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The Driver's Response to an Automated Highway System with Reduced Capability

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report presents the results of one in a series of experiments that investigated driver performance in a generic Automated Highway System (AHS) configuration. The experimental research was conducted in an advanced driving simulator, and it examined how well drivers could take over a function(s)—steering alone, speed control alone, or both—from the AHS when it was no longer able to perform that function(s). Drivers were given back control of their vehicles just as the vehicles were entering a curve, and most of the reduced AHS capability segment was on the curve. The major finding was that when drivers controlled steering (alone or with speed control), on average,they drifted near to the edge of the lane, with the right edge of their vehicle ending up either 0.39 m (1.42 ft) when they controlled only steering, or 0.10 m (0.45 ft) when they controlled steering and speed, from the edge of the 3.7-m- (12-ft-) wide lane. With narrower lanes, which have been proposed for the AHS to make the most efficient use of the available real estate, there is a risk that drivers will not be able to stay in their lanes if they must take back control of steering under the conditions of this experiment. This report will be of interest to engineers and researchers involved in Intelligent Transportation Systems and other advanced highway systems.

Sufficient copies of the report are being distributed to provide a minimum of two copies to each FHWA regional and division office and five copies to each State Highway agency. Direct distribution is being made to division offices.

A. George Ostensen, Director
Office of Safety and Traffic Operations
Research and Development

NOTICE

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16. Abstract

This experiment, one in a series exploring human factors issues related to the Automated Highway System (AHS), investigated the ability of the driver to deal with reduced capability in an automated highway. Most of the reduced AHS capability segment was on a 735-m (2410-ft) radius curve that veered left. The experiment was conducted in the Iowa Driving Simulator. It used a generic AHS configuration in which the left lane was reserved for automated vehicles, while unautomated vehicles traveled in the center and right lanes. The center lane was not a dedicated transition lane. There were no barriers between the automated and unautomated lanes. Sixty drivers participated in the experiment—half were male, half were female; half were between 25 and 34 years of age, half were age 65 or older. A comparison was made of driving performance when steering was controlled by the AHS (and velocity by the driver), when steering was controlled by the driver (and velocity by the AHS), and when both steering and velocity were controlled by the driver.

Results. (1) Lane-Keeping Performance and Reduced AHS Capability. In the reduced-capability segment, when the driver controlled the steering—whether controlling steering alone or both steering and velocity—the drift across the lane was four times greater, and in a different direction, than when the steering was controlled by the AHS. As the vehicle traveled around the curve, it drifted only 0.16 m (0.51 ft) to the left when controlled by the AHS. In contrast, it drifted laterally 0.66 m (2.17 ft) to the right when the driver controlled the steering alone, and 0.77 m (2.52 ft) when the driver controlled both the velocity and the steering. When it reached the end of the curve, the vehicle had overshot the center of the lane by 0.56 m (1.83 ft) and 0.86 m (2.81 ft), respectively, under these two conditions. Also, there was more steering instability when the steering was controlled by the driver. (2) Lane-Keeping Performance and Designated AHS Velocity. Whether the AHS or driver was controlling the steering, the vehicle was harder to steer when the designated AHS velocity was 153.0 km/h (95 mi/h) than when it was 128.8 km/h (80 mi/h)—both the steering drift and the steering instability increased substantially with velocity. (3) Velocity Control and Reduced AHS Capability. The time delay was zero when the AHS controlled velocity (and the driver was steering). When the driver controlled the velocity, the vehicle traveled slower: (a) when he/she controlled both velocity and steering rather than velocity alone; (b) with the older driver rather than the younger driver; (c) when the designated AHS velocity was 128.8 km/h (80 mi/h) rather than 153.0 km/h (95 mi/h); and (d) when the intra-string gap was 0.25 s rather than 0.0625 s.

Recommendations. If the situation explored in this experiment was allowed in an operating AHS, with adequate warning, the driver could take over the steering and/or velocity if there was a reduction in the AHS capability. However, if this was to occur, to avoid the possibility of encroaching into the center lane and threatening the traffic in it, the driver should be encouraged to reduce speed and warned about a possible overshoot. In addition, the lane width should not be reduced from the current standard of 3.66 m (12 ft).

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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SECTION 1: INTRODUCTION AND OVERVIEW

INTRODUCTION

A series of experiments examining human factors aspects of automated highway systems (AHS) is being conducted using the Iowa Driving Simulator. This series is part of a program administered by the Federal Highway Administration (FHWA). The experiments that have already been completed used a generic AHS configuration that, if it were to be implemented on current highways, would require minimal structural alteration to existing expressway cross-sections. The configuration consists of a three-lane expressway in which the vehicles controlled by the AHS travel in strings of up to four in the left-hand lane. The unautomated vehicles that remain under the control of their drivers travel in the center and right lanes. There is no dedicated transition lane to and from the AHS system and there are no barriers between the automated and unautomated lanes.

This report deals with the sixth experiment in the series—it was one of four experiments conducted as part of a complex multiple experiment that is described in more detail below. At the start of this experiment, the simulator vehicle was second in a string of three automated vehicles. The string was traveling in the automated lane toward a segment of the expressway in which the functionality of the AHS was known to be impaired—the AHS would be unable to control the steering and/or the speed of the vehicles in the automated lane in this segment. As the string approached the point at which the reduction in AHS functionality began, the AHS issued a message advising the driver that he/she would need to control the steering, or the speed, or both the steering and speed of the simulator vehicle while traveling through the segment. When the vehicle reached the end of the segment, the AHS resumed control of the vehicle. The experiment was conducted to determine how effective the driver would be in taking control of the function or functions that the AHS was unable to control.

In the first two experiments of the series, the transfer of control from the AHS to the driver as the simulator vehicle left the automated lane was investigated.(1) At the beginning of the trials in these two experiments, the vehicle was under automated control, in the middle of a string of three vehicles, in an automated lane. The driver's task was to take control of the vehicle, drive it out of the automated lane into an unautomated lane, and then leave the expressway at a designated exit. The drivers who participated in the first experiment were between 25 and 34 years old, while those who took part in the second experiment were age 65 or older.

The third experiment focused on the transfer of control from the driver to the AHS as the simulator vehicle entered the automated lane.(2) In this case, each trial started with the driver's vehicle on an expressway entry ramp, and the driver's task was to drive into the right lane of the expressway, move to the center lane, and then, after receiving an Enter command from the AHS, drive into the automated lane and transfer control of the vehicle to the AHS. At this point, under the control of the AHS, the vehicle began to accelerate. Its velocity was increased until it reached the designated AHS velocity in the automated lane. Then, the vehicle was merged with the string of vehicles that was approaching it from behind, becoming the new lead vehicle of that string.

The fourth, fifth, sixth, and seventh experiments were conducted together in a complex multiple experiment.

OVERVIEW OF THE MULTIPLE EXPERIMENT

The multiple experiment, of which the current experiment was the third part, continued the investigation of human factors aspects of the AHS, utilizing the same generic AHS configuration that was used in the first three experiments of the series and combining four experiments that were initially planned as separate studies. In the first of these—the fourth experiment in the series—three methods of transferring control (manual, partially automated, and fully automated) from the driver to the AHS when entering the automated lane were compared.(3) In the second—the fifth experiment in the series—the acceptability to the driver of decreasing vehicle separations during transitions into the automated lane was investigated.(4) The third—the sixth experiment in the series—which is reported here, determined the effectiveness of the driver when he/she had to take control of the steering and/or speed when traveling through a segment of the expressway in which the capability of the AHS was reduced. And in the fourth experiment—the seventh experiment in the series—the effect on normal driving behavior of traveling under automated control was determined.(5) Each driver participating in the multiple experiment drove in six simulator trials. Table 1 shows how the data collected in each section of the six trials were distributed in the four parts of the multiple experiment.

In trial #1, the driver began by driving on a two-lane rural road. Then, he/she entered a three-lane expressway and drove on it for the remainder of the trial—this expressway did not have an automated lane. The pre-AHS driving performance data obtained in this section of trial #1 were compared with the post-AHS driving performance data obtained in trial #6.

Table 1. The part of the multiple experiment in which data were collected in each section of each trial.

Trial	First section	Second section	Third section
Trial #1	Familiarization	Part 4 (Pre-AHS)	—
Trial # 2	Part 1	Part 2	Part 3
Trial # 3	Part 1	Part 2	Part 3
Trial # 4	Part 1	Part 2	Part 3
Trial # 5	Part 1	Part 2	Part 3
Trial #6	Part 1	Part 4 (Post-AHS)	—

There were three sections in each of the next four trials (trials #2, #3, #4, and #5)—the data for parts 1, 2, and 3 of the multiple experiment were collected in these sections. To the driver, the three sections appeared to be different parts of the same drive—this was because the simulation scenarios for these trials were developed in such a way that there were no breaks between the sections. Figure 1 shows the portion of expressway on which the first three parts of the multiple experiment were performed.

The first section of trial #6 was identical to the first section of trials #2 through #5. However, the trial did not continue in the same way—instead, at the beginning of the second section of trial #6, control of the vehicle was given back to the driver, so that post-AHS driving performance data could be obtained and compared with the pre-AHS driving performance data from trial #1.

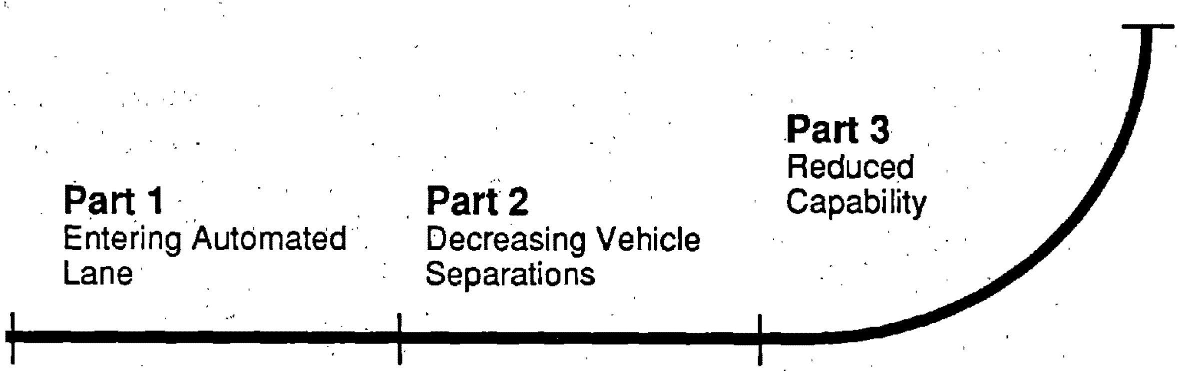


Figure 1. The relationship among parts 1, 2, and 3 of the multiple experiment.

A trial-by-trial description of the multiple experiment, showing the relationship of the four separate experiments to each other, is presented below.

Trial #1: Familiarization and start of part 4 of the multiple experiment—pre-AHS driving performance data

- Throughout trial #1, the simulator vehicle remained under the control of the driver.
- At the start of trial #1, the driver's vehicle was positioned on a two-lane rural highway.
- The driver drove on the two-lane road, with no other traffic present, and then moved onto the expressway and drove in the center and right lanes in the presence of low-density traffic—the density was 6.21 v/km/ln (10 v/mi/ln).
- The pre-AHS driving performance data obtained in the second section of this trial—while the simulator vehicle was traveling on the expressway—were compared with the post-AHS driving performance data collected in trial #6.

Trials #2, #3, #4, #5, and #6: Multiple experiment—part 1

- At the start of trials #2, #3, #4, #5, and #6, the simulator vehicle was positioned on the 2.44-m (8-ft) wide, hard-surfaced shoulder of the expressway.
- The driver moved into the right lane and then drove the vehicle to the center lane—the density of the traffic in the center and right lanes was 6.21 v/km/ln (10 v/mi/ln).
- Once the simulator vehicle was in the center lane, it was steered into the automated lane and control was transferred from the driver to the AHS, using a manual, a partially automated, or a fully automated transfer method.
- The AHS moved the driver's vehicle to the lead position of the string of vehicles approaching the simulator vehicle from behind.
- Part #1 of the multiple experiment ended at this point.

Trials #2, #3, #4, and #5: Multiple experiment—part 2

- In trials #2, #3, #4, and #5 (but not #6), part 2 of the multiple experiment began with the simulator vehicle under automated control, leading a string of vehicles.
- A second vehicle entered the automated lane ahead of the simulator vehicle.
- As the entering vehicle accelerated from 88.6 km/h (55 mi/h) to the designated AHS velocity of the automated lane, the simulator vehicle approached it from behind.
- In half of the trials, the entering vehicle moved into the inter-string gap relatively late, and it was necessary for the AHS to reduce the speed of the simulator vehicle as the distance between it and the entering vehicle decreased. In the other half of the trials,

the entering vehicle moved into the inter-string gap relatively early, and it was unnecessary for the AHS to reduce the speed of the simulator vehicle as it approached the entering vehicle.

- The entering vehicle became the new lead vehicle of the string.
- Throughout part 2, the driver moved a lever forwards or backwards to indicate comfort or discomfort.
- Part 2 of the multiple experiment ended with the simulator vehicle second in the string of vehicles.

Trials #2, #3, #4, and #5: Multiple experiment—part 3

- In trials #2, #3, #4, and #5 (but not #6), part 3 of the multiple experiment began with the simulator vehicle second in a string of vehicles in the automated lane.
- The driver received a *Reduced Capability* advisory stating that the vehicle was approaching a segment of expressway with reduced capability—in this segment, the AHS would be unable to: (1) steer the driver's vehicle, or (2) control its speed, or (3) both steer and control its speed.
- In the driver-controlled condition, the driver could take control of the lost function or functions when ready—if the driver did not take control, a *Reduced Capability* command was issued at the moment that the AHS relinquished control. In the situation-controlled condition, the driver could not take control when the *Reduced Capability* advisory was given, but had to wait for the *Reduced Capability* command, which was issued at the moment that the AHS relinquished control.
- The driver performed the lost function or functions.
- When the simulator vehicle reached the end of the segment of expressway with reduced capability, the driver received a *Resumption of Control* advisory.
- In the driver-controlled condition, on hearing this advisory, the driver transferred control back to the AHS when ready. In the situation-controlled condition, at the end of this advisory, the AHS resumed control of the driver's vehicle.
- Trials #2, #3, #4, and #5—and part 3 of the multiple experiment—ended with the simulator vehicle back under the control of the AHS.

Trial #6: Conclusion of part 4 of the multiple experiment—post-AHS driving performance data

- In trial #6, part 1 of the multiple experiment ended, and part 4 began with the driver's vehicle leading a string of vehicles in the automated lane.

- After traveling for up to 5 min, the driver received a *Reduced Capability* advisory. It stated that the driver was approaching a segment of expressway in which the AHS could not steer and could not control the speed of the vehicle.
- In the driver-controlled condition, the driver could take control of the steering and the velocity functions when ready—if the driver did not take control, a *Reduced Capability* command was issued at the moment that the AHS relinquished control. In the situation-controlled condition, the driver could not take control when the *Reduced Capability* advisory was given; instead, the driver had to wait until the AHS gave a *Reduced Capability* command containing a countdown that ended at the moment the AHS relinquished control.
- The driver drove the vehicle in the automated lane.
- The driver was informed that the AHS would not resume control of the vehicle, and was asked to drive the vehicle out of the automated lane.
- The driver moved the vehicle into the center lane and continued to drive the vehicle for 3 min.
- The density of the traffic in the center and right lanes was 6.21 v/km/ln (10 v/mi/ln).
- Post-AHS driving performance data obtained in this trial were compared with pre-AHS driving performance data collected in trial #1.
- Trial #6—and part 4 of the multiple experiment—ended with the simulator vehicle under the control of the driver.

REDUCED CAPABILITY IN AN AUTOMATED HIGHWAY

As mentioned above, the experiment discussed in this report was part 3 of the multiple experiment. In this experiment, the ability of the driver to deal with reduced capability in an automated highway was investigated. Figure 2 shows its relationship to the rest of the multiple experiment.

At the beginning of this experiment, the driver's vehicle was second in a string of three vehicles in the automated lane. The vehicle continued traveling under automated control, at 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h), for between 20 s and 180 s. Then, it arrived at a segment of expressway in which the functionality of the AHS was reduced in one of the following three ways:

(1) The lane-keeping function was not under automated control.
(2) The velocity control function was not under automated control.
(3) Neither the lane-keeping nor the velocity control function was under automated control.

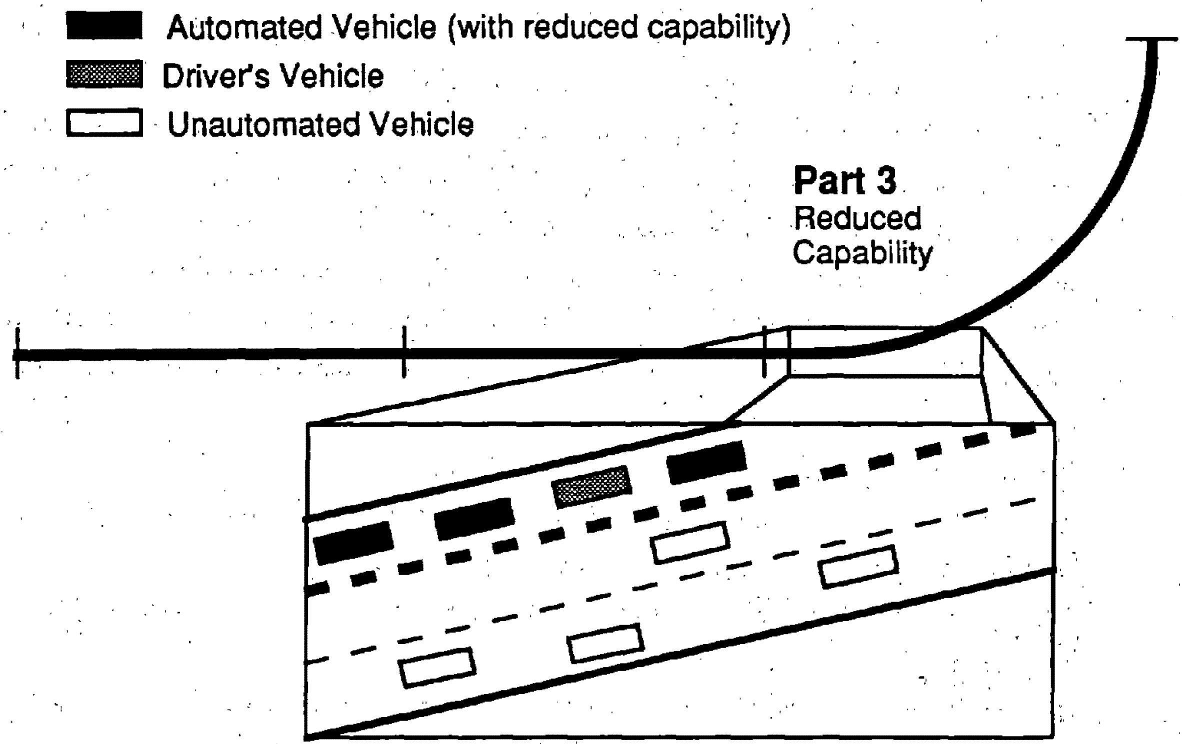


Figure 2. Part 3 of the multiple experiment—reduced AHS capability.

The segment extended for 810 m (2656 ft) along the expressway and most of the segment was on a curve to the driver's left. There was a 31-m (102-ft) straight tangent segment of expressway that led into the curve. The distance around the curve was 735 m (2410 ft). Then, another straight tangent segment that was 44 m (144 ft) in length lead out of the curve.

OBJECTIVE OF THIS EXPERIMENT

The objective of this experiment was to determine how effectively the driver was able to take partial or full control of the vehicle as it traveled through a segment of the expressway in which the AHS capability was reduced. The data analysis focused on the following experimental question:

Does the driver's ability to control the lost function vary with: (a) the age of the driver, (b) the designated AHS velocity of the automated lane, (c) the intra-string separation, (d) the reduced-capability mode, (e) the method of transferring control, or (f) some combination of two or more of these variables?

SECTION 2: METHOD

SUBJECTS

The following guidelines were used to select the drivers who participated in this experiment:

- The drivers had no licensing restrictions—other than wearing eyeglasses for vision correction during driving.
- The drivers did not require special driving devices—the simulator is not equipped for such devices.
- Thirty drivers were between 25 and 34 years of age.
- Thirty drivers were age 65 or older, with 15 between 65 and 69 years of age, and 15 age 70 or older.
- Half of the drivers in each age group were male and half were female.

The 60 drivers who participated in this experiment were volunteers who had replied to advertisements in the Iowa City and University of Iowa daily newspapers, and who met the above selection criteria.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator, located in the Center for Computer-Aided Design at the University of Iowa, Iowa City, is shown in figure 3.(6) The simulator consists of a projection dome mounted on a hydraulically actuated hexapod platform. For this experiment, a mid-size Ford sedan was mounted on this platform, and the simulator was controlled by a computer complex that included a Harris Nighthawk 4400, an Alliant FX/2800, and an Evans and Sutherland CT-6 Image Generator. The Nighthawk and Alliant systems were controlled simultaneously by the same operating system.(7) The Nighthawk was the system master—arbitrating subsystem scheduling and performing motion control, data collection operations, instrumentation, control loading, and audio cue control—while the Alliant, a 26-processor, shared-memory, parallel computer, performed the multibody vehicle dynamics and complex scenario control simulation.

The inner walls of the dome act as a projection screen. For the current experiment, the correlated images generated by the CT-6 were projected onto two sections of these walls—one was a 3.35-rad (192°) section in front of the simulator vehicle, the other was a 1.13-rad (65°) section to its rear. The driver of the simulator vehicle viewed the images shown on the forward section

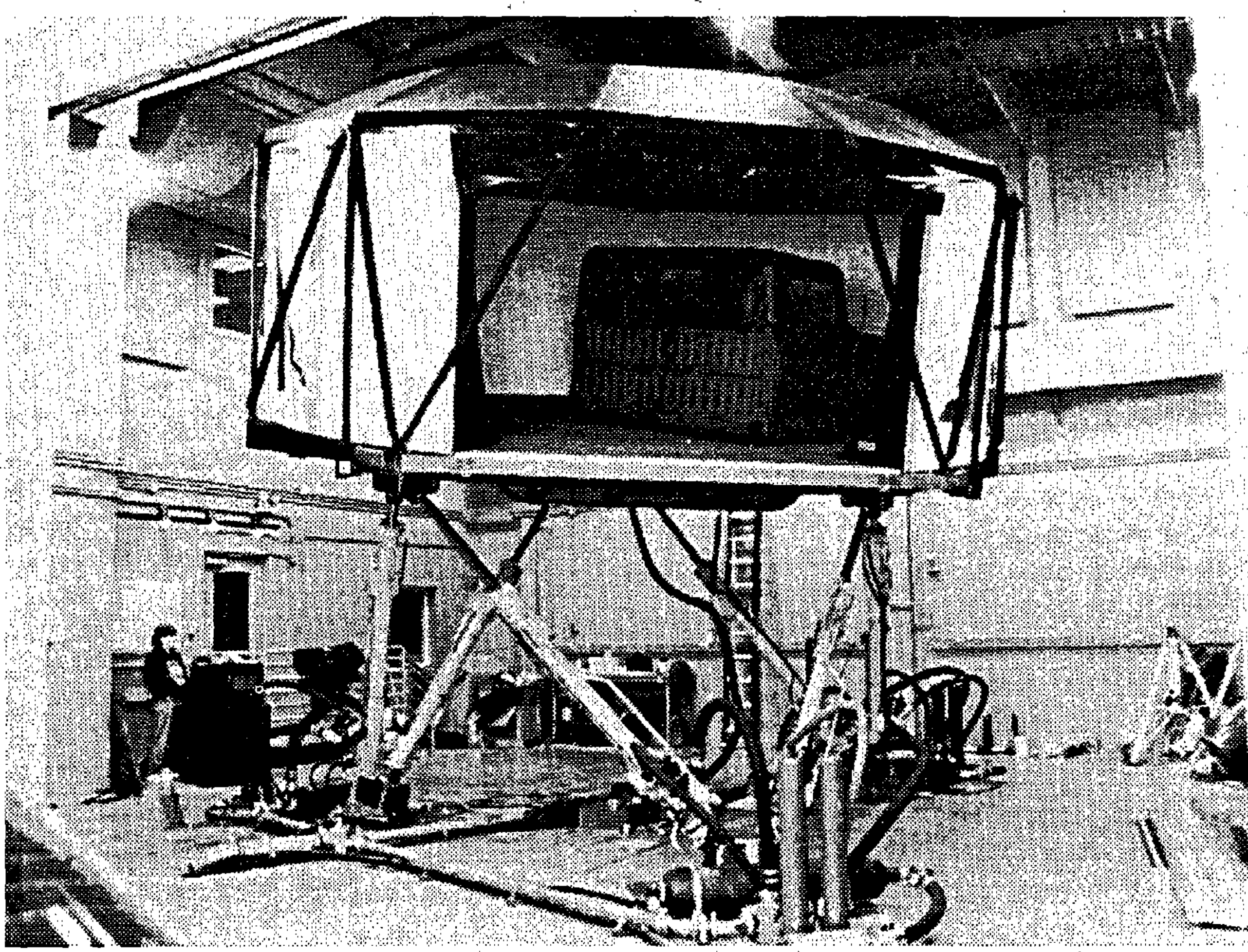


Figure 3. The Iowa Driving Simulator.

through the windshield and side windows, and viewed the images projected to the rear either by turning around, through an interior rearview mirror, or through a left-side exterior driving mirror.

THE DRIVER'S TASK

As this experiment began, the simulator vehicle was traveling under automated control at either 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h). It was approaching a segment of expressway in which the functionality of the AHS was reduced. On reaching this reduced-capability segment, the driver's task was to replace the AHS by taking control of the lost function, i.e., by controlling either the steering, or the velocity, or the steering and the velocity of the simulator vehicle. The driver maintained control of the lost function, attempting to keep the simulator vehicle in the automated lane, until the AHS was able to resume full control of the vehicle.

At the same time that control of the steering, or of the speed, or of the steering and speed of the simulator vehicle was transferred from the AHS to the driver, control of the same function(s) was also transferred from the AHS to the drivers of both the vehicle ahead and the vehicle behind the simulator vehicle. As far as steering was concerned, what this meant in practice was that, on reaching the reduced-capability segment, the steering control model used to steer the vehicle ahead and the vehicle behind the driver's vehicle changed from the AHS steering control model, used for all vehicles when they were under automated control, to the steering control model used for all the vehicles that were in the unautomated lanes (with the exception of the driver's vehicle). When ostensibly under the control of their drivers, the vehicles ahead and behind the driver's vehicle exhibited considerably more lateral movement than when they were under automated control. This increase in lateral movement change was quite noticable to the driver for the two reduced-capability modes in which the AHS gave up steering control. Thus, when control of the steering or control of the steering and speed of the simulator vehicle was transferred from the AHS to the drivers of the vehicles ahead and behind, the driver of the simulator vehicle was able to determine that the AHS capability had changed for these vehicles also.

However, as far as speed was concerned, a different approach was used. No prior data were available to indicate whether drivers would reduce speed, maintain the speed at which they were traveling, or increase speed on regaining control of a vehicle as it entered a segment of expressway in which the AHS no longer controlled speed. It was because of this that, in the current experiment, the velocity of the vehicles ahead and behind was indexed with reference to the driver's speed in each trial. This meant that the speed of the vehicles ahead and behind the driver's vehicle mirrored the speed selected by the driver. It also meant that the gaps between the driver's vehicle and these two vehicles remained constant throughout the reduced-capability segment and remained equal to the size they were when the AHS controlled the vehicles. If this experiment were to be repeated, it is recommended that the speeds of the vehicles immediately ahead and behind the driver's vehicle should be modeled independently using values selected from the range of velocities obtained from the drivers who participated in the current experiment. If this were to be done, then the gap between the driver's vehicle and the vehicle ahead would be selected by the driver. [The gap between the driver's vehicle and the vehicle behind would be obtained using the same procedure that was used to model the inter-vehicle spacing of the vehicles in the unautomated lanes—this method is described in detail by Bloomfield et al.(1)]

The reduced-capability segment of the expressway extended for 810 m (2656 ft) along the expressway. In both velocity conditions, the starting point for the reduced-capability segment began 31 m (102 ft) before a curve to the driver's left. The distance around the curve was 735 m (2410 ft). Then, there was a second straight tangent segment of expressway, which was 44 m (144 ft) long.

EXPERIMENTAL DESIGN

There were five independent variables in the current experiment. Three of the variables (the age of the driver, the reduced-capability mode, and the method of transferring control from the AHS to the driver) were between-subjects variables, while the remaining two (the designated AHS velocity and the gap between vehicles within a string) were within-subjects variables.

Two age groups, 3 reduced capability modes, and 2 methods of transferring control were used in the experimental design—giving 12 combinations of the 3 between-subjects variables. The 60 drivers who participated in the current experiment were divided into 12 groups of 5 drivers each. Each group of 5 drivers was assigned to one of the 12 combinations of driver's age, reduced capability mode, and method of transferring control.

Two design velocities and two intra-string gaps were used—so four combinations of the two within-subjects variables were tested. Each driver in all 12 groups participated in 4 trials, receiving 1 of the 4 combinations of designated AHS velocity and intra-string gap in each trial. A complete listing of the combination of conditions presented to each of the 60 subjects in the 4 trials is presented in appendix 1.

Details of the five independent variables are given below.

Age of the Driver

The 60 drivers who took part in the current experiment were from 2 age groups. The first group consisted of drivers between 25 and 34 years of age, while the drivers in the second group were age 65 or older. There were 30 drivers in each group. To ensure that they represented the populations from which they were drawn, both groups were balanced for gender—half of the drivers in each group were male and half were female. In addition, to ensure that the ages of the older drivers did not cluster around the lower limit for the group, 15 of them were between 65 and 69 years old and 15 were age 70 or older. As a result of these two selection strategies, there were 8 male and 7 female drivers between ages 65 and 69, and 7 male and 8 female drivers who were age 70 or older.

Designated AHS Velocity

Two designated AHS velocities were used in the current experiment—128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h).

A third designated AHS velocity—104.7 km/h (65 mi/h)—was used in addition to these two velocities in the first two parts of the multiple experiment. Because of this, for half the trials it was necessary to increase to the designated AHS velocity after the second part of the multiple experiment was completed and before the current experiment began. For all 80 trials in which the velocity had been 104.7 km/h (65 mi/h), it was increased to 128.8 km/h (80 mi/h). In addition, for 40 of the 80 trials in which the velocity had been 128.8 km/h (80 mi/h) for parts 1 and 2 of the multiple experiment, it was increased to 153.0 km/h (95 mi/h). The velocity was unchanged in the remaining trials, i.e., for the other 40 trials in which the velocity had been 128.0 km/h (80 mi/h), as well as for all 80 trials in which it had been 153.0 km/h (95 mi/h). As a result of the velocity adjustments carried out prior to the start, in the current experiment there were 120 trials in which the designated AHS velocity in the automated lane was 128.8 km/h (80 mi/h) and 120 trials in which it was 153.0 km/h (95 mi/h).

Intra-String Gap

The intra-string gap is the distance between the front bumper of the driver's vehicle and the back bumper of the vehicle ahead. Two intra-string gaps were used here—0.25 s and 0.0625 s. When the intra-string gap is measured in time units, it interacts with the designated AHS velocity that is selected for the vehicles in the automated lane: in this experiment, the result of this interaction produced the separation distances that are shown in table 2.

Table 2. The distance [in meters (and feet)] between the front bumper of the driver's vehicle and the back bumper of the vehicle ahead, for the four combinations of intra-string gap and designated AHS velocity.

	Intra-string gap	
Designated AHS velocity	**0.25 s**	**0.0625 s**
128.8 km/h (80 mi/h)	8.95 m (29.33 ft)	2.24 m (7.33 ft)
153.0 km/h (95 mi/h)	10.62 m (34.83 ft)	2.66 m (8.71 ft)

Reduced-Capability Mode

The following three reduced-capability modes were investigated:

(1) Loss of steering—the driver had to control the steering and keep the vehicle in the lane, while the AHS continued to control the vehicle's velocity.
(2) Loss of velocity control—the driver had to control the velocity of the vehicle, while the AHS continued to control the steering and keep the vehicle in the lane.
(3) Loss of both steering and velocity control—the driver had to control both the steering and the velocity of the vehicle.

Method of Transferring Control

There were two methods in which control could be transferred from the AHS to the driver and back again from the driver to the AHS. They were as follows:

(1) **Driver-Controlled Method.** With the driver-controlled transfer method, 20 s before the driver's vehicle arrived at the beginning of the reduced-capability expressway segment, the AHS issued a *Reduced Capability* advisory. After hearing this advisory, the driver was able to take control of the lost function or functions at any time in the next 20 s. If the driver failed to take control within that time, the AHS issued a *Reduced Capability* command—this command stated that the system was no longer

in control of the function (or functions) and that the driver should take control immediately. In addition, when the driver's vehicle reached the end of the reduced-capability segment, with the driver-controlled transfer method, the AHS issued a *Resumption of Control* advisory. This advisory stated that the AHS was now able to control the vehicle, and asked the driver to transfer control back to the AHS.[1]

(2) **Situation-Controlled Method.** The AHS also issued a *Reduced Capability* message with the situation-controlled transfer method, and this message was also issued 20 s before the driver's vehicle arrived at the beginning of the reduced-capability expressway segment. But in this case, the message was only preparatory. Its purpose was one of warning, so that the driver would be ready to take control when a second message—a *Reduced Capability* command—was issued. The command stated that the system was no longer in control of the function (or functions) and that the driver should take control immediately. As with the driver-controlled transfer method, when the driver's vehicle reached the end of the reduced-capability segment, the AHS issued a *Resumption of Control* advisory. However, for the situation-controlled transfer method, after the advisory, which stated that the AHS was able to regain control of the vehicle, the AHS took control back without any action being taken by the driver.

The drivers who participated in the first part of the multiple experiment, in which entering the automated lane was investigated, used one of three methods—manual, partially automated, or fully automated—to transfer control of the vehicle to the AHS.(3) Those drivers who used the manual method in the first part of the multiple experiment used the driver-controlled transfer method to regain control in the current experiments, while those who used the fully automated method earlier used the situation-controlled transfer method here. As for the drivers who used the partially automated method in the first part of the multiple experiment, in the current experiment, one-half used the driver-controlled method, while the other half used the situation-controlled method.

It should be noted that the drivers who were in the group that used the situation-controlled transfer method could not take control of the vehicle until they were 31 m (102 ft) from the start of the

[1] Fifteen older drivers and 15 younger drivers used the driver-controlled transfer method—each of them took part in 4 trials. Seven of the older drivers and four of the younger drivers did not take control of the vehicle until the AHS issued the *Reduced Capability* command in at least one trial. Most of these drivers waited for the *Reduced Capability* command in 2 or more trials—the 7 older drivers waited in 21 out of 28 trials; the 4 younger drivers waited in 14 of 16 trials. It should be noted that the drivers did take control after the command was issued.

curve. In contrast, the drivers who were in the group that used the driver-controlled transfer method could take control 20 s earlier than the drivers who used the situation-controlled method.

EXPERIMENTAL PROCEDURE

Introduction and Training Procedure

Each driver in the multiple experiment participated in two sessions. In the first of these sessions, the driver watched an introductory videotape, drove in the simulator, and filled out a questionnaire. In the second session, the driver's visual capabilities were assessed.

The videotape shown to the driver at the start of the experiment contained introductory material and instructions, and provided some interactive practice with the AHS interface and protocol. The driver was told that the experiment involved driving in the simulator and completing several vision tests and a questionnaire. Next, the driver was informed that the experiment was part of an on-going FHWA program exploring ways of designing an AHS, determining how it might work, and how well drivers would handle their vehicles in such a system. It was made clear that the experiment was a test of the AHS, not a test of the driver. Then, the video gave explanations of the subtasks for the entire multiple experiment—providing details to the driver on how to:

- Enter the automated lane (for part 1 of the multiple experiment).
- Indicate his/her comfort level (in part 2).
- Take control during a section of the expressway in which there would be a reduction in the AHS capability (for the current experiment).
- Transfer control back to the AHS at the end of the reduced-capability section (also for the current experiment).

Four different versions of this training video were prepared. The differences in these versions corresponded to differences in the methods of transferring control to the AHS for part 1 of the multiple experiment, and in the method of regaining control for part 3. The introduction was identical in all four videos. The narrations for the sections of the videos pertinent to the current experiment are presented in appendix 2.

The instructional sections of three versions of the videos lasted 12 min. The fourth version, which dealt with automated entry to the AHS in part 1 of the multiple experiment, required less detail and was 9 min long.

After the instructional section, each version of the video continued with a series of practice segments. The first of these segments contained subtask practices that dealt with entering the automated lane and transferring control to the AHS (for part 1 of the multiple experiment), indicating comfort level (part 2), and taking control of the lost capability and returning control of the lost capability to the AHS (part 3). There were three segments for each of these subtasks. If the driver responded correctly on the first two segments, the third was omitted. If the driver failed to respond correctly twice in a row for a particular subtask, the three segments were repeated for that driver until the task was accomplished.

Following the subtask practices, the videos continued with three more segments that covered the whole task for the driver—as before, if the driver responded correctly on the first two trials, the third was omitted, and if more than three trials were required, the segments were repeated.

Pre-Experimental Simulator Procedure

The driver was taken to the Iowa Driving Simulator and asked to sit in the driver's seat. Next, the driver was asked to put on the seatbelt and to adjust the seat and mirrors, and then was given instructions on how to use the simulator emergency button.

At the start of trial #1, the driver drove the simulator vehicle on a two-lane rural road with no other traffic present. After driving for approximately 2 min on this road, the driver entered a three-lane expressway. He/she drove in the center and right lanes for between 3 min and 4 min in the presence of low-density traffic—the density of the traffic was 6.21 v/km/ln (10 v/mi/ln), which is close to the upper boundary of the Transportation Research Board Level of Service A (LOS A).[8] While driving on the expressway, the experimenter asked the driver to change lanes from the right lane to the center lane and back again. Throughout trial #1, the simulator vehicle remained under the control of the driver.

AHS Experience

At the start of trials #2, #3, #4, and #5, the driver drove in the right lane of the expressway. The driver moved into the center lane, then entered the automated lane using a manual, partially automated, or fully automated method of transferring control to the AHS. Once in the automated lane, the simulator vehicle began to accelerate under the control of the AHS. The velocity of the vehicle was increased until it reached the designated AHS velocity. At this point, the vehicle became the leader of the string of automated vehicles that was approaching it from the rear.

After the simulator vehicle had been the lead vehicle of a string for between 0.5 min and 4 min, a second vehicle moved into the automated lane ahead of the simulator vehicle. The entering vehicle accelerated, under the control of the AHS, until it was traveling at the designated AHS velocity. It then replaced the simulator vehicle as the new lead vehicle of the string.

Experimental Procedure and Instructions

The current experiment—part 3 of the multiple experiment—started with the simulator vehicle in second place in a string of vehicles in trials #2, #3, #4, and #5. The vehicle continued to travel along in second place for between 0.5 min and 4 min. During this time, the vehicle was approaching a segment of the expressway in which the AHS was known to be operating at reduced capability—in it, the AHS was unable to control either the steering, or the velocity, or the steering and the velocity of the vehicle. Twenty seconds before reaching the point at which the reduction in capability began, the AHS issued a *Reduced Capability* advisory. The driver's response to this advisory depended on whether he/she was to use the driver-controlled or the situation-controlled method of regaining control of the vehicle.

If the driver was using the driver-controlled transfer method, he/she was able take control of the lost function (or functions) as soon as the *Reduced Capability* advisory was issued. If, for any reason, the driver did not regain control in the next few seconds, then 3 s before the vehicle reached the point at which the reduction in capability began, the AHS issued a *Reduced Capability* command. This command included a countdown that ended at the moment that the AHS relinquished control of the steering and/or the velocity of the vehicle. The driver then had to take control of the lost function (or functions).

If the driver was using the situation-controlled transfer method, he/she was not allowed to take control when the *Reduced Capability* advisory was issued—in this case, the advisory was used only to alert the driver. Instead, the driver had to wait until the AHS issued the *Reduced Capability* command 3 s before the vehicle reached the point at which the reduction in capability began. The *Reduced Capability* command was identical to that used in the driver-controlled condition. It included a countdown that ended at the moment that the AHS relinquished control of the steering and/or the velocity of the vehicle, and at this point, the driver had to take control of the lost function (or functions).

The driver controlled either the steering, or the velocity, or the steering and the velocity of the vehicle for an 810-m (2656-ft) segment of the expressway. Most of this segment was on a curve; it was a 0.78-rad (45°) standard expressway curve that veered to the driver's left. It had a radius of 915 m (3000 ft) and a superelevation of 0.065. The distance around the curve was 735 m (2410 ft), and the lengths of the straight tangent sections of the expressway that led into and out of the curve were 3 m (102 ft) and 44 m (144 ft), respectively.

When the vehicle reached the end of the reduced-capability segment, one of two procedures was used to enable the AHS to resume complete control of the vehicle. First, if the driver had used the driver-controlled transfer method in regaining control of the lost function, then the AHS issued a *Resumption of Control* advisory. After this advisory was issued, the driver was able transfer control of the steering, or velocity, or the steering and velocity back to the AHS when he/she was ready. Second, if the driver had used the situation-controlled transfer method in regaining control of the lost function, then the AHS also issued a *Resumption of Control* advisory. However, in this case, the message was different. After stating that the AHS was able to resume control of the vehicle, there was a countdown, at the end of which the AHS simply took complete control of the driver's vehicle without any action by the driver. At this point, trials #2, #3, #4, and #5 concluded.

Post-Experimental Procedure

Trial #6 began in the same way as trials #2, #3, #4, and #5—first, the driver was in control of the simulator vehicle until it entered the automated lane; second, the AHS was in control while the simulator vehicle accelerated up to the designated AHS velocity and became the leader of a string of automated vehicles. However, the continuation of trial #6 was different to that of trials #2, #3, #4, and #5—now, with the simulator vehicle leading a string of automated vehicles, the driver received a *Reduced Capability* advisory, and control was transferred back to the driver. When the driver had control, the AHS informed him/her that it would not resume control, and that he/she should move into the unautomated lanes and continue driving. The trial continued for 4 min with the driver in control of the vehicle, driving in the center and/or right lane. Throughout the trial, the density of the traffic in the center and right lanes was 6.21 v/km/ln (10 v/mi/ln).

After completing the sixth trial, the driver returned to the subject preparation room, where he/she was debriefed and asked to complete a questionnaire dealing with the driving simulator, the multiple experiment, and the Automated Highway System. A copy of this questionnaire is presented in appendix 3. At this point, the first session ended.

The driver returned for a second session, which was divided into two sections. In the first section, a Titmus Vision Tester was used to administer a battery of vision tests. The following visual capabilities of the driver were tested: (1) far-foveal acuity, (2) near-foveal acuity, (3) stereo depth perception, (4) color deficiencies, (5) lateral misalignment, and (6) vertical misalignment. In the second section, the spatial localization perimeter developed by Wall was used to determine the subject's reaction time and accuracy when detecting both static and dynamic peripheral stimuli.[9]

SECTION 3: RESULTS

FOCUS OF THE DATA ANALYSIS

The objective of this experiment was to determine the effectiveness of the driver when he/she took partial or full control of the simulator vehicle as it traveled through a segment of the expressway in which the AHS capability was reduced. The data analysis focused on the following experimental question:

> *Does the driver's ability to control the lost function vary with: (a) the age of the driver, (b) the designated AHS velocity of the automated lane, (c) the intra-string separation, (d) the reduced-capability mode, (e) the method of transferring control, or (f) some combination of two or more of these variables?*

In the reduced-capability segment of the expressway, there was a loss of steering, a loss of velocity control, or a loss of both steering and velocity control by the AHS. Table 3 shows how control was divided between the driver and the AHS for each of the three reduced-capability modes.

Table 3. The division of control between the driver and the AHS while the simulator vehicle was in the reduced-capability segment of the expressway for each reduced-capability mode.

Reduced Capability Mode	Steering controlled by:	Velocity controlled by:
Loss of steering	Driver	AHS
Loss of velocity control	AHS	Driver
Loss of steering and velocity control	Driver	Driver

It should be noted that, in the remainder of this section, the figures illustrating how the three reduced-capability modes affect driving performance are reported in terms of how the vehicle was controlled, rather than in terms of which function(s) the AHS was not controlling. This is because it is easier to understand what occurred in the trials when the reduced-capability modes are reported this way. For example, when dealing with lane-keeping performance, it is less ambiguous to report that "the steering was controlled by the AHS," than it is to report that "the AHS lost control of the velocity"; and to report that "the steering was controlled by the driver," instead of reporting that "the AHS lost control of the steering." Similarly, when dealing with velocity control, there is less ambiguity in reporting that "the velocity was controlled by the AHS," than there is in reporting that "the AHS lost control of the steering," and in reporting that "the velocity was controlled by the driver," instead of reporting that "the AHS lost control of the velocity."

PERFORMANCE MEASURES

The ability of the driver to control the steering of the simulator vehicle when there was either a loss of steering or a loss of both steering and velocity control was compared with the ability of the AHS to steer when there was a loss of velocity control—the lane-keeping measures developed by Bloomfield and Carroll were used to make this comparison.(10) Similarly, the ability of the driver to control the velocity of the simulator vehicle when there was either a loss of velocity control or a loss of both steering and velocity control was compared with the ability of the AHS to control velocity when there was a loss of steering control—this comparison was made using the delay time measures developed for the data analysis of the first four experiments of this series.(1,2,3) The two sets of comparisons are described in the next two subsections.

Lane Keeping

Comparisons of the ability of the driver and of the AHS to control the steering of the simulator vehicle in the reduced-capability segment of the expressway were made using recently developed lane-keeping measures. Bloomfield and Carroll use concepts derived from regression analysis to develop measures of lane-keeping performance and of the stability or smoothness of the ride.(10) They separate the previously used measure of deviation from the center of the lane into three distinct measures—two of which are lane-keeping measures (the position of the vehicle in a lane and steering drift across the lane), while the third is a measure of steering stability. In addition, they suggest replacing steering wheel reversals with the number of crossings of the center of the vehicle across the line of best fit.

Bloomfield and Carroll show how to determine a linear equation that is the line of best fit for a series of points on the track of a vehicle.(10) The equation describes the position of the vehicle relative to the center of the lane at any time, and indicates whether the vehicle is traveling parallel to the lane or veering to the left or right of the lane. Also, Bloomfield and Carroll use the variability of the track of the vehicle around this line of fit, along with the number of crossings of that line, to indicate the driver's steering stability, i.e., the driver's ability to maintain the track of the vehicle.

Bloomfield and Carroll use the following argument to suggest that the method of least squares can be used to obtain a line of best fit that gives the relative position of a vehicle in a lane throughout a segment of road.(10) Before dealing with a curved road segment—such as that used in the current experiment—they consider the case, illustrated in figure 4, where a driver is traveling along a straight road segment. In this case, it is possible to determine the position of the center of the vehicle on a line that is perpendicular to the lane, at any point in time.

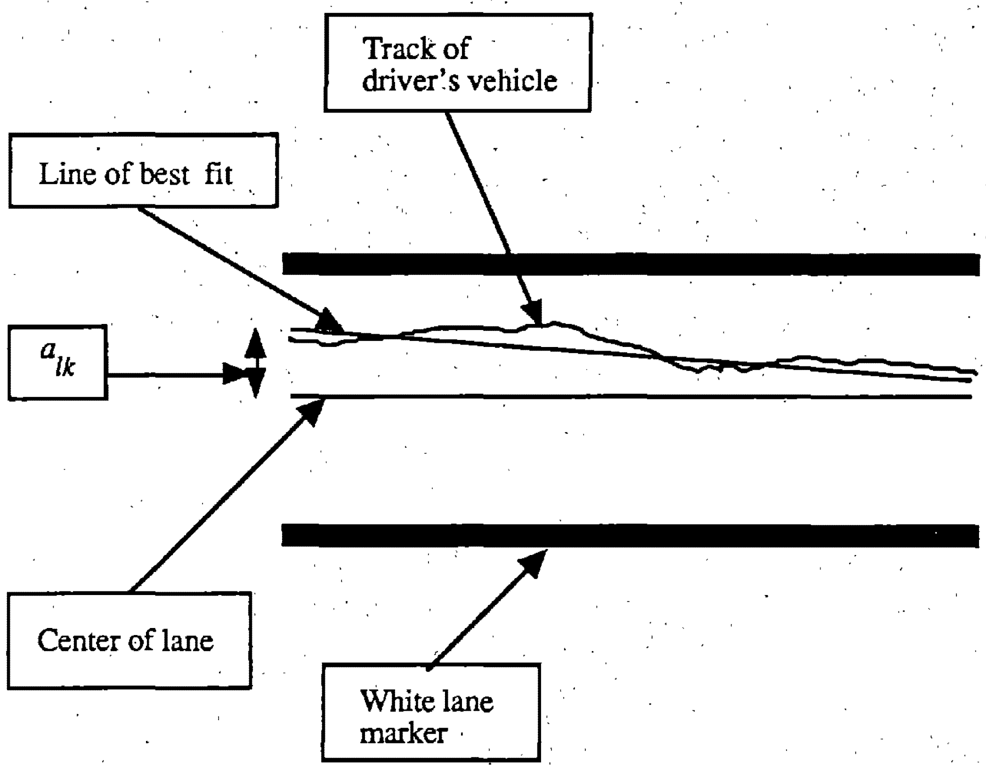


Figure 4. Schematic showing a cross-section of a lane, with the track of the driver's vehicle along the lane and the line of best fit. [Note: The cross-section of the lane is greatly exaggerated compared to distance along the lane.]

Bloomfield and Carroll assume that the series of positions can be described by the following linear equation:

$$p = a_{lk} - b_{lk}x \quad (1)$$

where:

- p is the point (representing the center of the driver's vehicle) at which the line of best fit crosses the perpendicular across the lane after the vehicle has traveled distance x.
- x is the distance traveled in the lane by the vehicle.
- a_{lk} is the point at which the line of best fit crosses the perpendicular at the start of the straight road segment.
- b_{lk} is the gradient of the line of best fit—it is essentially the steering drift.

The series of positions of the center of the vehicle is unlikely to fall exactly on a straight line. However, since in comparison to the 3.66-m (12-ft) width of the lane, the vehicle will travel along what is, relatively speaking, a very long, straight road segment, it is not unreasonable to assume that the series of positions can be described by a linear equation. Because the equation suggested by Bloomfield and Carroll is a linear regression equation, the line of best fit of this equation can be calculated using the method of least squares. Using the method of least squares, which minimizes the error in predicting p from x, the terms a_{lk} and b_{lk} are calculated as follows:

$$b_{lk} = \frac{\sum xp - \frac{(\sum x)(\sum p)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \qquad (2)$$

where n is the number of data points obtained in time x and

$$a_{lk} = \frac{1}{n}\left(\sum p - b_{lk} \sum x\right) \qquad (3)$$

In addition, the variability in b_{lk}—i.e., the residual standard deviation—can be used as an estimate of I_{lk} the steering instability. I_{lk} provides an estimate of the variability in steering that occurs when the driver is attempting to maintain a straight course along the line of best fit. It is given by the equation:

$$I_{lk} = \sqrt{\left[\sum p^2 - \frac{(\sum p)^2}{n} - \frac{\left\{\sum xp - \frac{(\sum x)(\sum p)}{n}\right\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}}\right] \div (n-2)} \qquad (4)$$

Bloomfield and Carroll suggest that equations 1 and 2 define the position of a vehicle in a straight road segment; equation 3 gives information on steering drift across the lane; and equation 4—along with the number of crossings of the direction of travel (or steering oscillations)—provides a measure of the smoothness or stability of the ride.(10) In particular, they suggest that lane-keeping performance should be determined using the following four measures:

(1) **Initial Lane Position.** The initial lane position, a_{lk}, is the point (representing the center of the driver's vehicle) at which the line of best fit crosses the perpendicular across the lane at the start of a selected segment—it is calculated using equation 3. It is important to note that a_{lk} is not the actual position of the vehicle at the start of the segment, but instead it is the initial position in the lane of the line of best fit for the series of points along the track of the vehicle. If a_{lk} equals zero, it crosses the perpendicular line at the center of the lane; if a_{lk} is positive, as in figure 4, the line of best fit starts to the left of the center line; and if a_{lk} is negative, it starts to the right of the center line.

(2) **Steering Drift.** The steering drift, b_{lk} measures the rate at which the vehicle is displaced laterally across the lane as a function of the distance it travels along the lane. b_{lk} is the gradient of the line of best fit for the series of points along the track of the vehicle—it is calculated using equation 2. If b_{lk} equals zero, the vehicle is either traveling along the center line of the lane or is traveling parallel to it. However, if b_{lk} is positive, then the vehicle is moving laterally from the right of the lane to the left as it travels along the lane. And, if b_{lk} is negative, as it is in figure 4, then the vehicle is moving laterally from the left to the right of the lane, as it travels along the lane.

(3) **Steering Instability.** The steering instability, I_{lk}, measures the variability in steering that occurs when the driver is maintaining his/her position in the lane. It is calculated using equation 4. Mathematically, I_{lk} is the variability—i.e., the residual standard deviation—of the track of the vehicle about the line of best fit.

(4) **Steering Oscillations.** A steering oscillation occurs every time the track of the vehicle crosses the line of best fit. The frequency with which steering oscillations occur is measured by determining the number of times that the track of the vehicle crosses the line of best fit per minute.

These four measures were used in analyzing the fourth part of the multiple experiment, which investigated the effect on normal driving behavior of traveling under automated control.(5) That experiment explored the lane-keeping performance of drivers while they were driving on a straight portion of expressway, both before and after they had experienced traveling under automated control

In the current experiment, as already mentioned, the length of the curved portion of the reduced-capability segment was 735 m (2410 ft), i.e., approximately 90 percent of the 810-m (2656-ft) long segment was on the curve. Because of this, the primary comparison of interest here was between the steering ability of the driver and the steering ability of the AHS while the vehicle traveled around the curve.

Bloomfield and Carroll point out that, under some circumstances, it is possible to use a linear equation to describe the track of a vehicle traveling around a curve.(10) Whether a linear equation can be used in this way or not depends on the way in which the vehicle's lane position is determined. If lane position is determined relative to the cross-section of the lane, then a linear equation can be used to describe a curved path. The reasoning is as follows. When a road is curved, if the position of a vehicle is determined relative to the cross-section of the lane, then, at each moment, lane position will be expressed relative to a line that is perpendicular to the tangent of the curve. In the current experiment, data were collected at a rate of 30 Hz—as a result, a series of tangents was considered at $^1/_{30}$-s intervals around the curve, with a cross-sectional line perpendicular to each tangent. The points at which the track of the vehicle intersected those cross-sectional lines, spaced $^1/_{30}$ s apart, constituted the lane-position data.

In order to determine how the lateral position of the vehicle across the lane varies as it travels around a curve, the series of cross-sectional lines are considered together. Since the data were not collected continuously, but rather at intervals that were $^1/_{30}$ s apart, there are segments of roadway between the cross-sectional lines where data were not collected. Note that this statement is true whether the road is curved or straight. On a straight road, the segments where data were not collected are rectangular; on a curved road, as it was in this experiment, they are wedge shaped. In either case, because the segments are so small when the data rate is as high as it was in this experiment, they can be ignored for purposes of statistical analysis. Because this is true, it does not matter for the analysis whether the roadway was straight or curved: a linear regression can be applied to the series of points indicating the position of the vehicle in the lane for both situations. Therefore, the set of equations presented above could be used to derive the values of the four measures of lane-keeping performance suggested by Bloomfield and Carroll from the data collected in the current experiment.(10) [It is interesting to note that on a real, standard expressway curve, the wedge-shaped slivers closely approximate rectangles. With the 915-m (3000-ft) radius curve used in the current experiment, the length along the lane of each wedge on the inside of the curve was only 0.4 percent smaller than the length of each wedge on the outside of the curve. For example, when the simulator vehicle was traveling at 153.0 km/h (95 mi/h), the length of the wedge on the inside of the curve was 1.414 m (4.635 ft) and the length on the outside of the curve was 1.419 m (4.654 ft).]

If, as it traveled around the curve, the track of the simulator vehicle was approximately parallel to the center of the lane, then b_{lk}, the steering drift (or gradient of the linear regression equation for lane position), would be approximately zero. In addition, if the vehicle closely maintained this parallel track, then I_{lk}, the steering instability, would be relatively small. In contrast, if the driver or the AHS were to oversteer as the vehicle traveled around the left curve, then b_{lk}, the steering drift, would be a negative; while if the driver or the AHS were to understeer, the steering drift would be positive. Alternatively, if there was an initial overshoot or undershoot that the driver or the AHS corrected before the end of the curve, then I_{lk}, the steering instability, would be relatively large and there would be very few steering oscillations.

Using the Bloomfield and Carroll equations, comparisons are made among:

(1) The ability of the driver to steer around the curve when he/she controlled only the steering of the vehicle.
(2) The ability of the driver to steer around the curve when he/she controlled both the steering and the velocity of the vehicle.
(3) The ability of the AHS to steer around the curve when the driver controlled the velocity of the vehicle.

Time Delay

The concept of time delay, utilized in the analyses of the earlier experiments in this series that were concerned with the transfer of control between the driver and the AHS, was employed again here.[1,2,3] In the current experiment, time delay was defined as the amount of time that the vehicle immediately behind the driver was delayed because the driver was controlling the velocity of the simulator vehicle while it traveled through the reduced capability segment of the expressway, i.e., the time delay experienced by the vehicle following the driver's vehicle that occurred during the time period that started at the moment that the driver took control of the lost function (or functions) and ended at the moment that the AHS resumed control of the lost function(s).

The time delay, T, is given by the following equation:

$$T = \frac{(d_1 - d_2)}{V} \tag{5}$$

where:

d_1 was the distance that would have been traveled by an automated vehicle if it was traveling at the designated AHS velocity during the time period that started at the moment that the driver took control of the lost function (or functions) and ended at the moment that the AHS resumed control of the lost function(s).

d_2 was the distance traveled by the driver's vehicle during the time period that started at the moment that the driver took control of the lost function (or functions) and ended at the moment that the AHS resumed control of the lost function(s).

V was the designated AHS velocity.

It should be noted that when the lost function was control of the steering, the AHS continued to control the velocity of the driver's vehicle and that, in this case, T had to be zero. In contrast, when the AHS did not control either the velocity or both the velocity and steering of the vehicle, T could only be zero if the driver drove exactly at the designated AHS velocity, and would be positive if the driver drove slower than the designated AHS velocity.

If the time delay is found to be relatively small, it should be because the driver drove at a speed that was close to the designated AHS velocity; while, in contrast, if the time delay is relatively large, it should be because the driver drove at a speed that was considerably slower than the designated AHS velocity. In order to explore these possibilities, the average speed of the driver's vehicle when the *Resumption of Control* advisory was issued at the end of the segment was compared to the time delay that was obtained.

DATA ANALYSIS

The focus of the data analysis for the current experiment was on lane keeping and average speed. The following data items were recorded in the current experiment:

- Designated AHS velocity of the vehicles in the automated lane.
- Track of the simulator vehicle.
- Continuous plot of the velocity of the simulator vehicle.

- Continuous plot of the position of the simulator vehicle.
- Whether the driver's vehicle collided with any other vehicles and, if so, when the collision occurred.
- Time at which the *Reduced Capability* advisory was issued (for the driver-controlled method of transfer).
- Time at which the *Reduced Capability* command was issued (for the situation-controlled method of transfer).
- Time when the driver took control of the lost function(s).
- Lane changes made during the time that the driver was partially or completely controlling the vehicle.
- Time at which the *Resumption of Control* advisory was issued.

In this experiment, the continuous data were sampled and collected at a rate of 30 Hz. Using equations 1 through 4, the following lane-keeping measures were calculated for each driver in each trial from these continuous data:

- Initial lane position—a_{lk}
- Steering drift—b_{lk}
- Steering instability—I_{lk}
- Number of steering oscillations per minute, i.e., the number of times per minute that the vehicle crossed the line of best fit.

A five-way analysis of variance (ANOVA) was conducted for each of these lane-keeping measures. Each ANOVA compared one of the aspects of the steering ability of the driver—as measured by the lane-keeping measures—when he/she controlled only the steering (while the AHS controlled speed) and when he/she controlled both steering and speed with the steering ability of the AHS when it controlled steering (and the driver controlled speed). The latter condition is essentially the baseline condition; by comparing it with the two conditions in which the driver controlled the steering, it was possible to determine whether the way in which the driver steered the vehicle was different from the way in which the steering was controlled by the AHS.

In addition to obtaining these measures of steering ability, the average speed while the vehicle was in the reduced-capability segment and the average speed at the end of the segment were determined for each driver in each trial. Additional five-way analyses of variance were conducted for each of these velocity measures.

The statistically significant results that were found in the analyses of the lane-keeping and velocity measures are discussed in the subsections that follow.

Initial Position in the Lane at the Start of the Curve

The first measure to be analyzed was the initial position in the lane (a_{lk}). It should be noted that the value of a_{lk} indicates the point at which the line of best fit for the track of the vehicle cuts the perpendicular line across the lane at the start of the segment being analyzed—it is not the actual position of the vehicle in the lane at the start of that segment.

Table 4 lists the statistically significant effects that were found when the analysis of variance (ANOVA) of the initial position in the lane (the a_{lk} value) at the start of the curve was conducted. The complete summary table for this ANOVA is presented as table 19 in appendix 4.

Table 4. Summary of the statistically significant effects found by the ANOVA conducted to determine whether the initial position in the lane at the start of the curve was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	p-value
Age of the Driver (A)	0.0033
Designated AHS Velocity (V)	0.0001
Control Transfer Method (T)	0.0001
Intra-String Gap (G)	0.0154
Reduced Capability Mode (R)	0.0001
A x R	0.0001
G x R	0.0345

As table 4 indicates, all five independent variables had significant effects on a_{lk}. In addition, the table shows that the variable of greatest interest in the current experiment—the reduced-capability mode—was involved in two interactions: with the age of the driver and with the intra-string gap. The discussion that follows deals first with these two interactions, then continues with a description of the effects of the control transfer method and the designated AHS velocity on the initial position in the lane.

Reduced-Capability Mode (With Age of the Driver and Intra-String Gap). The significant interactions of the reduced-capability mode with the age of the driver and with the intra-string gap are illustrated in figures 5 and 6, respectively. In both figures, the initial position of the vehicle in the lane is expressed in terms of the offset from the center of the lane—if the initial position of the driver's vehicle is to the left of the center of the lane, then the offset will be positive; if the driver's vehicle is to the right of the center of the lane, the offset will be negative.

The interaction between the reduced-capability mode and the age of the driver is explored in figure 5. The figure shows that at the start of the curve, when the AHS controlled the steering (i.e., when the driver controlled the velocity), the mean initial offset was to the left of the center of the lane—the a_{lk} value was between +0.16 m (+0.53 ft) and +0.28 m (+0.92 ft).[1] In contrast, when the driver controlled both the steering and the velocity, the mean initial offset was to the right of the center of the lane—the a_{lk} value was between –0.02 m (–0.07 ft) and –0.16 m (–0.52 ft).

For the third reduced-capability mode—when the driver controlled the steering (i.e., when the AHS controlled the velocity)—the offset of the older drivers was quite different from the offset of the younger drivers. In this mode, the older drivers had a mean initial offset that was to the left of the center of the lane: a_{lk} was +0.25 m (+0.82 ft)—a value similar to the offsets obtained when the AHS controlled the steering. On the other hand, the younger drivers had a mean initial offset to the right of the center of the lane—their mean a_{lk} value was –0.02 m (–0.06 ft), which was in the same direction as when the driver controlled both the steering and the velocity.

The interaction between the reduced-capability mode and the age of the driver occurred because the initial offsets were more to the left for the younger drivers than for the older drivers when the steering was controlled by the AHS, but more to the right for the younger drivers than for the older drivers in the other two reduced-capability modes.

[1] Differences in the offset position of the vehicle from the center of the lane occurred for the older and younger drivers when the AHS controlled the steering and the driver controlled the speed of the vehicle. This surprising finding occurred because of the method by which the AHS controlled the steering—which is described on page 66—and because of the way that this method interacted with velocity—see also the discussion on pages 67 through 69.

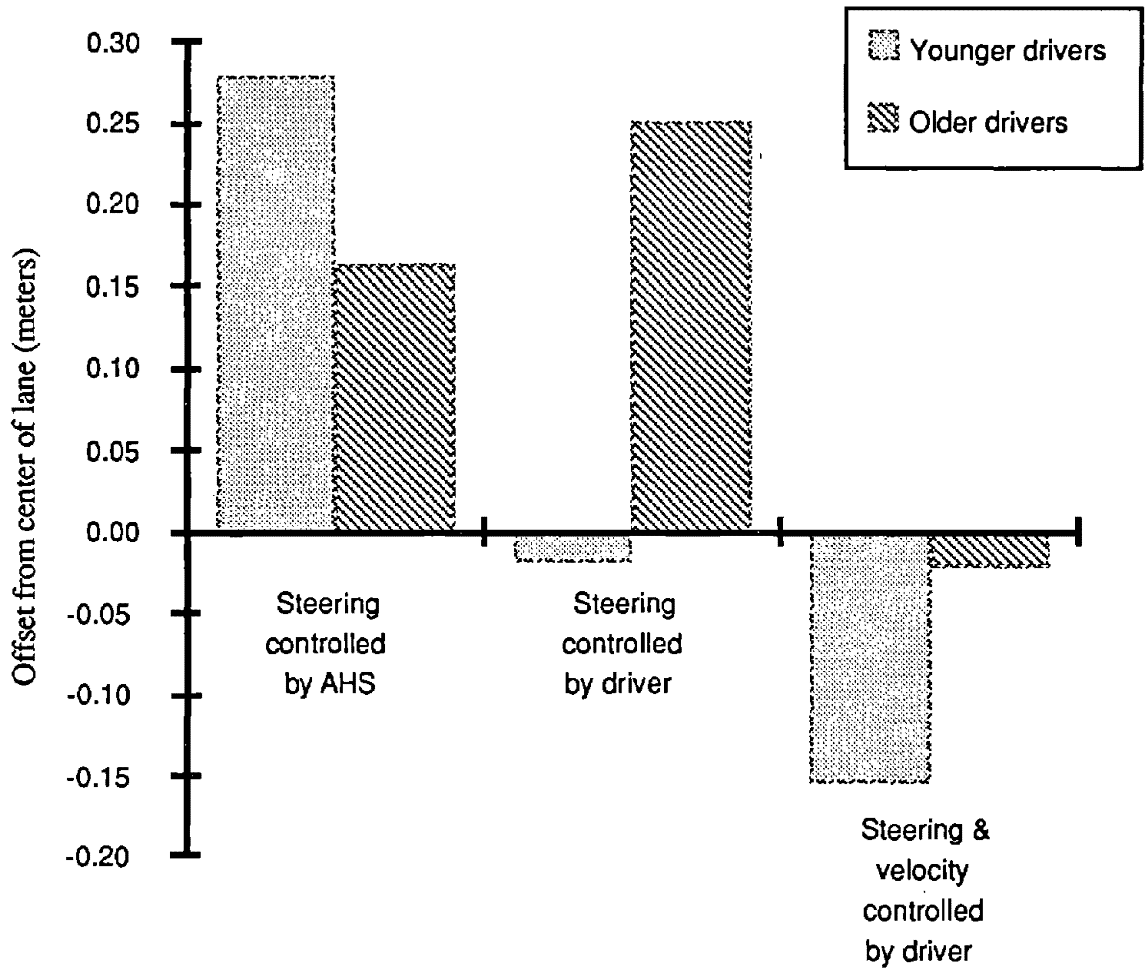


Figure 5. Mean initial offset of the driver's vehicle from the center of the lane, at the start of the 735-m (2410-ft) curve to the left, for both older and younger drivers, in all three reduced-capability modes. [Note: When the mean value is positive, the offset is to the left of the center line; when the mean value is negative, the offset is to the right of the center line.]

Figure 6—illustrating the interaction between the reduced-capability mode and the intra-string gap—is very similar to figure 5. It shows that at the start of the curve, when the AHS controlled the steering (i.e., when the driver controlled the velocity), the mean initial offset was to the left of the center of the lane—the a_{lk} value was between +0.21 m (+0.68 ft) and +0.24 m (+0.79 ft); and that, in contrast, when the driver controlled both the steering and the velocity, the mean initial offset was to the right of the center of the lane, with the a_{lk} value between –0.03 m (–0.10 ft) and –0.15 m (–0.49 ft).

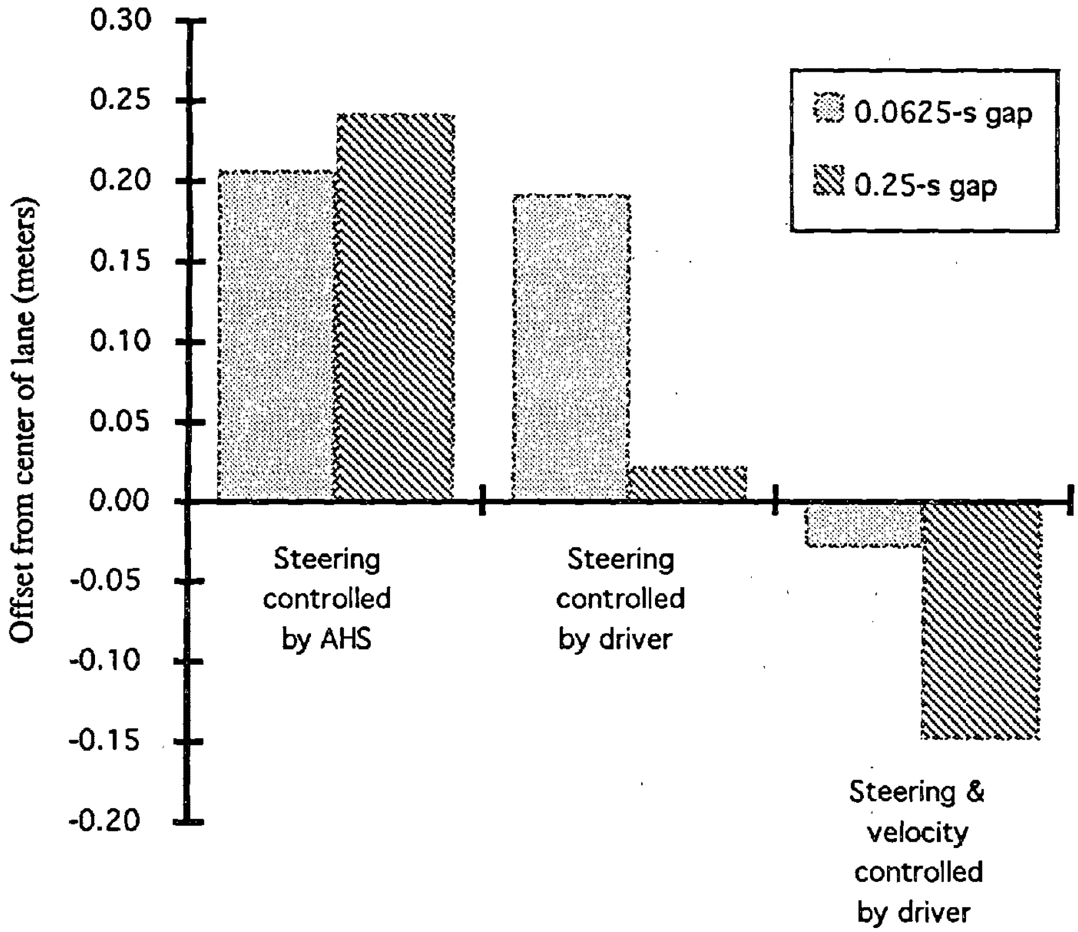


Figure 6. Mean initial offset of the driver's vehicle from the center of the lane, at the start of the 735-m (2410-ft) curve to the left, with both intra-string gaps, in all three reduced-capability modes. [Note: When the mean value is positive, the offset is to the left of the center line; when the mean value is negative, the offset is to the right of the center line.]

For the third reduced-capability mode—when the driver controlled the steering (i.e., when the AHS controlled the velocity)—figure 6 shows that while the offsets were both to the left, their magnitudes were distinctly different for the two intra-string gaps. The mean offset for the smaller (0.0625-s) gap was +0.19 m (+0.63 ft)—similar to the offsets obtained when the AHS controlled the steering—while for the larger (0.25-s) intra-string gap, the a_{lk} value of +0.02 m (+0.07 ft) was much smaller.

The interaction between the reduced-capability mode and the size of the intra-string gap occurred because for the 0.0625-s intra-string gap, the initial offset was more to the right than the offset for the 0.25-s gap when the steering was controlled by the AHS, but more to the left for both conditions in which the driver controlled the steering.

Control Transfer Method. The effect of the method of transferring control from the AHS to the driver on the initial lane position of the driver's vehicle at the start of the curve is illustrated in figure 7.

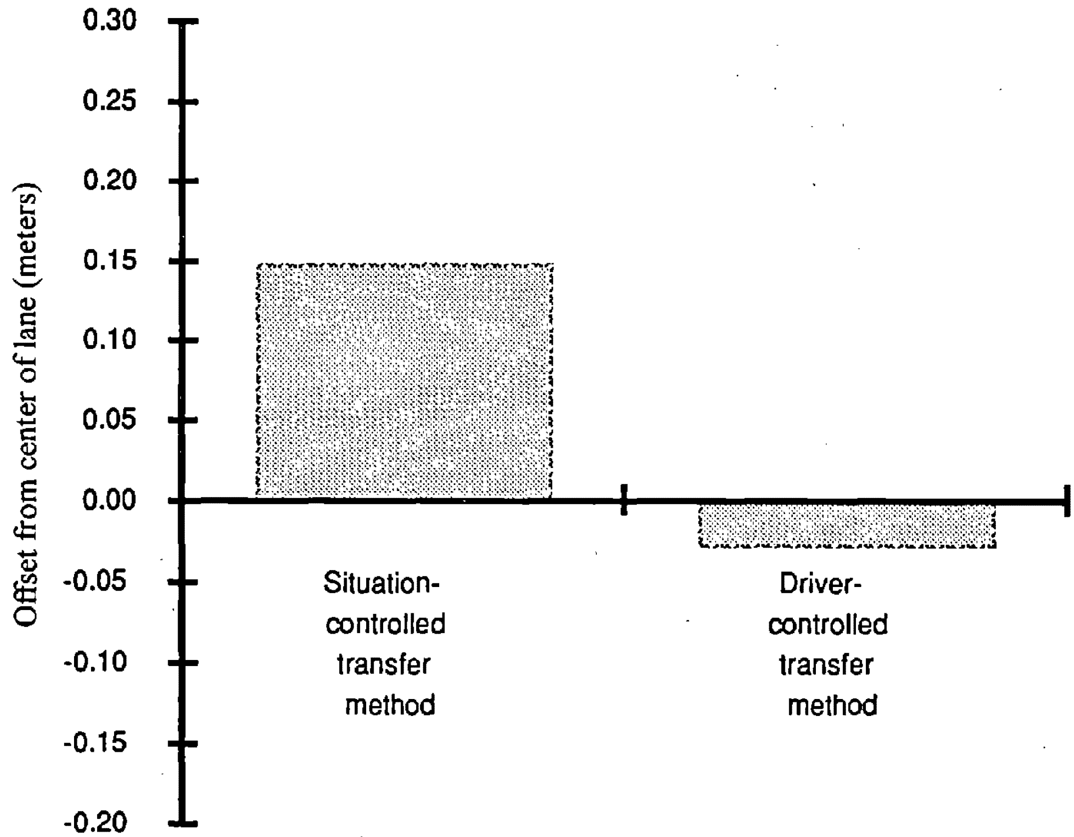


Figure 7. Mean initial offset of the driver's vehicle from the center of the lane, at the start of the 735-m (2410-ft) curve to the left, for both control transfer methods. [Note: When the mean value is positive, the offset is to the left of the center line; when the mean value is negative, the offset is to the right of the center line.]

When the situation-controlled method of transfer was used, the mean initial offset was to the left of the center of the lane—the a_{lk} value was +0.15 m (+0.48 ft); in contrast, when the driver-controlled method of transfer was used, the mean initial offset was to the right of the center of the lane—in this case, the a_{lk} value was –0.03 m (–0.10 ft).

It should be noted that there was a considerable difference in the distance traveled in the straight section of the expressway before the start of the curve for the drivers in the two control transfer groups. The drivers who used the situation-controlled method of transfer were unable to take control of the lost function until the simulator vehicle was approximately 30 m (98.4 ft) away from the start of the curve; while, in contrast, the drivers who used the driver-controlled method of transfer could take control of the lost function as early as 20 s or as late as 30 m (98.4 ft) before the simulator vehicle arrived at the start of the curve.

Designated AHS Velocity. The effect of variations in the designated AHS velocity on the initial lane position of the driver's vehicle is illustrated in figure 8. The figure shows that at the start of the curve, when the designated AHS velocity was 128.8 km/h (80 mi/h), the mean a_{lk} value was –0.02 m (–0.05 ft), so the initial offset was to the right of the center of the lane; when the designated AHS velocity was 153.0 km/h (95 mi/h), the mean a_{lk} value was +0.17 m (+0.55 ft) and the initial offset was to the left of the center of the lane.

Steering Drift

Steering drift was the second lane-keeping measure analyzed. The steering drift (b_{lk}) is the gradient of the line of best fit for the track of the vehicle—it indicates the distance that the driver's vehicle has moved laterally across the lane as a function of the distance the vehicle has traveled longitudinally along the lane.

Table 5 lists the statistically significant effects found when the ANOVA for the steering drift measure was conducted. The complete summary table for this ANOVA is presented as table 20 in appendix 4. Table 5 shows that the only independent variable that had a statistically significant effect on b_{lk}—the reduced-capability mode—was, in addition, involved in two significant interactions—one with the age of the driver, the other with the designated AHS velocity.

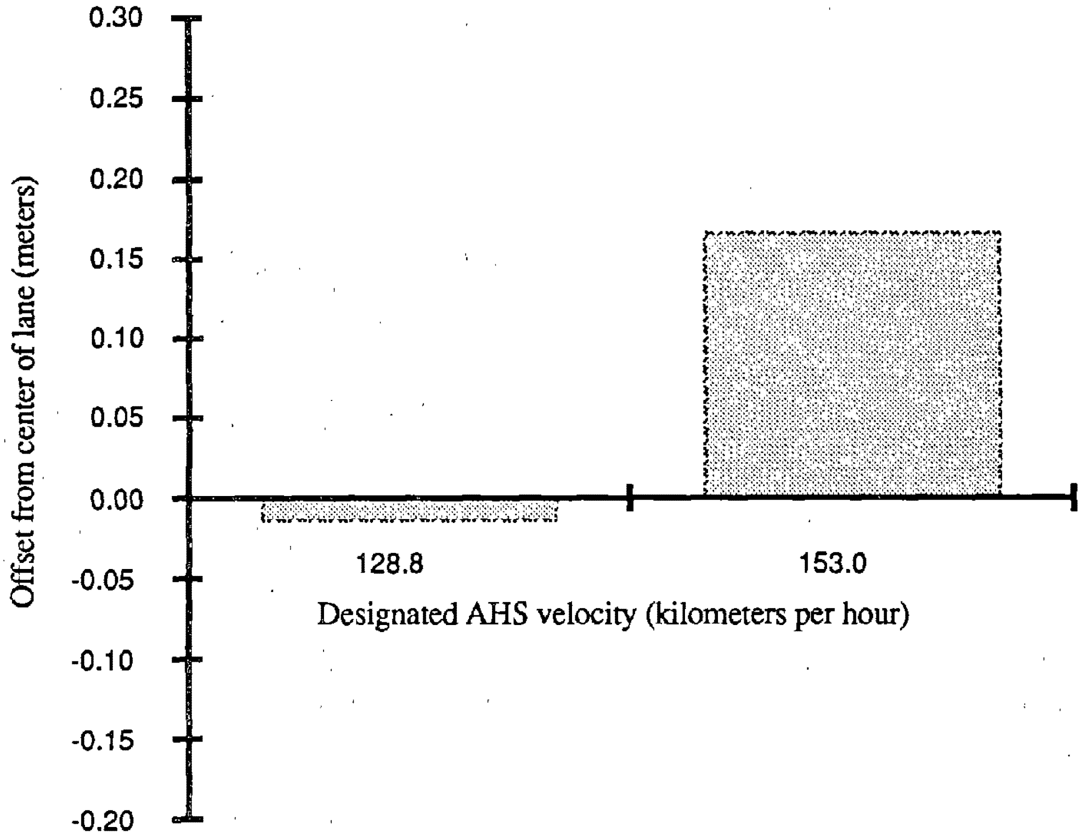


Figure 8. Mean initial offset of the driver's vehicle from the center of the lane, at the start of the 735-m (2410-ft) curve to the left, for both designated AHS velocities. [Note: When the mean value is positive, the offset is to the left of the center line; when the mean value is negative, the offset is to the right of the center line.]

Table 5. Summary of the statistically significant effects found by the ANOVA conducted to determine whether the steering drift was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	p-value
Reduced-Capability Mode (R)	0.0001
Age of the Driver (A) x R	0.0319
Designated AHS Velocity (V) x R	0.0009

The significant interactions of the reduced-capability mode with the age of the driver and with the designated AHS velocity are illustrated in figures 9 and 10, respectively. Irrespective of the initial position in the lane at the start of the curve, both of these figures indicate whether the simulator vehicle tended to drift towards the left or the right of the lane as it traveled around the curve. If the steering drift (i.e., the b_{lk} value) was positive, the vehicle was drifting across the lane from the right to the left; if it was negative, the vehicle was drifting from left to right.

Reduced-Capability Mode (With Age of the Driver). Figure 9 illustrates the interaction between the reduced-capability mode and the age of the driver. When the AHS controlled the steering (and the driver controlled the velocity), the steering drifts for both younger and older drivers

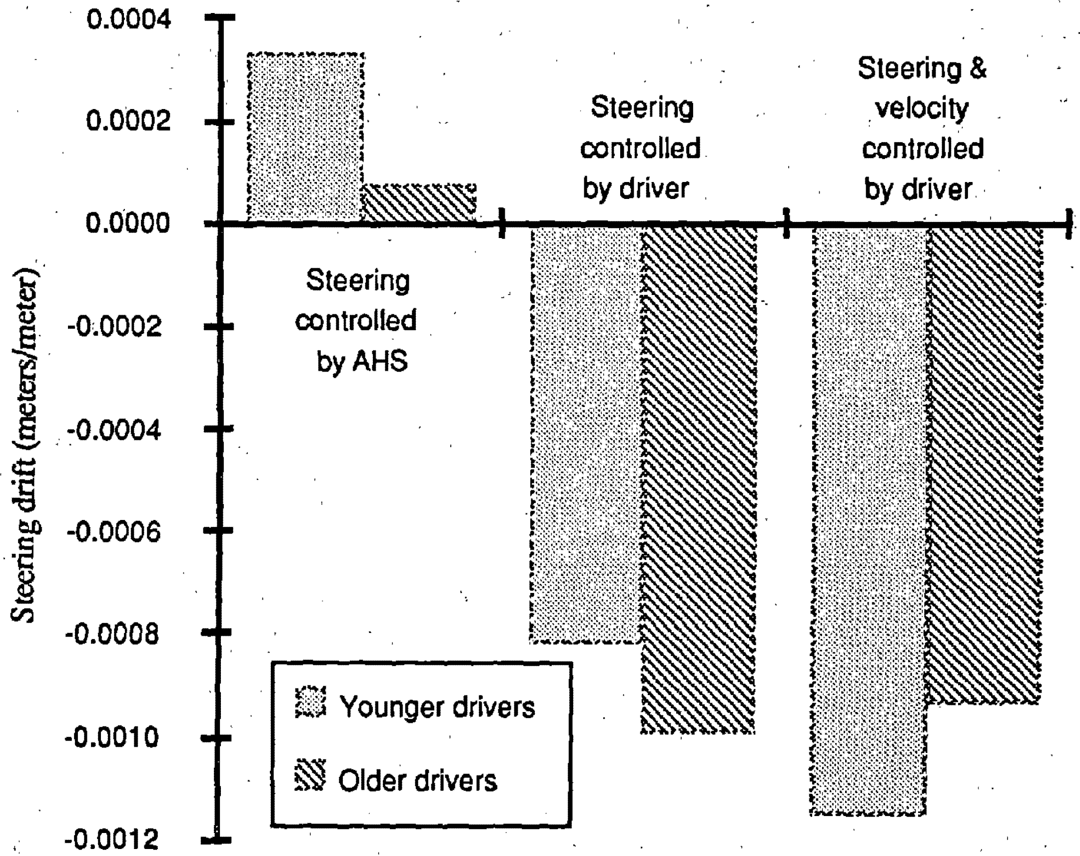


Figure 9. Mean steering drift as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode, for the older and younger drivers. [Note: If the steering drift is positive, the vehicle was drifting from right to left; if the steering drift is negative, the vehicle was drifting from left to right; and if the steering drift is zero, the vehicle was traveling parallel to or along the center line.]

were positive and relatively small—they were +0.00033 m/m (+0.00033 ft/ft) and +0.00008 m/m (+0.00008 ft/ft), respectively. These steering drift values indicate that the vehicle undershot the center line of the lane as it traveled around the curve. In contrast, for the two reduced-capability modes in which the driver controlled the steering, i.e., both when the AHS controlled the velocity and when the driver controlled the velocity as well as the steering, the steering drifts were negative and relatively large, with b_{lk} values ranging between –0.00082 m/m (–0.00082 ft/ft) and –0.00115 m/m (–0.00115 ft/ft). These steering drift values indicate that in both reduced-capability modes, the driver tended to allow the vehicle to drift to the right and overshoot the center line of the lane while steering the vehicle around the left curve.

Figure 9 also indicates why there was an interaction between the reduced-capability mode and the age of the driver. In the two conditions in which the control was split between the AHS and the driver (i.e., when the AHS controlled the steering and the driver controlled the velocity, and vice versa), the older drivers had more steering drift to the right than the younger drivers; when the driver controlled both the steering and the velocity, the younger drivers had more steering drift to the right than the older drivers.

Reduced-Capability Mode (With Designated AHS Velocity). Figure 10 illustrates the interaction between the reduced-capability mode and the designated AHS velocity. The figure shows that for both designated AHS velocities, when the AHS controlled the steering of the simulator vehicle, there were relatively small positive steering drifts of +0.00008 m/m (+0.00008 ft/ft) and +0.00036 m/m (+0.00036 ft/ft) for the 128.8-km/h (80-mi/h) and 153.0-km/h (95-mi/h) designated AHS velocities, respectively, indicating that the simulator vehicle undershot the center line of the lane as it traveled around the curve.

In contrast, when the driver controlled the steering alone or controlled both the steering and the velocity, the drifts were larger and negative—they were –0.00070 m/m (–0.00070 ft/ft) and –0.00109 m/m (–0.00109 ft/ft) for the 128.8-km/h (80-mi/h) and 153.0-km/h (95-mi/h) designated AHS velocities, respectively, when the driver controlled the steering alone; and –0.00093 m/m (–0.00093 ft/ft) and –0.00116 m/m (–0.00116 ft/ft) for the 128.8-km/h (80-mi/h) and 153.0-km/h (95-mi/h) designated AHS velocities, respectively, when the driver controlled both the steering and velocity. In each of these cases, the simulator vehicle overshot the center line of the lane as it traveled around the curve.

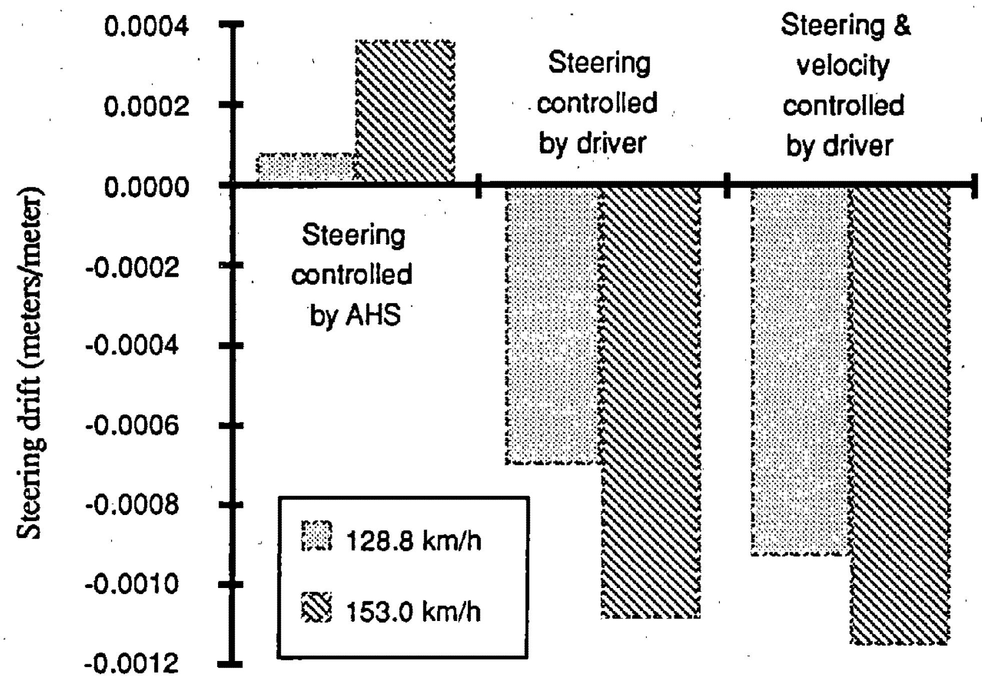


Figure 10. Mean steering drift as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode, for both designated AHS velocities. [Note: If the steering drift is positive, the vehicle was drifting from right to left; if the steering drift is negative, the vehicle was drifting from left to right; and if the steering drift is zero, the vehicle was traveling parallel to or along the center line.]

The interaction between the reduced-capability mode and the designated AHS velocity occurred, as figure 10 shows, because there was a greater drift to the left at 153.0 km/h (95 mi/h) when the AHS controlled the steering, but a greater drift to the right at that velocity in both conditions when the driver controlled the steering.

Steering Instability

The third lane-keeping measure analyzed was the steering instability (I_{lk}). I_{lk} is a measure of the variability in streeing around the line of best fit for the track of the vehicle.

The ANOVA conducted on I_{lk}, the steering instability, indicated that four of the independent variables had statistically significant effects, and that in addition, there were two significant interactions—they are listed in table 6. The complete summary table for this ANOVA is presented as table 21 in appendix 4.

Table 6. Summary of the statistically significant effects found by the ANOVA conducted to determine whether the steering instability was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	p-value
Age of the Driver (A)	0.0069
Designated AHS Velocity (V)	0.0001
Control Transfer Method (T)	0.0070
Reduced-Capability Mode (R)	0.0001
A x T x Intra-String Gap (G)	0.0268
V x T x G x R	0.0178

As table 6 shows, four of the independent variables—the age of the driver, the designated AHS velocity, the control transfer method, and the reduced-capability mode—had significant effects on I_{lk}. There were also two higher order significant interactions—one of which was a four-way interaction that involved all of the independent variables except the age of the driver, while the other was a three-way interaction among the age of the driver, the control transfer method, and the intra-string gap. In the subsections that follow, the four-way interaction is discussed first.

Reduced-Capability Mode (With Designated AHS Velocity, Control Transfer Method, and Intra-String Gap). Figure 11 illustrates the interaction of the reduced-capability mode—the variable of particular interest in this experiment—with the designated AHS velocity, the control transfer method, and the intra-string gap. The figure is complex because it shows steering instability as a function of the reduced-capability mode for each combination of designated AHS velocity, control transfer method, and intra-string gap. However, inspection of the figure reveals that there are two relatively large effects. First, for all eight combinations of designated AHS velocity, control transfer method, and intra-string gap, there was less steering instability when the AHS controlled the steering than when it was controlled by the driver. Second, for all 12 combinations of reduced-capability mode, control transfer method, and intra-string gap, there was less steering instability when the designated AHS velocity was 128.8 km/h (80 mi/h) than when it was 153.0 km/h (95 mi/h). These two effects are described in more detail in the two subsections that follow this discussion.

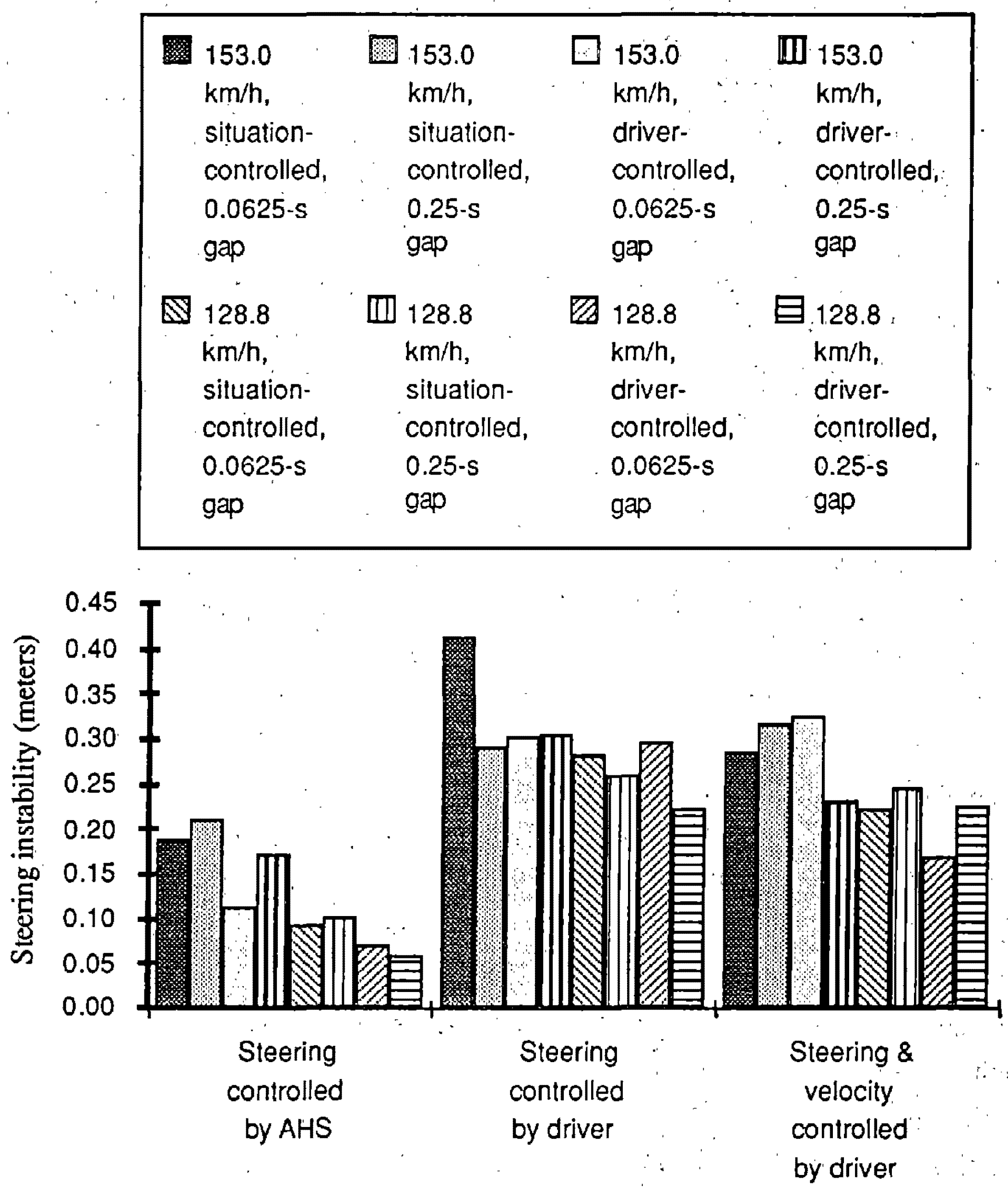


Figure 11. Mean steering instability as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode, for both designated AHS velocities, both control transfer methods, and both intra-string gaps.

The effects of the method of control transfer and of the intra-sting gap were less clear cut. First, considering the method of control transfer, there was more steering instability associated with the situation-controlled transfer method than there was with the driver-controlled transfer method for 9 of the 12 combinations of reduced-capability mode, designated AHS velocity, and intra-string gap; while in the remaining 3 cases, there was more steering instability when the driver-controlled transfer method was used. The three exceptions occurred when the driver controlled: (1) the steering alone with a 0.0625-s intra-string gap at a designated AHS velocity of 128.8 km/h (80 mi/h), (2) the steering alone with a 0.25-s intra-string gap at a designated AHS velocity of 153.0 km/h (95 mi/h), and (3) both the steering and velocity with a 0.0625-s intra-string gap at a designated AHS velocity of 153.0 km/h (95 mi/h).

Second, considering the intra-string gap, there was more steering instability associated with the 0.25-s intra-string gap than there was with the 0.0625-s intra-string gap for 7 of the 12 combinations of reduced-capability mode, designated AHS velocity, and control transfer method; while in the remaining 5 cases, there was less steering instability with the 0.0625-s intra-string gap than there was with the 0.25-s intra-string gap.

For two of the main effects involved in the four-way interaction shown in figure 11—reduced-capability mode and designated AHS velocity—each of their effects was in the same direction for **all combinations** of the other three variables. Because these effects stand out so clearly, they are discussed individually below.

Reduced-Capability Mode. The effect, mentioned in the subsection above, that varying the reduced-capability mode has on the steering instability can be seen clearly in figure 12. The figure shows that the steering instability was only 0.13 m (0.43 ft) when the AHS controlled the steering (and the driver controlled the velocity); the steering instability increased to 0.29 m (0.95 ft) when the driver controlled only the steering (and the AHS controlled the velocity); and the steering instability was 0.25 m (0.82 ft) when the driver controlled both the steering and the velocity.

Designated AHS Velocity. The second effect—also mentioned above—that varying the designated AHS velocity has on the steering instability is illustrated in figure 13. The figure shows that there was less steering instability when the designated AHS velocity was 128.8 km/h (80 mi/h) than when it was 153.0 km/h (95 mi/h)—the instability values obtained with these designated AHS velocities were 0.19 m (0.63 ft) and 0.27 m (0.88 ft), respectively.

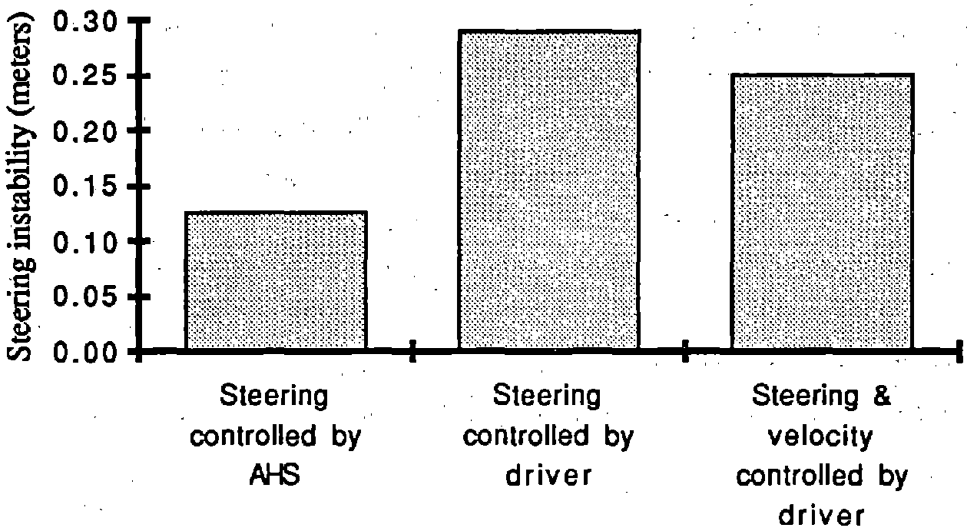


Figure 12. Mean steering instability as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode.

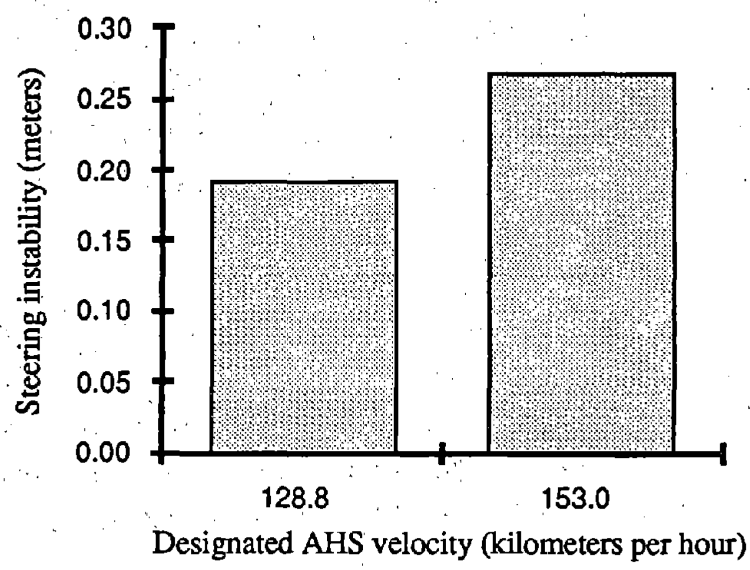


Figure 13. Mean steering instability as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the designated AHS velocity.

Age of the Driver, Control Transfer Method, and Intra-String Gap. Figure 14 explores the three-way interaction among the age of the driver, the control transfer method, and the intra-string gap that was found when the I_{lk} values were analyzed. The figure shows that the older drivers had less steering instability than the younger drivers in three of the four combinations of intra-string gap and control transfer method. The older drivers had less steering instability than the younger drivers when the intra-string gap was 0.0625 s and they transferred control using either the situation-controlled or the driver-controlled transfer method, as well as when the intra-string gap was 0.25 s and they transferred control using the driver-controlled method. The exception occurred when the situation-controlled transfer method was combined with the 0.25-s gap—in this case, the older drivers had more steering instability than the younger drivers.

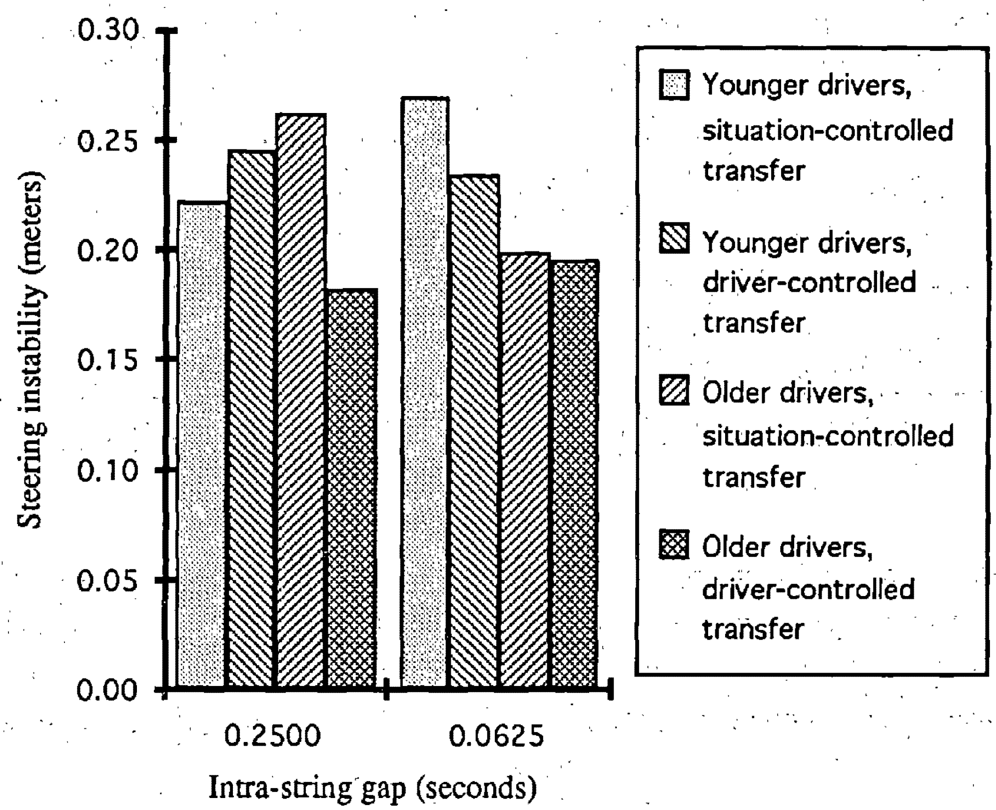


Figure 14. Mean steering instability as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the intra-string gap, for the younger and older drivers, and both control transfer methods.

Steering Oscillations

The fourth lane-keeping measure to be analyzed was the number of steering oscillations per minute, i.e., the number of times per minute that the track of the vehicle crossed the line of best fit. Table 7 lists the significant effects and interactions that were obtained when an ANOVA was conducted on the rate at which steering oscillations occurred when the driver was traveling around the curve. The complete summary table for this ANOVA is presented as table 22 in appendix 4.

Table 7 indicates that the age of the driver and the reduced-capability mode had statistically significant effects on the number of steering oscillations per minute, and that there was a significant interaction between these two variables. In addition, the table shows that the reduced-capability mode was also involved in interactions with the other three independent variables—there was a significant two-way interaction involving the reduced-capability mode and the designated AHS velocity, and a three-way interaction between the reduced-capability mode, the control transfer method, and the intra-string gap. These various interactions are discussed in the subsections that follow.

Table 7. Summary of the statistically significant effects found by the ANOVA conducted to determine whether the number of steering oscillations per minute was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	p-value
Age of the Driver (A)	0.0126
Reduced-Capability Mode (R)	0.0001
A x R	0.0038
Designated AHS Velocity x R	0.0001
Control Transfer Method x Intra-String Gap x R	0.0265

Reduced-Capability Mode (With Age of the Driver). Figure 15 explores the interaction between the reduced-capability mode and the age of the drivers. As expected, the figure shows that when the steering was controlled by the AHS (and the driver controlled the velocity), there was essentially no difference in the mean number of steering oscillations per minute that occurred with

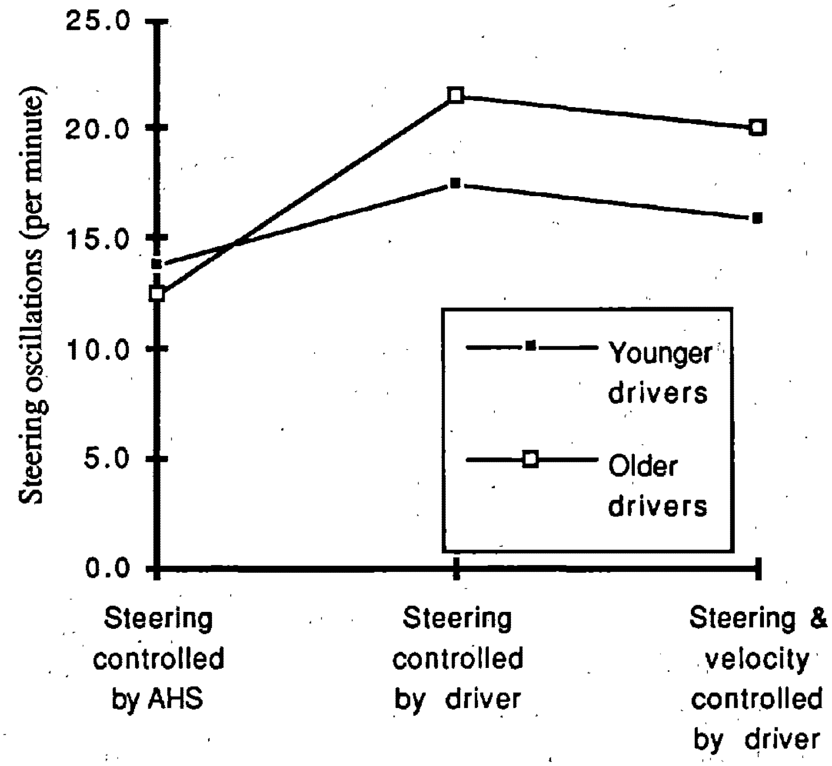


Figure 15. Mean number of steering oscillations per minute as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode, for the younger and older drivers.

younger drivers and with older drivers. However, there was an interaction between the reduced-capability mode and the age of the drivers: When the steering or the steering and the velocity were controlled by the driver, there were more oscillations per minute for the older drivers than for the younger drivers—20.1 and 21.5 steering oscillations per minute, respectively, for the older drivers, and 15.9 and 17.4, respectively, for the younger drivers. In contrast, there was essentially no difference in the number of oscillations for the two age groups when the AHS controlled the steering.

<u>Reduced-Capability Mode (With Designated AHS Velocity).</u> The interaction between the reduced-capability mode and the designated AHS velocity is explored in figure 16. The figure shows that when the steering was controlled by the AHS (and the driver controlled the velocity), there were more steering oscillations per minute when the designated AHS velocity was 128.8 km/h (80 mi/h) than when it was 153.0 km/h (95 mi/h)—the mean number of oscillations

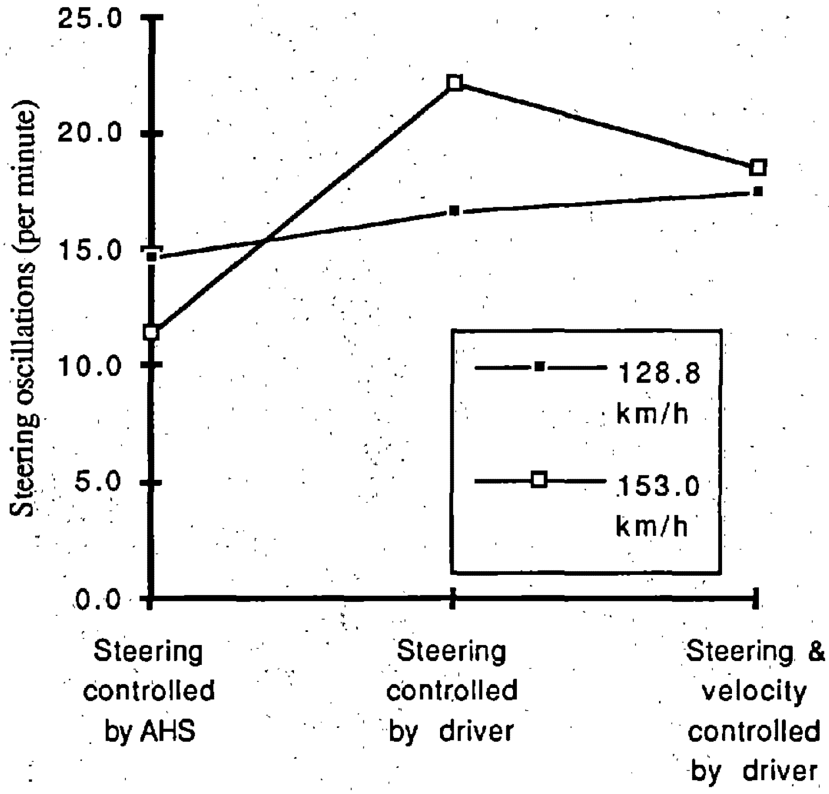


Figure 16. Mean number of steering oscillations per minute as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode, for both designated AHS velocities.

per minute for these two velocities were 14.6 and 11.5, respectively. However, this finding was reversed when the driver controlled only the steering (and the AHS controlled the velocity). In this case, there were more oscillations per minute when the velocity was 153.0 km/h (95 mi/h) than there were when the velocity was 128.8 km/h (80 mi/h)—the means were 22.1 and 16.6, respectively. And, when the driver controlled both the steering and the velocity, there was no statistically significant difference in the mean number of steering oscillations per minute obtained for the two designated AHS velocities—there were approximately 18 for both of them.

Reduced-Capability Mode (With Control Transfer Method and Intra-String Gap). The three-way interaction among the reduced-capability mode, the control transfer method, and the intra-string gap is illustrated in figure 17.

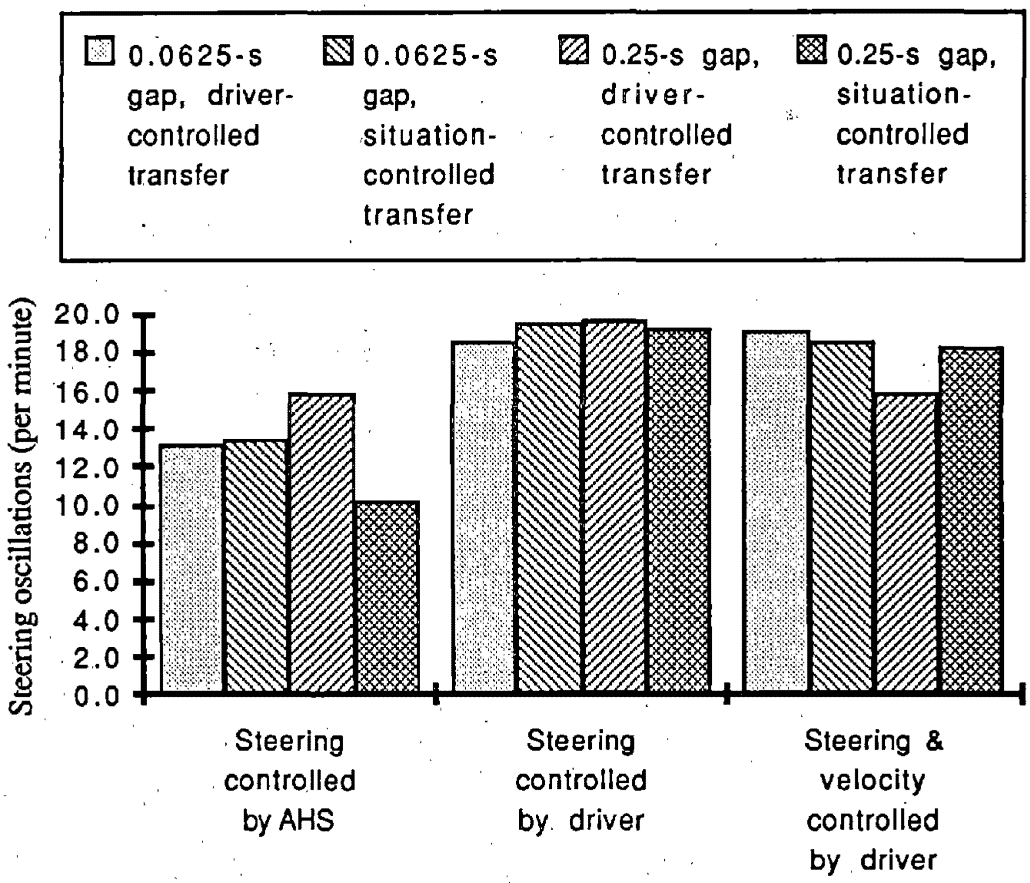


Figure 17. Mean number of steering oscillations per minute as the driver's vehicle traveled around the 735-m (2410-ft) curve to the left, as a function of the reduced-capability mode, for both control transfer methods, and both intra-string gaps.

As with figures 15 and 16, figure 17 shows that there were fewer steering oscillations per minute when the AHS was controlling the steering of the simulator vehicle (and the driver was controlling its velocity) than there were when the driver was controlling the steering.

The reason that there was an interaction among the three variables was as follows: In the situations where the driver was controlling only the steering and the situations where he/she was controlling both the steering and the velocity, the mean numbers of oscillations were essentially the same (approximately 18.5) for all combinations of control transfer method and for intra-string gap. In contrast, when the AHS was controlling the steering, there were relatively few steering oscillations (only 10.2) where the intra-string gap was 0.25 s and velocity control was transferred from the AHS to the driver using the situation-controlled method; while there were more oscillations per minute (approximately 13.3) where the intra-string gap was 0.0625 s and velocity control was transferred to the driver using either of the control transfer methods; and there were still more oscillations per minute (15.9) where the intra-string gap was 0.25 s and velocity control was transferred to the driver using the driver-controlled method.

Time Delay

Up to this point, the results that have been described all relate to steering control while the vehicle was in the curved portion of the reduced-capability segment. Now, by turning to the time delay measure, it is possible to determine if, and how, the velocity of the simulator vehicle was affected—however, this comparison was made for the whole of the reduced-capability segment, including the straight portion that occurred before the curve. Table 8 lists the significant variables and interactions that were obtained when an ANOVA was conducted on the time delay. The complete summary table for this ANOVA is presented as table 23 in appendix 4.

Table 8. Summary of the statistically significant effects found by the ANOVA conducted to determine whether the time delay was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	p-value
Age of the Driver (A)	0.0001
Designated AHS Velocity (V)	0.0098
Control Transfer Method (T)	0.0001
Reduced-Capability Mode (R)	0.0001
A x V	0.0001
A x T	0.0167
A x R	0.0001
V x Intra-String Gap (G)	0.0191
T x R	0.0001
A x V x T	0.0056
A x V x R	0.0102
A x T x G	0.0099
A x T x R	0.0001
V x G x R	0.0019
A x V x T x R	0.0319
A x T x G x R	0.0044

As table 8 shows, the ANOVA conducted on the time delay data indicated that four of the independent variables, five of the two-way interactions, five of the three-way interactions, and two of the four-way interactions were statistically significant. The discussions in the subsections below focus first on the two four-way interactions, then the four statistically significant main effects are discussed.

Reduced-Capability Mode (With Age of the Driver, Control Transfer Method, and Intra-String Gap). Figure 18 illustrates the interaction involving the reduced-capability mode, the variable of particular interest in this experiment, with three other variables—the age of the driver, the intra-string gap, and the control transfer method. Inevitably, since it illustrates a four-way interaction, figure 18 seems complex. However, as the figure is inspected, several findings emerge.

The block of eight columns to the left of the histogram in figure 18 shows the mean time delays that were obtained when the AHS controlled the velocity (and the driver controlled the steering); the block of eight columns in the center shows the time delays obtained when the driver controlled the velocity (and the AHS controlled the steering); and the block of eight columns to the right shows the time delays obtained when the driver controlled both the velocity and the steering.

First, consider the block of eight columns to the left in figure 18. It is clear that these eight mean time delays—obtained when the velocity of the simulator vehicle was controlled by the AHS (and the steering was controlled by the driver)—for each of eight combinations of the age of the driver, the control transfer method, and the intra-string gap, and which are practically invisible on the figure, were essentially zero.

Next, consider the block of eight columns in the center of figure 18. Each column represents the mean time delay obtained when the driver controlled the velocity (and the AHS controlled the steering) for one of eight combinations of the age of the driver, the designated AHS velocity, and the control transfer method. The set of four columns to the left in this block shows the mean time delays that were obtained by the younger drivers—of this set, the two to the right show essentially zero mean time delays when the younger drivers gained control of velocity using the situation-controlled transfer method; while the two to the left show mean time delays of 1.6 s and 1.0 s when the younger drivers gained control using the driver-controlled transfer method. The set of four columns to the right in the center block presents the mean time delays for the older drivers. For three of them, there were considerable time delays (11.3 s, 10.0 s, and 3.9 s)—the exception occurred with the combination of a 0.25-s intra-string gap with the situation-controlled method of transfer (in this case, the time delay was only 0.8 s).

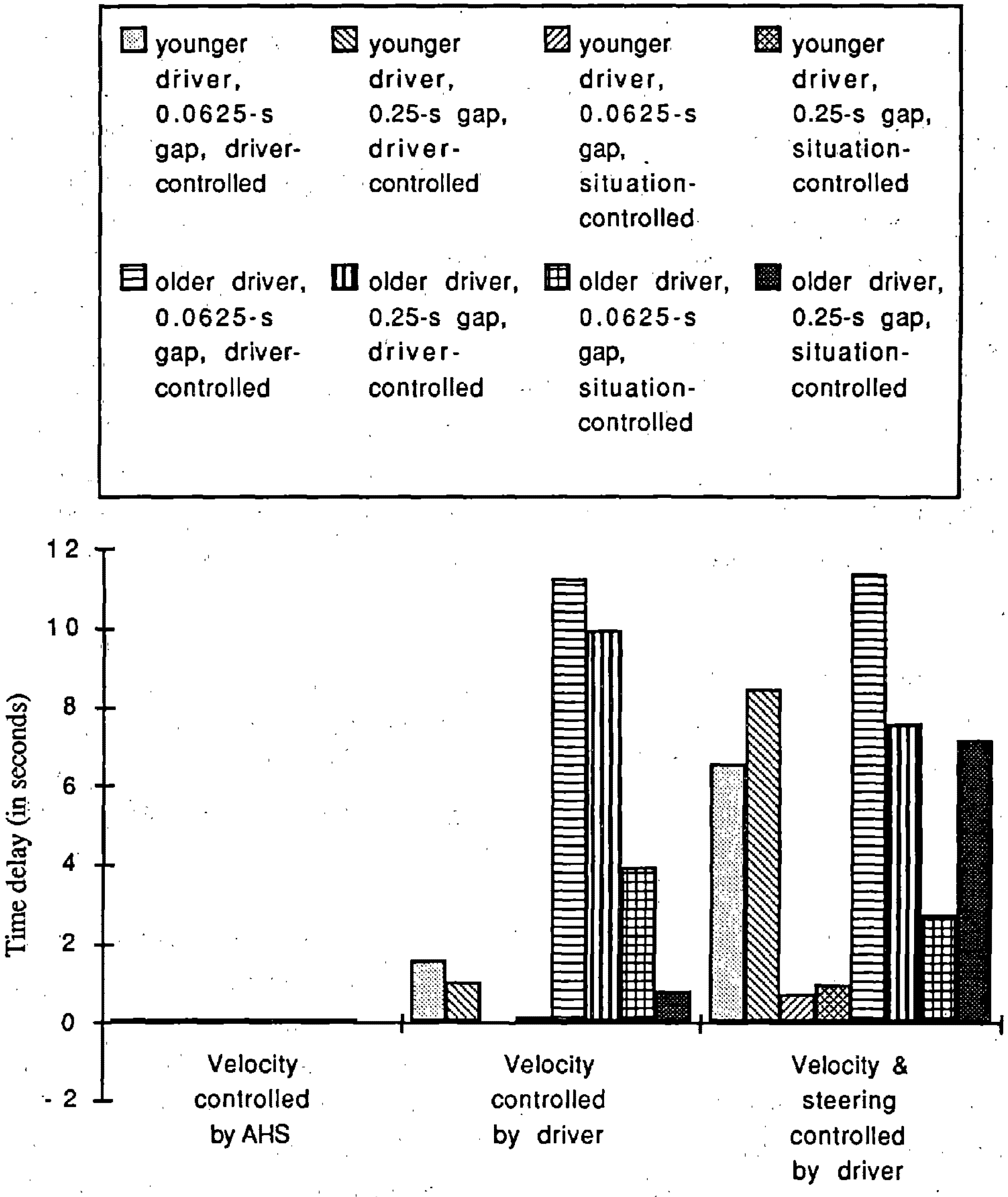


Figure 18. Mean time delay in the reduced-capability segment of the expressway, as a function of the reduced-capability mode, for the younger and older drivers, using both control transfer methods and driving with both intra-string gaps.

The eight columns in the right of the histogram in figure 18 represent the time delays that occurred when the driver controlled both the velocity and the steering. For two of the set of four columns in the left of this block—both of which represent time delays obtained when the younger drivers gained control using the driver-controlled transfer method—and three of the set of four columns in the right of the block representing mean time delays obtained with the older drivers, the time delays were in the range of 6.5 s to 11.4 s. The remaining three time delays were smaller—the two delays obtained when the younger drivers gained control with the situation-controlled transfer method were 0.8 s and 1.0 s, while the third (2.7 s) was obtained from the older drivers who had the 0.0625-s gap and the situation-controlled transfer method.

Reduced-Capability Mode (With Age of the Driver, Designated AHS Velocity, and Control Transfer Method). Like figure 18, figure 19 also illustrates a four-way interaction that was found when the time delay data were analyzed. In this case, there was an interaction involving the reduced-capability mode, the age of the driver, the designated AHS velocity, and the control transfer method.

As with the previous figure, if figure 19 is inspected block by block, several findings emerge. First, consider the block of eight columns at the left in the histogram in figure 18. They represent the mean time delays that were obtained (for the eight combinations of the age of the driver, the designated AHS velocity, and the control transfer method) when the velocity of the simulator vehicle was controlled by the AHS (and the steering was controlled by the driver). These eight columns are almost invisible, and after inspecting them, it can be concluded that when the velocity was controlled by the AHS, the simulator continued traveling at the designated AHS velocity, and the time delay was effectively zero—as it should be.

Next, consider the block of eight columns in the center of figure 19. These represent the time delays that were obtained when the driver controlled the velocity (and the AHS controlled the steering)—again, they were obtained for the eight combinations of the age of the driver, the designated AHS velocity, and the control transfer method. The set of four columns to the left in this block indicates the mean time delays for the younger drivers. The time delays for three of these combinations of designated AHS velocity and control transfer method were of the same order of magnitude as the time delay data in the first block of eight columns—and like them, they were essentially zero. The exception occurred for the combination of the 128.8-km/h (80-mi/h) designated AHS velocity and the driver-controlled transfer method—the mean time delay for this combination was 2.5 s. The mean time delays illustrated by the four columns in the right of this

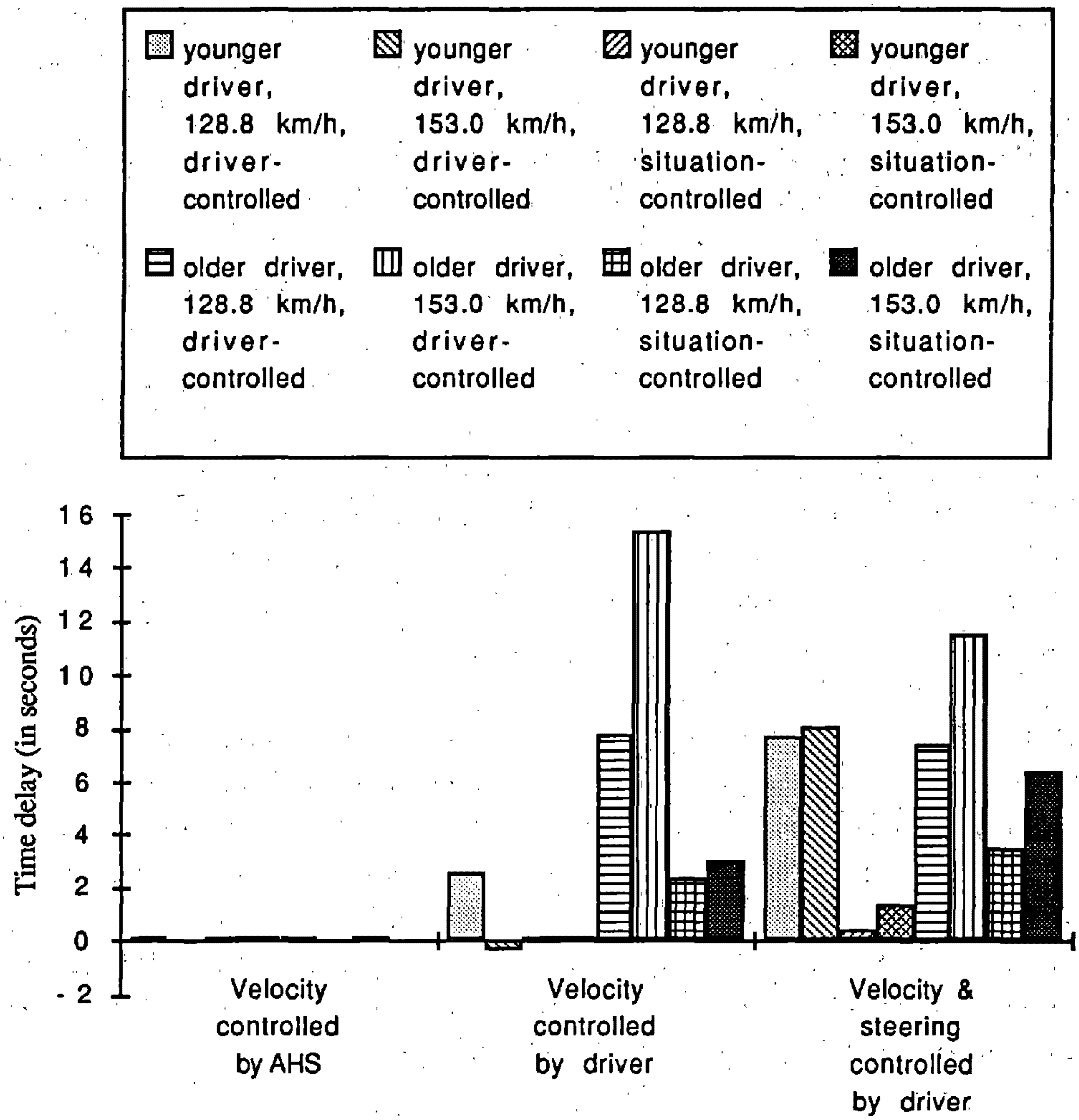


Figure 19. Mean time delay in the reduced-capability segment of the expressway, as a function of the reduced-capability mode, for the younger and older drivers, using both control transfer methods and driving at both designated AHS velocities.

central block of eight were obtained by the older drivers—in contrast to the data for the younger drivers, all four columns show time delays. For the older drivers who regained control of the vehicle with the situation-controlled transfer method, these delays were 2.3 s and 3.0 s when the designated AHS velocities were 128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h), respectively—time delays similar to the delay obtained for the younger drivers who experienced the driver-controlled transfer method with the designated AHS velocity of 128.8 km/h (80 mi/h). However, for the older drivers who regained control of the vehicle with the driver-controlled transfer method, the delays were much larger—7.8 s and 15.4 s when the designated AHS velocities were 128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h), respectively.

Finally, consider the third block of eight columns in the right of the histogram in figure 19. These columns represent the time delays that occurred when the driver controlled both the velocity and the steering. Again, the set of four columns in the left of this block represents mean time delays that occurred when the younger drivers controlled the vehicle. In this set, the two columns to the left show that when control was transferred to the driver using the driver-controlled method, the time delays were relatively large (7.7 s and 8.0 s) and, as will be seen shortly, this pair of time delays was in the same range as the time delays obtained by the older drivers. In contrast, the two columns to the right of the set for the younger drivers show that when the control was transferred to the driver using the situation-controlled method, the mean time delays were still relatively small (0.4 s and 1.3 s). The mean time delays obtained for the older drivers when they controlled both the velocity and the steering are shown in the four columns in the right of the block of eight—the mean time delays in these four columns were 7.4 s, 11.5 s, 3.5 s, and 6.4 s.

Reduced-Capability Mode. The main effect of varying the reduced-capability mode on the time delay is shown in table 9.

Table 9. Time delay associated with each reduced-capability mode.

Condition	Time delay
Velocity and steering controlled by driver	5.19 s
Velocity controlled by driver	3.09 s
Velocity controlled by AHS (steering controlled by driver)	0.02 s

As can be seen from the table, when the AHS controlled the velocity of the vehicle (and the driver controlled the steering), the time delay was—as it had to be—virtually zero. In contrast, when the driver controlled the velocity (and the AHS controlled the steering), the average time delay was 3.09 s; and, when the driver controlled both the velocity and the steering, the average time delay was 5.19 s.

Age of the Driver. The effect of the age of the driver on the time delay can be seen in table 10. The table shows that the time delay for the older drivers was, on average, considerably greater than the time delay for the younger drivers—the average time delays were 4.22 s and 1.27 s, respectively.

Table 10. Time delay for the older and younger drivers.

Condition	Time delay
Older drivers	4.22 s
Younger drivers	1.27 s

Designated AHS Velocity. The effect of the designated AHS velocity on the time delay can be seen in table 11. When the designated AHS velocity was 153.0 km/h (95 mi/h), the time delay was larger than it was when the designated AHS velocity was 128.8 km/h (80 mi/h)—the time delays were 3.09 s and 2.36 s, respectively.

Table 11. Time delay for both designated AHS velocities.

Condition	Time delay
153.0 km/h (95 mi/h)	3.09 s
128.8 km/h (80 mi/h)	2.36 s

Control Transfer Method. The effect of the method by which control was transferred from the AHS to the driver can be seen in table 12. When the driver-controlled method of transfer was

Table 12. Time delay for both control transfer methods.

Condition	Time delay
Driver-controlled	4.49 s
Situation-controlled	1.45 s

used, the time delay was relatively large (4.49 s); whereas, when the control was transferred using the situation-controlled method, the time delay was relatively small (1.45 s).

Time Delay and Ending Velocity

The various time delay effects discussed in the subsections above occurred because the driver did not drive at the designated AHS velocity when he/she took control of the velocity. The relationship between velocity and time delay can be seen by comparing figure 19 with figure 20. Figure 20 shows the difference between the designated AHS velocity and the velocity of the vehicle at the end of the reduced-capability segment, for each combination of the reduced-capability mode, the driver's age, the designated AHS velocity, and the control transfer method.

As can be seen from the first block of eight columns in figure 20, when the AHS controlled the velocity (and the driver controlled the steering), there were, of course, no differences in the designated AHS velocity and the velocity at the end of the reduced-capability segment. Similarly, in figure 19, no time delays were found in the first block of eight columns.

The differences between the designated AHS velocity and the velocity at the end of the reduced-capability segment when the driver controlled the velocity (and the AHS controlled the steering) are shown in the second block of eight columns in figure 20. The first four columns in this block of eight show the data for the younger drivers. When the designated AHS velocity had been 128.8 km/h (80 mi/h) and the younger drivers took control using the driver-controlled transfer method, they were driving 4.7 km/h (2.9 mi/h) slower than the designated AHS velocity by the end of the reduced-capability segment; and, as can be seen from the corresponding column in figure 19, there was a time delay of 2.54 s for these drivers with the same combination of conditions. In the remaining three cases for the younger drivers, their vehicles were traveling a little faster than the designated AHS velocity at the end of the reduced-capability segment—this was particularly noticeable when the designated AHS velocity had been 153.0 km/h (95 mi/h)

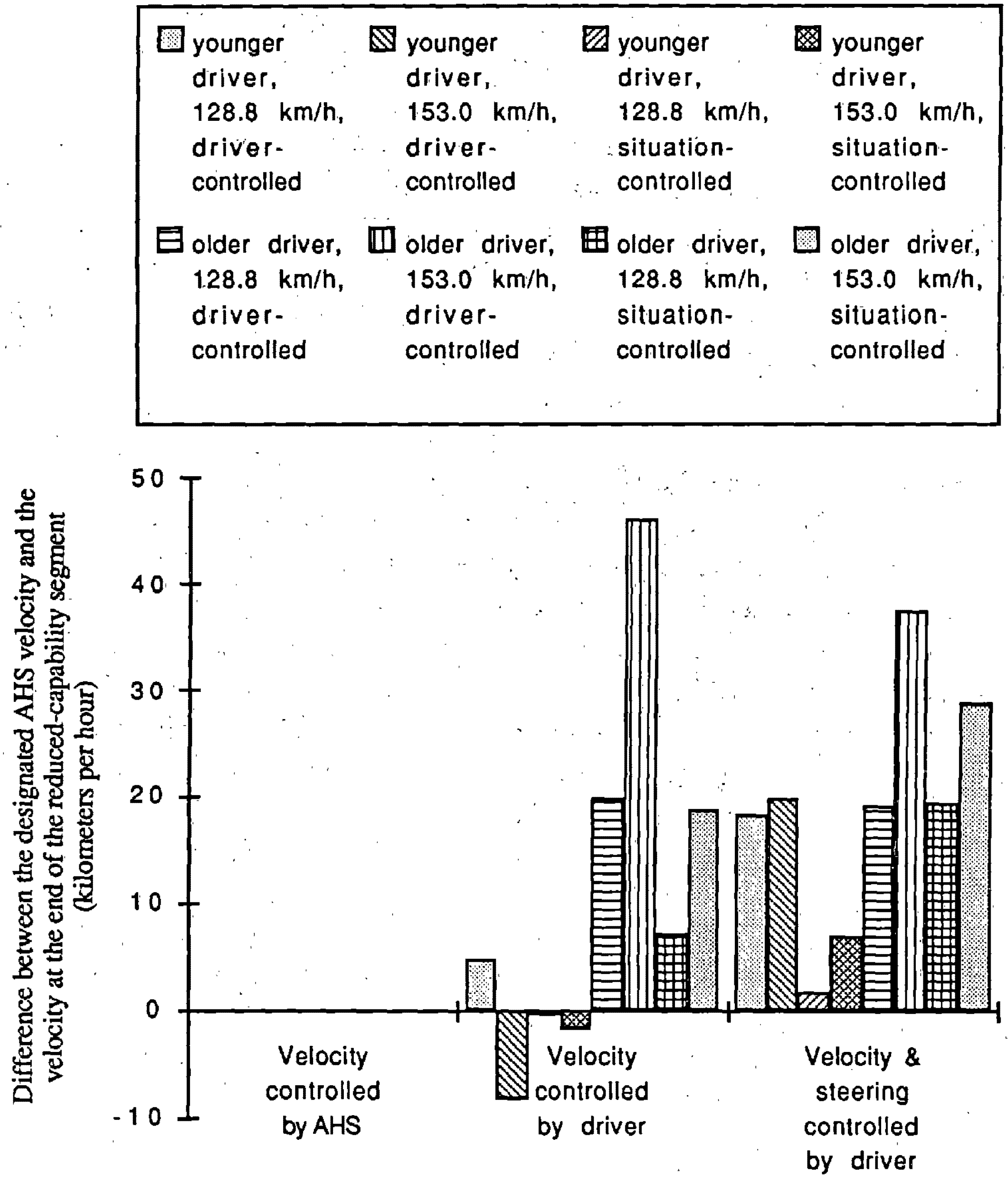


Figure 20. Difference between the velocity at the start and the end of the reduced-capability segment of the expressway, as a function of the reduced-capability mode, for the younger and older drivers, using both control transfer methods and driving at both designated AHS velocities.

and the younger drivers took control using the driver-controlled transfer method. In the latter case, as figure 19 indicates, there was a corresponding negative time delay; while in the other two cases for the younger drivers, the time delays were essentially zero.

The second set of four columns in the central block of figure 20 shows that, in contrast, when the older drivers controlled the velocity (and the AHS controlled the steering), there were velocity reductions from the velocity at the start of the reduced-capability segment (where the vehicle was traveling at the designated AHS velocity) to the velocity at the end of the reduced-capability segment—the reductions ranged between 7.20 km/h (4.47 mi/h) and 46.08 km/h (28.62 mi/h). Similarly, as figure 19 shows, there were corresponding time delays that ranged from 2.33 s to 15.35 s.

Finally, the velocity differences that were found when the driver controlled both the velocity and the steering are shown in the third block of eight columns in figure 20. In all eight cases, the velocity at the end of the reduced-capability segment was less than the velocity at the start of the reduced-capability segment (where the vehicle was traveling at the designated AHS velocity). The velocity reductions that occurred when the vehicle was traveling through the reduced-capability segment ranged from 1.80 km/h (1.12 mi/h) for the younger drivers using the driver-controlled transfer method when the designated AHS velocity had been 153.0 km/h (95 mi/h), to 37.44 km/h (23.25 mi/h) for the older drivers when they used the driver-controlled transfer method and the designated AHS velocity had been 153.0 km/h (95 mi/h). The pattern of mean velocity differences shown in figure 20 is mirrored by the time delay data already seen in figure 19, where the range of time delays was from 0.43 s for the younger drivers using the driver-controlled transfer method when the designated AHS velocity had been 153.0 km/h (95 mi/h), to 11.53 s for the older drivers when they used the driver-controlled transfer method and the designated AHS velocity had been 153.0 km/h (95 mi/h).

VISUAL CAPABILITIES TESTING

The Titmus Vision Tester was used to administer a series of standard visual tests. The drivers taking part in this experiment did not have any visual problems that could not be remedied by wearing corrective lenses. Each driver was also given two newly developed tests—they were tested with a perimeter that explored static and dynamic peripheral sensitivity out to 21° of eccentricity, under binocular viewing conditions. Initial comparison of the data from the drivers who took part in this experiment with data from ophthalmological patients examined in the

University of Iowa Hospitals indicated that the peripheral sensitivities of the drivers were typical of normal subjects drawn from the populations of equivalent age groups.

QUESTIONNAIRE DATA

A copy of the questionnaire used in the multiple experiment is presented in appendix 3—it consisted of 31 questions. After questions 1 through 26 and 30, a 103-mm response bar was presented. At each end of the response bar, there were anchor points reflecting the extremes of each possible response to the questions posed. A third anchor point was placed in the middle of the bar to reflect a neutral value between the two extremes. The drivers were asked to indicate their responses by marking the bar. Each response was measured, in millimeters, from the left end to the mark made by the driver. Scores between zero and 51 mm reflect responses that favor the extreme to the left—the closer the score is to zero, the more it favors the extreme position. Scores between 52 mm and 103 mm reflect responses that favor the extreme to the right—the closer the score is to 103 mm, the more it favors the extreme position. The neutral point was between 51 mm and 52 mm.

A series of ANOVA's was conducted on the data obtained for questions 1 through 26 and 30. The results of the analyses for many of these questions are presented in the reports dealing with the other three experiments that, along with the current experiment, were part of the multiple experiment. Table 13 lists each of the questions, the topics that they cover, and the reference numbers of the report(s) in which the responses are presented.

The results of the analyses for questions 14 through 17 and for question 22 (a and b)—all of which deal with reduced AHS capability—are presented below.

Dealing With Reduced AHS Capability

Questions 14 through 17 and question 22 (a and b) addressed how the drivers dealt with the segment of the expressway in which the capability of the AHS was reduced. ANOVA's were conducted on the responses to these questions in order to determine whether the reduced-capability mode, the method of transferring control, or the age and/or gender of the driver had an effect on the responses. The ANOVA's indicated that for questions 14 and 16, the gender of the driver significantly affected the responses (at the $p = 0.0486$ and $p = 0.0186$ levels, respectively). Table 14 shows the responses to these questions averaged over the age of the driver, the

Table 13. Reference numbers of reports in which questionnaire responses are presented.

Question	Topic	Number of report containing response[1]
1	Simulator experience	(3)
2	Simulator realism	(3)
3	Simulator realism	(3)
4	Simulator realism	(3)
5	Simulator realism	(3)
6	Simulator experience	(3)
7	AHS messages	(3)
8	AHS messages	(3)
9	Control	(3)
10	Control	(3)
11	Inter-string gap	(3), (4)
12	Designated AHS velocity	(3), (4)
13	Accuracy of the comfort lever	(4)
14	Reduced AHS capability	current report
15	Reduced AHS capability	current report
16	Reduced AHS capability	current report
17	Reduced AHS capability	current report
18	Safety and resumption of manual control	(5)
19	Safety	(3)
20	Attitude toward AHS	(3)
21	Attitude toward AHS	(3)
22a	Reduced AHS capability	current report
22b	Reduced AHS capability	current report
22c	Attitude toward AHS	(4)
23	Attitude toward AHS	(3), (4)
24	Attitude toward AHS	(3), (4)
25	Attitude toward AHS	(3), (4)
26	Attitude toward AHS	(3), (4)
30	Cruise control	current report

[1] Number in parentheses refers to reports listed in the references at the end of the current report.

reduced-capability mode, and the method of transferring control. For question 14, both the male and female drivers gave responses indicating that they felt in control of the situation when they received the reduced-capability advisory—the males indicated that they felt more in control of the situation than the females did. For question 16, both the male and female drivers gave responses indicating that they felt it was easy to fill in for the system—with the males indicating that they felt it was easier than the females did. There were no statistically significant differences for questions 15, 17, and 22 (a and b)—the mean responses to these questions, averaged over all variables, are presented in table 14.

Table 14. Questions dealing with reduced AHS capability.

Question	Male Drivers	Female Drivers
14. To what extent did you feel in control of the situation when you received the Reduced Capability advisory? L. Not at all R. To a great extent	74.6	61.9

Question	Overall Mean
15. How successful do you feel you were at filling in during the lost capability section? L. Very unsuccessful R. Very successful	71.2

Question	Male Drivers	Female Drivers
16. How easy was it to fill in for the system during the lost capability section? L. Not easy to fill in R. Easy to fill in	79.0	64.2

Question	Overall Mean
17. When you received the Resumption of Control message, did the transition back to automated control go smoothly? L. Not at all R. To a great extent	83.7
22. (a) During the portion of the drive where your speed was automatically controlled, but you had control of the steering, how did this feel? L. Very uncomfortable R. Very comfortable	59.3
22. (b) During the portion of the drive where your steering was automatically controlled, but you had control of your speed, how did this feel? L. Very uncomfortable R. Very comfortable	77.9

The responses to question 15 indicated that the drivers thought that they were successful at filling in during the reduced-capability section of the expressway. Similarly, the responses to question 17 indicated that after receiving the Resumption of Control message, they believed that the transition back to the AHS went smoothly.

It was expected that in the reduced-capability section of the expressway, those drivers who had control of the steering but not the velocity—as if they were using cruise control—would be more comfortable than those who faced the unfamiliar situation of having control of the speed but not the steering. However, as table 14 shows, the results of question 22 (a) and (b) suggest that this did not occur—those drivers who had control of the steering, but not velocity, were only slightly comfortable; while those who had control of the speed, but not steering, were clearly more comfortable.

Cruise Control

The responses to question 30, which dealt with cruise control, are presented in table 15. The ANOVA conducted on these responses showed that the older drivers were more likely to use cruise control on their own vehicles than the younger drivers—this result was significant at the $p = 0.0048$ level.

Table 15. Cruise control.

Question	Younger Drivers	Older Drivers
30. How often do you use the cruise control on your vehicle? L. Hardly ever R. Very often	64.9	83.1

SECTION 4: DISCUSSION

DEALING WITH REDUCED CAPABILITY IN AN AUTOMATED HIGHWAY SYSTEM

The objective of this experiment was to determine the effectiveness of the driver of a vehicle traveling in the automated highway system when he/she was required to take partial or full control when the vehicle arrived at a segment of the expressway in which the AHS capability was reduced—the AHS no longer controlled the lane-keeping function, or the velocity control function, or both the lane-keeping and velocity control functions. As it approached the start of the reduced-capability segment, the driver's vehicle was in the automated lane and was under the control of the AHS. It was positioned behind the lead vehicle of a string of three vehicles, and was traveling at either 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h). When the vehicle arrived at the start of the segment of expressway in which the functionality of the AHS was reduced, the driver had to take control of the steering, or the velocity, or both the steering and the velocity of the vehicle. Driving performance data were obtained from 60 drivers.

The length of the reduced-capability segment was 810 m (2656 ft), and most of it was on a curve that veered to the left of the driver. The length of the curved portion of the segment was 735 m (2410 ft). The primary comparisons of interest were between the ability of the driver and the AHS to steer around the curve and to maintain the velocity of the vehicle. The lane-keeping performance data were analyzed using newly developed lane-keeping performance measures.[9] And, the extent to which the driver was able to maintain the velocity of the vehicle in the reduced-capability segment was determined from time delay data.[1,2,3]

The lane-keeping performance data and time delay data were analyzed in a series of ANOVA's that compared the driving performance obtained with each of the three reduced-capability modes. The individual results of these analyses were presented in the previous section of this report. Not all the statistically significant effects that were found are of operational importance. Only those effects that appear to be of particular relevance to the AHS and its operations are discussed in this section.

Lane-Keeping Performance and Reduced AHS Capability

In the first of the three reduced-capability modes, the driver controlled the steering of the simulator vehicle while the AHS continued to control its velocity; in the second, the driver controlled the velocity of the vehicle, while the AHS controlled the steering; and in the third, the driver controlled both the steering and the velocity. Four lane-keeping measures were used to determine steering performance as the vehicle traveled around the curved portion of the reduced-capability segment. These lane-keeping measures were analyzed individually in a series of ANOVA's that compared the steering performance obtained with each of the three reduced-capability modes. In this section, the initial position in the lane and the steering drift (and their product), the steering instability, and the number of steering oscillations are considered together. Table 16 allows a direct comparison of lane keeping to be made for all three reduced-capability modes.

Table 16. Comparison of lane-keeping performance for the three reduced-capability modes.

	AHS controlled steering (driver controlled velocity)	**Driver controlled steering (AHS controlled velocity)**	**Driver controlled both steering and velocity**
(1) Position of vehicle relative to center of lane at start of curve—the a_{lk} value	+0.22 m (+0.73 ft) to left of center	+0.10 m (+0.34 ft) to left of center	–0.09 m (–0.29 ft) to right of center
(2) Steering drift—the b_{lk} value	+0.00021 m (+0.00069 ft)	–0.00090 m (–0.00294 ft)	–0.00104 m (–0.00341 ft)
(3) Total drift in curve —the b_{lk} value multiplied by 735 m	+0.15 m (+0.51 ft) to left	–0.66 m (–2.17 ft) to right	–0.76 m (–2.51 ft) to right
(4) Position of vehicle relative to center of lane at end of segment (line 1 plus line 3)	+0.37 m (+1.24 ft) to left of center	–0.56 m (–1.83 ft) to right of center	–0.85 m (–2.80 ft) to right of center
(5) Undershoot/overshoot	undershoot	overshoot	overshoot
(6) Steering instability	0.13 m (0.42 ft)	0.29 m (0.96 ft)	0.25 m (0.83 ft)
(7) Oscillations per minute	14.03	19.29	17.96

The first line of the table shows the position of the simulator vehicle relative to the center of the lane at the start of the curve for each of the reduced-capability modes (averaged over the remaining four independent variables—the age of the driver, the designated AHS velocity, the control transfer method, and the intra-string gap). For both reduced-capability modes in which the driver controlled the steering, the average position of the center of the simulator vehicle was closer to the center of the lane at the start of the curve than it was for the mode in which the steering was controlled by the AHS.

The second line of table 16 shows the steering drift in terms of b_{lk}, the average gradient of equation 1. Line 3 shows, for each of the reduced-capability modes, the average extent to which the simulator vehicle drifted across the lane from the start to the end of the curve, i.e., it shows the product $b_{lk}x$, where x is 735 m (2410 ft), the distance traveled in the curve. For both conditions in which the driver controlled the steering, the drift across the lane was in a different direction than it was for the case where the AHS controlled the steering: for the first two cases, there was an overshoot relative to the center of the lane; for the latter, there was an undershoot. In addition, the magnitude of the drift was at least four times greater when the driver controlled the steering—the steering drift from the beginning to the end of the curve was 0.66 m (2.17 ft) to the right of the lane when the driver controlled the steering alone, and 0.76 m (2.51 ft) to the right when the driver controlled both the steering and the velocity, as opposed to a steering drift of 0.15 m (0.51 ft) to the left when the AHS controlled the steering.

Line 4 in table 16 shows the position of the vehicle in the lane at the end of the curve—the values shown here are the sum of the initial position in the lane (from line 1) and the product $b_{lk}x$ (from line 3). The simulator vehicle was 0.37 m (1.24 ft) to the left of the center of the lane at the end of the curve when the steering was controlled by the AHS; in contrast, it was 0.56 m (1.83 ft) to the right when the driver controlled the steering alone, and 0.85 m (2.80 ft) to the right when the driver controlled the velocity as well as the steering. This means, as line 5 in the table shows, that the small steering drift obtained when the AHS controlled the steering resulted in the vehicle slightly undershooting the center of the lane, whereas the more substantial steering drifts that occurred in both conditions in which the driver controlled the vehicle produced considerable overshoots of the center of the lane.

The remaining two lines (6 and 7) in table 16 compare the steering instability and number of oscillations per minute for the three reduced-capability modes. Line 6 shows that the steering instability was approximately halved when the steering was controlled by the AHS—the instability was 0.13 m (0.42 ft) when the AHS controlled the steering, while it was 0.29 m (0.96 ft) when the driver controlled the steering alone, and 0.25 m (0.83 ft) when he/she controlled both steering and velocity. Finally, line 7 shows there were fewer oscillations per minute when the

AHS controlled the steering (14.03) than there were when the driver controlled the steering alone (19.29) or the steering and velocity together (17.96).

It is of note that when the driver was controlling the steering alone and the AHS controlled the velocity—a driving situation similar to that experienced currently by a driver using cruise control in normal driving—the total steering drift while the vehicle traveled around the curve was less than the total drift obtained when the driver was controlling both the steering and the velocity, as in normal driving.

It was to be expected that the steering would be controlled more precisely by the AHS than it would be by a human driver. This proved to be the case—there was at least four times as much steering drift and twice as much steering instability, and there were more steering oscillations per minute when the driver controlled the steering than when the vehicle was controlled by the AHS.

In contrast, at first it may seem surprising that at the beginning of the curve, the AHS positioned the vehicle twice as far from the center of the lane as did the driver. To explain why the AHS positioned the vehicle as far away from the center of the lane as it did at the start of the curve, it is necessary to examine how the AHS controlled steering. Every $^1/_{30}$ s, the AHS selected a point along the center line of the lane that was a fixed distance ahead of the vehicle's front bumper—30 m (98.4 ft) was the fixed distance in this experiment. Then the AHS steered the car toward that point. Most of the time when the vehicle was traveling along a straight portion of the expressway, the steering point being used by the AHS lay on a line passing through the center of the lane. However, when the vehicle was so close to the start of the curve that it was within the 30-m (98.4-ft) fixed distance, the direct line from the center of the car to the steering point no longer lay on the line passing through the center of the lane—instead it was offset to the left (i.e., in the same direction that the curve veered). Then, as the car got closer and closer longitudinally to the start of the curve, the AHS moved it laterally farther and farther away from the center of the lane.

This method of automatic steering—directing the vehicle toward a steering point ahead on a line that passes through the center of the lane—will always produce an undershoot relative to the center of the lane when a vehicle travels around a curve. The undershoot will be greater if the fixed distance is increased, and it will be reduced if the fixed distance is reduced. Also, if the vehicle were to travel around the curve at a relatively high velocity, then the distance between successive steering points would increase, producing a corresponding increase in the magnitude of the undershoot. In contrast, if the vehicle were to travel around the curve at a relatively low velocity, the distance between successive steering points would decrease and, in turn, the magnitude of the undershoot would also decrease.

When the driver controlled the steering—whether controlling the steering alone, or the steering and the velocity together—by the time the vehicle had reached the end of the curve, it had overshot the center of the lane by a considerable amount. While the vehicle traveled 735 m (2410 ft) longitudinally around the curve, the total steering drift was 0.66 m (2.17 ft) laterally across the lane when the driver controlled the steering alone, and 0.76 m (2.51 ft) when the driver controlled both steering and velocity. The most extreme offset from the center of the lane occurred at the end of the curve when the driver controlled both the steering and the velocity—in this case, the center of the simulator vehicle was 0.85 m (2.80 ft) to the right of the center of the lane. In itself, this need not be a problem—given a nominal passenger car width of 1.68 m (5.5 ft) and a lane width of 3.66 m (12 ft), if the center of the vehicle was 0.85 m (2.80 ft) to the right of the center of the lane, the edge of the vehicle would still have a clearance of 0.14 m (0.46 ft). However, these results suggest that it would be unwise to reduce the lane width of the expressway for any reason (e.g., to accommodate more AHS lanes), since then there would be a strong possibility that the driver's vehicle could drift out of lane and, when the curve is to the left, encroach into the center lane, threatening the traffic in it. (It is to be noted that in some AHS scenarios, a barrier separates the automated lane from the unautomated lanes. In that case, the drift just discussed, coupled with a narrower-than-conventional lane, could lead to the vehicle striking the barrier.)

Lane-Keeping Performance and Designated AHS Velocity

Table 17 presents a comparison of the four lane-keeping measures for the two designated AHS velocity conditions. As it shows—and as might be expected—it was harder to steer the vehicle when the designated AHS velocity before the driver took full or partial control of the vehicle was 153.0 km/h (95 mi/h) than when it was 128.8 km/h (80 mi/h). The steering drift and the steering instability were greater in all three reduced-capability conditions for the 153.0-km/h (95-mi/h) designated AHS velocity. In addition, the number of steering oscillations per minute was greater for the higher designated AHS velocity when the driver controlled steering alone and when he/she controlled both steering and velocity.

As mentioned in the previous section, the method of automating the steering that was used in this experiment, i.e., to steer the vehicle by directing it toward a steering point ahead on a line that

Table 17. Comparison of lane-keeping performance for the two designated AHS velocities.

		Reduced-capability mode		
Lane-keeping measure	**Designated AHS velocity**	**Steering controlled by AHS**	**Steering controlled by driver**	**Steering & velocity controlled by driver**
Initial lane position	128.8 km/h (80 mi/h)	+0.120 m (+0.39 ft) to left	–0.005 m (–0.02 ft) to right	–0.154 m (–0.51 ft) to right
	153.0 km/h (95 mi/h)	+0.344 m (+1.13 ft) to left	+0.213 m (+0.70 ft) to left	–0.020 m (–0.07 ft) to right
Steering drift	128.8 km/h (80 mi/h)	+0.00008 m (+0.00027 ft) to left	–0.00070 m (–0.00229 ft) to right	–0.00093 m (–0.00305 ft) to right
	153.0 km/h (95 mi/h)	+0.00036 m (+0.00118 ft) to left	–0.00109 m (–0.00358 ft) to right	–0.00116 m (–0.00379 ft) to right
Steering instability	128.8 km/h (80 mi/h)	0.085 m (0.279 ft)	0.262 m (0.858 ft)	0.220 m (0.722 ft)
	153.0 km/h (95 mi/h)	0.180 m (0.591 ft)	0.323 m (1.058 ft)	0.286 m (0.937 ft)
Steering oscillations per minute	128.8 km/h (80 mi/h)	14.63	16.64	17.44
	153.0 km/h (95 mi/h)	11.49	22.10	18.47

passes through the center of the lane—will always produce an undershoot relative to the center of the lane when a vehicle travels around a curve. Also, if the steering point is a fixed distance ahead of the vehicle, the undershoot will be greater for a vehicle traveling around the curve at a relatively high velocity than for a vehicle traveling around it at a relatively low velocity. This is the reason why in this experiment both the initial position in the lane and the steering drift were greater when the velocity was 153.0 km/h (95 mi/h) than when it was 128.8 km/h (80 mi/h).

Lane-Keeping Performance and Age of the Driver

Variations in the age of the driver had less effect on lane-keeping performance than did the reduced-capability mode and the designated AHS velocity. Nevertheless, as shown earlier in the results section, this independent variable was involved in several statistically significant interactions.

When the driver controlled the steering alone, at the start of the curve that veered to the left, the older driver positioned the vehicle 0.25 m (0.82 ft) to the left of the center of the lane—this may have been an anticipatory response by the experienced driver—while the younger driver positioned the vehicle in the center of the lane. When the driver controlled both steering and velocity, the difference between the older and younger drivers was of similar magnitude, although both responses were shifted to the right. In this case, at the start of the curve, the older driver positioned the vehicle virtually at the center of the lane, while the younger driver positioned it 0.16 m (0.52 ft) to the right. It is not clear why there was a difference in the initial offsets between the two modes, although it should be noted that (as will be discussed in the subsection on Velocity Control and Reduced AHS Capability later in this section) when the driver controlled both functions, he/she drove at a slower speed than the designated AHS velocity that was maintained by the AHS when the driver controlled the steering alone.

One of the few relatively clear effects involving the age of the driver was that there was slightly less steering instability for the older driver than there was for the younger driver—0.21 m (0.69 ft) vs. 0.24 m (0.80 ft), respectively. This was associated with there being more steering oscillations per minute for the older drivers than there were for the younger drivers (18.45 vs. 15.87, respectively). This combination of results—less steering instability with more steering oscillations—suggests that the older drivers may have been paying closer attention to the task of steering than the younger drivers.

It might have been expected that when the AHS controlled the steering, there would have been no difference in lane keeping between the older and younger drivers. However, as already discussed in the subsection on Lane-Keeping Performance and Reduced AHS Capability, the method of automatic steering used in this experiment—steering the vehicle toward a point a fixed distance ahead on a line that passes through the center of the lane—is bound to produce an undershoot relative to the center of the lane when a vehicle travels around a curve; and furthermore, the magnitude of that undershoot will be greater for a vehicle traveling at a relatively high velocity than for a vehicle traveling around it at a relatively low velocity. It will be shown—once again in the subsection on Velocity Control and Reduced AHS Capability that is to be found later in this section—that the older drivers drove at a slower speed than the younger drivers. And it is because the older drivers drove slower when the AHS controlled the steering that there was, in fact, a difference in steering performance for the older and younger drivers—even though neither were actually controlling the steering. For this reduced-capability mode, the initial offset to the left, the steering drift, and the steering instability were all smaller for the older drivers than they were for the younger drivers.

Lane-Keeping Performance, Intra-String Gap, and Control Transfer Method

As with the age of the driver, the intra-string gap and the control transfer method were involved in a number of statistically significant interactions. They are of minor importance as far as the implementation of an AHS is concerned and, as a result, are not discussed further here.

Time Delay, Velocity Control, and Reduced AHS Capability

Inspection of the time delay data shown in figures 18 and 19 shows that there was more time delay associated with the reduced-capability mode in which the drivers controlled both the steering and the velocity than in the mode in which they controlled the velocity alone. Closer inspection revealed that the difference in the time delays occurred for the younger drivers, but not for the older drivers, who had time delays of similar magnitude in both conditions. As was shown by comparing the time delay (in figure 19) and the difference in velocity at the beginning and at the end of the reduced-capability segment (figure 20), time delay is directly related to the velocity of the vehicle with each of the reduced-capability modes—the greater the time delay, the slower the velocity must have been. A second measure of the extent to which the velocity was reduced from the designated AHS velocity—the average velocity throughout the reduced-capability segment—is shown in table 18 for each combination of the age of the driver, designated AHS velocity, and reduced-capability mode.

First, and most obviously, table 18 shows that when the driver controlled the steering alone, the AHS kept the vehicle at the designated AHS velocity—as it was programmed to do.

Second, table 18 shows that when controlling both the steering and the velocity, the older drivers drove at a similar speed—just over 105 km/h (65 mi/h)—whether the designated AHS velocity had been 128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h). In addition, when controlling the velocity (while the AHS controlled the steering), the older drivers drove at a similar speed—just over 106.6 km/h (66.2 mi/h)—when the designated AHS velocity was 128.8 km/h (80 mi/h); and only a little faster—111.5 km/h (69.2 mi/h)—when the designated AHS velocity was 153.0 km/h (95 mi/h). In contrast, the pattern for the younger drivers was rather different. When controlling both the steering and the velocity after the designated AHS velocity had been 128.8 km/h (80 mi/h), the younger drivers' speed—112.0 km/h (69.6 mi/h)—was only a little faster than the older drivers' speed had been. However, for the same reduced-capability mode, after the designated AHS velocity had been 153.0 km/h (95 mi/h), the younger drivers' speed—129.0 km/h (80.1 mi/h)—was considerably faster than that of the older drivers.

Table 18. Average velocity while the vehicle traveled in the reduced-capability segment of the expressway for both driver age groups, both designated AHS velocities, and all three reduced-capability modes.

		Age of the Driver	
Reduced-Capability Mode	**Designated AHS Velocity**	**Older Drivers**	**Younger Drivers**
AHS controlled steering (driver controlled velocity)	**128.8 km/h (80.0 mi/h)**	106.6 km/h (66.2 mi/h)	124.0 km/h (77.0 mi/h)
	153.0 km/h (95.0 mi/h)	111.5 km/h (69.2 mi/h)	153.6 km/h (95.4 mi/h)
Driver controlled steering (AHS controlled velocity)	**128.8 km/h (80.0 mi/h)**	128.5 km/h (79.8 mi/h)	128.4 km/h (79.8 mi/h)
	153.0 km/h (95.0 mi/h)	153.2 km/h (95.2 mi/h)	153.2 km/h (95.1 mi/h)
Driver controlled both steering and velocity	**128.8 km/h (80.0 mi/h)**	105.1 km/h (65.3 mi/h)	112.0 km/h (69.6 mi/h)
	153.0 km/h (95.0 mi/h)	105.8 km/h (65.7 mi/h)	129.0 km/h (80.1 mi/h)

Third, when the mode in which the driver controlled the velocity (while the AHS controlled the steering) is considered, the difference between the younger and older drivers can be seen to increase. The younger drivers drove considerably faster—124.0 km/h (77.0 mi/h) vs. 106.6 km/h (66.2 mi/h)—when the designated AHS velocity was 128.8 km/h (80 mi/h); and then, when the designated AHS velocity was 153.0 km/h (95 mi/h), the younger drivers drove so fast that their average speed, 153.6 km/h (95.4 mi/h), was higher than even the designated AHS velocity (as compared with an older driver's average velocity of 111.5 km/h [69.2 mi/h]). It was surprising to discover that when performing the unfamiliar task of controlling only the velocity of the vehicle (while the AHS continued to control the steering), the younger drivers drove faster than when they were controlling both the steering and the velocity, as in normal driving. The older drivers also drove at speeds that were higher when controlling the velocity alone than when controlling both the velocity and the steering—although the difference was not nearly as large as it was for the younger drivers.

It should be noted that in the experimental instructions, the driver was asked ". . . to fill in for the System, until the lost capability is restored" (passage D.1 in the video narrative), while the simulator vehicle traveled through the reduced-capability section of the expressway. In addition, when in control of the lost function(s), he/she was also instructed as follows: ". . . you should try to maintain your position in the string of vehicles" (passage D.5 in the video narrative). With the exception of one condition, the driver drove at speeds that were slower than the designated AHS velocity. However, since in all four combinations of designated AHS velocity and reduced-capability mode, the older drivers drove at least 16.6 km/h (10.3 mi/h) faster than the speed limit in the unautomated lanes, it is possible that they attempted to drive at the designated AHS velocity while controlling the speed in the reduced-capability section. In the case of the younger drivers, this possibility seems more like a certainty: for all four combinations of the designated AHS velocity and reduced-capability mode, the younger drivers drove at speeds that were closer to what the designated AHS velocity had been—in one case even surpassing it—throughout the reduced-capability section of the expressway. It is very likely that the overshoots of the center line of the lane that were found in this experiment occurred because the drivers were traveling at velocities that were higher than those they usually experience.

The time delay and velocity control data can be summarized as follows:

- When the AHS controlled the velocity (and the driver controlled the steering), there could be no reduction in velocity, and therefore no time delay.
- When the driver controlled both the velocity and the steering, there was a greater

reduction in velocity compared to the designated AHS velocity and, therefore, more time delay than when the driver controlled velocity alone (and the AHS controlled the steering); this effect was particularly noticeable for the younger drivers.

- There was a greater reduction in velocity (and therefore more time delay) for the older drivers than there was for the younger drivers.
- When the driver-controlled transfer method was used, there was more reduction in velocity (and more time delay) than there was when the situation-controlled transfer method was used—this was because the driver controlled the vehicle for a shorter period of time when the situation-controlled transfer method was used than when the driver-controlled transfer method was used.
- There was a greater reduction in velocity (and more time delay) when the design velocity was 153.0 km/h (95 mi/h) than when it was 128.8 km/h (80 mi/h).
- There was more reduction in velocity (and more time delay) when the intra-string gap was 0.0625 s than when it was 0.25 s.

These effects may have occurred for the following reasons: There may have been a greater reduction in velocity when the driver controlled both the velocity and the steering than when the driver controlled the velocity alone because, in the latter case, when the driver was controlling only one function instead of two, he/she may have been able to pay more attention to the task of velocity maintenance, and thus was better able to "fill in for the System" as requested in the instructions to the experiment. It is likely that there was a greater reduction in velocity when the driver-controlled transfer method was used rather than the situation-controlled transfer method because with the situation-controlled method, the driver was actually in control of the velocity for a shorter time than when control was transferred with the driver-controlled method. There was more reduction in velocity for the older driver than there was for the younger driver, perhaps because the younger driver was more prepared to drive at high speeds that were close to the designated AHS velocities—this is in line with the suggestion from the lane-keeping results that the older driver may be a more careful driver (who pays closer attention to the task of steering than the younger driver). The next finding in the current experiment—that there was a greater reduction in velocity when the driver resumed control of a vehicle that had been under automated control traveling at 153.0 km/h (95 mi/h) than when it had been traveling at 128.8 km/h (80 mi/h)—was to be expected, since it repeated the results of the first two experiments in this series.(1) Finally, there may have been a greater reduction in velocity when the intra-string gap was 0.0625 s than when it was 0.25 s because the driver was less comfortable in maintaining velocities that were faster than those normally experienced when his/her vehicle was physically closer to the vehicle ahead and he/she could see far less of the other activity on the expressway.

RECOMMENDATIONS

If an AHS configuration like the one explored in the current experiment were to be operated under the assumption that in certain circumstances the driver might temporarily have to take full or partial control of his/her vehicle, the following recommendations can be made:

- Given adequate warning, the driver could take over the steering and/or velocity if there were a reduction in the AHS capability and maintain the traffic flow.
- If the AHS selects a designated AHS velocity of 128.8 km/h (80 mi/h) or higher, and if the driver is required to take control of the steering of the vehicle and has to negotiate a curve before returning control to the AHS, then he/she should not be asked to try to maintain the designated AHS velocity, but instead should be encouraged to reduce speed and should be warned about a possible overshoot. The encouragement and warning would be more effective if presented in training, and not just at the moment that the driver is required to take control of the lost function(s).
- If the AHS selects a designated AHS velocity of 128.8 km/h (80 mi/h) or higher, and the driver is required to take control of the steering of the vehicle and has to negotiate a curve before returning control to the AHS, the lane width should not be reduced from the current standard of 3.66 m (12 ft).

APPENDIX 1: ORDER OF PRESENTATION OF CONDITIONS

The orders in which combinations of designated AHS velocity and intra-string gap were presented to the 12 groups of 5 drivers assigned to each of the 12 combinations of the age of the driver, the reduced AHS capability mode, and the method of transferring control in the reduced-capability segment of the expressway are shown below.

[Key:
- Combination #2: Designated AHS velocity 128.8 km/h (80 mi/h), inter-string gap 0.0625 s.
- Combination #3: Designated AHS velocity 153.0 km/h (95 mi/h), inter-string gap 0.0625 s.
- Combination #5: Designated AHS velocity 128.8 km/h (80 mi/h), inter-string gap 0.25 s.
- Combination #6: Designated AHS velocity 153.0 km/h (95 mi/h), inter-string gap 0.25 s.]

Orders of combinations of designated AHS velocity and intra-string gap for younger drivers who took control of the steering using the driver-controlled transfer method

Driver	Order of Presentation			
YD01	3	5	2	6
YD04	6	3	5	2
YD07	2	3	5	6
YD10	3	5	6	2
YD13	5	6	2	3

Orders of combinations of designated AHS velocity and intra-string gap for younger drivers who took control of the velocity using the driver-controlled transfer method

Driver	Order of Presentation			
YD02	5	6	2	3
YD05	2	3	5	6
YD08	2	6	3	5
YD11	5	6	2	3
YD14	5	3	6	2

Orders of combinations of designated AHS velocity and intra-string gap for younger drivers who took control of both the steering and velocity using the driver-controlled transfer method

Driver	Order of Presentation			
YD03	2	6	3	5
YD06	5	2	6	3
YD09	6	2	3	5
YD12	5	2	6	3
YD15	2	5	3	6

Orders of combinations of designated AHS velocity and intra-string gap for younger drivers who took control of the steering using the situation-controlled transfer method

Driver	Order of Presentation			
YD16	2	3	6	5
YD19	3	5	6	2
YD22	3	2	5	6
YD25	5	2	6	3
YD28	2	6	3	5

Orders of combinations of designated AHS velocity and intra-string gap for younger drivers who took control of the velocity using the situation-controlled transfer method

Driver	Order of Presentation			
YD17	3	6	2	5
YD20	2	6	3	5
YD23	6	2	5	3
YD26	3	5	2	6
YD29	6	3	5	2

Orders of combinations of designated AHS velocity and intra-string gap for younger drivers who took control of both the steering and velocity using the situation-controlled transfer method

Driver	Order of Presentation			
YD18	6	2	5	3
YD21	5	3	2	6
YD24	6	5	3	2
YD27	5	6	2	3
YD30	2	3	5	6

Orders of combinations of designated AHS velocity and intra-string gap for older drivers who took control of the steering using the driver-controlled transfer method

Driver	Order of Presentation			
OD01	5	3	6	2
OD04	3	6	2	5
OD07	3	2	5	6
OD10	3	6	2	5
OD13	3	6	2	5

Orders of combinations of designated AHS velocity and intra-string gap for older drivers who took control of the velocity using the driver-controlled transfer method

Driver	Order of Presentation			
OD02	5	6	2	3
OD05	2	3	5	6
OD08	6	3	2	5
OD11	5	6	3	2
OD14	2	5	6	3

Orders of combinations of designated AHS velocity and intra-string gap for older drivers who took control of both the steering and velocity using the driver-controlled transfer method

Driver	Order of Presentation			
OD03	2	5	3	6
OD06	6	2	5	3
OD09	2	5	6	3
OD12	5	3	6	2
OD15	5	3	2	6

Orders of combinations of designated AHS velocity and intra-string gap for older drivers who took control of the steering using the situation-controlled transfer method

Driver	Order of Presentation			
OD16	3	2	5	6
OD19	5	2	3	6
OD22	3	2	5	6
OD25	2	3	6	5
OD28	3	6	2	5

Orders of combinations of designated AHS velocity and intra-string gap for older drivers who took control of the velocity using the situation-controlled transfer method

Driver	Order of Presentation			
OD17	6	3	5	2
OD20	2	3	6	5
OD23	5	6	3	2
OD26	5	2	3	6
OD29	6	3	5	2

Orders of combinations of designated AHS velocity and intra-string gap for older drivers who took control of both the steering and velocity using the situation-controlled transfer method

Driver	Order of Presentation			
OD18	6	5	3	2
OD21	6	5	2	3
OD24	2	5	6	3
OD27	2	5	6	3
OD30	5	6	3	2

APPENDIX 2: EXTRACTS OF THE NARRATIVE FOR THE TRAINING VIDEOS

[Note: There were four versions of the training videos used in this experiment—one for the manual, one for the fully automated, and two for the partially automated transfer conditions that were investigated in part 1 of the multiple experiment. In part 3 of the multiple experiment, i.e., in the current experiment, the drivers who had used partial automation in part 1 here used two different methods for regaining the lost function(s), and therefore required two different training tapes. Much of the narrative is repeated from one tape to the next. Here, all of the narrative that is relevant to the current experiment is supplied for the manual training tape—and the narrative that describes the other parts of the multiple experiment is deleted for the sake of brevity. Where in the remaining tapes the text is repeated from the manual tape, this will be noted, and the repeated text does not appear.]

VIDEOTAPE #1: MANUAL TRANSFER ON ENTRY TO AHS

[A. Introducing the AHS]

Passage A.1: The study in which you are about to participate is part of an on-going investigation of Automated Highway Systems. We are conducting the investigation for the FHWA, the Federal Highway Administration. The FHWA is responsible for safety and travel effectiveness on our highways. In this investigation, the FHWA is trying to determine how to design an Automated Highway System in order to reduce congestion and to increase highway safety. We are conducting a series of studies using the Iowa Driving Simulator. We will explore how an Automated Highway System might work, and how well drivers would handle their vehicles in such a system. The data provided by you, and others, will aid us in making accurate and responsible recommendations about how to design and operate the Automated Highway System. This is a test of the Automated Highway System, not a test of you, the driver. We will maintain your privacy—your data will never be presented with your name attached.

Passage A.2: The Automated Highway System could be designed in a number of ways. The version that you will drive in the simulator has been installed on a freeway with three lanes in each direction. In this freeway, the leftmost lane is reserved for automated traffic only. All the vehicles in this lane are under the control of the Automated System. They will be arranged in strings—there may be one, two, three, or four vehicles traveling together in each string. The vehicles in the automated lane will be traveling faster than the traffic in the other two lanes. The right and center lanes are not automated, and the speed limit in these lanes is 55 miles per hour.

[B. Entering the Automated Lane]

[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[C. Comfort Level]

[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[D. Reduced Capability]

Passage D.1: After you have been traveling in the automated lane for a few minutes, you will reach a section of the freeway where the System cannot operate at full capability. There will be a loss in capability—it will be unable to control the steering, or the speed of your vehicle, or both the steering and the speed. And, you will need to fill in for the System, until the lost capability is restored.

Passage D.2: Twenty seconds before you arrive at the lost capability section, you will receive a warning telling you which capabilities have been reduced. The warning for both steering and speed control loss will sound like this:
["In twenty seconds, the Automated System will not be able to control your vehicle. To regain control now, take hold of the steering wheel, place your foot on the accelerator, and push the *Off*-button."]

Passage D.3: If you take control at this point, you will hear the following message:
["You now have full control of your vehicle."]

Passage D.4: If you have not already taken control, when you reach the point at which the lost capability section starts, you will hear a second message. It will sound like this:
["After the countdown, the System will no longer control your vehicle.
Four... three... two... one... *now*.
You must control your vehicle."]

Passage D.5: When you hear this message, there will be no need to press the *Off*-button to take control. There will be no need to press it, because at this point the System will be unable to control the lost capability—you *must* take control. While you control the speed and steering, you should try to maintain your position in the string of vehicles.

Passage D.6: At the end of the section in which there is some lost capability, the System will be able to resume control of your vehicle, as long as it is still in the automated lane. When the lost capability is restored you will hear the following message:
["The Automated System can now regain total control of your vehicle.
Please push the *On*-button to transfer total control to the Automated System."]

Passage D.7: As soon as you press the *On*-button, the Automated System will take control of the vehicle and you will hear this message:
["Your vehicle is now under the control of the Automated System."]

Passage D.8: Let me review what will happen with the lost capability section of the freeway.
—Twenty seconds before you reach the section, you will receive a warning.
—It will tell you which capabilities the System has lost—speed, or steering, or both speed and steering.
—You may take control at this point by pressing the *Off*-button.
—If you do not take control at this point, when you reach the lost capability section you will be told that you *must* take control—since from here, the System will not control the lost capability.
—While you control the vehicle, please try to maintain your position in the string of vehicles.
—You will be informed when you reach the end of the lost capability section.
—And then, you should press the *On*-button to transfer control back to the System.

VIDEOTAPE #2: AUTOMATED TRANSFER ON ENTRY TO AHS

[A. Introducing the AHS]
Passage A.1: AS IN MANUAL.
Passage A.2: AS IN MANUAL.

[B. Entering the Automated Lane]

[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[C. Comfort Level]

[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[D. Reduced Capability]

Passage D.1: AS IN MANUAL.

Passage D.2: Twenty seconds before you arrive at the lost capability section, you will receive a warning telling you which capabilities have been reduced. The warning for both steering and speed control loss will sound like this:
["In twenty seconds the Automated System will not be able to control your vehicle."]

Passage D.3: Then, when you reach the point at which the lost capability section starts, you will hear a second message. It will sound like this:
["After the countdown, the System will no longer control your vehicle.
Four... three... two... one... *now*.
You must control your vehicle."]

Passage D.4: When you hear this message, the System will be unable to control the lost capability—you must take control. While you are in control, you should try to maintain your position in the string of vehicles.

Passage D.5: You must keep driving until you reach the end of the section in which there is some lost capability. Then, as long as you are still in the automated lane, the System will be able to resume control of your vehicle. When the lost capability has been restored, you will hear the following message:
["The Automated System can now regain total control of your vehicle.
It will regain control in three seconds.
Three... two... one... *now*."]

Passage D.6: As soon as the System has resumed control, this is what you will hear:
["Your vehicle is now under the control of the Automated System."]

Passage D.7: Let me review what will happen with the lost capability section of the freeway.
—Twenty seconds before you reach the section you will receive a warning.
—It will tell you which capabilities the System has lost—speed, or steering, or both speed and steering.
—When you reach the lost capability section, you will be told that you must take control—since from here, the System will not control the lost capability.
—While you control the vehicle, please try to maintain your position in the string of vehicles.
—You will be informed when you reach the end of the lost capability section.
—At this point, the System will resume control.

VIDEOTAPE #3: PARTIALLY AUTOMATED TRANSFER ON ENTRY TO AHS—DRIVER-CONTROLLED METHOD TO TAKE OVER LOST CAPABILITY

[A. Introducing the AHS]
Passage A.1: AS IN MANUAL.
Passage A.2: AS IN MANUAL.

[B. Entering the Automated Lane]
[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[C. Comfort Level]
[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[D. Reduced Capability]
Passage D.1: AS IN MANUAL.
Passage D.2: AS IN MANUAL.
Passage D.3: AS IN MANUAL.
Passage D.4: AS IN MANUAL.
Passage D.5: AS IN MANUAL.
Passage D.6: AS IN MANUAL.

Passage D.7: AS IN MANUAL.
Passage D.8: AS IN MANUAL.

VIDEOTAPE #4: PARTIALLY AUTOMATED TRANSFER ON ENTRY TO AHS—SITUATION-CONTROLLED METHOD TO TAKE OVER LOST CAPABILITY

[A. Introducing the AHS]
Passage A.1: AS IN MANUAL.
Passage A.2: AS IN MANUAL.

[B. Entering the Automated Lane]
[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

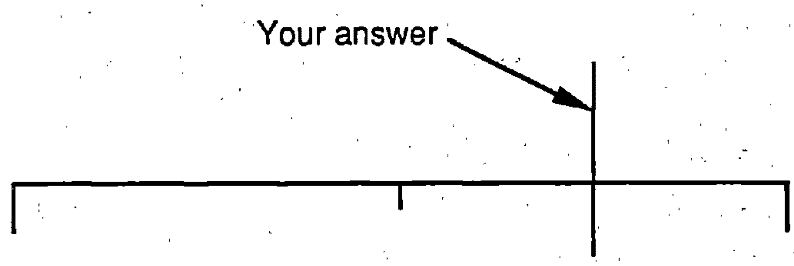
[C. Comfort Level]
[Note: The narrative for this section of the multiple experiment is omitted because it is not relevant to the current experiment.]

[D. Reduced Capability]
Passage D.1: AS IN MANUAL.
Passage D.2: AS IN AUTOMATED.
Passage D.3: AS IN AUTOMATED.
Passage D.4: AS IN AUTOMATED.
Passage D.5: AS IN AUTOMATED.
Passage D.6: AS IN AUTOMATED.

APPENDIX 3: QUESTIONNAIRE FOR THE MULTIPLE EXPERIMENT

The following series of questions deals with the driving simulator, the study that you just took part in, and the Automated Highway System. Each question is followed by a line. Please answer each question by marking this line in the appropriate place.

For example: If you were asked, "How would you rate the importance of the airbags in driver safety?" you might answer as shown below:



Completely unnecessary | Absolutely necessary

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1. How much did you enjoy driving the simulator?

Not at all | A great deal

2. How did driving in the simulator compare to driving in your car?

Very different | Very similar

3. How realistic was the view out of the windshield in the simulator?

Very artificial — Very realistic

4. How realistic were the sounds in the simulator?

Very artificial — Very realistic

5. How realistic was the vehicle motion in the simulator?

Very artificial — Very realistic

6. While driving the simulator, did you feel queasy or unwell?

Felt unwell — Felt fine

7. Was the message giving you the command to enter the automated lane easy to understand?

Hard to understand — Easy to understand

8. Did you have enough time to react to the message telling you to enter the automated lane?

Insufficient time — Sufficient time

9. To what extent did you feel in control of the situation when you drove into the automated lane and transferred control of your vehicle to the Automated Highway System?

Not in control	Very much in control

10. Did you control your car poorly or well as you left the manual lane and entered the automated lane?

Very poorly (controlled)	Very well (controlled)

11. When you entered the automated lane, the distance between strings of automated vehicles varied. Would you prefer a longer or shorter gap than the ones you experienced?

Strongly preferred longer distance	Strongly preferred shorter distance

12. When your car was under automated control, were you comfortable with the speed, or would you have preferred to have traveled faster or slower?

Would prefer much slower	Would prefer much faster

13. Did you feel that pulling and pushing on the lever with your right hand accurately reflected how comfortable you felt about the car in front of you?

Did not reflect my comfort level	Accurately reflected my comfort level

14. To what extent did you feel in control of the situation when you received the *Reduced Capability* advisory?

Not at all — To a great extent

15. How successful do you think you were at filling in during the lost capability section?

Very unsuccessful — Very successful

16. How easy was it to fill in for the system during the lost capability section?

Not easy to fill in — Easy to fill in

17. When you received the Resumption of Control message, did the transition back to automated control go smoothly?

Not at all — To a great extent

18. How safe did the speed at which you left the automated lane and entered the manual lane feel?

Very unsafe — Very safe

19. How safe did you feel when you drove into the automated lane?

Very unsafe — Very safe

20. In this study, you spent some time in the manual lanes and some in the automated lane: which did you prefer?

Strongly preferred manual lanes — Strongly preferred automated lane

21. Was it more challenging to be in the automated lane or the manual lanes?

More challenging in manual lanes — More challenging in automated lane

22 (a). During the portion of the drive where your speed was automatically controlled, but you had control of the steering, how did this feel?

Very uncomfortable — Very comfortable

22 (b). During the portion of the drive where your steering was automatically controlled, but you had control of your speed, how did this feel?

Very uncomfortable — Very comfortable

22 (c). During the portion of the drive where your steering and speed were automatically controlled, how did this feel?

Very uncomfortable — Very comfortable

23. How would you feel if an Automated Highway System was installed on I-380 between Iowa City and Waterloo?

Very unenthusiastic — Very enthusiastic

24. If an Automated Highway System was installed on I-380, would you prefer driving in the automated lanes or the manual lanes?

Strongly prefer manual lanes — Strongly prefer automated lanes

25. If an Automated Highway System was installed, would you feel safer driving on I-380 than you do now without the System?

Much safer with current freeways — Much safer with Automated Highway System

26. How will the installation of an Automated Highway System affect the stress of driving?

Will greatly decrease stress		Will greatly increase stress

27. Do you have any comments on the Automated Highway System?

____

____

____

____

____

28. What type of vehicle do you usually drive?

Type	Make	Year
Car		
Van		
Truck		
Motorcycle		
Other		

29. Does your vehicle have cruise control?

(a) Yes_____________(If you marked yes, please answer Question 30)

(b) No_____________(If you marked no, please skip Question 30, and answer Question 31)

30. How often do you use the cruise control on your vehicle?

Hardly ever ——————————————————— Very often

31. Have you had any accidents involving moving vehicles?

(a) Yes (b) No

Thank you for participating in this study!

APPENDIX 4: ANOVA SUMMARY TABLES

Appendix 4 contains the full summary tables for the ANOVA's conducted on the four lane-keeping performance measures and on the time delay data. They are presented on the following pages in the same order in which they were discussed in section 3 of the main report.

Table 19. Summary of the ANOVA conducted to determine whether the initial position of the vehicle in the lane was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F-value	p-value
Age of Driver (A)	1	0.41481138	0.41481138	8.92	0.0033
Transfer Method (T)	1	1.15114143	1.15114143	24.74	0.0001
A*T	1	0.04186020	0.04186020	0.90	0.3444
Reduced Capability (L)	2	2.82786634	1.41393317	30.39	0.0001
A*L	2	1.09266470	0.54633235	11.74	0.0001
T*L	2	0.05271954	0.02635977	0.57	0.5687
A*T*L	2	0.05027922	0.02513961	0.54	0.5837
Designated AHS Velocity (V)	1	1.50384629	1.50384629	32.33	0.0001
A*V	1	0.00476553	0.00476553	0.10	0.7494
T*V	1	0.02345616	0.02345616	0.50	0.4788
A*T*V	1	0.00930372	0.00930372	0.20	0.6554
L*V	2	0.08460169	0.04230085	0.91	0.4051
A*L*V	2	0.12843783	0.06421891	1.38	0.2547
T*L*V	2	0.05356381	0.02678190	0.58	0.5636
A*T*L*V	2	0.17964216	0.08982108	1.93	0.1487
Intra-String Gap (G)	1	0.27961827	0.27961827	6.01	0.0154
A*G	1	0.00835863	0.00835863	0.18	0.6723
T*G	1	0.06923568	0.06923568	1.49	0.2244
A*T*G	1	0.01801727	0.01801727	0.39	0.5347
L*G	2	0.32051218	0.16025609	3.44	0.0345
A*L*G	2	0.02256058	0.01128029	0.24	0.7850
T*L*G	2	0.05529058	0.02764529	0.59	0.5533
A*T*L*G	2	0.02840186	0.01420093	0.31	0.7374
V*G	1	0.00079354	0.00079354	0.02	0.8963
A*V*G	1	0.00863475	0.00863475	0.19	0.6672
T*V*G	1	0.02866200	0.02866200	0.62	0.4338
A*T*V*G	1	0.04795113	0.04795113	1.03	0.3117
L*V*G	2	0.02723454	0.01361727	0.29	0.7467
A*L*V*G	2	0.01217167	0.00608583	0.13	0.8775
T*L*V*G	2	0.10529741	0.05264871	1.13	0.3253
A*T*L*V*G	2	0.00622424	0.00311212	0.07	0.9353
Error	148	6.88535807	0.04652269		
Corrected Total	195	16.71412976			

Table 20. Summary of the ANOVA conducted to determine whether the steering drift was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F-value	p-value
Age of Driver (A)	1	0.00000028	0.00000028	1.47	0.2276
Transfer Method (T)	1	0.00000010	0.00000010	0.54	0.4641
A*T	1	0.00000023	0.00000023	1.20	0.2760
Reduced Capability (L)	2	0.00004679	0.00002339	122.81	0.0001
A*L	2	0.00000134	0.00000067	3.53	0.0319
T*L	2	0.00000088	0.00000044	2.31	0.1030
A*T*L	2	0.00000037	0.00000019	0.97	0.3808
Designated AHS Velocity (V)	1	0.00000062	0.00000062	3.24	0.0741
A*V	1	0.00000011	0.00000011	0.60	0.4395
T*V	1	0.00000004	0.00000004	0.19	0.6640
A*T*V	1	0.00000030	0.00000030	1.59	0.2090
L*V	2	0.00000283	0.00000141	7.43	0.0009
A*L*V	2	0.00000031	0.00000016	0.82	0.4443
T*L*V	2	0.00000066	0.00000033	1.73	0.1810
A*T*L*V	2	0.00000016	0.00000008	0.42	0.6579
Intra-String Gap (G)	1	0.00000001	0.00000001	0.05	0.8174
A*G	1	0.00000028	0.00000028	1.45	0.2306
T*G	1	0.00000045	0.00000045	2.37	0.1259
A*T*G	1	0.00000004	0.00000004	0.19	0.6637
L*G	2	0.00000098	0.00000049	2.57	0.0799
A*L*G	2	0.00000004	0.00000002	0.11	0.8941
T*L*G	2	0.00000013	0.00000006	0.33	0.7174
A*T*L*G	2	0.00000000	0.00000000	0.00	0.9950
V*G	1	0.00000001	0.00000001	0.03	0.8612
A*V*G	1	0.00000001	0.00000001	0.05	0.8178
T*V*G	1	0.00000009	0.00000009	0.45	0.5048
A*T*V*G	1	0.00000005	0.00000005	0.27	0.6038
L*V*G	2	0.00000004	0.00000002	0.11	0.8935
A*L*V*G	2	0.00000030	0.00000015	0.78	0.4602
T*L*V*G	2	0.00000009	0.00000004	0.23	0.7917
A*T*L*V*G	2	0.00000031	0.00000016	0.83	0.4402
Error	141	0.00002686	0.00000010		
Corrected Total	188	0.00009592			

Table 21. Summary of the ANOVA conducted to determine whether the steering instability was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F-value	p-value
Age of Driver (A)	1	0.04387792	0.04387792	7.52	0.0069
Transfer Method (T)	1	0.04371684	0.04371684	7.49	0.0070
A*T	1	0.01640720	0.01640720	2.81	0.0957
Reduced Capability (L)	2	0.79161957	0.39580978	67.83	0.0001
A*L	2	0.00395533	0.00197766	0.34	0.7131
T*L	2	0.00309645	0.00154823	0.27	0.7673
A*T*L	2	0.00306958	0.00153479	0.26	0.7691
Designated AHS Velocity (V)	1	0.24582967	0.24582967	42.13	0.0001
A*V	1	0.00709347	0.00709347	1.22	0.2721
T*V	1	0.00071159	0.00071159	0.12	0.7274
A*T*V	1	0.01034204	0.01034204	1.77	0.1852
L*V	2	0.00788639	0.00394320	0.68	0.5104
A*L*V	2	0.02210581	0.01105291	1.89	0.1542
T*L*V	2	0.00453524	0.00226762	0.39	0.6787
A*T*L*V	2	0.00634193	0.00317097	0.54	0.5820
Intra-String Gap (G)	1	0.00613345	0.00613345	1.05	0.3070
A*G	1	0.01535812	0.01535812	2.63	0.1069
T*G	1	0.00208903	0.00208903	0.36	0.5506
A*T*G	1	0.02919764	0.02919764	5.00	0.0268
L*G	2	0.02963443	0.01481722	2.54	0.0825
A*L*G	2	0.01047822	0.00523911	0.90	0.4097
T*L*G	2	0.01044043	0.00522021	0.89	0.4110
A*T*L*G	2	0.01651611	0.00825806	1.42	0.2462
V*G	1	0.00357481	0.00357481	0.61	0.4351
A*V*G	1	0.00702348	0.00702348	1.20	0.2744
T*V*G	1	0.00007856	0.00007856	0.01	0.9078
A*T*V*G	1	0.01480696	0.01480696	2.54	0.1134
L*V*G	2	0.02171570	0.01085785	1.86	0.1593
A*L*V*G	2	0.01575467	0.00787733	1.35	0.2625
T*L*V*G	2	0.04835451	0.02417725	4.14	0.0178
A*T*L*V*G	2	0.02252836	0.01126418	1.93	0.1488
Error	144	0.84029144	0.00583536		
Corrected Total	191	2.44486674			

Table 22. Summary of the ANOVA conducted to determine whether the number of steering oscillations per minute was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F-value	p-value
Age (A)	1	143.44104	143.44104	6.39	0.0126
Transfer Method (T)	1	20.81162	20.81162	0.93	0.3373
A*T	1	40.10575	40.10575	1.79	0.1835
Reduced Capability (L)	2	1049.70394	524.85197	23.38	0.0001
A*L	2	260.13164	130.06582	5.79	0.0038
T*L	2	101.76893	50.88446	2.27	0.1074
A*T*L	2	38.04725	19.02363	0.85	0.4307
Designated AHS Velocity (V)	1	46.26116	46.26116	2.06	0.1534
A*V	1	2.45136	2.45136	0.11	0.7416
T*V	1	0.00185	0.00185	0.00	0.9928
A*T*V	1	0.43392	0.43392	0.02	0.8896
L*V	2	585.81966	292.90983	13.05	0.0001
A*L*V	2	17.81719	8.90859	0.40	0.6732
T*L*V	2	27.88049	13.94025	0.62	0.5389
A*T*L*V	2	34.14863	17.07431	0.76	0.4693
Intra-String Gap (G)	1	12.76292	12.76292	0.57	0.4521
A*G	1	3.71905	3.71905	0.17	0.6846
T*G	1	61.91117	61.91117	2.76	0.0990
A*T*G	1	18.82679	18.82679	0.84	0.3614
L*G	2	23.47389	11.73695	0.52	0.5940
A*L*G	2	0.76271	0.38135	0.02	0.9832
T*L*G	2	167.23426	83.61713	3.72	0.0265
A*T*L*G	2	7.74278	3.87139	0.17	0.8418
V*G	1	26.47640	26.47640	1.18	0.2793
A*V*G	1	20.54060	20.54060	0.91	0.3404
T*V*G	1	1.19049	1.19049	0.05	0.8182
A*T*V*G	1	3.47716	3.47716	0.15	0.6945
L*V*G	2	36.76110	18.38055	0.82	0.4431
A*L*V*G	2	7.49354	3.74677	0.17	0.8465
T*L*V*G	2	45.13542	22.56771	1.01	0.3686
A*T*L*V*G	2	18.75675	9.37838	0.42	0.6593
Error	142	3187.99158	22.45064		
Corrected Total	189	6517.99597			

Table 23. Summary of the ANOVA conducted to determine whether the time delay was affected by the age of the driver, the designated AHS velocity, the control transfer method, the intra-string gap, or the reduced-capability mode.

Source	Degrees of Freedom	Type III Sum of Squares	Mean Square	F-value	p-value
Age of Driver (A)	1	423.158014	423.158014	55.62	0.0001
Transfer Method (T)	1	461.804656	461.804656	60.69	0.0001
A*T	1	44.619594	44.619594	5.86	0.0167
Reduced Capability (L)	2	949.788847	474.894423	62.42	0.0001
A*L	2	281.983321	140.991661	18.53	0.0001
T*L	2	252.622876	126.311438	16.60	0.0001
A*T*L	2	187.979378	93.989689	12.35	0.0001
Designated AHS Velocity (V)	1	52.156435	52.156435	6.85	0.0098
A*V	1	128.865769	128.865769	16.94	0.0001
T*V	1	3.624522	3.624522	0.48	0.4912
A*T*V	1	60.234481	60.234481	7.92	0.0056
L*V	2	35.934357	17.967179	2.36	0.0980
A*L*V	2	72.000802	36.000401	4.73	0.0102
T*L*V	2	20.941152	10.470576	1.38	0.2559
A*T*L*V	2	53.720239	26.860120	3.53	0.0319
Intra-String Gap (G)	1	1.479031	1.479031	0.19	0.6600
A*G	1	29.633498	29.633498	3.89	0.0504
T*G	1	14.121540	14.121540	1.86	0.1752
A*T*G	1	51.929587	51.929587	6.83	0.0099
L*G	2	43.286186	21.643093	2.84	0.0615
A*L*G	2	23.842636	11.921318	1.57	0.2123
T*L*G	2	23.671760	11.835880	1.56	0.2146
A*T*L*G	2	85.952262	42.976131	5.65	0.0044
V*G	1	42.770995	42.770995	5.62	0.0191
A*V*G	1	6.075576	6.075576	0.80	0.3730
T*V*G	1	12.512887	12.512887	1.64	0.2018
A*T*V*G	1	0.550854	0.550854	0.07	0.7883
L*V*G	2	99.254940	49.627470	6.52	0.0019
A*L*V*G	2	14.196654	7.098327	0.93	0.3958
T*L*V*G	2	26.951275	13.475637	1.77	0.1739
A*T*L*V*G	2	0.308968	0.154484	0.02	0.9799
Error	143	1088.034760	7.608630		
Corrected Total	190	4292.762220			

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