PB96-182894

U.S. Department of Transportation

Federal Highway Administration

Publication No. FHWA-RD-95-107
April 1996

The Driver's Response to Decreasing Vehicle Separations During Transitions into the Automated Lane

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

FOREWORD

This report presents the results of one of a series of experiments that investigated driver performance in a generic Automated Highway System configuration. The experimental research was conducted in an advanced driving simulator and examined driver comfort levels when they were in the lead vehicle in a string of vehicles and when another vehicle entered the automated lane ahead of them. On the average, drivers were relatively comfortable being in the lead vehicle of a string; males were more comfortable than females. Average driver comfort level decreased following entry of another vehicle into the automated lane ahead of the driver's vehicle. Several possible reasons for the decrease are explored. In addition to the performance data, questionnaire data related to the drivers' acceptance of the Automated Highway System were collected. 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, five copies to each State Highway agency. Direct distribution is being made to division offices.

Samuel C. Tignor, Ph.D., Acting Director
Office of Safety and Traffic Operations,
Research and Development

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

PB96-182894

Technical Report Documentation Page

1. Report No. FHWA-RD-95-107	2.	3. Recipient's Catalog No.
4. Title and Subtitle THE DRIVER'S RESPONSE TO DECREASING VEHICLE SEPARATIONS DURING TRANSITIONS INTO THE AUTOMATED LANE		5. Report Date April 1996
		6. Performing Organization Code
7. Author(s) Bloomfield, J.R., Christensen J. M., Carrol, S.A., and Watson, G.S.		8. Performing Organization Report No.
		10. Work Unit No. (TRAIS) 3B4d1012
9. Performing Organization Name and Address Honeywell Inc. 3660 Technology Drive Minneapolis, MN 55418		11. Contract or Grant No. DTFH61-92-C-00100
		13. Type of Report and Period Covered Working Paper 11/93-1/95
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR)—Elizabeth Alicandri, HSR-30

16. Abstract
This experiment is one in a series exploring human factors issues related to the Automated Highway System (AHS). The comfort level of the driver of the lead vehicle of a string of automated vehicles was determined (a) under normal AHS operating conditions, and (b) while a second vehicle was joining the string as the new lead vehicle. The experiment was conducted in the Iowa Driving Simulator. A generic AHS configuration was used—the left lane was reserved for automated vehicles, the center and right lanes contained unautomated vehicles, the center lane was not a dedicated transition lane, there were no barriers between the automated and unautomated lanes. Sixty drivers participated in the experiment—half male, half females; half between the ages of 25 and 34 years, half who were 65 or older. The experiment began with the simulator vehicle leading a string of vehicles in the automated lane—it was controlled by the AHS and traveling at the design velocity. A second vehicle entered the automated lane ahead of the simulator vehicle, traveling at 88.6 km/h (55 mi/h). It began to accelerate and the gap between it and the simulator vehicle decreased. It accelerated until its velocity matched the design velocity—then, it became the new leader of the string of vehicles. While the gap between the entering vehicle and the simulator vehicle was decreasing, the comfort level of the driver was monitored. The experiment determined the effect on the driver's comfort level of varying: the design velocity, the inter-string gap, the time at which the second vehicle entered the automated lane, and the age and gender of the driver.
Results: (1) When the simulator vehicle led a string of automated vehicles operating normally, with a fixed inter-string distance between it and the string ahead, positive comfort levels were recorded on 89.9 percent of the trials. (2) Also, when the simulator vehicle led a string of vehicles operating normally, the comfort level varied with the gender of the driver—the mean comfort level was higher for male drivers than for female drivers. (3) When a second vehicle entered the automated lane ahead of the simulator vehicle, in 86.2 percent of the trials the comfort level of the drivers decreased. In 71.6 percent of the trials it decreased to a negative comfort level. (4) Also, when a second vehicle entered the automated lane, the comfort level varied with both gender and age—the mean comfort levels were: – 0.37 for younger males, – 0.45 for younger females, – 0.54 for older males, and – 0.71 for older females. (5) There were indications that the sharp decrease in comfort may have been triggered by time to collision estimates, although it does not provide a complete explanation.

17. Key Words automated highway system, human performance, driving simulation, automation, intelligent vehicles, human factors		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 70	22. Price

Form DoT F1700.7 (8-72) Reproduction of Completed Page Authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

(Revised September 1993)

TABLE OF CONTENTS

TABLE OF CONTENTS (concluded)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (concluded)

SECTION 1: INTRODUCTION AND OVERVIEW

INTRODUCTION

A complex multiple experiment was conducted using the Iowa Driving Simulator. It was part of a series of simulation experiments exploring human factors issues related to the design and operation of the Automated Highway System (AHS). These experiments are being conducted for the Federal Highway Administration (FHWA). The multiple experiment consisted of four separate experiments. This report is concerned with the second of these experiments.

At the start of this experiment, the simulator vehicle was the lead vehicle of a string of vehicles in the automated lane of an AHS: it was under automated control—not under the control of the driver—and it was traveling at the design velocity for the automated lane. A second vehicle moved into the automated lane from the unautomated center lane: it entered the lane ahead of the simulator vehicle, and was traveling at approximately 88.6 km/h (55 mi/h)—slower than the AHS design velocity. Once in the automated lane, the entering vehicle began to accelerate. As it accelerated to the design velocity, the gap between it and the simulator vehicle was decreasing. The entering vehicle accelerated until its velocity matched the design velocity of the automated lane. At this point it became the new leader of the string of vehicles—relegating the simulator vehicle to the second position in the string. The objectives of the experiment were to determine the comfort level of the driver of the lead vehicle of a string of automated vehicles (a) under normal operating conditions, and (b) during the time that a second vehicle was joining the string as the new lead vehicle. To achieve these objectives, the comfort level of the driver of the simulator vehicle was monitored during the period of time before the entering vehicle moved into the automated lane as well as throughout the period in which the gap between the entering vehicle and the simulator vehicle was decreasing.

Three experiments in the series had been completed before the multiple experiment was conducted. The generic AHS configuration that was employed in the first three experiments was used again in the multiple experiment. This configuration would involve minimal changes to the existing freeway system. A standard three-lane expressway cross section was modeled, with the vehicles controlled by the AHS traveling in strings of one to four vehicles in the left lane, while the vehicles that remain under the control of their drivers travel in the center and right lanes. There are no barriers or raised medians between any of the lanes. In addition, the center lane is not a dedicated transition lane—in addition to being used by vehicles that are about to travel in the automated lane and by vehicles that have just left the automated lane, it is also used by unautomated through-traffic .

The first two experiments explored the transfer of control from the AHS to the driver of the simulator vehicle as the driver left the automated lane.(1) The drivers who participated in the first experiment were between 25 and 34 years old; those who took part in the second experiment were age 65 or older. In both of these experiments at the beginning of the experimental trials, the simulator vehicle was traveling 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, to drive it out of the automated lane into an unautomated lane, and then to leave the freeway at a designated exit.

The third experiment was focused on the transfer of control to the AHS from a driver who was entering the automated lane.(2) At the beginning of each trial in this experiment, the simulator vehicle was on a freeway entry ramp. The driver's task was to drive the vehicle into the automated lane and transfer control of the vehicle to the AHS. The driver had to take the vehicle onto the freeway, move it from the right lane to the center lane, then, after receiving an *Enter* Command, drive it into the automated lane and transfer control to the AHS. The AHS took control of the simulator vehicle, adjusted its velocity and the velocity of the string of vehicles approaching it from behind it, and maneuvered it to the lead position of that string of vehicles.

The multiple experiment continued the investigation of human factors aspects of the AHS using the same generic AHS configurations, and combining four experiments that were initially planned as separate studies. Before reporting the current experiment in detail, a brief overview of the complete experiment is given below.

OVERVIEW OF THE MULTIPLE EXPERIMENT

The multiple experiment combined four experiments. The first 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—reported here—investigated the acceptability to the driver of decreasing vehicle separations during transitions into the automated lane. The third explored the ability of the driver to take control of driving functions that became unavailable in a portion of the freeway with reduced AHS capability.(4) And in the fourth, the effect on normal driving behavior of traveling under automated control was determined.(5)

Each driver in the multiple experiment took part in six trials. Table 1 shows how the data that were 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 for which data were collected in each section of each trial.

	First section	Second section	Third section
Trial #1		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, the simulator vehicle remained under the control of the driver, who drove first on a two-lane rural road with no other traffic present, and second on a three-lane expressway operating with low-density—Transportation Research Board Level-of-Service A (LOS A)—traffic.[6] While the simulator vehicle was on the expressway in this trial, the pre-AHS driving performance data needed for the comparisons made in part 4 of the multiple experiment were obtained.

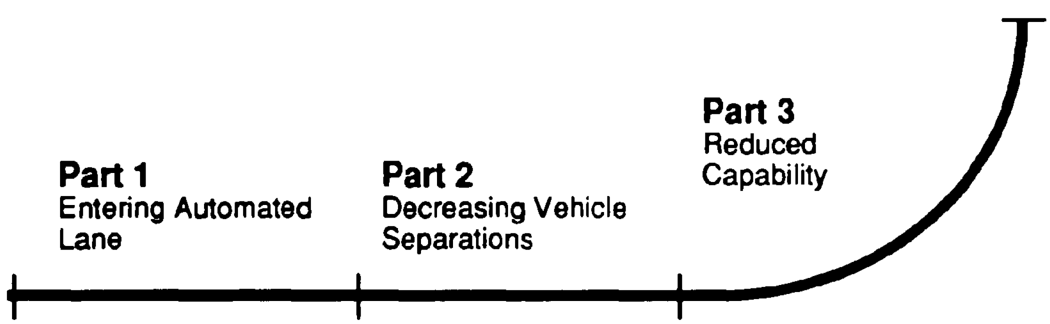

Figure 1. The relationship between parts 1, 2, and 3 of the multiple experiment.

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. Figure 1, above, shows the portions of expressway on which the first three parts of the multiple experiment were performed.

The first section of trial #6 was identical to the first section of trials #2 through #5: however, the trial did not continue in the same way—instead, at the beginning of the second section of trial #6, control of the vehicle was given back to the driver, so that post-AHS driving performance data could be obtained 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 freeway, and drove in the center and right lanes in the presence of low-density traffic—the density was 6.21 v/ln/km (10 v/ln/mi).
- The pre-AHS diving performance data obtained in the second section of this trial—while the simulator vehicle was traveling on the freeway—was 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 freeway.
- The driver moved into the right lane, and then drove the vehicle to the center lane—the density of the traffic in the center and right lanes was 6.21 v/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, a partially-automated, or a fully-automated transfer method.
- The AHS moved the driver's vehicle to the lead position of the string of vehicles approaching the simulator vehicle from behind.
- Part #1 of the multiple experiment ended at this point.

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

- In trials #2, #3, #4, and #5 (but not #6), part 2 of the multiple experiment began with the simulator vehicle under automated control leading a string of vehicles.
- A second vehicle entered the automated lane ahead of the simulator vehicle.
- As the entering vehicle accelerated from 88.6 km/h (55 mi/h) to the design velocity of the automated lane, the simulator vehicle approached it from behind.
- In half of the trials, the entering vehicle moved into the inter-string gap relatively late, and it was necessary for the AHS to reduce the speed of the simulator vehicle as the distance between it and the entering vehicle decreased.
- In the other half of the trials, the entering vehicle moved into the inter-string gap relatively early, and it was unnecessary for the AHS to reduce the speed of the simulator vehicle as it approached the entering vehicle.
- The entering vehicle became the new lead vehicle of the string.
- Throughout part 2, the driver moved a lever forwards or backwards to indicate comfort or discomfort.
- Part #2 of the multiple experiment ended with the simulator vehicle second in the string of vehicles.

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

- In trials #2, #3, #4, and #5 (but not #6), part 3 of the multiple experiment began with the simulator vehicle second in a string of vehicles.
- The driver received a *Reduced Capability* Advisory, stating that the vehicle was approaching a segment of freeway with reduced capability—the AHS was unable to (a) steer the driver's vehicle, or (b) control its speed, or (c) steer and control its speed.
- In the driver-controlled condition, the driver could take control of the lost function or functions when ready—if the driver did not take control, a *Reduced Capability* Command was issued at the moment that the AHS relinquished control.
- In the situation-controlled condition, the driver could not take control when the *Reduced Capability* Advisory was given, but had to wait for the *Reduced Capability* Command, which was issued at the moment that the AHS relinquished control.
- The driver performed the lost function or functions.
- When the simulator vehicle reached the end of the segment of freeway 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 to #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 freeway in which the AHS could not steer and could not control speed.
- In the driver-controlled condition, the driver could take control of the steering and the velocity functions when ready—if the driver did not take control, a *Reduced Capability* Command was issued at the moment that the AHS relinquished control.
- In the situation-controlled condition, the driver could not take control when the *Reduced Capability* Advisory was given: instead, the driver had to wait until the AHS gave a *Reduced Capability* Command containing a countdown that ended at the moment the AHS relinquished control.
- The driver drove the vehicle in the automated lane.
- The driver was informed that the AHS would not resume control of the vehicle and was asked to drive the vehicle out of the automated lane.
- The driver moved the vehicle into the center lane and continued to drive the vehicle for 3 min.
- The density of the traffic in the center and right lanes was 6.21 v/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.

DECREASING VEHICLE SEPARATIONS DURING ENTRY INTO THE AUTOMATED LANE

The acceptability of decreasing inter-vehicle separations to the driver of a vehicle that was leading a string of automated vehicles when another vehicle entered the automated lane and became the new lead vehicle was investigated in this second part of the multiple experiment. Figure 2 shows the relationship of part 2 to the rest of the multiple experiment.

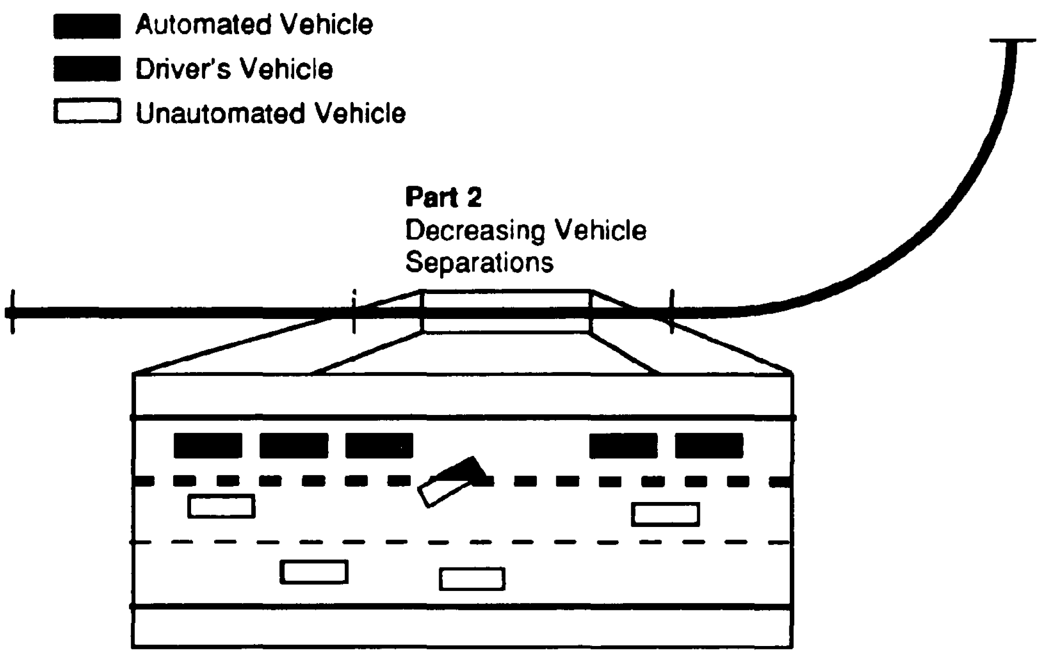

Figure 2. Part 2 of the multiple experiment—decreasing vehicle separations.

At the start of this part of the multiple experiment, the simulator vehicle was the leader of a string of automated vehicles traveling in the automated lane. It continued as the leader for a period that ranged between 30 s and 4 min. At the end of this period, another vehicle moved from the center lane into the automated lane ahead of the simulator vehicle. The velocity of this second vehicle as it entered the automated lane was approximately 88.6 km/h (55 mi/h). Under the control of the AHS, the entering vehicle accelerated until it attained the design velocity of the automated lane. While it was accelerating, the distance between the entering vehicle and the simulator vehicle gradually decreased until it equaled the design intra-string separation—so that, at approximately the same time that it attained the design velocity, the entering vehicle became the new leader of the string of vehicles, and the simulator vehicle became the second vehicle in the string.

Throughout this experiment, the driver held a lever that was mounted between the driver and the console-mounted gear-shift stick. This lever was used to indicate the driver's level of comfort. The driver pushed the lever forward to indicate comfort, and pulled it back to indicate discomfort—the greater the extent to which the driver moved the lever forward or backward, the greater the level of comfort or discomfort.

OBJECTIVES

As already mentioned, the objectives of this experiment were to determine the comfort level of the driver of the lead vehicle of a string of automated vehicles (a) under normal operating conditions, and (b) during the time that a second vehicle was joining the string and replacing the driver's vehicle as the lead vehicle. To achieve these objectives, the experiment focused on the following questions.

> *What was the driver's level of comfort when the driver's vehicle was the leader of a string of automated vehicles?*
>
> *When the driver's vehicle was the leader of a string of automated vehicles under normal operating conditions, did the driver's level of comfort vary with: (a) age, (b) gender, (c) the design velocity of the automated lane, (d) the inter-string gap, or (e) some combination of two or more of these variables?*
>
> *Did the driver's level of comfort change when a second vehicle entered the automated lane ahead of it?*
>
> *If the driver's level of comfort did change, did the extent of the change vary with: (a) age, (b) gender, (c) the design velocity of the automated lane, (d) whether the second vehicle entered early or late in the gap, or (e) some combination of two or more of these variables?*

SECTION 2: METHOD

SUBJECTS

Sixty drivers participated in the multiple experiment. Thirty of them were between the ages of 25 and 34—15 were male and 15 were female. The remaining 30 were at least 65 years old—15 (8 males and 7 females) were between the ages of 65 and 69, and 15 (7 males and 8 females) were age 70 or older. All 60 drivers were free of licensing restrictions, other than wearing eyeglasses for vision correction during driving. None of the drivers required any special driving devices—the simulator is not equipped for such devices. All 60 drivers were volunteers. They had been recruited either through the Iowa City and University of Iowa daily newspapers or by other participants in the experiment.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator is located in the Center for Computer Aided Design, at the University of Iowa, Iowa City.[7] The simulator, which is shown in figure 3, has a moving base hexapod-platform that is covered with a projection dome. In the current experiment a mid-size Ford sedan was placed on this platform, and the simulator was controlled by a computer complex that included a Harris Nighthawk 4400, an Alliant FX/2800, and an Evans and Sutherland CT-6 Image Generator. The Nighthawk and Alliant systems were controlled simultaneously by the same operating system.[8] The Nighthawk was the system master—arbitrating subsystem scheduling and performing motion control and data collection operations—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 CT6 visual projection system projected correlated imagery onto two sections of these walls—one a 3.35-rad (192°) section directly in front of the simulator vehicle, the other a 1.13-rad (65°) section to the rear of the vehicle. The driver of the simulator vehicle viewed the imagery shown on the forward section through the windshield and side windows, and the imagery projected to the rear, either through an interior driving mirror and a left-hand side driving mirror mounted outside the vehicle or by turning around.

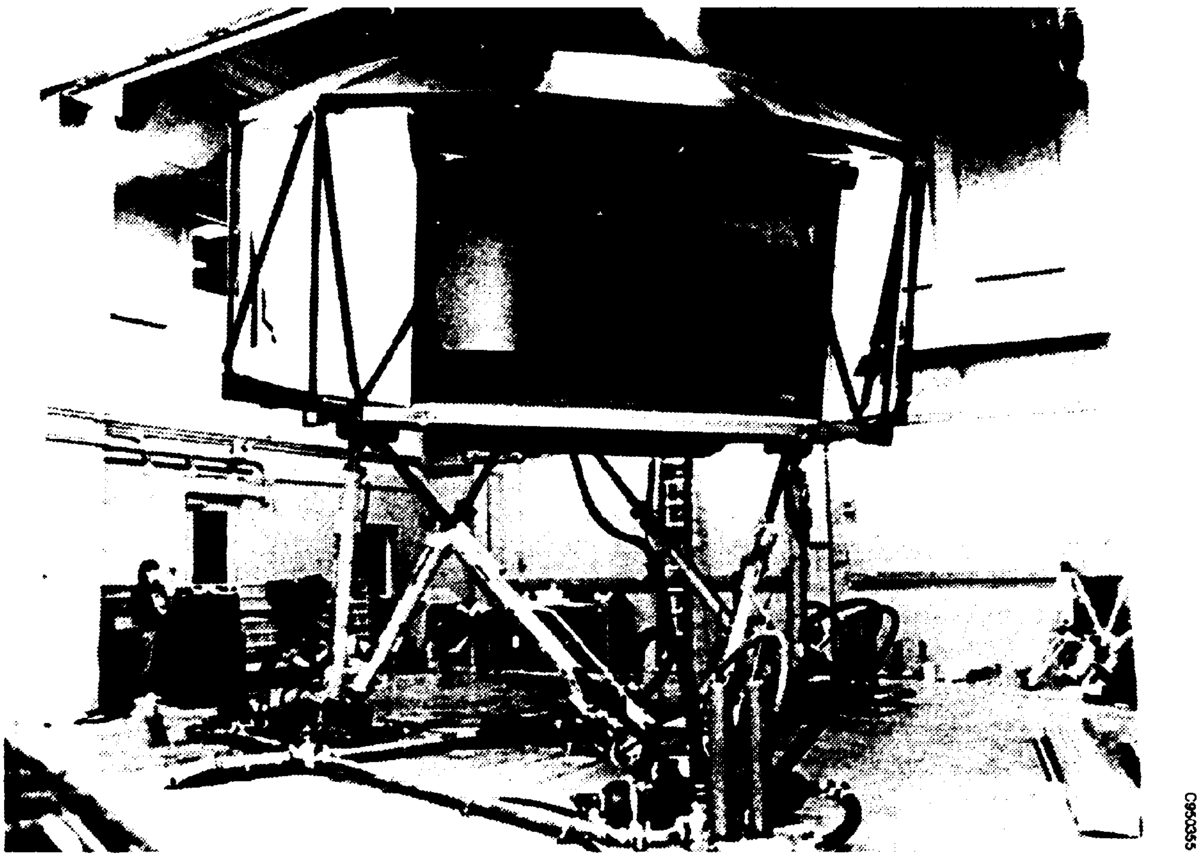

Figure 3. The Iowa Driving Simulator.

EXPERIMENTAL DESIGN

Throughout the experiment, the driver held a response lever that was installed between the driver and the console-mounted gear-shift stick. To allow the driver to indicate both comfort and discomfort, the anchor point was positioned in the center of the scale, so that the driver could make both positive and negative responses: when the driver felt comfortable, he/she pushed the lever forward—the more comfortable the driver felt, the further forward the lever was pushed; when the driver felt uncomfortable, he/she pulled the lever back—the more uncomfortable the driver felt, the further back the lever was pulled.

Two similar experimental designs were required in this experiment. In both, a factorial experimental design was used, and there were four independent variables, two of which were between-subjects variables, and two of which were partially within-and partially between-subjects variables. First, the driver's comfort level was determined while the driver's vehicle was the lead vehicle of an automated string traveling under normal operating conditions—i.e., with a fixed distance between the driver's vehicle and the last vehicle in the string ahead. In this case, the two between-subjects variables were the age and the gender of the driver, while the two partially within-and partially between-subjects variables were the design velocity and the inter-string gap. Second, the driver's comfort level was determined while another vehicle was joining the string: this vehicle entered the automated lane between the driver's vehicle and the string ahead—then, the AHS reduced the distance between the entering vehicle and the driver's vehicle until the entering vehicle became the new leader and the driver's vehicle had moved to the second place in the string. In this case, the driver's age and gender were again between-subjects variables, while the design velocity and the time at which the second vehicle entered the automated lane were the partially within-and partially between-subjects variables.

In both cases, the reason that two of the variables were partially, rather than completely, within-subjects variables was as follows. In both cases, there were six combinations of these two variables. However, each subject participated in only four trials in the multiple experiment. As a result, three subjects were required to provide two complete cycles of the six combinations of design velocity and the time at which the second vehicle entered the automated lane. Sixty drivers participated in the multiple experiment: there were 15 drivers in each of the 4 combinations of age and gender, and each driver participated in 4 trials—as a result, in both cases, there were 10 complete cycles of the 6 combinations of the 2 variables (design velocity and either the inter-string gap or the time at which the second vehicle entered the automated lane). For analysis purposes, all four independent variables were treated as between-subjects variables.

The complete listing of conditions that were presented to each of the 60 subjects is given in appendix #1.

Comfort Level: Normal Operations

The driver's comfort level was determined while the driver's vehicle was the lead vehicle of a string traveling under normal operating conditions—i.e., with a fixed distance between the driver's vehicle and the last vehicle in the string ahead. The following were varied for this part of the experiment:

Age of the Driver—There were 60 drivers—they were divided into two groups of 30. The drivers in one group were all between the ages of 25 and 34; those in the second group were all age 65 or older. Although half of those in the older group of drivers were between the ages of 65 and 69 and half were age 70 or older, the data from these two subgroups were treated together in the data analysis. The reason that the two subgroups were used was to ensure that the drivers would not all cluster around the lower age limit.

Gender of the Driver—Of the 30 in the younger group of drivers, who were between the ages of 25 and 34, 15 were male and 15 were female. Of the 15 who were between the ages of 65 and 69, 8 were male and 7 female, and of the 15 who were age 70 or older, 7 were male and 8 were female.

Design Velocity—The same three automated-lane design velocities that were used in the first three experiments of the series were reused in the current experiment—they were: 104.7 km/h (65 mi/h), 128.8 km/h (80 mi/h), and 153.0 km/h (95 mi/h).

Separation Between Strings of Vehicles—Two different separations (gaps) between the strings of vehicles in the automated lane were used with each of the three design velocities—they were the same inter-string gaps as were employed the third experiment. For the two faster design velocities—128.8 km/h (80 mi/h) and 153.0 km/h (95 mi/h)—the shorter of the two gaps was the minimum time required to allow a vehicle with the acceleration characteristics of the simulator vehicle to accelerate from 88.6 km/h (55 mi/h) to the design velocity, while the other gap was 2.0 s longer than this minimum time. For the slower design velocity—104.7 km/h (65 mi/h)—since only 0.4 s was required to allow a vehicle with the acceleration characteristics of the simulator vehicle to accelerate to the design velocity, and since it was obvious that the driver would be unable to change lanes within this time, a 2.0 s-gap was used as the shorter of the two

Table 2. The inter-string gap, in seconds, meters, and feet, for the six combinations of the shorter and longer inter-string gaps with the three design velocities.

Design Velocity of Automated lane [km/h (mi/h)]	Inter-String Separations			
	Shorter gap		Longer gap	
104.7 (65)	2.0 s	[58.15 m (190.67 ft)]	2.4 s	[69.78 m (228.80 ft)]
128.8 (80)	2.0 s	[71.57 m (234.67 ft)]	4.0 s	[143.15 m (469.33 ft)]
153.0 (95)	5.5 s	[233.73 m (766.33 ft)]	7.5 s	[318.75 m (1045.00 ft)]

separations. However, for this design velocity, the longer gap was 2.4 s, which, as with the two faster velocities, was the minimum time plus 2.0 s. Table 2 shows the separation times and the distances associated with them for the three automated lane velocities.

Comfort Level as a Second Vehicle Becomes the New Lead Vehicle

The driver's comfort level was also determined while another vehicle was joining the string. The following were varied for this part of the experiment:

Age of the Driver, Gender of the Driver, and Design Velocity—For these three variables the levels tested were the same as for the determination of comfort level under normal operating conditions (see above).

Time at which the Second Vehicle Entered the Automated Lane—The entering vehicle moved into the inter-string gap between the simulator vehicle and the last vehicle of the string that was immediately ahead either relatively early or relatively late. When entering relatively early, it entered the automated lane as close as possible to the last vehicle of the preceding string and as far away as possible from the simulator vehicle, and the need for the AHS to reduce the velocity of the simulator vehicle from the design velocity was minimized. When entering relatively late, the second vehicle entered the automated lane further away from the last vehicle of the preceding string and much closer to the simulator vehicle. For these trials, there were considerable reductions in the velocity of the simulator vehicle.

EXPERIMENTAL PROCEDURE

Training Procedure

Each driver participated in two experimental sessions—in the first, the driver was trained and then drove in the simulator; in the second, the driver's visual capabilities were assessed.

Before the start of the experiment, each driver watched a videotape containing introductory material describing this research program and the AHS, and providing some interactive practice with the AHS interface. 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 is part of an ongoing FHWA program that is exploring ways of designing an AHS, and 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. It provided details on how to:

- Enter the automated lane (for part 1 of the multiple experiment).
- Use the lever to indicate comfort level for the experiment described here.
- Take control during the reduced capability section of the trials, and transfer control back to the AHS at the end of the reduced capability section (in part 3 of the multiple experiment).

Four different versions of this training video were prepared. The differences in these versions corresponded to differences in the methods of transferring control to the AHS for part 1 of the multiple experiment, and in the method of regaining control for part 3. All four videos were identical in the section describing the current experiment—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 video continued with a series of practice segments. The first segments were part-task practices that dealt with the actions that the driver needed to perform in order to:

- Enter the automated lane and transfer control to the AHS (for part 1).
- Indicate the level of comfort (for the experiment reported here).

- Take control of the lost capability, and return control of the lost capability to the AHS (for part 3).

The video monitor was placed on a table. The driver watched the videotape while sitting at the table. A steering wheel was mounted at the leading edge of the table in front of the driver, and a comfort lever was positioned on the table to the right of the steering wheel.

There were three segments for each of these part-tasks. If the driver responded correctly on the first two segments, the third segment was omitted. If a particular driver did not respond correctly twice in a row during the first presentation of the three segments for a particular part-task, the segments were repeated until the driver did reach this performance criterion. After the part-task practices, three extended segments that covered the tasks that the driver would face in the complete experimental trial were presented. Again, if the driver responded correctly to the first two presentations, the third was omitted, and if more than three trials were required, the segments were repeated.

Pre-Experimental Procedure

When the training was completed, the driver was taken to the Iowa Driving Simulator. There, the driver was asked to sit in the driving seat of the simulator vehicle, adjust the seat, put on the seat belt, and adjust the mirrors. The driver was also given instructions on how to use the simulator emergency button. The driver was then ready to drive the simulator vehicle.

Trial #1 had two parts. In the first part, the driver drove the simulator vehicle on a two-lane rural road for about 60 s—there was no other traffic present on this section of road. In the second part, the driver drove from the rural road to an entry ramp, entered a three-lane expressway, and drove on it for 3 to 4 min in the presence of other vehicles. The density of the traffic was 6.21 v/ln/km (10 v/ln/mi), which is close to the upper boundary of the Transportation Research Board LOS B.(6) While driving on the freeway segment, the driver was asked to change lanes, from the right lane to the center lane, and then back again from the center lane to the right lane. Throughout trial #1, the simulator vehicle was under the control of the driver.

The next four trials—i.e., trials #2, #3, #4, and #5—started with the simulator vehicle positioned on the hard shoulder of the expressway. In the first part of these trials, the driver was asked to drive into the right lane, and then to maneuver the vehicle into the center lane when it was safe to do this. The driver was informed that the speed limit was 55 mi/h in the unautomated lanes.

Then the simulator vehicle entered the automated lane using a manual, partially-, or fully-automated method of transferring control. Whichever method was used, this section of the experiment ended with the simulator vehicle traveling at the design velocity of the AHS, leading a string of automated vehicles in the automated lane.

Experimental Procedure and Instructions

At the start of the second section of trials #2, #3, #4, and #5, the simulator vehicle was the leader of a string of automated vehicles. It continued as the lead vehicle for between 0.5 min and 4 min. Then, a second vehicle moved into the automated lane some distance ahead of the simulator vehicle. As it entered, the second vehicle was traveling at 88.6 km/h (55 mi/h). Then, it accelerated—under the control of the AHS—until it was traveling at the design velocity. Throughout the time that the entering vehicle was accelerating, the gap between the two vehicles was decreasing. As the velocity of the entering vehicle neared the design velocity, the velocity of both vehicles was adjusted until the relative distance between them was equal to the gap between the vehicles within the string. At this point, the entering vehicle had become the lead vehicle, and the simulator vehicle had moved into the second position in the string.

In the current experiment, there was no driving task for the driver. Instead, the driver was asked to hold a lever mounted between the driver and the console-mounted gear-shift stick. The driver used this lever to provide a continuous indication of comfort level throughout the experiment. The driver had been instructed to push the lever forward to indicate comfort, and to pull it back to indicate discomfort—and the greater the extent to which the lever was pushed or pulled, the greater the level of comfort or discomfort.

Post-Experimental Procedure

The third part of the multiple experiment occurred in the third section of trials #2, #3, #4, and #5, when the simulator vehicle passed through a segment of freeway on which the AHS was operating with reduced capability—with the steering, or the velocity control, or both steering and velocity control being relinquished by the AHS. While the vehicle was traveling in this segment, the driver was asked to provided the function that was unavailable.

Following trials #2, #3, #4, and #5, there was a sixth trial in which the driver provided data for part 4. After completing the sixth trial, the driver returned to the subject preparation room. There, the driver was debriefed, and asked to complete a questionnaire dealing with the driving simulator, the multiple experiment, and the Automated Highway System. At this point, the first session ended.

The driver returned for a second session. This 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 Dr. Michael Wall was used to determine the subject's reaction time and accuracy when detecting both static and dynamic peripheral stimuli.[9,10]

SECTION 3: RESULTS

FOCUS OF THE DATA ANALYSIS

The objectives of this experiment were to determine the comfort level of the driver of the lead vehicle of a string of automated vehicles (a) under normal operating conditions, and (b) during the time that a second vehicle was joining the string and replacing the driver's vehicle as the lead vehicle. To achieve these objectives, the experiment focused on the following four questions.

What was the driver's level of comfort when the driver's vehicle was the leader of a string of automated vehicles?

When the driver's vehicle was the leader of a string of automated vehicles under normal operating conditions, did the driver's level of comfort vary with: (a) age, (b) gender, (c) the design velocity of the automated lane, (d) the inter-string gap, or (e) some combination of two or more of these variables?

Did the driver's level of comfort change when a second vehicle entered the automated lane ahead of it?

If the driver's level of comfort did change, did the extent of the change vary with: (a) age, (b) gender, (c) the design velocity of the automated lane, (d) whether the second vehicle entered early or late in the gap, or (e) some combination of two or more of these variables?

Data Items

In order to explore these questions, the following data items were recorded or calculated:

- Design velocity of the automated vehicles.
- Continuous plot of the velocity of the simulator vehicle.
- Continuous plot of the position of the simulator vehicle.
- Time at which the second vehicle entered the automated lane.
- Time at which the second vehicle joined the string of vehicles.
- Continuous plot of the velocity of the entering vehicle.
- Continuous plot of the position of the entering vehicle.

- Continuous plot of the distance between the back bumper of the entering vehicle and the front bumper of the simulator vehicle.
- Continuous plot of the time to collision.
- Continuous plot of the level of comfort or discomfort of the driver—measured by monitoring the direction and extent to which the lever was pushed or pulled.

MEASURING THE COMFORT LEVEL OF THE DRIVER

Throughout the current experiment, the driver was asked to hold a response lever that had been installed between the driver and the console-mounted gear-shift stick. When the driver felt comfortable, the lever was to be pushed forward—the more comfortable the driver felt, the further forward the lever was pushed. When the driver felt uncomfortable, the lever was pulled back—the more uncomfortable the driver felt, the further back the lever was pulled. Every driver was able to push the lever fully forward and pull it fully backward while comfortably seated in his/her normal driving position.

This method of measuring the driver's comfort level was derived from Stevens's cross-modality matching method of expressing perceived intensity.[11] There were two main differences between the method used here and traditional cross-modality methods. First, in the current experiment, to allow the driver to indicate both comfort and discomfort, the anchor point was positioned in the center of the scale, so that the driver could make both positive and negative responses—in contrast, in Stevens' experiments, typically the anchor point was set at zero and only positive responses were possible. Second, in the current experiment, the situation was changing dynamically during the period in which the driver was responding—whereas in Stevens' experiments the stimulus presented to the subject did not change during an experimental trial.

In the current experiment before the second vehicle had entered the automated lane, the driver was asked to hold the lever and move it forward or backward to indicate comfort or discomfort. The driver was asked to continue to respond until the entering vehicle had become the new leader of the string of vehicles. With 60 drivers each participating in four trials, a total of 240 trials were conducted. Comfort level records were retrieved from 217 of these trials (they were not retrieved in the other 23 trials because the driver failed to enter the automated lane in part 1 of the experiment, or failed to use the lever, or because there was a simulator failure during the trial). For each of these 217 trials, comfort level was plotted against time. Figure 4 shows schematically the way in which the driver's comfort level varied as a function of time in most of these trials. As figure 4 shows, at the start of most of the trials the driver's comfort level was positive. It continued to be positive for some time, and did not change when the second vehicle entered the automated lane. However, typically, the driver's level of comfort did begin to decline as the separation between the driver's vehicle and the entering vehicle was reduced, and in most cases it became negative.

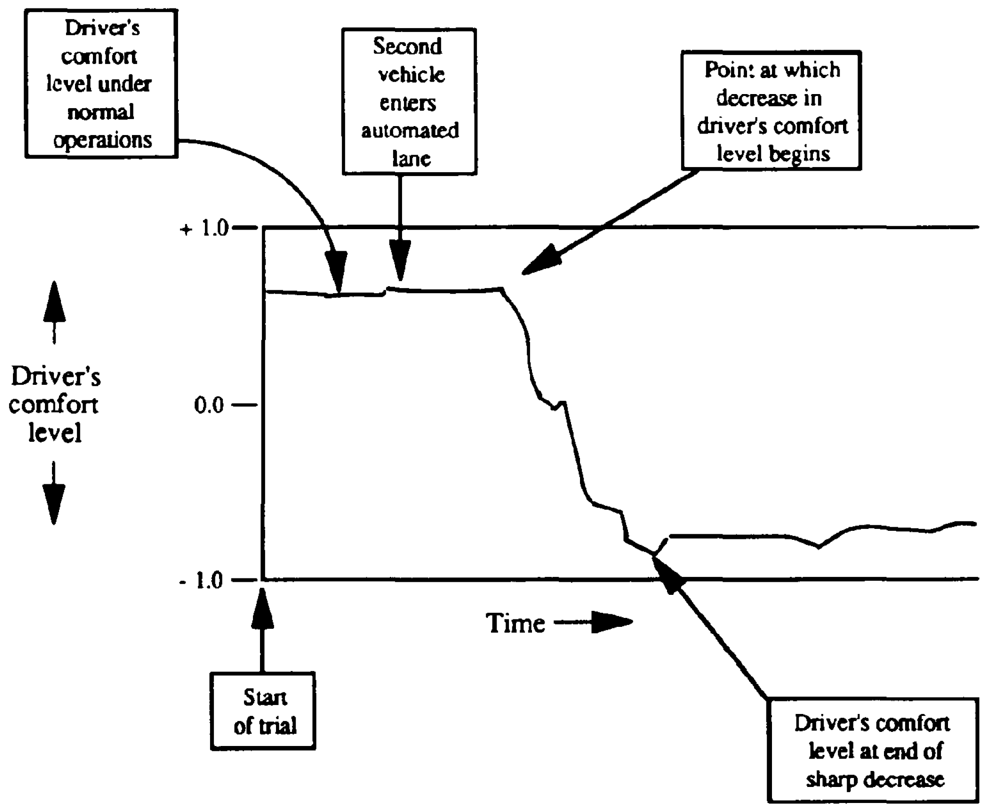

Figure 4. Schematic plot showing the driver's comfort level as a function of time during the course of an experimental trial.

Three examples of these plots are shown in the figure 5: the uppermost plot in figure 5 shows the variation in the comfort level for a younger male driver when the second vehicle entered relatively early and the design velocity was 104.7 km/h (65 mi/h); the central plot shows the comfort level for a younger male driver when the second vehicle entered relatively early and the design velocity was 128.8 km/h (80 mi/h); and the lower plot shows the comfort level for an older

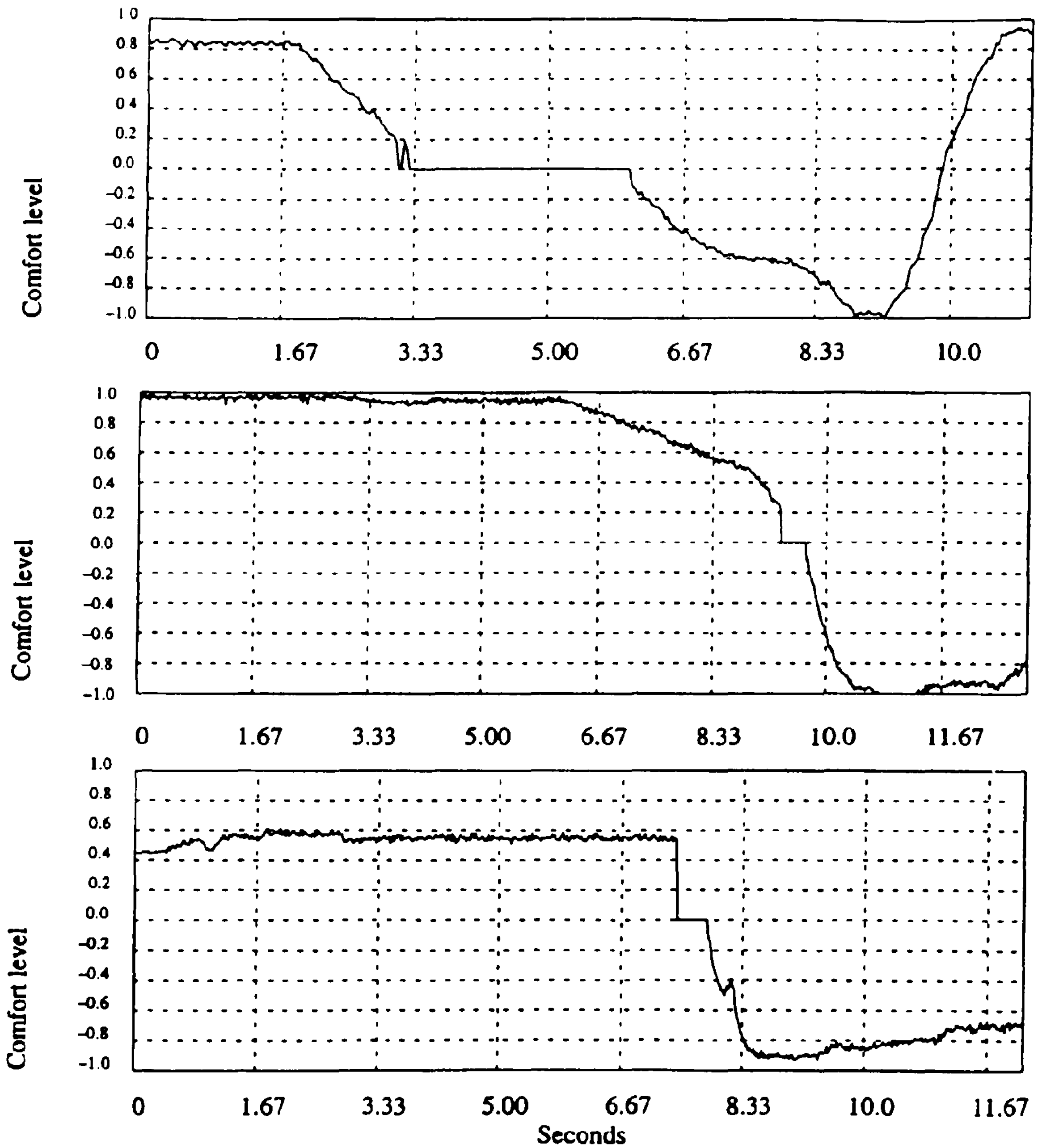

Figure 5. Comfort level as a function of time in seconds: (upper plot) a younger male driver, with early entry and a design velocity of 104.7 km/h (65 mi/h); (central plot) a younger male driver, with early entry and a design velocity of 128.8 km/h (80 mi/h); (lower plot) an older female driver, with late entry and a design velocity of 153.0 km/h (95 mi/h).

female driver when the second vehicle entered relatively late and the design velocity was 153.3 km/h (95 mi/h).

COMFORT LEVEL OF THE DRIVER IN NORMAL OPERATIONS

The first experimental question was:

> *What was the driver's level of comfort when the driver's vehicle was the leader of a string of automated vehicles?*

At the beginning of all 217 trials, the simulator vehicle was the leader of a string of automated vehicles traveling under normal AHS operating conditions—i.e., a fixed distance behind the last vehicle of the string ahead. Examination of the 217 comfort level plots showed that before the second vehicle entered the automated lane there was little variation in the comfort level—it was essentially flat and parallel to the time axis. This can be seen in figure 5, where for the uppermost plot the second vehicle entered during the first 1.67 s; for the central plot, where it entered in the first 5.0 s; and for the lower comfort level plot, where it entered in the first 6.0 s.

The comfort levels in these flat regions, obtained before the second vehicle entered the automated lane, were read from all 217 plots. The average of the 217 readings was + 0.54, indicating that the drivers were comfortable with their vehicle at the fixed inter-string distance from the string ahead—i.e., that they were comfortable when sitting in the driver's seat of a vehicle that was traveling at 104.7 km/h (65 mi/h), with an inter-string gap of 2.0 s or 2.4 s; at 128.8 km/h (80 mi/h), with an inter-string gap of 2.0 s or 4.0 s; and at 153.0 km/h (95 mi/h), with an inter-string gap of 5.5 s or 7.5 s. In 89.9 percent of the trials, the driver's comfort level was positive; in 3.2 percent the readings were neutral; and the driver indicated discomfort in only 6.9 percent of the trials.

Next, the comfort levels readings were analyzed using a four-way analysis of variance (ANOVA). This analysis addressed the second experimental question:

> ***When the driver's vehicle was the leader of a string of automated vehicles under normal operating conditions, did the driver's level of comfort vary with: (a) age, (b) gender, (c) the design velocity of the automated lane, (d) the inter-string gap, or (e) some combination of two or more of these variables?***

The ANOVA, summarized in table 10 in appendix 3, indicated that the driver's level of comfort did not vary with three of the main variables—i.e., with (1) the age of the driver, (2) the design velocity, or (3) the inter-string gap. In addition, there were no significant interactions. However, the ANOVA shows that the comfort level did vary with the gender of the driver. The mean comfort level was higher, at + 0.63, for the male drivers than it was, at + 0.46, for the female drivers —this difference was significant at the $p = 0.0001$ level.

COMFORT LEVEL OF THE DRIVER WHILE A SECOND VEHICLE JOINED THE STRING

The third experimental question was:

> *Did the driver's level of comfort change when a second vehicle entered the automated lane ahead of it?*

Further inspection of the 217 plots indicated that the driver's level of comfort was affected after a second vehicle entered the automated lane ahead of the driver's vehicle—there was a dramatic decrease to an average level of – 0.52. When the sign test was used to analyze the data, this result was found to be statistically significant (at the $p = 0.0001$ level). Examples of the decrease can be seen in all three plots on figure 5. The substantial decreases seen in figure 5 occurred in 187 of the 217 trials—i.e., in 86.2 percent of the trials. The decrease in comfort level occurred at some point during the time in which the gap between the entering vehicle and the driver's vehicle was decreasing. There was no trial in which there was an initial increase in the driver's comfort level after the second vehicle entered: in 30 of the 217 trials—i.e., in the remaining 13.8 percent of the trials—the driver's comfort level stayed constant throughout the experiment.

In some trials, although there was a decrease in the comfort level, the reading may have remained positive. However, when all 217 plots are considered, after a second vehicle entered the automated lane ahead of the driver's vehicle, the resultant comfort level reading was negative—indicating discomfort—in 71.6 percent of the trials, and positive on the remaining 28.4 percent.

The fourth experimental question was:

> *If the driver's level of comfort did change, did the extent of the change vary with: (a) age, (b) gender, (c) the design velocity of the automated lane, (d) whether the second vehicle entered early or late in the gap, or (e) some combination of two or more of these variables?*

To answer this question, the 187 plots in which there was a decrease were examined, and the low point of this initial decrease in the driver's comfort level was determined. These scores were analyzed using a four-way ANOVA. The summary of this ANOVA, presented in table 11 in appendix 3, shows that the driver's level of comfort after the decrease varied with both the gender and the age of the driver. Younger drivers were less uncomfortable than the older drivers —this difference was statistically significant at the $p = 0.0006$ level. Similarly, male drivers were less uncomfortable than female drivers—this difference was significant at the $p = 0.0174$ level. The mean comfort levels were: – 0.37 for younger males, – 0.45 for younger females, – 0.54 for older males, and – 0.71 for older females.

The ANOVA summary table also shows that comfort level did not vary with the design velocity or with the time at which the second vehicle entered the automated lane. In addition, none of the interactions were significant.

While there were significant differences between the comfort levels of male and female drivers, and between younger and older drivers, the more important results of this experiment are that:

(1) In 86.2 percent of the trials the comfort level of the drivers decreased after the second vehicle entered the automated lane.

(2) While experiencing normal AHS operations, before the second vehicle entered the automated lane, the drivers were comfortable in 89.9 percent of the trials—in contrast, after the second vehicle entered the automated lane, in 71.6 percent of the trials the drivers became uncomfortable.

It is not surprising that the drivers were less comfortable after the second vehicle entered the automated lane and the separation between the driver's vehicle and the entering vehicle decreased. However, it is of particular importance to note that in 71.6 percent of the trials the drivers were not just less comfortable, but were actually uncomfortable. AHS designers and engineers will need to devise ways for vehicles to join strings that minimize discomfort to the drivers.

COMPARISON OF THE COMFORT LEVELS IN NORMAL OPERATIONS AND WHILE A SECOND VEHICLE JOINED THE STRING

Figure 6 shows the difference between the mean comfort levels of the younger male, older male, younger female, and older female drivers during normal operations—i.e., with the fixed design inter-string gap between the driver's vehicle and the string ahead when the comfort level plots were essentially flat—and after the decrease that occurred during the time that the second vehicle was joining the string.

The figure shows the difference, indicated in the two ANOVA's above, between the male and female drivers that occurred both in normal operations and when the second vehicle was joining the string. It also shows that while there was no difference between the younger and older drivers during normal operations, when the second vehicle was in the process of joining the string, the younger drivers had less discomfort than the older drivers.

Figure 6 shows very clearly that the drivers were comfortable during the normal operation of the system—as mentioned above, on 89.9 percent of the trials positive comfort level readings were obtained—and that they were uncomfortable at some point while the second vehicle was joining the string—with negative comfort level readings on 71.6 percent of the trials.

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. Initial comparison of the data from the drivers who took part in this experiment with data from ophthalmological patients examined in the University of Iowa Hospitals indicated that the peripheral sensitivities of the drivers were typical of normal subjects drawn from the populations from equivalent age groups.

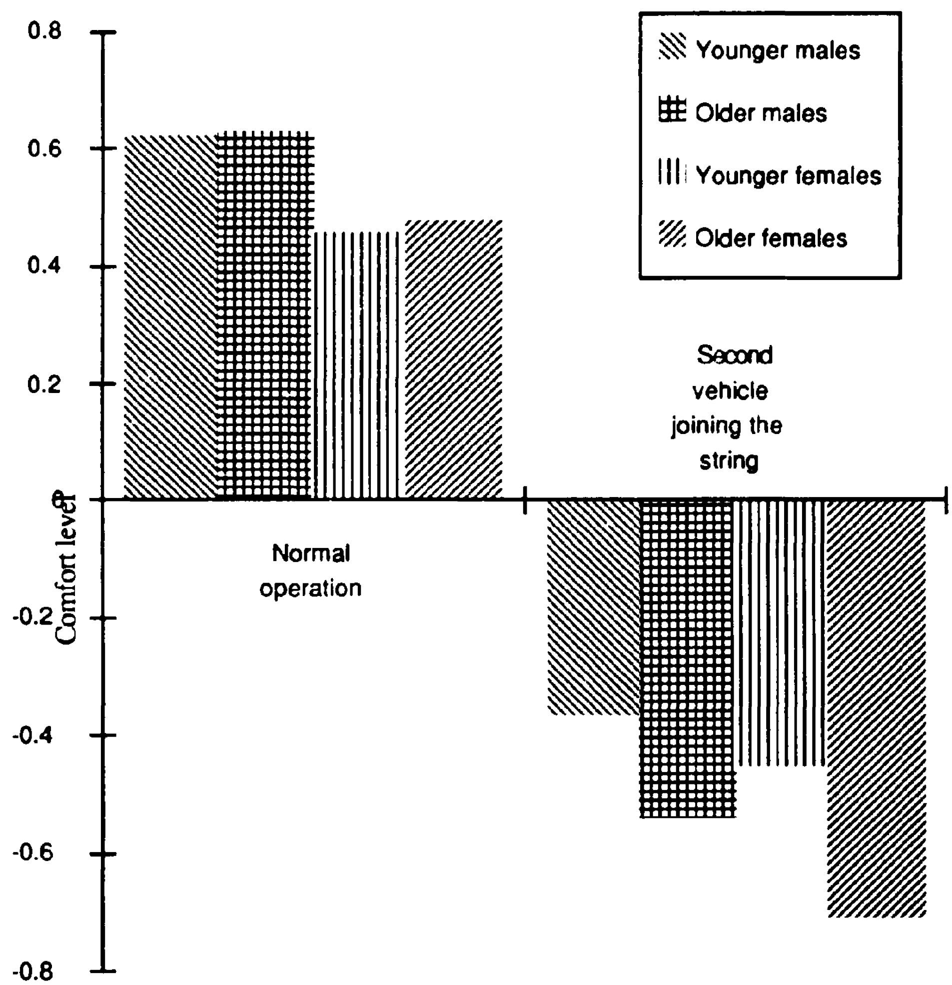

Figure 6. Comfort level for older and younger male and female drivers during normal operations and after the second vehicle had entered the automated lane.

SECTION 4: DISCUSSION

POSSIBILITIES

The dramatic decrease in the driver's level of comfort found while the second vehicle was joining the string warrants further investigation. What triggered this decrease?

While the second vehicle was joining the string, the driver was observing a dynamically changing situation—both the separation between the driver's and the entering vehicle, and the velocity differential between them, were varying. It was possible that the changes in either the separation or velocity differential alone could have produced the sharp change in the driver's comfort level. However, the explanation might not be that simple—it is possible that the decrease was triggered by the driver integrating the separation and differential velocity information to produce an estimation of the time to collision. Lee suggested that the driver of a vehicle approaching a static object of known size at constant velocity can obtain time to collision information directly from the optic flow field.(12) Subsequent work by van der Horst supports the hypothesis that, when a driver is approaching a static object of known size, both the decision to start braking and the control of the braking process are based on time to collision information derived from the optic flow field.(13) It is possible that this notion could be extended to the situation faced by the drivers in the current experiment—although this time the integration task might be more complex. As in the case considered by Lee and by van der Horst, in this experiment the driver would have to take into consideration a decreasing separation between the two vehicles, but instead of integrating this with velocity information about his/her own vehicle, the driver would have to integrate the separation information with dynamically changing differential velocity information—since in this case, both vehicles were moving. There may be more inaccuracy in the estimates of time to collision when the driver has to derive differential velocity information from optic flow fields.

If the sharp decrease in the driver's level of comfort was triggered by one of these parameters—i.e., by the separation between the driver's vehicle and the entering vehicle, by the velocity differential between these two vehicles, or by time to collision—then it is to be expected that the triggering parameter would be independent of the design velocity, and would not change as the design velocity varied. To test these possibilities, further analysis was performed.

First, the comfort level plots were re-examined, and the time at which the sharp decrease began was noted. Second, the velocity differential and the separation between the two vehicles, at that time, were calculated—the velocity and position of both vehicles had been recorded continuously throughout the experiment. Third, the velocity differential and the separation were used to calculate the time to collision at the moment that the sharp decrease began.

Figures 7, 8, and 9 show four plots that indicate how (a) the driver's comfort level, (b) the separation between the driver's vehicle and the second vehicle, (c) the differential velocity of the two vehicles, and (d) the time to collision, co-varied as a function of time for the three drivers whose comfort level plots were presented in figure 5. Since in each figure the four plots cover an identical period of time, direct comparisons can be made—for example, by scanning down each set of four plots, it is possible to see what the velocity differential, the gap, and the time-to-collision were at the moment that the comfort level first began to drop for each of the three drivers.

Figure 7 shows these functions for the younger male driver whose data were shown in the uppermost plot of figure 5—for this driver the second vehicle entered the automated lane early and the design velocity was 104.7 km/h (65 mi/h). Figure 8 shows the same four functions for the younger male driver whose comfort level plot was shown in the center of figure 5—in this case, the second vehicle entered the automated lane relatively early and the design velocity was 128.8 km/h (80 mi/h). Figure 9 shows these functions for the older female driver whose comfort level plot was the lower plot in figure 5—here, the second vehicle entered relatively late and the design velocity was 153.0 km/h (95 mi/h). Next, an ANOVA was conducted on each of these three parameters to determine whether any of them were affected by changes in the age or gender of the driver, the design velocity in the automated lane, the time at which the second vehicle entered the automated lane, or a combination of two or more of these variables. The results of these analyses are discussed below.

DECREASING SEPARATION

The ANOVA exploring the separation between the two vehicles at the moment that the decrease in comfort level began is summarized in table 12 in appendix 3. Two of the independent variables—the gender of the driver ($p = 0.0282$) and the design velocity ($p = 0.0001$)—were statistically significant. However, there were also two statistically significant interactions, one between design velocity and gender, the other between design velocity and the time at which the second vehicle entered the automated lane. These two interactions are explored in figures 10 and 11.

The interaction between design velocity and gender is shown in figure 10. There was little difference between male and female drivers at the two lower design velocities: when the design

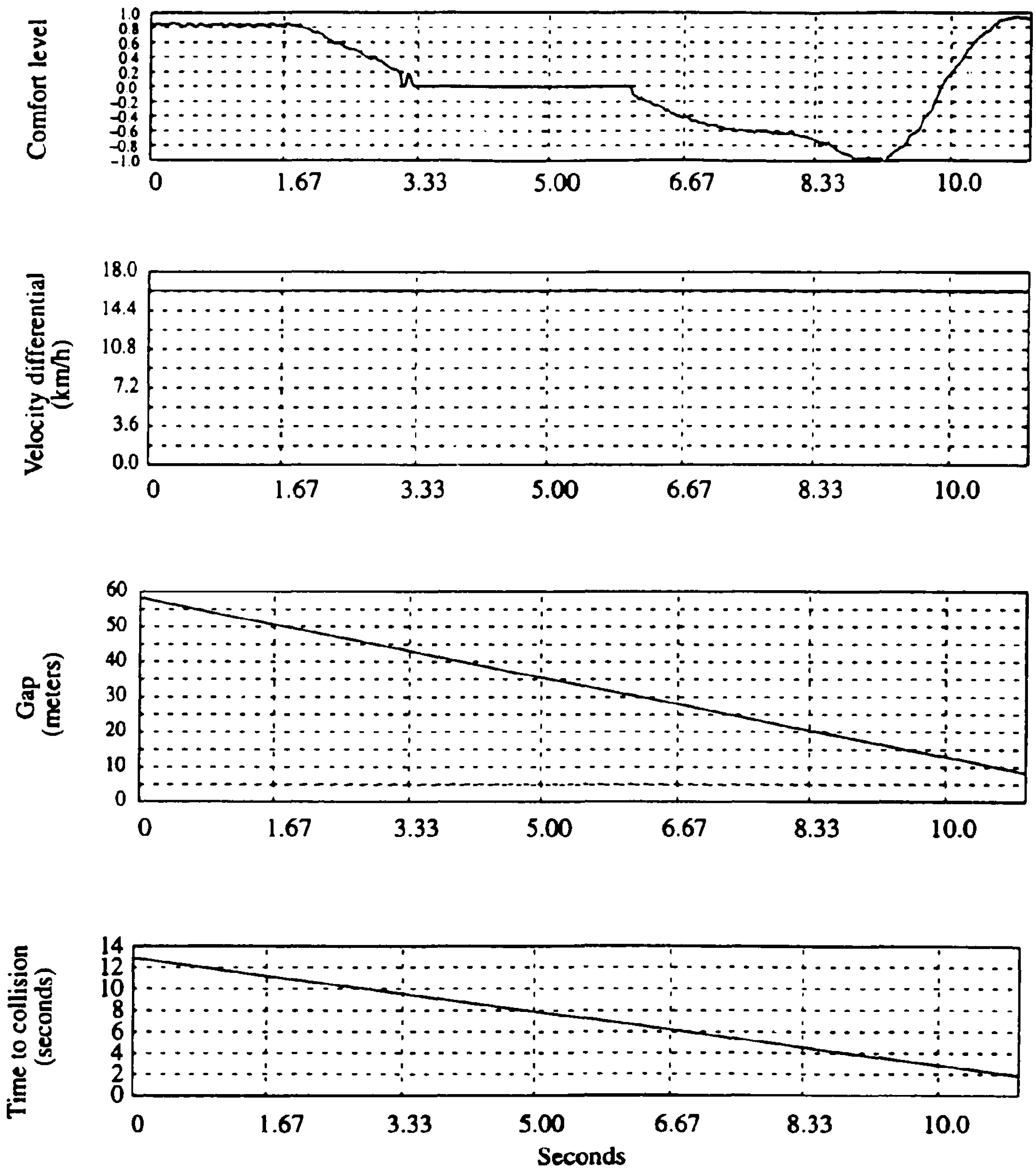

Figure 7. Comfort level, velocity differential, inter-vehicle gap, and time to collision as a function of time (in seconds) for a younger male driver, when the second vehicle entered early and the design velocity was 104.7 km/h (65 mi/h).

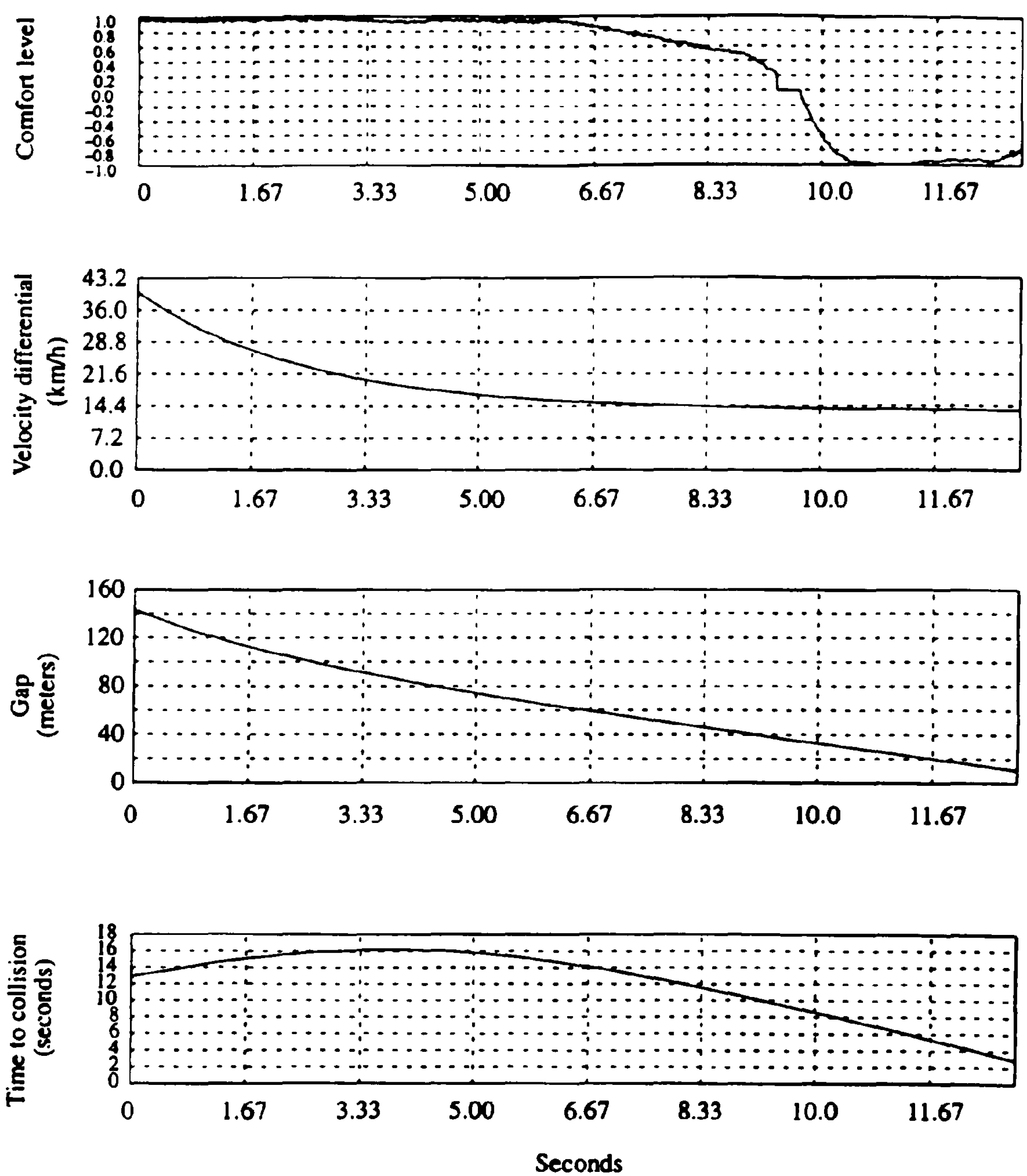

Figure 8. Comfort level, velocity differential, inter-vehicle gap, and time to collision as a function of time (in seconds) for a younger male driver, when the second vehicle entered early and the design velocity was 128.8 km/h (80 mi/h).

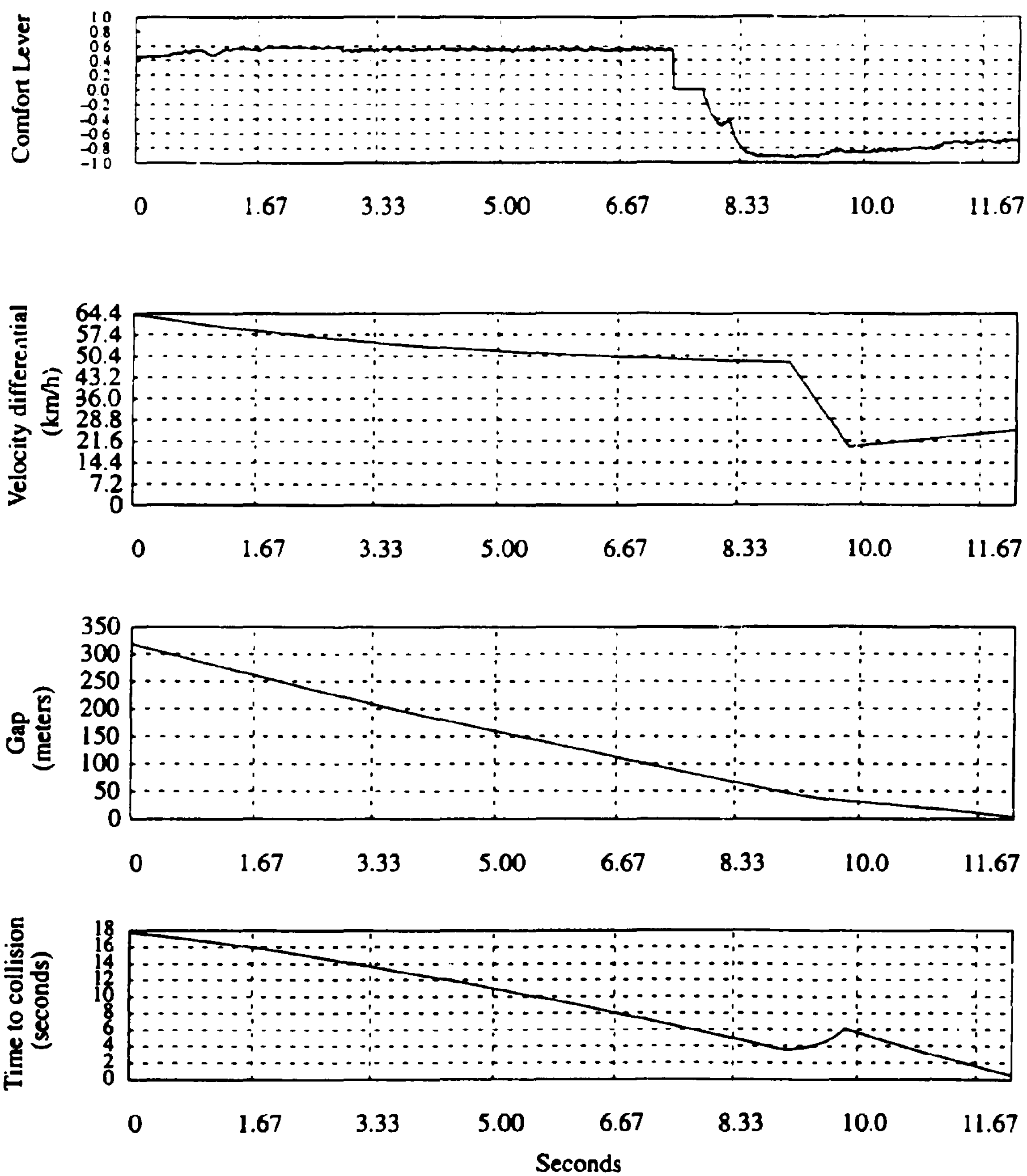

Figure 9. Comfort level, velocity differential, inter-vehicle gap, and time to collision as a function of time (in seconds) for an older female driver, when the second vehicle entered late and the design velocity was 153.0 km/h (95 mi/h).

velocity was 104.7 km/h (65 mi/h), the decrease in comfort occurred at 41.0 m (134.4 ft) for the male drivers and 47.4 m (155.4 ft) for the female drivers; when the velocity was 128.8 km/h (80 mi/h), the decrease occurred at 63.0 m (207 ft) for both the male and female drivers. However, when the design velocity was 153.0 km/h (95 mi/h), the separation between the driver's vehicle and the entering vehicle when the decrease in comfort began was significantly greater for the female drivers than for the male drivers—the separations were 123.8 m (406 ft) and 90.6 m (297 ft), respectively.

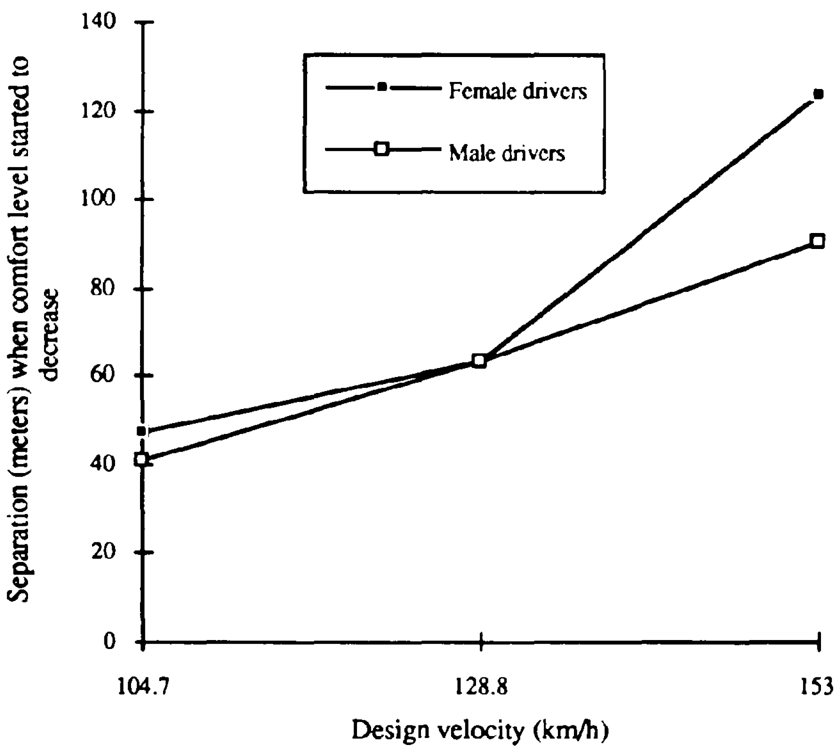

Figure 10. The separation distance at which the decrease in the driver's comfort level occurred as a function of the gender of the driver and the design velocity.

The interaction between design velocity and the time at which the second vehicle entered the automated lane is shown in figure 11. With the two lower design velocities—104.7 km/h (65 mi/h) and 128.8 km/h (80 mi/h)—the separation when the decrease in the driver's comfort level began was greater for the early time of entry than for the late entry time: in contrast, when the design velocity was 153.0 km/h (95 mi/h) this was reversed—the separation was smaller for the early time of entry than for the late entry time.

By inspecting figure 11 it is possible to determine whether the sharp decrease in comfort level was triggered by the driver's perception of the separation between the simulator vehicle and the entering vehicle. The separation between the vehicles does not appear to have been the triggering mechanism—figure 11 shows that the separation was not invariant with the design velocity: instead, it increased with design velocity, whether the second vehicle entered the automated lane relatively early or relatively late. The discomfort of the drivers cannot be attributed to the driver's perception of the separation between vehicles alone.

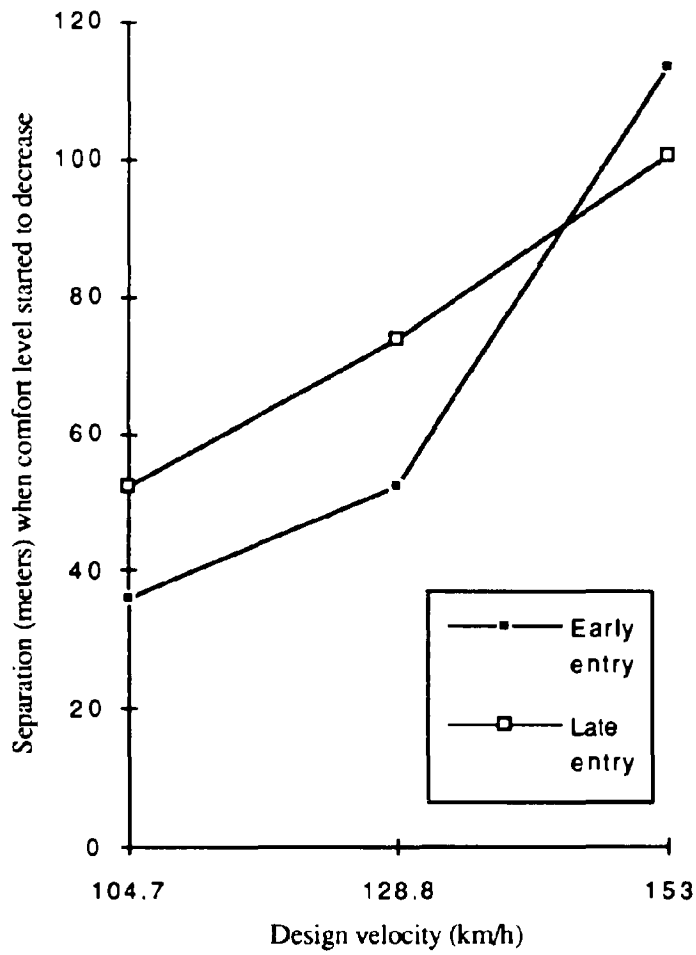

Figure 11. The separation distance at which the decrease in the driver's comfort level occurred as a function of the time of entry and the design velocity.

VELOCITY DIFFERENTIAL

The ANOVA exploring the velocity differential between the two vehicles at the moment that the decrease in comfort level began is summarized in table 13 in appendix 3. This analysis indicated that three of the independent variables were statistically significant. First, the gender of the driver was significant at the $p = 0.0075$ level—the velocity differential when the decrease in comfort level occurred was 42.3 km/h (26.3 mi/h) for the female drivers and 38.4 km/h (23.9 mi/h) for the male drivers.

There was an interaction between the other two significant variables—the design velocity, and the time at which the second vehicle entered the automated lane. Figure 12 explores this interaction, which was significant at the $p = 0.0001$ level (as were the two variables themselves).

Figure 12 shows that there was no difference in the velocity differential when the design velocity was 104.7 km/h (65 mi/h), but that when it was higher—128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h)—the velocity differential between the driver's vehicle and the second vehicle when the decrease in comfort level occurred was lower when the second vehicle entered relatively early, than it was when it entered relatively late.

As to whether the sharp decrease in the driver's level of comfort was triggered by a particular velocity differential, inspection of figure 12 shows that, when the second vehicle entered the automated lane relatively early, there was little variability in the differential velocity—however, when the second vehicle entered the automated lane relatively late, the velocity differential did increase with the design velocity. On the basis of these data, it is possible to argue that when the second vehicle entered the automated lane relatively early, and/or when the driver's vehicle was traveling at the lower design velocity, the sharp decrease in the comfort level was triggered by a differential velocity in the 15.0 km/h (9.3 mi/h) to 22.0 km/h (13.7 mi/h) range. However, it is clear that this did not happen when the second vehicle entered the automated lane relatively early and the driver's vehicle was traveling at the higher design velocities—128.8 km/h (80 mi/h) or 153.0 km/h (95 mi/h). The discomfort of the drivers cannot be attributed to the differential velocity alone.

TIME TO COLLISION

The ANOVA exploring the time to collision between the two vehicles at the moment that the decrease in comfort level began is summarized in table 14 in appendix 3. Two of the

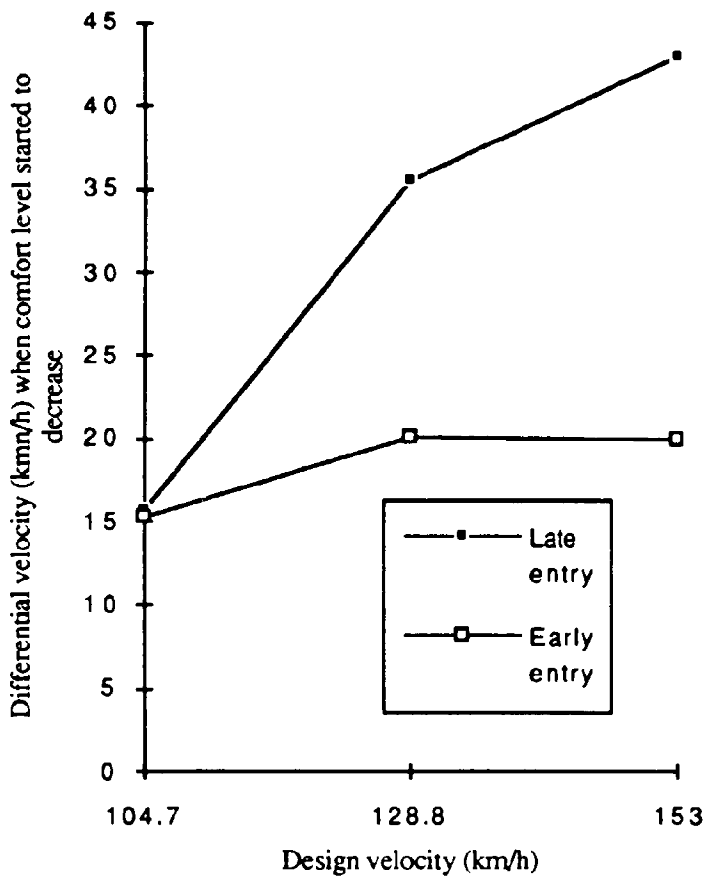

Figure 12. The velocity differential when the decrease in the driver's comfort level occurred as a function of the time of entry and the design velocity.

independent variables—the design velocity, and the time at which the second vehicle entered the automated lane—were significant, both at the $p = 0.001$ level, and once again there was a significant interaction between them—also at the $p = 0.0001$ level. This interaction is explored in figure 13.

As can be seen from figure 13, when the second vehicle entered late there was relative little difference in the time to collision at all three design velocities. When the second vehicle entered the automated lane relatively early the time to collision was much greater for the 153.0 km/h

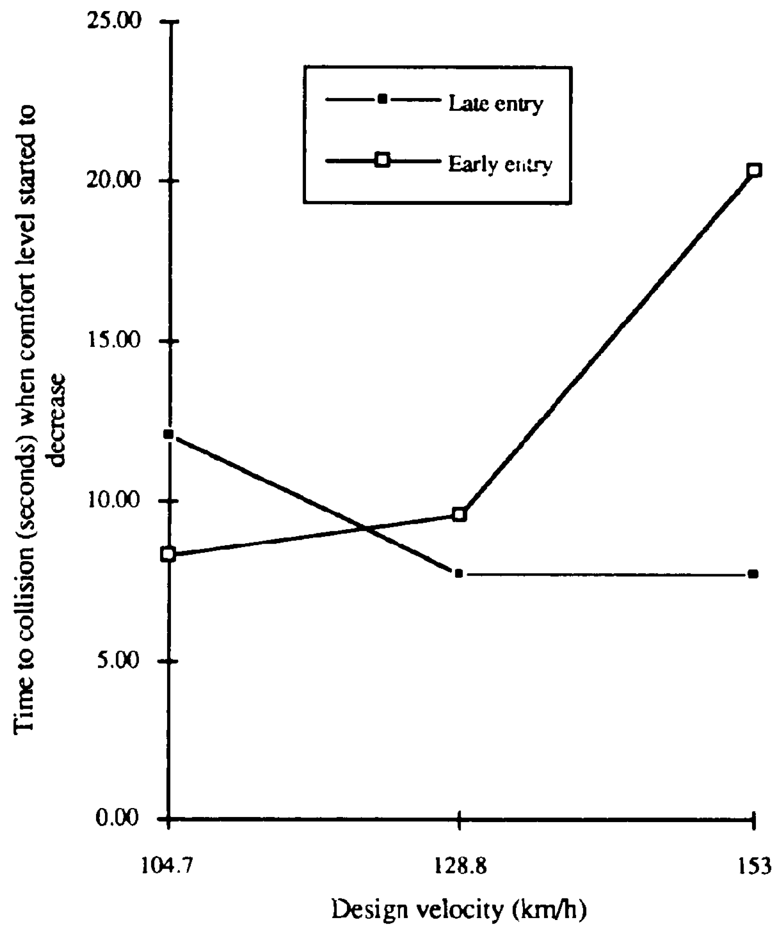

Figure 13. The time to collision when the decrease in the driver's comfort level occurred as a function of the time of entry and the design velocity.

(95 mi/h) velocity condition than it was at the two lower velocities —which were in the same range as the times to collision for the late entry.

Figure 13 was inspected to determine whether the time to collision parameter was any more likely to have triggered the sharp decrease in the driver's level of comfort than either the separation between the vehicles or the velocity differential were. From figure 13, it can be seen that there was relatively little variability in the time to collision, when the second vehicle entered the automated lane relatively late, and when the design velocity was 104.7 km/h (65 mi/h) or

128.8 km/h (80 mi/h) and the second vehicle entered the automated lane relatively early. It was only when the design velocity was 153.0 km/h (95 mi/h) and the second vehicle entered the automated lane relatively early that the time to collision was clearly different from the other five values. On the basis of these data, it is possible that when the second vehicle entered the automated lane relatively early, and/or when the driver's vehicle was traveling at the lower design velocity, the sharp decrease in the comfort level was triggered by the driver using information derived from the optic flow field when the time to collision was between 7.5 s and 12.0 s.

The sharp decrease in comfort level indicated by the drivers may be triggered by time to collision estimates. Although it does not provide a complete answer—when the second vehicle entered the automated lane relatively early and the driver's vehicle's design velocity was 153.0 km/h (95 mi/h), the decrease in the comfort level was triggered when the time to collision was much higher (20.4 s) than it was with the other combinations of design velocity and time of entry—nevertheless, time to collision is clearly a more likely trigger than the separation between the driver's vehicle and the entering vehicle, and it is also marginally better in this regard than the velocity differential.

SECTION 5: QUESTIONNAIRE DATA

INTRODUCTION

Seven of the questions in the questionnaire used for the multiple experiment are of relevance to the current experiment.

After each of these seven questions, a 103-mm (4-in) response bar was presented. At each end of the response bar, there were anchor points that reflected the extremes of each possible response to the questions posed. An anchor point was also placed in the middle of the bar to reflect a neutral value between the two extremes. The drivers were asked to mark the bar in a location that indicated their responses. Each response was measured, in millimeters, from the left end to the mark made by the driver. A score between 0 and 51 reflects a response that favors the extreme to the left—the closer the score is to 0 the more it favors the extreme position. A score between 52 and 103 reflects a response that favors the extreme to the right—the closer the score is to 103 the more it favors the extreme position. The neutral point was between 51 and 52.

An ANOVA was conducted on the responses to the seven questions to determine whether they were affected by the age or gender of the driver. The results of these analyses are presented in the subsections that follow.

INTER-STRING GAP AND DESIGN SPEED

Questions 11 and 12 dealt with design velocity and inter-string gaps. There were no statistically significant differences in the responses to question 11—consequently, the response data presented in table 3 are averaged over age and gender. Question 11 dealt with the gap between the driver's vehicle and the string of vehicles ahead. The average response was to the left—indicating that the drivers would have preferred longer gaps.

The responses to question 12 were significantly affected by the age of the driver ($p = 0.0392$) —consequently, the responses presented in table 3 are averaged over gender. For the younger drivers, the responses to question 12 were to the right—indicating that these drivers would have preferred the velocity in the automated lane to have been faster. In contrast, the responses of the older drivers were essentially neutral.

Table 3. Inter-string gap and design speed.

Question	Overall Mean
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? L. Strongly preferred longer distance R. Strongly preferred shorter distance	31.8

Question	Younger Drivers	Older Drivers
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? L. Would prefer much slower R. Would prefer much faster	59.8	49.0

ACCURACY OF THE COMFORT LEVER RESPONSE

No statistically significant differences were found when an ANOVA was conducted on the responses to the question that dealt with the accuracy of the comfort lever. The data presented in table 4—averaged over age and gender—are to the right, indicating that the drivers felt their responses with the comfort lever did reflect how comfortable they were about the vehicle directly ahead in the automated lane.

Table 4. Accuracy of the response with the comfort lever.

Question	Overall Mean
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? L. Did not reflect my comfort level R. Accurately reflected my comfort level	74.6

ATTITUDE TOWARD THE AHS

The next four questions dealt with the attitudes of the drivers towards the AHS.

A statistically significant interaction (p = 0.0323) between the age and gender of the driver was found for question 22(c)—the average responses of the younger male, older male, younger female, and older female drivers to this question are given in table 5. As can be seen from the table, the interaction occurred because the younger and older female drivers, as well as the younger male drivers, had average responses—all greater than 80—that indicated that they were considerably more comfortable with the portion of the drive where the simulator vehicle was under the control of the AHS than were the older male drivers (whose average score was 67.1).

Table 5. Attitude toward the AHS.

Question	Younger Female Drivers	Older Female Drivers	Younger Male Drivers	Older Male Drivers
22(c). During the portion of the drive where your steering and speed were automatically controlled, how did this feel? L. Very uncomfortable R. Very comfortable	81.1	88.2	84.5	67.1

Question	Overall Mean
23. How would you feel if an Automated Highway System was installed on I-380 between Iowa City and Waterloo? L. Very unenthusiastic R. Very enthusiastic	73.9
24. If an Automated Highway System was installed on I-380, would you prefer driving in the automated lanes or the manual lanes? L. Strongly prefer manual lanes R. Strongly prefer automated lanes	71.0

Question	Younger Drivers	Older Drivers
25. If an Automated Highway System was installed, would you feel safer driving on I-380 than you do now without the System? L. Much safer with current freeways R. Much safer with Automated Highway System	56.0	73.0

Since there were no significant differences for questions 23 and 24, the responses shown in table 5 were averaged over both age and gender. These responses indicate that the drivers were in favor of the AHS being installed on the local Interstate freeway and, if it were installed, would prefer traveling in the automated lanes rather than the manual lanes.

There was a statistically significant effect for the final question in this section—since the responses varied with the age of the drivers ($p = 0.0053$), they were averaged over gender in table 5. Although both the younger and older drivers thought that it would be safer to drive on the local freeway if the AHS were to be installed, it is clear that the older drivers, with a score of 73.0, believed this more strongly than the younger drivers, with a score of 56.0. This may be because the older drivers have come to lack confidence in their driving abilities and believe that the automated highway may be more reliable.

SECTION 6: SUMMARY OF RESULTS AND IMPLICATIONS FOR THE AUTOMATED HIGHWAY SYSTEM

The objectives of this experiment were to determine the comfort level of the driver of the lead vehicle of a string of automated vehicles (a) under normal operating conditions, and (b) during the time that a second was joining the string and replacing the driver's vehicle as the lead vehicle. The results of the experiment indicate that:

(1) When the simulator vehicle was the leader of a string of automated vehicles operating normally, with a fixed inter-string distance between it and the string ahead, the driver was comfortable: positive comfort levels were recorded on 89.9 percent of the 217 trials—the average value over all trials was + 0.54.

(2) Also, when the simulator vehicle was the leader of a string of automated vehicles operating normally, with a fixed inter-string distance between it and the string ahead, the level of comfort varied with the gender of the driver—the mean comfort level was higher for the male drivers than it was for the female drivers, perhaps because female drivers are more cautious than males, or because they may be more suspicious of new technology.

(3) When a second vehicle entered the automated lane ahead of the simulator vehicle, in 86.2 percent of the trials the comfort level of the drivers decreased after the second vehicle entered the automated lane. In 71.6 percent of the trials it decreased to a negative comfort level. The driver was not comfortable in this situation—the mean level dropped to – 0.52.

(4) Also, when a second vehicle entered the automated lane ahead of the simulator vehicle, the level of comfort varied with both the gender and the age of the driver —the mean comfort levels were: – 0.37 for younger males, – 0.45 for younger females, – 0.54 for older males, and – 0.71 for older females.

(5) There are indications that the abrupt discomfort indicated by the drivers may be triggered by time to collision estimates—time to collision is a more likely trigger than either the separation between the simulator vehicle and the entering vehicle, or the velocity differential, although it does not provide a complete explanation.

These results have the following implications for the design of the AHS: First, it is to be expected that drivers will be comfortable when they are in the lead vehicle of a string of automated vehicles during normal (AHS) operations—although female drivers may be somewhat less ready than male drivers to travel in the automated lane. Second, drivers are not likely to be comfortable when they are in the lead vehicle of a string of automated vehicles if another vehicle joins the string by taking over as the new leader. The joining procedure used in this experiment—where the entering vehicle did, in fact, join the string as the new leader—was necessary because of the large velocity differential between the speed limit in the unautomated lanes and the highest design velocity that was tested: it would take a very long time for a vehicle that was traveling at 88.6 km/h (55 mi/h) to catch up to a string traveling at 153.0 km/h (95 mi/h). It is probable that drivers would eventually become accustomed to this entering method, and no longer be uncomfortable as they approached the entering vehicle—although this experiment gives no indication of how long it might take for this to happen.

Another alternative would be to use a different entering procedure. If the velocity differential were small, it would be relatively easy for the entering vehicle to join the string as the trailing vehicle. In this case, it is far less likely that drivers would be uncomfortable as the distance between the entering vehicle and the last vehicle in the string was decreasing.

APPENDIX 1: ORDER OF PRESENTATION OF THE EXPERIMENTAL CONDITIONS

To minimize any learning effects, the order in which the experimental conditions were presented to the drivers was counterbalanced. The counterbalancing schemes used in the experiment are given below.

COMFORT LEVEL: NORMAL OPERATIONS

The order in which combinations of design velocity and inter-string separation were presented to the younger and older drivers in order to assess the comfort level of the driver in normal AHS operations is given in tables 6 and 7 respectively.

Keys for tables 6 and 7:

Combination #1: Design Velocity 65, Inter-String Separation 1
Combination #2: Design Velocity 80, Inter-String Separation 1
Combination #3: Design Velocity 95, Inter-String Separation 1
Combination #4: Design Velocity 65, Inter-String Separation 2
Combination #5: Design Velocity 80, Inter-String Separation 2
Combination #6: Design Velocity 95, Inter-String Separation 2

[Note
Design Velocity 65 is 104.5 km/h (65 mi/h)
Design Velocity 80 is 128.8 km/h (80 mi/h)
Design Velocity 95 is 153.0 km/h (95 mi/h)]

Table 6. The order of presentation of combinations of design velocity and inter-string separation for the younger drivers.

Driver	Order of Presentation			
YD01	3	4	2	5
YD02	4	5	1	2
YD03	1	6	3	4
YD04	6	2	5	1
YD05	2	3	4	6
YD06	5	1	6	3
YD07	2	3	4	6
YD08	1	6	2	4
YD09	6	2	3	5
YD10	3	4	5	1
YD11	4	5	1	3
YD12	5	1	6	2
YD13	4	5	1	2
YD14	5	3	6	1
YD15	2	4	3	6
YD16	1	2	5	4
YD17	3	6	2	5
YD18	6	1	4	3
YD19	3	5	6	1
YD20	1	6	2	4
YD21	4	3	1	5
YD22	2	1	5	6
YD23	6	2	4	3
YD24	5	4	3	2
YD25	5	1	6	3
YD26	3	4	2	5
YD27	4	5	1	2
YD28	1	6	3	4
YD29	6	2	5	1
YD30	2	3	4	6

Table 7. The order of presentation of combinations of design velocity and inter-string separation for the older drivers.

Driver	Order of Presentation			
OD01	5	3	6	1
OD02	4	5	1	2
OD03	2	4	3	6
OD04	3	6	2	4
OD05	1	2	4	5
OD06	6	1	5	3
OD07	2	1	4	6
OD08	6	3	2	4
OD09	1	4	5	3
OD10	3	6	1	5
OD11	4	5	3	2
OD12	5	2	6	1
OD13	3	6	2	4
OD14	1	5	6	3
OD15	4	3	1	5
OD16	2	1	5	6
OD17	6	2	4	1
OD18	5	4	3	2
OD19	4	1	3	5
OD20	2	3	6	4
OD21	6	5	1	3
OD22	3	2	4	6
OD23	5	6	2	1
OD24	1	4	5	2
OD25	1	2	6	4
OD26	5	1	3	6
OD27	2	4	5	3
OD28	3	6	1	5
OD29	6	3	4	2
OD30	4	5	2	1

COMFORT LEVEL WHILE A SECOND VEHICLE JOINED THE AUTOMATED LANE

The order in which combinations of design velocity and time to enter the automated lane were presented to the younger and older drivers in order to assess the comfort level of the driver while a second vehicle joined the string is presented in tables 8 and 9 respectively.

Key for tables 8 and 9:

Combination #1. Design Velocity 65, Intra-String Separation 1, Time to Enter 1
Combination #2. Design Velocity 80, Intra-String Separation 1, Time to Enter 1
Combination #3. Design Velocity 95, Intra-String Separation 1, Time to Enter 1
Combination #4. Design Velocity 65, Intra-String Separation 2, Time to Enter 1
Combination #5. Design Velocity 80, Intra-String Separation 2, Time to Enter 1
Combination #6. Design Velocity 95, Intra-String Separation 2, Time to Enter 1
Combination #7. Design Velocity 65, Intra-String Separation 1, Time to Enter 2
Combination #8. Design Velocity 80, Intra-String Separation 1, Time to Enter 2
Combination #9. Design Velocity 95, Intra-String Separation 1, Time to Enter 2
Combination #10. Design Velocity 65, Intra-String Separation 2, Time to Enter 2
Combination #11. Design Velocity 80, Intra-String Separation 2, Time to Enter 2
Combination #12. Design Velocity 95, Intra-String Separation 2, Time to Enter 2

[Note
Design Velocity 65 is 104.5 km/h (65 mi/h)
Design Velocity 80 is 128.8 km/h (80 mi/h)
Design Velocity 95 is 153.0 km/h (95 mi/h)]

Table 8. The order of presentation of combinations of design velocity, intra-string separation, and time to enter for the younger drivers.

Driver	Order of Presentation			
YD01	9	4	2	11
YD02	4	11	1	8
YD03	7	6	3	10
YD04	12	8	5	1
YD05	2	9	10	6
YD06	5	7	12	3
YD07	8	9	4	6
YD08	7	6	2	10
YD09	12	8	3	5
YD10	3	10	11	1
YD11	4	5	7	9
YD12	11	1	12	2
YD13	10	5	7	2
YD14	11	3	6	7
YD15	8	4	9	6
YD16	1	2	11	10
YD17	3	12	8	5
YD18	12	1	4	9
YD19	9	11	6	1
YD20	7	6	8	4
YD21	4	9	1	11
YD22	2	7	5	12
YD23	12	2	10	3
YD24	5	10	3	8
YD25	5	7	6	9
YD26	9	4	8	5
YD27	4	11	7	2
YD28	1	12	3	10
YD29	12	2	11	1
YD30	8	3	10	6

Table 9. Order of combinations of design velocity, intra-string separation, and time to enter for the older drivers

Driver	Order of Presentation			
OD01	11	3	12	1
OD02	4	11	1	8
OD03	8	4	3	12
OD04	9	6	2	10
OD05	7	2	10	5
OD06	6	7	5	9
OD07	8	1	4	12
OD08	12	3	2	10
OD09	1	10	11	3
OD10	9	6	7	5
OD11	4	11	9	2
OD12	5	8	6	7
OD13	3	6	8	10
OD14	7	11	6	3
OD15	4	9	7	5
OD16	2	1	11	12
OD17	12	8	4	1
OD18	5	10	9	2
OD19	4	1	9	11
OD20	2	9	6	10
OD21	12	5	7	3
OD22	5	8	10	6
OD23	3	12	2	7
OD24	1	4	11	8
OD25	1	2	12	10
OD26	5	7	9	6
OD27	8	4	11	3
OD28	9	12	1	5
OD29	6	3	10	8
OD30	4	11	2	7

APPENDIX 2: EXTRACT OF THE NARRATIVE FOR THE TRAINING VIDEOS FOR THE MULTIPLE EXPERIMENT

VIDEOTAPE #1: MANUAL TRANSFER ON ENTRY TO AHS

[A. Introducing the AHS]

[Camera position #1]

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.

[Camera position #1]

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]

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

[C. Comfort Level]

[Camera position #1]

Passage C.1: For the next few minutes, the Automated Highway System will move you along rapidly in the automated lane, steering your car and controlling its speed automatically. While this is happening, we will ask you to indicate how comfortable you are with the System by moving a lever situated close to the shift stick. The research host who accompanies you in the vehicle will let you know when you should do this.

If you are comfortable, please push this lever forward, away from you:

—the more comfortable you are, the further you should push the lever.

If you are uncomfortable, please pull it back, towards you.

—the more uncomfortable you are, the nearer you should pull the lever.

[D. Reduced Capability]

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

APPENDIX 3: ANOVA SUMMARY TABLES

Appendix 3 contains the full summary tables for the ANOVA's conducted on the data for this experiment. They are presented in the same order in which they are discussed in sections 3 and 4.

Table 10. Summary of the ANOVA conducted to determine whether the comfort level of the driver was affected by the age or gender of the driver, the design velocity, or the inter-string gap.[1]

Source	Degrees of Freedom	Sum of Squares	Variance Estimate	F	p
Age (A)	1	0.03240	0.03240	0.31	0.5810
Gender (G)	1	1.60303	1.60303	15.12	0.0001
Design Velocity (V)	2	0.01910	0.01910	0.09	0.9139
Inter-String Gap (I)	1	0.19148	0.19148	1.81	0.1805
A x G	1	0.00556	0.00556	0.05	0.8191
A x V	2	0.02859	0.01429	0.13	0.8739
A x I	1	0.24211	0.24211	2.28	0.1323
G x V	2	0.04162	0.04162	0.20	0.8219
G x I	1	0.09990	0.09990	0.94	0.3329
V x I	2	0.33464	0.16732	1.58	0.2089
A x G x V	2	0.03487	0.01744	0.16	0.8484
A x G x I	1	0.21949	0.21949	2.07	0.1518
A x V x I	2	0.08975	0.04488	0.42	0.6554
G x V x I	2	0.10326	0.05163	0.49	0.6152
A x G x V x I	2	0.15065	0.07532	0.71	0.4926
Residual	193	20.45738	0.10600		
Total	216	23.65383			

[1] There were 217 trials in which comfort level data were obtained before the second vehicle entered the automated lane ahead of the driver's vehicle.

Table 11. Summary of the ANOVA conducted to determine whether the comfort level—of the driver of the lead vehicle of a string when a second vehicle attempted to join the string as the new lead vehicle—was affected by the age or gender of the driver, by the design velocity or by the time at which the second vehicle entered the automated lane.[1]

Source	Degrees of Freedom	Sum of Squares	Variance Estimate	F	p
Age (A)	1	2.04433	2.04433	12.25	0.0006
Gender (G)	1	0.96281	0.96281	5.77	0.0174
Design Velocity (V)	2	0.65980	0.32990	1.98	0.1417
Entry Time (T)	1	0.08091	0.08091	0.48	0.4872
A x G	1	0.04462	0.04462	0.27	0.6058
A x V	2	0.32450	0.16225	0.97	0.3803
A x T	1	0.04355	0.04355	0.26	0.6101
G x V	2	0.19120	0.09560	0.57	0.5650
G x T	1	0.17841	0.17841	1.07	0.3026
V x T	2	0.61688	0.30844	1.85	0.1607
A x G x V	2	0.37137	0.18568	1.11	0.3311
A x G x T	1	0.09349	0.09349	0.56	0.4552
A x V x T	2	0.04195	0.02098	0.13	0.8819
G x V x T	2	0.72584	0.36292	2.18	0.1169
A x G x V x T	2	0.61350	0.30675	1.84	0.1623
Residual	163	27.19455	0.16684		
Total	186	34.18771			

[1] There were 187 trials in which there was a decrease in the driver's comfort level when another vehicle entered the automated lane ahead of the driver's vehicle.

Table 12. Summary of the ANOVA conducted to determine whether the separation between the driver's vehicle and the entering vehicle at the moment that the decrease in the driver's comfort level began, was affected by the age or gender of the driver, by the design velocity or by the time at which the second vehicle entered the automated lane.[1]

Source	Degrees of Freedom	Sum of Squares	Variance Estimate	F	p
Age (A)	1	3520.1	3520.1	2.34	0.1280
Gender (G)	1	7379.3	7379.3	4.91	0.0282
Design Velocity (V)	2	123244.3	61622.2	40.98	0.0001
Entry Time (T)	1	2951.8	2951.8	1.96	0.1632
A x G	1	1108.5	1108.5	0.74	0.3919
A x V	2	3800.4	1900.2	1.26	0.2855
A x T	1	1119.0	1119.0	0.74	0.3896
G x V	2	9570.6	4785.3	3.18	0.0442
G x T	1	247.7	247.7	0.16	0.6854
V x T	2	10502.4	5251.2	3.49	0.0328
A x G x V	2	2902.6	1451.3	0.97	0.3832
A x G x T	1	37.9	37.9	0.03	0.8740
A x V x T	2	6628.6	3314.3	2.20	0.1137
G x V x T	2	6,505.2	3252.6	2.16	0.1184
A x G x V x T	2	1,455.7	727.9	0.48	0.6172
Error	159	239103.4	1,503.8		
Total	182	417152.9			

[1] In 4 of the 187 trials in which there was a decrease in the driver's comfort level when another vehicle entered the automated lane ahead of the driver's vehicle, separation data were not available.

Table 13. Summary of the ANOVA conducted to determine whether the velocity differential between the driver's vehicle and the entering vehicle at the moment that the decrease in the driver's comfort level began, was affected by the age or gender of the driver, by the design velocity or by the time at which the second vehicle entered the automated lane.[1]

Source	Degrees of Freedom	Sum of Squares	Variance Estimate	F	p
Age (A)	1	7.884	7.884	1.36	0.2446
Gender (G)	1	42.365	42.365	7.33	0.0075
Design Velocity (V)	2	598.231	299.115	51.76	0.0001
Entry Time (T)	1	557.338	557.338	96.44	0.0001
A x G	1	11.354	11.354	1.96	0.1630
A x V	2	16.977	8.489	1.47	0.2333
A x T	1	7.147	7.147	1.24	0.2678
G x V	2	22.692	11.346	1.96	0.1438
G x T	1	1.840	1.840	0.32	0.5734
V x T	2	285.955	142.978	24.74	0.0001
A x G x V	2	7.921	3.960	0.69	0.5054
A x G x T	1	4.987	4.987	0.86	0.3543
A x V x T	2	18.673	9.336	1.62	0.2020
G x V x T	2	21.951	10.976	1.90	0.1531
A x G x V x T	2	7.124	3.562	0.62	0.5412
Error	159	918.872	5.779		
Total	182	2612.361			

[1] In 4 of the 187 trials in which there was a decrease in the driver's comfort level when another vehicle entered the automated lane ahead of the driver's vehicle, velocity differential data were not available.

Table 14. Summary of the ANOVA conducted to determine whether the time to collision at the moment that the decrease in the driver's comfort level began, was affected by the age or gender of the driver, by the design velocity or by the time at which the second vehicle entered the automated lane.[1]

Source	Degrees of Freedom	Sum of Squares	Variance Estimate	F	p
Age (A)	1	0.810	0.810	0.06	0.8009
Gender (G)	1	19.553	19.553	1.54	0.2165
Design Velocity (V)	2	934.583	467.291	36.81	0.0001
Entry Time (T)	1	534.698	534.698	42.12	0.0001
A x G	1	6.788	6.788	0.53	0.4657
A x V	2	15.436	7.718	0.61	0.5458
A x T	1	0.096	0.096	0.01	0.9307
G x V	2	29.173	14.587	1.15	0.3197
G x T	1	0.184	0.184	0.01	0.9044
V x T	2	1979.465	989.733	77.96	0.0001
A x G x V	2	43.871	21.935	1.73	0.1811
A x G x T	1	10.539	10.539	0.83	0.3637
A x V x T	2	13.656	6.828	0.54	0.5851
G x V x T	2	15.050	7.525	0.59	0.5541
A x G x V x T	2	36.501	18.251	1.44	0.2407
Error	155	1967.837	12.696		
Total	178	5925.481			

[1] In 4 of the 187 trials in which there was a decrease in the driver's comfort level when another vehicle entered the automated lane ahead of the driver's vehicle, time-to-collision data were not available.

SECTION 7: REFERENCES

1. Bloomfield, J.R., Buck, J.R., Carroll, S.A., Booth, M.W., Romano, R.A., McGehee, D.V., and North, R.A. (1995). "Human Factors Aspects of the Transfer of Control From the Automated Highway System to the Driver." Revised Working Paper (Contract No. DTFH61-92-C-00100; FHWA-RD-94-114). McLean, VA: Turner-Fairbank Highway Research Center, Federal Highway Administration. WDC: DOT FHWA.

2. Bloomfield, J.R., Buck, J.R., Christensen, J.M. and Yenamandra, A. (1995). "Human Factors Aspects of the Transfer of Control from the Driver to the Automated Highway System." Revised Working Paper (Contract No. DTFH61-92-C-00100; FHWA-RD-94-173). McLean, VA: Turner-Fairbank Highway Research Center, Federal Highway Administration. WDC: DOT FHWA.

3. Bloomfield, J.R., Christensen, J.M., Peterson, A.D., Kjaer, J.M., and Gault, A. (1995). "Human Factors Aspects of the Transfer of Control from the Driver to the Automated Highway System with Varying Degrees of Automation." Revised Working Paper (Contract No. DTFH61-92-C-00100; FHWA-RD-95-108). McLean, VA: Turner-Fairbank Highway Research Center, Federal Highway Administration. WDC: DOT FHWA.

4. Bloomfield, J.R., Carroll, S.A., Papelis, Y.E., and Bartelme, M., (in preparation). "The Ability of the Driver to Deal with Reduced Capability in an Automated Highway System" Report to be submitted to the Federal Highway Administration.

5. Bloomfield, J.R., Christensen, J.M., and Carroll, S.A. (1995). "The Effect on Normal Driving Behavior of Traveling Under Automated Control." Draft Working Paper (Contract No. DTFH61-92-C-00100; FHWA-RD-95-182). McLean, VA: Turner-Fairbank Highway Research Center, Federal Highway Administration. WDC: DOT FHWA.

6. Transportation Research Board (1985). "Highway Capacity Manual: Special Report 209." Washington, DC: National Research Council.

7. Kuhl, J.G., Evans, D.F., Papelis, Y.E., Romano, R.A., and Watson, G.S. (in press) "The Iowa Driving Simulator: An Immersive Environment for Driving-Related Research and Development." *IEEE Computer, 28*, 35–41.

8. Kuhl, J.G. and Papelis, Y.E. (1993). "A Real-Time Software Architecture for an Operator-in-the-Loop Simulator." *Proceedings of Workshop on Parallel and Distributed Real-Time Systems*. Newport Beach, California. Pages 117-126.

9. Wall, M. (1995). "Motion Perimetry in Optic Neoropathies. In.: Mills, R.P., and Wall, M. (1995) *Perimetry Update 1994/95*. New York: Kugler Publications, pp. 111–117.

10. Wall, M., and Montgomery, E.B. (1995). "Using Motion Perimetry to Detect Visual Field Defects in Patients with Idiopathic Intracranial Hypertension: A Comparison with Conventional Automated Perimetry." *Neurology, 45*, 1169–1175.

11. Stevens, S.S. (1959). "Cross-Modality Validation of Subjective Scales for Loudness, Vibration, and Electric Shock." *Journal of Experimental Psychology, 57*, 201-209.

12. Lee, D.N. (1976). "A Theory of Visual Control of Braking Based on the Information About Time-to-Collision." *Perception, 5*, 437-459.

13. van der Horst, R. (1991). "Time-to-Collision as a Cue for Decision-Making in Braking." In: Gale, A.G., Brown, I.D., Haselgrave, C.M., Moorhead, I., and Taylor, S. (editors) *Vision in Vehicles—III*. Elsevier Science Publishers B.V. (North-Holland), Amsterdam/New York, pp. 19-26