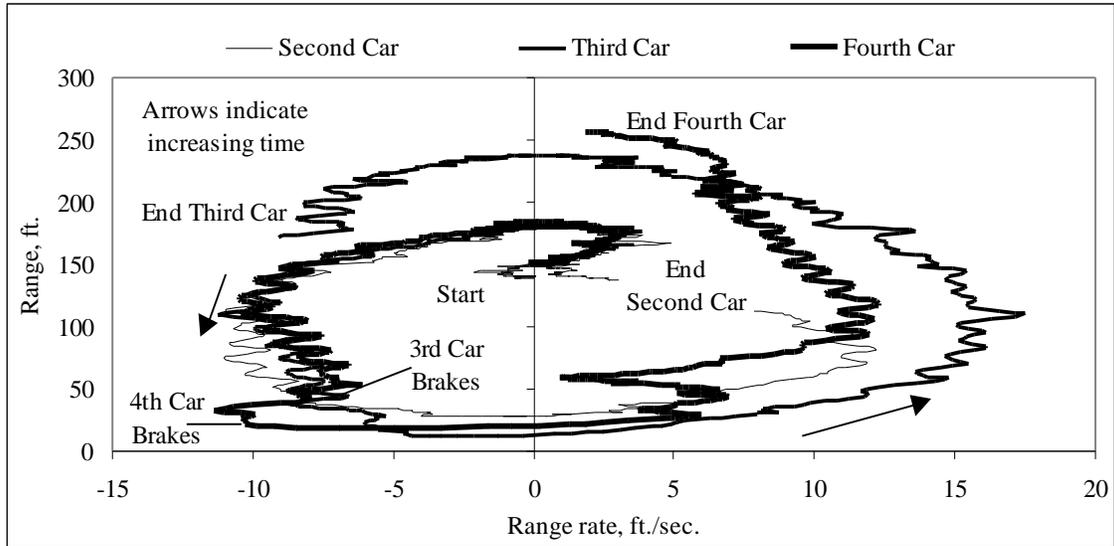


Figure 3. Range versus range-rate of three FOT vehicles in a string during a longitudinal disturbance

The disturbance consisted of a sinusoidal-like velocity change from an initial value of approximately 90 ft/sec. The lead vehicle reaches a maximum of 101 ft/sec and a minimum of 76 ft/sec in a total period of 60 seconds for the entire maneuver. (The maximum and minimum values corresponding to the response in figures 1 to 3 are shown in table 1.)

Table 1. Maximum and minimum values of velocity, range, and range-rate for a four-car string during a longitudinal disturbance

	First Car	Second Car	Third Car	Fourth Car
	Velocity, ft/sec			
Maximum	101.16	102.62	104.07	105.53
Minimum	76.19	70.35	65.25	59.33
	Range, ft			
Maximum	N/A	179.79	237.86	257.54
Minimum	N/A	28.21	12.46	18.70
	Range-rate, ft/sec			
Maximum	N/A	12.21	17.49	12.30
Minimum	N/A	-11.02	-11.20	-11.39

During the deceleration portion of this maneuver, from time = 20 to time = 40 seconds, the lead vehicle has an average deceleration of 0.04 gs. The responses of the other vehicles in the string are also shown in the figure. In this test, only the second car in the string has enough control authority to “handle” the disturbance of the first car without

driver intervention. The response of the second car shows that the vehicle does overshoot the velocity profile of the first vehicle and in this case the second vehicle reaches a maximum of 102 ft/sec and minimum of 70 ft/sec over a time span of 25 seconds. This represents an overall increase of 28 percent in velocity and a 25 percent increase in time to reach the extreme velocity values relative to the corresponding changes in the first car.

Of course, since the response of the second car constitutes the input for the third vehicle, we see further exaggerations in responses, with the third car reaching a maximum velocity of 104 ft/sec before beginning to decelerate. At a time of 50 seconds the driver of the third car is forced to intervene and use the service brakes to avoid a rear-end collision with car number two. Figure 2 shows the range as measured by the sensors of cars two, three and four during this disturbance. For car three, the figure shows a range of approximately 20 feet at the time of disengagement.

A similar scenario applies to the fourth vehicle of the string. This vehicle responds to the exaggerated changes of the third car, exhibiting an even greater overshoot early in its response and a driver intervention when range and range-rate reach uncomfortable levels. (The data show a range of 30 ft and a range-rate of -9 ft/sec when the driver applied the brakes in car four. The driver of car four applied the brakes 2.0 seconds after the commencement of braking by the driver of car three.)

Figure 3 below shows the range versus range-rate histories for cars two, three and four in response to this disturbance. The traces show the characteristic circular shape of response with large changes in range and range-rate. Because time is not shown in the plot, the start and end of the disturbance are indicated in the plot. (Time always progresses in a counter clockwise fashion in range range-rate diagrams.) During the initial segment of the maneuver, the vehicles are separating such that their range and range-rate values increase. This is shown in the figure as a small half circle starting at approximately 150 ft and zero range-rate and continues until the next zero range-rate value at a range of approximately 175 ft. At this point the vehicles have started to close on each other (crossing over to the negative range-rate side of the diagram) and, generally they tend to travel the same path in the range range-rate space until close range values are encountered. At this point, a clear deviation toward larger negative range-rate values is shown for the fourth car. This dramatic change is due to braking by the third car. Large changes in range-rate without a substantial change in range can only be achieved by large relative velocity changes between two vehicles over a short period of time. Such a relationship is reflected in the plot by the large horizontal change in the trace for the fourth car, caused when the driver of that vehicle reached a 0.2 g-peak deceleration level.

4.0 Observations and Objective Results for the Eight-Vehicle String Tests

The eight-vehicle string tests were conducted on two-lane and multi lane interstate highway segments. Observations and objective results for these tests are discussed in the two sections below.

4.1 Two-Lane Interstate Highway

The first eight-vehicle scenario consisted of a string of ACC-equipped vehicles traveling on a two-lane freeway. As in the four-vehicle scenario described above, this test was also conducted during the daytime when the road surface was dry. Traffic levels could be described as medium density. The drivers were all instructed to use a set-speed value of 76 mph. In the first half of the 30-mile test, drivers used a 1.4-second headway time. For the second half of the test, drivers used a 1.0-second headway time. As before, drivers were instructed to make a best effort to maintain an uninterrupted string of ACC-equipped vehicles.

4.2 Driver Observations

Following the test, drivers were asked to record their observations. The observations fell into three categories, that is ease of string formation, harmonic nature of the string, and effect of the string on traffic.

4.2.1 Formation concerns

The task of following specific cars in a specific order became exceedingly difficult as the string got longer. Clearly the anomaly of following in an intentional order has virtually no relevance to any plausible routine driving scenario. The experience of proceeding through even moderate traffic as an eight-element string offers another odd case by which to observe that the behavior of drivers in traffic involves highly developed sociological expectations. In addition, the intentional-order-following string, per se, constitutes an oddity that violates many of those expectancies. The condition of steady-state with eight vehicles was probably never achieved on this road type. At a headway time of 1.4 seconds, the tendency for headway instability can be better absorbed, but other cars and trucks constantly interfere with the retention of the integral string of vehicles. At a uniform headway time of 1.0 sec, less interference is encountered but the string is rendered unstable merely by delays, grades, etc (no artificial disturbance had to be introduced to destabilize the string).

4.2.2 Harmonic nature of FOT vehicles in a string

Rearmost vehicles had large range and velocity changes in response to longitudinal disturbances initiated at the front of the string and the condition of steady-state with eight vehicles was probably never achieved on this road type. Cars at the rear of the string experienced continuous oscillations that is, strong acceleration followed by the need for manual brake interventions during this test condition.

4.2.3 Effect of an eight-vehicle string on other traffic

The deliberate retention of an eight-vehicle string seemed to annoy the truck drivers tremendously. When the string occupied the right lane one practicable issue that was observed, is the problem presented to tractor semitrailers, whose overall length is around 60 to 100 feet. When using a one-second headway time, the gap between ACC-vehicles is only 90 to 100 feet at normal highway speeds, thus posing a small gap that impedes the truck driver's attempts to resume the normal right-lane position after they have once taken a position in the left lane. Further drama would be added to this case, though it was not actually observed if the driver of a long truck simply needed to recover a spot in the right lane in anticipation of an upcoming exit. The simple observation is that spacing between vehicles in normal traffic is rather randomized—perhaps in part because the individual driver is not highly skilled as a headway controller. Thus, a substantial distribution of spacing exists in the normal traffic stream, presumably offering long trucks and others concerned about lane changing ample opportunities for their desired lateral movements.

An additional concern with heavy vehicles is raised by their low levels of acceleration and deceleration capability relative to that of passenger vehicles. When heavy vehicles need to interact with an eight-car string, which could be about 1000 feet long, substantial traffic delays can result. In a two-lane setting, if a truck driver decides to pass a string of vehicles, it takes time to make this maneuver and can result in a queue of traffic behind the truck.

As for the influence of ACC headway time on the sensitivity of other traffic to string operations, it was clear that many more cut-ins and pass-throughs of passenger vehicles occurred on the two-lane freeway, without any disrupting outcomes, when the string was operated at a common value of 1.4-second headway time.

4.3 Three-Lane Interstate Highway

This scenario consisted of a string of eight ACC-equipped vehicles traveling in the center lane of a three-lane freeway, half of whose length incorporated no access ramps at all (i.e., an “express” segment of urban freeway). For this test, the set speed was not constant for each driver but was made dependent on each vehicle’s position within the string so as to ensure that any string gap, once opened, would be quickly reclosed, thereby keeping the string intact. The first vehicle used a set speed of 68 mph and each subsequent vehicle was assigned to increment the preceding vehicle’s set speed by 2 mph. (Thus, the last vehicle had a set speed of 82 mph.) For the first half of the 30-mile test, drivers were instructed to use a 1.4-second headway-time selection. During the second half of the test, drivers were instructed to use the 1.0-second headway-time selection.

4.4 Driver Observations

Following the test, the drivers were asked to record their observations, as before, to address the ease of string formation, harmonic nature of the string, and effect of the string on the surrounding traffic.

4.4.1 Formation concerns

Efforts at string formation were more successful on a three-lane highway due to less interference (and less traffic congestion) with other vehicles cutting into the string.

4.4.2 Harmonic nature of FOT vehicles in a string

Because there was less interference from other vehicles, the string was able to stay in formation and in a steady-state condition much longer than in the two-lane test. However, when there was a disturbance or destabilizing pulse caused by the first vehicle, it did propagate down the string and caused the rearmost vehicles to slow down very significantly (to the point of driver intervention via braking). The most severe transients arose when a significant braking was imposed at the first vehicle.

4.4.3 Effect of an eight-vehicle string on other traffic

The experiment indicated that an ACC string running in the middle lane at uniform values of 1.4-second headway time, posed virtually no cross-lane impediment. (It should be cautioned, however, that very few tractor semitrailers were present in this traffic stream.) Even with 1.4-second headway time, however, the weaving movement of other cars traversing the string lane either toward the right or toward the left is common. (Please note, the term weaving will be used here in the traffic engineering sense by which

freeway drivers succeed in changing lanes over relatively short lengths of roadway as part of the entry/exiting process and the transitions thereto, as discussed for example in [1].) When a 1.0-second headway time was used, it was clear that the string constituted a significant impediment to traffic that intended cross-lane movement and that only rather aggressive drivers were still able to change lanes by penetrating the string. It was also observed that distinctly higher lateral-velocity cut-ins were apparent when drivers did cut through the string under these conditions. A number of these lateral-cross-lane maneuvers went all the way through the center lane in a single maneuver with no discernible pausing to check the left-side destination lane. Other more cautious drivers were seen to travel along next to the string for substantial distances after having merged on the freeway. They were seen to travel along in the right lane, making hesitant moves toward the center lane, and then retreating to wait a while longer, while apparently seeking a suitable gap for access to the left-most lane. Such behavior should be expected by the large majority of traffic that seeks to occupy higher-speed lanes, after merging onto the roadway, thereby avoiding the conflicts that recur in the right lane due to entering and exiting traffic. It is hypothesized that the cross-lane impediments, posed by ACC strings, such as observed here, would tend to maximize in medium-density traffic having a substantial number of trucks occupying the right lane and in areas for which high entry and exit flows are prevalent.

4.5 Objective Results

A subset of the objective results for the eight-vehicle string tests are shown in figures 4 and 5. Figure 4 shows the velocity of the eight vehicles during and after a disturbance by the first car in the string. (The 1.0-second headway time value was selected during this test.) Figure 5 shows the corresponding range values for the following vehicles. For this set of results the drivers were able to stay in an uninterrupted string (with no intervention necessary) throughout the entire disturbance transient.

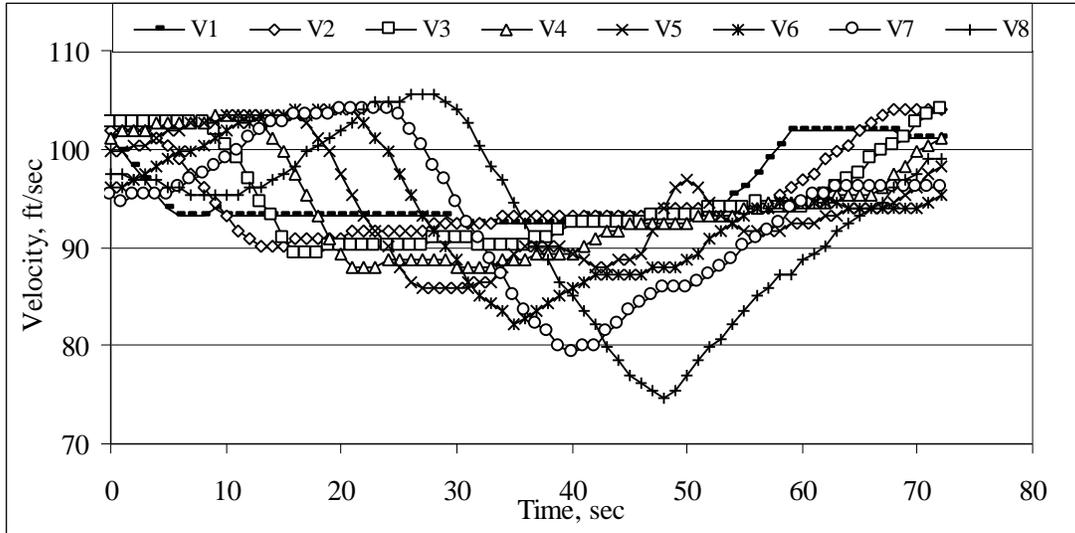


Figure 4. Velocity time history of eight FOT vehicles in a string with a longitudinal disturbance

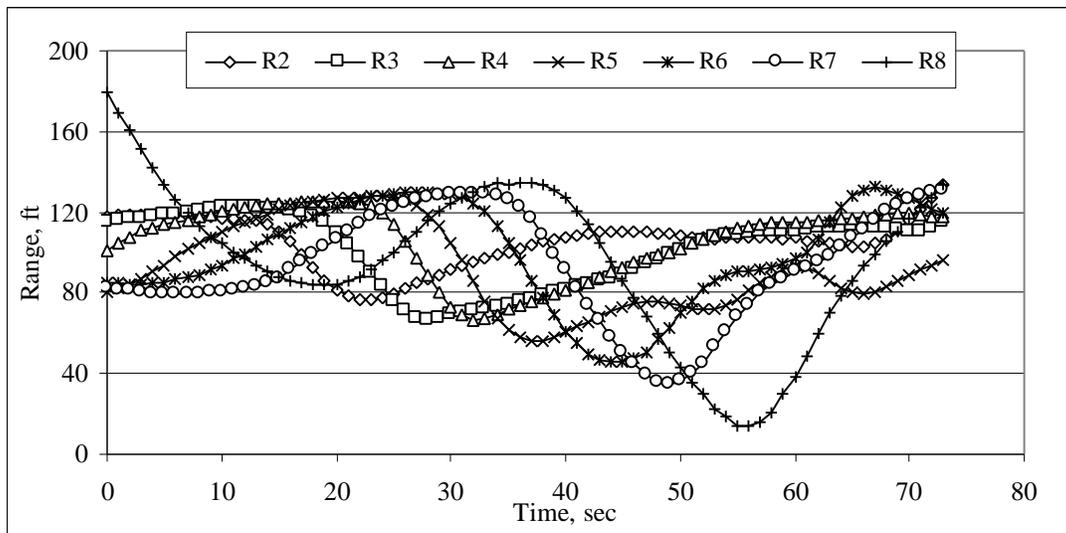


Figure 5. Range time history of seven FOT vehicles in a string, following a longitudinal disturbance

The lead vehicle disturbance for these results was a simple downward ramp/step in speed from 100 ft/sec to 93 ft/sec (a change of 5 mph) over a time of 8 seconds. The response of the other vehicles in the string is shown in the figure. Figure 4 clearly reveals the lag in response of each vehicle in the string. The effect of driving in a string with this ACC system is a more severe response by each successive vehicle as the overshoot propagates down the string. Table 2 shows the maximum and minimum values for

velocity, range and range-rate during this response sequence. For velocity, the minimum values range from 90 ft/sec in the second car to 75 ft/sec in the last car.

Table 2. Maximum and minimum values of velocity, range, and range-rate for a eight-car string during a longitudinal disturbance

	1st Car	2nd Car	3rd Car	4th Car	5th Car	6th Car	7th Car	8th Car
Velocity, ft/sec								
Maximum	101.9	104.1	104.1	103.3	103.3	104.1	104.1	105.5
Minimum	92.3	90.1	89.4	87.9	85.8	82.1	79.2	74.7
Range, ft								
Maximum	N/A	133.2	122.7	125.7	127.6	132.5	130.6	130.8
Minimum	N/A	76.4	66.6	66.6	56.4	45.9	34.8	13.8
Range-rate, ft/sec								
Maximum	N/A	5.6	2.6	3.4	4.2	8.2	8.4	9.8
Minimum	N/A	-7.1	-7.4	-9.2	-9.9	-9.5	-9.1	-12.8

Figure 5 shows the range values for the second through eighth car. These results are similar in shape and lag characteristics to those of velocity with the exception of more extreme values being reached by the rear most vehicles. Table 2 shows the minimum range going from 76 ft for the second car down to 14 ft for the last car. In the case of the eighth car, approximately 90 percent of the available headway range was used before it begins to separate from the seventh car.

5.0 Observations and Objective Results for the Eight-vehicle Cluster Tests

Two tests were conducted to see if the presence of multiple ACC-equipped vehicles would tend to form a cluster when traveling near each other on a two-lane suburban freeway. In both tests, the vehicles entered the highway at 5-second intervals and the drivers were instructed to simply engaged the ACC-system and drive as they would normally toward the destination point. Successive vehicles were dispatched at modestly incremented values of set speed, as shown in table 3. In the second test, all drivers used a set speed of 74 mph and a headway time of 1.4 seconds.

Table 3 Order, Set Speed, and Headway Time for Cluster Test 1

Highway Entry No.	Car Number	Set Speed, mph	Headway Time, sec
1	0	66	2.0
2	9	68	1.0
3	2	70	1.0
4	8	72	1.4
5	3	74	1.4
6	5	74	1.4
7	1	74	1.0
8	4	74	1.0

Following the test, the drivers were asked to record their observations, as discussed below.

5.1 Driver Observations for Cluster Test 1

The free-flowing cluster approach resulted in a concentration of the eight FOT vehicles within a group of approximately 20 vehicles during one segment of the trip. For this approximate 40 percent concentration of ACC cars (running at a 1.4-second headway) no discernible consequences were observed in terms of the freedom of other vehicles to proceed. The traffic during this leg was light. In some cases, the ACC equipped vehicles did follow each other, but when the road was clear, they did not get close enough to react to each other. Also, if one car got caught behind some slower traffic, other ACC cars

would just pass by rather than follow. For the most part, the cars with the higher set speeds simply passed the cars with the lower set speeds.

5.2 Objective Results

Objective results from the cluster test with initial conditions as described in table 3 are shown in figures 6 and 7. Figure 6 shows the relative distance between the eight vehicles as they traveled approximately 12 miles on a two-lane highway. The figure shows time along the abscissa and relative distance in feet along the ordinate axis. Car 1 is used as the zero-baseline for the results shown in figure 6. The figure shows that all vehicles started out “behind” the baseline vehicle. This negative gap increases during the first part of the test but as the rear most vehicles (i.e., those with higher set-speeds) enter the highway, they begin to close on the baseline vehicle and pass each other. At approximately 5.5 minutes into the test all but two of the eight vehicles have passed the baseline. The last vehicle, Car 8, passes the baseline between 7 and 7.5 minutes into the test. Overall, the figure does not suggest that the vehicles had a tendency to naturally cluster (except into two-car pairs such as vehicles numbered 1 and 2) and these results along with the driver’s comments suggest that multiple-ACC vehicles did not impede each other under these driving conditions.

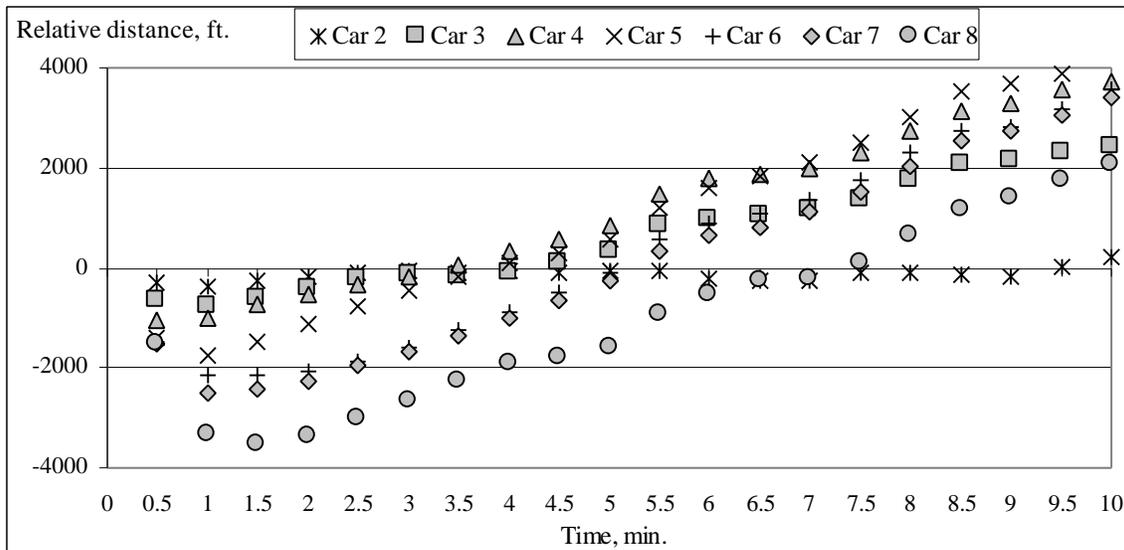


Figure 6. Relative distance during cluster test (Car 1 is baseline)

Figure 7 is a global position satellite (GPS) map of the route driven under the conditions outlined in table 3. (Note: Car 2 is missing from this list due to problems with

its GPS.) The figure reveals the nominal extent of clustering which did prevail, as expressed by the location and position of each vehicle at different snapshots taken each minute during the test.

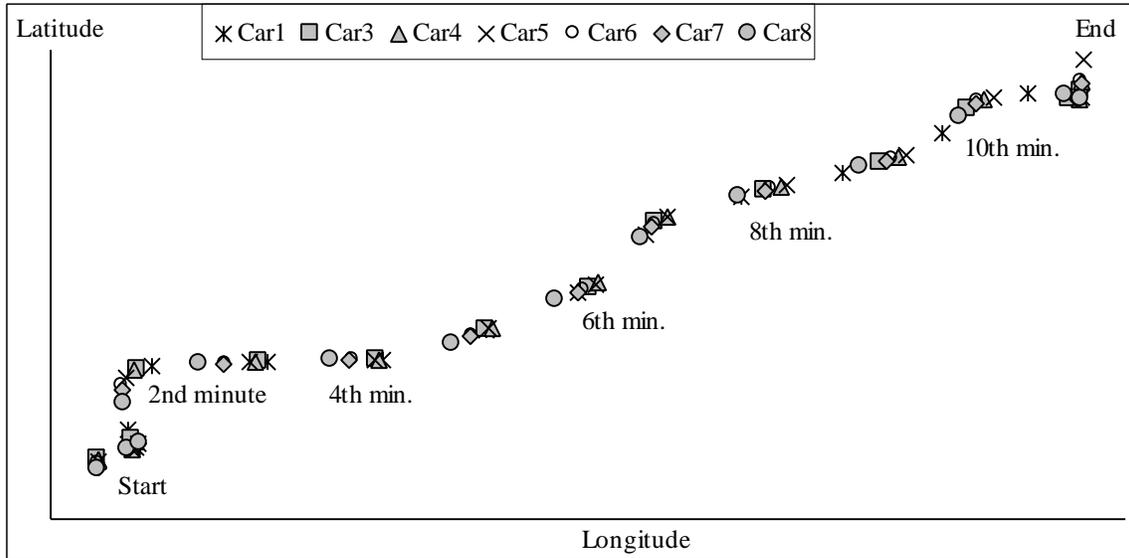


Figure 7. GPS map of FOT vehicles during cluster test

5.3 Driver Observations for Cluster Test 2

The second cluster test received a mixed response from drivers regarding the presence of cluster formation. Some of the drivers were able to avoid all impeding vehicles during the test and hence simply passed other vehicles (including FOT vehicles) that were travelling more slowly. However, when impeded by other vehicles some test drivers did report some clustering of the FOT. Nevertheless, it appears that any clustering occurred by driver choice rather than by necessity. This test implies that, for short urban distances, short strings might spontaneously occur from time to time and that during inter city trips, longer strings could occur, depending on the occurrence of vehicles having similar set speeds and depending on the degree of interference from other traffic, such as slower moving trucks.

6.0 Conclusions

The experiments conducted here involved a naturalistic traffic setting but a contrived procedure for inserting a dense grouping of ACC-equipped vehicles within the traffic stream. Conclusions from this activity pertain both to the issue of test methodology and to the long-term impacts of ACC on traffic operations.

6.1 Test Methodology

The principal research difficulties that arise when a group of confederated ACC drivers deliberately form an ACC string in traffic are the following: 1) merging and lane-changing movements of other vehicles tend to break up the string, 2) string-member drivers must occasionally undertake odd tactics to reposition themselves into strings that had become lost due to breakage, and 3) other drivers readily note the odd tactics of the string members and appear to become rather distracted by them. The outcome of these problems is that test productivity is low and questions of test validity arise from the “oddness” of the string-maintenance contrivance in a public traffic stream. On the latter point, it becomes difficult to discern which of the measured results is an artifact induced by the deliberately-intended formation and maintenance of the string and which is a true interaction such as would prevail in the future when ACC strings might form spontaneously.

A fully valid means of studying the interaction between multiple, proximate, ACC-equipped vehicles and other traffic would seem to require that ACC vehicles actually comprise a high fraction of the vehicle population in normal usage. If this were cultivated to occur, say through a massive localized field test, or if we simply waited until ACC had so penetrated the vehicle market that a high-population fraction had accrued over many years of ACC sales, the interactions between conventional traffic and naturally occurring strings or clusters of ACC-equipped vehicles could be observed directly. The limited results of the exercise described here suggest that fully instructive measurements will be very difficult to obtain, otherwise. Nevertheless, episodes of steady-state string operation do occur, even when the string is deliberately formed by confederate researchers. During these periods, certain apparently valid phenomena do manifest themselves.

6.2 Interactions between Multiple ACC Vehicles and Nearby Traffic

As implied above, it is assumed that high levels of ACC penetration into the vehicle population will cause extended strings of ACC-equipped vehicles to form spontaneously simply due to the probabilities of traffic mixing—even in the absence of any peculiar natural tendencies toward aggregation of vehicles under ACC control. Thus, the dynamic stability of ACC strings and their impact on the natural inter lane weaving movements of other traffic will constitute real issues if ACC becomes a successful product.

Observations from these tests have indicated that significant traffic impacts could arise from ACC strings. Firstly, considering simply the ACC system that was fielded here, (with its low deceleration authority and relatively sluggish re-acceleration response) a string of more than four of these vehicles will exhibit marginal stability levels, yielding exaggerated responses when longitudinally disturbed from the forward end of the string. With strings of eight vehicles equipped with this ACC controller, significant disruptions in the smooth movement of a traffic stream would ensue following modest disturbances.

Further to the string-stability issue, the authors of this report are not aware that this characteristic is being considered in the current design of automotive ACC products. In fact, an opposite approach has been apparent by which ACC control algorithms are “detuned” in some emerging products to render the controller unresponsive to brief misdetections by the range sensor. While string-stability problems would not manifest themselves as long as ACC-equipped vehicles are a rarity on the road, the issue will become highly important whenever the population density begins to precipitate long-string formation on a regular basis.

On the matter of cross-lane movements of other traffic, an important issue arises when an ACC string constitutes a sort of “moving wall” that impedes the natural weaving movement of other traffic. That is, due to ACC’s regularization of headway spacing, randomly extended gaps do not occur in the same manner as seen in manually-controlled traffic. Further, the ACC controller does not, by itself, respond to the “body language” of other drivers who maneuver alongside, in an adjacent lane, with the clear intention of weaving across into another destination lane. When headway time is in the vicinity of 1.0 second, at highway speed, it was seen that other motorists were basically thwarted in their attempts to change lanes through an eight-car string that occupied the next-to-right-most lane—occasionally exhibiting a fairly dramatic rate of penetrating the string in their apparent frustration to find a fully suitable gap in line with their exit/entrance transition

plans. (Note that, upon entering a freeway, some more aggressive drivers seek to occupy the “fast,” left-most lane as soon as possible—thus experiencing some frustration when they remain “stuck” in the rightmost lane while searching for a suitable gap.) When ACC headway times were uniformly set to 1.5 seconds, other drivers appeared to penetrate the string with minimal difficulty.

The string-penetration problem was seen to be most pronounced in the case of combination trucks whose great overall length made the gap-mismatch issue acute. Recognizing that many states legally require that heavy trucks use the right lane except when passing, the ability to readily recover the right-most lane position is fundamental to normal truck operations. Clearly, if an ACC string occupies the right lane, the ACC drivers simply must intervene upon the automatic-headway mode of control in order to create a suitable space for lane recovery by trucks. The readiness of ACC drivers to provide this courtesy, and indeed to recognize the need for it as a nuance of ACC control, has not been studied here.

When multiple-ACC vehicles appeared nearby one another in a noncontiguous, clustering type of distribution, no operational difficulties were noted. Even with a 40% density of ACC-equipped vehicles in a cluster of manually driven vehicles (but with no more than three ACC vehicles positioned in a continuous string at any one time) no disturbance of normal traffic movements was noted.

6.3 Future Test Possibilities

Alternative testing conditions that would extend the results presented here are listed below:

- Eight-car string of vehicles equipped with updated ACC systems (higher resume accelerations) and more deceleration authority through the use of the foundation brakes.
- String operation at closer headway (less than a second) to understand safety implications
- String operation in the presence of dense commuter traffic to study the extent of longitudinal disturbance responses on the localized movement of near-capacity traffic.
- String operation at longer headway (2 seconds) to better understand cut-in implications.
- Longer test-drives, one hour or more, to represent inter-city operations; including nighttime operations. Start out in a string with equal V_{set} (set speed) and T_h (headway time) values. See if drivers stay in a string and like it or would rather operate independently.

References

1. Fancher, P., Ervin, R., Sayer, J., Hagan, M., Bogard, S., Bareket, Z., Mefford, M., and Haugen, J. 1998. "Intelligent Cruise Control Field Operational Test. Final Report." University of Michigan, Ann Arbor, Transportation Research Institute, UMTRI-98-17. DOT HS-808-849 (Volumes I and II of this report).
2. Papageorgiou, M. and Ioannou, P. June 1993. "Traffic Flow Modeling and Control and Intelligent Highway Systems (IVHS)." Short course notes, SSC Systems, Los Angeles.
3. Swaroop, D., and Hedrick, J.K. 1994. "Direct Adaptive Longitudinal Control of Vehicle Platoons." IEEE Conference on Decision and Control. Proceedings. Vol. 1., IEEE Service center, Piscataway, NJ, pp. 684-689.
4. Fancher, P.S., and Bareket, Z. 1994. "The Influence of intelligent cruise control systems on traffic flow." International Symposium on Advanced Vehicle Control 1994. Proceedings. Tokyo, Society of Automotive Engineers of Japan, pp. 402-407. SAE 9438600.
5. "A Policy on Geometric Design of Highways and Streets." 1984. American Association of State Highway and Transportation Officials, Washington, D.C.

DOT HS 808 849
July 1998