The Effect on Normal Driving Behavior of Traveling Under Automated Control

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FOREWORD

This report presents the results of one of 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 investigated the effects on normal driving of traveling under automated control for a short period of time. Some lane-keeping measures and some velocity maintenance measures indicated that drivers may have been attending more closely to staying in their lanes after automated travel than before it, and that velocity maintenance may have suffered somewhat because of this. In addition to the AHS-travel effect, there was an age effect on some lane-keeping and some velocity maintenance measures. 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
The objective of this experiment, one in a series exploring human factors issues related to the Automated Highway System (AHS), was to determine whether traveling under automated control at velocities considerably higher than the speed limit and closer to the vehicles ahead and behind than usual affected driving performance. 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, and 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 the ages of 25 and 34 years, half were 65 years or older. Eight newly developed driving measures—four lane-keeping measures and four velocity maintenance measures—were used to compare driving performance collected before and after the drivers had traveled under automated control.

Results: (1) Effect of Automated Travel. Driving performance was measurably different after the drivers traveled under automated control. However, there was no evidence that lane-keeping behavior was in any way worse than before the drivers experienced automated travel. In fact, to the contrary, in post-AHS driving, the steering drift was close to zero, indicating that the course steered by the drivers was almost parallel to the white lane lines, and the drivers had low steering instability scores that were achieved with relatively few steering adjustments. With the velocity maintenance measures, although there was less velocity drift when the drivers were in the center lane after traveling under automated control, there was more velocity instability and there were fewer velocity fluctuations than there were before. This cannot be considered to be bad driving performance, but it does suggest that more prolonged travel under automated control might be problematic.

(2) Age of the Driver. There were more steering oscillations and more velocity fluctuations for the older drivers than there were for the younger drivers—suggesting that for the older drivers, the deviations about the lines of best fit, both for steering and for velocity maintenance, were greater in magnitude and shorter in duration than they were for the younger drivers, and that this might be why the older drivers drove more slowly than the younger drivers.

17. Key Words
Automated highway system, human performance, driving simulation, traffic flow, automation, intelligent vehicles, human factors.

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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.

Symbol	When You Know	Multiply By	To Find	Symbol
		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)

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

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. The series is part of a program administered by the Federal Highway Administration (FHWA). The experiments have investigated human factors issues using a generic AHS configuration that would require minimal structural alteration of the existing roadways in either cross section or vertical and horizontal geometry. The configuration consists of a three-lane expressway where the vehicles controlled by the AHS travel in strings of up to four in the left lane, while the vehicles that remain under the control of their drivers travel in the center and right lanes. There is no dedicated transition lane and there are no barriers between the automated and unautomated lanes.

This report describes the seventh experiment in the series; it was performed as part of a complex multiple experiment. Driving performance data obtained from 60 drivers before they experienced traveling in an automated lane were compared with driving performance data obtained from the same drivers after they had traveled under automated control. While in the automated lane, each driver traveled at speeds that were considerably higher than the usual expressway speed limit, while the gaps between the vehicles ahead and behind were smaller than those usually experienced in normal driving. The comparison was conducted in order to determine whether traveling in an automated lane under these conditions had an impact on driving performance.

The first two experiments of the series investigated the transfer of control from the AHS to the driver of the simulator vehicle.(1) At the beginning of the trials in these two experiments, the driver's 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 to 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 driver entered the automated lane.(2) In this study, each experimental 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 the vehicle to the center lane, and then, after receiving an *Enter* command, drive into the automated lane and transfer control of the vehicle to the AHS. At this point, the AHS moved the simulator vehicle into the lead position of the string of vehicles that was approaching it from behind.

OVERVIEW OF THE MULTIPLE EXPERIMENT

The multiple experiment continued the investigation of human factors aspects of the AHS, using the same generic AHS configuration that was used in the first three experiments of the series. It combined four experiments that were initially planned as separate studies. The first experiment compared manual, partially automated, and fully automated methods of transferring control of the vehicle from the driver to the AHS on entering the automated lane.(3) The second experiment investigated the acceptability to the driver of decreasing vehicle separations during transitions into the automated lane.(4) The third experiment explored the ability of the driver to take control of driving functions that became unavailable in a segment of the expressway in which the capability of the AHS was reduced.(5) And, in the fourth experiment (reported here), the effect on normal driving behavior of traveling under automated control was determined.

Each driver in the multiple experiment took part in six experimental trials. Table 1 shows how the data collected in each section of the six trials were distributed among the four parts of the multiple experiment.

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

In trial #1, each driver began by driving on a two-lane rural road, then he/she drove on a three-lane expressway that did not have the AHS installed—the pre-AHS driving performance data obtained in the expressway section of this trial were compared with the post-AHS driving performance data obtained in trial #6.

The simulation scenarios for trials #2, #3, #4, and #5 were developed in a way that allowed the data for parts 1, 2, and 3 of the multiple experiment to be collected as the three sections of these trials followed each other without a break.

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 for part 4 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 road.
- 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—6.21 v/ln/km (10 v/ln/mi)—for approximately 3 min.
- 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 hard shoulder at the side of the expressway.
- The driver moved into the right lane, and then drove to the center lane—the density of the traffic in the center and right lanes was 6.21 v/ln/km (10 v/ln/mi).
- Once the simulator vehicle was in the center lane, it was moved into the automated lane and control was transferred from the driver to the AHS using a manual, partially automated, or 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, 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.
- The driver received a *Reduced Capability* **advisory**, stating that the vehicle was approaching a segment of expressway with reduced AHS capability—the AHS was unable to: (a) steer the driver's vehicle, or (b) control its speed, or (c) both steer and control its speed.
- In the driver-controlled condition, the driver could take control of the lost function(s) 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(s).
- When the simulator vehicle reached the end of the segment of expressway with reduced capability, the driver received a *Ready-to-Resume-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 through #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.
- 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 for 4 min.
- The density of the traffic in the center and right lanes was 6.21 v/ln/km (10 v/ln/mi).
- 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.

OBJECTIVE OF THIS EXPERIMENT

The objective of this experiment was to determine whether traveling under automated control at high speed and a shorter-than-normal distance behind the vehicle ahead would affect normal driving behavior. Driving performance data obtained before and after each driver traveled under automated control in the automated lane were collected. The data analysis focused on the following experimental questions:

- *Is driving performance affected by traveling under automated control?*
- *Is driving performance affected by the age of the driver?*
- *Does the designated AHS velocity or the method of transferring control affect driving performance after the driver has traveled in the automated lane?*
- *Is driving performance affected by some combination of two or more of these variables—i.e., traveling in the automated lane, the age of the driver, the designated AHS velocity, and the method of transferring control?*

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 at least 65 years old, 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 took part 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 1.(6) The simulator consists of a projection dome mounted on a hydraulically actuated hexapod platform. In this experiment, a midsize Ford sedan was mounted on this platform, and the simulator was controlled by a distributed 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 screen. For the current experiment, the correlated images generated by the CT-6 were projected onto two sections of these walls—a 3.35-rad (192°) section in front of the simulator vehicle, and a 1.13-rad (65°) section to its rear. The driver of the simulator vehicle viewed the images shown on the forward section through the windshield and

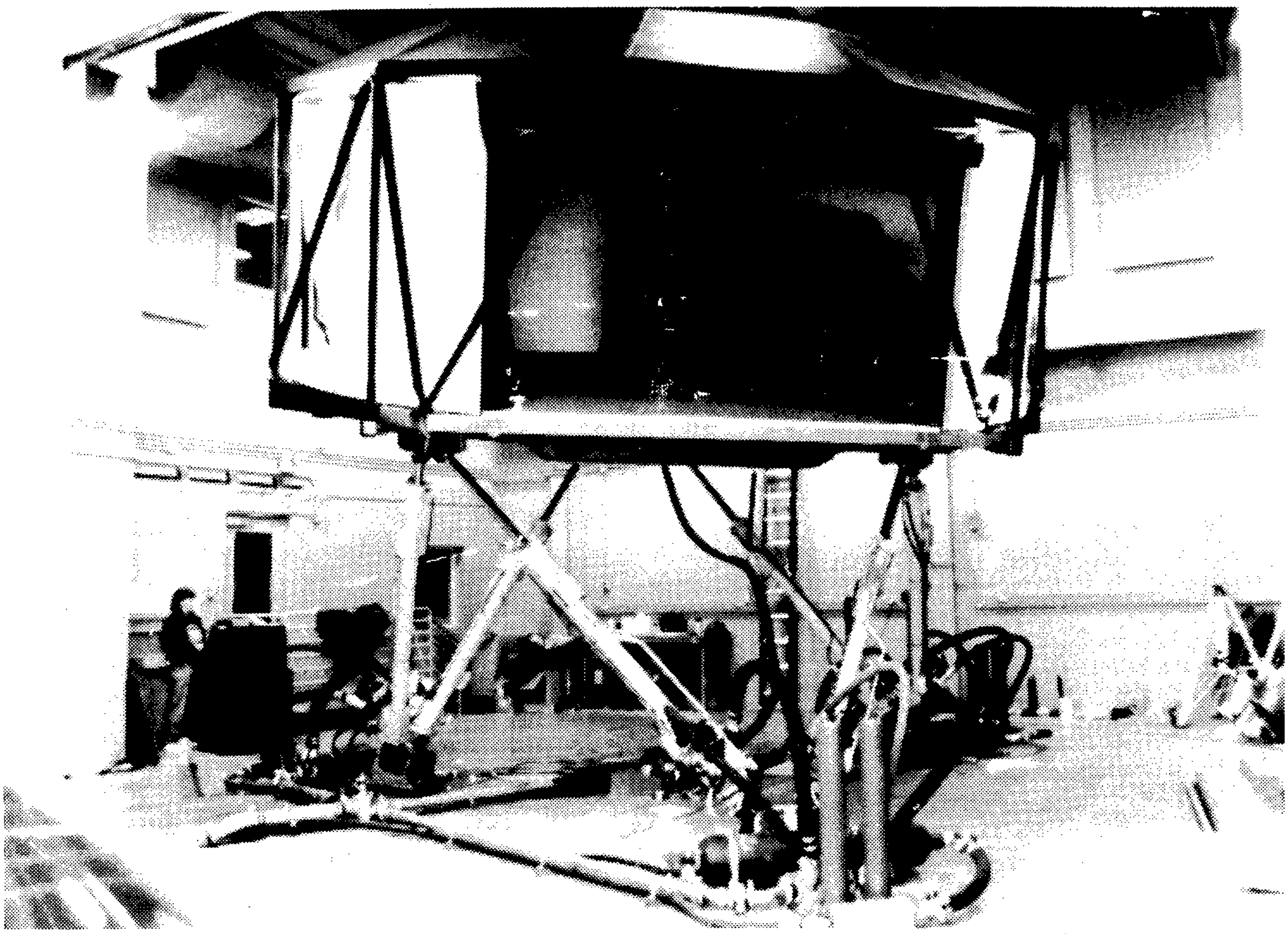


Figure 1. The Iowa Driving Simulator.

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

EXPERIMENTAL DESIGN

The current experiment was focused on the lane/trial variable, i.e., on the comparison between driving performance data collected before the driver had traveled under automated control and driving performance data collected after the driver had experienced automated travel. Two of the other three independent variables investigated here—the designated AHS velocity and the method of transferring control from the AHS back to the driver—were not experienced by the driver until he/she had traveled in the automated lane, and, therefore, could only affect driving performance in the post-AHS segment of the trial. Because of this, it was not expected that the main effect of either of these variables would be statistically significant—if either the designated AHS velocity or the control transfer method had an effect, it was expected to be in an interaction with the lane/trial variable. The fourth variable (the age of the driver) could have affected driving performance both before and after the driver had experienced automated travel. There were six combinations of designated AHS velocity and transfer control method, each of which was experienced by five older and five younger drivers. The designated AHS velocity presented to each of the 60 subjects in trial #6 is listed in appendix 1.

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 of age, and 15 were age 70 or older. As a result of these two selection strategies, there were eight male and seven female drivers between ages 65 and 69 , and seven male and eight female drivers who were age 70 or older.

Designated AHS Velocity

As in the prior experiments in the series, the following designated AHS velocities were used: (a) 104.7 km/h (65 mi/h), (b) 128.8 km/h (80 mi/h), and (c) 153.0 km/h (95 mi/h).[1,2] Table 2 shows the velocity differential between the automated and unautomated lanes for each of the three designated AHS velocities.

Table 2. The designated AHS velocity and the velocity differential between the automated and unautomated lanes.

Designated AHS velocity [km/h (mi/h)]	Velocity differential between automated and unautomated lanes [km/h (mi/h)]
104.7 (65)	16.10 (10)
128.8 (80)	40.25 (25)
153.0 (95)	64.40 (40)

Method of Transferring Control of the Vehicle

Control was transferred between the AHS and the driver in one of two ways. The first was the driver-controlled method. With this method, the AHS issued a *Reduced Capability* **advisory**, after which the driver was able to take control of the vehicle at any time in the next 20 s. If the driver failed to take control within that 20 s, the AHS issued a *Reduced Capability* **command** stating that the system would no longer control the vehicle and that the driver must take control. The second method was the situation-controlled method. With this method, the AHS gave the *Reduced Capability* **advisory** for information purposes only (i.e., the driver could not take control when the **advisory** was given), following it with the *Reduced Capability* **command** stating that the system would no longer control the vehicle and that the driver must take control.

All 60 drivers who participated in this experiment did take back control of the vehicle. Thirty of them regained control at the end of trial #6 using the driver-controlled method. Of the 30 drivers, 20 had relinquished control of the simulator vehicle manually, while the other 10 had relinquished control in a partially automated manner on entering the automated lane at the beginning of trials #2, #3, #4, #5, and #6. The remaining 30 drivers regained control at the end of trial #6 using the situation-controlled method—10 of these drivers also had relinquished control of the simulator vehicle in a partially automated manner on entering the automated lane at the beginning of trials #2, #3, #4, #5, and #6, while the other 20 had relinquished control manually.

Lane/Trial Variable

Samples of driving performance data were collected while the drivers drove in the right and center lanes in trial #1, before they had experienced automated travel, and in the center lane in trial #6, after they had experienced traveling in the automated lane. Then the driving performance data from trial #1 and trial #6 were compared.

EXPERIMENTAL PROCEDURE

The multiple experiment was administered in two sessions for each driver. In the first session, the drivers watched an introductory videotape, drove the Iowa Driving Simulator, and filled out a questionnaire. In the second session, the driver's visual capabilities were assessed.

Introduction, Training, and Practice Procedure

Before the start of the experiment, each driver watched a videotape that contained introductory material describing this research program and the AHS, and that provided some interactive practice with the AHS interface and protocol. The driver was told that the experiment involved first driving in the simulator and then completing several vision tests and a questionnaire. The driver was informed that this experiment was part of an ongoing FHWA program that was 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. The video then 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 segment of the expressway in which there is a reduction in the AHS capability (in part 3).
- Transfer control back to the AHS at the end of the reduced capability segment (also in part 3).

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 introductory section, which is all that is relevant to the current experiment, was identical in all four videos—the narration for this section is presented in appendix 2.

The instructional section of three versions of the videos lasted 12 min—the fourth version, which dealt with automated entry to the AHS, 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 dealing 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 from and returning it 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 did not respond correctly twice in a row for a particular subtask, the three segments were repeated for that driver until he/she accomplished this. 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 was seated in the driver's seat. The driver was asked to put on the seat belt and to adjust the seat and mirrors, and then was given instructions on how to use the simulator emergency button.

Experimental Procedure and Instructions I

The driver took part in six experimental trials. Only data from the first and sixth trials were used in the current experiment.

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 via an entrance ramp. Then, he/she drove in the right and center lanes of the expressway in the presence of low-density traffic—6.21 v/ln/km (10 v/ln/mi)—for approximately 3 min. While the driver was driving on the expressway, the experimenter asked him/her 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

Trials #2, #3, #4, and #5 started with the driver driving in the right lane of the expressway. The driver changed lanes and then, when the vehicle was in the center lane, entered the automated lane using a manual, partially automated, or fully automated method of transferring control. The AHS caused the simulator vehicle to accelerate until it reached the designated AHS velocity, at which point it became the leader of a string of automated vehicles. A second vehicle moved into the automated lane ahead of the simulator vehicle and accelerated—under the control of the AHS—until it was traveling at the designated AHS velocity when it, in turn, became the new lead vehicle of the string. When the simulator vehicle passed through a segment of expressway on which the AHS was operating with reduced capability, the driver provided the function(s) that were unavailable. While the driver's vehicle traveled through this segment, control of the unavailable function(s) for the vehicle ahead and the vehicle behind the driver's vehicle were also transferred from the AHS to their drivers—this was achieved by transferring control of the unavailable function(s) in these vehicles from the AHS control model to the driver behavior models used for the vehicles traveling in the center and right lanes throughout this series of experiments. At the end of the reduced capability segment, the AHS resumed full control of the vehicle. Each complete trial lasted between 5 and 7 min. There were brief breaks between trials while the simulator was reset.

Trial #6 began in the same way as trials #2, #3, #4, and #5—with the driver in control of the simulator vehicle until it entered the automated lane using one of the three control transfer methods. Then, with the AHS in control, the simulator vehicle accelerated to the designated AHS velocity and became the leader of a string of automated vehicles. At this point, the second part of the current experiment began.

Experimental Procedure and Instructions II

At the end of the first section of trial #6—in which data were provided for part 1 of the multiple experiment—the current experiment resumed. When the second section of trial #6 started, the simulator vehicle was the lead of a string of automated vehicles. After traveling this way for approximately 4 min, the driver received a *Reduced Capability* **advisory** stating that he/she was approaching a segment of expressway in which the AHS could not steer and could not control the speed of the vehicle. Control was transferred back to the driver in one of the following ways:

- For one group, the driver could take control of the steering and speed as soon as the *Reduced Capability* **advisory** was issued (driver-controlled transfer)—if the driver did not take control on hearing this advisory, then a second message, a *Reduced Capability* **command**, was issued at the moment that the AHS relinquished control.

- For the second group, the driver could not take control on hearing the *Reduced Capability* **advisory**—it was given only as a warning—but had to wait until the AHS issued a *Reduced Capability* **command** containing a countdown that ended at the moment the AHS relinquished control (situation-controlled transfer).

At the same time that the driver resumed full control of the simulator vehicle, control of the vehicle traveling behind the driver's vehicle was transferred from the AHS to the driver of that vehicle. This was achieved by transferring control of the vehicle from the AHS control model to the driver behavior models used for the vehicles traveling in the center and right lanes throughout this series of experiments.

After taking full control of the vehicle, the driver remained in the automated lane until the AHS issued another message informing the driver that it would not resume control. Then the driver moved into the unautomated lane and continued driving. The trial continued for 4 min with the driver in control of the vehicle and driving in the unautomated lanes. Throughout the trial, the density of the traffic in the unautomated lanes was 6.21 v/ln/km (10 v/ln/mi).

Post-Experimental Procedure

After completing trial #6, the driver returned to the subject preparation room. Once there, the driver was debriefed and asked to complete a questionnaire that contained questions 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 was 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.[8]

SECTION 3: RESULTS

FOCUS OF THE DATA ANALYSIS

The objective of this experiment was to determine whether normal driving performance changed as a result of the driver traveling under automated control at high speed and with shorter-than-normal inter-vehicle spacing. The data analysis focused on the following experimental questions:

- *Is driving performance affected by traveling under automated control?*
- *Is driving performance affected by the age of the driver?*
- *Does the designated AHS velocity of the automated lane or the method of transferring control affect driving performance after the driver has traveled in the automated lane?*
- *Is driving performance affected by some combination of two or more of these variables, i.e., traveling in the automated lane, the age of the driver, the designated AHS velocity in the automated lane, or the method of transferring control?*

DRIVING PERFORMANCE MEASURES

In order to determine whether the experience of traveling under automated control affected the performance of the 60 drivers who took part in the current experiment, it was first necessary to decide how to measure driving performance. This was not a simple task: in 1993, Nilsson suggested that the statement—"It has proved extremely difficult to define what is meant by driving performance and to develop adequate techniques of measuring it"—made by Crawford over 30 years ago still holds true.[9,10]

It is difficult to obtain detailed measures of the normal driving performance of a driver while he/she is driving on roads and expressways—direct observation can be used, but it is a method that lacks precision. More detailed information can be obtained by using an instrumented car. For example, Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, and Fleischman used an instrumented car to evaluate the driving and navigation performance of drivers who were using the TravTek system.[11] Dingus et al. collected the following driving performance measures:

mean speed, speed variance, longitudinal acceleration and braking, steering wheel position variance, steering wheel reversals greater than 6°, and variance in lateral acceleration. An instrumented vehicle was also used by Lechner and Perrin to characterize driving behavior on various types of road.(12) In their study, 12 drivers drove an instrumented vehicle on an 85-km (52.8-mi) route in Southern France. The route included sections of expressway, minor roads that had long straight sections, winding roads, and a town (Aix-en-Provence) with typically dense urban traffic. Lechner and Perrin analyzed driving performance in terms of the velocity (percentage of time in each 20-km/h [12.4-mi/h] velocity range), the longitudinal acceleration and braking rates, the lateral acceleration and braking rates, and steering wheel movements. For expressway driving, they found that the drivers drove at velocities that ranged between 100 km/h (62.1 mi/h) and 160 km/h (99.4 mi/h); that 86 percent of the longitudinal acceleration and braking was between $+0.1\ g$ and $-0.1\ g$ (where $1\ g = 9.81\ m/s^2$); that 80 percent of the lateral acceleration and braking was between $+0.1\ g$ and $-0.1\ g$, with only 3 percent higher than $0.2\ g$; and that the range of steering wheel movements decreased as the velocity of the vehicle increased.

It is possible to obtain more precise driving performance data than were obtained by Dingus et al. and by Lechner and Perrin if an instrumented track or a simulator is used—although with these, there may be some loss in validity. Investigators using simulators have typically looked at longitudinal performance in terms of mean velocity (and variability around the mean), and acceleration and deceleration rates; and lateral performance in terms of the deviation of the line of travel from the center of the lane and the number of steering wheel reversals.(13,14)

Lane-Keeping Behavior

The deviation of the line of travel from the center of the lane has been used as a measure of lane-keeping performance, while the number of steering wheel reversals has provided a measure of the stability or smoothness of the ride. Recently, Bloomfield and Carroll have used ideas derived from regression analysis to develop alternative, more accurate measures of both lane-keeping performance and of the stability or smoothness of the ride.(15) They suggest a method that effectively separates 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 by the driver's vehicle of the line of best fit (or direction of travel).

Bloomfield and Carroll show how to determine the linear equation that is the line of best fit for a series of points on the track of a vehicle. The equation describes the position of the vehicle relative to the center of the lane at any time. It indicates how far the vehicle is to the left, or right, of the center line of the lane at the beginning of the series of points. It also indicates whether the vehicle is veering to the left or to the right or is traveling parallel to the lane throughout the series of points. The variability of the actual track of the vehicle around this line of best fit can be used, along with the number of crossings of the direction of travel (or line of best fit), to indicate the stability of the driver in maintaining 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 while it remains in a lane.[15] They consider the case, illustrated in figure 2, where a driver is traveling in a lane along a straight road segment. At any point in time, it is possible to determine the position of the center of the vehicle on a line that is perpendicular to the lane. In the current experiment, data were collected at a rate of 30 Hz—so that, as the vehicle traveled along a straight road segment,

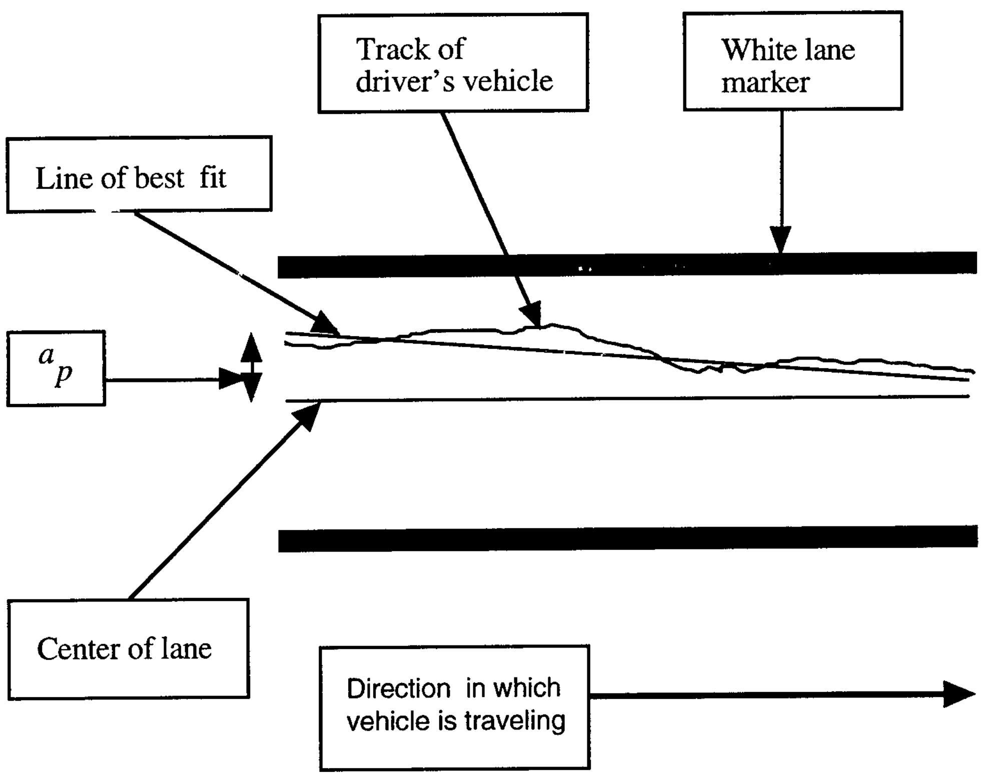


Figure 2. Schematic showing a cross section of a lane, with the track of the driver's vehicle along the lane and the line of best fit. [It should be noted that the cross section of the lane is greatly exaggerated compared to distance along the lane.]

the track of the vehicle could be used to determine the position of the center of the vehicle relative to a series of perpendicular lines drawn at 1/30-s intervals. Bloomfield and Carroll assume that the series of positions can be described by the following linear equation:

$$p = a_p + b_p x \tag{1}$$

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 a lane by the vehicle.
- a_p is the point at which the line of best fit crosses the perpendicular at the start of the straight road segment. If a_p equals zero, it crosses the perpendicular line at its center. If a_p is positive, as it is in figure 2, then the line of best fit starts to the left of the center line (assuming one is looking in the direction of travel); and if a_p is negative, it starts to the right of the center line.
- b_p is the gradient of the line. If b_p equals zero, the vehicle is traveling along the center line of the lane or parallel to it; if b_p is positive, the vehicle is moving from the right of the lane to the left (assuming one is looking in the direction of travel); and if b_p is negative, as it is in figure 2, the vehicle is moving from the left to the right of the lane.

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. Since 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—a_p and b_p are calculated as follows:

$$b_p = \frac{\sum xp - \frac{(\sum x)(\sum p)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \tag{2}$$

where n is the number of data points obtained while the vehicle traveled distance x, and

$$a_p = \frac{1}{n}\left(\sum p - b_p \sum x\right) \tag{3}$$

In addition, the variability in b_p —the residual standard deviation—can be used as an estimate of I_p, the steering instability. I_p 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:

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

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 (if there is any); 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.(15)

If there was to be a radical change in the direction of the vehicle—and the most radical change that could occur while the vehicle remains in a lane would occur if, for example, the vehicle first veered from the extreme right of the lane to the extreme left, then changed direction and veered from the extreme left back to the extreme right of the lane—then, the steering instability would be relatively large, but there would be only two steering oscillations.

The current experiment explored the driving performance of drivers while they were driving on a straight segment of expressway, both before and after they had experienced traveling under automated control. However, Bloomfield and Carroll also demonstrate that, under some circumstances, it is possible to use this linear equation to describe the track of a vehicle traveling around a horizontal curve.(15) Whether the linear equation can be used in this way or not depends on the way in which the position of the vehicle in the lane is determined. If its position is determined relative to the cross section of the lane—as it was in Bloomfield, Carroll, Papelis, and Bartelme's investigation of reduced AHS capability—then a linear equation can be used to describe a curved path.(5) When the road is curved and the position of the vehicle in the lane is determined relative to the cross section of the lane, then at each moment, the position of the vehicle will be expressed relative to a line that is perpendicular to the tangent of the curve. In the investigation of reduced AHS capability, as the simulator vehicle traveled around the curve, data were collected at a rate of 30 Hz.(5) As a result, there were series of tangents at $^{1}/_{30}$-s intervals around the curve, each with a cross-sectional line that was perpendicular to it. On the cross-sectional lines, a series of points that indicated a series of lane positions was recorded. When these cross-sectional lines were considered together—and the wedge-shaped slivers of the curve between them ignored—the curve that the vehicle traveled around could be treated mathematically as a straight line, and a linear equation could be used to describe the track of the vehicle.

Velocity Maintenance

Bloomfield and Carroll also suggest that a set of equations similar to those used to describe lane-keeping performance can be used to describe the driver's ability to maintain the velocity of the vehicle.(15) In this case, the measures that they derive can be used to replace the mean velocity and its standard deviation—their method produces two velocity maintenance measures (one giving the velocity at any given instant, the other indicating any tendency for the velocity to drift higher or lower), and a measure of the velocity maintenance stability, as well as using the number of velocity reversals across the line of best fit (or velocity maintenance line). The equations used in this case—which is illustrated in figure 3—differ in that p, a_p, b_p, and I_p in equations 1, 2, 3, and 4 are replaced by v, a_v, b_v, and I_v, respectively, in equations 5, 6, 7, and 8. Equations 5, 6, and 7 provide a description of how well the driver maintains velocity, while equation 8 is a measure of smoothness or stability in maintaining velocity. These equations are presented below:

$$v = a_v + b_v x \tag{5}$$

$$b_v = \frac{\sum xv - \frac{(\sum x)(\sum v)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \tag{6}$$

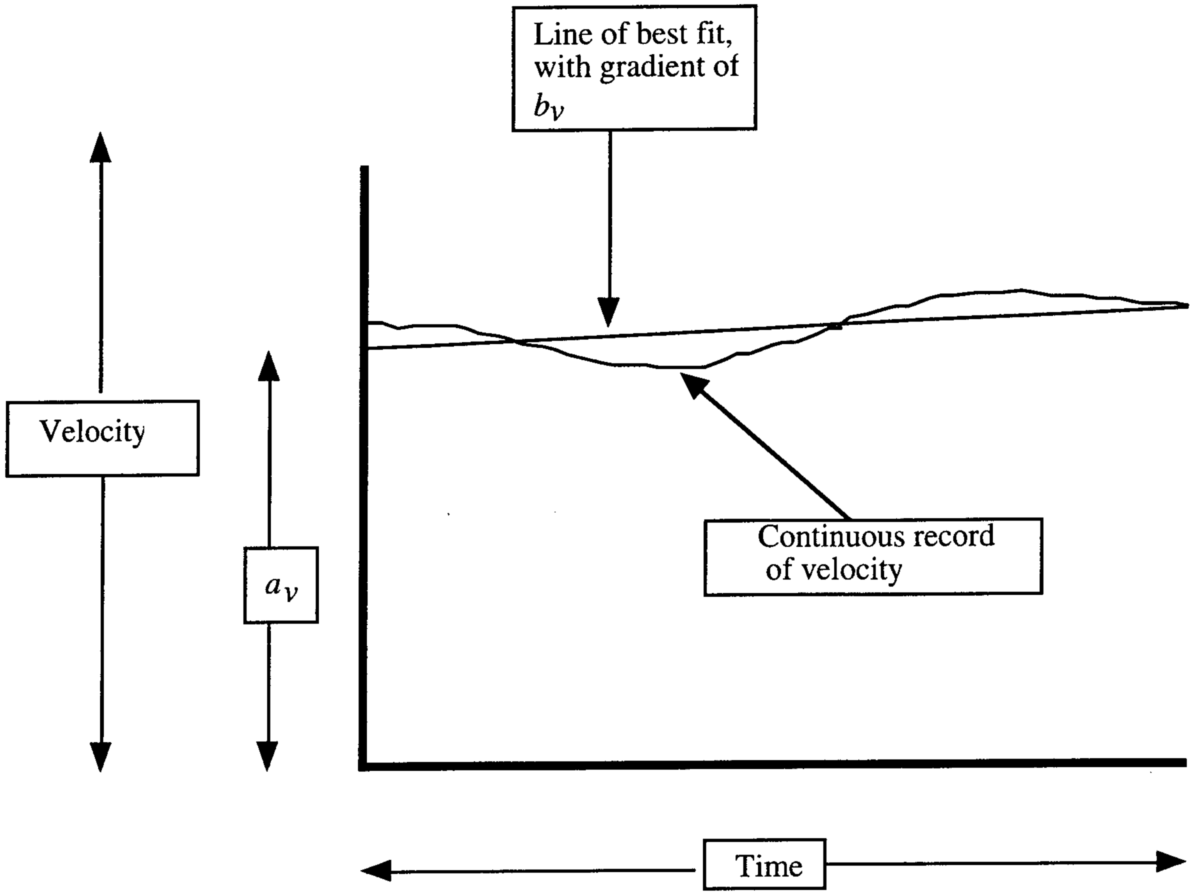


Figure 3. Schematic showing continuous record of velocity and the line of best fit.

$$a_v = \frac{1}{n}\left(\sum v - b_v \sum x\right) \tag{7}$$

$$I_v = \sqrt{\left[\sum v^2 - \frac{(\sum v)^2}{n} - \frac{\left\{\sum xv - \frac{(\sum x)(\sum v)}{n}\right\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}}\right] \div (n-2)} \tag{8}$$

where:

v is the velocity, indicated by the line of best fit, after the vehicle has traveled distance x.

a_v is the point at which the line of best fit intercepts the velocity axis at the start of the straight road segment.

b_V is the gradient of the line. If b_V equals zero, the vehicle is traveling at constant velocity; if b_V is positive, the velocity of the vehicle is gradually increasing, as it is in figure 3; and if b_V is negative, velocity is gradually decreasing.

x is the distance traveled in a lane by the vehicle.

n is the number of data points obtained in distance x.

I_V is the instability in velocity maintenance. It is an estimate of the extent of the velocity fluctuations that occur when the driver is attempting to maintain a chosen velocity.

DATA ANALYSIS

The focus of the data analysis for the current experiment was on lane-keeping and velocity maintenance. Collision and incursion data are also reported. Other driving performance data—for example, data that might be obtained when the driver changed lanes, or was accelerating on entering the expressway, or decelerating after leaving the automated lane—were not considered here. The following data items were recorded in the current experiment:

- Designated AHS velocity.
- Continuous plot of the velocity of the simulator vehicle.
- Continuous plot of the position of the simulator vehicle.
- Times at which the simulator vehicle began lane changes, i.e., times at which the first wheel of the simulator vehicle touched the white line between lanes, when a lane change was completed.
- Times at which the simulator vehicle ended lane changes, i.e., times at which the fourth wheel of the simulator vehicle crossed the white line between lanes.
- Number of times the vehicle began a lane change but failed to complete it—an incursion.
- Velocity of the driver's vehicle at the beginning and end of lane changes.
- Whether the driver's vehicle collided with any other vehicles.

In this experiment, continuous data, i.e., the first six data items, were sampled and collected at a rate of 30 Hz. Bloomfield and Carroll's lane-keeping and velocity maintenance measures were calculated for each driver from these continuous data, using equations 2, 3, 4, 6, 7, and 8.

Sixty drivers took part in the current experiment; however, data from seven of them—three who were older and four who were younger—could not be used, either because the driver did not complete trial #6, or because there was a simulator failure during trial #6, or because the data for trial #6 could not be retrieved. There were 53 drivers (27 who were older and 26 who were younger) for whom driving performance data were available. The lane-keeping and velocity maintenance measures obtained from these drivers while they drove in the right and center lanes of the expressway before experiencing travel in the AHS were compared with the driving performance measures obtained from them when they drove in the center lane after traveling in the AHS. With data from 53 drivers in 3 expressway segments, a maximum of 159 samples of each of the driving performance measures were available for analysis.

The pre-AHS driving data were collected in the second part of trial #1—after the driver had entered the expressway via an entrance ramp. If the driver did not initiate a lane change within 60 s of entering the right lane, the experimenter asked him/her to change lanes—first from the right lane to the center lane, then back again to the right lane. This ensured that in trial #1, each driver drove in the right lane on at least two occasions and in the center lane at least once. The length of time that the driver remained in a lane on each occasion was measured. Then, the driving performance data from the longer sample in each lane were used in the analysis. For the right lane, the first sample was longer for 33 drivers, while the second sample was longer for the remaining 20 drivers. For the center lane, the first sample was longer for 42 drivers, while the second was longer for the other 11 drivers.

The post-AHS driving performance data were collected in trial #6—they were collected toward the end of the trial, after the drivers had been asked to move from the automated lane to the center lane and were informed that they could use both the center and right lanes. There were center-lane driving performance data for each driver who completed trial #6. However, unlike trial #1, in trial #6 the drivers were not instructed to change from one lane to another. As a result, for the remainder of trial #6, 40 of the 53 drivers chose to stay in the center lane, and did not drive in the right lane. This meant that, for comparison purposes, too few samples of post-AHS driving performance were obtained while the drivers were in the right lane.

For the 13 drivers who drove in the center lane on more than 1 occasion after they traveled in the automated lane, the sample of driving behavior that was longer was used for further analysis—the first center-lane sample was longer for 10 of these drivers, while the second center-lane sample was longer for the remaining 3 drivers. For the 40 drivers who drove only in the center lane after they traveled in the automated lane, their first, and only, sample of center-lane driving performance was used in the comparison of pre- and post-AHS driving.

It should be noted that the lane position and velocity values referred to below as the initial lane position and the initial velocity—a_p and a_v, respectively—were the initial values at the beginning of the selected samples. They were the initial lane position and the velocity values on the line of best fit of all the data in the selected segments, as determined by the method of least squares, when the following two conditions were satisfied: (1) the driver's vehicle was completely in the lane, i.e., all four of the vehicle's wheels were in the lane, and (2) the driver's vehicle was not accelerating or decelerating, but had achieved cruising speed.

As with the previous experiments in this series, the data distributions were submitted to univariate analysis as a preliminary step before carrying out the significance testing. This analysis showed that within each set of distributions, two or more did not meet the requirements for parametric statistical testing. Some distributions were asymmetrical—so that both the mean and variance were distorted, while other distributions were leptokurtic—so that the variance was distorted. Given these distortions, the analyst can proceed in one of three ways: the data may be trimmed, the data may be transformed, or nonparametric statistical tests can be employed. First, nonparametric testing was considered. In analyzing the data obtained in the current experiment, it was preferable to use parametric statistical tests—rather than nonparametric tests—if possible. The reason for this was that in order to determine whether the designated AHS velocity or the method of transferring control from the AHS to the driver had an effect on the driver's post-AHS driving performance, it was desirable to examine the higher order interaction terms that are obtained when a four-way analysis of variance (ANOVA) is conducted. In addition, parametric tests are inherently more powerful than nonparametric tests. Next, data transformation was considered. Because when each set of distributions was examined, more than one distribution type was found within the set, it was not possible to find a single transformation that could be used on all six distributions in a set. As it was preferable to use parametric tests, and not possible to use transformations, the third approach, data trimming, was used for the current experiment. Details of the univariate analysis and the formal data trimming procedure adopted are presented in appendix 5.

Eight ANOVA's were conducted on the resultant data sets, which consisted of the four lane-keeping measures—a_V, b_V, I_V, and the number of times per minute that the vehicle crossed the direction of travel, and the four velocity maintenance measures—a_V, b_V, I_V, and the number of times the velocity maintenance line of best fit was crossed. All eight ANOVA's were four-way analyses in which three of the main effects—the age of the driver, the designated AHS velocity, and the method of transferring control—were between-subjects variables, while the other—the lane/trial variable, comparing pre-AHS driving in the right and center lanes in trial #1 with post-AHS driving in the center lane in trial #6—was a within-subjects variable.

THE EFFECT OF TRAVELING IN THE AUTOMATED LANE ON LANE-KEEPING PERFORMANCE

The four lane-keeping measures discussed in this section were derived as follows. For each driver, the line of best fit for the lane position data obtained in the selected segments was calculated using the method of least squares. Equations 2, 3, and 4 were used to derive the initial position in the lane, the steering drift, and the steering instability. In addition, the number of steering oscillations was calculated. Then, these values were used in the ANOVA's conducted in order to compare the driver's lane-keeping performance before and after traveling under automated control. The variables and interactions that had statistically significant effects on the lane-keeping measures are listed in table 3. The complete summary tables for the first four ANOVA's are presented as tables 8, 9, 10, and 11 in appendix 4.

Table 3. Summary of the four ANOVA's conducted to determine whether the lane-keeping performance measures were affected by the age of the driver (A), the method of transferring control (M), the designated AHS velocity (V), or the lane/trial variable (T).

Source	a_p (initial lane position)	b_p (steering drift)	I_p (steering instability)	Number of steering oscillations
A	—	—	—	0.0030
T	0.0001	0.0001	0.0001	0.0001
AT	0.0086	—	—	0.0048
AM	—	—	0.0199	—
AMT	—	—	0.0355	—
AVT	—	—	—	0.0426

As table 3 shows, the lane/trial variable had a statistically significant effect on all four lane-keeping performance measures; the age of the driver had a significant effect on the number of steering oscillations; while, as expected, the other two independent variables—the designated AHS velocity and the control transfer method—did not have a significant effect on any of the lane-keeping measures, although they were both involved in significant interactions. To determine whether the differences in a_p, b_p, I_p, and the number of steering oscillations were between-trial differences or between-lane differences, post hoc statistical tests were conducted using the Tukey-Kramer modification to the Tukey Studentized range test.[1]

[1] When cell sizes are unequal, the Tukey-Kramer modification of the Tukey Studentized range test is the post hoc test recommended in the *SAS/STAT® User's Guide.*[(16)] The Sudentized range test, proposed by Tukey in the early 1950's, controls the maximum experimentwise error rate under any complete or partial null hypothesis when the sample sizes are equal. Subsequently, Tukey and Kramer independently proposed a modification that controlled for unequal cell sizes.

Initial Position in the Lane

Lane/Trial Effects. As table 3 shows, the lane/trial variable had a statistically significant effect on a_p, the initial lane position. The initial lane position is the point at which the lane-keeping line of best fit, for lane position throughout the road segment, meets the perpendicular across the lane at the beginning of each segment. As will be seen in the next subsection of this report, since the steering drift is very small when short samples of driving behavior—like those obtained in this experiment—are considered, the initial lane position is essentially an indicator of whether the driver is driving to the left or right of the center of the lane throughout the sample. The Tukey Studentized range test, with the Tukey-Kramer modification, was used post hoc to examine the initial lane positions that were obtained while the drivers were driving in the right lane in trial #1, the center lane in trial #1, and the center lane in trial #6. The test indicated that all three initial lane positions were statistically different from each other (the differences are illustrated in figure 4). The figure shows that at the start of all three segments, the driver positioned the vehicle to the left of the center of the lane. The offset of the initial lane position from the center to the left of the lane was greatest when the drivers were in the right lane in trial #1, and least when they were in the center lane in trial #1. When they drove in the center lane in trial #6, the offset of the position from the center of the lane was between the two trial #1 lane positions.

Interaction Between the Lane/Trial Variable and the Age of the Driver. Table 3 also indicated that there was an interaction between the lane/trial variable and the age of the driver. This interaction is explored in figure 5, which shows that the offset to the left of the lane was smaller for the younger drivers than the older drivers when the vehicle was in the right lane in trial #1. In contrast, when the vehicle was in the center lane, both in trial #1 (before the driver had experienced automated travel) and in trial #6 (after the driver had traveled under automated control), the offset to the left was smaller for the older drivers than it was for the younger drivers.

Steering Drift

Lane/Trial Effects. Table 3 showed that the lane/trial variable had a statistically significant effect on b_p —the gradient of the line of best fit that indicates the direction and strength of the steering drift. The Tukey Studentized range test, with the Tukey-Kramer modification, was used to examine the values of b_p obtained while the drivers were driving in the right lane in trial #1,

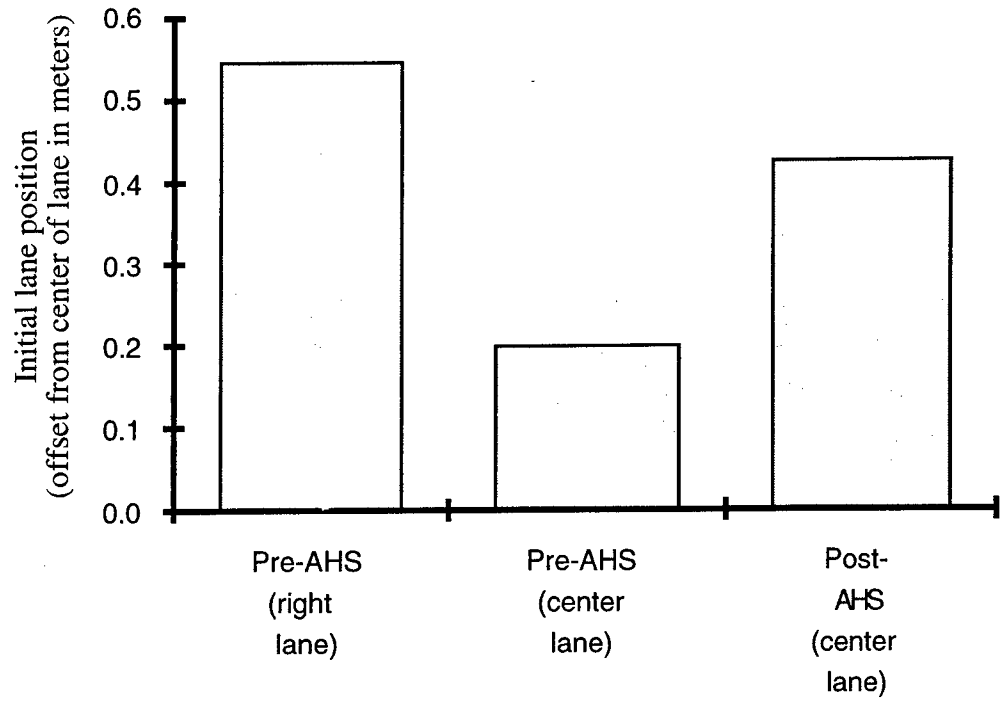


Figure 4. Initial lane position of the driver's vehicle in pre-AHS and post-AHS driving segments (averaged over all drivers). [Positive values indicate that the initial lane position was offset to the left of the center of the lane. Negative values would have indicated that the initial lane position was offset to the right of the center of the lane.]

the center lane in trial #1, and the center lane in trial #6. The test indicated that the three steering drifts were statistically different from each other (the differences are illustrated in figure 6).

As figure 6 shows, the steering drift was toward the right of the lane when the drivers drove in the right lane in trial #1 and when they were in the center lane in trial #6; it was to the left when they drove in the center lane in trial #1. The magnitude of the steering drift was greatest [–0.000190 m/m (–0.000190 ft/ft)] when the driver drove in the right lane in trial #1. When taken in conjunction with the fact that initial lane position was relatively far to the left, this steering drift shows that in steering to the right, the driver was steering the vehicle toward the center of the lane. There was a smaller steering drift [+0.000085 m/m (+0.000085 ft/ft)] when the driver drove in the center lane in trial #1, but in this case it was positive. In addition, while the initial lane position for the center lane was relatively close to, but to the left of, the center line, the steering drift indicates that the driver steered the vehicle farther away from the center of the lane. Finally, when the driver drove in the center lane in trial #6, there was a very small

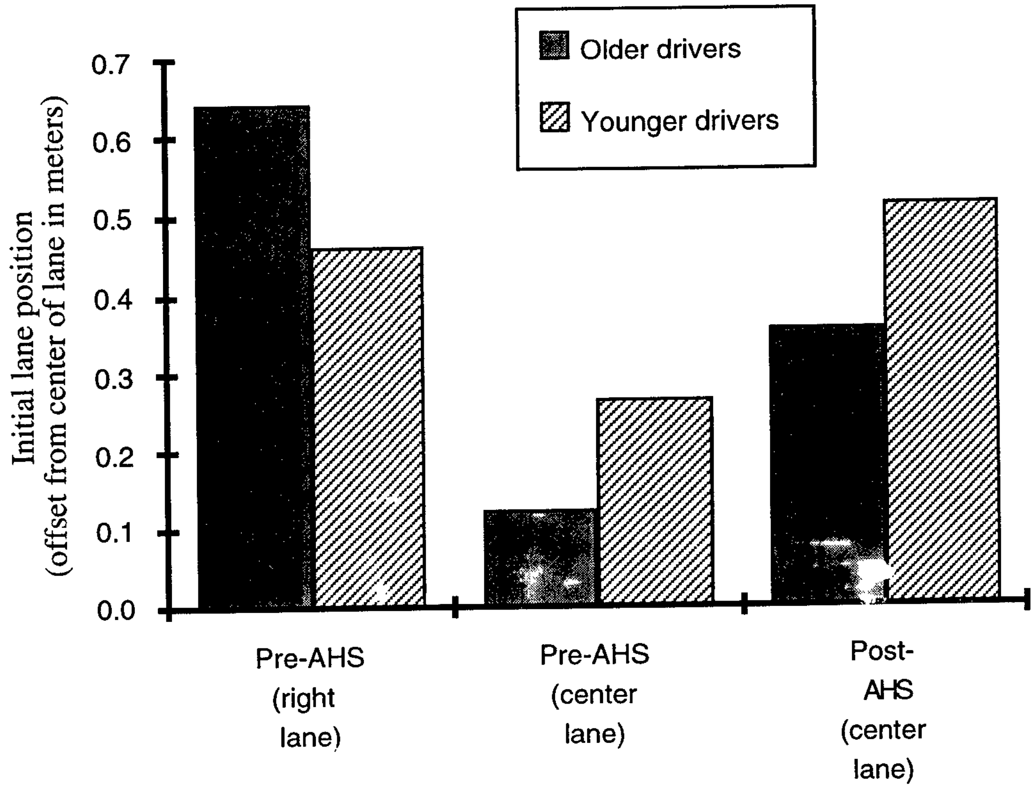


Figure 5. Initial lane position of the driver's vehicle in pre-AHS and post-AHS driving segments for the older and younger drivers. [Positive values indicate that the initial lane position was offset to the left of the center of the lane. Negative values would have indicated that the initial lane position was offset to the right of the center of the lane.]

steering drift—the b_p value was only –0.000006 m/m (–0.000006 ft/ft)—indicating that the driver held a course that was essentially parallel to the lane, after traveling in the automated lane.

Steering Instability

Lane/Trial Effects. Table 3 indicated that the lane/trial variable also had a statistically significant effect on I_p (steering instability). When used to examine the steering instability in each of the three road segments, the Tukey Studentized range test, with the Tukey-Kramer modification, showed that significantly more steering instability occurred when the drivers were driving in the center lane in trial #1 than when they drove in either the right lane in trial #1 or the center lane in trial #6. The average steering instabilities obtained in each of the three road segments are shown in figure 7.

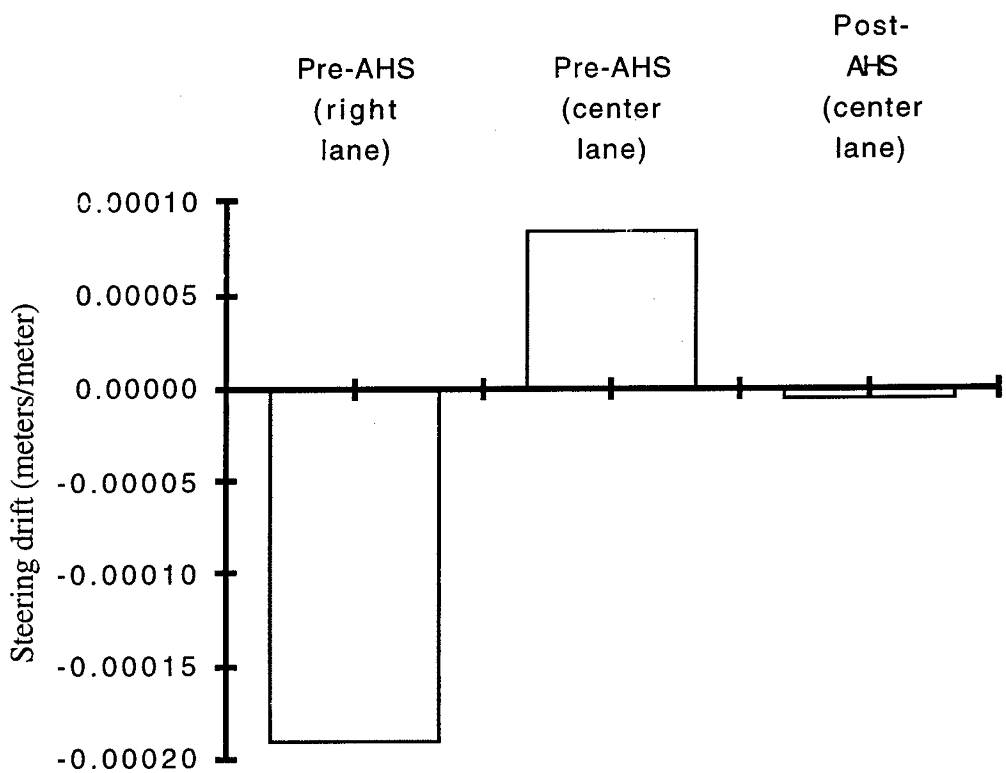


Figure 6. The steering drift in pre-AHS and post-AHS driving segments (averaged over all drivers). [Note: if the steering drift was zero, the vehicle was traveling along a line parallel to the center of the lane; if the steering drift was positive, the vehicle was drifting from right to left; and if the steering drift was negative, the vehicle was drifting from left to right.]

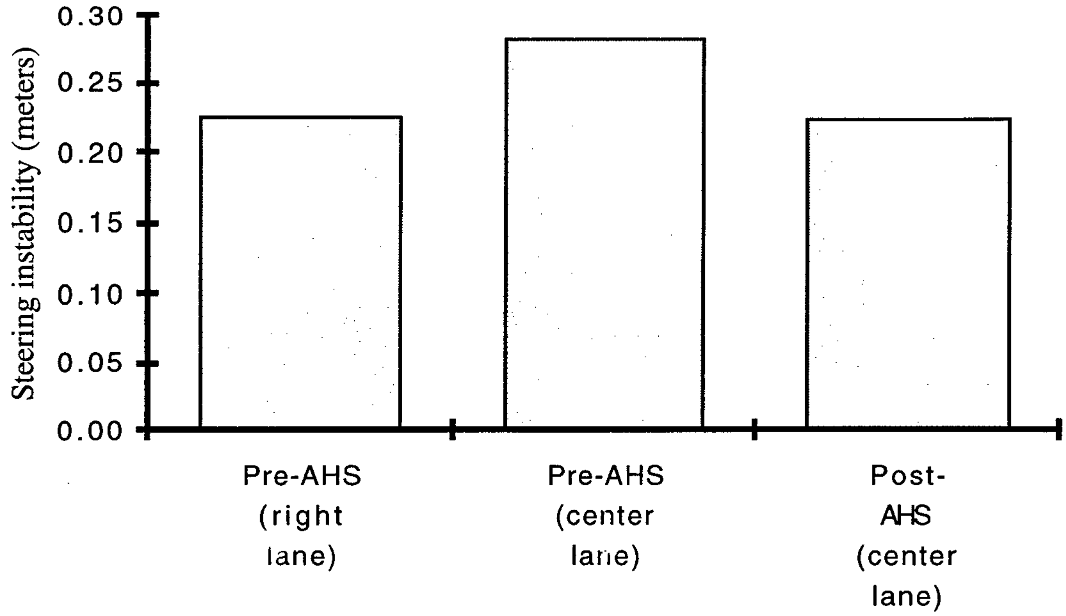


Figure 7. The steering instability in pre-AHS and post-AHS driving segments (averaged over all drivers).

Interaction of the Lane/Trial Variable, the Age of the Driver, and the Method of Control Transfer. Table 3 also indicated that there was a statistically significantly interaction involving the age of the driver, the method of transferring control in trial #6, and the lane/trial variable. This interaction is explored in figure 8.

Figure 8 shows the steering instability as a function of the lane/trial variable for the older and younger drivers using the driver-controlled and situation-controlled transfer methods. When the drivers were in the right lane in trial #1, there were virtually no differences in average steering instability scores for the four groups. In contrast, when they drove in the center lane, whether in trial #1 or trial #6, there were differences in the steering instability scores. When the drivers were in the center lane in trial #1, there was little difference in the steering instability scores of the two groups of older drivers. However, there was a difference in the instability scores for the younger drivers—the mean instability score for the younger drivers who used the driver-controlled transfer method was similar to the scores for the older drivers, while there was less steering instability for the younger drivers who used the situation-controlled transfer method. When the drivers were in the center lane in trial #6, after traveling in the automated lane, there was less steering instability for two of the groups—the older drivers using the driver-controlled transfer method and the younger drivers using the situation-controlled transfer method—than there

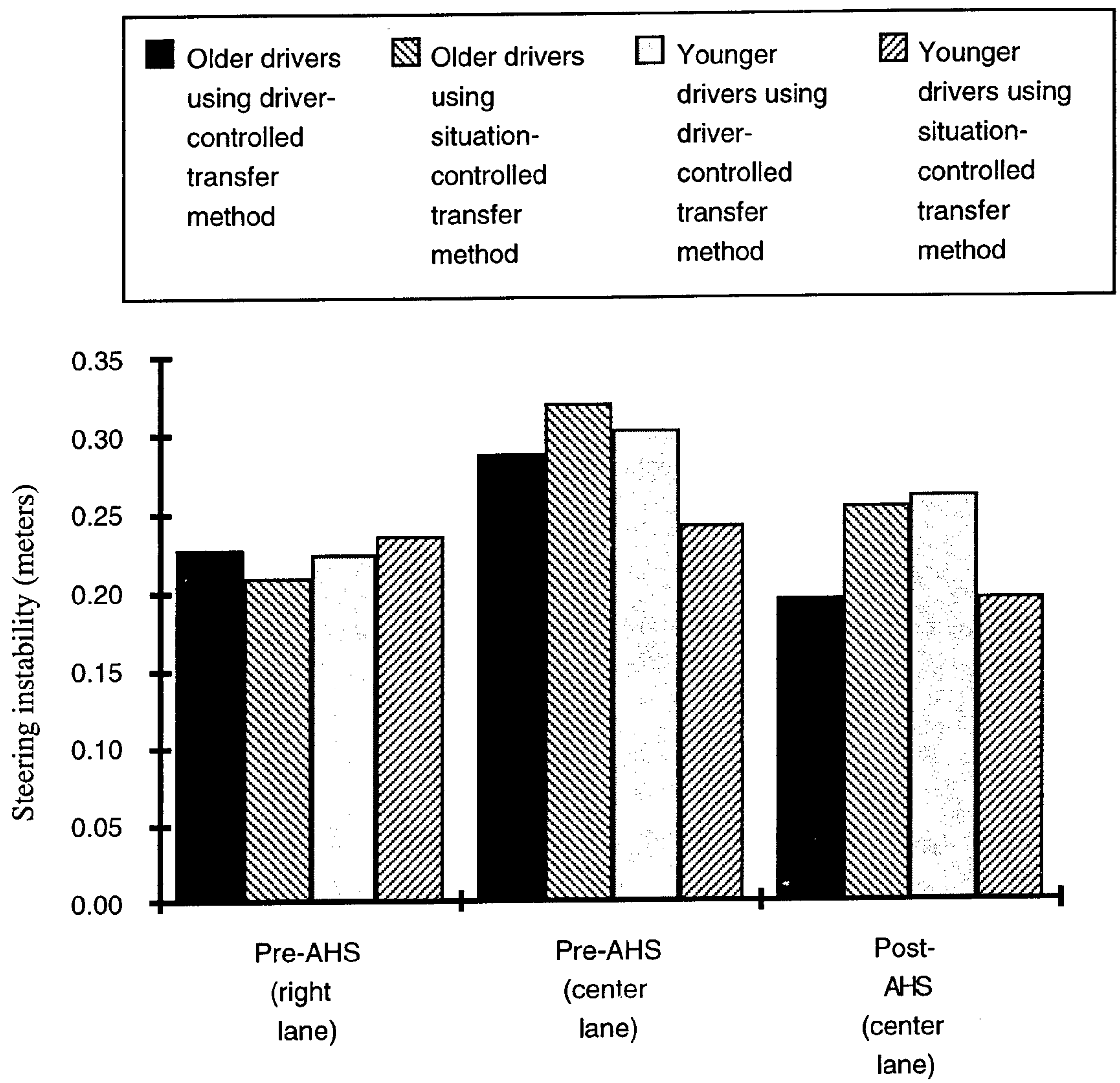


Figure 8. The steering instability in pre-AHS and post-AHS driving segments for the older and younger drivers using the driver-controlled and situation-controlled transfer methods in trial #6.

was for the other two groups—the older drivers using the situation-controlled transfer method and the younger drivers using the driver-controlled transfer method.

Number of Steering Oscillations

The Effects of the Lane/Trial Variable, the Age of the Driver, and the Interaction Between Them. Table 3 shows that the number of steering oscillations—the number of times the steering line of best fit was crossed per minute—was affected by the lane/trial variable and by the age of the driver. In addition, the interaction between these two variables was statistically significant, as was the three-way interaction between these two variables and the designated AHS velocity. The effect of these variables on the number of steering oscillations is best described in terms of the interaction among them. It is illustrated in figure 9.

Figure 9 shows several effects. First—and easiest to see—the effect of the driver's age is shown in that there were more steering oscillations for the older drivers than for the younger drivers in eight of the nine combinations of the lane/trial variable and the designated AHS velocity. The exception occurred when the driver drove at 104.7 km/h (65 mi/h) in the center lane in trial #1. Second, the difference between the older and younger drivers was greatest when the driver drove in the right lane in trial #1. Third, there were more oscillations for the older drivers when the driver drove in the right lane in trial #1 and fewer when the driver drove in the center lane in trial #6. Fourth—and hardest to discern—there were more oscillations for the younger drivers when the driver drove in the center lane in trial #1 than there were when the driver drove in either the right lane in trial #1 or in the center lane in trial #6.

THE EFFECT OF TRAVELING IN THE AUTOMATED LANE ON VELOCITY MAINTENANCE

As with the lane-keeping measures discussed in the previous section, the velocity maintenance measures were derived by calculating the line of best fit (using the method of least squares) for each driver from the velocity data obtained in the selected segments. Equations 6, 7, and 8 were used to derive the initial velocity, the velocity drift, and the velocity instability. In addition, the number of velocity fluctuations was calculated. Table 4 shows the statistically significant variables and interactions from the second group of four ANOVA's in which the velocity maintenance measures obtained before and after the driver traveled under automated control were compared. The complete summary tables for these four ANOVA's are presented as tables 12, 13, 14, and 15 in appendix 4.

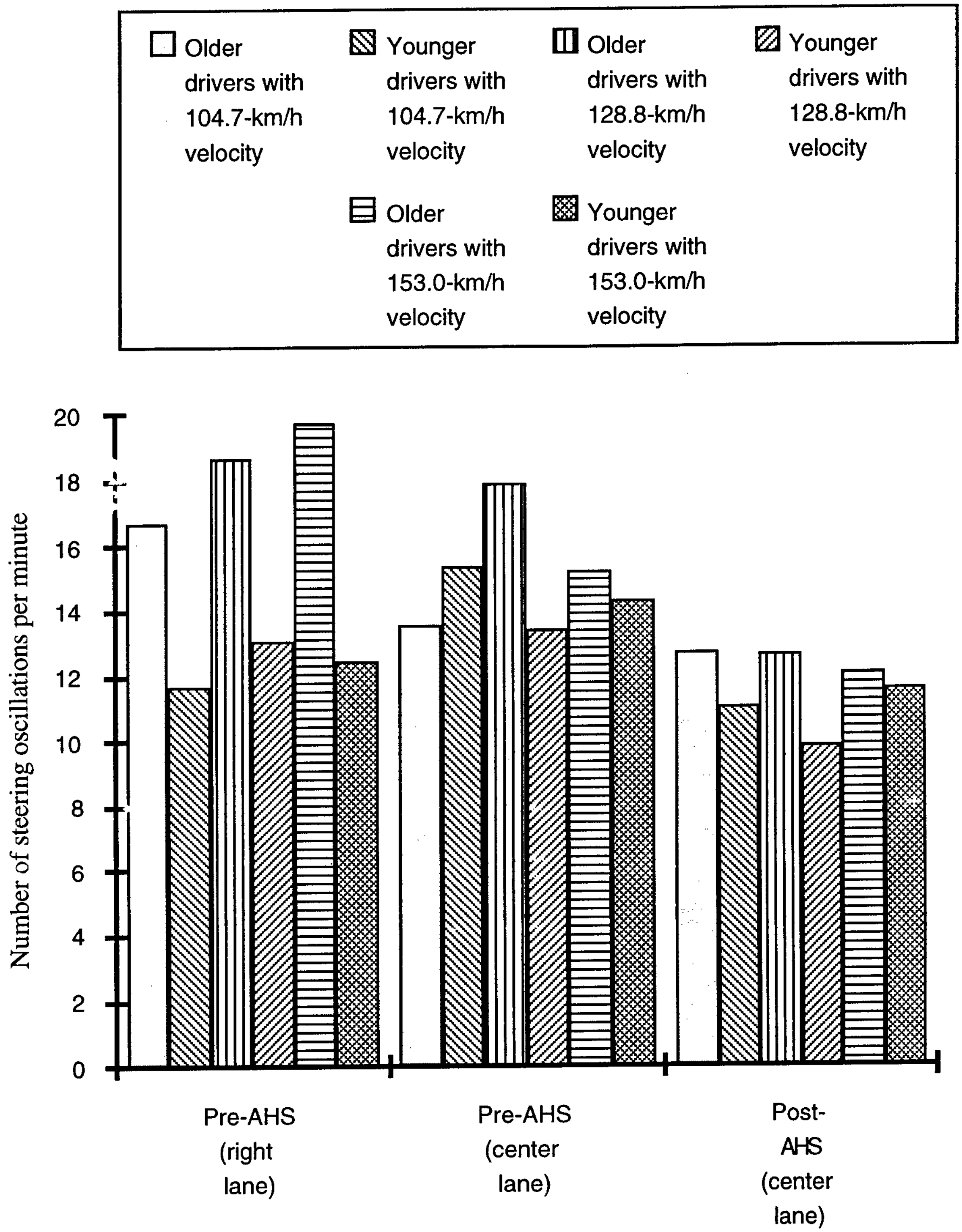


Figure 9. The number of steering oscillations per minute in pre-AHS and post-AHS driving segments, for the older drivers and for the younger drivers.

Table 4. Summary of the four ANOVA's conducted to determine whether the velocity maintenance performance measures were affected by the lane/trial variable (T), the age of the driver (A), the method of transferring control (M), or the designated AHS velocity (V).

Source	a_V (initial velocity)	b_V (velocity drift)	I_V (velocity instability)	Number of velocity fluctuations
A	0.0066	—	—	—
V	—	—	—	0.0262
T	—	0.0042	0.0135	0.0001
AV	—	—	—	0.0023
AM	0.0085	—	—	0.0212
AMVT	—	—	0.0352	0.0481

Table 4 shows that a_V, the initial velocity, was affected by the age of the driver, and that there was a significant interaction between the age of the driver and the method of control transfer used in trial #6. In addition, b_V, the velocity drift, was affected by only the lane/trial variable. There was a four-way interaction for I_V, the velocity instability, which was also affected by the lane/trial variable. The fourth velocity maintenance measure (number of velocity fluctuations) was affected by both the lane/trial variable and the designated AHS velocity in trial #6, and there were three statistically significant interactions. These various effects are discussed in detail below.

Initial Velocity

The Age of the Driver. As table 4 shows, only one of the four independent variables—the age of the driver—had a significant overall effect on a_V, the initial velocity (i.e., the point at which the velocity maintenance line of best fit intercepted the velocity axis at the beginning of each straight road segment). The mean initial velocity for the older drivers was 87.0 km/h (54.0 mi/h)—1.6 km/h (1.0 mi/h) slower than the speed limit. The initial mean velocity for the younger drivers was 90.1 km/h (55.9 mi/h)—1.5 km/h (0.9 mi/h) faster than the speed limit.

Interaction Between the Age of the Driver and the Method of Control Transfer. Table 4 shows that there was also a significant interaction between the age of the driver and the method of transferring control in trial #6. This interaction is explored in figure 10.

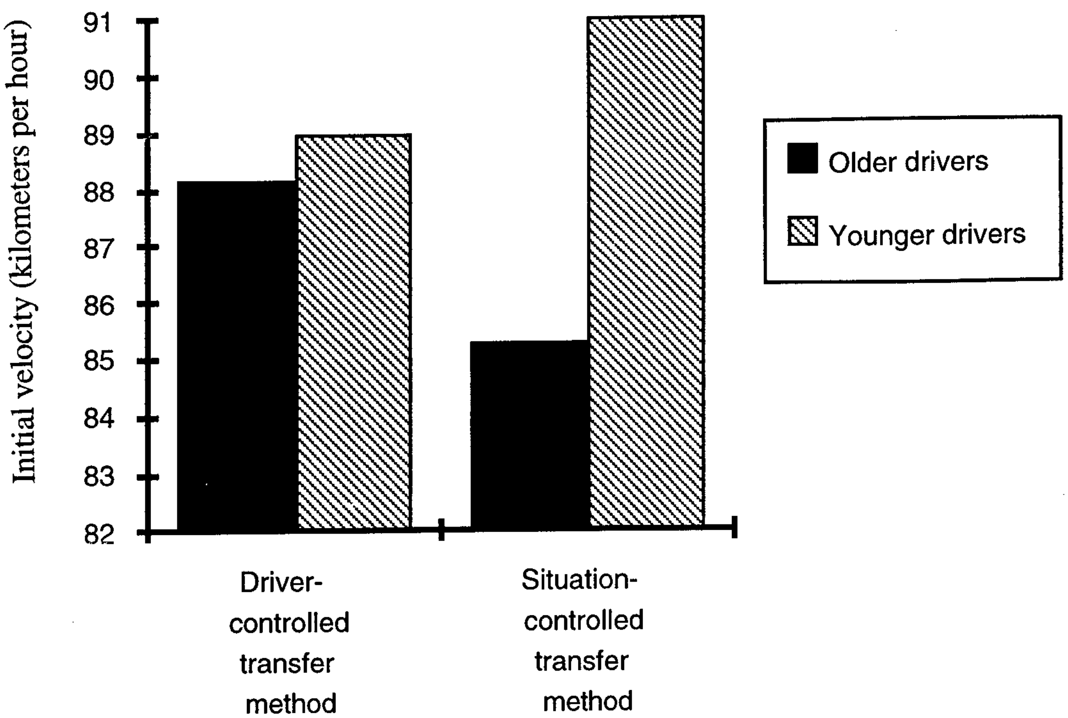


Figure 10. Initial velocity as a function of the control transfer method used in trial #6, for the older and younger drivers.

Figure 10 shows that overall, the initial velocity for the younger drivers was greater than that for the older drivers. Also, the difference was greater for the drivers who were in the situation-controlled transfer group in trial #6 than for those who were in the driver-controlled transfer group. For the drivers in both age groups, there were overall differences in the mean initial velocities obtained from the driver-controlled transfer group and the situation-controlled transfer group, although the differences were in opposite directions: The initial velocity of the younger drivers who used the driver-controlled method was slower than the initial velocity of the younger drivers who used the situation-controlled method, while the initial velocity of the older drivers who used the driver-controlled method was faster than the initial velocity of the older drivers who used the situation-controlled method. It had been expected that any such differences would not have been overall differences, but would instead have been differences only in trial #6. This was because since the trial #1 data were collected before the driver experienced the transfer of control, the initial velocity could not be affected in trial #1 by the variation in the control transfer method.

Velocity Drift

Lane/Trial Effects. Table 4 shows that b_V, the velocity drift (i.e., the gradient of the velocity maintenance line of best fit), was affected only by the lane/trial variable. The Tukey Studentized range test, with the Tukey-Kramer modification, was used to examine the values of b_V obtained in each of the three road segments. The test indicated that there was a lane effect, but not an AHS effect—the velocity drift was significantly different when the drivers were in the right lane in trial #1 than when they were in the center lane, either before or after traveling in the automated lane. This effect is shown in figure 11. There was no significant difference in the velocity drifts when the drivers were in the center lane in trial #1 and trial #6.

Figure 11 shows clearly that the magnitude of the velocity drift was much greater when the drivers were in the right lane at the beginning of trial #1. The magnitude of the effects shown in figure 11 can be put in perspective by considering the length of the segments of driving behavior being used throughout these analyses. The median segment length was approximately 40 s. As mentioned in the subsection above, the mean initial velocity at the start of the segments, for both the older and younger drivers, was within 1.6 km/h (1.0 mi/h) of the 88.6-km/h (55-mi/h) speed limit—therefore, in 40 s, the driver's vehicle would travel approximately 984 m (3226 ft). In 40 s, given the mean velocity drift shown in figure 11, a vehicle traveling in the right lane in trial #1 (pre-AHS) would slow down by approximately 5.1 km/h (3.2 mi/h). In contrast, the mean velocity drifts shown in figure 11 indicate that when traveling in the center lane, either pre- or post-AHS, the change in velocity in 40 s would have been minimal—for the vehicle traveling in the center lane in trial #1 (pre-AHS), there would have been a reduction in velocity of approximately 0.3 km/h (0.2 mi/h); while for the vehicle traveling in the center lane in trial #6 (post-AHS), there would have been an increase in velocity of approximately 0.5 km/h (0.3 mi/h).

Velocity Instability

Lane/Trial Effects. Table 4 shows that I_V, the velocity instability (i.e., the variability around the line of best fit for velocity), was affected by the lane/trial variable. When it was used to examine I_V, the Tukey Studentized range test, with the Tukey-Kramer modification, suggested that velocity instability might be affected by automated travel. There was a statistically significant difference between the value of I_V obtained pre-AHS in the right lane and the value post-AHS in the center lane; the I_V value obtained pre-AHS in the center lane lay between the other two values and was not significantly different from either of them. The effect of the lane/trial variable on I_V

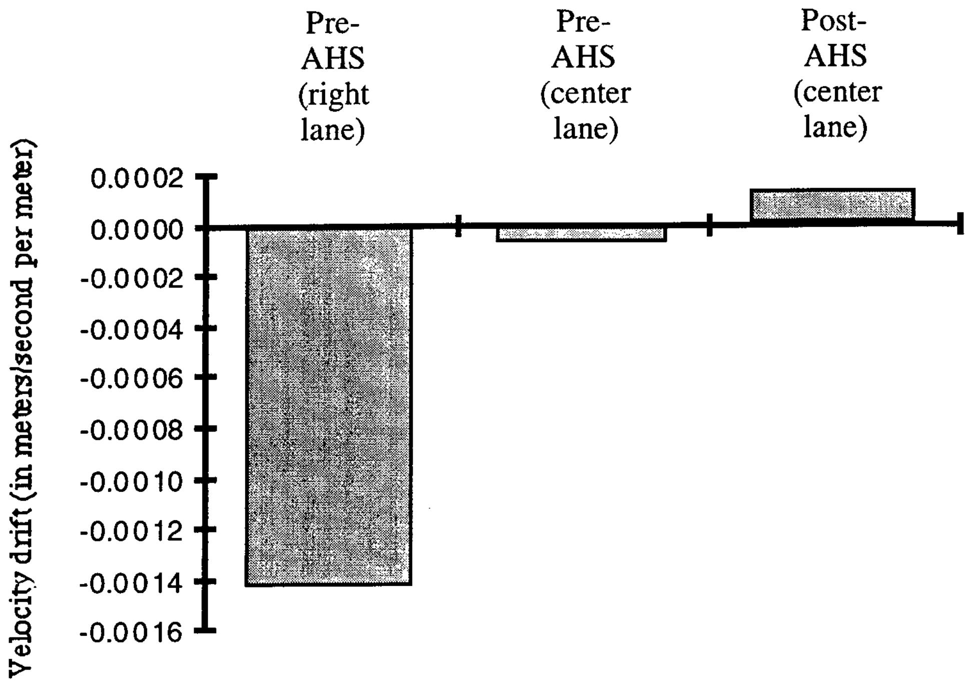


Figure 11. The velocity drift in pre-AHS and post-AHS driving segments (averaged over all drivers).

is shown in figure 12. As can be seen from the figure, the velocity instability increased after the drivers traveled under automated control.

Four-Way Interaction. Table 4 indicates that for I_V, the velocity instability, there was also a statistically significant four-way interaction among the age of the driver, the method of control transfer, the designated AHS velocity, and the lane/trial variable. In order to explore this interaction, the cell means of the 36 combinations of the 4 interacting variables were inspected. The current experiment was designed in such a way that for each combination of the four variables, data should have been provided by five drivers. Unfortunately, in the combination of conditions that produced the highest velocity instability, there were data from only one driver. The data from the remaining drivers in this group were unavailable or were removed because they were outliers. The four-way interaction appears to have occurred because of the lost or removed data; therefore, it is not analyzed further.

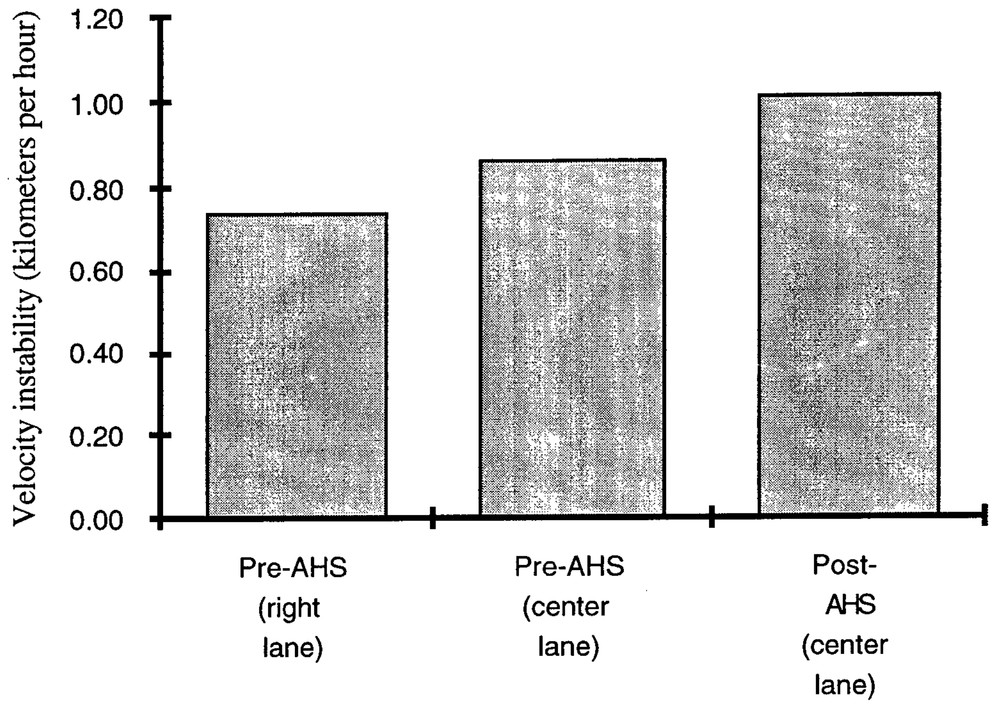


Figure 12. The velocity instability in pre-AHS and post-AHS driving segments (averaged over all drivers).

Number of Velocity Fluctuations

The final velocity maintenance measure is the number of velocity fluctuations, i.e., the number of crossings of the velocity maintenance line of best fit. Table 4 shows that it was affected by two independent variables and was involved in three interactions.

Lane/Trial Effects. Although the lane/trial variable was involved in a two-way and a four-way interaction, its overall effect was very clear, and, because of this, that effect is shown in figure 13.

The Tukey Studentized range test, with the Tukey-Kramer modification, was used to conduct a more detailed examination of the mean number of velocity fluctuations per minute that were obtained in each of the three road segments. The test showed that there were significantly more fluctuations per minute when the drivers were in the right lane pre-AHS than there were when they were in the center lane in either the pre-AHS or post-AHS segment.

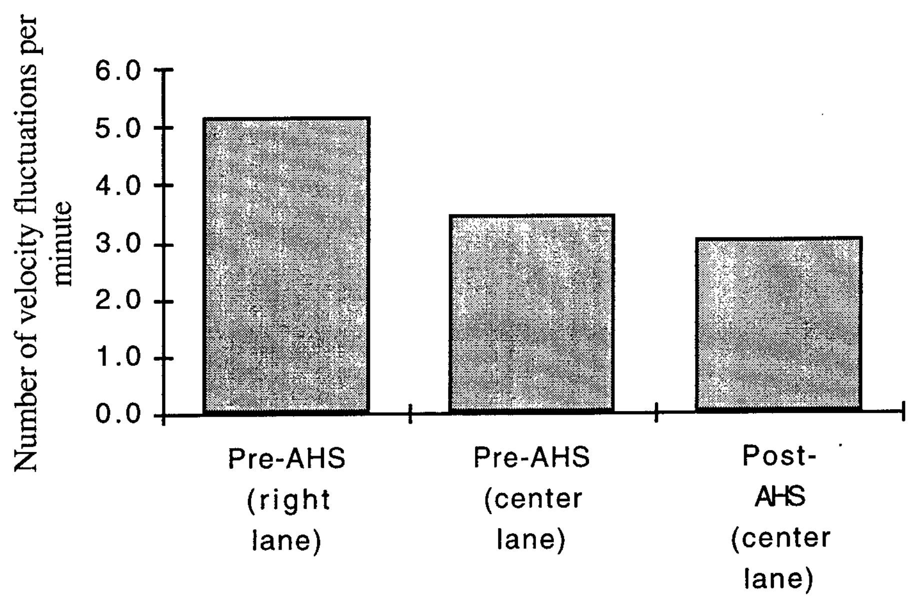


Figure 13. The number of velocity fluctuations per minute in pre-AHS and post-AHS driving segments (averaged over all drivers).

As figure 13 shows, there were 50 percent more velocity fluctuations per minute when the drivers were in the right lane in trial #1 than there were when they were in the center lane in either trial #1 or trial #6—there were 5.1 velocity fluctuations per minute when they were in the right lane and only 3.4 and 3.0 velocity fluctuations per minute when they were in the center lane in trials #1 and #6, respectively.

Designated AHS Velocity Effects. Table 4 indicated that there was a difference in the mean number of velocity fluctuations obtained from the drivers in the three designated AHS velocity groups. When the Tukey Studentized range test, with the Tukey-Kramer modification, was used to examine the means, it was found that there were more fluctuations for the drivers who experienced a designated AHS velocity of 153.0 km/h (95 mi/h) in trial #6 than there were for the drivers who experienced the 128.8-km/h (80-mi/h) designated AHS velocity in trial #6; while the number of fluctuations for the drivers who experienced a designated AHS velocity of 104.7 km/h (65 mi/h) in trial #6 lay between the other two values and was not significantly different from either of them. This overall effect of designated AHS velocity was not expected, since the three groups of drivers experienced the different designated AHS velocities only in the automated lane after the trial #1 data were collected. More information about this effect is provided in the subsection on the interaction between the designated AHS velocity and the age of the driver, which follows immediately.

Interaction Between the Designated AHS Velocity and the Age of the Driver. Table 4 indicated that the interaction between the age of the driver and the designated AHS velocity that he/she experienced in trial #6 was statistically significant. This interaction is represented in figure 14.

Figure 14 shows that there was essentially no difference in the number of velocity fluctuations per minute for the older drivers who were in the 104.7-km/h (65-mi/h) and 128.8-km/h (80-mi/h) designated AHS velocity groups, and no difference for the younger drivers who were in the 128.8-km/h (80-mi/h) and the 153.0-km/h (95-mi/h) designated AHS velocity groups. The age-by-designated AHS velocity interaction occurred because there were more velocity fluctuations per minute for the remaining two combinations of age and designated AHS velocity—the younger drivers in the 104.7-km/h (65-mi/h) designated AHS velocity group and the older drivers in the 153.0-km/h (95-mi/h) designated AHS velocity group.

Interaction Between the Method of Transferring Control and the Age of the Driver. Table 4 indicated that the interaction between the age of the driver and the method of transferring control that he/she experienced in trial #6 was statistically significant. This interaction is represented in figure 15. Figure 15 shows that there were approximately four velocity fluctuations per minute for three of the four combinations of age and transfer method. Only the younger drivers who used the driver-controlled transfer method had a lower number of velocity fluctuations—the mean number of fluctuations was 3.2 per minute.

Four-Way Interaction. Table 4 indicates that there was also a statistically significant four-way interaction among the age of the driver, the method of control transfer, the designated AHS velocity, and the lane/trial variable. In order to explore this interaction, the cell means of the 36 combinations of the 4 interacting variables were inspected. The current experiment was designed in such a way that for each combination of driver's age, control transfer method, designated AHS velocity, and the lane/trial variable, data should have been provided by five drivers. Unfortunately, in two combinations of conditions that produced extreme values of the number of velocity fluctuations, there were data from only one driver. There were data from only one driver because the data from the remaining four drivers who were in these groups were unavailable or were removed because they were outliers. The four-way interaction appears to have occurred because of the lost or removed data; therefore, it is not analyzed further.

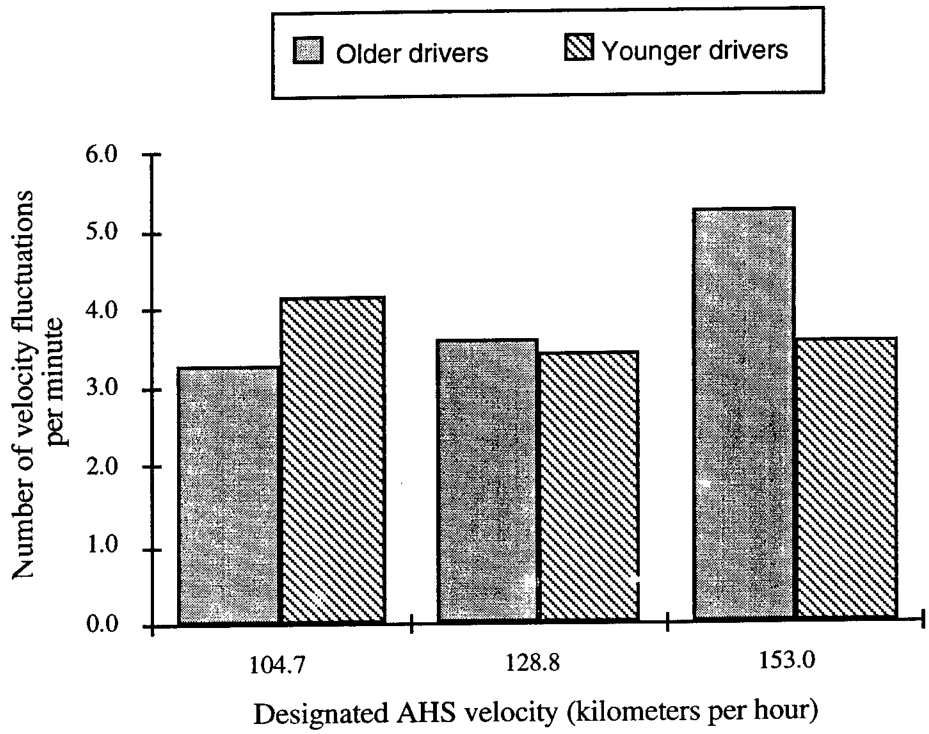


Figure 14. The number of velocity fluctuations per minute as a function of the designated AHS velocity for the older and younger drivers.

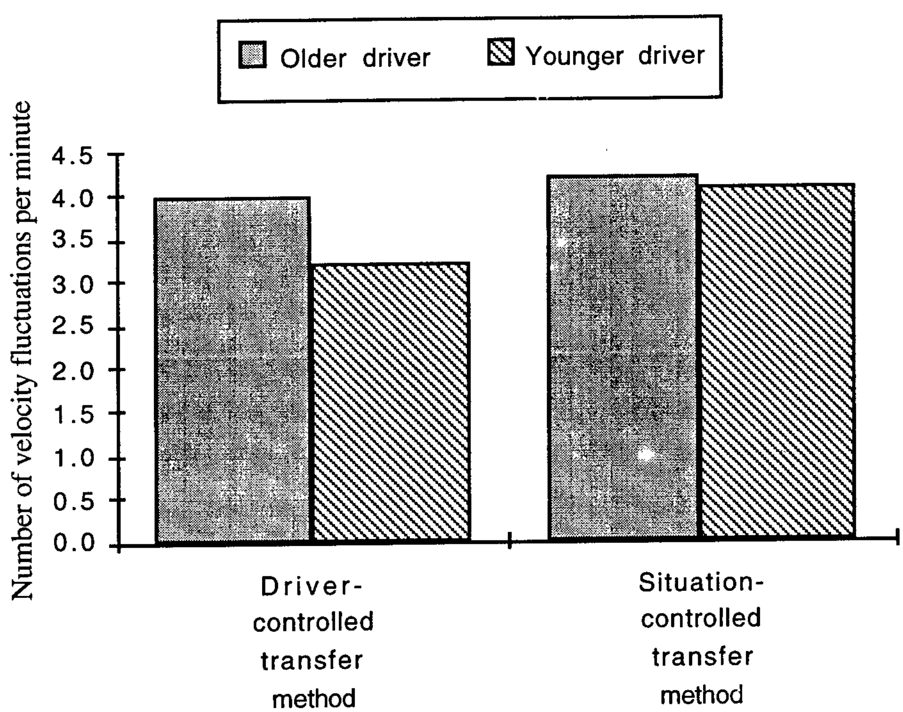


Figure 15. The number of velocity fluctuations per minute as a function of the method of transferring control for the older and younger drivers.

COLLISIONS AND LANE INCURSIONS

In this experiment, there were three collisions and five lane incursions—too few to perform meaningful statistical analyses. Table 5 shows the number of collisions and lane incursions that occurred before and after the older and younger drivers traveled in the automated lane.

Table 5. The number of collisions and lane incursions occurring before and after the older and younger drivers traveled under automated control.

	Pre-AHS		Post-AHS	
	Older drivers	Younger drivers	Older drivers	Younger drivers
Collisions	1	0	1	1
Incursions	1	1	2	1

As can be seen from table 5, 1 of the 3 collisions occurred in trial #1—it involved an older driver (who did not continue to drive in the experiment)—when all 60 drivers drove in the expressway for approximately 3 min. The other 2 collisions occurred in trial #6—one involved an older driver, the other involved a younger driver—when the remaining 59 drivers drove in the expressway for approximately 4 min after they had traveled in the automated lane.

Table 5 also shows the number of lane incursions that occurred. Lane incursions were defined as occasions when the driver began to change lanes but, for some reason, did not complete the maneuver and, instead, returned to the lane from which he/she started. Two of the five incursions occurred in trial #1—one involved an older driver, the other involved a younger driver. The remaining three occurred in trial #6—two involved older drivers, the third involved a younger driver—after they had traveled in the automated lane.

MINIMUM FOLLOWING DISTANCE

The minimum distances behind which the driver followed the vehicle ahead while the driver was in control of the vehicle were determined for both the pre-AHS and post-AHS segments. An analysis of variance examining these distances as a function of driver age found no significant differences. Thus, traveling under automated control did not affect how closely the driver followed the vehicle ahead.

VISUAL CAPABILITIES TESTING

The Titmus Vision Tester was used to administer a series of standard visual tests. None of the drivers taking part in this experiment were found to have any visual problems that were not remedied by the wearing of 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. 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 was an anchor point reflecting the extremes of each possible response to the question 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 0 mm and 51 mm reflect responses that favor the extreme to the left—the closer the score is to 0 mm, 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 to determine whether the age and/or gender of the driver affected the responses of the drivers. The results of the analyses for all but one 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 6 lists the numbers of the questions and the topics they cover, and gives the reference number(s) of the report(s) in which the responses have been presented.

Table 6. Reference numbers of reports in which questionnaire responses are presented.

Question	Topic	Reference number of report
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	(5)
15	Reduced AHS capability	(5)
16	Reduced AHS capability	(5)
17	Reduced AHS capability	(5)
18	Safety and resumption of manual control	current report
19	Safety	(3)
20	Attitude toward AHS	(3)
21	Attitude toward AHS	(3)
22a	Attitude toward AHS	(5)
22b	Attitude toward AHS	(5)
22c	Attitude toward AHS	(4), (5)
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	(5)

Resumption of Manual Control

Question 18 was an inquiry into how safe the driver felt when he/she left the automated lane and entered the manual lane in trial #6. No statistically significant difference was found when an ANOVA was conducted on the responses to this question. The average response of the drivers to this question is presented in table 7, and it indicates that the drivers felt safe at the speed at which they left the automated lane and entered the center lane in trial #6.

Table 7. Response to a question on the resumption of manual control.

Question	Overall Mean
18. How safe did the speed at which you left the automated lane and entered the manual lane feel? L. Very unsafe R. Very safe	69.9

SECTION 4: DISCUSSION

THE EFFECT OF TRAVELING UNDER AUTOMATED CONTROL

The objective of this experiment was to determine whether the experience of traveling under automated control at a high speed with shorter than normal inter-vehicle spacing affected driving performance. The primary focus of the data analysis was on the lane/trial variable—driving performance data obtained while the driver was in the center lane after traveling under automated control were compared to driving performance data obtained while the driver was in the right lane and center lane before experiencing automated travel. As reported in the previous section of this report, seven of the eight driving performance measures collected in the current experiment were affected by the lane/trial variable. The next step was to determine whether any of the differences in the driving measures, particularly any that occurred after the driver had traveled under automated control, gave indications that there had been a change in driving performance.

The first two driving performance measures—the initial position of the vehicle and the steering drift—gave information on the position of the driver's vehicle relative to the lane. For all three segments of driving behavior, the initial position of the driver's vehicle, a_p, was to the left of the center of the lane. The initial position of the vehicle was furthest to the left of the lane when the driver was in the right lane segment before traveling under automated control, it was nearest to the center of the lane when the driver was in the center lane segment before traveling under automated control, and it was between these two initial positions when the driver was in the center lane segment after traveling under automated control.

The steering drift, b_p, was from left to right for the segments in which the driver was either in the right lane before traveling under automated control or in the center lane after traveling under automated control. In these two segments, the driver's vehicle started to the left of the lane and drifted right towards the center of the lane as the segment continued. In the third segment, when the driver was in the center lane before traveling under automated control, the driver's vehicle again started to the left of the center of the lane—but with a smaller offset in this case—and then drifted further left as the segment continued.

The next two driving performance measures—the steering instability (I_p) and the number of steering oscillations (crossings of the direction of travel)—dealt with how well the driver maintained a straight course along the direction of travel. There was less steering instability when the driver was either in the right lane before traveling under automated control or in the center lane after traveling under automated control, than there was when the driver was in the center lane before traveling under automated control. And the number of steering oscillations was highest when the driver was in the right lane before traveling under automated control, and least when he/she was in the center lane after traveling under automated control. If these two findings are considered together, it is clear that when the driver was in the center lane after traveling under automated control, there was relatively little steering instability, and the driver achieved this with fewer steering adjustments than when he/she was in the right lane before traveling under automated control.

After considering the first four driving measures, which were all lane-keeping performance measures, it can be concluded that although the driver's lane-keeping behavior may have been different in the three segments, there is no evidence that it was in any way worse after the driver had experienced automated travel. In fact to the contrary, in the post-AHS center lane segment, the mean value of the steering drift was close to zero, indicating that the course steered by the drivers was almost parallel to the white lane lines. And also in this segment, the low steering instability score was achieved with relatively few steering adjustments.

The next four driving performance measures all dealt with velocity maintenance. The lane/trial variable had no effect on the first driving performance measure—there were no differences in a_V, the initial velocity at the start of each road segment—although it did affect the remaining three. The second velocity maintenance measure was b_V, the velocity drift—it was relatively small when the driver was in the center lane either before or after traveling under automated control. It was much larger (and negative) when the driver was in the right lane before traveling under automated control. As mentioned earlier, this may have occurred because once the driver had accelerated up to the approximate speed of the rest of the traffic, he/she allowed the velocity to decline because of being in the slower lane of the expressway.

There was more velocity instability (I_V)—the variability in velocity that occurred when the driver was attempting to maintain a chosen velocity—when the driver was in the center lane after traveling under automated control than there was when the driver was in the right lane before traveling under automated control. In contrast, there were fewer velocity fluctuations when the driver was in the center lane after the driver traveled under automated control than there were when the driver was in the right lane before experiencing automated control.

When the second set of driving measures (dealing with velocity maintenance) is considered, it can be concluded that although there was less velocity drift when the driver was in the center lane after traveling under automated control, there was more velocity instability and there were fewer velocity fluctuations. This means that in order to maintain a chosen velocity, before traveling in the AHS, the driver made more frequent, smaller velocity corrections; in contrast, after traveling in the AHS, the driver made less frequent, larger velocity corrections. It is possible that traveling under automated control, when the driver is not required to control the velocity of the vehicle, may cause the driver to become less attentive to speed. While the driver's velocity maintenance performance in this experiment cannot, in any way, be considered to be poor, it is possible that more prolonged travel under automated control might exacerbate this effect to the point where it becomes problematic.

At first sight, the relative lack of effect of traveling in the automated lane might appear to contradict the results reported by Bloomfield et al.(1) However, that study focused on the events that occurred during and just after the moment the AHS transferred control back to the driver. The driver took over while the vehicle was traveling at the designated AHS velocity, and was then responsible for decelerating and for the lane change from the automated to the center lane. When the designated AHS velocity was set at 128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h), the driver slowed down to some extent while in the automated lane. But, when the lane change from the automated lane to the center lane was complete, he/she was still driving at speeds that were considerably higher than the speed limit—when the designated AHS velocity was 128.8 km/h (80 mi/h), the driver entered the center lane at 104.4 km/h (64.9 mi/h); when the designated AHS velocity was 153.0 km/h (95 mi/h), the driver entered the center lane at 109.8 km/h (68.9 mi/h).

These effects were not found in the current experiment because, as mentioned earlier, the current experiment focused on post-AHS driving performance after the driver had changed lanes and after he/she had finished decelerating and had selected a cruising speed. The driving performance data equivalent to that reported by Bloomfield et al. were not examined here.(1)

The current experiment showed that when drivers experienced a relatively limited amount of travel under automated control, there was no decrement in their steering performance. Also, it suggested that while their velocity control was acceptable, more prolonged exposure might be problematic.

OTHER EFFECTS

The Age of the Driver

The age of the driver had a significant effect on two of the eight driving performance measures—the number of steering oscillations and the initial velocity at the start of the driving segments (a_V)—and was involved in several significant interactions. These various age effects are discussed below.

When the older drivers were in the right lane before traveling under automated control, the position of the vehicle in the lane was offset to the left of the center line to a greater extent than it was for the younger drivers; however, when they were in the center lane both before and after traveling under automated control, there was a smaller offset to the left of the center line for the older drivers than there was for the younger drivers. The data for the right lane were, for the most part, obtained before the data for the center lane in trial #1, and the older drivers may have been more uncertain than the younger drivers about driving in the simulator vehicle when the experiment began; subsequently, when they became familiar with the new vehicle, they were able to drive closer to the center of the lane.

There were more steering oscillations and more velocity fluctuations for the older drivers than there were for the younger drivers. Since there were no differences in the steering instability or in the velocity instability for the older and the younger drivers, the fact that there were larger numbers of oscillations and fluctuations for the older drivers suggests that, for them, the deviations about the lines of best fit—both for steering and for velocity maintenance—were greater in magnitude, while being shorter in duration than they were for the younger drivers. Given this fact, one might expect that the older drivers would drive more slowly than the younger drivers. The fact that the initial velocity was slower for the older drivers than it was for the younger drivers, while there was no difference in the velocity drift for the two groups, supports this expectation.

Designated AHS Velocity and Control Transfer Method

The designated AHS velocity and the control transfer method will be discussed together. There were several occasions when one or both of these variables appeared to have an effect.

There was a three-way interaction for the steering instability scores among the lane/trial variable, the age of the driver, and the method of transferring control in trial #6. When this was examined, it was found that after they had traveled under automated control, there was less steering instability for the younger drivers who used the situation-controlled transfer method and for the older drivers who used the driver-controlled method. At this time, there is no obvious explanation for this interaction.

There were two other effects that must be mentioned—both of them unexpected. First, the group of younger drivers who had the situation-controlled transfer method in trial #6 had less steering instability than the group of younger drivers who had the driver-controlled method in trial #6, when they were driving in the center lane in trial #1. Second, there was a difference in the initial velocity, over all three segments, for the drivers assigned to the driver-controlled transfer group as compared with those assigned to the situation-controlled group. Both effects were unexpected because the control transfer method could not have affected the driving performance measures until after the drivers had experienced traveling under automated control. It is possible that these effects occurred because it took longer for some drivers to become accustomed to driving the simulator vehicle than others, and although a counterbalancing scheme was used to place drivers in groups that experienced the various combinations of conditions, in one or two cases, drivers with similar relatively extreme responses were assigned to the same groups. Further examination of the data showed that the differences between the groups of drivers decreased as the experiment continued. It is to be expected that effects such as these will be avoided if more time is allowed for the drivers to become accustomed to driving in the simulator.

APPENDIX 1: ORDER OF PRESENTATION OF CONDITIONS

The designated AHS velocity experienced by each driver in trial #6 is shown below.

The designated AHS velocity experienced by the younger drivers using the driver-controlled transfer method

Driver	Condition
YD01	153.0 km/h (95 mi/h)
YD02	153.0 km/h (95 mi/h)
YD03	128.8 km/h (80 mi/h)
YD04	104.7 km/h (65 mi/h)
YD05	104.7 km/h (65 mi/h)
YD06	128.8 km/h (80 mi/h)
YD07	128.8 km/h (80 mi/h)
YD08	153.0 km/h (95 mi/h)
YD09	104.7 km/h (65 mi/h)
YD10	153.0 km/h (95 mi/h)
YD11	153.0 km/h (95 mi/h)
YD12	104.7 km/h (65 mi/h)
YD13	153.0 km/h (95 mi/h)
YD14	128.8 km/h (80 mi/h)
YD15	128.8 km/h (80 mi/h)

The designated AHS velocity experienced by the younger drivers using the situation-controlled transfer method

Driver	Condition
YD16	153.0 km/h (95 mi/h)
YD17	153.0 km/h (95 mi/h)
YD18	128.8 km/h (80 mi/h)
YD19	104.7 km/h (65 mi/h)
YD20	128.8 km/h (80 mi/h)
YD21	153.0 km/h (95 mi/h)
YD22	104.7 km/h (65 mi/h)
YD23	128.8 km/h (80 mi/h)
YD24	104.7 km/h (65 mi/h)
YD25	128.8 km/h (80 mi/h)
YD26	153.0 km/h (95 mi/h)
YD27	153.0 km/h (95 mi/h)
YD28	128.8 km/h (80 mi/h)
YD29	104.7 km/h (65 mi/h)
YD30	104.7 km/h (65 mi/h)

The designated AHS velocity experienced by the older drivers using the driver-controlled transfer method

Driver	Condition
OD01	128.8 km/h (80 mi/h)
OD02	153.0 km/h (95 mi/h)
OD03	104.7 km/h (65 mi/h)
OD04	128.8 km/h (80 mi/h)
OD05	153.0 km/h (95 mi/h)
OD06	104.7 km/h (65 mi/h)
OD07	128.8 km/h (80 mi/h)
OD08	104.7 km/h (65 mi/h)
OD09	153.0 km/h (95 mi/h)
OD10	104.7 km/h (65 mi/h)
OD11	153.0 km/h (95 mi/h)
OD12	153.0 km/h (95 mi/h)
OD13	104.7 km/h (65 mi/h)
OD14	128.8 km/h (80 mi/h)
OD15	128.8 km/h (80 mi/h)

The designated AHS velocity experienced by the older drivers using the situation-controlled transfer method

Driver	Condition
OD16	153.0 km/h (95 mi/h)
OD17	128.8 km/h (80 mi/h)
OD18	153.0 km/h (95 mi/h)
OD19	128.8 km/h (80 mi/h)
OD20	104.7 km/h (65 mi/h)
OD21	104.7 km/h (65 mi/h)
OD22	104.7 km/h (65 mi/h)
OD23	128.8 km/h (80 mi/h)
OD24	153.0 km/h (95 mi/h)
OD25	128.8 km/h (80 mi/h)
OD26	104.7 km/h (65 mi/h)
OD27	153.0 km/h (95 mi/h)
OD28	128.8 km/h (80 mi/h)
OD29	104.7 km/h (65 mi/h)
OD30	153.0 km/h (95 mi/h)

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 each of the types of control transfer investigated in the first part of the multiple experiment. Much of the narrative was repeated in each tape. The narrative presented here is the text relating to the current experiment for the manual transfer training tape, with only the changes to this text given for the remaining tapes. The text for the other phases of the multiple experiment has been omitted for the sake of brevity.]

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 left-most 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]

<u>Passage B.1</u>: Now, I will describe how you enter the automated lane and join one of the strings of automated vehicles.

<u>Passage B.2</u>: At the start of each drive, your vehicle will be on the hard shoulder of the freeway. You will drive into the right lane of the freeway, then move from the right lane to the center lane. While you are in the right and center lanes, you will drive among vehicles that are not under automated control—they will behave in the way that traffic usually behaves on a freeway.

<u>Passage B.3</u>: When you get into the center lane, you must let the System know that you are ready to enter the automated lane—you do this by pressing the *Resume* button. The System will reply as follows:

["Welcome to the automated highway system.
You will be able to enter the automated lane in a few moments.
Please wait for the signal."]

<u>Passage B.4</u>: The System will check out your vehicle, and determine which string of vehicles you should join. While you are waiting, please drive at 55 miles an hour and keep in your lane. When the System has decided it is appropriate for you to move into the automated left lane, you will hear the following *Enter* command:

["After the countdown, enter the automated lane.
Four...three...two...one...*enter*."]

<u>Passage B.5</u>: When this message starts, a string of vehicles will be passing you in the automated lane—so you must wait until you hear the *Enter* command. But, then, as soon as you *do* hear the *Enter* command, you should drive into the automated lane. As soon as your vehicle has crossed the white line and is completely in the automated lane, you should transfer control to the Automated System—you transfer control by pressing the *On* button, which is located to the left of the center panel of the steering wheel.

<u>Passage B.6</u>: You will know that you have transferred control when you hear the following message:

["Your vehicle is now under the control of the Automated System."]

Passage B.7: The System will automatically control your speed and the speed of the string behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

Passage B.8: By moving into the automated lane as soon as you hear the *Enter* command and transferring control quickly, you will give the System as much time as possible to take control of your vehicle before the next string of vehicles comes along.

Passage B.9: Let me review the entry procedure. You will start on the hard shoulder of the freeway, drive to the center lane, and press the *Resume* button to let the System know that you are ready to enter the automated lane. The System will welcome you and ask you to wait for the *Enter* command. As soon as you hear the *Enter* command, you will drive into the automated lane and press the *On* button to transfer control to the Automated System. Then, the System will adjust your speed and the speed of the string behind you until your vehicle becomes the lead vehicle of that string.

Passage B.10: Now, I will describe three possible problems with entering the automated lane.

Passage B.11: First, while you are in the center lane waiting for the *Enter* command, you should continue to drive in the center lane at 55 miles an hour. If you move out of your lane, you will hear the following warning:

["You're out of lane—you've crossed the white line.
Please return to the center lane."]

Passage B.12: Second, if you go too fast or too slowly, your vehicle will not be able to enter the automated lane safely, and you will hear this warning:

["You're driving at the wrong speed.
Please check your speed and drive at 55 miles an hour."]

Passage B.13: Third, if after you are given the *Enter* command, you take too long to move into the automated lane, you will not be able to enter safely, and you will hear the following warning:

["*Don't enter! Don't enter! Don't enter!*
Stay in the center lane—there's no room in the automated lane.
Please wait for another signal."]

Passage B.14: Now, let me briefly mention again what will happen when you enter the automated lane:

—You drive into the center lane and press the *Resume* button.

—The System will ask you to wait for the *Enter* command.

—While you wait, you should drive in the center lane at 55 miles an hour.

—You *must* wait until you hear the *Enter* command.

—Then, the moment that you *do* hear the *Enter* command, you should drive into the automated lane.

—As soon as your vehicle has crossed the white line into the automated lane, you press the *On* button to transfer control to the System.

—You will hear a message informing you that the System has taken control of your vehicle.

[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]

[*Note—The first part of the narrative for the reduced capability section of the multiple experiment is included here—it describes how the driver was instructed to regain control of the vehicle in trial #6.]

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 capacity. 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.

[Passages D.6 and D.7 are omitted here because they are not relevant to the current experiment.]

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.

[*Note—The remainder of the narrative for the reduced capability section of the multiple experiment is omitted because it is not relevant to the current experiment.]

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]

Passage B.1: **AS IN MANUAL**

Passage B.2: **AS IN MANUAL**

Passage B.3: When you get into the center lane, you must let the System know that you are ready to enter the automated lane—you do this by pressing the *On* button. Then the System will take control of your vehicle—and you will hear the following message:

["Welcome to the Automated Highway System.
Your vehicle is now under automated control."]

Passage B.4: While you are in the center lane, the System will steer your vehicle, control its speed, and keep it an appropriate distance from the vehicle ahead. Then, when there is room for your vehicle to join a string, the System will move it into the automated lane.

Passage B.5: Once you are in the automated lane, the System will automatically control your speed and the speed of the string behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

Passage B.6: So, to get into the automated lane:

—You have to drive into the center lane, then press the *On* button.

—You will hear a message informing you that the System has taken control of your vehicle.

—When there is room for your vehicle, the System will move you into the automated lane.

—Then it will control your speed and the speed of the string of vehicles behind you, adjusting both until your vehicle becomes the lead vehicle of that string.

[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.

[Passages D.5 and D.6 are omitted here because they are not relevant to the current experiment.]

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.

[*Note—The remainder of the narrative for the reduced capability section of the multiple experiment is omitted because it is not relevant to the current experiment.]

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]

Passage B.1: **AS IN MANUAL**

Passage B.2: **AS IN MANUAL**

Passage B.3: When you get into the center lane, you should adjust your speed to 55 miles an hour and let the System know that you are ready to enter the automated lane—you do this by pressing the *On* button. The System will take control of your speed, and reply as follows:

> ["Welcome to the Automated Highway System.
> You will be able to enter the automated lane in a few moments.
> Please wait for the signal."]

Passage B.4: While the System controls your speed, you must continue to steer your vehicle. When the System has decided it is appropriate for you to move into the automated left lane, you will hear the following *Enter* command:

> ["After the countdown, enter the automated lane.
> Four...three...two...one...*enter*."]

Passage B.5: When this message starts, a string of vehicles will be passing you in the automated lane—so you must wait until you hear the *Enter* command. But, then, as soon as you *do* hear the *Enter* command, you should drive into the automated lane.

Passage B.6: The System will take control of your vehicle as soon as it crosses the white line. Then, you will hear a second message—informing you that the System has taken control. This is what you will hear:

> ["Your vehicle is now under the control of the Automated System."]

Passage B.7: **AS IN MANUAL**

Passage B.8: By moving into the automated lane as soon as you hear the *Enter* command, you will give the System as much time as possible to take control of your vehicle, before the next string of vehicles comes along.

Passage B.9: Let me review the entry procedure. You will start on the hard shoulder of the freeway, and drive to the center lane. You will then press the *On* button to let the System know that you are ready to enter the automated lane. The System will control your speed and ask you to wait for the *Enter* command. As soon as you hear the *Enter* command, you will drive into the automated lane where the System will take full control of your vehicle. Then, the System will adjust your speed and the speed of the string behind you, until your vehicle becomes the lead vehicle of that string.

Passage B.10: Now, I will describe two possible problems with entering the automated lane.

Passage B.11: First, while you wait for the *Enter* command, you should continue to drive in the center lane. If you move out of the lane, you will hear the following warning:

["You're out of lane—you've crossed the white line.
Please return to the center lane."]

Passage B.12: And second, after you are given the *Enter* command, if you take too long to move into the automated lane, you will not be able to enter safely, and you will hear the following warning:

["*Don't enter! Don't enter! Don't enter!*
Stay in the center lane—there's no room in the automated lane.
Please wait for another signal."]

Passage B.13: Now, let me briefly mention again what will happen when you enter the automated lane:

—You drive into the center lane, and press the *On* button.

—The System will take control of your velocity and ask you to wait for the *Enter* command.

—You must wait until you hear the *Enter* command.

—Then, as soon as you do hear the *Enter* command, you should drive into the automated lane.

—When your vehicle has completely crossed the lane marker, you will hear a message informing you that the System has taken control of your vehicle.

[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]

[*Note—The first part of the narrative for the reduced capability section of the multiple experiment is included here—it describes how the driver was instructed to regain control of the vehicle in trial #6.]

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**

[Passages D.6 and D.7 are omitted here because they are not relevant to the current experiment.]

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

[*Note—The remainder of the narrative for the reduced capability section of the multiple experiment is omitted because it is not relevant to the current experiment.]

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]

Passage B.1: **AS IN MANUAL**

Passage B.2: **A~ IN MANUAL**

Passage B.3: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.4: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.5: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.6: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.7: **AS IN MANUAL**

Passage B.8: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.9: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.10: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.11: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.12: **AS IN PARTIAL/DRIVER-CONTROLLED**

Passage B.13: **AS IN PARTIAL/DRIVER-CONTROLLED**

[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]

[*Note—The first part of the narrative for the reduced capability section of the multiple experiment is included here—it describes how the driver was instructed to regain control of the vehicle in trial #6.]

<u>Passage D.1</u>: **AS IN MANUAL**

<u>Passage D.2</u>: **AS IN AUTOMATED**

<u>Passage D.3</u>: **AS IN AUTOMATED**

<u>Passage D.4</u>: **AS IN AUTOMATED**

[<u>Passages D.5 and D.6</u> are omitted here because they are not relevant to the current experiment.]

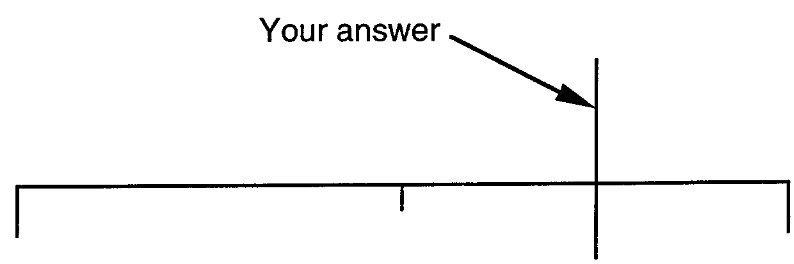
<u>Passage D.7</u>: **AS IN AUTOMATED**

[*Note—The remainder of the narrative for the reduced capability section of the multiple experiment is omitted because it is not relevant to the current experiment.]

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 air bags 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 go to 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 eight ANOVA's conducted on the lane keeping and velocity maintenance performance measures. They are presented on the following pages in the same order in which they were discussed in section 3 of the main report.

Table 8. Summary of the ANOVA conducted to determine whether a_p, the initial lane position, was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	0.06318340	0.06318340	2.81	0.1015
Transfer Method (M)	1	0.05383300	0.05383300	2.43	0.1264
Designated AHS Velocity (V)	2	0.24586349	0.12293174	1.76	0.1846
A x M	1	0.03289455	0.03289455	3.36	0.0739
A x V	2	0.04837648	0.02418824	0.26	0.7736
M x V	2	0.15033456	0.07516728	1.85	0.1708
A x M x V	2	0.53808826	0.26904413	3.09	0.0564
Subjects (within A x M x V) [S (w/A x M x V)]	41	0.49830900	0.24915450		
Trial (T)	2	2.62536914	1.31268457	41.68	0.0001
A x T	2	0.31952434	0.15976217	5.07	0.0086
M x T	2	0.14462431	0.07231216	2.30	0.1076
V x T	4	0.08819618	0.02204905	0.70	0.5943
A x M x T	2	0.04033175	0.02016587	0.64	0.5300
A x V x T	4	0.08819618	0.02204905	0.35	0.8418
M x V x T	4	0.05105199	0.01276300	0.41	0.8043
A x M x V x T	4	0.03289051	0.00822263	0.26	0.9020
S x T (w/A x M x V)	76	2.39384903	0.03149801		

1 Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, two outliers were removed from this data set using the procedure described in appendix 5.

Table 9. Summary of the ANOVA conducted to determine whether b_p, the steering drift, was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	0.00000002	0.00000002	0.41	0.5258
Transfer Method (M)	1	0.00000007	0.00000007	1.26	0.2690
Designated AHS Velocity (V)	2	0.00000006	0.00000003	0.57	0.5673
A x M	1	0.00000006	0.00000006	1.01	0.3198
A x V	2	0.00000002	0.00000001	0.16	0.8524
M x V	2	0.00000002	0.00000001	0.17	0.8401
A x M x V	2	0.00000005	0.00000002	0.43	0.6534
Subjects (within A x M x V) [S (w/A x M x V)]	41	0.00000232	0.00000006		
Trial (T)	2	0.00000154	0.00000077	12.87	0.0001
A x T	2	0.00000006	0.00000003	0.50	0.6108
M x T	2	0.00000027	0.00000013	2.25	0.1126
V x T	4	0.00000016	0.00000004	0.65	0.6284
A x M x T	2	0.00000006	0.00000003	0.52	0.5959
A x V x T	4	0.00000009	0.00000002	0.14	0.9660
M x V x T					
A x M x V x T	4	0.00000016	0.00000005	0.87	0.4587
S x T (w/A x M x V)	69	0.00000412	0.00000006		

1 Note: In addition to the data from 7 drivers that were unavailable for the reasons described in the report, 10 outliers were removed from this data set using the procedure described in appendix 5.

Table 10. Summary of the ANOVA conducted to determine whether I_p, the steering instability, was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	0.00762613	0.00762613	0.94	0.3384
Transfer Method (M)	1	0.00000159	0.00000159	0.00	0.9889
Designated AHS Velocity (V)	2	0.02850768	0.01425384	1.75	0.1860
A x M	1	0.04775805	0.04775805	5.88	0.0199
A x V	2	0.00022677	0.00011338	0.01	0.9861
M x V	2	0.01539293	0.00769647	0.95	0.3963
A x M x V	2	0.00203665	0.00101832	0.13	0.8825
Subjects (within A x G x M V) [S (w/A x G x M x V)]	40	0.32171748	0.00804294		
Trial (T)	2	0.10554321	0.05277160	19.05	0.0001
A x T	2	0.01088778	0.00544389	1.97	0.1475
M x T	2	0.00371488	0.00185744	0.67	0.5145
V x T	4	0.02292130	0.00573033	2.07	0.0936
A x M x T	2	0.01936044	0.00968022	3.49	0.0355
A x V x T	4	0.01067827	0.00266957	0.96	0.4327
M x V x T	4	0.00627893	0.00156973	0.57	0.6876
A x M x V x T	4	0.00385357	0.00096339	0.35	0.8447
S x T (w/A x M x V)	73	0.20220570	0.00276994		

1 Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, six outliers were removed from this data set using the procedure described in appendix 5.

Table 11. Summary of the ANOVA conducted to determine whether the number of steering oscillations was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	249.401964	249.401964	9.98	0.0030
Transfer Method (M)	1	5.272140	5.272140	0.21	0.6485
Designated AHS Velocity (V)	2	23.263503	11.631751	0.47	0.6312
A x M	1	32.679944	32.679944	1.31	0.2596
A x V	2	53.522301	26.761151	1.07	0.3523
M x V	2	5.514251	2.757126	0.11	0.8958
A x M x V	2	40.325696	20.162848	0.81	0.4534
Subjects (within A x M x V) [S (w/A x M x V)]	40	999.610202	24.990255		
Trial (T)	2	343.439628	171.719814	17.70	0.0001
A x T	2	111.769244	55.884622	5.76	0.0048
M x T	2	0.886507	0.443253	0.05	0.9554
V x T	4	26.016084	6.504021	0.67	0.6146
A x M x T	2	29.623964	14.811982	1.53	0.2242
A x V x T	4	101.209955	25.302489	2.61	0.0426
M x V x T	4	73.485707	18.371427	1.89	0.1208
A x M x V x T	4	12.316475	3.079119	0.32	0.8654
S x T (w/A x M x V)	72	698.448831	9.700678		

[1] Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, seven outliers were removed from this data set using the procedure described in appendix 5.

Table 12. Summary of the ANOVA conducted to determine whether a_V, the initial velocity, was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	29.977460	29.977460	8.19	0.0066
Transfer Method (M)	1	3.717998	3.717998	1.02	0.3193
Designated AHS Velocity (V)	2	3.503981	1.751990	0.48	0.6229
A x M	1	27.988386	27.988386	7.65	0.0085
A x V	2	7.798215	3.899108	1.07	0.3538
M x V	2	10.260833	5.130416	1.40	0.2576
A x M x V	2	1.300680	0.650340	0.18	0.8378
Subjects (within A x M x V) [S (w/A x M x V)]	41	149.998728	3.658506		
Trial (T)	2	2.811391	1.405695	0.49	0.6118
A x T	2	1.299710	0.649855	0.23	0.7961
M x T	2	7.286097	3.643048	1.28	0.2836
V x T	4	2.333550	0.583387	0.21	0.9347
A x M x T	2	0.837667	0.418834	0.15	0.8632
A x V x T	4	8.695089	2.173773	0.76	0.5514
M x V x T	4	0.459002	0.114750	0.04	0.9968
A x M x V x T	4	3.755674	0.938918	0.33	0.8567
S x T (w/A x M x V)	74	210.275968	2.841567		

[1] Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, four outliers were removed from this data set using the procedure described in appendix 5.

Table 13. Summary of the ANOVA conducted to determine whether b_V, the velocity drift, was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	0.00000961	0.00000961	2.91	0.0955
Transfer Method (M)	1	0.00000261	0.00000261	0.79	0.3793
Designated AHS Velocity (V)	2	0.00000280	0.00000140	0.42	0.6568
A x M	1	0.00000564	0.00000564	1.71	0.1986
A x V	2	0.00000024	0.00000012	0.04	0.9640
M x V	2	0.00001512	0.00000756	2.29	0.1140
A x M x V	2	0.00000178	0.00000089	0.27	0.7652
Subjects (within A x M x V) [S (w/A x M x V)]	41	0.00013534	0.00000330		
Trial (T)	2	0.00004182	0.00002091	5.93	0.0042
A x T	2	0.00000067	0.00000034	0.10	0.9092
M x T	2	0.00000887	0.00000443	1.26	0.2907
V x T	4	0.00000579	0.00000145	0.41	0.8007
A x M x T	2	0.00000186	0.00000093	0.26	0.7693
A x V x T	4	0.00000134	0.00000034	0.10	0.9836
M x V x T	4	0.00000544	0.00000136	0.39	0.8180
A x M x V x T	3	0.00001596	0.00000399	1.13	0.3486
S x T (w/A x M x V)	71	0.00025041	0.00000353		

1 Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, seven outliers were removed from this data set using the procedure described in appendix 5.

Table 14. Summary of the ANOVA conducted to determine whether I_V, the velocity instability, was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	0.0395190	0.03951899	0.11	0.7468
Transfer Method (M)	1	0.1431982	0.14319820	0.38	0.5395
Designated AHS Velocity (V)	2	0.1542988	0.07714942	0.21	0.8145
A x M	1	0.1747941	0.17479406	0.47	0.4981
A x V	2	2.0838419	1.04192096	2.79	0.0734
M x V	2	0.0656644	0.03283219	0.09	0.9161
A x M x V	2	0.1640241	0.08201204	0.22	0.8040
Subjects (within A x M x V) [S (w/A x M x V)]	41	15.3346887	0.37401680		
Trial (T)	2	1.1701352	0.58506761	4.56	0.0135
A x T	2	0.0459359	0.02296797	0.18	0.8364
M x T	2	0.6365784	0.31828919	2.48	0.0903
V x T	4	0.8326628	0.20816570	1.62	0.1771
A x M x T	2	0.5204914	0.26024570	2.03	0.1385
A x V x T	4	0.3086574	0.07716434	0.60	0.6626
M x V x T	4	0.5638735	0.14096838	1.10	0.3632
A x M x V x T	4	1.4002384	0.35005959	2.73	0.0352
S x T (w/A x M x V)	76	9.7464333	0.12824250		

[1] Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, three outliers were removed from this data set using the procedure described in appendix 5.

Table 15. Summary of the ANOVA conducted to determine whether the number of velocity fluctuations was affected by traveling under automated control, the age of the driver, the method of transferring control, or the designated AHS velocity.[1]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Age (A)	1	1.432210	1.432210	0.46	0.5024
Transfer Method (M)	1	0.128707	0.128707	0.04	0.8403
Designated AHS Velocity (V)	2	24.926203	12.463102	3.98	0.0262
A x M	1	17.977164	17.977164	5.75	0.0212
A x V	2	44.080261	22.040130	7.05	0.0023
M x V	2	8.838316	4.419158	1.41	0.2551
A x M x V	2	8.316367	4.158183	1.33	0.2758
Subjects (within A x M x V) [S (w/A x M x V)]	41	136.226252	3.322592		
Trial (T)	2	85.778715	42.889357	12.95	0.0001
A x T	2	5.101544	2.550772	0.77	0.4667
M x T	2	4.826166	2.413083	0.73	0.4861
V x T	4	11.729522	2.932380	0.89	0.4771
A x M x T	2	13.834348	6.917174	2.09	0.1313
A x V x T	4	4.631179	1.157795	0.35	0.8435
M x V x T	4	10.575711	2.643928	0.80	0.5302
A x M x V x T	4	33.449357	8.362339	2.53	0.0481
S x T (w/A x M x V)	72	238.442105	3.311696		

[1] Note: In addition to the data from seven drivers that were unavailable for the reasons described in the report, six outliers were removed from this data set using the procedure described in appendix 5.

APPENDIX 5: PRELIMINARY DATA ANALYSIS AND PROCEDURE FOR DEALING WITH NONPARAMETRIC DISTRIBUTIONS

As with the previous experiments in this series, a preliminary analysis of the data distributions was conducted before carrying out the significance testing. For the preliminary testing, which involved univariate analyses of the *moments* of the distributions, the data were divided into eight sets of six distributions. There was one set of distributions for each of the eight driving performance measures—three of the six distributions within each set were obtained from the older drivers when they drove in the two pre-AHS and one post-AHS expressway segments, while the remaining three distributions within each set were obtained from the younger drivers when they drove in the same three expressway segments. After the univariate analyses were carried out, a comparison of the six distributions within each of the eight sets of data showed that within each set, two or more of the distributions did not meet the requirements for parametric statistical testing. Some distributions were asymmetrical—being either positively skewed or negatively skewed—so that both the mean and variance were distorted, while other distributions were leptokurtic—so that the variance was distorted. Given these distortions, the analyst can proceed in one of three ways: the data may be trimmed, the data may be transformed, or nonparametric statistical tests can be employed.

First, nonparametric testing was considered. In analyzing the data obtained in the current experiment, it was preferable to use parametric statistical tests—rather than nonparametric tests—if possible. The reason for this was that in order to determine whether the designated AHS velocity in the automated lane or the method of transferring control from the AHS to the driver had an effect on the driver's post-AHS driving performance, it was desirable to examine the higher order interaction terms that are obtained when a four-way analysis of variance (ANOVA) is conducted. In addition, parametric tests are inherently more powerful than nonparametric tests.

Next, data transformation was considered. As already mentioned, when each set of six distributions was examined, more than one distribution type was found within the set. Because of this, it was not possible to find a single transformation that could be used on all six distributions in a set. For example, the set of distributions obtained for the steering drift (b_p) contained both a positively skewed distribution (for the older drivers when they drove in the center lane in trial #1) and a negatively skewed distribution (for the older drivers when they drove in the right lane in trial #1). The appropriate transform for a positively skewed distribution is the logarithmic transform—it reduces the skew and stabilizes the variance of that distribution. If this transform were to be applied to the set of steering drift distributions, it would deal with the positively skewed distribution in an appropriate way—however, when it was applied to the negatively skewed distribution, it would increase its skew and destabilize its variance. Because it was preferable to use parametric tests, and not possible to use transformations, the third approach, data trimming, was used for the current experiment.

The univariate analyses showed that the distributions of the lane-keeping and velocity maintenance measures contained a number of *outliers*, i.e., data points that lie outside the main region of a data distribution. Outliers inflate the standard deviation (and variance) and tend to distort the mean of a distribution. In the 1970's, Tukey developed formal procedures for dealing with outliers—these procedures are used to determine whether outlying data points are extreme enough to be identified as outliers.[17] The description provided below was taken from a more recent formulation of these procedures.[18]

The first step in determining whether the extreme data points obtained in the current experiment should be considered as outliers was to consider the data distributions of all eight driving performance measures for both the older and younger drivers. Next, the *fourth-spread*—the range of the data defined by the upper and lower fourth of the data—was determined for each of the resultant 16 distributions. [Note: The *fourth-spread* is closely related to the *interquartile range*, although technical differences between quartiles and fourths distinguish the two concepts.[18]] To give precision and technical meaning to the term *outlier*, Tukey recommended that the outlier cutoffs should be defined as $F_L - \frac{3}{2}d_F$ and $F_U + \frac{3}{2}d_F$, where F_L and F_U denote the lower and upper fourths, respectively, and d_F is $F_U - F_L$, the fourth-spread. Data values that are smaller than $F_L - \frac{3}{2}d_F$ or larger than $F_U + \frac{3}{2}d_F$ are outliers. If this procedure were to be used on a sample randomly drawn from a normal population, outliers would occur 7 times in a sample of 1000.[19] The discovery of more outliers than this in a sample is evidence that the underlying distribution from which the sample was drawn is not normal. Certainly, no outliers are expected from samples of 30 observations—the size used in this experiment—if they are drawn from a normal distribution.

The outlier cutoffs were calculated as described above for each distribution, and the outliers were identified and removed from the data sets. Table 16 shows the number of outliers removed from each distribution. The remaining data were analyzed as described in section 3 of the report.

Table 16. Number of outliers for each distribution.

	Trial #1—right lane		Trial #1—center lane		Trial #6—center lane		
Variable	Younger drivers	Older drivers	Younger drivers	Older drivers	Younger drivers	Older drivers	Total
a_p	1/26	0/27	0/26	0/27	1/26	0/27	2/159
b_p	2/26	1/27	1/26	2/27	2/26	2/27	10/159
I_p	2/26	2/27	1/26	0/27	1/26	0/27	6/159
oscilla-tions	2/26	0/27	2/26	0/27	1/26	2/27	7/159
a_v	0/26	1/27	1/26	1/27	1/26	0/27	4/159
b_v	1/26	0/27	1/26	1/27	4/26	0/27	7/159
I_v	0/26	0/27	0/26	1/27	0/26	2/27	3/159
fluctua-tions	1/26	0/27	2/26	1/27	1/26	1/27	6/159
Total	9/208	4/216	8/208	6/216	11/208	7/216	45/1272

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